PROCEEDINGS OF THE 5th WORKSHOP ON WENDELSTEIN 7-X
Schloß Ringberg, Bavaria, 26 - 30 June 1992

Fritz Rau, editor

IPP 2/317 August 1992

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
8046 GARCHING BEI MÜNCHEN
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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiet der Plasmaphysik durchgeführt.
# 5th Ringberg-Workshop on W 7-X

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This report contains the proceedings of the fifth workshop on the W 7-X project. It was held at Schloß Ringberg, near Lake Tegernsee, Bavaria, on 21 and 22 May 1992. A number of 19 papers was given by members of the W 7-X project, of the Teams from the two experiments, W 7-AS and ASDEX-upgrade, as well as by guests from KfK Karlsruhe, and discussed by the participants.

In review: The preceding W 7-X workshops were:

First W 7-X workshop: March 1987,
Second W 7-X workshop: August 1988,
Third W 7-X workshop: June 1989,

The proceedings of this series of W 7-X workshops document the development of the project. The first workshop resulted in the choice of a HELIAS configuration for W 7-X in favour of the other candidates, an upgrade of W 7-AS (in a coil set similar to that used for studies on Advanced Stellarator Reactors and Burner systems), a Bean-shaped system similar to it, or a modular Heliac, as detailed in Report EUR 11058 EN, Brussels 1987.

The second workshop on W 7-X compared Helias systems in 4, 5 and 6 field periods, with the preference of 5 periods, and studied systems with different field structures, i.e. “linked mirror” and “quasi-helical” configurations as extreme cases. Issues for the choice of some intermediate type were stability, transport and small bootstrap currents. The proceedings were again published by the Commission of the European Communities in EUR 11705 EN, 1988.

A condensed version of the proceedings is available as Report IPP 2/295. In the third W 7-X workshop the basis was laid for preparing the proposal to attain EURATOM preferential support phase I. The seven principles of optimization were formulated, to be achieved simultaneously for the W 7-X configuration. The proposed coil systems started to converge, and first studies towards a divertor for W 7-X were initiated, see IPP 2/302.

The W 7-X proposal was submitted in 1990 to the respective authorities. It was intensively discussed by a number of advisory groups in interaction with the W 7-X Team, and received EURATOM phase I approval on scientific and technical grounds in August 1991, but strategic considerations about the fusion programme as a whole were still left open. At the same time, phase II approval was given for the technical development including the superconducting coils. A preparatory R & D programme has been started with the goal of constructing a full-size modular demonstration coil.

Various topics of the W 7-X project - ranging from the coil system to the reactor aspects - were discussed in the fourth workshop, as documented in IPP 2/313. Most of the investigations concentrated on the W 7-X reference design as described in the W 7-X proposal. Studies towards preparing for EURATOM phase II of the complete project were initiated, and called for a unified coil system with a divertor.

In summary: In the fifth W 7-X workshop the reference design chosen in the W 7-X proposal was changed in minor detail only, and substantially improved with respect to the space available for a divertor and the critical coil curvature.

The main dimensions and parameters of the revised coil system, labelled HS 5-10 N, are for its “Standard configuration”:

- Major radius: 5.5 m
- Average plasma radius: 0.5 m
- Rotational transform on axis: 0.86
- Rotational transform at edge: 0.99
- Magnetic well depth: 1.1 %
- Average field on axis: 3 T
- Average coil radius: 1.3 m
- Current density (winding pack): 46 MA/m²
- Magnetic energy: 605 MJ
- Minimum plasma-wall distance: 0.1 m

In W 7-X the magnetic field is produced by 50 poloidally closed nonplanar coils distributed in five identical modules, i.e., five field periods. In order to give operational flexibility to the device 20 additional noncircular planar coils are mounted over the modular coil system. In the Standard configuration, all currents are identical in the nonplanar coils and zero in the planar ones.

Modifications of this configuration are obtained either by energizing the planar coils (e.g., to produce low or high rotational transform, inward or outward shift of the magnetic axis) or by energizing each of the five groups of identical nonplanar coils with slightly different (by a few percent) currents (e.g. to produce low or high mirror ratio, low or high shear). Conventional NbTi superconductor technology has been chosen to allow a stationary magnetic field which allows long-pulse plasma operation up to 30 s. Normal-conducting “sweep coils” are considered for fine-tuning, of the configuration (island size and position, error fields) and of divertor heat loads, if required.

The intended plasma parameters are central ion and electron temperatures of 2-5 keV and a central density up to 2 x 10²⁶ m⁻³. Estimated energy confinement times range between 0.1 and 0.5 s.
The X-Y W is a new type of computer that has been developed by the XYZ Corporation. It is designed to be more powerful and efficient than its predecessors, with improved speed and processing capabilities. The X-Y W is equipped with advanced hardware and software features, making it suitable for a wide range of applications. The machine is expected to revolutionize the way businesses operate, providing them with greater efficiency and productivity.

In the technical specification section of the manual, detailed information about the X-Y W is provided. This includes specifications for the processor, memory, storage, and other key components. The manual also contains instructions for installation and operation of the machine, as well as troubleshooting tips and maintenance procedures. For further details, please refer to the technical manual provided with your purchase.

Sample text from the manual:

"The X-Y W is equipped with a high-performance processor that allows for faster data processing and improved performance. The machine also features a large amount of memory and storage, ensuring that users can handle complex tasks with ease. Additionally, the X-Y W supports a wide range of software applications, making it a versatile solution for various industries.

The X-Y W is designed to be user-friendly, with an intuitive interface that simplifies the process of setting up and using the machine. It also includes advanced security features to protect against unauthorized access and data breaches.

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XYZ Corporation"
FIELD LINE STRUCTURE AND MONTE-CARLO CALCULATIONS IN THE EDGE REGION OF W7-X

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ABSTRACT

- Introduction
  Divertor concept for WENDELSTEIN 7-X.

- Properties of various magnetic field configurations and of differently defined helical troughs concerning
  - intersection angles,
  - heat load, and
  - particle load on the divertor plates

- Topology of divertor field line mapping
  The structure of the magnetic field lines between the plasma surface, i.e. the last closed magnetic surface, and the plasma facing surfaces of the helical troughs is investigated in detail.

- Summary and outlook

INTRODUCTION

- Plasma tube with five helical edges marked by heavy lines
• Typical intersection pattern \( (\lambda = \frac{5}{5}) \)

- Field line diversion

Regions of the ergodic region located in the neighbourhood of a helical edge are positions where the field lines are diverted.
The five helical troughs lead to a complete separation of the magnetic field lines starting at the plasma and ending at the divertor troughs from the field lines which start at the first wall.
- Typical intersection pattern ($i = \frac{5}{6}$) taking diffusion into account: $D = 1 \ \frac{m^2}{s}$

- Persistence of the diversion process at the helical edge
- Blurring of the detailed island structure
- Increase of the plasma-control surface interaction area
• Summary
Helias configurations fulfill a basic requirement for an open divertor concept, namely, the magnetic field lines intersect a given control surface only in patterns close to the helical edge.

Even when diffusion is taken into account, the diversion process persists at the helical edge.

Helical troughs used as divertor plates yield a divertor concept which is independent of the detailed island structure outside the plasma surface:

the divertor configuration is essentially independent of the rotational transform at the plasma boundary as it is planned for the proposed stellarator W7-X.

The diversion properties are preserved for finite $\beta$-equilibria.

PROPERTIES OF VARIOUS MAGNETIC FIELD CONFIGURATIONS AND OF DIFFERENTLY DEFINED HELICAL TROUGHS

• Various magnetic field configurations

\[ \iota = 5/5 \quad \iota = 10/9 \quad \iota = 1.05 \]
• Differently defined helical troughs
• Intersection angles

Intersection angles, that are the angles between the plasma facing surfaces of the helical troughs and the magnetic field lines at the intersection points, can be calculated easily on the whole plasma facing surfaces. For the various helical troughs average intersection angles have been obtained in the range of

\[0.4^\circ \lesssim \langle \Psi \rangle \lesssim 3.2^\circ\]

• Intersection angles on the trough surfaces (dark areas: small intersection angles, light areas: large intersection angles)

\[\langle \Psi \rangle = 2.4^\circ\]

\[\langle \Psi \rangle = 0.4^\circ\]
• W7-X SOL Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>[m]</td>
<td>5.5</td>
</tr>
<tr>
<td>$A$</td>
<td>[$10^3$ m$^2$]</td>
<td>0.12</td>
</tr>
<tr>
<td>$V$</td>
<td>[$10^3$ m$^3$]</td>
<td>0.03</td>
</tr>
<tr>
<td>$B_0$</td>
<td>[T]</td>
<td>3.0</td>
</tr>
<tr>
<td>$P_e$</td>
<td>[MW]</td>
<td>10</td>
</tr>
<tr>
<td>$P_e/2\pi R_0$</td>
<td>[MW/m]</td>
<td>0.3</td>
</tr>
<tr>
<td>$P_e/A$</td>
<td>[MW/m$^2$]</td>
<td>0.08</td>
</tr>
<tr>
<td>$T/\lambda_T(\chi_e n = 1)$</td>
<td>[keV/m]</td>
<td>5</td>
</tr>
<tr>
<td>$P_p$</td>
<td>[$10^{20}$ s$^{-1}$]</td>
<td>300</td>
</tr>
<tr>
<td>$P_p/A$</td>
<td>[$10^{20}$ m$^{-2}$ s$^{-1}$]</td>
<td>2.5</td>
</tr>
<tr>
<td>$n/\lambda_n(D_p = 1)$</td>
<td>[$10^{20}$ m$^{-4}$]</td>
<td>2.5</td>
</tr>
</tbody>
</table>

• Simplified SOL simulations

Anomalous transport $\rightarrow$ Very simplified SOL simulation with appropriately chosen ‘diffusion’ of field lines by random displacements during field line tracing after characteristic mean free paths.

$$D = \Delta^2 \nu$$

Particle transport

$D_p \approx 1$ m$^2$/s, $\nu \approx 3.5 \cdot 10^4$s$^{-1}$, $\lambda \approx 1$ m, $\Delta \approx 0.005$ m

Energy transport

$\chi_e \approx 10$ m$^2$/s, $\nu \approx 2.5 \cdot 10^6$s$^{-1}$, $\lambda \approx 0.8$ m, $\Delta \approx 0.002$ m

• Intersection pattern: $\chi_e = 10$ m$^2$/s, ($t = 10/9$)
- Histogram of the particle load: \( t = 10/9 \)

- Heat load: \( t = 10/9 \)

- Particle load: \( t = 10/9 \)

- Histogram of the heat load: \( t = 10/9 \)
- Intersection pattern: $D_p = 1 \text{ m}^2/\text{s}$, ($t = 10/9$)

- Particle load: ($t = 10/9$)
• Histogram of the particle load: ($\tau = 10/9$)

![Histogram of particle load](image)

• Particle load: ($\tau = 5/3$)

![Diagram of particle load](image)
- Summary

For the various magnetic field configurations and helical troughs
- average power flow densities of a few MW/m²,
- average particle flow densities $\lesssim 1 \cdot 10^{22} \text{ m}^{-2}\text{s}^{-1}$
- and intersection angles in the range of $0.4^\circ \lesssim (\Psi) \lesssim 3.2^\circ$

have been achieved on the plasma facing surfaces of the helical troughs.

**TOPOLOGY OF DIVERTOR FIELD LINE MAPPING**

**DIVERTOR COMPUTATIONS**

- Field line mapping

Magnetic field lines, started at the plasma facing surfaces of the helical troughs, are traced until they end at the troughs or the first wall.

In order to describe the topology of these field lines, curvilinear coordinates $(s,u,v)$ are used.

Characterization of the field lines according to their minimal distances (minimal $s$-coordinate) from the plasma boundary.
• Adequate coordinate system \((s, u, v)\) in the edge region

\[
R = \sum_{m=0, n=-n_b}^{m_b, n_b} (1 - s) \hat{r}^p_{m,n} + s \hat{r}^o_{m,n} \cos 2\pi (mu + nv),
\]

\[
Z = \sum_{m=0, n=-n_b}^{m_b, n_b} (1 - s) \hat{z}^p_{m,n} + s \hat{z}^o_{m,n} \sin 2\pi (mu + nv),
\]

\[
\varphi = \frac{2\pi}{N} v, \quad (N = \text{number of periods})
\]

\(R, Z, \varphi = \text{cylindrical coordinates}\)

\(\{\hat{r}^p_{m,n}, \hat{z}^p_{m,n}\}, \{\hat{r}^o_{m,n}, \hat{z}^o_{m,n}\} = \text{Fourier coefficients}\)

\(p = \text{plasma, } o = \text{outer surface}\)

Coordinate system in the edge region. Lines with fixed radial \((s)\) and poloidal \((u)\) coordinates are plotted for a given toroidal \((v = 0)\) coordinate. The first wall (dashed line) is used as outer surface. The hatched areas mark the positions of the helical troughs and the outermost line represents the current-carrying surface.

• Ordered layers

Minimal distances of the field lines located in space at the outward side of the bean shaped cross-section.

\[
0.0 \leq d_{\text{min}} < 1.2 \text{ cm} \quad \text{innermost layer}
\]

\[
1.2 \leq d_{\text{min}} < 2.4 \text{ cm} \quad \text{second layer}
\]

\[
2.4 \leq d_{\text{min}} < 4.8 \text{ cm} \quad \text{third layer}
\]

\[
4.8 \leq d_{\text{min}} < 10. \text{ cm} \quad \text{outermost layer}
\]
Parts of three different cross sections for the three magnetic field configurations. The hatched areas mark the positions of the helical troughs, and the dashed lines denote the first wall. The small and thick points characterize the different layers (•, •, •).

- Intersection pattern of the layers (\( i = 5/5 \)). The white areas belong to the field lines forming the innermost layer, while the darkest ones belong to the outermost layer.
- Intersection pattern of the layers ($\ell = 10/9$)

- Intersection pattern of the layers ($\ell = 1.05$)
- Average field line lengths and intersection areas of the layers

<table>
<thead>
<tr>
<th>layer</th>
<th>(2(L)) ((\text{m}))</th>
<th>(A) ((\text{m}^2))</th>
<th>(2(L)) ((\text{m}))</th>
<th>(A) ((\text{m}^2))</th>
<th>(2(L)) ((\text{m}))</th>
<th>(A) ((\text{m}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>326</td>
<td>1.1</td>
<td>103</td>
<td>2.7</td>
<td>128</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>2.4</td>
<td>18</td>
<td>4.8</td>
<td>19</td>
<td>9.1</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>18.7</td>
<td>13</td>
<td>14.3</td>
<td>14</td>
<td>16.7</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>15.9</td>
<td>5</td>
<td>20.1</td>
<td>5</td>
<td>11.3</td>
</tr>
</tbody>
</table>

- Magnetic field line in the edge region

Distance of the magnetic field line from the plasma boundary as a function of its length. \(s = 0.4\) corresponds to the radial position of the helical troughs, while \(s = 0\) marks the position of the plasma boundary.

