W7-AS Contributions to the 6th Toki Conference
(29 Nov - 2 Dec 1994, Toki City, Japan)

W7-AS Contributions to the
10th International Stellarator Conference
(22-26 May 1995, Madrid, Spain)

W7-AS Contributions to the 22nd EPS Conference on
Controlled Fusion and Plasma Physics
(3 - 7 July 1995, Bournemouth, Great Britain)

IPP/111/203
Sept 1995

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
85748 GARCHING BEI MÜNCHEN
W7-AS Contributions to the 6th Toki Conference  
(29 Nov - 2 Dec 1994, Toki City, Japan)

W7-AS Contributions to the  
10th International Stellarator Conference  
(22-26 May 1995, Madrid, Spain)

W7-AS Contributions to the 22nd EPS Conference on  
Controlled Fusion and Plasma Physics  
(3 - 7 July 1995, Bournemouth, Great Britain)

Measurement and Calculation of Radial Electric Fields  
IPPIII/203  
Sept 1995

Stability Analysis of low χ Configurations with  
Different Toroidal Ripples in W7-AS  
J. Geiger

Edge Transport Studies on the W7-AS Stellarator  
P. Grigull

Topological Aspects of Island Divertors in  
Wendelstein 7-AS  
J. Hofmann

Ion Confinement in "Transport Optimized" Configurations  
of the Stellarator W7-AS  
M. Kück

Transport Experiments in W7-AS  
U. Stroth

W7-AS with Modified Minor Ratio at High χ-Values  
F. Rau

Global Alfvén Eigenmodes in Wendelstein 7-AS  
A. Weller

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem  
Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die  
Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.
W7-AS Contributions to the 6th Toki Conference  
(29 Nov - 2 Dec 1994, Toki City, Japan)

W7-AS Contributions to the 10th International Stellarator Conference  
(22-26 May 1995, Madrid, Spain)

W7-AS Contributions to the 22nd EPS Conference on Controlled Fusion  
and Plasma Physics  
(3 - 7 July 1995, Bournemouth, Great Britain)

<table>
<thead>
<tr>
<th>Title: 6th Toki Conference Japan</th>
<th>Contents</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent Transport Experiments in W7-AS</td>
<td>U. Stroth</td>
<td></td>
</tr>
<tr>
<td>A Summary on H-Mode Studies in W7-AS</td>
<td>F. Wagner</td>
<td></td>
</tr>
</tbody>
</table>

| Title: 10th Stellarator Conference Madrid 95: |
| Measurement and Calculation of Radial Electric Fields in W7-AS | J. Baldzuhn |
| Stability Analysis of low \( \zeta \) Configurations with Different Toroidal Ripples in W7-AS | J. Geiger |
| Edge Transport Studies on the W7-AS Stellarator | P. Grigull |
| Topological Aspects of Island Divertors in Wendelstein7-AS | J. Hofmann |
| Ion Confinement in "Transport Optimized" Configurations of the Stellarator W7-AS | M. Kick |
| Transport Experiments in W7-AS | U. Stroth |
| W7-AS with Modified Mirror Ratio at High \( \zeta \)-Values | F. Rau |
| Global Alfvén Eigenmodes in Wendelstein 7-AS | A. Weller |

| Title: 22nd EPS-Conference Bournemouth 95: |
| High Power Heating Experiments on Wendelstein 7-AS Stellarator | R. Jaenicke |
| Transport Studies of Injected Impurities in the Stellerator Wendelstein AS | R. Burhenn |
| Topological Aspects of Island Divertor Studies on W7-AS | J. Das |
Response of the Plasma Confinement on Shear Modification by Electron Cyclotron Current Drive at W7-AS  V. Erckmann

Combined Analysis of Steady State and Transient Transport by the Maximum Entropy Method  L. Giannone

Correlation between Helium Particle Transport and Electron Density Profiles in W7-AS  M. Hirsch

Influence of L- and H-Mode and Rotational Transform on the Edge Density Profiles in W7-AS  G. Kocsis

ECRH Absorption of Second Harmonic X- and O-Mode at the W7-AS Stellarator  H. Laqua

Scrape-Off Layer Turbulence in the ASDEX Tokamak and the Wendelstein 7-AS Stellarator: T_e Fluctuations and Structures  H. Niedermeyer

Kinetic Description of ECRH produced Superthermal Electrons in the Wendelstein 7-AS Stellarator  M. Romé

Edge Transport and Modelling on the W7-AS Stellarator  F. Sardei

Collective Scattering of Powerful 140 GHz Radiation at W7-AS  E. Suvorov

Simulation and Analysis of Neutral Particle Spectra for W7-AS  B. Wolle
6th International Toki Conference
on Plasma Physics and Controlled Nuclear Fusion
"Research for Advanced Concepts in Magnetic Fusion"
November 29 - December 2, 1994
Ceratopia Hall in Toki-City, Japan
Recent Transport Experiments in W7-AS

U. Stroth, J. Baldzuhn, B. Brañas*, V. Erckmann, T. Estrada*,
L. Giannone, M. Hirsch, H.-J. Hartfuß, M. Kick, G. Kühner,
H. Ringler, F. Wagner, ECRH Group, W7-AS Team
Max-Planck-Institut für Plasmaphysik, EURATOM-IPP Association, 85748 Garching, Germany
EURATOM/Ciemat Association, 28040 Madrid, Spain

Abstract

Parameter scans in density, heating power and isotope mass have been carried out in W7-AS. ECRH at a frequency of 140 GHz has allowed to study the density scaling of the energy confinement time of ECRH plasmas up to densities of $10^{20} m^{-3}$. In power scans it has been tried to relate the power degradation of the energy confinement to a local plasma parameter. Transport analyses using power balance an heat wave techniques indicate that the transport coefficient does not depend on the electron temperature or related parameters. This observation can be reconciled with power degradation if the transport coefficient is formally allowed to vary with changes in the heating power on a faster than the diffusive time scale. Such a transport process describes also the observations in the dynamic phases following large changes in the heating power.

II. Density dependence transport

The energy confinement time of W7-AS plasmas increases with density. A previous regression analysis done on a restricted database yielded a dependence like $\tau_E \sim n_e^{0.7}$ for ECRH plasmas and $\tau_E \sim n_e^{0.5}$ if also NBI heated discharges were included. The database was limited by two restrictions. The use of 70 GHz ECRH limited investigations of ECRH plasmas to $n_e \leq 4 \times 10^{19} m^{-3}$ and difficulties with density control did not allow to study stationary NBI heated discharges at low densities.

The installation of 140 GHz ECRH now allows for the first time to heat plasmas up to $n_e \approx 10^{20} m^{-3}$ by ECRH only. The progress made in wall conditioning by boronization and helium glow discharges as well as the use of combined heating will allow to study density-controlled NBI discharges more closely in the future.

ECRH plasmas can be compared with ohmically heated tokamak plasmas, which also show a clear density dependence of $\tau_E$ (LOC regime). In tokamaks, the regime of improving $\tau_E$ with density is followed by a saturated one (SOC) where $\tau_E$ becomes density independent. Ohmic heating and ECRH have in common that only the electrons are heated directly. Energy is coupled to the ions by electron-ion collisions.

The increase of $\tau_E$ with density, is it a genuine effect of stellarator transport or just an image of the tokamaks LOC regime? To investigate this, high density ECRH discharges have been carried out in W7-AS. The experiments were done at $B_t = 2.5 T$ and $\varphi_a = 0.34$. The heating power of $P = 0.45 MW$ was supplied.
by 140 GHz ECRH. A typical discharge is depicted in Fig. 1. As input for a power balance the relevant profiles have been measured during the stationary phases. Electron density from Thomson scattering and temperature from ECE measurements have been used. The ion temperature profile is from a set of CX neutral-particle analysers. The centrally measured $Z_{\text{eff}}$ ranges from 3 to 2 with increasing density. Radiation profiles were measured by a bolometer array; the total radiated power is always below 15% of the heating power. In order to get an independent estimate for the electron heat conductivity from transient analyses a heat wave was induced by modulating the ECRH with a frequency of 92 Hz ($\Delta P \approx 10\%$).

It has also been tried to relate the parameter dependence of the energy confinement to changes in the plasma turbulence level indicated by fluctuations of the plasma parameters. The amplitude of the density fluctuations was measured by a heterodyne reflectometer. In order to obtain radial profiles, the frequency was ramped up in steps of 10 ms duration.

The global energy confinement time of this series of discharges is shown in Fig. 2. It increases up to a line-averaged density of $\bar{n}_e \approx 5 \times 10^{19} \text{m}^{-3}$. A regression of the data in Fig. 2 up to this density yields a strong density dependence of $\tau_E \sim \bar{n}_e^{0.85}$. For comparison, the data of a previous database yielding $\tau \sim \bar{n}_e^{1.7}$ are overlaid. Please notice that in the latter data set also other parameters than the density are varied.

At densities $\bar{n}_e \geq 5 \times 10^{19} \text{m}^{-3}$ a saturation of $\tau_E$ sets in. This is a new feature in W7-AS. Figs. 3 and 4 give relevant profile information in order to discuss the similarity of the saturation to the tokamak SOC regime. The profiles were taken at low, middle and high density. In Fig. 4 it can be seen that at the two lower densities the ions are almost de-coupled from the electrons. As expected, at higher densities where the saturation occurs the coupling becomes stronger and $T_e$ and $\bar{T}_i$ come very close in the confinement region. But there is a second effect superimposed. The $T_e$ profile at high density has a flattened area in the vicinity of 9 cm. Looking at many profiles shows clearly that this region increases with density. Since these discharges have a very flat $\bar{\epsilon}$ profile in the vicinity of $\epsilon = 1/3$ it is possible that the flat region is related to a distortion of the magnetic configuration. It has also been tried to change the $\bar{\epsilon}$ profile by horizontally shifting the plasma and it could indeed be observed that the step in $T_e$ becomes smaller. The energy confinement time of the discharges with modified configuration are indicated by open triangles in Fig. 2. The optimising procedure increases the energy content but the gap to the line given by the scaling expression could not yet be filled.

In summary, $\tau_E$ of W7-AS plasmas saturates with density in a similar way as in the tokamaks SOC regime.
But it is not clear yet how much of the saturation is due to a distortion of the magnetic configuration.

The comparison of measured ion temperatures made in Fig. 4 to the prediction by neoclassical theory is satisfactory. For the neoclassical description the DKES code with an ambipolar electric field was used.

In Fig. 5, it can be seen that the saturation sets in first in the electron energy. The total energy continues to increase until the ion energy also saturates. As shown in Fig. 4, the saturation occurs when $T_e$ and $T_i$ become almost equal. The fraction of the energy carried by the ions compared to the electrons increases from 5% at the lowest density up to 50% at $n_e = 5 \times 10^{19} m^{-3}$. The maximum values are reached at $r \approx 15$ cm; further out $T_i$ is larger than $T_e$ and the ions couple the energy back to the electrons.

Power balance analyses using a purely diffusive ansatz were carried out for the density scan. Ray tracing calculations were used as basis for the power deposition profile. In Fig. 6 the results for the electron heat conductivity can be seen. In order to avoid contributions from the flat region in the temperature profile, the transport coefficient is given in radial zones inside and outside of the flat region. The values in the figure represent radial averages around a normalised radius of $\rho = 0.4 \ (5 \leq r \leq 8.5 \ cm)$ and $\rho = 0.8 \ (12 \leq r \leq 15 \ cm)$. The error of the transport coefficient was estimated by performing power balances with modified temperature profiles. Both the $T_e$ and $T_i$ profiles were separately increased and decreased by a constant amount of 10% and, in order to change gradients in the confinement region, by adding and subtracting a cosine with an local amplitude of 10% of the temperature. The error bars cover the highest and lowest $\chi_e$ obtained from transport analyses with the eight different profile combinations.

At both radial positions in Fig. 6 electron and ion channel can be separated with sufficient accuracy. In the inner and outer regions of the plasma a saturation of the improvement in $\chi_e$ with density is observed at density values of 4 to 5 $10^{19} m^{-3}$. At this density also...
the electron energy content saturates (see Fig. 5).

It has also been tried to relate the transport coefficient to the level of density fluctuation measured by a reflectometer. For each discharge, radial profiles are available in the density gradient region. In Fig. 7 the fluctuation level at fixed radii is depicted as a function of density. The fluctuation level decreases and saturates with density in the same way as $\chi_e$ does (see Fig. 6 at $\rho = 0.8$).

The ion energy transport becomes an important issue for stellarators as soon as the ions enter the long-mean-free-path regime. At low collisionalities, neoclassical theory predicts increasing transport coefficients with decreasing collisionality. If no relevant radial $E_r$ field develops, this could lead to high ion energy losses when fusion relevant ion plasma parameters are reached. The transport coefficient also would depend strongly on the radial electric field $E_r$.

Conditions with the lowest values of the ion collisionality in W7-AS, under which a test of the neoclassical predictions would be possible, are achieved with combined NBI and ECRH. ECRH allows for density control and NBI provides direct heating of the ions. Under these conditions, central ion temperatures of up to 950 eV could be achieved. In Fig. 8, experimental and neoclassical ion energy fluxes are compared for a discharge heated with 800 kW of balanced NBI and 750 kW ECRH. The neoclassical fluxes are calculated by the DKES code, taking the ambipolar radial electric field into account. If the dependence of the transport coefficient on $E_r$ is neglected, the fluxes increase by about a factor of 2. The accuracy of the experimental fluxes is not high enough to discuss whether the influence of $E_r$ on the ion transport coefficients is described correctly by neoclassical theory. This might change, when lower collisionalities will be achieved for which the role of $E_r$ will become more pronounced. But, at the onset of the long-mean-free-path regime, the magnitude of the experimental ion energy fluxes is described reasonably well by neoclassical theory.

The ambipolar electric field used in Fig. 8 is confirmed experimentally. In Fig. 9, the ambipolar field is compared to values deduced from measurements of the poloidal rotation. The measurements were carried out using CXR spectroscopy on He.

### III. Power dependence of transport

The power degradation can be observed in discharges where the temperature is the only local parameter changed by the heating power. Hence, temperature $T$ or its gradient $VT$ are the obvious local parameters through which the transport coefficients could change with heating power. The first being favoured by collisional as well as drift wave-type of theories and the second by models using marginal stability of modes at some critical temperature gradient. Alternatively, it could be thought of the heating power as a global parameter which could directly influence the transport behaviour of the plasma (i.e. by non-thermal particle populations which drive turbulence). In steady state, the heating power is roughly equal to the local power flux $q$.

A power dependence like $\tau_E \sim P^{-0.6}$, for example,
Figure 8: Ion energy flux derived from a power balance using a CX ion temperature profile compared to neoclassical theory including an ambipolar electric field. For the neoclassical heat flux in one case the dependence of the transport coefficients on the radial electric field was taken into account, in the other the values at $E_r = 0$ were used.

could be caused equally well by three different forms of transport coefficients:

$$\chi_e \sim \nabla T^{\frac{1}{2}}$$
$$\chi_e \sim T^{\frac{3}{2}}$$
$$\chi_e \sim q^{\frac{5}{2}}.$$  \hspace{1cm} (1)

This can be easily seen by using $\tau_E = a^2 / \chi$ and $\tau_E \sim nT / P$ together with $\nabla T \sim T / a$.

In steady state, it is principally not possible to distinguish between the local $\nabla T$ and the global $P$ as degrading agents. They are linked by the relation $P \sim n_0 \chi \nabla T$. Only the transient behaviour of the plasma allows this distinction.

A valid model not only has to describe the global and the power balance results correctly, also the behaviour of the plasma in transient phases lays strict experimental constraints especially on the dependence of $\chi_e$ on $T_e$ and $\nabla T_e$. These constraints will be separately discussed in Sec. V. In the following the dependence of the electron transport coefficient $\chi_e$ on $T_e$, $\nabla T_e$ or $P$ will be investigated from the view point of the power balance.

In order to disentangle the role played by the different parameters, on and off-axis power scans have been carried out in W7-AS. The experiments were done

Figure 9: The radial electric field as derived from plasma rotation measured by CXRS on He compared to the neoclassical ambipolar field.

at $B_t = 2.5 \, T$, $\tau_e = 0.34$ and $n_e = 2.5 \times 10^{19} \text{m}^{-3}$. The power was varied from 0.1 to 0.85 $\text{MW}$ using two $70 \, \text{GHz}$ gyrotrons at about $0.2 \, \text{MW}$ power each and a $140 \, \text{GHz}$ gyrotron at $P = 0.45 \, \text{MW}$. At all power levels the plasma is well diagnosed during stationary phases and the same data as described for the density scan in Sec. II are available.

In Fig. 10, the global confinement time for on and off-axis power scans are plotted as a function of heating power. The change in heating position only influences the central part of the profiles, which does not contribute much to the total energy content. The difference in the global confinement time is less than 10% and both, on and off-axis data, are well represented by a dependence like $\tau_E \sim P^{-0.5}$.

In Fig. 11 some of the profiles are depicted. For the on-axis power scan the density profiles are different at the lowest heating powers (0.1 and 0.2 $\text{MW}$). The central density of these discharges is 30% higher but the line averaged densities are the same. The increase of the total energy with heating power is achieved not only by steepening the gradients but, at least in the low power range, also by an increasing plasma radius.

The comparison of the discharges is done with help of a power balance analysis in the same way as described in Sec. II. The results presented in Figs. 12-13 concern again averages of small radial regions in the inner part and the outer part of the plasma.

In Fig. 12 the local energy flux in the electrons is plotted as a function of the electron temperature gradient. In both radial zones a non-linear dependence of $q$
Figure 10: Global energy confinement time for on and off-axis power scans as function of heating power. The plasma parameter were $\varepsilon = 0.34$, $B_t = 2.5 \, T$ and $n_e = 2.5 \times 10^{19} \text{m}^{-3}$.

on $\nabla T$ can be seen. Under the assumption of a diffusive transport model ($q = n\chi \nabla T$), this indicates a dependence of the transport coefficient on $T$, $\nabla T$ or related quantities.

In Fig. 13 the transport coefficient for the inner plasma region is related to the local electron temperature and its gradient. There is a clear increase of $\chi_e$ with $T_e$ as well as with $\nabla T_e$ and the degradation of the confinement time is also reflected in the local transport coefficients. But it is of course trivial that a power scan which changes $\nabla T$ leads to a correlation between $\chi_e$ and $\nabla T$ as well as $T$ when simultaneously the confinement degrades with heating power.

A dependence of $\chi_e$ on $T$, $\nabla T$ or $P$ can only be discriminated in a transient experiment where the parameters can be modified on different time scales. As it will be discussed in Sec. IV, dependencies as observed above will have consequences for the transient transport properties of the plasma.

IV. Transient transport studies

Transient transport studies are an independent method to determine transport coefficients from the response of the plasma to small perturbations. The comparison of the energy transport coefficient from heat wave ($\chi_e^{HW}$) and power balance analyses ($\chi_e^{PB}$) gives information on the dependence of $\chi_e$ on $T_e$ and $\nabla T_e$:

$$\chi_e \sim T^\alpha \rightarrow \frac{\chi_e^{HW}}{\chi_e^{PB}} = 1 + \frac{c}{\sqrt{\gamma_m}}$$

$$\chi_e \sim \nabla T^\beta \rightarrow \frac{\chi_e^{HW}}{\chi_e^{PB}} = 1 + \beta$$

(2)

If a $T_e$ dependence exists a dependence of the ratio on the power modulation frequency $f_m$ is introduced. A dependence on $\nabla T_e$ or the local heat flux $q$ cannot be separated and leads consistently to $\chi_e^{HW}/\chi_e^{PB}$ ratios larger than 1. In tokamaks indeed $\chi_e^{HW}/\chi_e^{PB}$ ratios well above one are measured and can be taken as a signature of a $\nabla T_e$ dependence of $\chi_e$.

In W7-AS, strong dependencies on $T_e$, $\nabla T_e$ or the local power flux can be excluded\cite{6,5}: In Fig. 14, the two $\chi_e$ values are compared for the density and the power scan. It can be seen that the transport coefficient deduced from heatwave analysis is of comparable magnitude of $\chi_e^{PB}$ and also shows a similar scaling with heating power and density. A dependence stronger than $\chi_e \sim \nabla T_e^{0.5}$ can be excluded up to the highest heating power. That there is also no temperature dependence can be seen from Fig. 15. $\chi_e^{HW}$ does not depend on the modulation frequency of the heating power.

From the transient transport results and those from the power scan in W7-AS an apparent contradiction emerges: In Figs. 13 $\chi_e$ increases clearly with $T_e$, $\nabla T_e$. On the other hand it has just been shown that $\chi_e$ cannot depend on either of these parameters.

This contradiction can be resolved with a phe-
Figure 12: Local electron energy flux radially averaged between 5 and 8.5 cm ($\rho = 0.4$) and between 12 and 15 cm ($\rho = 0.8$) as function of temperature gradient.

Figure 13: Radially averaged electron heat diffusivity of the power scan as function of electron temperature and temperature gradient.

A nomenclature model in which $\chi_e$ does not significantly depend on the local power flux but on a process which depends directly on the heating power inside the respective flux surface. The idea is that the transport coefficient reacts on a change in heating power along a faster than the diffusive time scale. Of course, such a model yields power degradation. But also the result from transient processes are described correctly. The basic idea is explained in Fig. 16: If transport is governed only by local parameters the energy flux must follow the line $q = \eta x VT$. The transport coefficient corresponds to the slope of a straight (dotted) line from the origin to a point on the line. If the power is modulated by $\delta P$ the slope of a tangent ($\chi^{inc}$) is measured as transport coefficient, which is larger than the real $\chi$. If $\chi$ changes on a fast time scale with $P$, the local heat flux $q$ follows the fat line: When the power is decreased, $q$ changes at a constant $VT$ down to a point which corresponds to $\chi$ at the lower heating power ($\chi^-$). Then the plasma returns diffusively back to the point valid for stationarity. $q$ runs through the second half of the square if the power is increased again. After a sharp increase $q$ follows again diffusively back to the point of departure. The result is a heat wave which does not propagate with $\chi^{inc}$ but with $\chi^-$ and $\chi^+$, both being very close to the average $\chi$ value measured by the power balance.

A model with a rapidly changing $\chi_e$ was also successful in describing the transient response of the plasma after a large amount of the heating power was switched on or off. In Fig. 17 the time evolution of the electron temperature measured by the ECE radiometer is depicted after changes in the heating power from 0.2 to 0.6 and back to 0.2 MW. It has been tried to simulate the time behaviour by different models using a time dependent transport code. $\chi_e$ models using a $T_e$ dependence or assuming that $\chi_e$ stays constant predict a too fast response of the plasma. Only the model where $\chi_e$ changes after times shorter than 1 ms to the steady state value at the new power level can describe the time traces correctly.
The contradictions gathered in comparing steady state and transient transport coefficients can be solved in a satisfactory way if one assumes that the transport coefficient reacts on a faster than the diffusive time scale on changes in heating power. At present, it is, however, unclear what physical mechanism can transmit the information of a central change in power on such a fast time scale to the plasma periphery. For the conclusions it is essential that the power deposition profile does not appreciably deviate from what is known from ray-tracing calculations and high frequency power modulation experiments.

V. Isotope effect

For tokamaks, the favourable dependence of the confinement time on isotopic mass is well established. No detailed studies are available for stellarators. In order to examine the isotope mass scaling of W7-AS, H and D discharges are compared at the same plasma parameters: $B_t = 2.5 \, T$, $\tau = 0.52$, $\bar{n}_e = 3.5 \times 10^{19} \, m^{-3}$ and $P = 0.4 \, MW$. In both cases the vessel was freshly boronised using $B_2H_6$ and $B_2D_6$ for the documentation of H and D discharges, respectively.

The time traces of two representative discharges are depicted in Fig. 18. At the same density and heating power a 20% higher energy content is obtained in the deuterium discharges. The improvement is in the electron channel, which is also the dominant loss channel in these discharges. The analyses of all discharges gives a preliminary isotopic effect like $\tau_E = m^{0.2 \pm 0.15}$.

VI. Conclusions

Density and power scans have been carried out to investigate the local parameter dependence of the transport coefficients.

An ECRH density scan reveals similarities between the favourable density scaling in W7-AS with the tokamak LOC regime. The improvement of $\chi_e$ with density saturates at $\bar{n}_e \geq 5 \times 10^{19} \, m^{-3}$. No major deviation of ion energy transport from neoclassical theory have been observed. A comparison of hydrogen and deuterium discharges indicates the existence of a small isotopic effect in W7-AS. Isotopic mass and density are local plasma parameter dependencies, consistent with the picture of a local transport model as indicated by the gyro-Bohm-like scaling behaviour of W7-AS confinement.

Under the assumption that the power deposition profile does not deviate dramatically from the ray tracing results, no local parameter could be related to power degradation of confinement. Three different types of transport experiments could be consistently described only if a transport coefficient is assumed which changes almost instantaneously with heating power. A possible physical picture would be, that stationary plasma conditions can be described by local parameters, while the reorganisation of the plasma state, occurring after
Figure 16: The different results for $\chi_e$ from heatwave studies produced by a transport coefficient depending on a local plasma parameter and one which changes on a fast time scale with heating power.

Figure 17: Time evolution of the electron temperature at two different plasma radii during transient phases after changes in the ECRH power of $\pm 0.4$ MW. The lines are simulation results from a time dependent transport code using different models for $\chi_e$: a constant $\chi_e$ at the value before the change in $P$ (a), $\chi_e \sim T^{1.5}$ (b) and a $\chi_e$ which adjusts at the time point of the change in $P$ to the steady state value valid for the new power level.

Figure 18: Time traces of two comparable discharges in hydrogen and deuterium at $B_t = 2.5$ T and $\tau = 0.52$ changes in heating power, leads transiently to a different type or level of turbulence which can propagate on a fast time scale across the plasma.

References

A SUMMARY ON H-MODE STUDIES IN W7-AS


Max-Planck-Institut für Plasmaphysik
Boltzmannstrasse 2
85748 Garching, Germany, EURATOM Association

* CIEMAT, Spain
** KFKI, Hungary
*** IPF, University Stuttgart

ABSTRACT

We will give a summary on the status of H-mode studies on W7-AS stellarator. The major H-mode characteristics compare well with those known from the tokamak H-mode. All major characteristics of the H-mode are reproduced: The transition is spontaneous above a power and density threshold; particle and energy confinement improve simultaneously; a transport barrier at the edge develops with steep pressure gradients and ELMs appear; small scale fluctuations are strongly reduced and the development of a radial electric field is indicated by increased perpendicular impurity flow velocity. The temporal development of the transition seems to be distinctively slower than in tokamaks. The H-mode can be initiated by ECRH or NBI, respectively. The power threshold can be smaller than that of tokamaks. With ECRH, the density threshold is found to increase with heating power. The H-mode develops in small windows of the accessible iota range. These operational islands are characterised by a negative electric field already prior to the H-mode and a distinct maximum in space potential at the separatrix.

I. INTRODUCTION

Stellarators need an improvement of their confinement to meet the ignition conditions of a future reactor of attractive size. Like for tokamaks, the H-mode may provide sufficient improvement. In addition, the H-mode in W7-AS contributes to the understanding of H-mode physics because of the large differences of this device to tokamaks. W7-AS is a low shear stellarator. It can be expected that both the type of turbulence and its level as well as the stability of gross MHD instabilities are affected thereby and can give rise to differences to tokamaks.

Another important parameter of W7-AS is the large aspect ratio (A = 10) resulting in lower poloidal flow damping (via magnetic pumping). The non-axisymmetric stellarator configuration should allow for a different ion loss geometry, there should be toroidal flow damping with a non-negligible neo-classical contribution, the poloidal damping should have contributions from toroidally and locally trapped particles and the radial neo-classical flux components are not intrinsically ambipolar. At present the full flexibility of the magnetic configuration of W7-AS (e.g. the possibility to vary the mirror ratio) has not yet been used for H-mode investigations.

II. H-MODE CHARACTERISTICS

The H-mode of W7-AS develops spontaneously. It shows all characteristics as known from the tokamak H-modes [1]: edge plasma parameters (ne, Te and Ti) increase within the LCFS, fluctuations (density and magnetic field) instantly decrease, the poloidal impurity flow velocity at the edge vφ (BIV) increases in the electron drift direction, the transition is frequently preceded by limit-cycle oscillations (dithers), and ELMs can develop. The increase in confinement is, however, moderate and not more than 30%.

Figure 1 summarises the major H-mode characteristics observed in W7-AS. Plotted is (from top left to bottom right) the energy content W of an ECF heated plasma (140 GHz, 0.4 MW), the line density, the core electron temperature, the perpendicular flow velocity of BIV, the magnetic fluctuation level and Hα. The transition is
indicated by the double line. It develops typically within 10 ms and is slower than in tokamaks where it can be shorter than 0.1 ms. In the frame of a bifurcation, it corresponds more to a soft transition. Dithers frequently appear at the transition.

III. TRANSPORT BARRIER AND FLUCTUATION LEVEL

The development of a transport barrier [2] is well documented. Both $T_e$ and $T_i$ increase at the edge; the density increases and develops steep gradients. Within the error bars it can be determined that the $n_e$-gradient steepens also within the SOL. The space potential sharply drops inside the LCFS indicating an electric field of about 100 V/cm; this value is also borne out by the flow measurement (BIV). The fluctuations decrease in the zone of the transport barrier.

Figure 2 shows the time development of fluctuations from the magnetic probe, reflectometry probing the edge, and microwave scattering. The $H_\alpha$ trace is shown for reference. Also shown is a schematic of the microwave scattering geometry. At the transition the fluctuation level decreases. The effect is weak within the plasma core (sampled by $\mu$-waves). Also the edge fluctuation decrease slower than known from tokamaks. The drop in core fluctuations seems to be further delayed.

Figure 3 shows results from Langmuir probe studies in the SOL and within the transport barrier. The major radius of the LCFS and the approximate accuracy of its location are indicated. Within the transport barrier the particle flux, obtained from correlated density and potential fluctuations is strongly reduced after the transition. Similar results were obtained from DIII-D [3] and PBX-M [4]. Fig. 3 also compares the spectra of the fluctuations in potential and ion saturation current. In particular the latter decreases after the transition. The decrease occurs over the whole frequency range.