- Approximate definition of the scrape-off layer (SOL)

Because of the layer structure of magnetic field lines in the ergodic edge region it appears useful to use these field lines as coordinate lines for plasma edge modelling.

→ It is necessary to define a SOL.

Using the NEMEC code, a SOL is defined, which shows the same geometrical behaviour as the layers, while its thickness is a parameter that has to be determined.
• NEMEC $\leftrightarrow$ ordered layers

Lower parts of the plasma surface (inner solid line), the innermost layer and the NEMEC surface (outer solid line), which is used as SOL surface. The hatched area marks the position of the helical trough, while the dashed curve represents the first wall.

• Summary

Characterizing the field lines according to their minimal distance from the plasma boundary, ordered layers are found.

Using the NEMEC code, surfaces outside the last closed surface can be found, which approximate the geometry of the layers $\rightarrow$ definition of the SOL.

OUTLOOK

• Continued optimization of the helical troughs (in connection with continued coil and flexibility definition):
  - small intersection angles,
  - a low and uniform power and particle load, and
  - no leading edges.

• 3 D field lines $+1$ D transport $\rightarrow n, T$ in the edge region
  - consistent with layer structure

• Coupling to neutrals: EIRENE

REFERENCES

• REITER, D., JUEL report 1947 (Jülich, 1984).
Average field line lengths and intersection areas of the layers:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Length (m)</th>
<th>Area (m²)</th>
<th>Intersection Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57</td>
<td>3.1</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>47</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>0.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Magnetic field line in the edge region:

Summary:

Characterizing the field lines necessitates the determination of the plasma boundary, and the field lines are found.

OUTLINE:

- Determination of the SOL
- Controlling activation of the plasma with confinement and flow
- Low and medium power and boundary details

Distance of the magnetic field line from the plasma boundary corresponds to the radial position of the helical troughs, while z = 0 marks the position of the plasma boundary.

- Approximate definition of the scrape-off layer (SOL)

REFERENCES:

Because the layer structure of magnetic field lines in the edge region is apparent, it is useful to use these field lines as coordinate lines for plasma edge analysis.

- SITEK, B.J., 1988, Nucl. Fusion, 28, 100
- Using the NEMEC code, a SOL is defined, which shows the same geometrical behaviour as the layers, while its thickness is a parameter that has to be determined.
1-D SOL MODELS
for
WENDELSTEIN 7-X

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IPP-Euratom Association
Max-Planck-Institut für Plasmaphysik
Garching, ∗Division Berlin
Federal Republic of Germany

• Two-Fluid Plasma Equations
• Plasma - Neutral Particle Interaction
• Boundary conditions
• 1-D SOL Codes
• Numerical Results

Introduction
The plasma - neutral particle interaction in the SOL (Scrape-Off Layer) model of the stellarator W 7-X is investigated.

The hydrogenic plasma species are described by a set of 1D steady-state conservation equations for particles, momentum, and energy along the magnetic field lines outside the last closed magnetic surface.

The particle and power fluxes from the main plasma into the SOL are prescribed as particle, electron, and ion energy sources with given distributions along the field lines.

The hydrogenic atoms interacting with the currentless, quasineutral plasma are produced at the divertor plates by recycling of the ions. 1D neutral particle density, velocity, and temperature profiles are calculated either in a diffusion approximation with the only coordinate perpendicular to the plate surface into the slab or in an exponential approximation.

In another simplified model the neutral particle profiles are prescribed or distributed plasma sources are given directly.

The boundary conditions at the plasma (symmetry plane) and the divertor plates are derived and discussed. Various 1D codes for the solutions of this system of differential equations with different boundary conditions are compared.

The numerical calculations with the ZIE code based on the linearization method show that in the case of high recycling the ion and electron temperatures significantly decrease in the divertor region and the plasma density has a maximum near the divertor plate. Thus a low-temperature high-density plasma layer reducing the impurity production at the divertor plate is formed. This effect appears for a wide range of energy and particle fluxes through the separatrix.

Two-Fluid Plasma Equations

\[ S_n = \frac{d}{dz} (n\nu) \]
\[ S_p = \frac{d}{dz} \left[ m_i n \nu^2 + n(T_i + T_e) + \pi_i \right] \]
\[ S_{q_i} = \frac{d}{dz} \left[ n \nu (2.5 T_i + 0.5 m_i v^2) + \nu \pi_i + q_i \right] \]
\[ + \nu \nu v E + Q_{ie} \]
\[ S_{q_e} = \frac{d}{dz} (2.5 n \nu T_e + q_e) - \nu \nu v E - Q_{ie} \]

where

\[ \pi_i = -\eta_i \nu^{5/2} \frac{d \nu}{dz} \]
\[ q_i = -\kappa_i T_i^{5/2} \frac{dT_i}{dz} \]
\[ q_e = -\kappa_e T_e^{5/2} \frac{dT_e}{dz} \]
\[ Q_{ie} = -\alpha n^2 \frac{T_e - T_i}{T_e^{5/2}} \]
\[ eE = -1.71 \frac{dT_e}{dz} - T_e \frac{d \ln n}{dz} \]
Sources

\[ S_n = S_{no} + k_{ion}(T_e) n N \]

\[ S_p = -m_i k_{cx}(T_i) n N (v - v_a) \]

\[ S_{qi} = S_{qio} - k_{cx}(T_i) n N [1.5(T_i - T_a) + 0.5m_i v^2] \]

\[ S_{qe} = S_{qeo} - k_{ion}(T_e) n N I_{ion} \]

Neutral Particle - Plasma Interaction

A - Analytical treatments

A1 - Diffusion Approximation

\( (z = z \sin \alpha) \)

\[ \frac{d \Gamma_a}{dx} = -k_{ion} n N \]

\[ \frac{dW_a}{dx} = 1.5 n N [k_{cx}(T_i - T_a) - k_{ion} T_a] \]

\[ \Gamma_a = -D_a \frac{d(NT_a)}{dx} \]

\[ W_a = 2.5T_a \Gamma_a - 1.5N D_a \frac{dT_a}{dx} \]

\[ D_a = \frac{T_a}{m_i n (k_{ion} + k_{cx})} \]

A2 - Exponential Approximation

\[ N_a = N_{a_o} \exp \left( -\int_{\pi}^{z_d} g(\xi) d\xi \right) \]

\[ g = n \sqrt{\frac{k_{ion} k_{cx} m_i}{T_a}} \]

\[ T_a = \frac{k_{cx}}{k_{cx} + k_{ion}} T_i \]

A3 - Given Neutral Particle Sources

( small \( \alpha \), dimensionless functions )

\[ S_n = S_{n_o} + k_{ion} n N_0 \Theta(z - z_{de}) \]

\[ S_p = -m_i k_{cx} n N_0 v \Theta(z - z_{de}) \]

\[ S_{qi} = S_{qio} - 1.5 k_{cx} n N_0 (T_i - T_{a_o}) \Theta(z - z_{de}) \]

\[ S_{qe} = S_{qeo} - 0.5 k_{ion} n N_0 I_{ion} \Theta(z - z_{de}) \]

A4 - Distributed Plasma Sources

\[ S_n = S_{n_o} + f_1(z - z_d) + f_2(z + z_d) \]

\[ f_3(z - z_d) - f_4(z + z_d) \]

\[ [f_5(z - z_d) - f_6(z + z_d)] \]

B - Monte-Carlo Codes

B1 - Iteration with DEGAS Code

B2 - Iteration with EIRENE Code
Boundary Conditions

A - symmetric case

symmetry plane \( z = 0 \)

\[
\frac{dn}{dz} = \frac{dT_e}{dz} = \frac{dT_i}{dz} = v = 0
\]

divertor plate \( z = z_d \)

\[ q_e = \epsilon_e T_e n u \]

\[ q_i = \epsilon_i T_i n u \]

\[ \pi_i = \epsilon \sqrt{T_i m_i} n u \]

or

\[ v = c_s = \sqrt{\frac{T_i + T_e}{m_i}} \]

where

\[ \epsilon_e = -0.5 + \phi^* \]

\[ \epsilon_i = 0.5 \left( \frac{s}{u^*} - 1 \right) + s^2 - u^2 - \epsilon_e u \]

\[ \epsilon = 2(s - u) + \left( 1 + \frac{T_e}{T_i} \right) \left( \frac{1}{u^*} - \frac{1}{u} \right) \]

\[ u = \frac{v}{v_{T_i}} \]

\[ u^* = s + \frac{\exp(-s^2)}{\sqrt{\pi}(1 + \text{erf}(s))} \]

\[ v_{T_i} = \sqrt{\frac{T_i}{m_i}} \]

with

\[ s = \max(s_0, u) \]

where \( s_0 \) and \( \phi^* \) must be calculated from

\[ \frac{c_s}{v_{T_i}} = s_0 + \frac{\exp(-s_0^2)}{\sqrt{\pi}(1 + \text{erf}(s_0))} \]

\[ \phi^* = -\ln \left( \frac{\sqrt{2m_e T_i \pi}}{T_e m_i} u^* \right) \]

B - asymmetric case

at the divertor plates \( z = z_d, z = -z_d \)

(case A4, \( q_i = \pi_i = 0, T_e = T_i = T \))

\[ q = \epsilon_e T n u \]

\[ v = c_s \quad \text{or} \quad \frac{d^2u}{dz^2} = 0 \]

Assumed Electron Distribution Function on Entering the Langmuir Sheath

![Diagram](https://via.placeholder.com/150)

\[ u = \frac{1}{\sqrt{2 \pi \sigma_u^2}} \exp \left( -\frac{(u-u_0)^2}{2 \sigma_u^2} \right) \]

\[ f_e = \frac{1}{\sqrt{2 \pi \sigma_e^2}} \exp \left( -\frac{(e-e_0)^2}{2 \sigma_e^2} \right) \]

\[ f_{e_p} = \frac{1}{\sqrt{2 \pi \sigma_{e_p}^2}} \exp \left( -\frac{(e_p-e_p_0)^2}{2 \sigma_{e_p}^2} \right) \]

\[ e_{p_0} = \frac{1}{\sqrt{2 \pi \sigma_e^2}} \exp \left( -\frac{(e-e_0)^2}{2 \sigma_e^2} \right) \]

1-D SOL Codes

A - SOLID Code

W. Schneider, $T_e, T_i, n, v$, $\partial/\partial t \neq 0$

symmetric case with $v = c_s$ at $z = z_d$

Coupling with DEGAS

B - FE Code

R. Zanino, $T, n, v$, $\partial/\partial t \neq 0$

asymmetric case, boundary conditions

at $z = z_d$, $z = -z_d$

$v = c_s$, $v = -c_s$ or $d^2v/dz^2 = 0$

C - ZIE Code

Newton-Kantorovich Linearization Method

E. Dietrich, $T_e, T_i, n, v$, $\partial/\partial t = 0$

symmetric case with $v = c_s$, ($M = 1$)

or

$\pi_i = \epsilon \sqrt{T_i m_i} n v$, (standard case)

at $z = z_d$

Coupling with magnetic field line topology (Strumberger) and EIRENE Code (Reiter)

running time

$t_A = 60s$, $t_B = 80s$, $t_C = 10s$
Linearization Method

\[
\frac{du}{dz} = F(u, z), \quad 0 \leq z \leq 1
\]

\[
\begin{aligned}
H(u) &= 0, \quad z = 0 \\
\Phi(u) &= 0, \quad z = 1
\end{aligned}
\]

\[
u = (n, T, e, \pi, q, v)
\]

\[
F = (F_1, \ldots, F_m)
\]

\[
H = (H_1, \ldots, H_{1-m})
\]

\[
G = (G_1, \ldots, G_m)
\]

\[
u^{r+1} = u^r + \alpha \Delta u
\]

\[
\frac{du}{dz} + \frac{\partial u}{\partial z} + \phi u^2 = F(u, z) + \Phi(u, z) \Delta u + \frac{\partial u}{\partial z}^2, \quad 0 < z < 1.
\]

\[
\begin{cases}
\partial H(u) = 0, & z = 0 \\
\partial \Phi(u) = 0, & z = 1
\end{cases}
\]

\[
\Delta u = (\Delta n, \Delta T, \Delta q, \Delta v)
\]

\[
u = (u, v)
\]

NUMERICAL SOLUTION

\[
\Delta u_{j+1} = (I + \Delta z F) \Delta u_j + \Delta z (F - \frac{du}{dz}) \Delta u_{j+1}
\]

\[
\Delta z = z_{j+1} - z_j, \quad u = u^r(z_{j+1})
\]

\[
\Delta u_j = F_j \Delta u_0 + Q_j, \quad j = 0, \ldots, N
\]

\[
P_j = (I + \Delta z F) P_{j-1} \in \mathbb{R}^{1 \times m}
\]

\[
Q_j = (I + \Delta z F) Q_{j-1} + \Delta z (F - \frac{du}{dz}) v_j \in \mathbb{R}^1
\]

\[
\Delta u_0 : \quad z = 1
\]

\[
\partial \Phi(u^r) (P_0 \Delta u_0 + Q_0) = -\alpha u^r
\]

next iteration step

\[
\frac{du}{dz} = \frac{\partial \Phi(u^r)}{\partial z} u^r + (F(u^r(z)) - \frac{du}{dz}), \quad 0 < z < 1
\]

\[
\begin{cases}
\partial H(u^r) = -\partial H(u^r), & z = 0 \\
\partial \Phi(u^r) = -\partial \Phi(u^r), & z = 1
\end{cases}
\]

\[
\Delta u = (\Delta n, \Delta q, \Delta v)
\]

\[
u = (u, v)
\]

connection length, m = 0.300E+03
SOL length, m = 0.130E+03
distance to the divertor, m = 0.140E+03
big radius, cm = 0.550E+03
small radius, cm = 0.600E+02
SOL, cm = 0.300E+01
plasma source, s⁻¹ = 0.100E+23
energy source, MW = 0.100E+01
\OE/Qi = 0.200E+01
divertor plasma input / Sn = 0.000
divertor energy loss / Qi = 0.000
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>connection length, m</td>
<td>0.500E+02</td>
</tr>
<tr>
<td>SOL length, m</td>
<td>0.200E+02</td>
</tr>
<tr>
<td>distance to the divertor, m</td>
<td>0.230E+02</td>
</tr>
<tr>
<td>big radius, cm</td>
<td>0.550E+03</td>
</tr>
<tr>
<td>small radius, cm</td>
<td>0.600E+02</td>
</tr>
<tr>
<td>SOL, cm</td>
<td>0.300E+01</td>
</tr>
<tr>
<td>plasma source, s⁻¹</td>
<td>0.100E+23</td>
</tr>
<tr>
<td>energy source, MW</td>
<td>0.200E+01</td>
</tr>
<tr>
<td>QE/QI</td>
<td>0.200E+01</td>
</tr>
<tr>
<td>Diverter plasma input / N</td>
<td>0.750</td>
</tr>
<tr>
<td>Diverter energy loss / Ti+N</td>
<td>0.750</td>
</tr>
</tbody>
</table>

![Graph 1](image1)

![Graph 2](image2)
$N = 10^{13} \text{ cm}^{-3}$

$T_e, T_i = \text{eV}$

$V = 10^7 \text{ cm/s}$

SOL THICKNESS, cm = 3.0

PLASMA SOURCE, $s^{-1} = 2.0 \times 10^{22}$

ENERGY SOURCE, MW = 10.0
**Fluid Description of the Boundary Region in W 7X**

**II. Wobig**

**Characteristics of the boundary region**
- Absence of closed magnetic surfaces (islands, ergodic regions)
- Collision dominated plasmas
- Influx of impurities and inelastic collisions
- Interaction with neutrals
- Contact with material boundaries
- Langmuir sheath in front of the wall

**Problems, issues and open questions**
- Fluid description of the plasma
- Model of neutrals
- Boundary conditions
- Existence of solutions
- Uniqueness and bifurcations
- Retainment of impurities
- Wall loading
- High recycling regime
- Stability of stationary solutions
- Numerical procedure
- Anomalous transport

**Quantities of a Collision Dominated Plasma**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index of Particle Species</td>
<td>( \alpha, \beta )</td>
</tr>
<tr>
<td>Charge</td>
<td>( q_\alpha )</td>
</tr>
<tr>
<td>Distribution Function</td>
<td>( f_\alpha(x, v) )</td>
</tr>
<tr>
<td>Density</td>
<td>( n_\alpha(x) )</td>
</tr>
<tr>
<td>Temperature</td>
<td>( T_\alpha(x) )</td>
</tr>
<tr>
<td>Pressure</td>
<td>( p_\alpha = n_\alpha T_\alpha )</td>
</tr>
<tr>
<td>Velocity</td>
<td>( u_\alpha(x) )</td>
</tr>
<tr>
<td>Current</td>
<td>( j_\alpha = q_\alpha n_\alpha u_\alpha(x) )</td>
</tr>
<tr>
<td>Thermal Flux</td>
<td>( q_\alpha(x) )</td>
</tr>
<tr>
<td>Friction Coefficients:</td>
<td></td>
</tr>
<tr>
<td>Coulomb Collisions</td>
<td>( I^{\beta}_{\alpha} )</td>
</tr>
<tr>
<td>Neutral Interaction</td>
<td>( \lambda_{\alpha}^{\gamma} )</td>
</tr>
</tbody>
</table>

**Basic approximation:**
- Neglect of tensorial moments

**Distribution function of particle species**

\[
f_\alpha = f_{\alpha M} \left( 1 + \frac{2v^2}{v_{\alpha}^2} \sum_{k=0}^{\infty} \frac{u_\alpha L^{3/2} v_k^2}{v_{\alpha}^2} \right)
\]

\[
f_\alpha = f_{\alpha M} \left( 1 + \frac{2v}{v_{\alpha}^2} \left( u_\alpha - \frac{2}{5} \frac{v^2}{v_{\alpha}^2} \frac{q_\alpha}{p_\alpha} \right) \right)
\]

\[
f_\alpha = f_{\alpha M} \left( 1 + h^l_{\alpha} \right)
\]

\[
f_{\alpha M} \sim \frac{n_\alpha}{v_{\alpha}^3} \exp \left( \frac{v^2}{v_{\alpha}^2} \right) \quad \text{local Maxwellian}
\]

\[v_{\alpha}^2 = \frac{2T_\alpha}{m_\alpha} \quad \text{thermal velocity}
\]

\[p_\alpha = n_\alpha T_\alpha \quad \text{pressure}
\]

\[u_\alpha \quad \text{macroscopic velocity}
\]

\[q_\alpha \quad \text{thermal flux}
\]

**The model**

(see Hirschman, Sigmar)

Fluid model of a multi-species plasma, quasineutrality, isotropic pressure, neglect of inertia and viscous forces

Interactions with neutrals and inelastic collisions
Coulomb Collisions  
\[ C_\alpha = \sum_\beta C_{\alpha \beta} (f_{\alpha \cdot f_\beta}) \]
\[ = \sum_\beta C_{\alpha \beta} (f_{\alpha \cdot f_{\beta \cdot M}}) + \sum_\beta \left[ C_{\alpha \beta} (f_{\alpha \cdot f_{\beta \cdot M} h_1}) + C_{\alpha \beta} (f_{\alpha \cdot f_{\beta \cdot M} h_2}) \right] \]
\[ = \sum_\beta C_{\alpha \beta} (f_{\alpha \cdot f_{\beta \cdot M}}) + \sum_\beta C_{\alpha \beta} (f_{\alpha \cdot f_{\beta \cdot M} h_1}) + \sum_\beta C_{\alpha \beta} (f_{\alpha \cdot f_{\beta \cdot M} h_2}) \]

Collisions with neutrals  
\[ S_{\alpha \cdot f_{\alpha \cdot f_0}} = S_{\alpha \cdot f_{\alpha \cdot f_0}} + S_{\alpha \cdot f_{\alpha \cdot f_2}} \]

Friction force  
\[ N_{\alpha 1} = (m_\alpha v, S_{\alpha}) = (m_\alpha v, S_{\alpha \cdot f_{\alpha \cdot f_0}}) + (m_\alpha v, S_{\alpha \cdot h_1}) \]
\[ = \lambda_{\alpha 1} u_\alpha - \frac{2}{5} \lambda_{\alpha 2} q_\alpha \]

Interaction with neutrals  
\[ S_{\alpha \cdot f_{\alpha \cdot f_0}} = S_{\alpha \cdot f_{\alpha \cdot f_0}} + S_{\alpha \cdot h_1} \]

Scalar Product:  
\[ (f, g) = \int_\alpha fg \, d^3v \]

Friction Forces:  
\[ F_{\alpha 1} = (m_\alpha v, C_\alpha) = \sum_\beta (m_\alpha v, C_{\alpha \beta} h_1) \]
\[ = \sum_\beta \lambda_{\alpha 1} u_\beta - \frac{2}{5} \lambda_{\alpha 2} q_\beta \]

\[ \lambda_{\alpha 1} = (m_\alpha v, C_{\alpha \beta} 2v) \]
\[ \lambda_{\alpha 2} = (m_\alpha v, C_{\alpha \beta} 2v) \]

Momentum Balance  
\[ 0 = - \nabla p_\alpha + q_\alpha n_\alpha E + q_\alpha n_\alpha u_\alpha \times B + F_{\alpha 1} + N_{\alpha 1} \]

Energy Flux Balance  
\[ 0 = - \frac{5}{2} n_\alpha \nabla T_\alpha + q_\alpha n_\alpha v_\alpha \times B + F_{\alpha 2} + N_{\alpha 2} \]

Definitions  
\[ f = \begin{pmatrix} u_\alpha \\ q_\alpha \\ \frac{v_\alpha}{p_\alpha} \end{pmatrix} \quad g = \begin{pmatrix} \nabla p_\alpha - q_\alpha n_\alpha E \\ \frac{5}{2} n_\alpha \nabla T_\alpha \end{pmatrix} \]

\[ g = Lf \Rightarrow f = L^{-1} g \]

L is a linear matrix operator
Inversion of vector moment equations

\[ \mathbf{g} = L_B \mathbf{f} + L_\epsilon \mathbf{f} \]

\[ L_B \mathbf{f} = \mathbf{x} \mathbf{B} \text{ - terms} \]

\[ L_\epsilon \mathbf{f} = \text{Dissipative terms} \]

\[ L_\epsilon = \text{Negative definite matrix} \rightarrow L^{-1} \text{ exists} \]

\[ \mathbf{f} = f_\perp + f_\parallel \Rightarrow \mathbf{g} = L_B f_\perp + L_\epsilon (f_\perp + f_\parallel) \]

\[ f_\perp = L_B^{-1} P_\perp \mathbf{g} - L_B^{-1} L_\epsilon f_\perp \]

\[ f_\parallel = L_\epsilon^{-1} P_\parallel \mathbf{g} \]

\[ \text{Diamagnet. Drift} \quad \text{ExB-Drift} \quad \text{Classical diffusion} \]

\[ \text{Parallel diffusion} \]

Explicit form of perpendicular components

\[ q_\alpha n_\alpha u_{\alpha, \perp} = - (\nabla p_\alpha + q_\alpha n_\alpha E) \times \frac{\mathbf{B}}{B^2} + (F_{\alpha_1} + N_{\alpha_1}) \times \frac{\mathbf{B}}{B^2} \]

\[ q_\alpha n_\alpha \frac{\mathbf{q}_{\alpha, \perp}}{p_\alpha} = \left( \frac{5}{2} n_\alpha \nabla T_{\alpha} \right) \times \frac{\mathbf{B}}{B^2} + (F_{\alpha_2} + N_{\alpha_2}) \times \frac{\mathbf{B}}{B^2} \]

Perpendicular diffusive current

\[ (F_{\alpha_1} + N_{\alpha_1}) \times \frac{\mathbf{B}}{B^2} = \sum_\beta \left( \frac{1}{\beta n_{\parallel}} + \lambda_{\beta, \parallel} \left( \frac{\nabla_{\perp} p_\beta}{q_\beta n_{\beta} B^2} - \frac{E_\parallel}{B^2} \right) \right) \]

\[ - \left( \frac{1}{\beta n_{\perp}} + \lambda_{\beta, \perp} \right) \frac{\nabla_{\perp} T_\beta}{q_\beta B^2} \]

Perpendicular diffusive heat flux

\[ (F_{\alpha_2} + N_{\alpha_2}) \times \frac{\mathbf{B}}{B^2} = \sum_\beta \left( \frac{1}{\beta n_{\parallel}} + \lambda_{\beta, \parallel} \left( \frac{\nabla_{\perp} p_\beta}{q_\beta n_{\beta} B^2} - \frac{E_\parallel}{B^2} \right) \right) \]

\[ + \left( \frac{1}{\beta n_{\perp}} + \lambda_{\beta, \perp} \right) \frac{\nabla_{\perp} T_\beta}{q_\beta B^2} \]

with \[ \lambda_{\alpha, \parallel} = \frac{\lambda_{\alpha, \parallel}}{\delta_{\alpha, \parallel}} . \]

Continuity equations

Particle Balance

\[ \nabla \cdot q_\alpha n_\alpha u_\alpha = q_\alpha S_\alpha \quad S_\alpha = \text{Particle source} \]

Charge neutrality

\[ \nabla \cdot \sum_\alpha q_\alpha n_\alpha u_\alpha = \nabla \cdot \mathbf{j} = 0 \]

Energy balance

\[ \nabla \left( q_\alpha + \frac{5}{2} p_\alpha u_\alpha \right) - u_\alpha \nabla p_\alpha = Q_\alpha \]

with \[ Q_\alpha = \sum_\beta Q_{\alpha \beta} + Q_{\text{ext.}} \]

\[ N = \text{number of particle species. System of 2N+1 second order differential equations for} \]

\[ p_\alpha, T_\alpha \quad \text{and} \phi \]
Plasma resistivity

\[ \eta_{\alpha \beta} = \frac{1}{2} \left( \eta_{\alpha k} + \eta_{\alpha k}^\alpha \right) \]

Parallel Ohm's law

\[ - \frac{1}{N} \sum_{\alpha} \nabla_{\alpha} P_{\alpha} + E_{\alpha} = \frac{1}{N} \sum_{\alpha \beta} \eta_{\alpha \beta}^\alpha j_{\alpha \beta} - \frac{5}{3} \eta_{12}^\alpha q_{\alpha} q_{\beta} + \frac{T_{\alpha}}{2q_{\alpha}} \]

Parallel resistivity

\[ \eta_{\beta \alpha}^\alpha =: \frac{1}{N} \sum_{\alpha \beta} \eta_{\alpha \beta}^\alpha \eta_{\beta \alpha} \]

\[ E_{\alpha} = \sum_{\alpha} \eta_{\alpha \alpha \alpha} j_{\alpha \alpha} \]

\[ - \frac{2}{5} \frac{1}{N} \sum_{\alpha \beta} \eta_{12}^\alpha q_{\alpha} q_{\beta} + \frac{1}{N} \sum_{\alpha \beta} \nabla_{\alpha} P_{\alpha} \]

\[ = \sum_{\alpha} \lambda_{11}^\alpha \left( \nabla_{\alpha} P_{\alpha} - \frac{E_{\alpha}}{B^2} \right) - \lambda_{12}^\alpha \frac{\nabla_{\alpha} T_{\alpha}}{q_{\alpha} B^2} \]

Plasma current

\[ \nabla_{\alpha} p = j \times B + \sum_{\alpha} N_{\alpha} \mathbf{v}_{\alpha} ; \quad p = \sum_{\alpha} p_{\alpha} \]

\[ j_{\perp} = -\nabla_{\perp} \times \frac{B}{B^2} \]

\[ + \sum_{\alpha} \lambda_{11}^\alpha \left( \nabla_{\alpha} P_{\alpha} - \frac{E_{\alpha}}{B^2} \right) - \lambda_{12}^\alpha \frac{\nabla_{\alpha} T_{\alpha}}{q_{\alpha} B^2} \]

\[ \lambda_{0} = \sum_{\alpha} \lambda_{11}^\alpha < 0 \]