IV. PERPENDICULAR ROTATION AND SPACE POTENTIAL

Figure 4 shows the temporal evolution of $H_\alpha$, $T_i(a)$, the impurity flow velocity $v_i$, and the floating potential of probes mounted into the limiter or that of the limiter $\Phi_f \lim$ itself during an H-mode transition at $\zeta(a) = 0.53$. The $H_\alpha$ trace indicates the distinct drop into the H-phase. Simultaneously, $v_i$ (representing the $E \times B$ component as the diamagnetic contribution can be neglected), the edge electron and ion temperature (BIV), and the edge density increase at the transition. The sharp drop in floating potential at the H-transition is caused predominantly by a drop in space potential. The H-mode transition is accompanied by a stronger negative electric field at the edge [5]. The strong temporal development of the edge parameters can be used to explore their correlation. $\Phi_f \lim$ scales linearly with $v_i$ in the expected manner (see Fig. 4 d). At the H-transition, both $v_i$ and $\Phi_f \lim$ jump. This jump can occur at different combinations of $v_i$ and $\Phi_f \lim$ and can be of different magnitude. $\Phi_f \lim$ can be measured with good time resolution. The increase of $\Phi_f \lim$ precedes that of $H_\alpha$ in a back transition by about 50 $\mu$s.

V. OPERATIONAL BOUNDARIES FOR THE H-MODE

The H-mode in W7-AS can be reached with ECRH (70 or 140 GHz) or NBI. The power threshold is lower than expected from the tokamak scaling. For the high iota-case ($\zeta(a) = 0.53$), the H-mode was obtained for 1.25 and 2.5 $T$ (the two field values for 70 and 140 GHz ECRH application) with the minimal power of one gyrotron (200 kW) which corresponds to a P/S value of 0.015 MW/m$^2$.

There is clearly a density limit which is itself a function of heating power. The density limit is about 3$\times 10^{13}$ cm$^{-3}$; for larger power higher density is required.

Figure 5 compares the low density discharge #28959 (3$\times 10^{13}$ cm$^{-3}$) with the higher density discharge #28960 (4$\times 10^{13}$ cm$^{-3}$). Plotted is the energy content W, the line averaged density $n_e$ (dashed lines), the electron and ion (dashed) temperatures $T_e$ and $T_i$ (please note the different ordinates for $T_e$ and $T_i$) and the perpendicular flow velocity (BIV). The heating scenario is 70 GHz at 0.2 MW followed by 0.4 MW. The phases with H-modes are indicated in the $v_{perp}$ diagrams.

In both cases, $T_i$ drops when the increased heating sets in. This seems to be caused by the loss of coupling to $T_e$. The coupling efficiency depends on density. For the low density case $T_i$ drops more strongly and the H-mode disappears toward higher heating power. When the heating power is turned off, the H-mode transiently appears for a short period. The changes in confinement are indicated by the changes in perpendicular flow.

At higher density (right side of figure) the electron-ion coupling is still affected when the power is stepped up but the plasma remains within a dithering H-mode.

Two additional comments should be made.

(1) Both cases (high and low density) show the strong coupling between $T_i$ and $v_{perp}$. Like $v_i$, $T_i(a)$ correlates better than $T_e(a)$ with all H-mode transition conditions. Also during the preceding density ramp-up phase to meet the threshold
condition, both $v_\|$, $T_i(a)$ increase whereas $T_e(a)$ decreases (after the transition, it also increases).

(2) in a similar way short H- phases followed an L-mode discharge had been observed on ASDEX after the heating power has been switched off (see [6] Fig. 71).

A peculiarity of the H-mode of W7-AS is its restriction to a narrow $\zeta$ range $0.51 \leq \zeta(a) \leq 0.53$ where it occurs already for the lowest available heating power. This $\zeta$ range is characterised by the 5/9 island chain with little interference from the up-down limiters. The limiters restrict the connection length $L_c$ at the edge to about 10 circumferences. This $\zeta$ range provides good confinement also in the "L-mode". Detailed edge studies at low density in the "L-mode" have revealed that in this $\zeta$ range, the space potential $\Phi_{sp}$ has a singular and precisely defined maximum [7]. The radial E-field shows a strong step close to or at the LCFS from being positive in the SOL to negative inside the LCFS.

Figure 6 shows the variation in a wide iota range of the energy content and the floating potential of a probe embedded within the limiter. These results are obtained at 2.5 T outside the H-mode operational range in the L-mode. The H-mode is easily obtained around $\zeta(a) = 0.53$ where a deep minimum in potential (mostly space potential) is found already in the L-mode. This favourable precondition seems to ease the H-transition. Recently dithering H-modes have also been realised with ECRH of 0.4 MW around $\zeta(a) = 0.47$. Also at this $\zeta$-value, a low potential prevails.

VI. SUMMARY AND CONCLUSIONS

W7-AS differs strongly in its magnetic configuration in comparison to tokamaks. The existence of the H-mode in this device proves the universality of the mechanism which quenches the edge turbulence. The aspect of low magnetic shear at the edge (factor =10 lower than in tokamaks) enlarges the parameter regime for the study of ELMs; apart from rather irregular appearance, they do not seem to deviate from those observed in tokamaks at low power fluxes. Though the edge turbulence level is strongly reduced, the increase in energy content at the transition is clearly below the one of divertor tokamaks. This situation did not improve after the up-down limiters were removed. An improvement was expected as it is well known that excessive neutral gas degrades the H-mode [8]. We have to conclude that the limitation in confinement improvement at the transition may be more fundamental than originally anticipated. It is not clear at present whether the deficiency is based on insufficient development of the pedestal or of the core parameters. In comparison to ASDEX, the relative increase of the electron density is smaller and the relative increase in electron temperature seems to be restricted more to the edge.

Like in tokamaks, a strong electric field develops at the edge. The transition seems to develop, however, along a slower time scale than in tokamaks (ms instead of 0.1 ms). The experimentally observed characteristics of the H-mode transition are similar to those of tokamaks, and the findings are not in conflict with the decorrelation of edge turbulence via sheared flow [9]. The causality in the development of the radial electric field - if the search for it is meaningful at all - is still unresolved. The intrinsic possibilities of W7-AS to contribute to this question are not fully exploited yet. What has become clear from the small iota ranges where the H-mode can develop, is the existence of a preconditioned situation. This preconditioning can most clearly be recognized at $\zeta(a) = 0.53$. Only a small heating power is necessary there to realise the H-mode transition conditions. This iota value is characterised by a deep negative floating potential of a probe just within the LCFS and the existence of a negative electric field within the plasma periphery already prior to the H-transition.

On the other hand, the existence of a preconditioned state highlights the fact that the H-mode transition can be obstructed. It has long been known, that excessive neutral density surrounding the plasma can prevent or quench the transition. Therefore, the question arises whether the L-mode is the natural plasma state and a specific not yet identified mechanism initiates the H-mode or, vice versa, whether the H-mode with its concomitant flows is the natural plasma state whose development is prevented in the L-mode. The course of H-mode development points toward the latter view. In early experiments on tokamaks, the H-mode required specific device conditions and appeared in a restricted window of the operational range. Now, new devices which incorporate advanced wall properties and can operate at high plasma current develop the H-mode right in the ohmic regime and for some devices it is difficult to realise the L-mode. Therefore, the search for the transition mechanism should not only concentrate on a trigger mechanism which suddenly appears but also on an obstructing mechanism which causes L-mode conditions and which suddenly disappears. One obvious example is the fact that the H-mode can be prohibited by the abundant neutral density at the edge.

Sufficient heating power and the sawtooth trigger in the case of tokamaks may provide the H-mode because the neutral density within the plasma is
reduced and the edge pressure gradient is increased. There is ample evidence that the H-mode development is linked to the ion pressure at the edge and the electric field contribution its gradient provides. Though the limited edge diagnostic of ASDEX pointed toward the decisive role of the edge electron temperature it is clear from other studies and the close correlation between edge ion temperature, edge radial field and the development of the H-mode, as presented here, that it is actually the ion thermal equilibrium or radial force balance which determines the H-mode. Also recent post mortem ASDEX low energy neutral particle analysis of NBI heated discharges indicates an increase of the ion temperature in the plasma periphery at the transition surpassing that of the local electron temperature. In W7-AS the role of \( T_i \) is most clearly indicated by the power dependence of the density threshold at least as long as the ions are only collisionally heated. Higher ECRH heating power gives rise to larger electron and lower ion temperature. In order to establish the appropriate edge conditions higher density is necessary for the transition. It is interesting to note that insufficient conditions nevertheless allow the H-mode to transiently develop when the heating power is switched off. Such observations where also made on ASDEX. In tokamaks, the minimum H-mode threshold density is in the neighbourhood of the density where ohmic confinement changes from LOC to SOC. This transition density is also determined by ion-electron equilibration. The H-mode threshold density is somewhat lower because at the plasma edge ion coupling is achieved at lower electron temperature than in the bulk. From the aspect of equipartition it is obvious that the minimum transition density should decrease somewhat with size of the device. In ASDEX the transition density was about \( 1-2 \times 10^{13} \text{ cm}^{-3} \) and the LOC-SOC transition density was between \( 2.5 - 3 \times 10^{13} \text{ cm}^{-3} \); in W7-AS the H-mode requires a density above \( 4-5 \times 10^{13} \text{ cm}^{-3} \) whereas saturation in confinement has been observed for \( n_e > 8 \times 10^{13} \text{ cm}^{-3} \) [10]. We conjecture that the natural plasma state both for stellarators and tokamaks could be the H-mode. If so, the plasma state, necessarily far from thermal equilibrium, could nevertheless be a quiescent one. There is evidence that the bifurcation loop is set-up by the ion pressure gradient length \( \lambda_p \) which causes a characteristic E-field length \( \lambda_E \) which affects the radial correlation length of the turbulence \( \delta_{\text{corr}} \) which finally sets the level of turbulence and thus the pressure gradient: \( \lambda_p \rightarrow \lambda_E \rightarrow \delta_{\text{corr}} \rightarrow \lambda_p \). Whether there is a separate step necessary to initiate such a process cannot be concluded from the present results of W7-AS.

REFERENCES

[7] F. Wagner et al., IAEA 1994 (Sevilla)
FIGURE 1
Shown are H-mode characteristics (from top left to bottom right): energy content $W$, line average density, core electron temperature, perpendicular flow velocity from BIV, magnetic fluctuations, $H_\alpha$ trace. The H-transition is indicated by the vertical double bar.

FIGURE 2
Plotted are magnetic and density fluctuations from the plasma edge (via reflectometry) and further inward (from $\mu$-wave scattering). $H_\alpha$ is shown for reference; the scattering geometry is also depicted; the scattering results are obtained from the 6$^\circ$ channel.

FIGURE 3
The particle flux as obtained from density and potential fluctuations (using a Langmuir probe) are shown in the L- and H-mode. The data are plotted versus major radius from within the transport barrier and the SOL. Frequency spectra from the floating potential and the ion saturation current in L and H-mode are also plotted.

FIGURE 4
(a) $H_\alpha$-trace showing the H-transition.
(b) Ion temperature $T_i(a)$ and poloidal rotation $V_{\phi}^l$ (BIV) at the plasma edge during the discharge.
(c) Floating potential of two Langmuir probes within the transport barrier during the discharge.
(d) Limiter floating potential $\Phi_{lim}$ versus $V_{\phi}^l$ for three discharges with H-transitions.

FIGURE 5
Shown are two discharges at lower and at higher density and plotted is energy content $W$, density (dashed curves), electron and ion temperatures (dashed curves) and the perpendicular flow velocity (BVI). The heating scenario is given in the upper diagrams; ECRH at 0.2 MW is followed by ECRH at 0.4 MW. The H-mode phases are indicated within the lower diagrams. Please note the different ordinates for $T_e$ and $T_i$.

FIGURE 6
Variation of the energy content $W$ and the floating potential $\Phi_{lim}$ of a Langmuir probe within the upper limiter on iota(a). The results are obtained at low field and low density in the "L-mode". The ranges where the H-mode appears are indicated.
10th International Conference on Stellarators
22 - 26 May, 1995
Madrid, Spain
Measurement and Calculation of Radial Electric Fields in W7-AS
I. Baldzuhn, W. Ohlendorf, H. Maassberg, U. Stroth, G. Kühner, W7-AS-Team
Max-Planck-Institut für Plasmaphysik IPP, EURATOM-Association
85748 Garching, Germany

ABSTRACT
The radial electric field \( E_r \) in the advanced stellarator W7-AS [1] is determined by means of active charge exchange spectroscopy CXRS for a variety of plasma parameters. These measurements are compared with the „neoclassical“ ambipolar electric field, which is obtained by DKES calculations. The measurements are consistent to the „ion root“ solution of the ambipolarity condition. Impurity particle transport is investigated by spectroscopic measurements of helium and „neoclassical“ impurity transport calculations. The role of \( E_r \) herein is discussed.

MOTIVATION
The radial electric field plays an important role in the „neoclassical“ theory of stellarator plasmas. Attention is focused in this report on the question, in how far „neoclassical“ theory is adequate to describe the formation of \( E_r \). For the case that any „anomalous“ contribution appears as intrinsically ambipolar, \( E_r \) can be predicted numerically and its impact on transport can be estimated [3], for the present and for future plasma experiments.

Even moderate values of \( E_r \) can reduce the transport coefficients in the \( 1/\nu \) regime drastically [2]. Furthermore, for the „electron root“ solution a strong improvement in the confinement is expected, but it is still an open question how to bring about the „electron root“ experimentally.

Finally, positive \( E_r \) is expected to induce outward convection of the impurity ions [7]. This is of particular interest for the stellarator with its potential for steady state operation.

EXPERIMENTAL SETUP
For several discharges with different plasma parameters a short He gas puff is applied at the beginning of the discharge such that about 1% He concentration is achieved. Helium is used as „tracer impurity“ to measure spectroscopically the CX Doppler line shift, broadening and line intensity in a diagnostic neutral beam. For the ion-diamagnetic drift contribution in the momentum balance, the He II CX line intensity is measured. From this the He III density profiles are determined by a recursive algorithm, which takes into account the attenuation of the diagnostic beam in the plasma. The beam is pulsed with 10 Hz to allow for the subtraction of background radiation from the CX line radiation.

The toroidal and poloidal plasma rotation velocity, the ion temperature \( T_i \) and the He III concentration are determined as a function of the minor radius. This are all needed parameters which enter the momentum balance equation to evaluate \( E_r \) experimentally.

COMPUTER PROGRAMS
For the „neoclassical“ calculation of the radial electron and proton fluxes the DKES code is used (Drift Kinetic Equation Solver) [4], which takes into account several plasma parameters and the complete Fourier spectrum of the magnetic configuration. These fluxes enter the ambipolarity condition and allow thus for the calculation of all
"roots" for $E_r$. Normally, three solutions can be obtained. The "electron root" has high positive $E_r$ above the resonance condition $E_{\text{res}} = \text{iota} V_{\text{thermal}} B r / R$, the "ion root" has small $E_r$ below $E_{\text{res}}$, and a third "root" between them is unstable with respect to the solution of the time dependent ambipolarity condition for non-stationary plasmas. So far, no additional "anomalous" contribution to transport is taken into account.

For a "neoclassical" calculation of the He transport the IONEQ code is used [5]. It is a 1-D collisional impurity transport code and evaluates, among other things, the He III density profiles and charged radial impurity fluxes. It considers contributions from Banana-Plateau and Pfirsch-Schlüter regimes to the impurity transport by taking into account collisions, CX with a neutral gas background, recombination and ionization as well as radiation. The charged radial impurity fluxes are calculated to control for a possible influence on the ambipolarity condition of the DKES code particle flux results.

RESULTS
Fig. 1 shows the measured and calculated $E_r$ as a function of the effective minor radius for a 140 GHz ECRH discharge, heating power 400 kW, magnetic field 2.5T, $T_e(0) = 900$ eV, $T_i(0) = 600$ eV, mean $n_e = 3 \times 10^{19}$ m$^{-3}$, shots # 30097 - 30106. The separatrix is at 18 cm. The dots indicate spectroscopic measurements, the open circles Langmuir probe measurements [6]. The solid line shows the results of the DKES calculation, the broken lines the DKES results for the case that 20% measurement errors are assumed for $T_i$, $T_e$ and $n_e$.

Fig. 2 shows the measured and calculated $E_r$ for a 70 GHz ECRH discharge, heating power 400 kW, magnetic field 1.28T, $T_e(0) = 1500$ eV, $T_i(0) = 100$ eV, mean $n_e = 1 \times 10^{19}$ m$^{-3}$, shots # 27377 - 27399. The separatrix is at 17 cm. The dots indicate spectroscopic measurements, the solid line the DKES result for the "ion root" solution, the broken line for the "electron root" solution.
Fig. 3 shows a measured He III density profile (squares) for a 70 GHz ECRH discharge together with the result of the IONEQ calculation (dashed line). The separatrix is at 17 cm.

The calculated charged radial impurity fluxes from IONEQ play no role for the ambipolarity condition. The formation of \( E_r \) is therefore determined only by the electron and proton fluxes, as they are calculated by DKES.
DISCUSSION

Within the error bars, the measured $E_f$ are consistent with the "neoclassical" calculations. That holds for all 27 discharges investigated so far, which had been heated with 70 GHz, 140 GHz ECRH and NBI with heating powers between 200 kW and 1.6 MW, magnetic fields of 1.25T and 2.5T, and iota(a) = 0.34 and = 0.52. We find a "common" $E_f$ profile shape for all discharges, with small values near the magnetic axis, a minimum of $E_f$ between -50 V/cm and -300 V/cm about 3-6 cm within the separatrix and again small values for $E_f$ near the separatrix, and positive outside. The radial position of the minimum of $E_f$ and its value correlates well with the radial position and the maximum value of the ion temperature profile.

The Dokes calculations show that even the "ion root" solution can have positive values $= + 10 V/cm$ near the plasma axis for the case of high $T_e$, small $T_i$ and low $n_e$. This seems to have strong impact on the impurity transport. The He III density measurements as presented in Fig. 3 show a positive gradient inside 8 cm, stronger than predicted by the IONEQ calculations. The additional steepening of the gradient can be simulated for the IONEQ calculations by taking an additional $E_f$ for the flux equation into account. Again we find $E_f = + 10 V/cm$, as above. This could be an indication that the slightly positive $E_f$ leads to an additional outward convection of impurities. The appearance of the steepened gradients correlates with the appearance of positive "ion root" solutions in the plasma center. For the case that $T_e$ is comparable to $T_i$, or that $n_e$ is above $1 \cdot 10^{-19} m^{-3}$, the calculated and measured He III density profiles do not show that characteristic deviation from each other.

The measured higher negative gradient of the He III density profile outside 8 cm, compared to the IONEQ result, might have the corresponding cause, i.e. negative $E_f$ near the separatrix. These additional effects for the helium transport can not be considered by IONEQ calculations, because in this code the proton and electron fluxes are calculated not in the full geometry. In all discharges investigated so far, the "electron root" solution is never found experimentally. Only the "ion root" appears. From the consistency between measured and calculated $E_f$ we conclude that the formation of $E_f$ can be described by a "neoclassical" numerical model only. Any additional "anomalous" contribution which might play a role is intrinsically ambipolar and does therefore not influence $E_f$.

REFERENCES

The W7-A Team, NI Group, Nucl. Fus. 25 (1985), page 1593
Introduction: Wendelstein 7-AS is a modular low shear stellarator with 5 field periods. The operational range of the rotational transform is from about 0.25 to 0.7. Compared to a conventional stellarator W7-AS has reduced PS-currents due to its optimization which is only partial as compared to W7-X. The reduced PS-currents lead to a reduction of the Shafranov shift and lessen the influence of the pressure on the profile of the rotational transform \( \iota \). Stability against pressure driven modes is provided by a vacuum magnetic well of up to 2\% depending on the configuration. Since the parallel currents are driving terms in the Mercier- and resistive interchange stability criterion their reduction leads to improved stability properties.

Experimentally the most significant mode activity attributed to high beta has been observed at frequencies of 4-8kHz with NBI powers of \( \approx 1.5MW \) at 1.25T. The mode structure as inferred from soft X-ray data corresponds to \( k_{||} = 0 \) with \((m,n) = (3,1),(5,2),(2,1)\) in the vicinity of the corresponding \( \iota \)-values. Previous analysis with respect to Mercier-modes and ideal global modes predicted stability for these conditions [1]. We therefore extend the analysis to resistive interchange modes having lower stability limits. Moreover, to clarify the role of the magnetic configuration with respect to the stability behaviour, we also investigate configurations deviating from the usually considered ones.

Equilibrium configurations: The magnetic configuration of W7-AS is determined by the currents in the four coil systems, namely in the modular coils (I_m), in the large special coils (I_s) located in the region of strongest toroidal curvature at the mid period ("elliptical" cross section), the toroidal field coils (I_t) and in the vertical field coils (I_v). Therefore, up to the magnetic field strength the configuration is fixed by three coil current ratios which are related to different descriptive quantities of the magnetic field: \( I_v/I_m \) is related to the position of the magnetic axis and is known to reduce the vacuum magnetic well when the axis is shifted inward, \( I_t/I_m \) can be used to adjust the rotational transform \( \iota \) and \( I_s/I_m \) determines the toroidal ripple \( r_t \) of the magnetic field strength, B, as defined by its Fourier components in Boozer coordinates \((r_t = B_{0,1}/B_{0,0}; B_{m,n} \text{ with } m, n \text{ the poloidal and toroidal mode number, respectively})\). The standard configuration is defined by \( I_s/I_m = 1 \) and has \( r_t \approx 0 \).

We limit our investigations on configurations at \( \iota_{vac} \approx 0.34 - 0.35 \) where high-\( \beta \) programs had been performed including configurations with a large toroidal magnetic ripple \( r_t = 0, \pm 10\% \) (see also [2,3]). In this definition \( r_t > 0 \) has a decreased magnetic field strength in the mid period plane (Fig. 1a). Such a configuration is not relevant for reactors because the highly localized trapped particles are in the region of unfavourable curvature. In earlier experiments when the top and bottom limiters limited the plasma in the elliptical cross section, vertical fields of \( B_z/B_0 \approx 0.007 - 0.011 \) had been applied to center the plasma (\( B_0 = \text{mean magnetic field strength})\). Recently performed experiments without these limiters and with the upgraded NBI from 4 to 8 injectors used higher vertical fields of about \( B_z/B_0 \approx 0.017 - 0.025 \) in the "standard" configuration.

Stability analysis of configurations with different toroidal ripple: Toroidal net current free equilibria had been calculated using the free-boundary version of the NEMEC-code [4] assuming pressure profiles proportional to \( (1 - \delta)^2 \), \( \delta \) being the normalized toroidal flux, resulting in \( \beta_0/ \beta > \gamma \approx 3 (\gamma < ... > \gamma \text{ is the volume average})\). These profiles are actually more typical for ECRH- than for NBI-plasmas. The effective minor radius \( a_{eff} \) has been kept constant with about 15,6cm. Fig.1 shows the toroidal field ripple on the magnetic axis (a) and the vacuum magnetic well at the boundary and on the axis (b) (the values of \( V'' \) in the pictures of [3]...
Figure 1: a. Magnetic field strength on axis: the fields are fixed to 1.27T in the $\varphi = 36^\circ$ plane. b. Vacuum magnetic well of considered configurations with different vertical fields. The solid lines are $V''(a_{\text{eff}})$, the dashed lines $V''(0)$.

have to be corrected by a factor $5 \equiv$ number of field periods). It can be seen that a higher vertical field for a certain ripple configuration reduces the vacuum magnetic well leading to less stable configurations which is also known from torsatrons. Moreover, the change in magnetic configuration by introducing the toroidal ripple affects the vacuum magnetic well, too. The positive ripple configuration has nearly the same vacuum well as the standard configuration, whereas the negative toroidal ripple reduces the magnetic vacuum well so that for the highest considered vertical fields of the configuration with $r_t = -10\%$ a vacuum magnetic hill appears at the boundary. This connection between negative toroidal ripple and vacuum magnetic well was used to further increase the magnetic hill region in a vacuum configuration with a toroidal ripple of $-20\%$ keeping the vertical fields comparable as well as the effective minor radius. For low shear stellarators the stability criterion for resistive interchange modes is in a good approximation given by [5]

$$p'V'' - \int d\theta d\phi \frac{\sqrt{q}}{|\nabla q|^2} > 0,$$

if the modes are localized around rational flux surfaces and if we do not have toroidal net currents. This shows the importance of the magnetic well for the stabilization of resistive interchange modes. The stability analysis was performed using the JMC-code [5] which evaluates the Mercier- and the resistive Interchange stability criterion on the flux surfaces using Boozer coordinates. The results shown in Fig. 2 reflect the fact that the configurations with $r_t < 0$ have decreasing values of the vacuum magnetic well. The case $r_t = 10\%$ has the same stability boundaries as the standard configuration. The deepening of the well with increasing $\beta$ is not sufficient for stabilization. The configuration with $r_t = -20\%$ already shows a significant resistive interchange unstable region even at very low $\beta$ values ($s = 0.5$ corresponds to about $r_{\text{eff}}/a_{\text{eff}} = 0.71$, since $s \approx (r_{\text{eff}}/a_{\text{eff}})^2$). All configurations are for the considered profiles and $\beta$-values Mercier stable.

Stability of a highly inward shifted standard configuration: Due to the removal of the top and bottom limiter the high $\beta$ discharges in the running experimental campaign have to be performed with higher vertical fields, so that the plasma boundary is always defined by the inner limiters. The upgrade of the NBI from 4 to 8 injectors gave also access to higher input power (roughly about 2.2MW). We investigate the discharge 31114 which was run at a main field of 1.25 T. A vertical field of 31.5mT lead to a shift of the magnetic axis of about 12cm in
Figure 2: Stability boundaries from resistive interchange analysis. From left to right: \( r_l = -20\%, -10\%, 0\% \). The thick dashed lines are the boundaries for lower vertical field configurations. The thin lines are contours of the magnetic well \( V'' \) as derived from the free-boundary equilibria.

Figure 3: left: \( \beta \) profiles for electrons, ions and their sum. right: Comparison of vacuum flux surfaces with those of the finite \( \beta \) calculation inside the vacuum vessel in the \( \varphi = 0 \) plane (triangular plane).

The \( \varphi = 0 \) plane and produced a marginal magnetic hill throughout the vacuum configuration. After the startup with ECRH (70 GHz) the NBI power was switched on in 3 steps (from 2 to 4 to 8 injectors). The diamagnetic energy came up to about 12kJ. The peak electron density and temperatures from the Thomson scattering were about \( 2 \times 10^{20} m^{-3} \) and about 370 eV, respectively.

The equilibrium was calculated using the NEMEC code, too, assuming vanishing toroidal net current density using the electron pressure profile as inferred from the Thomson scattering system. The equilibrium was iterated to symmetrize the electron pressure data from Thomson and to satisfy the kinetic energy content as inferred from the diamagnetic signal. The resulting equilibrium has a peak-\( \beta \) of 4\% and \( < \beta > V \) is about 1.8\% . Fig. 3 shows the final pressure profiles and the Thomson data transformed from real space to the flux surface coordinate. Also shown are the flux surfaces of the vacuum and the finite \( \beta \) configuration which differ drastically due to the high \( \beta \). The kinetic energy content is correct up to 10\% which gives also an error estimate for the volume averaged \( \beta \). A comparison of the flux surfaces with the tomographically reconstructed soft X-ray emission shows that the shift of the emission center is consistent with the shift of the magnetic axis as calculated by NEMEC.
Figure 4: left: terms of the resistive interchange criterion and their sum for the reconstructed equilibrium ($\langle \ldots \rangle$ is a weighted flux surface average: $\int g/|V_s|^2 d\theta d\omega$, see [5]). right: terms of the resistive interchange criterion for a pressure profile proportional to $(1-s)^2$ with the same central pressure value.

The equilibrium has been investigated with respect to the resistive interchange criterion. The analysis shows a resistive interchange unstable region for $s > 0.5$ (see Fig. 4). The inner part of the plasma is stabilized by the magnetic well produced by the finite $\beta$. Since the used $\beta$ profile ($\approx$ pressure profile) of the discharge is almost linear in $s$, an equilibrium had been calculated using the same profile as in the previous analysis ($\beta \sim (1-s)^2$) having the same central $\beta$ value. The stability of this equilibrium proves to be worse, since the unstable region covers a much larger part of the plasma ($s > 0.25 \iff r_{eff}/a_{eff} > 0.5$). The reason for this difference in stability behaviour seems to be the more uniform and wider magnetic well deepening due to the broader $\beta$ profile.

Discussion and Summary: We have examined magnetic configurations of W7-AS at low $\iota$ with different toroidal magnetic field ripples with respect to resistive interchange modes. As result we showed that there exist configurations which are unstable in the outer plasma regions ($r_{eff}/a_{eff} > 0.7$) for peaked profiles (i.e. $\beta \sim (1-s)^2$) even for very low $\beta$ values. The used profiles are more representative for ECRH discharges. Experiments to test the configuration with $r_i = -20\%$ looking for the effects of resistive interchange modes are in preparation.

In a second investigation we examined a high $\beta$ discharge in a highly inward shifted vacuum configuration. The equilibrium has been reconstructed to be consistent with experimental data. It seems that a peak-$\beta$ of 4% and $\beta > \nu$ of 1.8% has been reached. The outer part of the equilibrium is predicted to be resistive interchange unstable. A $\beta$-profile which is more peaked than the experimental one increases the unstable region due to the radially different deepening of the magnetic well. An evaluation of the experimental data in view of the results is in preparation.

References

Edge transport studies on the W7-AS stellarator

P. Grigull, F. Sardei, Y. Feng, G. Herre, D. Hildebrandt, G. Kocsis, G. Kühner, W7-AS Team
Max-Planck-Institut für Plasmaphysik, EURATOM Ass., D-85748 Garching, Germany

1. Introduction. Plasmas in W7-AS can be separatrix- or limiter-bounded (t > 1/2 or < 0.4, respectively). This study is restricted to the latter, more transparent case where smooth flux surfaces extend to within the SOL. Until recently, even for this case a transport analysis was, in addition to the strong non-axisymmetry of the configuration, complicated by asymmetric connection lengths Lc in the SOL which were introduced by two asymmetric limiters (top and bottom, shifted by one field period). SOL ne and Te radial profiles showed strong deviations from exponential decay (shoulders) which "invert" with B-field inversion [1]. They are ascribed to E x B particle drifts caused by the poloidal Lc inhomogeneity. This situation was now changed by replacing the asymmetric limiters by a set of poloidal limiters (two per field period) at the radial inside, which, different from the former limiters, do not break the basic symmetry. Connection lengths are now quasi-homogeneous and, consequently, this type of shoulders vanished, and the profiles became much closer to exponential. We focus on this last constellation and present first results.