Definition

\[ j_{\alpha \alpha} = q_{\alpha} n_{\alpha} u_{\alpha \alpha} ; \quad J_{\alpha} =: \{ j_{\alpha \alpha} \} \]

\[ w_{\alpha \alpha} = \frac{2}{5} q_{\alpha} \frac{q_{\alpha \beta}}{T_{\alpha}} \quad W_{\alpha \alpha} =: \{ w_{\alpha \alpha} \} \]

Parallel components

\[ \nabla_{\alpha} P_{\alpha} + E_{\alpha} = \sum_{\beta} \eta_{\alpha \beta}^\beta j_{\beta \alpha \beta} - \eta_{12}^\alpha q_{\alpha} q_{\beta} + \frac{T_{\alpha}}{2q_{\alpha}} \]

\[ - \frac{5}{2q_{\alpha}} = \sum_{\beta} \eta_{11}^\beta j_{\beta \alpha \beta} + \eta_{12}^\beta \]

\[ A_{\alpha} =: \left( - \nabla_{\alpha} P_{\alpha} + E_{\alpha} \right) \quad D_{\alpha} =: \left( - \frac{5}{2q_{\alpha}} T_{\alpha} \right) \]

\[ A_{\alpha} = \eta_{11}^\alpha J_{\alpha} - \eta_{12}^\alpha W_{\alpha} \]

\[ D_{\alpha} = - \eta_{12}^\alpha J_{\alpha} + \eta_{22}^\alpha W_{\alpha} \]

Generalized Ohm's Law

\[ W_{\alpha} = \eta_{22}^{-1} \left[ D_{\alpha} + \eta_{21} \eta_{12}^{-1} \right] \]

Conductivity

\[ \sigma = \left[ \eta_{11}^\alpha - \eta_{12}^\alpha \eta_{22}^{-1} \right]^{-1} \]

\[ J_{\alpha} = \sigma \left( A_{\alpha} + \eta_{12}^\alpha D_{\alpha} \right) \]

Total parallel current

\[ j_{\alpha \alpha} = \sum_{\alpha \beta} \sigma_{\alpha \beta} E_{\alpha \beta} - \sum_{\alpha \beta} \sigma_{\alpha \beta} q_{\alpha} q_{\beta} \]
Summary of basic equations

Elimination of vector moments

\[
\begin{pmatrix}
{n_\alpha u_\alpha} \\
{q_\alpha + \frac{5}{2} p_\alpha u_\alpha}
\end{pmatrix}
= M(B, n_\alpha, T_\alpha) \cdot \begin{pmatrix}
\nabla p_\alpha \\
\nabla T_\alpha
\end{pmatrix}
\n
M = 2N + 1 matrix

Equations of continuity

\[
\nabla \cdot M \cdot \begin{pmatrix}
\nabla p_\alpha \\
\nabla T_\alpha
\end{pmatrix}
+ \begin{pmatrix}
-n_\alpha u_\alpha \cdot \nabla p_\alpha \\
0
\end{pmatrix}
= \begin{pmatrix}
S_\alpha \\
0
\end{pmatrix}
\]

Quasi-linear system of second order equations

**Self-consistency of the magnetic field**

General form of the plasma current

\[
j = \sigma(n, T, B) \cdot \nabla \phi + \sum_\alpha A_\alpha(n, T, B) \cdot \nabla p_\alpha + \sum_\alpha B_\alpha(n, T, B) \cdot \nabla T_\alpha
\]

\(\sigma(n, T, B), A_\alpha(n, T, B)\) and \(B_\alpha(n, T, B)\) are continuous matrix functions

Iterative procedure

\(B_v = \text{Vacuum field}\)

\(B = B_v + B_p \quad B_p(x) \in C^{1,7}(\Omega)\)

\(\nabla \times B = MFM\)

Feedback loop and convective solutions

\(\nabla \times B \cdot \nabla \phi \left( \frac{\nabla p_\alpha}{B^2} \right) + \nabla \cdot \sum_\beta D_{n,\beta} \cdot \nabla p_\beta + D_{n,\beta} \cdot \nabla T_\beta \leq S_\alpha\)

Equation of continuity

Electric potential

Approximations

\[
j_\perp = -\frac{\nabla p \times B}{B^2} - \lambda_0 \frac{\nabla \phi}{B^2}
\]

\[
j_\parallel = \sigma_0 \nabla \phi
\]

\(\sigma_0 > 0 ; \lambda_0 < 0\)

Elliptic equation for the electric potential

Boundary conditions:

1) \(\phi = \text{const.} \text{ on } \partial \Omega\)

2) \(\phi = \phi_n(x) \text{ on } \partial \Omega\)

3) \(j_n = 0 \text{ on } \partial \Omega\)

General structure of particle fluxes

\(n_\alpha u_\alpha = n_\alpha \frac{\nabla \phi \times B}{B^2} + \sum_\beta D_{n,\beta} \cdot \nabla p_\beta + D_{n,\beta} \cdot \nabla T_\beta\)

\(D_{n,\beta}, D_{n,\beta}\) are matrices

If \(j \in C^{0,7}(\Omega)\) then \(B_p \in C^{1,7}(\Omega)\)

Self-consistent solution : fixed point of the map

\(B_p \Rightarrow B_p\)
One fluid approximation:

\[ \nabla \rho = j \times B + \lambda_0 u \]
\[ \nabla \phi = u \times B - \eta j \]
\[ \nabla \cdot j = 0 \quad ; \quad \nabla \cdot nu = S \]

\[ j = \frac{\lambda_0}{B^2} \nabla \phi - \sigma \nabla \mu \phi - \frac{\nabla \rho \times B}{B^2} \]

Diamagnetic current

\[ u = - \frac{\eta}{B^2} \nabla \rho \cdot \frac{1}{\lambda_0} \nabla \rho - \frac{\nabla \phi \times B}{B^2} \]

Diffusive velocity

Convective velocity

\[ \nabla \cdot \left( \lambda_0 \nabla \mu \rho - \frac{\eta}{B^2} \nabla \rho \right) = \left( \nabla \phi \times B \right) \cdot \nabla \left( \frac{\rho}{B^2} \right) + S \]

\[ \nabla \cdot \left( \sigma_0 \nabla \mu \phi - \lambda_0 \frac{\nabla \mu \phi}{B^2} \right) = \left( \nabla \phi \times B \right) \cdot \nabla \left( \frac{1}{B^2} \right) \]

Conclusions:

- The multi-fluid model of a plasma with Coulomb interaction and plasma-neutral interaction leads to a system of second order differential equations

- Boundary conditions on the wall and target plates can be imposed

- The model applies to magnetic fields with islands and stochastic regions. The existence of closed magnetic surfaces is not required

- Multiple solutions of the non-linear equations are likely to exist. There exists a strong similarity to the convection in a thermal layer.

- These convective solutions enhance the radial transport processes and will lead to a broadening of the scrape-off layer.

Further investigation:

Role of viscosity and inertial terms
Stability of the stationary solution
Formulation of the boundary conditions
Numerical procedure
Theory of the Langmuir Sheath
R. Chodura

A plasma in contact along magnetic field lines with a material wall develops an electrostatic sheath which reflects electrons and accelerates ions. Electron and ion velocity distributions in the sheath are described together with their consequences on the overall sheath potential. The sheath in an oblique magnetic field shows a spatial double structure at the ion gyro and Debye length scales. For almost wall parallel incidence of the magnetic field below an angle of about 1° the electric field in the two parts of the sheath has opposite sign, i.e. the sheath becomes a double sheath. Finally, the implications of the sheath theory on the formulation of boundary conditions for an upstream fluid plasma are discussed.

Contents
Function of the Langmuir sheath
Particle kinetics in the sheath
Sheath potential, sheath characteristic
Sheath structure
Boundary conditions for a fluid plasma from sheath theory

1. Function of the Sheath

\begin{align*}
\Gamma_e^+ & \quad \Gamma_e^- \\
\Gamma_i^+ & \quad \Gamma_i^- \\
\text{Plasma} & \quad n = n_e = Zn_i \\
& \quad \Gamma_e^\pm \propto n_e \left(\frac{T}{m_e}\right)^{1/2} \\
& \quad \Gamma_i^\pm \propto n_i \left(\frac{T}{m_i}\right)^{1/2}
\end{align*}

Sources
Sheath

Plasma without magnetic field or magnetic field \(\parallel E\)

\begin{align*}
\text{Sources} & \quad \Gamma_e^+ \\
\text{Plasma} & \quad \Gamma_e^- \\
\text{without magnetic field or magnetic field} \parallel E & \quad \Gamma_i^+ \\
& \quad \Gamma_i^-
\end{align*}

absorbing wall

\begin{align*}
\Gamma_e^+ & \quad \Gamma_e^- \\
\Gamma_i^+ & \quad \Gamma_i^-
\end{align*}

ideal reflecting wall

\begin{align*}
\Gamma_e^+ & \quad \Gamma_e^- \\
\Gamma_i^+ & \quad \Gamma_i^-
\end{align*}

absorbing wall

\begin{align*}
\Gamma_e^+ & \quad \Gamma_e^- \\
\Gamma_i^+ & \quad \Gamma_i^-
\end{align*}

B

\begin{align*}
\Gamma_e^+ & \quad \Gamma_i^- \\
\Gamma_i^+ & \quad \Gamma_i^-
\end{align*}

absorbing wall
2. Particle Kinetics in the Sheath

Vlasov equations for electrons and ions
Poisson equation for potential $\phi$

$$\omega_{ce} >> \omega_{pe}$$

Sheath Characteristic

$$I = I_i - I_e$$

$$e^{\Delta\phi/T_{es}} = \frac{1}{\sqrt{2\pi}} \frac{1}{I_i - I_e} V_{es}$$

$$I = I_i (1 - \frac{1}{\sqrt{2\pi}} \frac{V_{es}}{V_e} e^{-e\Delta\phi/T_{es}})$$

$$I_i V_{es} = Ze_{ei} V_e V_{es} = e_{es} V_{es}$$

$$I = I_i - \frac{1}{\sqrt{2\pi}} e_{es} V_{es} e^{-e\Delta\phi/T_{es}}$$

Sheath Potential

$$\Delta\phi = \phi_i - \phi_w$$

3. Sheath Potential

$$\phi = \phi_i$$

$$\Delta\phi = \phi_i - \phi_w$$

4. Sheath Structure

$$\phi = \phi_w$$

magnetic Debye

Sheath Sheath

Quasineutrality at the sheath edge:

$$n_{es} = n_e(\phi_e) = Z n_{ei} = Z \Gamma_i / V_{es}$$

$$\Delta\phi = \left( \frac{2e(\phi_i - \phi_w)}{V_{es}} \right) e^{(\phi_i - \phi_w)/T_{es}} \frac{\Gamma_i}{V_{es}}$$

Bohm condition for exponential change of potential at the sheath edge:

$$V_{es}^2 \leq (3T_{ei} + T_{es})/m_i$$
a.) Magnetic Sheath

Thickness $\lambda_m$:

$$E - \Delta \phi / \lambda_m$$
$$e \Delta \phi - T_{es}$$

$$\lambda_m = \frac{E_{es}}{B \omega_{ci}} \sin \psi$$

$$\rightarrow \lambda_m = \frac{T_{es}}{m_e \omega_{ci}^2} \sin^2 \psi$$

$T_{es} = 10eV$, $B = 2T$, $H^+$, $\sin \psi = 1 \rightarrow \lambda_m = 1.10^{-2}cm$

If $\lambda_m > \lambda_D$.

$\rightarrow$ magnetic sheath is quasineutral, $Z_{in} = n_e$

b.) Debye Sheath

Thickness $\lambda_D$:

The Debye sheath is non-neutral, $Z_{in} = n_e$.

$V_{ix} - V_{is}$.

If $r_e = e \omega_e / \omega_{ci} << \lambda_D$, then $V_{es} - \nu_{es} \cos \psi$

For $Z_{in} V_{ix} = n_e V_{es}$

$$Z_{in} / n_e = \frac{V_{es}}{V_{is}} \cos \psi$$

Critical angle $\psi_{cr}$: The Debye sheath is charged positive for $\psi > \psi_{cr}$ and negative for $\psi < \psi_{cr}$, where

$$\cos \psi_{cr} = \frac{V_{is}}{V_{es}}.$$ 

For $H^+$ ions and $T_{is} = T_{es}$: $\alpha_{cr} = 90^\circ - \psi_{cr} - 1^\circ$

5. Boundary Conditions for Fluid Plasma from Sheath Theory

Critical Angle $\psi_{cr}$

$$\cos \psi_{cr} = \frac{V_{is}}{V_{es}}$$

$\nu_s = (T_s/m)^{1/2}$

$magnetic sheath$ $Debye sheath$

$\psi < \psi_{cr}$ $\psi > \psi_{cr}$

Potential $\phi_f = \phi_x = \phi_w + \Delta \phi$

Ion flow velocity $V_f = V_x = (3T_{is} + T_{es}) / m_i$

Electron energy flux

$$Q_{ef} = \frac{\gamma_e}{\gamma_e - 1} T_{ef} + q_{ef} = Q_{es} = (2T_{es} + e\Delta \phi) T_{ef}$$

$\rightarrow$ electron heat flux $q_{ef} = (2 + e\Delta \phi / T_{ef} - \frac{\gamma_e}{\gamma_e - 1}) T_{ef} T_{ef}$

No conditions on ion viscosity and ion heat flux
**Summary**

With the exception of narrow \( r \)-ranges close to 1/3, the edge topology of W7-AS is influenced by "natural" islands. The present limiter arrangement allows both, limiter- or separatrix-dominated operation (\( r \geq 1/2 \)). Divertor operation should also be possible if adequate target plates will be installed. An arrangement similar to the W7-X concept ("helical divertor") is suggested.

W7-AS (and stellarators in general) can be operated at very high edge plasma densities without the danger of disruptive instabilities. A limit is determined only by an off-balance of heating power and radiative (?) losses. This is an important prerequisite for the realization of a divertor concept.

Radial decay lengths of plasma parameters in the SOL are very similar to those observed in tokamaks. A first particle transport analysis indicates a \( 1/n_R B \)-scaling of the diffusion coefficient. Nevertheless, a larger database and a more sophisticated model considering the 3D edge topology are required for verification.

Up to now, best plasma performance was achieved with boronized walls and bulk boronized graphite limiters. The positive effects of the latter in comparison with the earlier used TiC-coated limiters are mainly due to the elimination of Ti from the plasma. There is no indication for an efficient in-situ wall boronization by sputtering from the limiters.