2. Experimental. SOL ne and Te radial profiles were measured by two fast reciprocating Langmuir probes (CFC tips, single mode, sweeping frequency 1 kHz, sampling frequency 250 kHz) and an energetic Li beam (ne) at three different positions (Fig. 1a). The discharges analysed were net current-free, flat-top ECRH (70 and/or 140 GHz) at Bo = 2.5 T and t = 0.34 ("standard" low-4 configuration with optimum confinement).

3. Flux coordinates. Local parameters are referred to equilibrium flux coordinates calculated by the KW (free boundary) equilibrium code [2]. Though there is not absolute evidence, two aspects strongly indicate a sufficient quality of this approximation, at least outside the LCMS: SOL parameter profiles measured at topologically different positions, which more or less strongly differ in vacuum flux coordinates, become well congruent even in detail, and the measured absolute radial position and outward shift of the maximum of the space potential (velocity shear layer) in dependence on β agrees well with the code predictions for the LCMS (Fig.1b). The space potential was estimated from probe data as Φsp = Φf + 2.5kTe/e with Φf the floating potential. The radial position of Φsp,max, is, within reasonable limits, very insensitive to the sheath factor in front of Te because Φf very steeply drops down inside a certain radius.

4. Edge parameters, SOL characteristics. Small wetted limiter areas, small radiative losses (=20%) from ECRH discharges, and power flux decay lengths λq decreasing with increasing density (Fig. 6a) cause relatively high power densities in the SOL and, consequently, high Te values at the LCMS (Figs. 4a, b). As can be seen from from Fig. 2, the parameter range analyzed is centered around the border between predominant kinetic effects at lower densities and significant parallel Te gradients and related effects towards much higher densities. Except for highest densities, the parallel heat transport is flux-limited [3].

Te is found to scale with nea -0.3(P - Pr)/0.4 (Figs. 4a, b), with P being the heating power, Pr the total radiated power (from bolometer) and the index a denoting the LCMS. Considering the findings nea ∝ n ei (0.9 and λq ∝ (P - Pr)/ne ≥ 0.33 (Figs. 3, 6a, b), the simple slab estimate P - Pr = 1/2n ei c sKTea γ s/λ q, with c s the ion sound speed, γ s the sheath energy trans-
mission factor and w the wetted limiter width, yields \( T_{ea} \approx \left( \frac{P - P_t}{n_{ea} T_{ea}} \right)^{0.4} \), which is in fair agreement. Moreover, inserting probe values for \( n_{ea} \) and \( T_{ea} \) into the above estimate yields absolute agreement within a factor of two (examples in Fig. 5), which is also fair in view of the uncertainties in particular of \( T_e \) evaluations from probe data. The relatively moderate increase of \( n_{ea} \) with \(<n_e>\) (Fig. 3) can be explained by decreasing particle transport coefficients \( D_\perp \) with increasing density (see next chapter). This is shown in Fig. 3 by comparison with a simple slab treatment of \( <n_e> V \tau_p = \frac{1}{2} n_{ea} c_s \lambda_p w \) and \( \tau_p = \frac{1}{2} \lambda_p / D_\perp \), with \( V \) being the plasma volume, \( \tau_p \) the particle replacement time and \( \lambda_{ez} = v_0 / 0.5 n_e(0) <v_{\parallel}> \) the ionization length. The values used for the neutral particle velocity and the ionization rates are \( v_0 = 2 \times 10^4 \text{ m/s} \) and \( <v_{\parallel}> = 3 \times 10^{-14} \text{ m}^3 \text{s}^{-1} \), respectively. Scaling laws for \( T_e, D_\perp \) and \( \lambda \) were taken from the probe data. The line would be much steeper without \( D_\perp \) scaling with the inverse of the density and demonstrates the tendency only, without claiming to be a precise description.

5. SOL particle transport. From the above characterization it is suggested that, in this parameter range, the SOL particle transport can be satisfactorily described by a simple 1D (radial) fluid approximation. Particle diffusion coefficients were estimated from \( D_\perp = \lambda_{ez} c_s / 2 c_L \) [4] with \( c_L = (k T_i + T_e) / m_i \), \( m_i \) the ion mass and the ion temperature \( T_i = T_{ei} \). Decay lengths \( \lambda_{ni} \) were obtained by exponentially fitting experimental \( n_e \) profiles within the first e-folding length outside the LCMS. In most cases, the profiles are well exponential over more than one order of magnitude. The results are shown in Figs. 7a, b, 8. \( D_\perp \) is found to be independent on the positions and is well correlated to the global parameters heating power and averaged density, \( D_\perp \approx (P - P_t)^{0.85} <n_e>^{1.1} \). The absolute values of \( D_\perp \) are estimated to be correct within a factor of two or three. Correlations with the "representative" local parameters \( T_{ei} \) and \( n_{ea} \) are found to be much worse than with the global parameters and, in particular, a Bohm-like scaling is very unlikely. Studies on the B-field dependency are under way.

6. Summary and conclusions. Edge parameters and particle transport coefficients are obtained for limiter-bounded, low-\( t \) ECRH discharges at \( B = 2.5 \text{ T} \). Local edge parameters are referred to equilibrium flux coordinates obtained by the KW code which seems to be an adequate description. The SOL is characterized by relatively high \( T_{ea} \) values. It behaves like a "model SOL" for a simple 1D fluid treatment of the particle transport. Considering experimental decay lengths, \( T_{ea} \) and \( n_{ea} \) dependencies on the externally adjustable parameters \( P \) and \( <n_e> \) are consistent with simple model expectations. \( \lambda_{ni}, \lambda_{ni} \) and \( D_\perp \) decrease with increasing density (which confirms former results under these new, more transparent conditions) and increase with the non-radiated part of the heating power, the latter a positive aspect in view on power and particle exhaust in higher power experiments. The degradation of the particle confinement at the edge with increasing heating power seems to be somewhat stronger than in the core and may be an explanation for the "pump out" effect observed in W7-AS in discharges with combined NBI and ECRH: by adding ECRH with comparable power to NBI, the density control is significantly improved in comparison with pure NBI discharges.

References:

Figure captions:

Fig. 1: a) Positions of the fast reciprocating Langmuir probes and the Li beam.

   b) Radial outward shift of the space potential maxima (from Langmuir probe data) in dependence on the central $\beta$, and KW code predictions for the LCMS positions.

Fig. 2: Mean free path $\lambda_{ee,ii}$ for electron or ion self collisions at the LCMS versus the edge density $n_{ea}$ for thermal particles and electrons with $v = 3.7v_{th}$, the latter being mainly responsible for the parallel heat transport. Respective $T_{ea}$ values were considered from the fit in Fig. 4a. The range corresponds to that analyzed with respect to particle transport (Figs. 7a, b, Fig. 8).

Fig. 3: Electron density $n_{ea}$ at the LCMS from Langmuir probes versus the volume-averaged density $<n_{e>}_{\text{vol}}$ (from Thomson scattering). Limiter-bounded, net current-free ECRH discharges at $t_{h} = 0.34$ and $B = 2.5$ T ($n_{ea} > 3 \times 10^{18}$ m$^{-3}$) and 1.25 T ($n_{ea} < 3 \times 10^{18}$ m$^{-3}$). NBI discharges are shown for comparison. Line: slab model (see text).

Fig. 4: a) Electron temperatures $T_{ea}$ at the LCMS as function of the LCMS density $n_{ea}$ from Langmuir probes. Discharge conditions as in Fig. 3.

   b) $T_{ea}$ as function of the non-radiated part of the heating power for two different densities. ECRH, $B = 2.5$ T, other conditions as in Fig. 3.

Fig. 5: Power in the SOL from simple power balance with probe data ($n_{ea}$, $T_{ea}$, $\lambda_{ee}$) in comparison with the non-radiated part of the heating power. ECRH at $B = 2.5$ and 1.25 T (lower left part), other conditions as in Fig. 3. The limiter load (from calorimetry) is only 30-40% of $P_{\text{rad}}$. Geometric considerations indicate that a large part of the power hits other installations.

Fig. 6: Density and power decay lengths in the SOL for a) a density scan at constant heating power, and b) heating power scans at two different densities. ECRH, $B = 2.5$ T, other conditions as in Fig. 3.

Fig. 7a, b: Particle diffusion coefficients, parameter scans as in Figs. 6a, b.

Fig. 8: Linear regression of $D_{1}$ for the combined parameter scans (Figs. 7a, b) and a further density scan with 300 kW ECRH.
Fig. 4a

Fig. 4b

Fig. 5

Fig. 6a

Fig. 6b

Fig. 7a

Fig. 7b

Fig. 8
Topological Aspects of Island Divertors in Wendelstein 7-AS

J.V. Hofmann, J. Das, P. Grigull, G. Herre, J. Kißlinger, F. Sardei
W7-AS Team, ECRH Group, NI Group
Max-Planck-Institut für Plasmaphysik, IPP-EURATOM-Ass.,
D-85748 Garching bei München, Germany

Introduction: Wendelstein 7-AS is a modular stellarator with m=5 periods. Within each period the plasma cross section varies from elliptical to triangular and vice versa. The rotational transform of $t_a = 0.4$ of the modular coil set can be varied between 0.25 and 0.67 by means of the planar toroidal field coils. The vacuum field shear is very small.

![Diagram of 5/10 islands intersecting an inboard limiter](image)

*Fig. 1: calculated 5/10 islands in W7-AS intersecting an inboard limiter (#29296, tₐ=0.512)*

W7-AS exhibits a very flexible boundary topology which can be controlled by means of the external rotational transform. The structure of the plasma boundary is characterized by the presence of 5/m natural islands, like 5/9 or 5/10, and this topology can be used to study island divertors for power and particle exhaust. The 5/m islands can exist either as a closed chain or they can be intersected by the inboard limiters. These limiters provide a nearly homogeneous scrape-off layer and can be used for preliminary investigations exploring the divertor potential of

J. V. Hofmann et al.
W7-AS. This is especially important in the context of the planned island divertors for W7-AS and W7-X.

**W7-AS natural islands**: natural islands in W7-AS appear at rational \( \tau \) values. They originate from radial magnetic field components in the Fourier spectrum of the modular coil set and exhibit the symmetry of the device. The harmonics are of the type \((5n)/m\), with integer values of \(n\) and \(m\). These natural islands are an intrinsic property of the ideal vacuum field but are, nevertheless, perturbations of an optimum magnetic field [1]. Apparently, these islands provide an intrinsic diversion of the edge field lines, Fig. 1.

With decreasing \( \tau \), the islands are shifted radially outwards and are eventually intersected by the inboard limiters. Finite \( \beta \) drives the plasma radially outwards (Shafranov shift), away from the limiters. However, it also changes the absolute value of \( \tau \), its profile and the shear and thus changes the size of the islands, depending on iota and shear, and, via a resulting change in the iota profile, also shifts the islands radially. The Shafranov shift may be compensated by an additional vertical field which, additionally, reduces the absolute value of \( \tau \).

![Diagram](attachment:diagram.png)

**Fig. 2**: W7-AS island divertor at \( \phi = 36^\circ \) and 5/9 boundary islands.

J. V. Hofmann et al.
The resulting transitions from closed to open islands are clearly reflected by the experimental data. The 5/m structures are found to be rather stable against moderate variations in the plasma parameters, especially beta-induced perturbations.

**The island divertor concept:** since these natural 5/m islands facilitate an intrinsic diversion of the edge field lines for resonant $t$ values their intersection with properly designed target plates may be used for an island divertor. In addition to the control of the island position and size via the edge rotational transform, active control of the island size, connection lengths and divertor operation is required by means of additional control loops. In contrast to a tokamak divertor which is toroidally closed and facilitates the resonance at $t = 0$ due to an additional coil set which compensates the poloidal field in the x-point, the W7-AS island divertor will consist of five top and bottom modules located around the elliptical plasma cross section at $\phi = 36^\circ$. Divertor operation with this island divertor is possible at several resonant $t$-values (e.g. $t_n = 5/8, 5/9, 5/10$), Fig. 2.

![W7-AS Video](image)

**Fig. 3:** W7-AS intensity contours versus $t_n$. The resonant natural island structures are clearly reflected in the bright maxima.

**Experimental evidence for natural islands:** The viability of the island divertor concept critically depends on the stability of the island structure against external and internal magnetic field perturbations due to imperfections in the coil system, plasma currents and beta effects. In order to assess the relevance of vacuum field structures and of perturbative fields for plasma transport and recycling at the boundary, we have investigated the boundary topology for several
series of edge iota ($\iota_a$) scans at various densities ranging from $0.290 \leq \iota_a \leq 0.640$, $0 \text{ mT} \leq B_z \leq 80 \text{ mT}$, $8 \times 10^{18} \text{ m}^{-3} \leq <n_e> \leq 1.6 \times 10^{21} \text{ m}^{-3}$.

A Langmuir probe array was used to measure the poloidal $n_e$ (and $T_e$) profiles at the boundary while the distribution of the neutral gas density was monitored by measuring the spatial variation of the $H_\alpha$ intensity by $H_\alpha$-arrays. Poloidally resolved calorimetry at the inboard limiters was used to measure the power load on the individual limiter tiles. Video-cameras were used to image the position and edge structure of the plasma in a tangential view while details in the edge topology were investigated by viewing one of the inboard limiters, Fig. 3.

Experimental results from these diagnostics show clear evidence of the presence of the 5/8, 5/9, 5/10, 5/11, 5/12 and 5/15 island chains and resonances at the plasma edge in excellent agreement with vacuum field calculations. The maxima in the measured temperature, density and intensity profiles reflect the presence of higher density and temperature areas around the closed islands. The transitions from closed to open islands, resulting from scans in $\iota_a$ and finite $\beta$ effects, are clearly reflected in the experimental data as a doubling of the maxima in the density, temperature and intensity profiles. The 5/m structures also dominate at finite $\beta$ and are found to be rather stable against moderate variations in the plasma parameters, especially beta-induced perturbations.

Conclusions:

- W7-AS is well suited to perform island divertor pre-studies to explore the island divertor concept and operational regimes with respect to W7-X.

- Changes in the boundary topology as a function of $\iota_a$ are reflected in the power load distribution on the limiter tiles, the intensity of the $H_\alpha$ radiation in front of the limiters, the tangential and limiter video observations and the poloidal $n_e$ (and $T_e$) profiles at the boundary from the Langmuir probe array.

- For low $\beta$, there is experimental evidence that the relevant 5/m boundary islands in W7-AS behave as expected from vacuum field calculations. They dominate the edge structure also at higher $\beta$.

- These edge diagnostics which excellently verify the vacuum field topology at low $\beta$ allow the study of finite $\beta$ effects beyond the range accessible to our code calculations.

- Size and radial position of the 5/m islands will be actively controlled by moderate currents in additional control loops.

- Quasi stationary operation at high density will require active pumping for density control.

- A system of 10 identical island divertor modules with baffles is proposed and studied with respect to pumping efficiency by the EIRENE code. Start of operation is planned (not yet approved) in the mid of 1997 with pumping by getters.

Introduction

In the standard configuration of W7-AS -i.e., the current ratio in the "large special" coils with respect to the modular field coils, $I_S/I_M = 1$, and without vertical magnetic field, $B_z$, the experimental ion heat flux ($Q_i = \int r dr (P_{NBI} + P_{ei} - P_{CX})$) is found to be neoclassical if the electric field deduced from the ambipolarity condition is taken into account. With combined heating of the plasma with about 700 kW of ECRH, deposited off axis, together with about 510 kW of NBI (counter-injection with respect to the bootstrap current) at $B_0 = 2.5$ T, $n_e = 4.2 \cdot 10^{19}$ m$^{-3}$ $(n_d(\theta) = 1 \cdot 10^{20}$ m$^{-3}$) and $\tau = 0.53$, highest ion temperatures of about 1 keV, measured by active charge exchange analysis have been obtained /1/. Due to calibration errors of the by that time used CX analyzers the formerly published ion temperatures must be corrected by a factor of at least 1.2.

In order to improve the neoclassical ion confinement, the magnetic configuration of W7-AS can be further optimized by reducing the magnetic field variations in the region of strong toroidal curvature. This can be realized e.g. by moderately increasing the ratio $I_S/I_M$. Theoretical considerations for the limiter region without electric field indeed show an improvement for an "effective diffusion coefficient" /2/ at $r_{eff}/2$ by about a factor of 2 compared to the "standard configuration" (see Fig.1) and even more, if $I_S/I_M \geq 1.3$ is chosen for comparison as an example of a "bad ion transport" configuration. A different way to improve the configuration and by this the ion confinement is neoclassically predicted to be the inward shift of the plasma column, similar as in torsatrons. Largest improvements in this case can be gained for $B_z = 0.01 - 0.03$ T at $B_0 = 2.5$ T. Both "transport optimized" configurations lead to about the same factor of confinement improvement, see Fig.1.

Fig.1: Bounce averaged diffusion coefficient $<D>$, (limfp,without electric field), as figure of merit, as a function of $I_S/I_M$ and $B_z$. 


Max-Planck-Institut für Plasmaphysik, Association EURATOM-IPP, D-85748 Garching, Germany
*A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russia
**Institut für Plasmaphysik and D-70569 Stuttgart, Germany
Experimental results

First hints that inward-shifting of the plasma column indeed globally improves the ion confinement have been derived when first experiments with $B_z = 0.012$ T at $t = 0.345$, $B_0 = 2.53$ T at $n_e = 5.8 \cdot 10^{19}$ m$^{-3}$ have been made. Central ion temperatures of about 1.1 keV -i.e. 10% higher than in the standard configuration- have been gained in a plasma with combined heating of ECR, 140GHz, 700kW, deposited on axis, and balanced NBI of about 540 kW.

Further experiments with inward shifted plasmas have been made recently at $t = 0.345$, $B_0 = 2.53$ T and $B_z = 0.026$ T at $n_e = 4.2 \cdot 10^{19}$ m$^{-3}$. These discharges have been started by 70 GHz ECR (o-mode at 2.5T) and taken over by 140 GHz ECR (2nd harmonic, x-mode). In a later phase NBI, starting with counter injection followed by co injection, has been added. Central ion temperatures of up to 1.2 keV have been obtained with combined heating of about 400 kW input power of ECRH, deposited on axis, and additional 290 kW of NBI, co injection, whereas 250 kW at counter injection combined with 400kW of ECRH only showed about 0.8 keV. The deposited powers of NBI for configurations with $I_{S/I_M} \geq 1.0$ at the moment are merely first estimates because FAFNER code (Monte Carlo) calculations for these magnetic configuration with inboard limiters and without rail limiters have not been made yet.

In the purely ECR heated phase ion temperatures are about 0.64 keV.

### Pure ECRH:

<table>
<thead>
<tr>
<th>$I_{S/I_M}$</th>
<th>$t$</th>
<th>$B_0$</th>
<th>$B_z$</th>
<th>$n_e(0)$</th>
<th>$T_e(0)$</th>
<th>$T_i(0)$</th>
<th>pECRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s)</td>
<td></td>
<td></td>
<td></td>
<td>(10$^{20}$ m$^{-3}$)</td>
<td>(keV)</td>
<td>(keV)</td>
<td>kW</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.55</td>
<td>1.70</td>
<td>0.65</td>
<td>400 (on axis)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.55</td>
<td>0.60</td>
<td>0.60</td>
<td>400 (off axis)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.55</td>
<td>0.75</td>
<td>0.63</td>
<td>725 (off axis)</td>
</tr>
<tr>
<td>1.30</td>
<td>2.53</td>
<td>0.026</td>
<td>0.345</td>
<td>0.65</td>
<td>1.20</td>
<td>0.65</td>
<td>400 (on axis)</td>
</tr>
</tbody>
</table>

### Pure NBI:

<table>
<thead>
<tr>
<th>$I_{S/I_M}$</th>
<th>$t$</th>
<th>$B_0$</th>
<th>$B_z$</th>
<th>$n_e(0)$</th>
<th>$T_e(0)$</th>
<th>$T_i(0)$</th>
<th>pNBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s)</td>
<td></td>
<td></td>
<td></td>
<td>(10$^{20}$ m$^{-3}$)</td>
<td>(keV)</td>
<td>(keV)</td>
<td>kW</td>
</tr>
<tr>
<td>1.0</td>
<td>0.56</td>
<td>2.53</td>
<td>0.026</td>
<td>0.345</td>
<td>0.55</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.3</td>
<td>0.56</td>
<td>2.53</td>
<td>0.026</td>
<td>0.345</td>
<td>0.55</td>
<td>0.85</td>
<td>0.9</td>
</tr>
</tbody>
</table>

### Combined ECRH and NBI:

<table>
<thead>
<tr>
<th>$I_{S/I_M}$</th>
<th>$t$</th>
<th>$B_0$</th>
<th>$B_z$</th>
<th>$n_e(0)$</th>
<th>$T_e(0)$</th>
<th>$T_i(0)$</th>
<th>pECR</th>
<th>pNBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s)</td>
<td></td>
<td></td>
<td></td>
<td>(10$^{20}$ m$^{-3}$)</td>
<td>(keV)</td>
<td>(keV)</td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.60</td>
<td>2.00</td>
<td>0.85</td>
<td>400 (on axis)</td>
<td>170(cir)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.85</td>
<td>0.95</td>
<td>0.82</td>
<td>400 (off axis)</td>
<td>260(cir)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.85</td>
<td>1.30</td>
<td>0.82</td>
<td>400 (on axis)</td>
<td>250(cir)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.85</td>
<td>1.20</td>
<td>0.80</td>
<td>400 (on axis)</td>
<td>250(cir)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.85</td>
<td>1.40</td>
<td>1.15</td>
<td>400 (off axis)</td>
<td>290(co)</td>
</tr>
<tr>
<td>1.3</td>
<td>2.54</td>
<td>0.020</td>
<td>0.345</td>
<td>0.65</td>
<td>1.10</td>
<td>0.74</td>
<td>400 (on axis)</td>
<td>250(cir)</td>
</tr>
<tr>
<td>1.3</td>
<td>2.54</td>
<td>0.020</td>
<td>0.345</td>
<td>0.65</td>
<td>1.25</td>
<td>0.98</td>
<td>400 (on axis)</td>
<td>290(co)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.0</td>
<td>0.530</td>
<td>0.75</td>
<td>1.15</td>
<td>0.95</td>
<td>725 (off axis)</td>
<td>510(cir)</td>
</tr>
<tr>
<td>1.0</td>
<td>2.54</td>
<td>0.012</td>
<td>0.345</td>
<td>0.45</td>
<td>1.75</td>
<td>1.10</td>
<td>700 (on axis)</td>
<td>540(bal)</td>
</tr>
<tr>
<td>1.3</td>
<td>2.54</td>
<td>0.020</td>
<td>0.345</td>
<td>0.45</td>
<td>1.90</td>
<td>1.35</td>
<td>700 (on axis)</td>
<td>580(co)</td>
</tr>
<tr>
<td>1.5</td>
<td>2.54</td>
<td>0.020</td>
<td>0.345</td>
<td>0.48</td>
<td>1.25</td>
<td>0.86</td>
<td>700 (on axis)</td>
<td>540(bal)</td>
</tr>
<tr>
<td>1.5</td>
<td>2.54</td>
<td>0.020</td>
<td>0.345</td>
<td>0.60</td>
<td>1.10</td>
<td>1.10</td>
<td>700 (on axis)</td>
<td>580(co)</td>
</tr>
</tbody>
</table>

* standard configuration

**Table 1:** Experimental results for different heating scenarios and different magnetic configurations of W7-AS: standard ($I_{S/I_M} = 1.0$, $B_z = 0$ T), inward shifted ($I_{S/I_M} = 1.0$, $B_z > 0$ T) and with $I_{S/I_M} > 1.2$, $B_z > 0$ T (increased transport).
At the time the "standard configuration" of W7-AS is not available since the upper and lower rail limiters have been demounted. Therefore W7-AS plasmas at $B_0 = 2.5$ T need to be inward shifted by a vertical field of at least 0.02 T for compensating the Shafranov shift in order to keep the plasma away from the outer wall of the vacuum vessel or installations repectively. For comparison to the "transport optimized" configuration, therefore, a configuration with increased $I_s/I_M (\geq 1.3)$ has been chosen. Concerning the ion transport this configuration is predicted to show even higher transport losses than the standard case, see Fig.1. At comparable heating conditions as in the inward-shifted case at $t = 0.345$, $B_0 = 2.53$ T and $B_z = 0.020$ T at $n_e = 4.2 \cdot 10^{19} \text{ m}^{-3}$ the central ion temperature dropped to about 1.0 keV for co-injection, to about 0.74 keV for counter-injection and 0.60 keV for pure ECRH.

In discharges heated with 700kW of ECRH, starting by 70 GHz and 140 GHz added, combined with NBI, co-injection of 580 kW, in the inward-shifted case central ion temperatures of up to 1.35 keV are measured, whereas in the configuration with increased $I_s/I_M (\geq 1.3)$ with the same heating scenario about 1.2 keV or less (1.1 with $I_s/I_M = 1.5$) has been measured. Results are summarized in Table 1.

**Ion Power Balance**

Since the measurements taken for the analysis have been carried out just before this conference a preliminary evaluation only can be presented here. The ion power balance is carried out with the neoclassical DKES code /3/ for the above described discharges on the basis of the measured $n_e$, $T_e$ profiles from Thomson scattering and $T_i$ profiles from CX analysis. For comparison the "standard configuration" /1/ has been analyzed with updated $T_i$ profiles. The evaluation is carried out in the inner part of the plasma ($r \leq 12$ cm). In this first attempt only CX data which are available for inner radii only are taken for this evaluation. CXRS data for outer radii have been measured and will be taken into account for future more detailed considerations.

For the standard configuration the ion power balance proves to agree with neoclassical predictions if the corrected ion temperature profiles are taken. The earlier statement /1/ of an agreement only within a factor of 2 -3 must thus be revised.

As an example for a non standard configuration, in Fig. 2 the local ion power balance is shown for the transport reduced, $I_s/I_M = 1.0$, $B_z = 0.26$ T, configuration. The ECRH power of 400 kW at 140 GHz, x-mode, is deposited on the plasma axis. NBI, co-injection, of about 290 kW absorbed power is added. The experimental ion heat flux ($Q_i = \int r \, dr \left( P_{NBI} + P_{el} - P_{CX} \right)$) is well below the neoclassically calculation with electric field (derived from the ambipolarity condition) for the standard configuration as has been predicted /2/, see Fig. 1. Electric fields derived from CXRS measurements at W7-AS in most cases agree well with the ones calculated from ambipolar fluxes /4/.

**Conclusions**

Reducing the effective helical ripple in the unfavourable region of strong toroidal curvature either by shifting the plasma inward via a vertical magnetic field, $B_z$, or by slightly increasing the magnetic field in this region by increasing the current ratio between "special" and modular coils, $I_s/I_M$, has been predicted to result in "transport optimized" magnetic configurations of W7-AS. Simple neoclassical considerations (lmpf, no electric field) /2/ predict a reduction of ion transport compared to the standard configuration or to configurations with a large mirror ratio.
Fig. 2: Profiles of $T_e$ and $T_i$ (upper left, full and dashed lines resp.), $n_e$ (upper right), radial electric field from ambipolarity condition (lower left) and ion power balance (lower right, dash-dotted: integrated heating power, dashed: neoclassical prediction for the standard configuration with electric field and dotted line without electric field) for a combined heated discharge, 400 kW on axis ECR and 290 kW absorbed co NBI in an inward shifted ("transport reduced") configuration.

Experimental results are consistent with these predictions: global parameters show an improvement if "transport reduced" configurations are compared to non reduced ones. This holds for different heating scenarios and different heating powers. Optimum parameters have been gained under the following -transport optimized- conditions: $t = 0.345, B_0 = 2.53$ T and $\bar{n}_e = 3.7 \cdot 10^{19}$ m$^{-3}$ with $B_z = 0.026$ T and $I_S/I_M = 1.0$ in ECR combined with NBI heated discharges, heating power totally about 1.3 MW: $T_e = 1.9$ keV and $T_i = 1.35$ keV, compared to $T_e = 175$ keV and $T_i = 1.20$ keV with the same heating scenario but for a transport enhanced configuration with $I_S/I_M = 1.3$.

First neoclassical power balance calculations show the same tendency. The experimental ion heat flux in "improved" configurations is well below the calculated one for the standard configuration. More detailed evaluations on the basis of already gained experimental data as well as further experiment, e.g. with $I_S/I_M = 1.1 - 1.2$, which are more relevant to the configuration of W7-X have to be made.

References

/2/ C. D. Beidler, et al., this conference
/4/ J. Baldzuhn, et al., this conference
Transport Experiments in W7-AS

U. Stroth, J. Baldzuhn, B. Brañas*, V. Erckmann, T. Estrada*,
L. Giannone, M. Hirsch, H.-J. Hartfuß, M. Kick, G. Kühner,
ECRH Group, W7-AS Team
Max-Planck-Institut für Plasmaphysik, EURATOM-IPP Association, 85748 Garching, Germany
*EURATOM/CIEMAT Association. 28040 Madrid, Spain

I. Introduction

The energy confinement time of W7-AS plasmas is known to increase with plasma volume, magnetic field and density and to degrade with heating power. No dependence on isotopic mass has been reported so far. In general, electron heat transport is strongly enhanced above the level predicted by neoclassical theory while ion transport is predicted in the right order of magnitude.

Recently, experiments have been carried out in order to extend the investigated parameter range and to continue the investigation of finding the local plasma parameters which determine the transport behaviour of the plasma.

II. Density dependence transport

The energy confinement time of W7-AS plasmas increases with density. A previous regression analysis done on a restricted database yielded a dependence like $\tau_E \sim n_e^{0.7}$ for ECRH plasmas. The database was limited by two restrictions. The use of 70 GHz ECRH limited investigations of ECRH plasmas to $n_e \leq 4 \times 10^{19}$ m$^{-3}$ and difficulties with density control did not allow to study stationary NBI heated discharges at low densities.

The installation of 140 GHz ECRH now allows for the first time to heat plasmas up to $n_e \simeq 10^{20}$ m$^{-3}$ by ECRH only.

The increase of $\tau_E$ with density, is it a genuine effect of stellarator transport or just an image of the tokamaks LOC regime? To investigate this, high density ECRH discharges have been carried out in W7-AS. The experiments were done at $B_t = 2.5$ T and $\tau_e = 0.34$. The heating power of $P = 0.45$ MW was supplied by 140 GHz ECRH. As input for a power balance the relevant profiles have been measured during the stationary phases. Electron density from Thomson scattering and temperature from ECE measurements have been used. The ion temperature profile is from a set of CX neutral-particle analysers. The centrally measured $Z_{eff}$ ranges from 3 to 2 with increasing density. Radiation profiles were measured by a bolometer array; the total radiated power is always below 15% of the heating power.

It has also been tried to relate the parameter dependence of the energy confinement to changes in the plasma turbulence level indicated by fluctuations of the plasma parameters. The amplitude of the density fluctuations was measured by a heterodyne reflectometer. In order to obtain radial profiles, the frequency was ramped up in steps of 10 ms duration.

The global energy confinement time of this series of discharges is shown in Fig. 1. It increases up to a line-averaged density of $n_e \simeq 5 \times 10^{19}$ m$^{-3}$. A regression of the data in Fig. 1 up to this density yields a strong density dependence of $\tau_E \sim n_e^{0.85}$. For comparison, the data of a previous database yielding $\tau \sim n_e^{0.7}$ are overlaid. Please notice that in the latter data set also other parameters than the density are varied.

At densities $n_e \geq 5 \times 10^{19}$ m$^{-3}$ a saturation of $\tau_E$ sets in. This is a new feature in W7-AS. In Fig. 2 it can be seen that at the two lower densities the ions are almost de-coupled from the electrons. As expected, at higher densities where the saturation occurs the coupling becomes stronger and $T_e$ and $T_i$ come very close in the confinement region. But there is a second effect super-imposed. The $T_e$ profile at high density has a flattened area in the vicinity of 9 cm. Looking at many profiles shows clearly that this region increases with density. Since these discharges have a very flat $\varepsilon$ profile in the vicinity of $\varepsilon = 1/3$ it is possible that the flat region is related to a distortion of the magnetic configuration.

In summary, $\tau_E$ of W7-AS plasmas saturates with density in a similar way as in the tokamaks SOC regime. But it is not clear yet how much of the saturation is due to a distortion of the magnetic configuration.

The comparison of measured ion temperatures made in Fig. 2 to the prediction by neoclassical theory is satisfactory. For the neoclassical description the DKES code with an ambipolar electric field was used.

Power balance analyses using a purely diffusive
ansatz were carried out for the density scan. Ray tracing calculations were used as basis for the power deposition profile. In Fig. 3 the results for the electron heat conductivity can be seen. In order to avoid contributions from the flat region in the temperature profile, the transport coefficient is given in radial zones inside and outside of the flat region. The values in the figure represent radial averages around a normalized radius of $\rho = 0.4$ (0.05 $\leq r < 8.5$ cm) and $\rho = 0.8$ (12.0 $\leq r < 15$ cm).

The error of the transport coefficient was estimated by performing power balances with modified temperature profiles. Both the $T_e$ and $T_i$ profiles were separately increased and decreased by a constant amount of 10% and, in order to change gradients in the confinement region, by adding and subtracting a cosine with a local amplitude of 10% of the temperatures. The error bars cover the highest and lowest $\chi_e$ obtained from transport analyses with the eight different profile combinations.

At both radial positions in Fig. 3 electron and ion channel can be separated with sufficient accuracy. In the inner and outer regions of the plasma a saturation of the improvement in $\chi_e$ with density is observed at density values of 4 to 5 $10^{19}$m$^{-3}$. At this density also the electron energy content saturates (see Fig. ??).

It has also been tried to relate the transport coefficient to the level of density fluctuation measured by a reflectometer. For each discharge, radial profiles are available in the density gradient region. In Fig. 4 the fluctuation level at fixed radii is depicted as a function of density. The fluctuation level decreases and saturates with density in the same way as $\chi_e$ does (see Fig. 3 at $\rho = 0.8$).

III. Power dependence of transport

The power degradation can be observed in discharges where the temperature is the only local parameter changed by the heating power. Hence, temperature $T$ or its gradient $\nabla T$ are the obvious local parameters through which the transport coefficients could change with heating power. Alternatively, it could be thought of the heating power as a global parameter which could directly influence the transport behaviour of the plasma (i.e. by non-thermal particle populations which drive turbulence). In steady state, the heating power is roughly equal to the local power flux $q$.

In steady state, it is principally not possible to distinguish between the local $\nabla T$ and the global $P$ as degrading agents. They are linked by the relation $P \sim n_e \chi \nabla T$. Only the transient behaviour of the plasma allows this distinction.

In order to disentangle the role played by the different parameters, on and off-axis power scans have been carried out in W7-AS. The experiments were done at $B_t = 2.5$, $T_e = 0.34$, and $\bar{n}_e = 2.5 \times 10^{19}$m$^{-3}$. The power was varied from 0.1 to 0.85 MW using two 70 GHz gyrotrons at about 0.2 MW power each and a 140 GHz gyrotron at $P = 0.45$ MW. At all power levels the plasma is well diagnosed during stationary phases and the same data as described for the density scan in Sec. II are available.
In Fig. 5, the global confinement time for on and off-axis power scans are plotted as a function of heating power. The change in heating position only influences the central part of the profiles, which does not contribute much to the total energy content. The difference in the global confinement time is less than 10% and both, on and off-axis data, are well represented by a dependence like \( \tau_E \sim P^{-0.5} \).

The comparison of the discharges is done with help of a power balance analysis in the same way as described in Sec. II. The results presented in Figs. 6-7 concern again averages of small radial regions in the inner part and the outer part of the plasma.

In Fig. 6 the local energy flux in the electrons is plotted as a function of the electron temperature gradient. A non-linear dependence of \( q \) on \( \nabla T_e \) is indicated. Under the assumption of a diffusive transport model (\( q = n_e \chi_e \nabla T_e \)), this indicates a dependence of the transport coefficient on \( T_e, \nabla T_e \) or related quantities.

In Fig. 7 the transport coefficient for the inner plasma region is related to the local electron temperature gradient. There is a clear increase of \( \chi_e \) with \( \nabla T_e \) (and also \( T_e \)) and the degradation of the confinement time is also reflected in the local transport coefficients. But it is of course trivial that a power scan which changes \( \nabla T_e \) leads to a correlation between \( \chi_e \) and \( \nabla T_e \) as well as \( T_e \) when simultaneously the confinement degrades with heating power.

A dependence of \( \chi_e \) on \( T_e, \nabla T_e \) or \( P \) can only be discriminated in a transient experiment where the parameters can be modified on different time scales.

Transient transport studies are an independent method to determine transport coefficients from the response of the plasma to small perturbations. The comparison of the energy transport coefficient from heat wave (\( \chi_e^{HW} \)) and power balance analyses (\( \chi_e^{PB} \)) gives information on the dependence of \( \chi_e \) on \( T_e \) and \( \nabla T_e \).

In W7-AS, strong dependencies on \( T_e, \nabla T_e \) or the local power flux can be excluded\(^2\)\(^3\). The transport coefficient deduced from heatwave analysis is of comparable magnitude of \( \chi_e^{PB} \) and also shows a similar scaling with heating power and density. A temperature dependence can be excluded because \( \chi_e^{HW} \) does not depend on the modulation frequency of the heating power.

From the transient transport results and those from the power scan in W7-AS an apparent contradiction emerges: In Figs. 7 \( \chi_e \) increases clearly with \( \nabla T_e \) (or \( T_e \)). On the other hand it has just been shown that \( \chi_e \) cannot depend on either of these parameters.

This contradiction can be resolved with a phenomenological model\(^4\) in which \( \chi_e \) does not significantly depend on the local power flux but on a process which depends directly on the heating power inside the respective flux surface. The idea is that the transport coefficient reacts on a change in heating power along a faster than the diffusive time scale. Of course, such a model yields power degradation. But a model with a rapidly changing \( \chi_e \) was also successful in describing the transient response of the plasma after a large amount of the heating power was switched on or off.\(^5\)
Figure 5: Global energy confinement time for on and off-axis power scans as function of heating power. The plasma parameter were $\varepsilon = 0.34$, $B_t = 2.5T$ and $n_e = 2.5 \times 10^{19} m^{-3}$.

Figure 6: Local electron energy flux radially averaged between 5 and 8.5 cm ($\rho = 0.4$) as function of temperature gradient.

Figure 7: Radially averaged electron heat diffusivity of the power scan as function of temperature gradient.

analyses of all discharges gives a preliminary isotopic effect like $\tau_E \sim m^{0.2\pm0.15}$.

V. Conclusions

Density and power scans have been carried out to investigate the local parameter dependence of the transport coefficients.

An ECRH density scan reveals similarities between the favourable density scaling in W7-AS with the tokamak LOC regime. The improvement of $\chi_E$ with density saturates at $n_e \geq 5 \times 10^{19} m^{-3}$. No major deviation of ion energy transport from neoclassical theory are observed. A comparison of hydrogen and deuterium discharges indicates the existence of a small isotopic effect in W7-AS.

No local parameter could be related to power degradation of confinement. Three different types of transport experiments could be consistently described only if a transport coefficient is assumed which changes almost instantaneously with heating power.

References


W7-AS with Modified Mirror Ratio at High $\tau_a$-Values


Max-Planck-Institut für Plasmaphysik, IPP-EURATOM-Association
D-85748 Garching, Germany

A series of operation points is established in this paper for the three configuration types "R", "M" and "A" with modified mirror ratio in W7-AS, at various values of the edge rotational transform $\tau_a > 0.49$. We use stationary low-\(\beta\) plasmas in order to compare to vacuum field calculations. The first part of this paper describes vacuum field properties for the three configuration types, the second part gives experimental data.

The number of trapped particles and their localization can be modified in W7-AS by a change of the mirror ratio, defined as $\text{MR} = (B_{36} - B_0) / (B_{36} + B_0)$, via the axis field values at the toroidal angles $\phi = 0$ and $36^\circ$ in the 5 field periods of the device. This is done by different input currents in the non-planar coils at $\phi = 36^\circ$ compared to the currents in the other non-planar coils. The mirror ratio changes its sign in "R" with $\text{MR} = 10\%$ and "A" with $\text{MR} = -10\%$. A new configuration type, "M" with minimum values of $\text{MR} < 1\%$, is introduced in the vicinity of the standard case, "S". In all cases the field value $B_{36}$ is kept to $= 1.26$ T for ECRH plasma production and heating: the average axis field is largest in "A" and lowest in "R". The sizes of the edge magnetic surfaces differ at $\phi = 0$ and $36^\circ$: for "R" they are larger at $\phi = 0$ than at $36^\circ$, and vice versa for "A".

Vacuum fields for various values of $\tau_a$ are shown in Fig.1 for "R" and "A" with $\text{MR} = \pm 10\%$, as well as for "M" with $\text{MR} = 0.2\%$. No vertical fields are applied. The input data for the calculations are from actual shot data, except for the case at $\tau_a = 5/7$. The plasma edges are corrugated according to the effective main resonance, $\tau_a = 5/N$, with $N = 7$ to 10 in the range of interest. The corrugation increases with decreasing local shear and is largest in "A" near $\tau_a = 5/9$ (not shown in the figure). Internal islands at $\tau = 5/9$ (or $5/10$) can exist within closed edge surfaces in the vacuum fields of "R", "S" and "M" at slightly differing $\tau$-values on axis. The radial extension of these islands increases towards the edge, it is smaller in "R" than in "M". Higher-order resonances, e.g. the combinations of $5/10$ and $5/9 \Rightarrow 10/19$ or $5/9$ and $5/8 \Rightarrow 10/17$ can be seen in the vacuum fields at specific $\tau$-values.

Fig.2 summarizes the dependences of minor radius, global shear and global well depth vs $\tau_a$ for the three configuration types. The minor radius is defined by the average size of the 'last closed' surface not touching the inboard limiters or by the size of the separatrix; its value shrinks with increasing $\tau_a$. When changing from "R" via "M" to "A" at $\tau_a = 0.55$, the minor radius stays between 15 and 16 cm, the magnetic well deepens from -0.7 to -1.3%, but the shear is reduced from 6% for "R" to nearly zero for "A". This is accompanied by a minimum of the minor radius at the 5/9 resonance in the latter configuration. Similar minima are indicated for "R" and "M" at $\tau_a = 5/8". 
Vacuum vessel

"R" at $t_a=5/10$

$R=150.0$

$R=200.0$

$R=150.0$

Internal islands $t=5/9$ enclosed by edge surfaces

"M" Larger islands $t=5/9$ enclosed by edge surfaces

$R=150.0$

$R=200.0$

"A" Internal double-resonance at 10/19.

$R=150.0$

$R=200.0$

$R=150.0$

Fig. 1: Magnetic surfaces in W7-AS at modified mirror ratio, $\phi=0$. Fig. 2: Minor radius, shear and magnetic well for "R", "M" and "A" versus $t_a$. 
Fig. 3 "R" \( I_p = 0 \) and free development

Fig. 4: Thomson profiles for "R" at 0.54 s: \#31838 \( I_p = 0 \) (dots); \#31839 Free development (circles).
Experimental details. The plasma radius, $a$, was set in W7-AS until 1994 at low $\beta$ by the two movable main limiters at $\phi=36^\circ$, and subsequently by the fixed inboard limiters near $\phi=0$ via an appropriate axis shift by a vertical field. At high $\beta$ the separatrix defines the plasma radius. In earlier experiments with modified mirror ratio the edge rotational transform was mainly adjusted for $t_a=0.34$, see /1/ and /2/. Any increase in $\beta$ causes an increase of $t$ in the vicinity of the magnetic axis; other changes of the $t$-profile are correlated with residual plasma currents $I_p$, (bootstrap, Ohmic and/or electron-cyclotron-driven current). Then the resulting $t$-profile locally deviates from that of the vacuum field, and its edge value differs from $t_a$. Effects of magnetic islands at resonant $t$-values are difficult to predict. They may also change the plasma radius. Details of the edge configuration of the standard case, "S", and results of correlated experiments for $I_p=0$ are given in /3/. In these net-current-free plasmas, the bootstrap current was compensated by an Ohmic current.

Plasma start-up in the present investigation is with $\approx 0.4$ MW input power. After 0.1s one of the two gyrotrons is switched off, the second one is continued at a moderate power of about 0.2 MW for 1s pulse time. The line-integrated density is controlled by feed-back of an external gas valve, together with recycling from the vessel walls. We study discharge pairs with $I_p=0$ and a free development of the residual plasma current. Fig.3 gives for example various quantities of interest for two discharge pairs in "R", #31838 and #31847 at $I_p=0$, as well as #31839 and #31848 with free development of $I_p$. Minor radii of 14.3 and 13.8 cm, average axis fields of 1.16 and 1.14 T, and values of $t_a=5/10$ and 0.55, resp., are calculated in the vacuum configurations of these discharges. Identical values of the diamagnetic energy, $W_{dia}=1.1 \text{kJ}$, are obtained in the pair #31838-39; in #31847-48 $W_{dia}$ has successively smaller values by $\approx 10\%$. The discharge #31847 ($I_p=0$, $t_a=0.55$) is influenced at its end by an edge probe. This perturbation should be neglected. Free-developing currents of $I_p=1.4$ and 0.6 kA are seen in #31839 and #31848, with differing time behavior: $I_p$ in #31839 tends to saturate at about 1s near the end of the discharge, that of #31848 has a much faster saturation and may be influenced by $t_a=5/9$. Values of $I_p=4I_p/(Ba^2)=0.02$ and 0.01 result for these discharges from the cylindrical approximation using vacuum field data. Peeled $T_e$ and slightly hollow $n_e$ profiles are nearly identical for the pair of discharges shown in Fig.4, profiles of other cases in "R", "M" and "S" (two discharge pairs) are similar, $T_e$ profiles in "A" are broader, however. Central values scale roughly as $W_{dia}$ in all cases. With increasing $t_a$ the values of $W_{dia}$ decrease to typically 0.9 kJ in "R" and "M"; the observed $H_a$-signals at the inboard limiter show small variations, those at the wall tend to increase marginally. No space-resolution of $H_a$-signals was attempted.

Summary and conclusions: Three configuration types, "R", "M" and "A" with modified mirror ratio are investigated in W7-AS at $t_a=0.49$ by extending vacuum field properties for "R" and "M" up to $t_a=0.7$ and for "A" up to $t_a=0.6$. Initial experimental data with low-power ECRH plasmas cover the transition towards separatrix-dominated cases for "R" and "M" up to $t_a=0.58$, and yield similar $T_e$- and $n_e$-profiles with central values of 0.8-1.3 keV and $1.4-1\times10^{19}m^{-3}$, resp.. The new operation points thus provide a basis for further more detailed studies of the transition from limiter-dominated to separatrix-dominated configurations, magnetic islands and effects of trapped particles.

/3/ J. Das et al., paper submitted for this conference
Global Alfvén Eigenmodes in WENDELSTEIN 7-AS
(10th International Stellarator Conference, 22-26 May 1995, Madrid, Spain)

A. Weller, D.A. Spong, C. Görner, R. Jaenicke,
F.P. Penningsfeld, C.Y. Teo, W7-AS Team, NBI Group

Max-Planck-Institut für Plasmaphysik, IPP-EURATOM-Association,
D-85748 Garching, Germany

*) Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

1. Introduction.
In the presence of fast particle populations marginally stable global modes in the shear Alfvén branch can be destabilized by wave particle resonances. This is particularly of concern in future large devices, where losses of resonant particles (α-particles in a reactor) may then limit the available heating power and also may cause damage of the first wall. In tokamaks TAE modes inside toroidicity induced gaps of the shear Alfvén continua have been found [1,2]. In stellarators with very weak shear like W7-AS low-n TAE-gaps do not occur but gaps below the shear Alfvén continua with mode numbers m and n, if the resonant values \( \frac{\ell}{m} = n/m \) do not exist in the plasma volume \( (k_{\parallel} = (m \cdot \ell - n) / R \neq 0) \). Under these conditions GAE modes with frequencies \( \omega_{\text{GAE}} \leq (k_{\parallel} \cdot v_A)_{\text{min}} \) are the favoured modes [3]. The investigation of GAE modes could also be of relevance in the case of advanced tokamak equilibria with flat or inverted q-profiles in the central region [4].

2. Experimental Results.
GAE modes with frequencies in the range 10-70 kHz (Fig. 1) have been studied in W7-AS during neutral beam injection (NBI). The fast particle drive is inferred from the transient

![Fig. 1: Frequency spectra (Mirnov coil) showing GAE activity. Left: (3,1) modes grow at transition to low energy (t = 0.4 s, "density limit" reached, B = 1.25 T). Right: high temperature case at B = 2.5 T. The frequency decreases with increasing density.](image_url)
which extend over up to half of the plasma radius. The helical structure agrees with the lowest possible mode numbers $m$ and $n$, which are aligned most closely with the equilibrium field. Since the corresponding resonant surface with $\mathbf{f} = n/m$ is not contained in the plasma, the magnetic perturbations are of non-resonant type (small but finite $k_{||}$). In most cases the Alfvén velocity is found to be larger than the energetic particle velocities. Therefore, the modes are excited via toroidal $m \pm 1$ sideband resonances with $v \ll v_A$.

3. Comparison with Theoretical Predictions.

Global modes have been found in MHD calculations including a gyrofluid model for the fast particles [5,6]. The model takes various damping effects (e.g. continuum damping, Landau damping, effects of collisional damping and resistivity) into account. The frequencies are consistent with the GAE gap structure of the low $(m,n)$ shear Alfvén continua and agree with the experimental data. Also the spatial structures and saturation amplitudes correspond to the experimental data. The calculations show, that the stabilization at higher $\beta$ (in the high density, low temperature regime) is the consequence of enhanced continuum damping due to increased shear in combination with reduced fast ion drive. The model also verifies, that the energetic particle destabilization of GAE’s in W7-AS mainly occurs by ions with parallel velocities clearly below $v_A$. In most cases, where GAE’s are found, the full energy ions (45 keV) do not reach $v_A$ in the plasma core. The destabilization, therefore, takes place via the toroidal $m \pm 1$ sideband drift resonances at much lower particle velocities $\nu_{\text{res}} = \frac{\omega_{\text{GAE}}}{|k_{||,m\pm 1}|} \ll v_A$, since $|k_{||,m\pm 1}| > |k_{||,m}|$ due to the observed mode helicity (same as for equilibrium field) and weak shear in W7-AS. The contributing particles in the slowing down distribution are mainly those injected with 1/3 of the full NBI energy.

Fig. 3: Measured and calculated (nonlinear calculation) GAE frequency spectra and mode structures $(m=3,n=1)$. 

Measured Mirnov Spectrum

Simulated Spectrum
mode behaviour during NBI switch-on/off, since the mode decay is much faster than the fast ion slowing down time and the time in which the plasma pressure changes. The understanding of the conditions, under which the GAE's are driven unstable, is still an issue under investigation. These modes are preferentially excited in phases, where the plasma energy has already started to decay as the density limit is approached, which is determined by the available heating power. In this case the energetic particle drive ($\propto \beta_{\text{fast}}$) is expected to decay faster than the electron Landau damping ($\propto \beta_e$). The experiments together with gyrofluid code calculations indicate, that additional effects connected with changes of the magnetic shear, of the Alfvén velocity, of the beam deposition and fast particle profiles, and of the beam slowing down distribution have to be taken into account. Particularly in the higher $\beta$ range ($\beta > 0.5\%$) the modes disappear probably due to increased continuum damping, since the internal shear is increased by the pressure induced equilibrium currents. Recently a new parameter regime of GAE activity was found at high temperature and relatively low density (combined NBI and ECRH, $T_e, T_i > 1\text{ keV}, n_e < 6 \cdot 10^{13}\text{ cm}^{-3}$) with frequencies up to 70 kHz. Under these conditions the fast ion drive is larger, whereas the iota-profile can still be flat due to low plasma $\beta$ and effects associated with the bootstrap current.

The modes are identified in terms of Alfvén waves by their frequency in the plasma rest frame and the dependency of their frequency on the Alfvén velocity. This was investigated (Fig. 2) by varying the magnetic field (in the range 0.7-2.5 T) and the mass density (comparison of similar discharges of $H \rightarrow H$ with $D \rightarrow D$ injection). The propagation of the modes is in the direction of the (fast) ion diamagnetic drift as expected, since the drive energy originates from the fast particle drift motion in conjunction with their spatial gradient. Apart from transient phases during NBI switch-on the fast ion distribution in velocity space leads to Landau damping (in addition to electron Landau damping and other damping mechanisms).

The spatial mode structure is determined from reconstructions using data from soft X-rays, ECE, reflectometer and Mirnov coils. The radial structure corresponds to global modes,
Fig. 4: The stability of GAE modes depends on shear (gyrofluid calculations). Left: iota profiles used in the calculation. Right: linear growth rates vs. shear parameter.


The main features of the observed beam driven MHD instabilities in W7-AS can be explained in terms of global Alfvén modes. Although for particular cases quantitative agreement was found with theoretical predictions, it seems difficult to make quantitative predictions of the stability of these modes in general, because effects both of the damping by the main plasma and the drive due to the fast particles cannot be separated clearly. Therefore, investigations have been started to study the Alfvén spectrum and the damping mechanism by launching waves with an external antenna [7]. No evidence of GAE induced particle or energy losses have been found so far, the observed magnetic perturbations of $\tilde{B}/B \leq 10^{-4}$ at the plasma edge agree with nonlinear gyrofluid calculations and seem to stay below critical values. Experiments with deuterium injection have been started in order to improve the diagnostics of energetic particle losses by exploiting the neutron flux. The experiments in W7-AS in conjunction with code calculations are considered to provide useful information concerning the issue of $\alpha$- and beam-driven instabilities in future machines, in particular those with extended regions of weak shear.

References
High power heating experiments on
WENDELSTEIN 7-AS stellarator

R Jaenicke, J Baldzuhn, V Erckmann, J Geiger, P Grigull,
J V Hofmann, M Kick, J Kisslinger, G Kühner, H Maassberg,
H Niedermeyer, W Ott, F P Penningsfeld, H Ringler, U Stroth,
A Weller
W7-AS Team, NBI Team, ECRH Group

Max-Planck-Institut für Plasmaphysik, EURATOM Association.
85748 Garching, Germany

Abstract. The upgraded NB heating power on W7-AS allowed extension
of the accessible parameter space. In first experiments, a remarkable increase
of the ion temperatures was obtained. The results are discussed on the basis
of a detailed transport analysis which confirms the neoclassical nature of the
ion transport up to the limpf regime. The maximum NB heating power was
applied to investigate beta limits. Although beta values close to the predicted
stability limit could be reached, no clear indication of a limit has been found
so far. Several experimental observations on W7-AS point to the necessity of
a divertor. The feasibility of a divertor making use of the natural islands in an
optimized stellarator was investigated, and a possible solution for an island
divertor on W7-AS is outlined.

1. Introduction

The W7-AS stellarator is a medium-size experiment with respect to the major radius of about
2 m, but the average plasma radius is rather small, usually less than 18 cm, resulting in a
large aspect ratio of 11 or even larger. A specific feature is that the magnetic field is essen-
tially created by a modular field (MF) coil set [1]. The MF coils are nonplanar coils which
generate toroidal and poloidal field components at the same time. They thus produce closed
vacuum field flux surfaces, so that the set of MF coils alone is sufficient to confine a plasma.

All the other coils of W7-AS are just for experimental flexibility. The TF coils are used
to produce an additional toroidal field component, thus allowing the rotational transform
$t = 1/q$ to be varied. Small vertical fields are applied to shift the plasma horizontally, and
the OH transformer is commonly used to compensate toroidal currents, such as the bootstrap
current, to zero, this being called "net-current-free" operation.

The plasma cross-section varies toroidally between a more triangular shape and an almost
elliptical shape. The magnetic axis is not circular, but rather pentagonal in keeping with the 5
toroidal field periods. The field structure resembles five toroidally linked mirrors where the
magnetic field at the corners of the pentagon can be varied separately. The flux surfaces are
thus fully 3 dimensional, which allows one to tailor the flux surfaces in 3 dimensions and
optimize the magnetic field properties to a very large extent [2]. W7-AS represents just a first
step on the way to an optimized stellarator. The goal was to reduce the Pfirsch-Schlüter cur-
rents by a factor of about 2. The reduction of these currents results in an equivalent reduction
of the Shafranov shift and a reduction of the neoclassical transport, again by a factor of about 2. The proposed W7-X project [3] will be the first fully optimized stellarator.

The experiments described in the following use two heating methods, electron cyclotron resonance heating (ECRH) and neutral beam (NB) heating. Two 70 GHz gyrotrons with 200 kW of heating power each can be applied, depending on the wave polarization, at $B_0 = 1.25$ T or 2.5 T, the cut-off density being $3 \times 10^{13}$ cm$^{-3}$ or $6 \times 10^{13}$ cm$^{-3}$, respectively. The 140 GHz gyrotron is a 700 kW prototype, and with X2 mode heating at 2.5 T the cut-off density is $1.2 \times 10^{14}$ cm$^{-3}$. NB heating needs a target plasma which is produced by ECRH. Thus the operation is restricted to the 2 resonance fields 1.25 and 2.5 T. After doubling the number of NB sources 4 co and 4 counter sources are now available, allowing balanced and unbalanced injection. The total heating power available is thus almost 1 MW of ECRH and more than 2 MW of NB heating applied to a plasma volume of about 1 m$^3$.

Further details on the W7-AS experiment itself, the plasma parameters achieved, transport properties and so on can be found in the introduction to Ref. [4].

The experiments discussed in this paper were performed with 10 inboard limiters only. The plasma thus had to be shifted inward by a larger vertical field than with the former top and bottom limiters to keep the plasma radius sufficiently small. First, experiments are reported where the attempt to optimize the neoclassical ion heat transport led to a remarkable increase in central ion temperatures. A detailed transport analysis is presented for these discharges. Secondly, the upgraded NB heating power was used to investigate the stability of high beta plasmas at reduced toroidal field. The lack of recycling control and the high power fluxes at the plasma boundary in these NB heating experiments point to the necessity of a pumped divertor. Therefore, in the last part of the paper a divertor concept for optimized stellarators will be discussed on the basis of experimental edge studies on W7-AS.

2. Ion Heat Transport in the LMFP Regime

In the W7-AS experiment, access to the ion long mean free path (lmfp) regime turned out to be a serious problem even at high heating power. Central ion temperatures were restricted to about 1 keV [5]. In contrast to low density ECRH discharges (electron temperatures of up to 3 keV) with access to the deep lmfp regime for the electrons, NB heating has to be applied for direct ion heating in order to obtain high ion temperatures. However, discharges with high-power NB heating lead to high densities (see Section 3), and so the temperatures generally stay low. Substantial additional ECRH power was mandatory to obtain density control and stationary conditions in this case [6]. This result can be explained by a particle diffusivity D which scales roughly as $D \propto P/n$ at the plasma edge (see Section 4).

Recently, access to the ion lmfp regime was obtained for substantial NB heating at fairly low additional ECRH power with stationary conditions at densities of about $5 \times 10^{13}$ cm$^{-3}$. Very good wall conditions are essential to ensure recycling control under these conditions. At still lower densities the NB heating efficiency degrades.

2.1 Neoclassical transport

In the following, we discuss the barrier to obtaining high ion temperatures within the framework of neoclassical theory. For the flat or even slightly hollow density profiles characteristic of stellarators, rather small radial electric fields $E_r$ are expected. Only in the density gradient region are significant values $E_r < 0$ predicted. These neoclassical predictions based on the ambipolarity condition of the particle fluxes are reasonably well confirmed by active CXRS measurements [7]. Starting from the plateau collisionality regime, where the ion heat flux scales as $q_i \propto T_i^{5/2}$, the adjacent $1/v$ regime with the scaling $q_i \propto T_i^{9/2}$ at very small $E_r$ represents the barrier to obtaining higher ion temperatures and thus lower collisionalities,
\( v^* = vR/T \), \( v_{th} \propto n/T^2 \), at fixed density (see figure 1, on the right). With increasing negative \( E_r \) access to the so-called \( \sqrt{v} \) regime with \( q_i \propto T_i^{-3/2} \) is obtained \[8\]. The "tokamak-like" \( v \) regime with \( q_i \propto T_i^{1/2} \) applies for very low \( v^* \) only (see figure 1, on the left). In the intermediate Lmfp regime, where the neoclassical electron heat transport coefficients are less than the ion ones, the feature of the "electron root" \[9\] with rather strong \( E_r > 0 \), for which the neoclassical electron transport coefficients are significantly decreased, does not appear, and the electrons stay in the \( 1/v \) regime.