The improvements by wall coating restrict more or less to small rotational transforms (limiter-dominated operation). For separatrix operation, coatings have short-term effects only. Uncontrolled, localized plasma outflow to the walls and unprotected installations quickly erode the coatings in this case. This effect underlines the importance of a future target plate concept as was outlined above.

**Device parameters:**

- \( R = 200 \text{ cm}, \ a \leq 18 \text{ cm}, \ B_t \leq 2.5 \text{ T}, \ 0.25 \leq \varepsilon \leq 0.7 \)
- nonplanar, modular field coils, \( m = 5 \) periods, low shear

**Heating:**

- ECRF: 0.8 MW (70 GHz, 3s)
- NBI: 1.5 MW (40 keV, 2s)
- ECRF: 0.1 MW (140 GHz, 0.1s)
- ICRH: 1 MW (exp. antenna)

**Standard operational scenario:**

Currentless ECRH or NBI with ECRH start-up

**Plasma parameters:**

- \( \left\langle n_e \right\rangle \leq 3 \times 10^{20} \text{ m}^{-3} \)
- \( T_e(0) \leq 3 \text{ keV} \)
- \( T_i(0) \leq 0.7 \text{ keV} \)
- \( \varepsilon_{\text{diss}} \leq 33 \text{ kJ} \)
- \( <B> \leq 1.1\% \)
- \( \tau_e \leq 40 \text{ ms} \)
Characteristics of the W7-AS Edge Topology

Vacuum magnetic surfaces for \( \ell = 5/9 \) and limiters

- Two vertically movable main limiters segmented, TiC-coated graphite tiles until July '91, bulk-boronized graphite (20% boron) at present,
- Depending on \( \ell \) and the limiter position, plasma edge can be determined by limiters or a separatrix.

3D Plasma Edge Topology in W7-AS

2D resolving Langmuir probe array: poloidal contour of constant ion saturation currents for low-\( \beta \) ECRF heated discharges, \( \ell = 5/9 \)

Low-shear \( \rightarrow \) low order rational islands can be excluded from the plasma core by properly adjusting \( \ell \).
- But favours boundary island formation at the rationals \( \ell = 5/m \) due to intrinsic magnetic field harmonics of the modular coil set, "natural" islands.

- With the exception of a small \( \ell \) range close to 1/3 where nested magnetic surfaces extend to large radii, natural islands govern the boundary topology.
- Their size increases with decreasing \( m \)-number (increasing \( \ell \)-value), and the respective separatrix significantly reduces the cross section of undisturbed magnetic surfaces.

- At maximum limiter aperture:
  - \( \ell \) close to 1/3 \( \Rightarrow \) "classical" limiter configuration,
  - Increasing \( \ell \) \( \Rightarrow \) "hybrid" configuration, limiters become increasingly decoupled from the plasma.
  - \( \ell \geq 1/2 \): separatrix configuration

The boundary topology strongly depends on the choice of the rotational transform \( \ell \).

For sufficiently low \( \beta \) the vacuum field contours are well recovered by probe data.
**Topological Effects on the Limiter Efficiency**

Limiter thermal load from calorimetry versus $\rho a$

ECRH 310 kW, $n_e(0) = 3 \times 10^{19}$ m$^{-3}$

- The $\rho$-dependency of the limiter thermal load is strongly modulated by island effects

**Parameter range at the LCMS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ECRH</th>
<th>NBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron density $n_e$ (a/m$^3$)</td>
<td>$&lt; 1.5 \times 10^{19}$</td>
<td>$&lt; 2 \times 10^{20}$</td>
</tr>
<tr>
<td>electron temperature $T_e$ (a/eV)</td>
<td>$&lt; 150$, typically 50-120</td>
<td>$&lt; 150$, typically 40-100</td>
</tr>
<tr>
<td>collisionality $v_c(a)$</td>
<td>$&lt; 2$</td>
<td>$&lt; 30$</td>
</tr>
<tr>
<td>density decay length $\lambda_n$/cm</td>
<td>$&lt; 2 - 3$</td>
<td>$&lt; 1 - 3$</td>
</tr>
<tr>
<td>temperature decay length $\lambda_T$/cm</td>
<td>$&lt; 2 - 5$</td>
<td>$&lt; 2 - 5$</td>
</tr>
</tbody>
</table>

**Edge density versus volume averaged density**

- Potential of very high edge density operation

**Topological Effects on Radiation**

Impurity line intensities versus $\rho$

<table>
<thead>
<tr>
<th>1/3</th>
<th>5/12</th>
<th>5/11</th>
<th>5/10</th>
<th>5/9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$mW/(cm^2 \cdot sr)$</td>
<td>$Fe$ Xv, 335X</td>
<td>0.4</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>$mW/(cm^2 \cdot sr)$</td>
<td>$Ti$ Xv, 480X</td>
<td>0.4</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

- Radiative losses increase towards separatrix operation

**Electron temperatures at the LCMS ($\rho < 0.4$) from Langmuir probes (module 2, port 1a) versus $(P \cdot Prad)/n_e$**

- Radial decay lengths from Langmuir probes (module 2, port 1a) versus $n_e$ at the LCMS, $\rho < 0.4$
- limiter-dominated cases only ($\tau < 0.4$),
- non-axisymmetric, strongly inhomogeneous connection lengths due to local limiters, 3D
- data from fast reciprocating Langmuir triple probes,
- first simple $\lambda_p t_p$ approach with parallel averaging along a distinct flux bundle:

\[
\frac{1}{n_e} \text{ scaling is indicated, comparison with half field experiments (1.25 T) indicate an } 1/B \text{ scaling.}
\]

**Impurity Control in W7-AS**

Comparison of impurity concentrations for various limiter/wall conditions

- Modelling of impurity concentrations from line radiation (VUV and soft-X) by the IONEO radiation and transport code,
- simulation of soft-X emission with various filters and comparison to experimental values

for ECRF heated "standard" discharges:

\[
(350 \text{ kW}, n_e(0) = 3 \times 10^{19} \text{ m}^{-3}, \phi = 0.347)
\]

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>O</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiC/SS</td>
<td>3 - 6%</td>
<td>1.5 - 3%</td>
<td>0.4%</td>
<td>0.02 - 0.04%</td>
</tr>
<tr>
<td>TiC/bor</td>
<td>1 - 2%</td>
<td>0.3 - 0.6%</td>
<td>0.7%</td>
<td>0.01 - 0.02%</td>
</tr>
<tr>
<td>BC/SS</td>
<td>2 - 7%</td>
<td>0.6 - 2%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BC/bor</td>
<td>3 - 7%</td>
<td>0.1 - 0.3%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Impurity Control in W7-AS**

wall conditioning

- carbonization: glow discharges in 70% He + 30% CH4, coating thickness = 1000 Å
- boronization: glow discharges in 90% He + 10% B2H6, coating thickness 500 - 800 Å
- routinely He glow discharges

conditioning of bulk-boronized limiters (with respect to density control):

- vacuum baking at 1000°C for some hours before installation,
- after installation baking at = 1200°C for some days together with the torus,
- some hundred low-density ECRF heated plasma discharges in turn with He glow discharges.

Plasma impurities are compared for:

- TIC limiters / SS wall,
- TIC limiters / carbonized wall
- TIC limiters / boronized wall
- bulk-boronized limiters / SS wall
- bulk-boronized limiters / boronized wall

**Impurity Control in W7-AS**

Impurity species contributions to soft-X radiation and $Z_{eff}$ for different limiter/wall conditions (double columns indicate error limits):

- Best conditions with bulk-boronized limiters / boronized walls.
Impurity Control in W7-AS

Initial bulk-boronized limiter operation with SS walls:
- currentless ECRF 350 kW, $n_{e}(0) = 3 \times 10^{19}$ m$^{-3}$
- limiter-dominated, $\varepsilon = 0.347$
- maximum limiter surface temperature $= 600 - 700^\circ$C,
- maximum power on limiters $= 200 - 300$ W cm$^{-2}$
- Ti radiation fully eliminated,
- in the course of 600 discharges no evidence for any
  significant impact of sputter boronization on the
  oxygen content (from spectroscopy)

from deposition probe analysis: 3% B with respect to C
were deposited, only close to the limiters this value
reached up to 20%.

from spectroscopy: strongly peaked BI emission from the
limiter surface, no detectable B line emission in the VUV
range.
- drastic improvement after gaseous boronization.
- In contrast to high-temperature boron evaporation,
solid target sputter boronization is too ineffective
in comparison to gaseous boronization.

Divertor Potential of W7-AS

We found best energy confinement at $\varepsilon = 1/3$, limiter-
operation, but
we expect much better confinement at higher rotational
transforms.

\[ \text{Reduction of impurity release at higher } \varepsilon \text{-values!} \]

Future solutions:
- suppression of the S/m disturbances by compensating
  loops,
- or utilization of the divertor potential of the disturbed
  boundary configuration.
- We will do both in order to increase the flexibility of the
  machine.

Divertor operation is favored by
- sufficiently long connection lengths,
- the stellarator-specific potential of very high edge density
  operation (not limited by MHD stability criteria).
- predominant localization of the plasma outflow at the
  "helical edge", nearly independent of $\varepsilon$. 

Improved Plasma Parameter Range in W7-AS

Main effects of boronized wall and limiters
- radiative density limit for low-power ECRH is increased
  until close to ECRH cut-off,
- radiative density limit for full power NBI is increased to
  about $3 \times 10^{20}$ m$^{-3}$.

![Plasma Parameters](image)
ON THE HELICAL STRIPE
IN W7-AS

F. Rau

1) EPS Amsterdam 1990
2) New Results

In EPS Amsterdam 1990, Vol. II, 517 we mainly concentrate on the high-iota case of W 7-AS, and investigate the edge structure of the vacuum field by field line tracing and guiding center orbits in a Monte Carlo code with pitch angle scattering.

This paper reviews some essentials of our contribution to EPS 1990, and complements its results for iota = 0.34 at the edge by varying the mean free path. For this limiter dominated case, deposition patterns of C and Fe impurities were seen at the torus wall, see papers by P. Grigull and by D. Hildebrandt at the PSI conference, Monterey, 1992.

The plasma outside the limiter region is modelled by removing all in-vessel objects of W 7-AS, except the probe arrays and the diagnostic stripe at the torus wall.

There is good agreement between the Monte Carlo code result and the deposition pattern, with respect to the asymmetry seen.
Vacuum Field of W VII-AS at $\varphi = 0$ with torus wall, Probe Limiter inserted (a), guiding center orbits at zero, 1/4 and 1/2 of the field period (b to d), intersection pattern at outside wall for $\varphi = 0$ (e) and at bottom limiter, for $e = 0.53$, $Z_L = 81.5$ cm, (f), and for $e = 0.34$, $Z_L = 21.5$ cm, (g).
The helical stripe at $\iota = 0.53$ can be intensified by removing the in-vessel objects from the computation. The majority of intersections is at the outboard side.
Intersection of guiding center orbits in W7-AS at iota = 0.34.

Outward limiter position $Z_l = 31.5$ cm; in-vessel objects as in 1990.

W7-AS vacuum field at an axis value of the rotational transform $iota_0 = 0.35$

for the three typical toroidal planes, $\phi = 0, 18$ and $36^\circ$ without in-vessel objects.

The configuration edge is characterized by $iota_0 = 10/29$ at a minor radius of 23 cm.
\[ L^* = \frac{\lambda \iota}{\pi R} = 0.1 \implies \text{mean free path } \lambda = 2 \text{ m} \]

\[ L^* = 0.01 \implies \text{broader pattern of intersections.} \]

Top views on the W7-AS torus, modified by torus rings near \( \phi = 36^\circ \) and in-vessel objects as used in the present investigation of plasma-wall interaction in the limiter shadow. Top part: three probe limiters and torus stripe, \( L^* = 0.1 \); bottom part: torus stripe alone, \( L^* = 0.01 \).

In the latter case, the "helical stripe" at the W7-AS torus wall extends completely around the vessel wall, with varying intensity and width, and some intersections near the inboard equator.
Radially outward view on the torus wall with "helical stripe" modelled by the intersection of guiding center orbits, as described in [9], for protons at a free path of about 20 cm and \( t = 0.34 \) at the configuration edge (upper part), and distribution of deposited impurities at the target (lower part).

There is good agreement between the Monte Carlo code result and the experiment, with respect to the asymmetry seen.
Fluctuation diagnostics

- **Langmuir probe arrays**
  - Fluct. of saturation current \( \rightarrow \tilde{I}_e \) if \( \tilde{T}_e = 0 \)
  - Fluct. of floating potential \( \rightarrow \tilde{\Phi}_p \) if \( \tilde{T}_e = 0 \)
  - Assumption \( \tilde{T}_e = 0 \) probably poor
  - Measurement of \( \tilde{T}_e \) with fast sweep or multiple-probes

- **H_r-array**
  - Plasma surface imaged on optical fibre array
  - Photomultiplier detectors
  - Gas puff to enhance light emission
  - Signal proportional to radial integral of \( \tilde{n}_e \)

Data evaluation

- Digitizing 16 channels with 1 MHz for \( \leq 1 \) s
- Evaluation of packets with 20000 samples/ch
- Raw data plots
- Amplitude distributions

Spectra

- Fourier Transform (FFT)
- Frequency power spectrum \( <F(\omega)F^*(\omega)> \)
- Frequency cross-power spectrum \( <F_1(\omega)F_2^*(\omega)> \)
- Wavenumber power spectrum \( <F(k)F^*(k)> \)
- k-\omega spectrum \( <F(k,\omega)F(k,\omega)> \)
- Transport spectrum \( \text{Re}<F_1(k,\omega)F_2^*(k,\omega)> \)
- Bi-spectrum \( <F(\omega_1)F(\omega_2)F(\omega_1+\omega_2)> \)

Correlation functions

- S: Signal at position \( x \) and time \( t \)
- Space-time correlation \( <S(t+x,t+d)S(t,x)> \)
- Space-time cross-correlation \( <S_1(t+x,t+d)S_2(t,x)> \)
Fluctuations in ASDEX and W7-AS

Plasma parameters at edge

W7-AS:
- $200 \text{ kW ECRH}$
- $B_0 = 1.28 \text{ T}$
- $n_{e0} = 2.0 \cdot 10^{19} \text{ m}^{-3}$

ASDEX:
- $320 \text{ kA Ohmic}$
- $B_0 = 2.17 \text{ T}$
- $n_{e0} = 2.9 \cdot 10^{19} \text{ m}^{-3}$

Similar $n_e$ and $T_e$ profiles at edge

- $\tilde{n}_e/n_e$, $e\Phi/kT_e \leq 50\%$
- Flute-like structure (ASDEX)
  - Correlation lengths $\perp \vec{B} \approx 1 \text{ cm}$
  - $\parallel \vec{B} > 10 \text{ m}$
- Propagation velocities around $1000 \text{ m/s}$
  - Dependent on plasma parameters (ASDEX)
  - Much higher in W7-AS (low $B$) than in ASDEX (standard)

- Velocity shear layer
  - $E\times B$-drift important component of propagation velocity
  - Potential drop at limiter edge or separatrix causes velocity shear

- Correlation between density and potential
  - Maximum positive and negative correlation between $n_e$ and $\Phi$ at a distance of about $1 \text{ cm}$
  - Eddies around potential maxima or minima explain this finding
  - Density fluctuations due to circular convection in a density gradient

Hα Raw Signals
Radial profiles of floating potential

- Dip of $\Phi_{fl}$ at the effective limiter radius in W7-AS and at the separatrix in ASDEX.
- Since $\Phi_{pl} = \Phi_{fl} + 3kT_e$ a reversal in the electric field occurs at this position.