**Figure 1.** Neoclassical electron and ion heat diffusivities (diagonal term in the transport matrix) for an improved W7-AS configuration \( r = 10 \text{ cm}, B_0 = 2.5 \text{ T}, B_z = 200 \text{ G} \) with the radial electric field as parameter. On the left: versus the collisionality \( v^* \) for fixed temperature (1 keV) and with \( E_r = 1 \text{ V/cm} \) (solid lines), 3 V/cm (dashed lines), 10 V/cm (dotted lines), and 30 V/cm (dot-dashed lines). \( v^* \) for typical parameters \( T_e = T_i = 1 \text{ keV}, n_e = 5 \times 10^{13} \text{ cm}^{-3} \) is marked by dashed vertical lines. On the right: \( X_i, X_e \) versus temperature for fixed density (i.e. \( v^* \) increases to the left) and \( E_r \propto T \) (the values given in the left figure apply for \( T = 1 \text{ keV} \)).

Neoclassical transport estimates for the complex 3D magnetic field topology of W7-AS are based on a database of DKES calculations. The DKES code \[10\] solves the mono-energetic drift-kinetic equation for general Fourier spectra of \( B \) on each flux surface, depending on the collisionality and radial electric field. To reduce the amount of DKES computations, numerical fits of the mono-energetic diffusion coefficients to the DKES results in the different collisionality regimes, where the functional dependence of these coefficients is equivalent to those of traditional analytic theory, have been developed \[8\]. This technique leads to a very good representation of the neo-classical transport properties for the different W7-AS configurations and is rather efficient for the energy conservation to calculate the thermal 2x2 transport matrix.

For low \( \xi = 1/3 \), where the higher harmonics in the B-Fourier spectrum are less pronounced than for \( \xi = 1/2 \), two different concepts for neoclassically improved configurations have been analyzed \[11\]: (i.) the inward shift of the plasma column by applying a vertical field similar to that in torsatrons, and (ii.) the local increase of the magnetic field strength (see Section 1) in the region of strong toroidal curvature (elliptical plasma cross-section), shifting a significant portion of the ripple-trapped particle to the straighter part of the magnetic axis (with the triangular plasma cross-section). For both optimized configurations a transport improvement by a factor of about 2 was found in the \( 1/v \) regime with respect to the standard configuration in the DKES calculations. This improvement holds also for small \( E_r \) in the \( \sqrt{v} \) regime \[8\].
2.2 Combined ECRH and NB heating experiments

In the last experimental campaign, rather high vertical fields ($B_z = 200$ to 260 G at 2.5 T) had to be used to control the plasma radius (see Section 1). This resulted in one of the above mentioned optimized magnetic field configurations [5], where with $T_i(0)$ up to 1.6 keV at $n_e(0) = 5 \times 10^{13}$ cm$^{-3}$ the highest ion temperatures have been obtained so far. In figure 2, measured profiles for such a discharge are shown together with the results of the transport analysis and the neoclassical predictions. The discharge was heated by 400 kW ECRH and by three NB sources with co-injection. The powers absorbed by electrons and ions are about 650 kW and 600 kW, respectively. The FAFNER code Monte Carlo calculations indicate a fairly peaked ion heating profile with about 2/3 of NB power being absorbed by the ions due to the rather high electron temperatures ($T_e(0) = 1.8$ keV). With counter-injection, the global NB heating efficiency is reduced, and a flat ion heating profile is predicted.

![Figure 2. Profiles, transport analysis and neoclassical predictions for a stationary discharge with combined ECRH and NB heating ($B_0 = 2.5$ T, $B_z = 260$ G). Upper line: electron (solid line, full dots from Thomson) and ion temperatures (dashed line, open squares from CX) on the left; electron density (from Thomson) in the centre; and the calculated ambipolar radial electric field $E_r$ on the right. Lower line: ambipolar neoclassical particle flux; ion heat flux $Q_i$ (neoclassical prediction: dashed line, from power balance; dot-dashed line) in the centre; and electron heat flux $Q_e$ (neoclassical prediction: solid line, from power balance; dot-dashed line) on the right.](image)

Ion temperature data from the active CX diagnostic are available for $r \leq 13$ cm only, and so the transport analysis (figure 2) is restricted to this range. The ion heat flux $Q_{i\text{neo}}$ only slightly exceeds the experimental value from the power balance. For these experiments with H injection into a D$^+$ target plasma, a rather high ratio of H$^+$ to D$^+$ (roughly 1:1) is indicated. The $Q_{i\text{neo}}$ given is estimated on the assumption of pure H$^+$, and $Q_{i\text{neo}}$ turned out to be about 20% higher for D$^+$. Some additional uncertainty is introduced in the neoclassical prediction since DKES results for $B_z = 200$ G are used instead of the 260 G in the experiments, and, furthermore, the mono-energetic transport coefficients in the $\sqrt{v}$ regime are scaled by an improvement factor of 2 (see Section 2.1) with respect to the standard configuration.
(B_z = 0). With these restrictions, fairly good agreement of the neoclassical ion heat flux, where E_r from the ambipolarity condition is included, with the experimental power balance is found. The electron heat flux estimated from the power balance exceeds the neoclassical prediction by a factor of up to 2. However, some uncertainty is introduced by the smoothed T_e profile, which is used for the neoclassical predictions, in the region of the ECRH power deposition expected slightly off-axis at about 4 cm due to the Shafranov shift.

The neoclassical particle flux, \( \Gamma_{p,\text{neo}} \), is roughly consistent with the beam fuelling rate in the region of the flat density profile, \( r \leq 10 \text{ cm} \). In this inner region, fairly small \( E_r \) values of up to 40 V/cm (figure 2) are predicted, and the ambipolar particle flux is mainly driven by the off-diagonal term (\( \propto \sqrt{T} \)) in the transport matrix. Nevertheless, these electric fields are sufficient to reduce the neoclassical ion heat transport by more than an order of magnitude (see figure 1). They allow access to the \( \sqrt{v} \) regime and thus to high T_i values. The strong density gradient at \( r \geq 11 \text{ cm} \) drives the \( E_r \) strongly negative. Here, the particle sources due to recycling become dominant (almost no external gas puffing was necessary to maintain the discharge).

Later in this discharge the ECRH was completely switched off. No fully stationary conditions could be obtained since the line averaged density was slightly increasing. About 40 ms after ECRH switch-off, \( T_i \) was nearly unchanged whereas \( T_e(0) \) was decreased by 500 eV (\( T_i > T_e \)). The transport analysis leads to similar conclusions, i.e. again fairly good agreement of the neoclassical predictions with the power balance is found.

![Figure 3. Electron (from Thomson scattering, upper plot) and ion (from CX diagnostic, lower plot) temperature profiles for a NB heating power scan (\( B_\theta = 2.5 \text{ T}, B_z = 260 \text{ G} \)). Solid lines: 400 kW ECRH and 1 NB source; dashed lines: 700 kW ECRH and 2 NB sources; dotted lines: 400 kW ECRH and 3 NB sources (same discharge as in figure 2).](image)

In figure 3, the electron and ion temperatures are shown for a NB power scan with 1 to 3 co-sources (about 250 to 300 kW of heating power each), where the density profiles are similar to that of figure 2. The ion heating by the NB's is dominant, the collisional power transfer \( P_{ei} \) being of minor importance. Even in the scenario with 700 kW ECRH and 2 NB sources, where the central \( T_e \) significantly exceeds \( T_i \), \( P_{ei} \) in the region \( r \leq 12 \text{ cm} \) is well below 100 kW. The analysis of the ion heat flux from the power balance at \( r = 10 \text{ cm} \) (where the density gradients vanish) leads to a temperature dependence of about \( q_i \propto T_i^{3/2} \) in agreement with the \( \sqrt{v} \) regime scaling. With all uncertainties taken into account, access to the Lmfp regime with improved neoclassical confinement is directly confirmed.
First experiments with a slightly deoptimized magnetic configuration in W7-AS do not allow such clear conclusions. By increasing the current in the large special coils located in the region of strong toroidal curvature with respect to the other MF coils system by 30%, higher losses are indicated by the "bounce-averaging" of the VB drift on flux surfaces [11] in comparison with the optimized configurations of Section 2.1. Indeed, both the electron and ion temperatures were reduced by about 15% in the experiments. However, also the average magnetic field is 7% smaller for this slightly deoptimized configuration, and the neoclassical transport coefficients scale as $B^{-2}$. As the DKEs database and exact NB heating profiles for this configuration are not available at present, changes in the neoclassical heat flux due to the modified magnetic field configuration cannot be discriminated sufficiently well against changes due to $q_i \approx T_i^{3/2}/B^2$.

3. First results with high power NB heating

The upgrade in the NB heating power gave access to higher energy contents and consequently higher beta values. Therefore, a major aim of the first experiments was to test the achievable beta values and compare them with theoretically predicted beta limits.

3.1 Experimental results

Discharges in W7-AS with high NB heating power are characterized by a rapid increase of the density. Thus very high densities are reached (up to $2.5 \times 10^{14}$ cm$^{-3}$) so that the maximum energy content and also the time behaviour of the discharge are quite often determined by impurity radiation. Whenever the radiation exceeds about half of the heating power the discharge is quenched along an energy confinement time scale. To some extent the radiation and also the density rise can be influenced by strong external gas puffing. Also a slower density rise is observed after He glow discharges. This effect gradually vanishes, and after a long series of shots the density rise becomes even larger, probably due to particles deposited in the graphite limiters. Since the energy confinement scales almost linearly with the toroidal field [4], the highest beta values are obtained at reduced magnetic field.

Figure 4 presents profiles for such a high-beta discharge at 1.25 T. The central densities are about $2 \times 10^{14}$ cm$^{-3}$, the central electron temperatures around 350 eV and, due to the high density, the ion temperatures are not very different (no measurements available at present). For this discharge a central beta of about 4% and an average beta of between 1.7 and 1.8% are estimated. These beta values approach the earlier predicted beta limits of W7-AS in the order of 2% [12]. Therefore, in the following Section measurements of the MHD activity will be analyzed, and updated stability predictions are presented.

3.2 Stability analysis

We can roughly distinguish between two possible beta limits, namely the equilibrium and the stability beta limit, the latter depending on the considered instability.

The consequences of exceeding the equilibrium beta limit in stellarators are not clear. Problems are expected for large Shafranov shifts, which can be estimated from the simple equation [13]

$$\frac{\Delta}{a} \bigg|_{axis} = \frac{1}{2} \frac{R_0}{a} \frac{<\beta>}{2 + 2} \leq \frac{1}{2}$$

It follows that the Shafranov shift will be relatively large in W7-AS because of the large aspect ratio, and because the rotational transform can be rather low (e.g. $\tau \geq 1/3$). The shift is reduced by a factor of about 2 (added in front of the equation) due to the optimization of the W7-AS configuration.
Figure 4. Density (a) and electron temperature (b) profiles measured by Thomson scattering for a high beta discharge at $B_0 = 1.25 \text{ T}$ and $P_{NI} \leq 2.2 \text{ MW} \, (#31114)$. For the beta profile (c) the ion contribution was estimated. The average beta $\langle \beta \rangle$ is between 1.7 and 1.8%, depending on the exact contribution by the ions and the exact plasma radius.

Figure 5. Comparison of vacuum field (broken line) and finite beta equilibrium flux surfaces calculated by the NEMEC code for the discharge conditions of figure 4 (constant vertical field). Shown are the rather triangular (weak toroidal curvature) and the rather elliptical plasma cross-sections (strong toroidal curvature). Radial and vertical coordinates are given in cm.

A better prediction can be obtained from the free boundary equilibrium code NEMEC [14] by using experimental pressure profiles. The electron part of the pressure profile is taken from Thomson scattering data. The ion contribution is adjusted to match the measured diamagnetic signal. Figure 4 shows the resulting beta profile. Internal toroidal net currents (bootstrap, ohmic and Okhawa current) have been neglected because of the low electron temperatures. The calculated equilibrium shown in figure 5 exhibits the expected large shift between the vacuum field and finite-beta equilibrium flux surfaces. In figure 6 the calculated equilibrium flux surfaces are compared with surfaces of constant sX-ray intensity obtained with two sX-ray cameras by tomographic reconstruction. The Thomson temperatures measured in an equivalent poloidal cross-section along a major radius are also shown. The pre-
dicted Shafranov shift agrees well with that experimentally observed, as already found earlier [15]. The relatively large shift of the magnetic axis leads to a considerable compression of the flux surfaces on the outside. Thus high local pressure gradients may be expected to lead to instabilities. This effect is especially pronounced at the elliptical cross-section of the plasma (see figure 5).

![Diagram of plasma cross-section](image)

**Figure 6.** The calculated finite beta flux surfaces of figure 5 (triangular plasma cross-section) are compared with: 1) surfaces of constant sX-ray intensity obtained with two sX-ray cameras by tomographic reconstruction. 2) electron temperatures measured along a major radius by Thomson scattering.

Experimentally, increased MHD activity has been observed in some discharges in Mirnov and sX-ray signals. Two phenomena can be distinguished. Firstly, bursts of high-frequency oscillations in the Mirnov coils are observed at the end of the energy content rise or at the beginning of the stationary phase. According to the sX-ray signals they are localized at the plasma edge, leading to a relaxation process throughout the plasma cross-section (figure 7). This is observed particularly in cases of maximum inward shift, where the vacuum well depth is marginal. The sX-ray intensity profile width shrinks a little bit, and also the energy content is reduced somewhat perhaps by a small rearrangement of the pressure profile.

Secondly, low-frequency oscillations located at the plasma boundary occur typically late in the stationary phase, these being similar to coherent mode activity of medium-beta discharges [16]. In this case the frequencies are between 4 and 8 kHz; the mode numbers could not yet be determined. These modes can also lead to a small reduction of the plasma energy. However, a hard stability beta limit has not yet been seen.

The observed MHD activity will be related to predictions of stability codes [17]. The stability calculations are based on finite beta equilibria obtained with the NEMEC code. Without toroidal net currents only pressure driven modes have to be considered. The JMC
stability code [18] analyzes the stability criterion applied to flux surface averages of two modes: firstly, Mercier modes, which are generally stable, and, secondly, resistive interchange modes, which are predicted to be unstable for the discharges presented in figures 4 and 7. The rather high vertical field in these discharges reduces the vacuum magnetic well to marginal. Finite beta deepens the well again but also increases the destabilizing terms in the resistive interchange criterion. The plasma thus proves to be unstable for r/a > 2/3. At the plasma boundary the resistive interchange criterion is identical to the stability criterion for ideal free boundary modes ("peeling modes") [19]. Therefore, resistive interchange and peeling modes could be candidates for the increased high frequency non-coherent MHD activity seen in the Mirnov and sX-ray signals. The locally high pressure gradients might lead to ballooning modes. For this purpose calculations with GARBO ("GArcching Resistive Ballooning cOde") have been initiated.

![Graph](image)

**Figure 7.** Fluctuations observed in a high beta discharge similar to that in figure 4. Left: A small drop of the plasma energy (top) occurs around 0.1966 ms correlated with a short burst in the Mirnov signal (bottom). Right: time resolved signals from Mirnov coil and sX-ray diodes. The X-ray signals indicate, that the perturbation starts in the outside region (the X-ray signals are marked by their chord radius, where negative values correspond to inboard and positive values to outboard lines of sight, respectively). It leads to a fast cooling of the outside region as seen by the contraction of the sX-ray emission profile width (left, centre).

### 3.3 Global plasma parameters

Since fluctuation measurements do not clearly indicate a beta limit, the NB heating power was varied in order to see whether a limitation in global confinement can be observed. In fact the diamagnetic energy content does not linearly increase with heating power up to the highest available power. However, such a nonlinear dependence has to be discriminated against the usual power degradation of the confinement [4]. Power scans at B₀ = 1.25 T and 2.5 T where \( <\beta>_{\text{max}} \) differs by about a factor of 1.5 show saturation effects which are too similar to allow a definite distinction in a preliminary analysis.

Another possibility of exploring the equilibrium beta limit is to vary the rotational transform since the Shafranov shift scales as \( 1/t^2 \). In figure 8 the energy content of discharges with maximum NB heating power and constant line density is plotted as a function of the rotational transform. The Shafranov shift increases with decreasing \( t \) together with the plasma radius since, at constant vertical field, the plasma is shifted away from the inboard
limiters, which determine the plasma radius. This growing plasma radius can roughly explain the increasing energy content according to $\tau_E \propto a^2$ [4] if we assume otherwise constant transport properties. At the lowest $t$ values a slight saturation of the energy content can be seen, which could indicate an incipient equilibrium beta limit. However, average beta values ($\langle \beta \rangle = 1.6 \ldots 1.7\%$) are rather constant during this $t$ scan and slightly lower than in the discharge presented in figure 4. The measured MHD activity does not indicate any strongly confinement-degrading instabilities.

**Figure 8.** The diamagnetic energy content as a function of the vacuum field rotational transform $r_\alpha$ at the plasma boundary. The discharge conditions are similar to those in figure 4 ($t_\alpha = 0.38$ except for the smaller vertical field.

4. Experimental investigation of an island divertor concept

As mentioned in the previous Sections, high power NB-heated discharges on W7-AS suffer from an uncontrollable density increase and require a low impurity content. Even now the limiter thermal load was found to exceed the critical value of 10 MW/m² at high heating power. In addition, plasma edge measurements also indicate the necessity of a divertor.

The plasma edge is defined in these experiments as the last closed flux surface determined by 10 poloidal inboard limiters. It was found that in the density range up to $n_{ce} = 10^{14}$ cm⁻³ the edge temperature $T_{ce}$ is rather high, typically between 50 and 100 eV, and depends only weakly on the heating power and edge density [20]. The edge density is almost proportional to the volume averaged density with, for example, $n_{ce} = 2 \times 10^{13}$ cm⁻³ at $\langle n_c \rangle = 10^{14}$ cm⁻³. These parameters indicate an unfavourable "high-$T_e$ solution" [21] without significant parallel $T_e$ gradients and particle flux enhancement, as is typical of limiter scrape-off layers. Particle diffusion coefficients at the edge were found to depend on the non-radiated part of the heating power and the inverse of the density, $D_\perp \propto (P_{\text{heat}} - P_{\text{rad}})^{0.85} <n_c>^{-1.1}$ [20]. In this case the power degradation of the transport is a positive aspect because it leads to broadening of the power deposition zones on the limiters or target plates. However, the density dependence aggravates the density control. Due to the strong coupling between near-target and core plasma it is very unlikely that, even at higher densities, favourable regimes such as high recycling or controlled detachment can be established with limiters. But, as in tokamaks, these problems could be overcome by a divertor.

The optimized stellarator could now offer an elegant solution to the divertor problem, that is by using the so-called "natural islands". These natural islands are an intrinsic property of non-axisymmetric flux surfaces, which means they are created by the MF coils as well, and additional coils to produce a divertor x-point are not required. The natural islands are resonant magnetic field islands appearing for $n = n/m$, where $n=5$ is given by the 5 toroidal field periods. They can be large enough to be used for an island divertor [22]. Figure 9 shows two examples of natural islands at the toroidal position of one of the inboard limiters. The $t$ at the plasma edge is about 1/2 or 5/10; thus there are 10 islands or, as a consequence, 10 x-points on the poloidal circumference. Due to the small shear of W7-AS a small change of
t causes a significant radial shift of the islands. On the left of figure 9, the island tips just touch the limiter, resulting in 2 or maybe 3 interaction zones in the experiment. On the right, the islands have been shifted outward, so that the inboard limiters intersect the islands, and the number of, for example, light stripes should have doubled.

These expectations were verified by several diagnostics [23] such as a poloidal Langmuir probe array, Hα diode arrays and a video camera. The measurements obtained with the Langmuir probes from a low-beta discharge [23] were compared with the results from plasmas with finite toroidal current and with medium beta produced by medium-power NB heating, which changes the shear at the plasma boundary and the shape of the flux surfaces. In fact, the density pattern measured by the probes changes somewhat, but the important result is that the main structures are very similar. It must be emphasised that changes have to be expected because W7-AS is only a partly optimized stellarator. In a fully optimized stellarator like W7-X, bootstrap currents will be so small that a loop voltage is no longer envisaged to compensate them to zero, and the modification of the magnetic field configuration by finite plasma pressure effects is significantly reduced [2].

![Figure 9. Vacuum field flux surfaces with natural magnetic islands at the boundary intersecting one of the inboard limiters. Due to the small shear of W7-AS a small change of \( t_A \) leads to a significant radial shift of the island position.](image)

Figure 10 presents observations with the video camera. Shown are the light pattern on one of the inboard limiters for the two island positions of figure 9, yielding the expected single and double structures. The situation in the upper part of the figure corresponds best to the divertor tokamak situation. The narrow light stripes are very similar to the footprints of the divertor legs on the divertor target plates. They suggest replacing the limiters in W7-AS with target plates at appropriate positions in order to take the first step toward a divertor.

A possible solution for a divertor on W7-AS is sketched in figure 11. Due to different connection lengths and confirmed by MC code calculations, the essential plasma-wall interaction should take place on the top and bottom plates, which are therefore labelled target plates. The other plates are intended to act as baffles. The divertor modules will be closed by baffles also in the toroidal direction. From EIRENE code calculations with SOL plasma parameters extrapolated from experimental values it is estimated that about 5% of the particle
Figure 10. Light emission in front of one of the inboard limiters as seen by a video camera. The rotational transform $\tau_a$ in the experiment was very similar to the two cases shown in Figure 9 (the top picture corresponds to the left flux surface).

$#29704,$
$\tau_a = 0.520$

$#29700,$
$\tau_a = 0.510$

Figure 11. Sketch of a cross-section through a proposed island divertor on W7-AS together with boundary vacuum field flux surfaces (elliptical plasma cross-section).
flux onto the targets could be actively pumped off by Ti gettering behind the left baffle (figure 11). Coupled B2/EIRENE code calculations to obtain a more quantitative check of the divertor potential and optimize the target and baffle arrangement are under way. It should be mentioned that the island divertor designed for the proposed larger W7-X [22] is based on the same ideas.

5. Summary and discussion

In optimized stellarators the neoclassical transport can be reduced by properly adjusting the magnetic field strength on flux surfaces. The attempt to optimize in this way the ion heat transport in W7-AS led to an increase of the central ion temperatures from about 1 to 1.6 keV. However, a detailed transport analysis showed that the key element for this improvement was ambipolar radial electric fields of the order of 10 to 50 V/cm, which reduce the neoclassical ion heat conductivity by more than an order of magnitude. Good density control, an efficient heating scenario and partly also the optimized magnetic field configuration contributed to the progress.

After doubling the number of NB sources the available higher heating power was used to investigate beta limits in W7-AS. In first experiments a central beta of 4% and an averaged beta of 1.7 to 1.8% were achieved. The JMC code predicts resistive interchange modes to be unstable. Nevertheless, fluctuation measurements as well as global plasma parameters do not clearly indicate a beta limit so far. This implies that the experimentally achieved beta values are essentially still power or radiation limited.

The high central beta values lead to a considerable Shafranov shift of the flux surfaces and consequently to high local pressure gradients. Resulting problems with the equilibrium beta limit are easy to avoid. W7-AS can be operated at higher rotational transform, and on a fully optimized stellarator like W7-X the shift of the flux surfaces as compared with the vacuum field remains small even at an average beta of 5% [24].

The desired recycling control in NB heated discharges, the high power fluxes observed even now and the plasma edge parameters measured on W7-AS indicate the necessity of a divertor also in stellarators. Measurements of, for example, the poloidal dependence of the edge density or of the light emission on limiters under various plasma conditions have demonstrated that the so-called natural islands could provide the necessary divertor x-points. These magnetic islands are an intrinsic property of the non-axisymmetric field of optimized stellarators. They can be sufficiently large and be suitably positioned at the plasma boundary. To complete and optimize a first proposal for such an island divertor on W7-AS additional code calculations are being performed.

References

Boozer A 1995 This Conference (to be published in Plasma Phys. Control. Fusion )
1990" (Proc. 13th Int. Conf., Washington, USA, 1990) Vol. 3 IAEA Vienna 525
[5] Kick M et al 1995 To be published in Proc. 10th Int. Conf. on Stellarators, IAEA
Techn. Committee Meeting, Madrid, Spain, 22-26 May 1995


[13] Nührenberg J 1995 Private communication, see also [18]


[19] Lortz D 1975 Nucl. Fusion 15 49


Transport Studies of Injected Impurities in the Stellarator Wendelstein 7-AS

Institut für Plasmaforschung, Universität Stuttgart, D-70569 Stuttgart, FRG

1. Introduction

In contrast to strong efforts concerning the improvement of energy confinement in fusion plasma devices, the confinement of so-called impurity atoms released from plasma facing in-vessel components by plasma-wall interaction should simultaneously be as worse as possible. Their presence in the plasma can cause a strong reduction of the plasma temperature by impurity radiation cooling and a significant dilution of the fusion mixture, both, depending on its concentration, having serious effects on the ignition criteria for a fusion plasma. For these reasons, there is an urgent need to understand the impurity transport, especially with respect to steady-state operation of future fusion devices. For toroidal plasmas the neoclassical transport theory describes the collisional dissipation. Often, however, a large fraction of the transport cannot be explained by this theory alone and the difference is attributed to additional turbulent transport which is not yet well understood. It is important to find out whether the impurity transport in the stellarator W7-AS is basically governed by turbulent mechanisms or possibly is described by collisional transport. In the latter case an understanding of the nature of the impurity transport is provided with the possibility to predict the behaviour in future devices.

The study of the non-stationary temporal behaviour of non-intrinsic impurity tracers injected into the plasma is a well-known technique to investigate impurity transport. At W7-AS, laser blow-off and gas-oscillation experiments have been performed in ECR-heated discharges and were simulated by the transport and radiation code SITAR.

2. Injection methods

With laser blow-off technique the impurity material (Al, Fe) under investigation, being evaporated (thickness 1μm) onto the surface of a glass substrate, is ablated by a short pulse of a focussed (~ 2-3mm) Q-switched ruby laser beam (1J, 30ns) into the stationary phase of an ECR-heated plasma discharge. From the temporal evolution of spectral lines from different ionization states (Al IX-XIII, Fe XVI-XXI) of the tracer, directly following the injection, information about its transport can be derived. With exception of the soft-X camera only central line-of-sight observation was possible. Additional observation of lowest ionization states (Al I-III) along the injection path confirmed the already known feature, that the impurity beam consist of a short pulse (~50μs width) of fast neutrals followed by a broader distribution (=1-3ms
width) of slower clusters. The relative abundance depends strongly on the laser energy density on the target and on the target thickness [1]. Measurements of the penetration depth of the clusters into the plasma reveal that their deposition takes place at the last close flux-surface whereas a large amount of the neutral component is already ionized outside the plasma edge and probably lost. Hence, a source function was used in the code simulations having similar time behaviour as the emission of the lowest ionization states and being localized at the plasma edge for both impurity species.

Another powerful method for impurity transport investigation applied at W7-AS is the gas-oscillation technique [2], which provides better access to the radial dependence of the transport. Here, a gaseous impurity tracer (e.g. H$_2$S for S, F$_3$CH for F) is injected by a sinusoidal modulated gas valve (5-10Hz) at the vessel wall during the whole stationary phase of the plasma discharge. Depending on the radial transport, the tracer wave penetrates into the plasma, steadily undergoing a phase delay and damping of its amplitude relative to its source function at the plasma edge. The required source function was again obtained by observing spectral lines of lowest ionization states (S II, F II) along the injection path. The soft-X camera turned out to be the most suitable tool for measuring the radial phase and amplitude profiles of the impurity wave. Although the soft-X camera cannot distinguish between different spectral lines, the observed spectral range could be restricted to line radiation from helium- and hydrogen-like ions by using proper absorption filters (25 μm Be for S, 5 μm Be for F) in front of the camera. In a further step, these line-of-sight integrated and filtered radial profiles were simulated by the transport and radiation code SITAR.

3. Code simulation

The transport and radiation code SITAR [3] time-dependently solves the complete set of coupled continuity equations for all ionization states z. These calculations can be done either with an ansatz for the particle fluxes $\Gamma$ derived directly from neoclassical transport theory or using an heuristic ansatz $\Gamma = -D(\delta n/\delta r) - v n$ with selectable radial values for the diffusion coefficient $D$ and the convection velocity $v$, being identical for all ionization states. In the expression for the neoclassical fluxes originally implemented in the code [3] several coefficients which had been approximated by constant values, were replaced by collisionality dependent analytical expressions [2,4] in order to consider correctly the contributions from the different transport regimes (Banana-Plateau and Pfirsch-Schlüter transport). The influence of the impurity background on the tracer transport is considered by a single species only, represented by one typical ionization state, being radially fixed to the electron density profile. Electron transport is not calculated and hence not selfconsistently taken into account.

Concerning the errors of the neoclassical simulations, the calculations are highly sensitive on the radial profiles of electron and ion temperature and electron density as well as the reasonable
consideration of - possibly more than one - additional background impurity. Uncertainties in these input data can cause significant errors (factors 1.5-2) in the simulated results.

4. Results and Discussion

At the low shear stellarator W7-AS (R=2m, a=12-18cm, B0=1.25/2.5T, 0.25 ≤ (t=1/q) ≤ 0.7) a variety of experimental plasma conditions were investigated by laser blow-off measurements. No difference in the transport behaviour was observed between injected iron and aluminium. The following results were obtained with aluminium as tracer. The confinement time $\tau_{Al}$ was calculated from fitting the temporal decaying part of the line radiation from highest ionization states by a function $\exp(-t/\tau_{Al})$ and represents the impurity transport in the core plasma. From a statistical analysis (53 discharges) the following scaling law was derived for $n_{eo} ≤ 5·10^{19} \text{ m}^{-3}$:

$$\tau_{Al}[\text{ms}] = 4.6·10^{-2} \ a_p[\text{m}]^{-2.4} \ B_0[T]^{0.3} (\pm 0.2) \ P[\text{MW}]^{-0.8} (\pm 0.2) \ n_{eo}[10^{19} \text{ m}^{-3}]^{1.2} (\pm 0.2)$$

(plasma radius $a_p$, magnetic field $B_0$, ECR heating power $P$, central electron density $n_{eo}$). Unfortunately, $Z_{eff}$ could not be taken into account, because $Z_{eff}$-measurements were not available for most of the discharges. Additionally, no clear dependence on the rotational transform as well as the working gas (H,D) could be identified. Nevertheless, there is a clear and stable dependence of the confinement time on the plasma density, the heating power and the plasma radius. Compared to the energy confinement time $\tau_E$, obtained from the ratio of plasma energy (diamagnetic loop) and heating power, a nearly proportional relation $\tau_{Al} \equiv 4 \tau_E$ was found.

Concerning the density dependence of the transport, similar results were obtained from gas-oscillation method during a density scan [2] ($a_p=18cm$, $B_0=2.5T$, $P=450kW$, $t=1/q \equiv 1/3$) with sulfur as a tracer. For these discharges $Z_{eff}$ changed inversely to the electron density.

Fig.1 shows the overall phase delay between a central channel of the soft-X camera and the source function (S II) at the plasma edge for the different densities. This is compared with neoclassical expectations. In fig.2 the corresponding central diffusion coefficients $D$, derived from the simulations of the experimental results are plotted versus the electron density, together with results from laser blow-off experiments at $B_0=1.25T$.

For the lowest density the measured phase delay is smaller and consequently the transport higher than neoclassically predicted. This is also confirmed by simulations of the radial profiles of phase and amplitude, requiring enhanced values for the diffusion coefficients. To match the experimental results, the neoclassical fluxes had to be enlarged by factors of 2-4. Although this deviation is close to the errors of the simulations, the tendency is obvious and supported by laser blow-off measurements at lowest density. This discrepancy might be explained either by additional turbulent transport or - in particular under these low-density conditions, where the
coupling of electrons and ions is weak - the neglect of electron transport and resulting radial electric fields in the simulation.

At medium densities the experimental data are in agreement with the neoclassical simulations within the errors, but with a trend towards better agreement using reduced neoclassical fluxes at increased density. Due to the optimization of the magnetic field topology in W7-AS, a reduction of the Pfirsch-Schlüter-currents by a factor 2 is predicted, so that the experimental findings would not be in contradiction to expectations.

At the highest density, however, the transport seems to be only explainable using a drastic reduction of the neoclassical fluxes by factors of 4-10 in the simulations, which is not yet understood and subject to further investigations. The corresponding data points in fig.1 and 2 (with arrow) represents the upper/lower limit with respect to uncertainties of the input data.

Close to the plasma edge nearly no phase delay was observed, indicating an enhanced radial transport in this region. This was confirmed by measurements of radial line radiation profiles of fluorine (FV-VII) from ionization states, which are located in this region. These profiles could be simulated only with a transport exceeding the neoclassical one by an order of magnitude.

References
Topological Aspects of Island Divertor Studies on W7-AS

J. Das, P. Grigull, G. Herre, J.V. Hofmann, F. Sardei
W7-AS Team, ECRH Group, NBI Group
Max-Planck Institut für Plasmaphysik, IPP-EURATOM Association
D-85748, Garching bei München, Germany

Introduction

The W7-AS is a modular stellarator with $m=5$ periods. Within each period the plasma cross-section varies from elliptical to triangular and again to elliptical. The rotational transform of the modular coil set can be varied between 0.25 and 0.67 by means of planar toroidal field coils. The structure of the plasma boundary is characterized by the presence of $5/m$ natural islands[1] and this topology can be used to study the feasibility of island divertors for power and particle exhaust. The $5/m$ islands can exist either as a closed chain or they can be intersected by the inboard limiters. These limiters provide a well defined scrape-off layer which has the inherent stellarator symmetry and can be used for preliminary investigations exploring the divertor potential of W7-AS. This is especially important in context of the planned island divertor for W7-X.

![Diagram of W7-AS with islands](image)

Fig. 1 Calculated 5/10 islands in W7-AS at the poloidal position of the inboard limiters in W7-AS ($\epsilon_a=0.512$).
The natural islands in W7-AS appear at rational \( \ell \) values and are a consequence of the radial magnetic field components present in the Fourier spectrum of the modular coil set. The harmonics are of the type \( 5n/m \) where \( n \) and \( m \) are integers. As shown in fig.1 the resulting intrinsic diversion of the field lines provide a configuration ideal for studying island divertors. A decrease in \( \ell_a \) causes the islands to move radially outwards where they eventually come into contact with the inboard limiters. Finite values of \( \beta \) also lead to a radial shift of the island position together with a change in island size.

**Experimental Results**

The viability of the island divertor concept[2] depends critically on the stability of the island structure against external and internal magnetic field perturbations caused by imperfections in the coil system, plasma current and beta effects. In order to assess the relevance of the vacuum field structures and of perturbative fields for plasma transport and recycling at the boundary, we have investigated the boundary topology for different values of the edge rotational transform (\( 0.290 \leq \ell_a \leq 0.640 \)) and for different values of the density \( (10^{18} \text{ m}^{-3} \leq n_e \leq 10^{20} \text{ m}^{-3}) \).

![Diagram](image)

**Fig.2** Plot of \( n_e \) contours measured with the Langmuir probe array located at the triangular plane (toroidal angle \( \phi = 72^0 \)). The darkest areas indicate \( n_e < 3 \times 10^{17} \text{ m}^{-3} \) and the brightest areas \( n_e > 1.5 \times 10^{18} \text{ m}^{-3} \) in a linear scale.
A Langmuir probe array located at a fixed radius outside the separatrix and covering about 1/3 of the poloidal plasma circumference was used to measure the poloidal $n_e$ (and $T_e$) profiles at the boundary while the distribution of neutral gas was monitored by measuring the spatial variation of the $H_\alpha$ intensity. Poloidally resolved calorimetry was used to measure the power load on the individual limiter tiles and video cameras monitored the visible radiation at the edge.

Experimental results from these diagnostics show clear evidence of the presence of the 5/8, 5/9, 5/10 and 5/11 island chains at the plasma edge. Fig. 2 shows the $n_e$ profiles at the edge within the range $0.42 \leq \rho_a \leq 0.64$. The higher density, higher temperature areas around the closed islands are indicated by the brighter areas in the figure. The change in the separatrix symmetry between odd and even values of $m$ (X-point at the midplane for 5/8 and 5/10 islands, O-point for 5/9 and 5/11 islands) can be clearly seen in the $n_e$ profiles. Decreasing $\rho_a$ causes the islands to move radially outward and they are eventually intersected by the inboard limiters. This leads to a loss of confinement within the islands resulting in the decay of the plasma pressure within the island core. The sharp edges of the bright areas in fig. 2 arise due to this sudden loss in confinement. The transition from closed to open islands is reflected in the experimental data as a doubling of the maxima in the temperature and density profiles. This is because the intersection with the limiters results in the formation of two SOL branches and the intersection with the limiter now occurs along two zones per island. The figure also demonstrates that the 5/m structures are not significantly perturbed by lower order resonances even at $\rho_a=1/2$ where such perturbations are expected to have a major influence. Measurements carried out at higher $\beta$ ($\beta=0.8\%$) indicate that despite deviations in detail the 5/m island chains are still dominant under these conditions.

![Fig. 3](image)

**Fig. 3** Poloidal profile of the $H_\alpha$ intensity in front of the lower inboard limiter in Module 3 and power load distribution on the limiter tiles.
Comparison of the experimentally measured poloidal phase of the islands, in particular their location with respect to the inboard limiters with that predicted by vacuum field calculations is a good measure of the relevance of these structures for a real plasma. Fig.3 shows a poloidal \( H_o \) intensity profile along the surface of the lower inboard limiter in Module 3 along with the power load distribution on the tiles of the same. The edge rotational transform was fixed at 0.512 for this discharge. It is clearly seen that the predicted 5/10 island positions (at limiter tiles 9, 13 and 16) as shown in fig.1 are in excellent agreement with the location of the maxima in the \( H_o \) and power load profile. The same is also true for discharges where the plasma edge is characterized by the 5/8, 5/9 and 5/11 islands.

**Conclusion**

In conclusion it can be said that 2D spatially resolved measurements at the edge of W7-AS confirm the inherent diversion of the plasma by the islands. This is a basic prerequisite for an island divertor as that planned for W7-X. Changes in the boundary topology with changing edge rotational transform are reflected in the \( H_o \) intensity profile in front of the limiters, in the power load distribution on the limiter tiles and in the poloidal \( n_e \) (and \( T_e \)) profiles at the edge. For low \( \beta \) the location of the 5/m islands at the boundary are in excellent agreement with that predicted by vacuum field calculations. These islands remain dominant also for finite \( \beta \) values and are found to be rather stable against moderate variations in plasma parameters.

**References**


RESPONSE OF THE PLASMA CONFINEMENT ON SHEAR MODIFICATION BY ELECTRON CYCLOTRON CURRENT DRIVE AT W7-AS

Max-Planck-Institut für Plasmaphysik, EURATOM Ass., 85748 Garching, Germany

W. Kasparek, G.A. Müller, P.G. Schülter  
Institut für Plasmaphysik, Univ. Stuttgart, 70569 Stuttgart, FRG

1. Experimental conditions and theoretical modelling

The confining magnetic field in the W7-AS Stellarator has a flat profile of the rotational transform $t_{\ldots\ldots}$ with a weakly positive shear (up to +2%) above and weakly negative shear (up to -2%) below $t_{\ldots\ldots}$ = 0.4. Low order rational values of $t_{\ldots\ldots}$ can thus be excluded from the confinement region by a proper choice of $t_{\ldots\ldots}$, which can be tuned within the range $0.25 < t_{\ldots\ldots} < 0.65$. The global confinement depends sensitively on $t_{\ldots\ldots}$ with maxima in the close vicinity of the low-order rations $t_{\ldots\ldots} = 1/2, 1/3...[1,2]$. The total stored energy from the diamagnetic signal is shown in Fig.1 as a function of the edge value of $t_{\ldots\ldots}$ (a) for ECR heated plasmas with low $\beta$ and zero net current. Under such conditions one may expect to operate close to the vacuum field conditions.

The low shear configuration of the vacuum magnetic field is, however, modified by internal plasma currents such as the pressure driven bootstrap current, Pfirsch-Schlüter (PS) current and diamagnetic current under finite-$\beta$ conditions. The Shafranov shift of finite-$\beta$ plasmas plays an important role and modifies the profile of the rotational transform. Externally controlled plasma currents are introduced by Electron Cyclotron (ECCD) and/or inductive current drive. The EC-driven current is decoupled from the plasma conductivity profile even under steady state conditions in contrast to the inductive current, its position and magnitude is controlled by the resonance layer position and launch angle of the incident microwave beams [3].

Net current-free plasma start up and heating is provided by ECRH at 70 GHz and/or 140 GHz with a plasma density up to $n_{e,\text{crit}} = 0.3 \times 10^{20} \text{ m}^{-3}$ (1.25 T, X2-mode), $n_{e,\text{crit}} = 0.6 \times 10^{20} \text{ m}^{-3}$ (2.5 T, O1-mode) and $n_{e,\text{crit}} = 1.2 \times 10^{20} \text{ m}^{-3}$ (2.5 T, X2-mode). Both the 70 GHz (< 1.0 MW, 3 s) and 140 GHz beams (0.5 MW, 1.1 s) are launched from the low field side in the equatorial plane and can be steered to arbitrary toroidal directions for current drive. The radial plasma current distribution is calculated assuming a linear superposition of the different current contributions. The bootstrap current is calculated by the DKES code [4] and the inductively driven current is calculated assuming neoclassical conductivity and are based on the measured profiles of temperature and density. The EC-driven current is calculated in the framework of the linear theory [5] within the ‘adjoint approach’ [6] taking into account the measured profiles of $n_e$ and $T_e$ and trapped particle effects with a 3D ray tracing code. The modelling of the different current contributions was investigated in specially tailored experiments [e.g. 3,5] with respect to magnitude, radial distribution and plasma parameter dependence.
2. Experiments without inductive currents

Under optimum co-ECCD conditions (0.6 MW, 70 GHz, $B_0 = 1.25$ T, X2) a net current of 15 kA is measured, whereas with ctr-ECCD the bootstrap current is completely compensated. The net current levels off after typically 1.5 s due to the long $L/R$-time. The profiles of the electron temperature and rotational transform are compared in Fig. 2 for both cases. The density in both discharge types was feedback controlled to $n_{eo} = 1.6 \times 10^{19}$ m$^{-3}$. The ions play a minor role in these low density discharges, because of the weak collisional coupling to the electrons.

The significant differences in the profiles indicate the influence of the radial shape of $\tau_{ci}$ with negative shear in the co-CD case and positive shear in the ctr-CD case. The major resonances $\tau_{ci} = 0.5, 1.0 \ldots$, which are crossed with comparatively weak shear cause a confinement deterioration in the co-CD case, as indicated by the flattening of the temperature profile within the region $8 \text{ cm} < r < 16 \text{ cm}$. However, high central temperatures with steep gradients are maintained in the plasma centre, where the higher resonances are crossed with strong shear.

![Fig. 2: Radial profiles of $T_e$ and $\tau_{ci}$ for a 15 kA discharge with the EC driven current in the direction of the bootstrap current (co-CD, right) and with the EC-driven current compensating the bootstrap current (counter CD, left). The dashed curve is the vacuum rotational transform (modified by the PS-currents only) for reference.](image)

In the counter-CD case the confinement is deteriorated in the plasma centre at $r < 7 \text{ cm}$, where the modelling of the rotational transform predicts $\tau_{ci} = 0$. This is indicated by the flat temperature profile despite the strong central ECRH. No confinement is expected within the $\tau_{ci} = 0$ surface. In the co-CD case sawtooth activity ($m=1$) is measured in the centre around $r = 5 \text{ cm}$. Close to the plasma edge around $r = 15 \text{ cm}$ relaxations are seen, which are presumably due to $m = 2$ modes. The observed MHD activity supports the calculated $\tau_{ci}$-profile. No MHD activity is observed in the counter-CD case with zero net current.

3. Experiments with inductive current control ($I_p = 0$)

The inductive compensation of both the EC-driven current and the bootstrap current allows an easy control of the edge value of $\tau_{ci}$. It should be noted, however, that the modification of the $\tau_{ci}$-profile by finite pressure effects (diamagnetic currents and PS-currents) needs to be included in the analysis and becomes important already at moderate $\beta$-values (about 0.5% ). In general, with increasing $\beta$ the $\tau_{ci}$-value increases in the plasma centre and decreases in the outer plasma region as compared to the vacuum case. We compare net-current-free discharges with...
0.4 MW ECRH power ($B_0 = 2.5$ T, X2) at high ($n_{eo} = 0.75 \times 10^{20}$ m$^{-3}$) and low density ($n_{eo} = 0.17 \times 10^{20}$ m$^{-3}$) with $\beta$ on axis of 0.6 % and 0.3 %, respectively.

For both types of discharges a launch angle scan, i.e. a scan of the EC-driven current, was performed to modify the balance between the contributing internal plasma currents while maintaining zero net current. Fig.3 shows the calculated EC-driven current and the total stored plasma energy as a function of the launch angle for both types of discharges.

Fig.3: Calculated EC-driven current (left) and total stored plasma energy (right) vs. the toroidal launch angle of the microwave beam for low and high plasma density.

The total stored energy and thus the global confinement changes from 11.5 kJ (ctr-CD) to about 8 kJ (co-CD) in the high density case. Note, that the bootstrap current is compensated by the inductive current alone at perpendicular launch (no ECCD). The increase of the stored energy is due to a steepening of both the density and electron temperature gradients. In the low density case a much smaller (7%) but reproducible dependence of the stored plasma energy on the EC-driven current is observed, which points into the opposite direction, i.e. slightly better confinement at co-CD as compared to counter-CD. Whereas, in the high density case, the edge value $\tau_{ci} = \tau_{ci}(a)$ is somewhat below 1/3 due to the finite $\beta$ effect, it was set to 0.345, slightly above 1/3 in the low density case. As a consequence, the resonance is crossed under counter-CD conditions in the low density case and at co-CD conditions in the high density case, which supports the hypothesis of confinement degradation due to rational values of $\tau_{ci}$.

Both the bootstrap and EC driven currents are of comparable magnitude and much larger in the low density case (about 6-8 kA) than in the high density case (about 2-3 kA). Thus higher shear is introduced in the low density case, which reduces the degradation due to rationalities (stabilization of resonant modes or reduction of island width). The calculated $\tau_{ci}$ profiles for three cases with co-, counter-, and no ECCD are shown in Fig.4.

In contrast to the corresponding low density discharge, the resonant $\tau_{ci} = 1/3$ is met with weak shear in the co-CD case giving rise to a flattening of the stationary temperature profile. In the case of no ECCD, $\tau_{ci}$ is almost constant over the minor radius and low order rational values of $\tau_{ci}$ are avoided. In this sense this discharge represents an ideal example for the shearless stellarator. Good confinement is achieved under this condition (see Fig.3, launch angle 0°), however, the discharge is difficult to control and sensitive to minor changes of the discharge parameters. For counter-CD a more robust situation is achieved, but it has to be accepted, that the natural resonance at $\tau_{ci} = 5/16$ with its influence on the confinement (see Fig. 1) appears at the plasma periphery. The discharge exhibits bifurcational characteristics, i.e. small changes of the heating power (15 %) lead to a smooth transition to a new equilibrium with only about 60 % of the initial stored plasma energy. This may be related to a rearrangement of the internal current density and, consequently, to the $\tau_{ci}$-profile. At the high densities investigated here, changes of the pressure profile (here the significant drop of $T_e$) affects both the PS- and the bootstrap current contribution to the rotational transform decreasing the slightly positive shear. As a conse-
quence, the theoretically predicted position of the $\tau$; $= 5/16$ resonance moves inward. The analysis of the heat wave propagation from the modulated electron temperature measured by the ECE diagnostic as shown in Fig.5 supports these predictions.

Flat regions are measured in both phase and amplitude of the propagating heat wave indicating a short circuit in radial heat transport. This regions are typically 2-3 cm wide and move radially inward on a slow time scale until they remain localized at a fixed position after 0.2 s. The discharge has arrived at a new equilibrium then and is stationary again. The stationary $T_e$-profiles show decreased gradients also outside the predicted $5/16$ resonance region, which is not covered by this explanation. Two effects at the higher densities have to be considered: the collisional electron-ion coupling prevents the separation of the different loss channels, and the role of the particle confinement at the plasma periphery, as indicated by the steepening of the density gradients observed in the launch angle scan while comparing discharges with co- and counter current drive. Much more work is required to clarify the influence of the internal current profile in high density ECRH discharges.

Fig.4: Radial profiles of $\tau$; $= 5/16$ for the high density discharges (see Fig.5) at maximum co-CD (launch angle +8°, top), no CD (launch angle 0°, centre) and maximum ctr-CD (launch angle -8°, bottom).

Fig.5: Phase and amplitude profiles of the $T_e$-perturbation from ECE. The heat wave is excited on plasma axis by ECRH power modulation. For clarity one phase profile (■) was given an offset of 1, one amplitude profile (*) an offset of 10 to separate both profiles in the graph. The two time slices show perturbed regions, which move radially inward during the decay phase.

References
Combined analysis of steady state and transient transport by the maximum entropy method

L. Giannone, U. Stroth, J. Köllermeyer, M. Alexander, H. J. Hartfuss, F. Rytter, W. Suttrop, ECRH Team, W7-AS Team and the AUG Team

Max-Planck-Institut für Plasmaphysik, EURATOM-IPP Association, D-85748 Garching, F.R.G.

1. Introduction

The maximum entropy method has previously been used in plasma physics for Abel inversion and spectroscopic deconvolution [1]. A maximum entropy approach has now been developed to determine the radial profile of the heat conductivity, $\chi_e$, in transient transport experiments. In general, either a power balance on the steady state electron density and temperature profile is performed or the measurements of temperature perturbations are analysed separately. In both cases the input data and the associated error bars represent a set of non-linear constraints to the power balance equation. In the analysis presented these constraints may be applied concurrently as the zero order power balance equation is used for modelling. The $\chi_e$ profile is the function to be found. By taking a discrete set of points, $\chi_e(r_i)$ in the radial direction then the entropy, $S$, given by:

$$
S = - \sum_{i=1}^{N} q_i \log q_i \quad \text{where} \quad q_i = \frac{\chi_e(r_i)}{\sum_{j=1}^{N} \chi_e(r_j)}
$$

is maximised subject to the non-linear constraints. The flattest $\chi_e$ profile that is consistent with the data and its error bars is found. In this way a self-consistent determination of the radial profile of $\chi_e$ in the transient transport experiment is carried out.

The first evaluation of sawtooth propagation experiments in ASDEX Upgrade (AUG) and results from ECRH power modulation experiments on the Wendelstein 7-AS Stellarator (W7-AS) with the simultaneous analysis of up to four modulation frequencies yielding the power deposition profile and required modulation power as well as the radial profile of $\chi_e$ are presented. ECRH power switching experiments in W7-AS in a standard and magnetic hill configuration demonstrate that independent of possible broadening of the power deposition profile a change of $\chi_e$ in a short time scale is required.
2. Sawtooth propagation in ASDEX Upgrade

The heat pulse generated by a sawtooth crash has been considered as a means of determining the value of $\chi_e$ [2]. This value has consistently been observed to be larger than that obtained by power balance. In AUG, experiments in hydrogen with NBI heating of 1.8 MW, $I_p = 1.0$ MA, $B_0 = 2.48$ T, $n_{e0} = 6 \times 10^{19}$ m$^{-3}$ and $q_{95} = 3.9$ were analysed. The 18 channel ECE radiometer measures the temperature perturbation propagating radially outward. Boxcar averaging of typically 30 sawteeth is carried out and this input data is fitted at typically 20 uniformly spaced time points spread over the period of the sawtooth. As shown in Fig. 1(a), a good fit ($\chi^2/N = 2.1$) up to a radius of $r/a = 0.7$ could usually be achieved assuming only a diffusive component of the linearised power balance equation. In the limited number of discharges considered, the heat pulse outside $r/a = 0.7$ could not be fitted with a purely diffusive model. A typical value of $\chi_e = 5-10$ m$^2$/s, as shown in Fig. 2(a), considerably higher than that calculated by power balance (1-2 m$^2$/s) [3] is obtained.

3. ECRH power modulation in W7-AS

The temperature perturbations generated by modulation of the ECRH power have previously been analysed in W7-AS with a predictive code [4] and a Fourier code considering four modulation frequencies simultaneously [5]. The analysis here also uses the amplitudes and phases of the temperature perturbations of up to four modulation frequencies simultaneously together with the temperature profile in a zero order power balance equation. A Gaussian power deposition profile is fitted concurrently with the fit of the radial profile of $\chi_e$. Transport modelling with the Crank-Nicolson method allows simulations of temperature dependencies, temperature gradient dependencies or power dependencies of $\chi_e$ in a straightforward way.

For a 400 kW ECRH discharge with $B_0 = 2.5$ T and $n_{e0} = 2.1 \times 10^{19}$ m$^{-3}$ and 70 GHz gyrotrons, the radial profile of $\chi_e$ derived is in good agreement with that found by an independent power balance calculation. The modulation power needed to fit the measured amplitudes favour a constant $\chi_e$ model rather than a power dependent $\chi_e$ model (assuming $\gamma = 0.5$ for $\chi_e \propto P^\gamma$). Although the fit to the time delays at $r > 8$cm appears to favour the power dependent $\chi_e$ model, this feature can also be modelled by a low level of broad power deposition. The fitting procedure considering only those time delays and amplitudes at $r < 8$cm yields a power deposition profile with a FWHM of 3cm for both the constant and the power dependent $\chi_e$ model, in good agreement with ray tracing. The constant $\chi_e$ model is therefore favoured in this series as the necessary modulation power is in fair agreement with the experimental value. This result is not yet conclusive as the evaluation of another series favours the power dependent model. In either case, the power balance value of $\chi_e$ can therefore adequately model the power modulation experiment, in contrast to the sawtooth propagation experiment.
4. ECRH power switching in W7-AS

The time evolution of the temperature profile after a change in the ECRH deposition power has previously been analysed with a power balance code [6]. It was found that even on time scales as short as 1ms that the value of $\chi_e$ changed to the power balance value associated with the new input power level. This result has been confirmed using the maximum entropy approach. In a discharge with $B_0=2.5$ T and $n_{eo} = 4 \times 10^{19}$ m$^{-3}$, the ECRH power was switched from 540kW to 140kW. Using the $T_e(r,t)$ as the non-linear constraints (see Fig. 1(b)), the $\chi_e$ profile before and after the change in power was determined. In both a standard and a magnetic hill configuration, the radial profile of $\chi_e$ assumes a power balance value associated with the new power level (see Fig. 2(b)), showing that possible broadening of the power deposition profile by the gradient B drift of suprathermal trapped electrons can be discounted. Power modulation in these discharges before the switch in power also shows that the power balance value of $\chi_e$ can adequately fit the measured time delays and amplitudes of the temperature perturbations.

5. Conclusions

The maximum entropy approach has been shown to be a useful tool in the analysis of the three transient transport experiments considered. In modulation experiments, where the modulation power is typically 10% of the input power, a constant $\chi_e$ model with $\chi_e$ equal to the power balance value is favoured. In the power switching experiments, where the power step is a considerable fraction of the input power, a power dependent $\chi_e$ has been found. In both a standard and magnetic hill configuration, the change in a short time scale of $\chi_e$ has been confirmed, excluding the possibility that a broader deposition profile than expected could explain this result. It is suggested that a power scan of ECRH pulses of duration equal to the sawtooth period and power up to the heating power would be useful in further investigations concerning the higher value of $\chi_e$ found in sawtooth propagation compared to the power balance value.

6. References

Fig 1. Fits of the time evolution of the electron temperature perturbation for:
(a) sawtooth propagation and
(b) a decrease in ECRH input power from 540kW to 140kW

Fig. 2. Radial profile of the thermal conductivity, $\chi_e$, determined by a maximum entropy approach (ME) yielding the flattest profile consistent with the data and its errors for:
(a) sawtooth propagation and
(b) a decrease in ECRH input power from 540kW to 140kW

In the first case $\chi_e$ is greater than the power balance value and in the latter case $\chi_e$ is less than the power balance (PB) value at the time preceding the switch in power.
Correlation between Helium Particle Transport and Electron Density Profiles in W7-AS

M. Hirsch, J. Baldzuhn, B. Brañas*, E. de la Luna*, W. Ohlendorf
Max-Planck-Institut für Plasmaphysik, EURATOM-Ass, 85748 Garching, Germany
*Asociación EURATOM-CIEMAT, Madrid, Spain

Introduction
To test the validity of a neoclassical description for impurity transport measured impurity profiles can be compared with code calculations. At W7-AS density profiles of impurities are obtained from active charge exchange spectroscopy CXRS by means of a diagnostic neutral beam injector. For the neoclassical transport of He the IONEQ code predicts, that the He III profile has a similar shape than the profile of the electron density. In the gradient region of the core plasma the required electron density profile can be measured from mm-wave reflectometry with a high spatial and temporal resolution. A comparison between these density profile and the measured He III profile should show, whether a neoclassical description is valid or anomalous contributions to He particle transport exist.

Electron density fluctuations possibly generate anomalous transport. An anomalous component in He transport therefore could be correlated with the density fluctuation level as it is measured with reflectometry.

Electron density profiles and density fluctuations measured by reflectometry
At W7-AS edge density profiles and electron density fluctuations are measured by a broadband heterodyne reflectometer [1]. The system is operated in extraordinary mode polarization probing densities 1 to $6 \times 10^{19}$ m$^{-3}$ within less than 1ms. Depending on plasma conditions radial positions range from $0.3 < r/a < 1.1$, with $a \approx 18$cm. Gaussian beam optics for final signal launch and detection permits a beam waist of less then 2cm at the plasma location. The mm-wave launched to the plasma is amplitude modulated, and both the phase of the modulation envelope and the phase of the carrier are measured simultaneously. From the phase of the modulation envelope, i.e. the time delay of the reflected signal, the density profile $n(r)$ is obtained. For the profile recovery by numeric Abel inversion an edge profile up to the lowest probed density has to be assumed. It is fitted to the probed part via the gradient. The density profiles obtained by that for the investigated discharges agree with Thomson scattering and Lithium beam data. An example is shown in Fig.1.

Phase fluctuations of a reflected mm-wave give information about the density fluctuations at or close to the probed cut-off layer [2]. Heterodyne detection technique allows to measure the required phase fluctuations independent of fluctuations in the amplitude of the reflected signal. Coherent contributions to the phase spectrum, e.g. modes, are filtered
numerically and only the turbulent component of the spectrum is taken into account. The density fluctuation level $\Delta n(r)$ is evaluated from the rms value of the measured phase fluctuations $\Delta \Phi$, using the local gradient $\text{grad}[n(r)]$ of the density profile:

$$\Delta n(r) = (4\pi)^{-1} \cdot \lambda_{\text{eff}} \cdot \text{grad}[n(r)] \cdot \Delta \Phi.$$ 

The effective probing wavelength $\lambda_{\text{eff}}$ is obtained from numerical calculations [1][3]. For each discharge density fluctuation profiles are measured under stationary plasma conditions with the mm-wave frequency ramped up every 10ms to probe the different radial positions. An accurate knowledge of the local density gradient is crucial for the estimation of the density fluctuation level. Therefore the density profile is taken with the mm-wave frequency sweeping continuously over the entire range before and after the fluctuation measurement. The relative density fluctuations $\Delta n/n$ obtained with this method for the same discharge with profiles shown in Fig.1 are given in Fig.3. For all discharges $\Delta n/n$ increases towards the edge with typical values of 10 to 15% at the limiter respective the separatrix position. As an example the fluctuation profiles from a density scan at fixed ECRH heating power are summarized in Fig. 2.

**CXRS-Measurement and Code-Calculations of He-Profiles**

Density profiles of fully stripped He are obtained by active charge exchange spectroscopy CXRS. A diagnostic neutral beam injector is pulsed with 10 Hz to allow for a subtraction of background light originating from the plasma edge. The density of He III is derived from the CX spectral light intensity of He II at 4686 Å, which occurs after charge exchange with the beam neutrals. The CX light is guided by a turnable mirror to a 1.26m grating spectrometer to resolve the single CXRS spectral lines. One radial position can be chosen per discharge. To maintain constant He density conditions for a series of discharges, a short He gas puff is applied at the beginning of each shot. Due to a recycling coefficient $R=1$ an almost constant helium concentration of about 1% is obtained for the whole discharge.

For the calculation of the He III density profile the neutral beam attenuation in the plasma is calculated by an iterative algorithm, taking into account charge exchange and ionization by the background plasma as well as by the impurities. Ion temperatures are obtained from the Doppler broadening of CXRS spectral linewidth. For the ion density $n_i(r)=n_e(r)$ is assumed and the electron density $n_e(r)$ with $(0<r<a)$ is taken from Thomson scattering measurements. A detailed description of the whole procedure is given in [4]. Fig. 3 shows the He III density profile (open circles) for the discharge taken as example.

With the IONEQ code [5] impurity density profiles can be calculated using a neoclassical transport model. For each flux surface a set of coupled continuity equations is solved which take into account radiation, ionization and recombination as well as diffusive
and convective transport. The measured density and temperature of the "background" electrons and protons and a background neutral gas profile are required as input parameters.