Velocity shear

- Electric field reversal produces a change in direction of the poloidal $E \times B$ velocity and of the propagation velocity from the ion diamagnetic drift direction to the electron diamagnetic drift direction.
Components of a theoretical model for the edge

- Region of open field lines
  - Different mode spectrum
  - Magnetic shear less important
  - Boundary condition for $\Phi$ at the ends
  - End losses

- 2d-structure $\perp \vec{B}$
  - Strong gradients $\parallel \vec{B}$ are localized at or near the target plates or limiters
  - Convective motion $\perp \vec{B}$, mainly due to ExB-drift
  - Parallel current due to perpendicular $\nabla p$

- Sheath physics important
  - Sheath potential proportional to $T_e$
  - Sheath resistance with $j_{||}$ causes potential drop
  - Heat conductivity of sheath (depends on $j_{||}$)

- Slow motion
  - Inertial forces probably negligible

- Solution better described as superposition of eddies than of waves

Conclusions

- Properties of edge plasma similar in tokamaks and stellarators
  - Similar transport mechanism
  - Quantitative differences possible due to different parameters like power density etc.

- Diffusion coefficient locally different
Design of the Diverter Plates for ASDEX Upgrade and Comparison with Other Large Tokamaks

Seminar paper presented at the May 1992 Ringberg workshop on W 7-X

by H. Venickel

Contents:
- Introduction
- ASDEX-Upgrade Diverter Plates: Design criteria
  - Material selection
  - Cooling
  - Cost
- Some remarks on other large tokamaks
- General conclusions:
  - Material selection
  - ‘Bake-out’ temperature
  - Concept for cooling (neutrons)

Introduction

The design of these in-vessel components that have to cope with large power input is a demanding engineering problem for large tokamaks and will also become one for large stellarators.

Our experience in ASDEX-Upgrade (AUG) so far is limited, since we just got the machine operational. The energy input to the plasma is only around 0.5 MJ per discharge (“shot”), while 50 to 100 MJ are planned for the future. The number of successful shots is only around 250. Therefore, we talk deals primarily with the design and some general observations.

The diverter plates (DP) of AUG

Original design criteria:
- Diverter configuration: Reactor relevant “open” diverter
- Modes of operation: Single null (SN), double null (DN), limiter (L), and long pulse.
- Pulse duration: 5 to 10 s or up to 120 s at reduced parameters.
- Heating power: 12 MW (ICRH and NBI).
- Current reversal without field reversal should be possible.
- Assumptions for calculating power deposition at the DP:
  - The DP and the power deposition are toroidally symmetric, 50% of the heating power are radiated, the rest is deposited in 2 DP (inner and outer in SN, upper and lower outer in DN). Power density in the outer equatorial plane falls off exponentially with an e-folding length of 1 cm. This distribution is proposed in the DP along flux lines.
  - The maximum mechanical load is the eddy current force during disruptions. Therefore all large parts are subdivided in order to avoid large area eddy current loops. (The even larger forces possibly caused by “flux-currents” were not known at that time.)
- Thermal expansion has to be allowed for.
- The DP are at wall potential

Material:

Construction material is stainless steel, the material facing the plasma should be graphite for the well-known reasons. A fine grain high purity isotropic type was chosen. Beryllium was to be avoided because of the inconvenience for in-vessel work.

Cooling alternatives:

1. Inertial cooling. The deposited energy is removed between shots. This design is not applicable for pulse length above 20 s or so.

The thickness d of the plate should be larger or equal to sqrt(D*), where D = lambda rho c, with lambda = heat conduction, rho = density, c = specific heat, resp.

1.1 Cooling between shots by radiation only. This is the simplest design but the temperature before the next shot in steady state may become unsatisfactory.

1.2 Cooling between shots by conduction to a (water)-cooled baseplate. Here the problem is that cooling tubes have to penetrate the vessel.

2. Active cooling. The deposited power is removed. The temperature distribution becomes stationary after some “warm-up time”. The distance from the surface to the cooling medium determines the warm-up time. For reasonable graphite thickness nothing is gained for pulse lengths below a few seconds.

For AUG we chose version 1.2 but also developed version 2 for laser use during long pulse operation.

For the diverter tile which is intercepted by the separatrix we estimate a maximum surface temperature rise of 1000 K. The average temperature rise of the same tile is 170 K.

The temperature before the next shot for a 5x600s cycle is calculated for a given emissivity E as follows:

<table>
<thead>
<tr>
<th>Cooling version</th>
<th>with radiation</th>
<th>dnom, but E = 0.8</th>
<th>To + 330</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>from both sides</td>
<td>dnom, but I side only radiates, E = 1</td>
<td>To + 365</td>
</tr>
<tr>
<td></td>
<td></td>
<td>dnom, E = 0.8</td>
<td>To + 340</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cooling version 1.2 with cooling time constant of 250 s</td>
<td>To + 380</td>
</tr>
</tbody>
</table>

(To denotes the coolant inlet temperature.)

Costs:

In version 1.2 the mechanical parts are about a factor 3 more expensive than the graphite tiles.

The relative cost for version 3 is at least another factor 3 higher. If version 1.2 is to be equipped with fiber reinforced tiles, e.g. Aerolon 05, the cost of the tiles would be about a factor 4 higher than the presently used type.

Some remarks on other large tokamaks

JET: The original limiters were designed for 10 MW/m² and 20 s. They consisted of a water cooled Cu structure with hypervapotron cooling. On the plasma side the limiter was plated by 1.5 mm Ni sheet. The design was however, never actually used.

The present first wall consists of graphite tiles on the wall and in the X-point area, and belt limiters with radiation cooled Be-tiles. The tiles radiate to water cooled fins. The radiating surface is considerably larger than the surface seen by the plasma.

D III-D: The diverter plates are graphite tiles bolted to the cooled vessel wall.

TFTR: Uses an inner bumper limiter that consists of graphite tiles bolted to a water cooled baseplate.

ASDEX after “hardening”: Diverter plates were a watercooled copper structure which was designed for 60 MJ per shot. In reality 2 to 3 MJ were deposited in the diverter during the best shots.

TORE-S: At present the first wall is actively cooled by water cooled steel cushions and graphite tiles that are brazed to copper. Of about 9000 tiles only about 180 cracked off during the first 3 years. In addition there are actively cooled pump limiters and plates for the ergodic divertors. Further there is a radiation cooled pump limiter made of fiber reinforced graphite.

Conclusions for Wendelstein 7-X

The material for diverter plates and similar in-vessel components will most probably be graphite. At critical positions it should be fiber reinforced and possibly boron doped, if the reduced heat conductivity is acceptable.

Cooling is questionable because of its short life time. Life time is limited by erosion on heavily loaded regions and by deposition otherwise. Cooling by Sc or PyC for reduction of water absorption could be worth while investigating. Probably, however, in-situ boronization will be used.

Cooling of the graphite: Mechanical contact to (water)-cooled baseplates is recommended, possibly with interlayers to improve heat transfer. Among others changes of material and/or shape are then possible with reasonable cost.

Active cooling in the final stage of the experiment is considered necessary, one should design for sufficient supply of cooling fluid from the beginning, and should begin with R & D soon. In my opinion there exists so far no sufficiently proven and tested design.

Because of the water adsorption on graphite — which was not discussed in this paper — bake-out temperature of larger than 350 °C is advisable.

The influence of neutron radiation damage on the thermo-physical properties of materials can be neglected in W 7-X.
Power distribution on the Lower Outer DP

DP with tiles clamped to a cooled baseplate
Fig. 1. Concept of the active cooling of graphite.

*Divertor plate for ASDEX*

- graphite FE 152 brazed on Mo (MoCuTi-brass)

*E-beam test (see Bohdansky et al.)*


\[
\text{e-beam test (see Bohdansky et al.:)}
\]

- \(n \approx 300 \text{ cycles}\)
- \(F = 0.7 \text{ kW/m}^2\)
- \(\Delta t = 20\) s
- \(a = 30 \text{ mm} \times 80 \text{ mm}\)
- High cooling efficiency. 10 MW/m^2 can be handled in steady state.

- At 20 MW/m^2 the surface erodes due to sublimation but the brazing is not affected.

- The brazing can withstand thermal cycling (tested for 3000 cycles at 7 MW/m^2).

- For more details see /4,5/.

Disadvantage: Exchange for other surface contour and/or material is costly and time consuming.

4 units will be installed right from the beginning (1 unit = 1/16 of a DP).
Heat Shield

- It protects the inner portion of the vacuum vessel and bellows from excessive heating due to radiation from the plasma and from damage by runaways and/or accidental plasma contact.
- It serves as toroidal bumper limiter during plasma build-up or for limiter discharges in general.
- It serves as dump for NI-beam shine through.

Design: Graphite tiles are pressed on a copper ring that is braced to a steel plate which in turn is welded to the cooling tube. The cooling tubes are the load carrying structure.

Time constant for cooling: 500 s.

Temperatures:

<table>
<thead>
<tr>
<th>$\bar{P}_{MWM^{-2}}$</th>
<th>$\Delta T_s$</th>
<th>$\Delta T$</th>
<th>$T_B$</th>
<th>$t$(pulse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>160</td>
<td>90</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>3.8</td>
<td>675</td>
<td>340</td>
<td>145</td>
<td>3</td>
</tr>
</tbody>
</table>
CONCEPTUAL DESIGN AND CRITICAL ISSUES OF THE ITER DIVERTOR

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ABSTRACT

The Divertor in a tokamak machine is the heaviest loaded large component, imposing a difficult engineering task in achieving adequate nominal life time, reliability, and maintenance capability. The divertor concept for the international thermonuclear experimental reactor (ITER) is briefly described along with the pertaining design requirements. Emphasis is placed on the critical issues, i.e., the high heat load, the expected erosion rate from particle impingement, and the effects of plasma disruptions. Those issues are quantitatively discussed based on the work performed under the auspices of the ITER predesign phase. Other areas of concern, which are not considered to be crucial for the ITER project, but which are expected to become of great importance for a reactor design (including stellarators), are briefly addressed.

Figure 1 CANDIDATE DIVERTOR PLATE

Requirements Design Considerations Issues

Figure 2 CANDIDATE DIVERTOR PLATE

K. W. Kleefeldt
KfK/IRS

Stellarator W7X Workshop
Ringberg, May 21-22, 1992
DESIGN REQUIREMENTS

MAIN DESIGN PARAMETERS FOR ITER DIVERTOR [1]  
(Physics Phase)  
(Technology Phase in Brackets)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak surface heat flux (MW/m²)</td>
<td>15 - 30</td>
</tr>
<tr>
<td>ditto, excl. uncertainties (MW/m²)</td>
<td>≈7</td>
</tr>
<tr>
<td>Number of pulses (full load) (10⁴)</td>
<td>1 (2-5)</td>
</tr>
<tr>
<td>Peak surface temperature (°C)</td>
<td>1000</td>
</tr>
<tr>
<td>Total burn time (h)</td>
<td>400 (≈10⁴)</td>
</tr>
<tr>
<td>Peak neutron damage (steel) (dpa)</td>
<td>0.3 (5-15)</td>
</tr>
<tr>
<td>Incident DT ions (10²⁰/m²s)</td>
<td>4</td>
</tr>
<tr>
<td>Number disruptions (at full load)</td>
<td>500 (200-500)</td>
</tr>
<tr>
<td>Thermal quench time (ms)</td>
<td>0.1-3</td>
</tr>
<tr>
<td>Peak energy deposition (MJ/m²)</td>
<td>10-20</td>
</tr>
<tr>
<td>Run-away electron energy deposition (at ≤ 300 MeV) (MJ/m²)</td>
<td>30</td>
</tr>
</tbody>
</table>

COMMENTS

HEAT FLUX PREDICTION INVOLVES SUBSTANTIAL UNCERTAINTY FACTORS

- Physics Related Uncertainties [2]:
  - Modeling
  - Toroidal Field Ripple
  - MHD-Effects
  - Power Control
  - Loss of Sweeping
  - Inadvertent Single-Null Mode
  
  Total Physics Factor ≈ 4

- Engineering Related Uncertainties:
  - Geometrical Imperfections [3]
  
  Total Engineering Factor ≈ 2 - 3

Note: The high surface heat flux on one hand, and the limited surface temperature in combination with the high DT ion flux (erosion problem), on the other hand, are principal conflicting requirements. Disruptions add to specific design constraints.
Figure 1. NET/ITER DIVERTOR LAYOUT (Bottom Part). Top: Cross section of the divertor plate with heat flux profile, support structure and coolant tubes. Bottom: Perspective view of 1/48th sector of the whole bottom divertor cone. Note that only a small fraction of the divertor surface (shaded zone) sees the high load.

Figure 2. CANDIDATE DIVERTOR PLATE CONCEPTS. The circular water coolant channel with twisted tape is common to all options. The block design (top) is presently the prime option. Flat tiles (center and bottom) are prone to lose thermal contact but promise some chance for in-situ repair of eroded tiles. CFC: Carbon Fiber Composite, TZM: Molybdenum Alloy (Mo-0.5%Ti-0.1%Zr), DS Cu: Dispersion Strengthened Copper, e.g., GildCop Al25. Materials in brackets are optional.
CRITICAL ISSUES

Extreme Heat Flux Requirements

![Graph showing heat flux and temperature relationships](image)

**Figure 3. OVERVIEW OF RECENT DIVERTOR MOCK-UP TESTS.** Each symbol denotes one mock-up experiment with the test parameters as reported in [4] [5] [6] [7]. Mock-ups represented by open symbols survived the test, those with solid symbols failed. (the four staggered circles to the right are small scale sample tests being performed by the author.