**He-transport and electron density profile**

He-transport properties and electron density fluctuations have been characterized for different plasma conditions and heating scenarios. ECRH-, NBI-heated and discharges with combined heating covering central densities 2 to $10 \times 10^{19}$ m$^{-3}$ have been studied.

The neoclassical transport model predicts that the He III density profile shape is very close to the density profile of the electrons. An example of calculated He density and the respective electron density profile used as an input is shown in Fig.3. For the calculation the central He III density is fixed to 1% relative concentration.

Within the experimental error we find that the measured He III density profile shape (see e.g. open circles in Fig.3) is consistent with the calculated one [6]. As density profile information is available from reflectometry in the gradient region, Fig. 4 compares the gradient of the measured He-profiles at $r/a=0.9$ with the respective gradient of the measured electron density for a number of different discharges. Within the limits of experimental error no significant deviation from the results of the corresponding neoclassical calculation (black dots and line) is observed. So far our result supports the conclusion that He-particle transport in W7-AS can be described quite well with the neoclassical theory only, without the assumption of an additional anomalous contribution.

Access to possible anomalous transport contributions is given from the deviations between measured and calculated He III profiles. Electron density fluctuations possibly generate anomalous transport. In this case anomalous contributions to the impurity transport should be related the density fluctuation profile obtained by reflectometry (black dots in Fig.3). Nevertheless up to now we find that deviations between measured and calculated He III profiles are below the level of experimental error. Dynamic He-profile measurements as a finer instrument for particle transport are subject to further investigations. Due to their increased information on He-transport and the detailed knowledge of the electron density profile in the gradient region also minor anomalous contributions to impurity transport can be addressed.

**References**


Fig. 1: Electron density profiles measured with Thomson scattering and reflectometry for a ECRH heated discharge (B=2.5T, iota = 0.34). The plasma edge as determined from the limiter position and magnetic field configuration is shown as dashed line.

Fig. 2: Density fluctuation profiles for a series of ECRH heated discharges (P=450kW) with different densities.

Fig. 3: HeIII density measured with CXRS (open circles) compared with IONEQ code calculations (thick line) for the same discharge as Fig.1. The calculated He density fits with the electron density (dotted line). Electron density fluctuations (filled circles, right scale) typically show values of 10-15% at the limiter (dashed line).

Fig. 5: Comparison of electron density gradient with HeIII gradient at r/a=0.9. The respective results of the neoclassical calculation are shown for comparison.
Influence of L- and H-mode and Rotational Transform on the Edge Density Profiles in W7-AS

G. Kocsis¹, S. Zoletnik¹, S. Fiedler²,³ P. Grigull², G. Herre², K. McCormick²,
J. Schweinzer² and W7-AS Team²

¹ KFKI–RMKI, P.O.Box 49, 1525 Budapest-114, H-1525 HUNGARY
² Max-Planck-Inst. für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, GERMANY
³ Institut für Allg. Physik, TU Wien, Wiedner Hauptstr.8-10, 1040 Wien, AUSTRIA

In W7-AS plasma performance is strongly affected by the three dimensional edge topology. Two principally different edge topologies can be distinguished: a) at low rotational transform (iota ≤ 0.4) the last closed flux surface is determined by the limiters, whereas b) at higher iota (≥0.4) separatrix-dominated configurations are possible. For iota ≈ 0.53 the H-mode of W7-AS is accessible above a power and density threshold[1]. Transient phenomena (dithers, ELMs) frequently appear before and after the L-H transition.

The edge electron density distribution sensitively depends on both the magnetic field topology and the confinement mode, thus its investigation can reveal phenomena leading to changes in global plasma performance. This paper presents a detailed study of the density profile behaviour at different edge topologies and confinement modes.

The experiments were done using the high-energy neutral Lithium beam diagnostic, which can measure \(n_e(r,t)\) from the outer SOL to deep within the main plasma[2]. The time - (≤0.2ms) and spatial - (0.6-1cm) resolution of the diagnostic permits determination of both the fast temporal variation of \(n_e\) and its fine radial structure.

Density profiles at different edge configurations. In order to get a more symmetric SOL in W7-AS the main limiters were replaced by a set of poloidal limiters (two per field period). The structure of the edge was investigated at different rotational transforms, ECRH heating powers and line integrated densities.

Fig. 1. shows as a contour plot the density profile vs edge rotational transform \(\iota_s\) (low \(\beta\), low density, net current free, \(B_0 = 1.25T\), ECRH discharges) for the separatrix dominated case (\(\iota \geq 0.4\)). The thick solid, dashed and dash dot lines on this figure represent the vacuum field calculated boundary of the scrape-off layer with a connection length of less than 50 m in the positive and negative toroidal direction, and the separatrix position, respectively. It can be clearly seen, that characteristic changes in the position of these lines are accompanied by similar changes in the contour lines of the density in the SOL, justifying the reliability of the vacuum field calculation.

This figure establishes, that the plasma globally shrinks for increasing \(\iota_s\) values. Repeated deviations from this general trend can be observed around that rotational transform values, where the natural 5/m islands appear: 0.463, 0.512, 0.57 and 0.635 (see the surface plot of Fig. 2.). Moving along the \(\iota_s\) axis from the lower values a shoulder appears step by step accompanied by a steeper density profile outside the shoulder. Moving further in \(\iota_s\) the density increases behind the shoulder, which gradually disappears this way. After this the profile moves inside until the next resonant value where a similar shoulder will appear. One might explain the appearance of the shoulder with the presence of the 5/m islands[3] partly intersected by the limiters, because they introduce a radial short cut in the particle and energy transport by a strong parallel component. The radial position of the profile shoulders agree well with the position of the vacuum field calculated islands.
For the limiter dominated case (ι ≤ 0.4) neither the density profile nor the vacuum field calculated connection length changes drastically in the SOL at different rotational transforms. Density e-folding lengths (in flux coordinates) in the SOL in a density scan with constant ECRH heating power (140GHz, P=460kW, B=2.5T, B\textsubscript{r}=25mT, ι\textsubscript{a} = 0.34) and in a power scan with constant volume averaged density (70/140GHz, B=2.5T, B\textsubscript{r}=17 mT, ι\textsubscript{a} = 0.34, (ne)\textsubscript{vol} = 1.48 × 10\textsuperscript{13}cm\textsuperscript{-3}) are shown in Fig. 3. The e-folding length decreases with increasing density and increases with the non radiated part of the heating power. These results are in good agreement with Langmuir probe measurements\cite{4,5}.

Density profile change at the L-H transition. L-H mode transition is achieved at ι ≈ 0.5, B\textsubscript{r} = 2.5T with 140 GHz ECRH heating if the electron density of the plasma is increased above a certain threshold. The onset of the H-mode is best characterized by a sharp drop in the H\alpha radiation from the limiter and wall. Due to the improved confinement the line averaged electron density of the plasma increases after the transition even if the gas feed rate is reduced.

The difference between the L and H mode electron density profile is shown in Fig. 4. As one can see, the profile steepens significantly around the LCFS, indicating the improvement of confinement. Analysis of the fast time evolution around the L-H transition shows, that this steepening develops in about 5 ms.

The change of the density profile in the H-mode phase of the discharge during a
Fig. 3. SOL electron density e-folding length as a function of line density and radiated power for series of shots.

Fig. 4. L and H mode electron density profiles close to the L-H transition.

Fig. 5. Electron density profile change in H-mode during a density ramp-up.

Continuous increase of the line integrated density is shown in Fig. 5. Although the line density, and also the local density in the core plasma increase by a factor of two between the first and last profile, there is no change in the SOL density distribution. The decay length of an exponential fit to the SOL density profile shows no change opposed to the behaviour found in the L-mode at $\tau \approx 0.3$. This "locking" of the H-mode SOL density profile is in agreement with similar tokamak measurements[6].

Transient phenomena in H-mode shots The L-H transition is preceded by fluctuations of the $H_\alpha$ signals. The modulation amplitude is increasing towards the transition and forms pulses with a faster (0.5 ms) rise and a slower ($\approx$ 1 ms) decay time. Similar phenomena are often observed in the H-mode, with less repetition frequency. The Li$_2$p light profile exhibits characteristic changes during these transients, but the calculation of the density profile change is difficult due to similar changes of the background light profile which is measured by chopping the Li-beam at every 60 ms. In some cases nearly identical pulses (in the $H_\alpha$ signal) can be found in the same shot at close times, one during chopper time interval and the other during a beam-on interval. In these cases the background light can be subtracted from the total detected light by using the background light time evolution found during the pulse in the chopper interval. Several events have been processed this way, and a characteristic density profile change can be deduced from these measurements. Fig. 6. shows density profiles at different times during an $H_\alpha$ pulse before the final L-H transition (dithering) and in the H-mode (ELM). Both figures show the same characteristic change; the profile flattens around the LCFS, and becomes closer to an L-mode profile. In this sense, there is no difference between dithering and ELMs. Observations also show, that the density profile starts to change about 200 $\mu$s before the
Fig. 6. Electron density profiles during a dithering pulse (left) and an ELM (right). Part of the $H_\alpha$ signals (for beam-on and beam-off pulses) is shown as an inset for reference.

$H_\alpha$ signal starts to rise. This time delay is equal to the time resolution of the diagnostic, thus its exact value cannot be determined.

Conclusions. It was found that the high energy Lithium beam diagnostic can routinely measure the edge electron density distribution of W7-AS plasmas with 0.2ms temporal and $\approx 1cm$ spatial resolution. However, the temporal resolution can be exploited only if a good estimate is available for the background light intensity on the same time scale.

Density profile changes in the edge and SOL are in good agreement with changes in the calculated vacuum magnetic field configuration. Local shoulders appear close to the calculated position of magnetic islands. The SOL e-folding length of the density distribution increases with the total edge power loss and decreases with increasing volume averaged density, indicating similar changes in the SOL cross diffusion coefficient. These results are in good agreement with Langmuir probe measurements[4,5].

The SOL and edge density distribution steepens at the L-H transition in about 5 ms. In the H-mode the SOL density distribution becomes independent of the line averaged density, in agreement with observations on ASDEX[6]. The density profile change during a dithering cycle, is very similar to changes during an ELM, and both have characteristics resembling an H-L backtransition. The wall $H_\alpha$ signal delay shows a few hundred $\mu$s propagation time for the ELM density pulse to reach the wall.

Acknowledgements. The work of one of the authors (S.F.) has been partially financed by the Austrian "Friedrich Schiedel Stiftung für Energietechnik" (project leader: H. Winter). The authors from KFKI-RMKI would like to thank the hospitality and support of IPP-Garching.

References
ECRH ABSORPTION OF SECOND HARMONIC X- AND O-MODE AT THE W7-AS STELLARATOR

H. Laqua, V. Erckmann, H. J. Hartfuß, M. Romé, A. Weller, W7-AS Team
Max-Planck-Institut für Plasmaphysik, EURATOM Ass., 85748 Garching, Germany

G.A. Müller, ECRH-Group
Institut für Plasmaforschung, Univ. Stuttgart, 70569 Stuttgart, Germany

Gyrotron-Group*, ECRH-Group**
*) Inst. of Applied Physics, Nizhny Novgorod, Russia
**) Kurchatov Institute, Moscow, Russia

1. Doppler shifted absorption of the second harmonic x-mode

A good knowledge of the total absorbed heating power and the corresponding deposition profile is important for the investigation of plasma transport with both stationary and perturbative methods. Electron Cyclotron Resonance Heating (ECRH) at 2nd harmonic X-mode provides a well localised power deposition profile and an almost complete single pass absorption for the relevant W7-AS temperatures and densities below the cut-off density $1.2 \cdot 10^{20} \text{ m}^{-3}$ at 140 GHz ($B_0=2.5 \text{ T}$).

The absorption layer for oblique launch is altered as compared to perpendicular launch by the Doppler shift of the wave particle resonance. The resonance condition is:

$$1 - N_\parallel \frac{v_\parallel}{c} - \frac{n\Omega_e}{\omega} \gamma = 0$$

where $\omega$ is the frequency, $N_\parallel$ and $v_\parallel$ are the components of the refractive index and the electron velocity parallel to the magnetic field, $n\Omega_e$ is the $n$th harmonic of electron cyclotron frequency, $c$ is the velocity of light and $\gamma$ the relativistic factor.

In the experimental set-up the 140 GHz beam with 0.4 MW power in x-mode polarisation was launched for 0.9 s from the low field side in the equatorial plane with different toroidal angles up to $18^\circ$ with respect to the perpendicular launch.

In the pure ECRH plasma with a central magnetic field of 2.42T the electron cyclotron resonance (ECR) layer was located at the high field side at an effective radius of 7.5 cm as sketched in Fig. 1. In this set-up, for perpendicular launch ($N_\parallel=0$) the resonance condition (1) can only be fulfilled at the high field side of the ECR layer. The absorption starts with the low energy electrons. For the oblique launch, however, the resonance condition (1) could also be fulfilled for the low field side of the ECR layer at

$$\frac{n\Omega_e}{\omega} \geq \sqrt{1 - N_\parallel^2}.$$

The absorption is shifted then towards the plasma centre. Since the absorption starts in this case with electrons with finite parallel velocity $v_\parallel = c \cdot N_\parallel$ the shift of the absorption zone and the absorption profile are functions of the launch angle and the temperature. Both effects were measured independently.

The absorption profiles were determined by analysis of the soft x-ray signals. The x-ray emission was monitored by an array of 36 silicon detectors with a 25 $\mu$m beryllium filter. The time resolution was 0.1 ms. To obtain the radial x-ray emission profile the signals were inverted to the magnetic flux co-ordinates. Since for small time scales the radial heat transport is negligible and soft X-ray emission can be linearized with respect to the temperature, the difference of two soft X-ray profiles with $\Delta t=0.2\text{ms}$ immediately after the
ECRH switch-off represents the relative ECRH absorption profile. In addition, for low density and high temperature discharges the input power was modulated by 20% in a wide range of frequencies and the perturbed electron temperature was measured by coherent detection of ECE. With both methods the same absorption profiles were measured. In Fig. 2 the Doppler effect is shown for a fixed temperature of 1.4 keV ($n_e=2\times10^{19}\text{m}^{-3}$). The measured deposition profiles are compared with ray-tracing calculations in which the weakly relativistic hot dielectric tensor was used [1]. As shown in Fig. 3, both half width and position of the measured profiles fit within the error bar to the calculated power deposition profiles.

2. Absorption at the second harmonic o-mode.

Electron Cyclotron Resonance Heating (ECRH) at the second harmonic ordinary polarisation mode (O2-mode) has a low single pass absorption at the typical W7-AS plasma parameters but offers the possibility to access a density twice the cut-off density limit of the extraordinary mode (X2-mode), which is the routinely used ECRH mode at W7-AS. In the next step stellarator W7-X a much higher single pass absorption of the O2-mode is expected and O2-mode ECRH will be an attractive scenario [2] The general absorption properties of the O2-mode were therefore investigated. Into NBI-sustained target plasmas with a magnetic field of 2.5 T and with central electron densities of 0.8 - 1.9x10^{20}\text{m}^{-3} 140 GHz pulses in O2-polarisation at an optimum oblique angle of 20° were launched. The power of the 40 - 100 ms long pulses was 0.7 MW. The absorbed heating power was estimated by time derivative of the diamagnetic signal at the heating pulse switch off. In Fig.4 the plasma energy content represented by the diamagnetic signal increased by about 1.5 kJ compared to an similar discharge with NBI only. The absorbed power was about 110 kW. Here the central plasma density was 1.8x10^{20}\text{m}^{-3} which is well above the X2 cut-off density. The electron temperature was only 0.4 keV under these high density conditions. To determine the power deposition zone again the soft X-ray emission was analysed. Since now the switched absorbed power was low only a low resolution soft-x camera could be used. The lines of sight of nine soft X-ray detectors were located tangential to the flux surfaces at different effective radii with a spatial resolution of about 2 cm. Despite of the low spatial resolution it was possible to resolve the time delay in-between the different X-ray detector signals after heating power switch off. This time delay with respect to the time of power switch off is sketched in Fig. 5 as a function of the radial position of the X-ray emission. Since the time delay increases with the effective radius the heating power must have been absorbed in the dense plasma core at the ECR layer. In Fig. 6 the calculated single path absorption and measured absorption efficiencies were compared. In the density range up to 1.4x10^{20}\text{m}^{-3} the both results fits well together, but for the high density discharges the measured efficiency is always twice the calculated. The discrepancy could not be satisfactorily explained up to now but may originate in the fact that for all the high density measurements the plasma starts to become unstable which causes an overestimate of the absorbed power.

3. Conclusions

The Doppler effect to the ECR absorption could be well demonstrated and is in an excellent agreement with the theory. The ECRH with the O2-mode shows even higher efficiency than calculated which gives confidence that for W7-X this will be an attractive heating scenario at densities above 1.2x10^{20}\text{m}^{-3}.

References


Fig. 1: ECRH launch geometry with inward shifted ECR layer.

Fig. 2: Doppler shifted and broadened absorption profiles for different launch angles.

Fig. 3: Calculated and measured shift and FWHM of the absorption profile versus the temperature with a launch angle of 18°. The left scale refers to the empty and the right scale to the filled markers.
Fig. 4: Energy content represented by the diamagnetic signal of a NBI-discharge combined with NBI O2-mode ECRH (upper curve) and of a pure NBI-discharge (lower curve). The time window of the ECRH pulse is shown by the markers.

Fig. 5: Time delay of the soft X-ray emission at different effective radii with respect to the ECRH switch off.

Fig. 6: Measured and calculated absorption efficiencies for ECRH with the O2-mode.
Scrape-Off Layer Turbulence in the ASDEX Tokamak and the Wendelstein 7-AS Stellarator: \( T_e \) Fluctuations and Structures

G. Theimer, M. Endler, L. Giannone, H. Niedermeyer, A. Rudyj, ASDEX and W7-AS Teams
Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany

R. Balbín, C. Hidalgo
Asociación EURATOM-CIEMAT, 28040 Madrid, Spain

Introduction

The SOL turbulence in the ASDEX tokamak and in the W7-AS stellarator was investigated with high poloidal and temporal resolution using Langmuir probe arrays and arrays of \( H_\alpha \) detectors both extending in poloidal direction. A very high correlation of the fluctuations parallel to the magnetic field is observed requiring to take the interaction of fluctuations with the target plates into account. Measurements in a wide range of discharge parameters confirm a linearized curved 2d fluid model involving sheath physics in addition to the \( E\times B \) and diamagnetic drifts [1].

Temperature fluctuations are included in the model but have been assumed to be zero in the analysis of the ASDEX experiments with the result of a reduced accuracy of density and potential measurements. In W7-AS fluctuations of electron temperature \( T_e \), density \( n_e \) and space potential \( \phi \) have been measured simultaneously with high time and space resolution in the plasma edge region by means of the fast swept probe technique [2]. Power spectra, phase velocities, spatial correlations and coherency between different quantities were determined under SOL conditions comparable to that of ASDEX.

An attempt to get more insight into the non-linear processes establishing the SOL turbulence is made by working out typical structures in the spatio-temporal evolution of the fluctuations by means of a fitting method. The 2d probe signal functions depending on the poloidal coordinate and on time are decomposed into a sum of "events" with given shape functions in space and time and defined by their amplitude, size, lifetime, velocity and location in time and space. The database of events can be used for any kind of statistical analysis. Averaging of the surroundings of selected events is used to identify typical structures.

\( T_e \) Fluctuations

The voltage of four probe tips separated 2 mm in the poloidal direction was swept simultaneously at a frequency of 500 kHz, in order to measure the poloidal correlation of the fluctuations. Probes were placed in the scrape-off layer at a radial position approximately 2 cm outside the last closed flux surface. Measurements were done in electron cyclotron resonance heated (ECRH) plasmas with heating power 400 kW, central mean density \( n_e = 3\times10^{19} \text{ m}^{-3} \), \( f = 0.34 \) and magnetic field \( B = 2.5 \text{ T} \).

Figure 1 shows the power spectrum of density, temperature and floating potential fluctuations measured at a radial position \( r/a_e = 1.1, a_e \) being the location of the velocity shear layer. The level of temperature fluctuations is in the range 15-25 \%, \( \delta T_e / T_e = \delta n_e / n_e \), the potential fluctuations \( \delta \phi / T_e \) are in the range 30-45 \% and fluctuations are dominated by frequencies below 100 kHz. These results are slightly different from results obtained in previous
measurements at lower magnetic field (1.28 T) where the dominant frequencies were higher (up to 150 kHz) [2].

![Fig. 1 Power spectrum of electron density $n_e$, electron temperature $T_e$ and floating potential $\Phi_f$.](image1)

![Fig. 2 Spatial coherence of the density, temperature and floating potential fluctuations at a poloidal distance of 2 mm.](image2)

Figure 2 shows the spatial coherence between density ($\tilde{n}_e$), temperature ($\tilde{T}_e$) and floating potential ($\tilde{\Phi}_f$) fluctuations obtained from two probes separated 2 mm in the poloidal direction. For all of them the coherence is statistically significant for frequencies below 50 kHz. The strong similarity of the spatial coherence for the three studied parameters ($\tilde{T}_e$, $\tilde{n}_e$ and $\tilde{\Phi}_f$) is remarkable. As the level of spatial correlation between $\tilde{T}_e$, $\tilde{n}_e$ and $\tilde{\Phi}_f$ was sufficiently high it was possible to deduce the phase velocity of the fluctuations ($\tilde{\theta}_{ph}$) from the cross-phase. The fluctuations of all three quantities propagate with $\tilde{\theta}_{ph} = 0.2$ km s$^{-1}$. Furthermore, significant correlation between density and temperature fluctuations have been observed for frequencies below 100 kHz, as shown in figure 3. The relative phase between $\tilde{n}_e$ and $\tilde{T}_e$ is close to zero both at the plasma edge in the proximity of the velocity shear layer ($r < a_s$) and in the scrape-off layer region ($r > a_s$).

![Fig. 3 Correlation between density and temperature fluctuations](image3)

![Fig. 4 E×B particle flux calculated with and without correction for $T_e$ fluctuations](image4)

Figure 4 shows the E×B particle flux computed from the fluctuations of $T_e$, $n_e$, and $\Phi$ using two different assumptions: first, neglecting the influence of electron temperature fluctuations (i.e. the electric field is calculated from the probe floating potential and the density...
fluctuations depend only on the probe ion saturation current fluctuations) and second, taking into account temperature fluctuation effects (i.e., the electric field is calculated from the plasma potential measurements with \( \Phi = \Phi_0 + 2kT/e \) and the density \( n_p \propto I_p T_e^{-1/2} \)). In both cases, the particle transport has a maximum between 20 kHz and 30 kHz and is negligible at frequencies above 100 kHz. The value of the total particle transport due to the electrostatic turbulence is around \( 3 \times 10^{19} \text{ m}^2\text{s}^{-1} \). The particle transport calculated taking into account the temperature fluctuations is strikingly similar to the one calculated under the assumption \( \dot{T}_e/T_e \approx 0 \). This result is mainly due to the fact that the cross phase between density and temperature fluctuations is very close to zero.

**Structures**

The time-space dependent signals (saturation current, potential or particle flux) determined from probe arrays are considered as a superposition of events each described by a product of a time function and a space function with the amplitude, position in time and space, size, lifetime and velocity as parameters (“events”).

\[
E_k(y, t) = A_k \exp\left(-\left[(y - Y_k - v_k(t - T_k))/L_k\right]^2\right)/\cosh\left((t - T_k)/\tau_k\right)
\]

First estimates for the amplitude and position are obtained from the maxima and minima of the two-dimensional correlation function of the raw data with functions of the shape above, a velocity equal to that determined from correlation functions and beginning with large size and lifetime. A fit minimizing the sum of the absolute values of the residua is chosen because it ignores fairly well superimposed structures with different parameters thus permitting to determine the events sequentially. The fitted events are subtracted from the raw data and the procedure is iterated. The data base of event parameters serves for further analysis. If the shape of the fitting functions used is not properly adapted correlations between events of different size or lifetime will show up. Arbitrary selection criteria are possible for the statistical investigation of the dynamics in the surroundings of events. In [3] it was shown that a major part of the transport occurs mainly as outward bursts of plasma between pairs of electrostatic dipoles. The flow pattern might be considered as a strongly damped double-eddy.

An eddy involves flow velocities in inward and outward direction. Both parts of the flow however result in an outward particle flux if the inward flow carries plasma of reduced density. Positive particle flux is the result of an outward motion of increased density (positive density fluctuation) or inward motion of decreased density (negative density fluctuation). In fig. 5 the averaged surroundings of selected negative density events is shown. The electric field in the centre of the frame resulting from the potential distribution (top right) leads to an inward \( E \times B \) drift and to a positive particle flux (bottom right). This means that we investigate the surroundings of the inward flow velocity zones. The outward flow of the double eddy is seen in the bottom right frame below the centre. It is accompanied by a density increase (bottom left). There is a weaker density increase above the centre resulting in a weak particle flux (nearly invisible above the centre in the bottom right frame). This means that the double eddies show a statistical asymmetry. The average reverse particle flow at a distance of about 1.5 cm is also seen in the surroundings of positive or negative potential events (not shown here). Many more features are observed if we select flux events or if we choose narrower selection criteria. It will be necessary to accompany these investigations by numerical simulations in order to understand the details of the dynamics.
**Discussion and conclusion**

Electron temperature fluctuations have been measured in the plasma boundary region in the W7-AS stellarator by using the fast swept probe technique. Temperature fluctuation levels (≈ 10-20 %) are similar to the level of density fluctuations. Statistically significant correlation between density and electron temperature fluctuations has been measured: the phase angle between them is zero both in the scrape-off layer side of the velocity shear layer and at the plasma edge. All these findings agree with the expectations of the model [1] mainly derived from ASDEX experiments. Radiative instabilities are not likely the dominant mechanism to explain edge turbulence in W7-AS. The usual evaluation of the net E×B particle flux due to correlated density and electric field fluctuations neglecting temperature fluctuations yields rather accurate results because temperature and density fluctuations are in phase.

A method of decomposing measured space-time dependent signals into a sum of “events” has been applied to investigate the dynamics in the saturated turbulence. Averaged evolution of plasma parameters around selected potential, density and particle flux events supports the hypothesis that the plasma loss in the SOL occurs in bursts resembling strongly damped double eddies.

**References**


Kinetic Description of ECRH Produced Suprathermal Electrons in the Wendelstein 7-AS Stellarator

M Romé, H J Hartfuß, H Maasberg, W7-AS Team
Max-Planck Institut für Plasmaphysik
EURATOM Association, D-85748 Garching, Germany

N Marushchenko
Institute of Plasma Physics, 310108 Kharkov, Ukraine

Introduction.
A general stellarator magnetic field configuration is characterized by the existence of local (helical and toroidal) mirrors, and therefore of quite different populations of trapped particles. In the $Imf$-regime, the neoclassical confinement properties depend on the complete Fourier spectrum, $\beta_{mn}$, of the magnetic field strength, $B = |B|$, on every flux surface, $B(r, \theta, \zeta) = B_0 \cdot \sum_{m,n} \beta_{mn}(r) \cdot \cos(m \theta - N_p n \zeta)$, $\theta$ and $\zeta$ being the poloidal and toroidal angles in Boozer coordinates, respectively, $r$ the effective radius labelling the magnetic surfaces, and $N_p$ the number of field periods.

In general, different local minima and maxima of $B$ can be found on a given magnetic surface, and no analytical classification of the different populations of trapped particles is available. Close to the magnetic axis of W7-AS (a modular low shear stellarator, with $N_p = 5$), the toroidal components, $\beta_{0n}$, dominate in the Fourier expansion of $B$ ($\beta_{mn} \propto r^n$). In this case, essentially three populations can be distinguished: "passing" particles, particles being trapped in the toroidal mirror where the ECRH is launched, and particles being trapped in the other mirrors.

Bounce-averaged Fokker-Planck code.
Two-dimensional bounce-averaged Fokker-Planck (FP) codes being available for axisymmetric magnetic field geometry can treat only one population of trapped particles [1]. With the use of the three (analytically given) invariants of motion, a reduced bounce-averaged FP equation in a three-dimensional phase space (with radial drifts included) can also be treated numerically [2]. For stellarator geometry, only two global invariants of motion exist in the five dimensional phase space, and, in general, bounce-averaging has to be performed numerically.

Close to the magnetic axis, poloidal variations of $B$ are neglected, and a simplified bounce-averaging procedure can be defined: $\langle \cdots \rangle \equiv \int \cdots d\zeta / v_\parallel \int d\zeta / v_\parallel$. A system of FP equations for the electron distribution function, $f_e$, is obtained for the different populations $\alpha$ (passing particles, and particles trapped in the different toroidal ripples)

$$\frac{\partial}{\partial t} \langle f_e \rangle_\alpha = (C(f_e))_\alpha + (S_\parallel(f_e))_\alpha - (S_t(f_e))_\alpha \quad \text{with} \quad S_\parallel(f_e) = \frac{1}{v_\perp} \frac{\partial}{\partial v_\perp} \{v_\perp Q_\parallel \perp \frac{\partial}{\partial v_\perp} f_e \} .$$

In the collision operator, $C(f_e)$, the non-linear electron-electron part includes the first two Legendre harmonic terms, allowing for conservation of both total momentum and energy. The ECRH is described by the usual quasi-linear diffusion operator, $S_\parallel$, where only the $Q_\perp \perp \perp$ component of the diffusion tensor (computed by means of a three-dimensional Hamiltonian ray-tracing code) is taken into account [3]. In typical ECRH discharges, the energy transport is the main loss channel. In the FP simulations, different models for the energy loss term $S_t$ (related to the radial transport) have been used: an isotropic loss
Fig. 1. Magnetic field strength on-axis, normalized to the resonant field at the ECRH launching position, versus the toroidal angle within one field period for $e_0 \approx 0.345$. The dotted line represents the standard magnetic configuration of W7-AS, the solid line corresponds to an enhanced negative ripple, and the dashed line to a positive ripple configuration.

term, proportional to $(v^2 - <v^2>)f_e$, and a convective loss term, limited in the trapped particle region of the velocity space (which simulates the loss of electrons trapped in local magnetic mirrors due to the $\nabla B$-drift).

The newly developed bounce-averaged FP code allows to consider an arbitrary number of toroidally trapped particle populations. The conservation of the total particle flux between trapped and passing electrons represents the boundary condition in velocity space connecting the different populations. The bulk temperature is kept constant in the time iteration.

The bounce-averaged code has been bench-marked with the FPPAC code [1], where a homogeneous magnetic field is used, by considering only one trapped particle population, and then reducing the size of the trapped particle region in velocity space. Full agreement has been obtained.

The numerical simulations reported here refer to situations experimentally realized at W7-AS. A toroidally averaged input power density of 10 $W/cm^3$ has been considered. This value corresponds to the ray-tracing estimate for the ECRH power deposition in a range $r \leq 3 cm$ (400 kW input power for on-axis heating). Scenarios of 2nd harmonic X-mode and fundamental O-mode heating in low density ($n_e \approx 1 - 2 \cdot 10^{13} cm^{-3}$), high temperature ($T_e \approx 1.5 - 2.5 keV$) plasmas have been analyzed. Furthermore, different magnetic configurations have been considered, where either a minimum or a maximum of $B$ on the axis is placed in the RF injection plane (Fig. 1).

In the case of "minimum $B$" launch, ECRH at the 2nd harmonic X-mode leads to very high power densities for the electrons being trapped in the local mirror at the launching plane. The formation of a strong tail is predicted by the FP simulations for this population of electrons (Fig. 2). A heating effect, though much smaller, can be observed in the other toroidal ripples as well, due to the collisional energy transfer from the mirror where the RF is injected. The distribution of passing particles, on the contrary, remains close to the initial Maxwellian distribution. In the equivalent fundamental O-mode scenario ($Q_{\perp \perp} (v_{\|} = 0, v_{\perp}) = 0$), a much smaller suprathermal tail in the trapped particle population within the mirror at the ECRH launching position is obtained.

The importance of the magnetic configuration is evident also in the computation of the quasi-linear absorption efficiency, defined by $\sum_\alpha (S_\alpha (f_e)) / \sum_\alpha (S_\alpha (f_e^M))$ ($f_e^M$ being the Maxwellian distribution). Its degradation with the input power turns to be stronger than in the case of a homogeneous magnetic field (Fig. 3). Observe that this quasi-linear degradation of the absorbed power scales (roughly) inversely proportional to the plasma density.

A different situation is found for the "maximum $B$" launch. In this case, the input power is gained essentially only from passing particles, and is evenly distributed over the whole
Fig. 2. Left: Isoline plots of the bounce-averaged electron distribution function with the trapped particle population within the ECRH launching plane (top) and for the other field periods (bottom), in the case of "minimum B" launch. The dashed line indicates the boundary between passing and trapped electrons. The plasma parameters are: \( n_e = 1 \cdot 10^{13} \text{ cm}^{-3} \), \( T_e = 1.5 \text{ keV} \). The toroidally averaged input power is 10 W/cm\(^3\) for X-mode heating. Right: Energy spectra of the bounce-averaged electron distribution function: for \( v_{\parallel} = 0 \) in the mirror with ECRH launch (solid line), for \( v_{\parallel} = 0 \) in the other mirrors (dash-dotted line), and for the passing particles with \( v_{\perp} = 0 \) (dashed line); the initial Maxwellian distribution (dotted line) is given for reference.

Fig. 3. Quasi-linear absorption efficiency for "minimum B" launch (solid line) in comparison with the results of the FPPAC code [1] (dashed line). The plasma parameters are the same as in Fig. 2 for X-mode launching. The diamond represents the result of the bounce-averaged code for \( n_e = 2 \cdot 10^{13} \text{ cm}^{-3} \).

flux surface, due to their fast parallel motion. The heating of the particles trapped in the toroidal mirrors is due to collisional energy transfer from the passing particles leading only to a small suprathermal tail. The results for the power degradation are close to those of the FPPAC code.

Experimental results.
Suprathermal tails in the electron distribution function (being related to relativistically down-shifted emission) can be identified by the ECE diagnostic in those low frequency channels corresponding to positions outside of the plasma along the horizontal viewing
Fig. 4. Amplitudes of the modulated temperature for a modulation frequency scan as a function of the ECE channel frequencies, in the case of "minimum B" launch (left) and "maximum B" launch (right), in power modulation experiments, for X-mode launching, and $n_e = 1 \cdot 10^{13}$ cm$^{-3}$.

chord (no reabsorption by the thermal plasma). Fig. 4 shows the amplitude of the modulated temperature, measured by the ECE during ECRH power modulation experiments, in the case of "minimum B" and "maximum B" scenarios, at low $n_e$, for X-mode launching ($B = 1.25 \ T$). Modulation frequencies in the range 100 Hz to 1 kHz have been considered. For equivalent experiments at higher $n_e$, the suprathermal feature is drastically reduced. These findings are consistent with the picture of a strong suprathermal tail in the trapped electron population (comp. Fig. 2) generated close to the magnetic axis, with radial $VB$-drift and collisional detrapping.

Considering a purely diffusive model of the radial heat diffusivity, the integrated Fourier transformed energy balance has been fitted both to the $T_e$ modulation amplitudes and to the phase shifts, allowing for the estimation of the power deposition profile. Generally, the highly peaked power deposition profiles as predicted from the ray-tracing code are obtained, with an additional much broader contribution. No significant difference for O-mode and X-mode launch (both at $B = 2.5 \ T$), and for X-mode launch at $B = 1.25 \ T$ and $B = 2.5 \ T$, respectively, is found. An increased broadening of the power deposition at lower $n_e$ is obtained, for both X- and O-mode launch at $B = 2.5 \ T$. The same result is obtained for the "minimum B" scenario for X-mode launching at $B = 1.25 \ T$, in comparison to both the "standard" and the "maximum B" case, even at higher $n_e$ (for the low $n_e$ experiments, the strong "suprathermal feature" in Fig. 4 leads to a poor reliability of this kind of analysis).

Conclusions.

The newly developed bounce-averaged Fokker-Planck code is well suited to treat the on-axis ECRH in the W7-AS stellarator for quite different magnetic configurations. In particular, the power absorption by the electrons trapped in the toroidal mirror at the ECRH launching position leads to strong suprathermal tail formation being related to a significant quasi-linear power degradation. Non-thermal features observed by the ECE diagnostic support these theoretical predictions.

References.


Edge Transport and Modelling on the W7-AS Stellarator

Max-Planck-Institut für Plasmaphysik, EURATOM Ass., D-85748 Garching, Germany
*Royal Institute of Technology, S-10405 Stockholm, Sweden
**KFKI-RMKI, 1325 Budapest-114, Hungary

1. Introduction

The region of closed flux surfaces in W7-AS is generally bounded by a chain of "natural" islands or island fragments corresponding to a low order $\epsilon = 5/m$ resonance. For low $\epsilon (< 0.4)$, smooth flux surfaces extend deep into the limiter SOL. For high $\epsilon (> 0.5)$, the LCFS lies inside the limiter radius and the SOL is governed by the $5/m$ resonant structures outside the separatrix [1]. Up to now a detailed quantitative analysis of the edge transport, supported by a radial 1D fluid model for particle and energy transport [2], has been restricted to low $\epsilon$ discharges with small to medium plasma density, for which the "simple SOL" assumption (small parallel gradients, low recycling) is justified. Recent results of these transport studies are presented in the first part of the paper. For high $\epsilon$ discharges, there is experimental evidence that the plasma closely follows the corrugations of the $5/m$ edge resonances and is diverted by the island X-points [3,4]. Transport analysis is more difficult in this topology and adequate transport models are being developed to describe the plasma and impurity behaviour in the diverted island structures, especially for high recycling conditions. Recent results from 3D Monte Carlo transport modelling are reported in the second part of the paper.

2. Experimental results

For low-$\epsilon$, small density discharges, the density profiles (from two fast reciprocating Langmuir probes) are basically exponential. However, during operation with the two up-down rail limiters, a radial modulation of the profiles (shoulders) was typically observed, which "inverted" after inverting the magnetic field [5] (Fig. 2a). The amplitude of the shoulders scales with $B^{-1}$. These features can be ascribed to $E_x \times B$ drifts arising from small poloidal electric fields associated with the $L_e$ inhomogeneities introduced by the limiters. They could also be reproduced qualitatively by adding a poloidal plasma rotation (consistent with the radial electric field from the Langmuir probe) to a particle Monte Carlo code with cross-field diffusion (see below).

After replacing the two up-down limiters by short poloidal inboard limiters matching the fivefold symmetry of W7-AS, the $L_e$ became nearly homogeneous and the $n_e$ profiles much closer to exponential. Furthermore, for both vanishing and finite $\beta$ discharges, $n_e$ profiles from the two probes and an energetic Li beam, which are located at three different poloidal positions, became congruent after mapping their radial positions into each other. This result seems to exclude a significant poloidal dependence of the particle transport. It also shows the good quality of the finite-$\beta$ correction of the configuration as predicted by the KW code [6]. For the quite homogeneous SOL defined by the inboard limiters, a scaling of the edge parameters and particle transport with density and input power has been obtained from the analysis of net current free, flat top ECRH discharges at $B = 2.5$ T and $\epsilon_a = 0.34$ (standard low $\epsilon$ configuration with optimum confinement).
Radial profiles of $n_e$ and $T_e$ were available from the two Langmuir probes. Additional $n_e$ profiles from the Li beam. $T_e$ at the limiter radius is quite high (50 to 100 eV), due to the relatively high power density in the SOL, and scales as $T_{se} \propto n_e^{-0.3} (P - P_r)^{0.4}$. ($P_r$ = radiated power). The power decay length and the particle diffusion coefficient (estimated from the first e-folding length of exponentially fitted density profiles) were found to scale as $\lambda_q \propto (P - P_r)/<n_e>^{0.35}$, $D_\perp \propto (P - P_r)^{0.85} <n_e>^{-1.1}$ [7] (Fig. 1). A scaling consistent with $D_\perp$ was found for the confinement time of injected Al in the plasma core [8]. The favourable scaling of $\lambda_q$ with power may help reducing the power load density on limiter and divertor plates.

3. Monte Carlo Modelling

The Monte Carlo approach is less flexible than the fluid approach for handling the full Navier-Stokes equations, but is more flexible for handling variable, open and closed magnetic structures, as encountered in W7-AS for different $\epsilon$ values. A simple MC code, describing cross-field diffusion of particles moving with a constant velocity along the field lines, has been used extensively to estimate the power load distribution on the W7-X divertor plates [9]. After several applications to W7-AS, the code has been extended recently to include poloidal rotation on flux surfaces. It could then reproduce qualitatively the mentioned "shoulders" of the density profiles correlated with field inversion (Fig. 2b). The effect can be explained by the deviation of the particle path from the field line associated with poloidal rotation. This path defines "particle connection lengths", $L_{c \text{ part}}$, between the two limiters, which vary with the rotation velocity. At a representative radial position, ($r_{eff} = 17$ cm), the Langmuir probe, depending on the field sign, lies outside or inside the common "shadow" of the two limiters, as defined by the $L_{c \text{ part}}$. As a consequence, $L_{c \text{ part}}$ is larger in the first case, resulting in a higher local plasma density (Fig. 2b). The two density profiles cross at $r_{eff} \approx 16$ cm, which is close to the position of the plasma potential peak, as measured by the probe. This is consistent with the expectation that the effect should disappear if the rotation vanishes.

As a second step towards a selfconsistent MC transport code for stellarator edge transport, the parallel and cross-field heat conduction equation has been implemented for arbitrary W7-AS configurations. Classical and anomalous conductivities are assumed according to $\kappa_\parallel \propto T_e^{5/2}$ and $\chi_\perp \propto 1/n$. The power loss at the plates is 8 kW per particle. We choose, as an example, a $\epsilon_a = 5/9$ configuration bounded by a chain of closed natural islands (Fig. 3). The islands are intersected by 10 up-down symmetric target plates, each extending toroidally 15°. The radial density profile ($n_e(\text{sep}) = 5 \times 10^{19} m^{-3}$, $<n_e>(\text{target}) = 1 \times 10^{19} m^{-3}$) is chosen so as to give, for an input power of 500 kW through the separatrix, an average $T_e$ drop from 100 eV at the separatrix to 20 eV at the targets. $\chi_\perp = 2 m^2/s$ is assumed near the targets. The resulting $T_e$ distribution (Fig. 4a) is poloidally quite homogeneous, showing a very weak correlation with the island structure. This is consistent with the small "island $\epsilon$", $\epsilon_i$, of this configuration ($\approx 30$ toroidal turns of a field line to get once around the island), which leads to a small poloidal component of the parallel transport. The temperature drop from 160 eV at the separatrix to 9 eV at the outermost island edge is due almost completely to cross-field transport. The plasma is not diverted and behaves like that of a limiter SOL. Then we increased the $\epsilon_i$, for the same configuration, by a factor of 5.
which approximates the $\varepsilon_i$ of a more realistic island divertor case with 9 open islands. In this case the $L_e$ are 5x smaller, the parallel transport becomes dominant and the outflux is localized to a small channel close to the X-points (Fig. 4b). The resulting $T_e$ at the separatrix is lower, $T_e = 85$ eV, and the poloidal drop is 50 eV, as compared to 150 in the first case. Neutral recycling at the plates, which is not included here, would, of course, further reduce $T_e$ at the plates. These results are understood as toroidal averages along the island flux tubes. In the small $\varepsilon_i$ case, a toroidal variation of $T_e$ by a factor of 2.5 is found along the field lines, which is due to the toroidal asymmetry of both the plasma and the targets. This asymmetry is less pronounced in the large $\varepsilon_i$ case with higher target temperature, i.e with higher parallel transport.

References

[4] J. Das et al., this conference
[8] R. Burhenn et al., this conference

---

**Fig. 1:** Electron density and power decay lengths for a) a density scan at fixed ECRH power and b) an ECRH power scan at two fixed densities. c) shows the result of a multiple linear regression analysis of particle diffusion coefficients $D_\perp$, which were derived by exponentially fitting the $n_e$ profiles over the first e-folding length. The pre-factor of the fit function is 12 for $n_e$ in $10^{19}m^{-3}$ and $P$ in MW. Absolute $D_\perp$ values are estimated to be correct within a factor of two or three.
Fig. 2: a) Radial modulation (shoulders) of the density profiles in the SOL defined by the two up-down limiters and correlation with the sign of the magnetic field. b) Monte Carlo simulation of the profiles taking into account poloidal plasma rotation.

Fig. 3: $\epsilon_a = 5/9$ configuration (elliptical cross section, upper half) used for the 3D Monte Carlo simulation of the heat transport. The islands are intersected by 10 up-down target plates.

Fig. 4: a) $T_e$ distribution in the triangular cross section resulting from the MC simulation of the heat transport for the given configuration, and b) for a more realistic case with a 5x larger value of the "island $\epsilon$".
COLLECTIVE SCATTERING OF POWERFUL 140 GHz RADIATION AT W7-AS


Inst. of Applied Physics, Nizhny Novgorod, Russia

W.Kasperek, E.Holzhauer

Inst. für Plasmaforschung, Univ. Stuttgart, 70569 Stuttgart, FRG

V.Erckmann, T.Geist, M.Kick, H.Laqua, W7-AS Team, NBI Team

MPI für Plasmaphysik, EURATOM Association, D-85748 Garching, FRG

1. Introduction

Collective Thomson Scattering (CTS) of electromagnetic radiation from thermal plasma density fluctuations allows to measure the velocity distribution function of plasma ions and their composition in the plasma (see eg. [1]). Experiments with IR [2] and FIR [3] lasers showed the principle capability of CTS. The lack of proper sources prevented, however, to establish CTS as a routine plasma diagnostics. The advantage of using gyrotron radiation for CTS is the long pulse duration which allows to increase essentially the signal-to-noise ratio by the factor \( g = \sqrt{\Delta f \cdot \tau} \) (so called "radiometric gain"), where \( \Delta f \) is the bandwidth of a spectrum analyzer channel and \( \tau \) is the integration time. We experimentally demonstrate for the first time, that a gyrotron can be used to measure the thermal ion feature in a fusion plasma. The results offer promising prospects for fast ion and alpha particle diagnostics as planned for reactor size tokamaks with D/T operation [4].

Below we present the results of experimental investigations on CTS of powerful 140 GHz gyrotron radiation at the stellarator W7-AS in IPP (Garching) which were obtained using an existing 140 GHz ECRH system (gyrotron with 450 kW of rf power in a 1 sec pulse) and a specially designed, manufactured and installed receiving antenna block and detection system for registration of CTS spectra.

2. Experimental set-up

The block-diagram of the 140 GHz CTS experiment at W7-AS is presented in Fig.1. The scattering angle is fixed (160°, i.e. close to back-scattering) yielding a scattering parameter [1] of >2 under all experimental conditions. The antennas can be steered both in toroidal direction (±18°) resulting in a variation of the component of the scattering wavevector \( k \) parallel to the magnetic field \( B \) and in the poloidal direction allowing a vertical shift of the scattering volume (±20 cm). Both probing and receiving beams are gaussian with a FWHM of about 4 cm. The detection system is based on a superheterodyne 140 GHz receiver with a DSB equivalent noise temperature of 2000 K and includes a BWO phase locked local oscillator with a frequency stability of about 10⁻⁷. A single-mode notch-filter with a bandwidth of 70 MHz at -3 dB level provides up to 60 dB attenuation in the line center. The 32-channel IF spectrum
analyzing system covers the range from 50 to 1200 MHz with a frequency separation between neighbouring channels of about 10% of the channel frequency. An additional 20-channel narrow-band spectrum analyzer with a frequency band of 100 MHz and 5 MHz resolution was used to investigate fine structures in the spectra.

The operational regimes of W7-AS are related to resonant values of the magnetic field for the existing 70 GHz ECRH system which is used for plasma start-up: 1.25 T (2nd harmonic) and 2.5 T (1st harmonic). The 140 GHz detection system was calibrated using second harmonic ECE from NBI sustained plasma at 2.5 T as a reference; its sensitivity was determined to be about 1 eV by measuring the fourth harmonic ECE level in 1.25 T regimes.

3. Experimental results from CTS

3.1. CTS spectra from thermal fluctuations

Operation at 1.25 T, which is at 4th harmonic for 140 GHz, provides optimal conditions for scattering, because the absorption of the scattering beam is negligible and the ECE background is 1 - 3 eV only. A toroidal angle of 72° between \( k \) and \( B \) was chosen to avoid modulation of thermal spectra by ion cyclotron harmonics typical for \( k \) being perpendicular to \( B \). Measurements were performed with a gyrotron pulse duration (and integration time) not more than 30 ms. As no beam dump could be installed in the vessel, a rather high level of stray radiation with a corresponding gyrotron noise was observed. In spite of the fact, that the thermal CTS spectra were obtained by subtracting the background measured without plasma from the scattered signal with plasma, the gyrotron noise covered the scattered power at low frequencies. Reliable data were obtained in the frequency range above 200 MHz. An example of a measured thermal ion spectrum for a plasma density of \( N_e = 0.35 \times 10^{13} \text{ cm}^{-3} \) is shown in Fig. 2 together with the calculated spectrum for a hydrogen plasma with 2% C6+ contamination as a typical figure. The calculated spectrum takes into account the radial profile functions of both electron and ion temperatures and of the plasma density.

A best fit with \( T_{e0} = 550 \text{ eV} \) from independent diagnostics yields \( T_{i0} = 480 \text{ eV} \) with an estimated error of \( \pm 80 \text{ eV} \), which is quite consistent with \( T_{i0} = 440 \text{ eV} \pm 40 \text{ eV} \) measured with charge-exchange (CX) neutral particle analysis.

3.2. CTS spectra from nonthermal fluctuations

A number of different types of nonthermal CTS spectra were registered with \( B = 2.5 \text{ T} \) in ECRH sustained plasmas (see [5]). The most detailed investigation was performed for a very narrow spectral feature which appeared only when a relatively weak (=30 kW) diagnostic neutral particle beam (for independently measuring the ion temperature profile) with an energy mix of 22 keV, 11 keV and 7.3 keV was launched into the plasma perpendicularly to the magnetic field. Scattered signals were measured in one or two neighbouring channels and correspond to the frequency of lower-hybrid (LH) waves \( \omega_{\text{LH}} = \omega_p / \sqrt{1 + \omega_p^2 / \omega_e^2} \) propagating perpendicular to \( B \). The bandwidth of this feature was not more than 20-30 MHz. The dependence of the frequency on plasma density is given in Fig. 3 and shows good agreement with the calculated frequency from the kinetic theory (dashed line) and in the magnetized cold plasma approximation (solid line), (see also [5]). The initially reported angular wave propagation spread around the direction perpendicular to \( B \) within a FWHM of 8° [5] was determined more precisely (less than 3° FWHM) after readjusting the emitting-receiving antenna block. A supporting observation of LH wave generation is the appearance of a high-energy ion tail with a temperature of about 2 keV. Fig. 4 shows the time behaviour
of the scattered power in 3 adjacent channels together with a high-energy CX-spectral channel during neutral beam modulation. To distinguish LH waves traveling in opposite directions measurements with LO frequency shifted with respect to the gyrotron frequency have been performed. As it follows from Fig.5 these waves have comparable amplitudes; the gyrotron line weakened by the notch-filter can be also seen in the spectrum.

4. LH wave generation mechanism

The narrow-band feature looks like an instability triggered by the injection of diagnostic neutral beam transverse to the magnetic field. By charge-exchange collisions in the plasma, fast ions travelling perpendicular to B are generated, which can excite plasma instabilities. The possible candidate is the instability under the double resonance condition when the LH frequency coincides exactly with a high harmonic of the beam ion gyrofrequency [6]. The dispersion relation is of the form:

\[ 1 - \frac{\omega_p^2}{\omega^2} + \frac{\omega_p^2}{\omega_e^2} - \alpha \frac{\omega_p^2}{\omega_e^2} \sum_{n=-\infty}^{\infty} \frac{n < 2J_{\ell} J'_{\ell} / \xi >}{\omega - n\omega_e} = 0 \]

where \( \alpha \) is the ratio of beam and ion densities, the argument of Bessel functions is \( \xi = kV_B / \omega_e \), and averaging is performed over the beam ion distribution function. This dispersion relation has an unstable solution at double resonance (\( \omega_{LH} = n\omega_e \)), if the averaged value in the dispersion relation is negative. The instability growth rate is proportional to the square root of \( \alpha \) which is high enough even with \( \alpha \) being \( 10^{-4} \sim 10^{-5} \); this is compatible with the diagnostic NB current and its life-time estimated from the vertical drift in the inhomogeneous magnetic field.

5. Conclusions

Both thermal and nonthermal CTS spectra have been registered at W7-AS using powerful 140 GHz gyrotron radiation in a backscattering geometry. The measurements of the (still spatially averaged) ion temperature obtained from the fit to theoretical spectra demonstrate the potential for local ion temperature measurements in a 90°-scattering geometry which is constructed at present. The ideas of using powerful gyrotron radiation for alpha particle diagnostics by CTS technique have been strongly supported. The narrow-band LH wave instability triggered by the ion beam perpendicular to the magnetic field have been registered and investigated experimentally.

The financial support of the Bundesministerium für Forschung und Technologie of FRG is gratefully acknowledged.

References
[5] E.V.Suvorov et al., First results on ion temperature measurements at W7-AS by collective scattering of 140 GHz gyrotron radiation, 9-th Joint Workshop on ECE and ECRH, Jan.22-26, 1995, Borrego Springs, California, USA.
Fig. 1: Block diagram of CTS experiment at W7-AS.

Fig. 2: Measured thermal ion spectrum (dots) together with calculated one (solid line).

Fig. 3: Narrow-band feature frequency dependence on the plasma density.

Fig. 4: Scattering signal in neighbouring channels and 5.7 keV CX ion flux in the course of diagnostic NB modulation.

Fig. 5: LH waves traveling forward and back from the measurement with LO frequency shift.
Simulation and Analysis of Neutral Particle Spectra for W7-AS

Institut für Angewandte Physik, Universität Heidelberg, D-69120 Heidelberg, Germany
”Max-Planck-Institut für Plasmaphysik
Association EURATOM-IPP, D-85748 Garching, Germany

1. Introduction
Good confinement of energetic ions is one of the optimization criteria for the W7-X stellarator [1]. Therefore, it is of importance to improve present experimental and theoretical methods for the investigation of the physics of fast particle confinement. Here, we present first results of a detailed experimental and theoretical study on analysis and interpretation of non-thermal neutral particle spectra for W7-AS which are strongly related to the ion energy distribution.

2. Experimental Setup
The neutral particle diagnostics (NPA) at W7-AS consists of 4 neutral particle energy-analysers, built and calibrated up to 22 keV at Joffe Institute [2]. They have lines-of-sight in a vertical plane and are mounted on a lift that can be moved in vertical direction. A neutral particle diagnostic beam with an energy of 22 keV is passing vertically through the plasma center. This allows spatially resolved measurements at the crossing-points of the beam with the lines-of-sight of the analysers. The observation angle of the diagnostic system is about 35° to the magnetic field lines. For the measurement of the ion energy distribution two analysers are used, each having 10 energy channels.

3. Neutral Particle Flux
The local charge-exchange particle flux $S(v, \mu, t)$ from the plasma is given by

$$S(v, \mu, t) = g n_i n_0 f(v, \mu, t) \langle \sigma v \rangle_{ex} \cdot \exp \left[ -\int_0^1 \left( n_i \langle \sigma v \rangle_{ex} + n_e \langle \sigma v \rangle_e \right) \right].$$

(1)

Here, $f(v, \mu, t)$ is the time-dependent 2D ion velocity distribution, $v$ is the particle velocity, $\mu = v_\parallel/v$ the pitch-angle, $g$ is a geometrical factor, $n_i$ and $n_0$ are the ion and neutral particle densities, $\langle \sigma v \rangle_{ex}$ and $\langle \sigma v \rangle_e$ are the rate coefficients for charge-exchange and electron impact ionization [3]. The exponential factor of eq. 1 describes the absorption of the particles on their trajectory through the plasma which is important for the low-energy part in the measured spectra and depends on the absolute values of the ion and electron density profiles.
4. Simulation of the Ion Distribution Function

For the comparison with the measured neutral particle spectra it is important that the simulation of the ion velocity distribution includes pitch-angle scattering. Therefore we calculate the non-thermal ion velocity distributions of neutral-beam-heated ions by using the time-dependent 2D Fokker-Planck code NRFPS [4] which solves the Fokker-Planck equation for the velocity distribution $f(v, \mu, t)$.

Numerical calculations were carried out for W7-AS discharges with H$^0$-injection into H$^+$-plasma. The central density was $2.8 \times 10^{19} \text{ m}^{-3}$, the central electron and ion temperatures were 0.5 and 0.44 keV, respectively. The injection angle of the neutral-beam injection was 22°. The electron temperature and density were taken from Thomson scattering and the ion temperature was taken from the neutral particle diagnostics. The deposition profile for the injected particles was calculated with the 3D Fañer code. Since $Z_{\text{eff}}$-measurements were not available, $Z_{\text{eff}} = 2$ due to carbon impurities was assumed. Fig. 1 shows the calculated ion velocity distribution for some different pitch-angles in the presence of neutral-beam injection.

![Fig.1: Calculated normalized ion velocity distribution for different pitch-angles.](image)

The plasma data are:
- $n_e = 2.8 \times 10^{19} \text{ m}^{-3}$, $Z_{\text{eff}} = 2$,
- $T_e = 0.5 \text{ keV}$, $T_i = 0.44 \text{ keV}$
- and 45 keV injection with a power density of $H_0 = 1.2 \text{ W/cm}^2$.

For detailed analysis of the NPA spectra it is important to understand the influence of the different plasma parameters on the fast ion distribution. Therefore we carried out numerical studies varying one plasma parameter and keeping the others unchanged.

We found that a change in the electron temperature of 15 % has little effect on the ion-distribution function below 5 keV and the high energy part is changing by less than 20 %. This is in the order of the error of the NPA measurements. A change of the ion temperature directly changes the slope in the low-energy part of the distribution function but has no effect on the high-energy range.

Lowering the electron density leads to an increase of the non-thermal part at the cost of the thermal part (below ~ 5 keV). However, we found that a small change in the electron density of about 5 to 10 % has no measurable effect on the ion distribution function.
An decrease of $Z_{\text{eff}}$ from 2 to 1 enhances the plasma ion density. This leads to an enhanced pitch-angle scattering and an depletion of the particle distribution function at the injection energy. Our calculations show that $Z_{\text{eff}}$ is a critical parameter in the high-energy region (see fig. 2).

5. **Comparison of the flux calculation and measurements**

In order to compare the calculated ion distribution function $f(v, \mu, t)$ with experimental data, a theoretical particle flux from the plasma $S(v, \mu, t)$ was calculated according to eq. 1. The absorption term in eq. 1 was calculated with respect to the real stellarator geometry.

![Comparison of calculated neutral particle flux with experimental data.](image)

Fig. 2: Comparison of calculated neutral particle flux with experimental data. 

$n_e = 2.8 \times 10^{19} \text{ cm}^{-3}$

$T_e = 0.5 \text{ keV}$

$T_i = 0.44 \text{ keV}$

2a: $Z_{\text{eff}} = 2$

2b: $Z_{\text{eff}} = 1.5$

![Energy vs. log(S) plots](image)

Fig 2. shows the comparison of these calculations with the experimental result for the $Z_{\text{eff}}$ values of 2 (fig. 2a) and 1.5 (fig. 2b). From thermal energies up to energies of 24 keV the comparison between the measurement and the calculation is rather good. Small discrepancies in the low-energy region may result from uncertainties in the absorption term due to errors in the density profiles. Larger deviations above 24 keV show the importance of using accurately measured $Z_{\text{eff}}$-values. Additional work needs to be done for the investigation of the ion velocity distribution in this energy-region. The comparison is also sensible on the energy calibration of the NPA that has to be set properly.
6. **Effects of field ripple on fast particle confinement**

The good agreement of the calculations with the experimental data up to 24 keV will, for the future, allow to investigate the influence of global Alfvén waves [5] and the losses due to vertical drifts of magnetically trapped particles (1/\nu regime).

First measurements observing slowing-down particles from the neutral particle diagnostic beam in the presence of a changed toroidal field ripple show a clear coherence between the fast particle loss and the toroidal field ripple.

![Fig. 3: NPA flux at an energy of 4974 eV for different magnetic configurations. Particles are injected during four 50 ms diagnostic beam-pulses beginning at 240 ms at an toroidal angle \( \phi \) of about 36°. H: Presence of a magnetic hill (passing particles). S: Standard configuration with a small magnetic well. W: Presence of a deep magnetic well (trapped particles).](image)

In fig. 3, the neutral particle flux at the energy of 4976 keV is shown for the different magnetic field configurations indicated in the right. If the diagnostic beam is injected in a magnetic hill position, the fast ions are passing particles and therefore confined. They can be observed. The NPA flux decreases if a small well is present (standard configuration) and all particles are trapped and therefore lost if the beam is injected in a strong magnetic well.

References