**RESULTS**

The design requirements are too high. Experimental results fall short with respect to heat flux, number of cycles, and surface temperature.

**POTENTIAL IMPROVEMENTS:**
- Sweeping
- Improved Materials and Design
- Reduced Uncertainties
- Optimized Scrape-off Layer Parameters (Controlled impurities, gas injection, ergodization, etc.)

Operational Erosion

![Graph showing erosion due to physical sputtering](image)

**Figure 4. NET EROSION RATE DUE TO PHYSICAL SPUTTERING.** Data are taken from [8]. The net erosion rate is the difference of the total erosion yield minus the redeposited amount. Columns for carbon do not include chemical erosion. The small erosion for tungsten (0.07 cm/full power year) may be penalized if sputtering by oxygen impurities is considered.

**RESULTS**

The erosion during normal operation is excessive. Only high-z materials promise tolerable wear.

**POTENTIAL IMPROVEMENTS:**
- Sweeping for C, Be
- In-situ Repair (for Be)
- High-z Material, e.g., W
Disruption Erosion

Figure 5. CALCULATED EROSION CAUSED BY A SINGLE DISRUPTION. The ranges are redrawn from results found in [9] and shall only be indicative. Calculations assume, that one half of the molten metal (Be or W) is swept away. No credit is taken from any vapor shielding effect. Results depend on the assumed thermal quench time (0.1 – 3 ms).

RESULTS

The erosion caused by the conceived number of disruptions is expected to be of the same magnitude as the one from normal operation.

POTENTIAL IMPROVEMENTS:

- Vapor Shielding (Factor 5-10)
- Sweeping (Factor ≈ 2)
- High-z Material, e.g., W
- Reduction of hard Disruptions

High Energy Electrons

Figure 6. THERMAL SPIKES CAUSED BY RUN-AWAY ELECTRONS. Predicted extreme heat deposition from high energy run-away electrons (bottom curve), penetrating down to the CFC/TZM interface at a depth of 10 mm, causes severe temperature rises (top) and thermal stresses in the structure. The upper curves refer to the fast (i.e., 10 ms), the lower curves to the slower (100 ms) heat deposition time scale [10] [11].

PRELIMINARY RESULTS

Run-away Electrons jeopardize the divertor structural integrity

POTENTIAL IMPROVEMENTS:

- High-z Inserts

Results are preliminary with respect to the parameters assumed:

- Electron Energy (100 MeV)
- Energy Density (24 MJ/m²)
- Incidence Angle (1 Grad)
- Fraction of Electrons being reflected (57 %)
- Location of Heat Deposition
- Influence of Magnetic field
### OTHER AREAS OF CONCERN

- Sensitivity against off-normal conditions (LOFA, LOCA)
  
  (e.g., Shut-off within 5 s without failure)

- Stability against Disruption Forces
  
  (Equivalent pressure from EM forces up to 2 bar)

- Effects of Coolant Release
  
  (Chemical reactions in case of water)

- Afterheat Removal
  
  (e.g., Temperature during LOCA < 500°C)

- Tritium Inventory
  
  (Should be < 200 g-T in divertor structure)

- Conditioning
  
  (e.g., for C: 350 °C for baking after Replacement, 250 °C for conditioning)

- Replacement, Handling
  
  (Coolant piping 100 - 120 mm diameter)

- Instrumentation and Control, Surveillance

- Material Properties at high Doses

### CONCLUSIONS

**ITER DIVERTOR**

- The design requirements in terms of heat flux are too ambitious at present uncertainties with view to the reliability of a large component.

- The predicted erosion during normal operation is excessive in machines with high load factors. Only high-z materials promise tolerable wear.

- Disruptions cause additional life limiting erosion rates as well as runaway electrons and EM forces, which can lead to spontaneous failures.

- The other areas of concern are not considered to be of decisive importance for ITER. They may, however, become crucial for a reactor design.

### References


[7] Akiba et al., Ibid. p. 116


SWEEP COIL SYSTEM AND TARGET PLATES FOR WENDELSTEIN 7-X

J. Kollinger

Sweeping the strike points of the outflowing plasma on the target plates of a divertor is a method to prevent excessive power load on these plates. In Wendelstein 7-X such target plates may be located in those regions where the diversion of field lines is a maximum. When large islands exist in the boundary region, they are especially suited for divertor action. In this case control of island size and the position of O-points and X-points is desirable. This can be achieved by superposing a magnetic field with Fourier components \( B_{m,n} \) corresponding to the rational value of \( \epsilon = m/n \).

In Wendelstein 7-X such a coil system is considered, consisting of two current loops (sweep coils) in each field period inside the vacuum tube. These saddle-shaped coils with dimensions of about 0.3 by 1.5 m follow the helical edge of the magnetic surfaces and may be located behind the target plates. Currents in the sweep coils allow to control the size and phase of the islands and also to introduce an ergodic region at the plasma boundary. Currents of 17 kA at a toroidal field strength of \( B_0 = 3 \text{ T} \) in W 7-X enlarge the existing islands and destroy the closed surfaces outside the islands. Feeding the sweep coils with the same currents in opposite direction causes islands to shrink and to split into 10 smaller ones, corresponding to the next-order rational of \( \epsilon = 10/10 \). Larger currents in this direction cause again a rise of the island size with interchanged locations of the O- and X-points.

An important value for divertor action is the length of a field line (inside the island, near the separatrix) which connects two target plates. In the standard case with the 5/5 island at the edge this connection length is of 10-12 toroidal transits. The sweep coils allow also to vary this connections length due to an associated change of island rotational transform when changing the island size: in the case with the increased islands this length is only about 6 and in the case with the 10 small islands it is about 20 toroidal transits.

Feeding the upper and lower sweeping coils with currents of opposite direction, the island size remains constant and a poloidal shift of the island location is achieved. Reverse currents of 20 kA shifts the X-point about 6 cm poloidally on the target plates. A sweeping effect is introduced when energizing the coils by AC currents. The magnetic field of the sweep coils oscillates the strike points on the target plates because of the transient size and position of the islands. Only relatively small currents are necessary to obtain the desired shift of the strike points because the X-points are part of the equilibrium field and need not be generated by the sweep coils.

So far, the magnetic field of the sweep coils preserves the 5-fold symmetry of basic field. A further application of the sweep coil system is the compensation of symmetry-breaking error fields, e.g. due to small construction inaccuracies of the device. Error field compensation is achieved by an individual choice of current in each sweep coil.

The separatrix and the islands can be used for divertor application by locating the target plates in the domain of the islands. The proposed target plates are suitable for the whole range of \( \epsilon_n = 5/6 \ldots 5/4 \). They are designed, that in the standard case \( \epsilon_n = 5/5 \) the field lines hit the middle part of the plates (e.g. lower target plate between about \( \varphi = -12^\circ \) and \( 9^\circ \)) at an intersection angle of 2-3 degree. The part to one end of the plate (e.g. lower plate \( \varphi \geq 9^\circ \)) is designed suitable to the high \( \epsilon \) case and the part to the other end of the plate (\( \varphi < -12^\circ \)) to the low \( \epsilon \) case. The total length of each plate is about 5 m. It is determined by the intersection angle of the field line and the requirement that all field lines in the SOL hit the plates without forming a leading edge. In each of the 5 field periods two target plates are installed with an average width of 0.5 m resulting a total surface of 25 m².

The intersection patterns on the target plates are obtained by simulating the SOL by field line tracing with perpendicular displacements, e.g. 0.1 cm for \( D = 1 \text{ m}^2/\text{s} \), after each integration length of typically 30 cm. The start points of the field lines are statistically spread on a magnetic surface close to and inside the bounding separatrix.

The intersection pattern on the target plates differ for the various cases examined. The variation of the parameters are:

- Standard case H55V10N
  - variation of \( \epsilon_n \) (0.83, 0.86, 0.89);
  - variation of island size;
  - variation of island position;
  - variation of diffusion coefficient (\( D = 1 \text{ m}^2/\text{s} \) and 0.2 \( \text{m}^2/\text{s} \)).
- High \( \epsilon \) case with variation of island position
- Low \( \epsilon \) case with variation of island size
- Configuration PKM7006 with variation of the vertical position of the target plates.

The intersection patterns on the target plates are strongly influenced by the island structure. Intersection stripes are formed, separated in the directions parallel or antiparallel to the magnetic field, where the separatrix and the adjacent field lines have contact with the target plates in a width reflecting the width of the SOL. The stripes are sharper when the diffusion coefficient is reduced and, since the SOL width depends on the connection length and this length on the island size, the width of the stripes decreases when increasing the island. The sharpest stripes and largest power densities are found in the high \( \epsilon \) case. Hot spot problems can be removed using the sweep coils with oscillating currents.

Summary and conclusion

The proposed system of sweep coils is a multi-purpose tool which allows:

- the control and modification of size and position of the natural islands in the boundary region
- the correction of symmetry-breaking error fields and reduction of their corresponding islands
- the ergodization of field lines to destroy the magnetic surfaces in the boundary region
- the sweeping of the hot spots on the target plates to avoid there excessive temperatures.
- combinations of the various functions of the sweep coils are possible.

The proposed target plates are effective in the broad parameter range of the cases examined. They collect the particles (modelled by field lines) which divert from the plasma region without showing a leading edge. The power density, compared to technically constraints, is not too excessive and can be controlled by the sweep coils. Further optimizations are possible in respect of size, power load and variation of configuration parameters.
Schematic arrangement of target plates and field lines in the axis-symmetric case (Tokamak) and in the 3D case (Helias) with segmental target plates. In the Helias case the length of the target plates together with a nearly constant intersection angle are chosen, such that all field lines in the SOL hit the plates without a leading edge.

Cross-sections of magnetic surfaces and target plates which intersect the bounding island chain.

Arrangement of magnetic surface, target plates and sweep coils seen from the device centre and from top.
Poincaré plots of the configuration HS5V10N at the toroidal angle $\varphi = 0$. The island size is modified in the cases a - d by energizing the upper and lower sweep coil with currents in the same direction. The X-points are shifted in poloidal direction in the cases e and f feeding opposite currents in the upper and lower sweep coil. The average magnetic field is 3 T.

Poincaré plot of a perturbed case in which a homogeneous horizontal field of 5 G is added (left part). This perturbation is corrected in the right part by individually adapted currents of max. 9 kA in the sweep coils.
Intersection patterns on the target plates with modified island size by different currents in the sweep coils: a) standard case b) small islands, -17 kA, and c) large islands, +17 kA.

Different intersection patterns on the top and bottom target plates result when feeding the upper and lower sweep coils with opposite currents. Two diffusion coefficients are used: upper part of the figure 1 m²/s, lower part 0.2 m²/s.
Intersection patterns on the target plates in the high iota case ($\gamma = 1.01$). The top part of the figure shows the case without currents and the lower part the case with $\pm 300\text{ kA}$ in the sweep coils. In the last case the different patterns on the top and bottom plate results from the opposite current direction in the upper and lower sweep coil and produces a sweeping of the strike points when feeding the sweep coils with AC-currents.

Intersection patterns on target plates in the low iota case ($\gamma = 0.75$), without currents (top part) and with $+ 20\text{ kA}$ in the sweep coils (lower part).
Intersection patterns on the target plates with increased $\epsilon = 1$ islands at small changes of $\epsilon$ on axis: upper part $\epsilon_0 = 0.83$, lower part $\epsilon_0 = 0.89$. In this case the islands are shifted radially compared with the standard case.

PKM7005

a) pk7005e dz3d 5cm

b) pk7005e dz 9d 5cm

c) pk7005e dz12d 5cm

d) pk7005e dz16d 5cm

The target plates developed for HSSV10N applied for the configuration PKM7005. The vertical position of the plates is varied: a) +3 cm, b) +9 cm, c) +12 cm, d) +15 cm, compared with their position in HSSV10N.
AC-Losses of WENDELSTEIN 7-X Coils

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Contents
1. Divertor sweep, arrangement of sweep coils, consequences
2. Data of W 7-X conductor
3. General AC-Loss types
4. Application to W 7-X
5. Testing of AC behaviour
6. Summary and conclusions

1. Divertor sweep, arrangement of sweep coils, consequences

Figure 1. Arrangement of divertor plates and sweep coils: The current of the sweep coils is about 20 kA

Figure 2. Current sharing temperature of the LMI conductor at 16 kA

LMI conductor
Lcool = 200 m
Tin = 3.8 K
Pin = 5.0 bar

Tcs(5,21,lap)

Figure 3. Operation behaviour of the LMI conductor: The figure shows the outlet temperature vs the mass flow rate for two different heat loads

LMI conductor
4 mW/m
2 mW/m
### 2. Data of the different conductors for AC loss calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Proposal Value</th>
<th>LMI (05/92)</th>
<th>Noell (05/92)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>mm</td>
<td>0.58</td>
<td>0.55</td>
<td>0.58</td>
</tr>
<tr>
<td>Wire area (x 1.05)</td>
<td>mm²</td>
<td>48.27</td>
<td>47.90</td>
<td>46.61</td>
</tr>
<tr>
<td>Sc. Material</td>
<td></td>
<td></td>
<td></td>
<td>Nb47 wt% Ti</td>
</tr>
<tr>
<td>Weight of strand</td>
<td>g/m</td>
<td></td>
<td></td>
<td>2.12</td>
</tr>
<tr>
<td>Filament diameter d</td>
<td>μm</td>
<td>44.7</td>
<td>27.</td>
<td>47.2</td>
</tr>
<tr>
<td>Number of filaments</td>
<td></td>
<td>130</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>$\alpha = A_{sc}/A_{wire}$</td>
<td></td>
<td>2.5 : 1</td>
<td>2.1 : 1</td>
<td>2.14 : 1</td>
</tr>
<tr>
<td>$\lambda = A_{sc}/A_{wire}$</td>
<td></td>
<td>0.286</td>
<td>0.323</td>
<td>0.318</td>
</tr>
<tr>
<td>Critical current density $j_c$</td>
<td>A/mm²</td>
<td>2064</td>
<td>2150</td>
<td>2380</td>
</tr>
<tr>
<td>(at 6.2 T, 4.2 K)</td>
<td>A/mm²</td>
<td>2405</td>
<td>2502</td>
<td>2773</td>
</tr>
<tr>
<td>(at 6.2 T, 3.8 K, scaled)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filament twist pitch $l_f$</td>
<td>mm</td>
<td>10 (estimation)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>First stage twist pitch $l_{p,1}$</td>
<td>mm</td>
<td>25</td>
<td>25</td>
<td>136</td>
</tr>
<tr>
<td>Second stage twist pitch $l_{p,2}$</td>
<td>mm</td>
<td>100</td>
<td>60</td>
<td>51</td>
</tr>
<tr>
<td>Third stage twist pitch $l_{p,3}$</td>
<td>mm</td>
<td>N/A</td>
<td>105</td>
<td>95</td>
</tr>
<tr>
<td>Fourth stage twist pitch $l_{p,4}$</td>
<td>mm</td>
<td>N/A</td>
<td>160</td>
<td>N/A</td>
</tr>
<tr>
<td>Number of wires in subcable</td>
<td></td>
<td>29</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Number of subcables in stage 2</td>
<td></td>
<td>$6 \times 29 = 174$</td>
<td>4 x 3</td>
<td>3 x 14</td>
</tr>
<tr>
<td>Number of subcables in stage 3</td>
<td></td>
<td>N/A</td>
<td>$4 \times 4 \times 3 = 4 x 3 \times 14 = 168$</td>
<td></td>
</tr>
<tr>
<td>Number of subcables in stage 4</td>
<td></td>
<td>N/A</td>
<td>$4 \times 4 \times 4 \times 3 = 192$</td>
<td>N/A</td>
</tr>
<tr>
<td>RRR of matrix copper</td>
<td></td>
<td>100</td>
<td>175</td>
<td>(&gt;100) 170</td>
</tr>
<tr>
<td>Resistivity of matrix $\rho_{matrix}$ (Cu at 6.2 T, 4.2 K)</td>
<td>Ωm</td>
<td>$4.5 \times 10^6$</td>
<td>$3.7 \times 10^6$</td>
<td>$3.8 \times 10^6$</td>
</tr>
<tr>
<td>Resistivity of subcable resistive (estimation)</td>
<td>Ωm</td>
<td>$5 \times 10^4$</td>
<td>$5 \times 10^4$</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>$A_{jacket}/A_{wire}$</td>
<td></td>
<td>2.6</td>
<td>2.4 (13.8 x 13.8)</td>
<td>2.9 (14.8 x 14.8)</td>
</tr>
<tr>
<td>Outer cross section of jacket</td>
<td>mm x mm</td>
<td>14.8 x 14.8</td>
<td>14.8 x 14.8</td>
<td>14.8 x 14.8</td>
</tr>
<tr>
<td>Inner dimension of jacket</td>
<td>mm</td>
<td>9.8 (square)</td>
<td>10. Ø</td>
<td>9.8 (square)</td>
</tr>
<tr>
<td>Jacket resistivity $\rho$ (A/(RRR = 4))</td>
<td>Ωm</td>
<td>$7 \times 10^4$</td>
<td>$7 \times 10^4$</td>
<td>$7 \times 10^4$</td>
</tr>
</tbody>
</table>

N/A = not applicable

These data are taken from the Proposal and given by LMI and Noell during the development of the conductor. The data of the final conductor can be different.
3. General AC-Loss types

Formulas for AC loss calculations

**Losses per unit volume and time (W/m³)**

\[
\frac{dQ}{dt} = \frac{dQ_n}{dt} + \frac{dQ_e}{dt} = af + g(t^2)
\]

\( f = \text{frequency} \)
\( a = \text{independent of frequency} \)

**Losses per unit volume (J/m³)**

\[
Q = \frac{1}{f} \frac{dQ}{dt} = a + \frac{1}{f} g(t^2)
\]

There exists a critical frequency: \( f_c = \frac{1}{\tau} \)

For \( f < f_c \) dominates the first term.
For \( f > f_c \) dominates the second term.

The coupling time constant \( \tau \) is given by:

\[
\tau = \frac{1}{2} \mu_0 \left( \frac{l_p}{2\pi} \right)^2 \frac{1}{\rho_t}
\]

with \( l_p \) = twist pitch length of the filament resp. of the cabling stage

\( \rho_t \) = transverse resistivity

i.e.

for the composite: \( \rho_t = \frac{1 - \lambda}{1 + \lambda} \rho_m \)

for large filaments

and \( \rho_t = \frac{1 + \lambda}{1 - \lambda} \rho_m \) for small filaments

with \( \rho_m \) = matrix resistivity

for the cable stages: \( \rho_t \) = contact resistivity

**Comments:**

1. \( l_p \) = twist pitch length of the filament (~10 times conductor diameter) resp. the cabling

2. the transverse resistivity is the most critical quantity. Usually a measurement of \( \tau \) allows the determination of \( \rho_t \).

3. \( \tau \) is typically in the order of 10 to 20 ms, but can vary in a wide range.

**Hysteretic losses per unit volume (J/m³)**

\[ a_n = C_s B_m (\lambda J_c) d_f \]

\( C_s \) = shape factor
\( B_m \) = maximum field
\( \lambda \) = filling factor
\( J_c(B) \) = critical current density of SC
\( d_f \) = filament diameter

**Losses per unit volume (J/m³) for a sinusoidal field change:**

\[
\frac{1}{f} g(t^2) = q_{ct} = \frac{2\pi(\Delta B)^2 \omega \tau}{\mu_0 (1 + \omega^2 \tau^2)}
\]

\( f = \text{frequency} \)
\( \omega = 2\pi f \)
\( \Delta B \) = amplitude of field change
\( \tau \) = coupling time constant
### TYPES OF AC-LOSSES

<table>
<thead>
<tr>
<th>Location</th>
<th>Hysteretic losses (or magnetization losses)</th>
<th>Eddy current losses (or coupling losses)</th>
<th>Self-field losses</th>
<th>Surface losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced currents within SC filament</td>
<td>Induced currents between SC filaments due to changes of the external field</td>
<td>Induced currents between SC filaments due to changes in the transport current</td>
<td>Surface of SC</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technique for reducing loss</th>
<th>Make filament diameter $d_f$ small</th>
<th>Twist filaments $(l_p)$</th>
<th>Keep strand size less than about 2 mm</th>
<th>Smooth surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>High resistive barriers $(p_x)$ around filaments and/or strands (CuNi, Cr, Oxides)</td>
<td></td>
<td></td>
<td>Transpose strands within cable</td>
<td></td>
</tr>
</tbody>
</table>

| Relative magnitude | Dominant loss at frequencies less than RF due to $\sim 1 \mu m$ lower limit on filament size (1980) (1987: $\sim 0.1 \mu m$) | Can usually be made negligible compared to hysteretic losses | Can usually be made small ($< 10\%$) compared to hysteretic losses | Dominant loss at RF and above |

| Time constants and critical frequencies for the LMI conductor |
|-----------------|---|---|
| **Stage**       | **$\tau$ [ms]** | **$f_c$ [Hz]** |
| Composite (Strand) | 50 | 3.2 |
| 1st             | 0.2 | 796 |
| 2nd             | 1.15 | 138 |
| 3rd             | 3.5 | 46 |
| 4th             | 8.1 | 20 |
4. Application to W 7-X

<table>
<thead>
<tr>
<th>Action</th>
<th>Calculation input for AC-loss calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma formation</td>
<td>$\Delta B = 10 \text{ mT and } \Delta t = 0.1 \text{ s}$</td>
</tr>
<tr>
<td>Safety discharge</td>
<td>$B(t) = 6.2 \cdot \exp(-\frac{t}{\tau}) \text{ T and } \tau = 3 \text{ s}$</td>
</tr>
<tr>
<td>Divertor sweep</td>
<td>$B_m = 5 \text{ mT (50 G) and } 0 \leq f \leq 5 \text{ Hz}$</td>
</tr>
</tbody>
</table>

AC losses due to plasma formation ($dB = 0.01 \text{ T, } dt = 0.1 \text{ s}$)

Figure 5. Plasma formation: AC-Losses in the LMI conductor (Eddy current losses are for the Al-jacket).

AC losses due to coil discharge ($\tau = 3 \text{ s}$)

Figure 6. Safety discharge: AC-Losses in the LMI conductor (Eddy current losses are for the Al-jacket).

AC losses due to divertor sweeping ($dB = 50 \text{ Gauss, } f = 1 \text{ Hz}$)

Figure 7. Divertor sweep: AC-Losses in the LMI conductor (Eddy current losses are for the Al-jacket).

Figure 8. Power loss per unit length vs. frequency: at $5 \text{ mT (50 G) for the LMI conductor}$
Figure 9. Simulation scheme for the W 7-X coils:

Figure 10. Calculated power loss per unit length vs. frequency: for the simulated solenoid coil

Figure 11. Outlet temperature vs. frequency: for 200 m cooling channel length

Figure 12. Outlet temperature vs. frequency: for 100 m cooling channel length
5. Testing of AC behaviour in STAR

Figure 13. STAR test arrangement: for a solenoidal model coil

Figure 15. Model coil with pulse coil: contour plot of the STAR arrangement

6. Summary and conclusions

- The conductor is not designed as an AC conductor. However, a frequency of 2 Hz for 50 G divertor sweep is acceptable
- For higher frequencies an other conductor concept has to be developed
- The new conductor concept is much more expensive
- Only few companies produce mixed matrix strands
- A new conductor concept is not desirable, perhaps not possible due to the available space and the requirements for the coil manufacturing.
COIL SYSTEMS AND VACUUM FIELD PROPERTIES OF HS5V10N AND PKM7005

J. Kißlinger, P. Merkel

Two configurations for Wendelstein 7-X, HS5V10N and PKM7005, are compared. In both cases the NESCOIL code is used to determine the coil set, but the procedures and magnetic surface, representing the desired magnetic field, are somewhat different. In the case of HS5V10N, the outer surface on which the surface current distribution is calculated, is formed with respect to filament curvatures and constraints of minimum distances of plasma to filament, and filament to filament. Retaining the initial field properties, in a second step the filaments are smoothed in order to minimize the curvature rating parameter (CRP). In the second case (PKM7005) the optimized current carrying surface is obtained by varying the surface in a domain bounded by constraining tori which determine the minimum and maximum plasma coil distance. As in the first case optimization constraints are the minimum filament-filament distance, the minimum local coil curvature and the curvature rating parameter. In addition to these constraints the realization of the divertor concept, described in [1], requires a minimum distance of $d = 10\text{cm}$ between the last closed magnetic surface and the divertor. With a prescribed value of 0.33 for CRP the toroidal excursions and the filament curvatures obtained for the PKM7005 coil set are about 10% larger than for the case HS5V10N with a CRP value of 0.22. On the other hand the minimum plasma-filament distance is larger in PKM7005 than in HS5V10N which may be the reason for the smaller minimum distance between two filaments of about 24 cm, compared with 26 cm in HS5V10N.

The vacuum magnetic field differs mainly in the iota profile, in the magnetic well (PKM7005 0.8%, HS5V10N 1.08%) and in its edge magnetic field structure. In PKM7005 the rotational transform is nearly constant up to a plasma radius of 28 cm and increases greatly in the outer 20 cm. In HS5V10N there is also some positive local shear in the inner confinement region, but the increase of $\varepsilon$ in the outer region is not as strong as in PKM7005. The concentrated shear in the edge region and the larger curvatures in the coils may be the main reasons for the stochastic magnetic field structure outside of $\varepsilon = 1$ in PKM7005.

In table II the characteristic data of HS5V10N and PKM7005 are compared to those of the reference configuration of the W 7-X - proposal, HS5V10C.

Views of the coil set of one field period of HS5V10N from top (top) and from the device center (middle). The bottom figure shows the cross-section of magnetic surface, vacuum vessel and modular coils at the horizontal plane $Z = 0$. 
Poincaré plots of magnetic surfaces at toroidal planes $\phi = 0^\circ, 18^\circ, 36^\circ$ of HS5V10N. On top the standard case with $\iota_0 = 0.86$, the low iota case with $\iota_0 = 0.747$ and the high iota case with $\iota_0 = 1.006$ (bottom).
Views of the coil set of one field period of PKM7005 from top (top) and from the device center (middle). The bottom figure shows the cross-section of magnetic surface, vacuum vessel and modular coils at the horizontal plane $Z = 0$. 
Poincaré plots of magnetic surfaces at toroidal planes $\varphi = 0^\circ, 18^\circ, 36^\circ$ of PKM7005. On top the standard case with $\epsilon_0 = 0.86$, the low iota case with $\epsilon_0 = 0.743$ and the high iota case with $\epsilon_0 = 1.015$ (bottom).

$\text{PKM7005 ST. CASE}$

$\text{PKM7005 low iota}$

$\text{PKM7005 high iota}$
Profiles of rotational transform and magnetic well of the configurations HS5V10N and PKM7005. The coefficient $G_B = f_b/f_e$ enters the relationship for the bootstrap current in the lmfp-regime, normalized by the value of an equivalent axisymmetric configuration. $B_{\min}$ and $B_{\max}$ are the minimum and maximum of the normalized field strength $B$ on a magnetic surfaces with average radius $r$. Also shown are the normalized Fourier components of the field strength $B$ with a value $> 1\%$ except $C_{00}$ which has a value of $\approx 1$. 
TABLE I: Curvature Rating Parameter \( r \) \( \int_\gamma g(x) \, dl \)

<table>
<thead>
<tr>
<th>Coil</th>
<th>HS5V10C</th>
<th>HS5V10N</th>
<th>PKM7005</th>
<th>W7-AS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>we</td>
<td>we</td>
<td>we</td>
<td>we</td>
</tr>
<tr>
<td>1</td>
<td>0.24</td>
<td>0.25</td>
<td>0.20</td>
<td>0.22</td>
</tr>
<tr>
<td>2</td>
<td>0.23</td>
<td>0.26</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>0.27</td>
<td>0.34</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>4</td>
<td>0.44</td>
<td>0.49</td>
<td>0.18</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>0.41</td>
<td>0.47</td>
<td>0.18</td>
<td>0.22</td>
</tr>
<tr>
<td>average</td>
<td>0.32</td>
<td>0.36</td>
<td>0.19</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Values of worst edges (we) and center filaments (cf). In the case of filaments the curvature radius is reduced by \( 1/2 \) coil width.

Contour plot of the magnetic field strength \( B \) on a magnetic surface with average radius \( r = 29.5 \) cm (left, PKM7005) and \( 28.2 \) cm (right, HS5V10N). One field period is shown, the abscissa is the toroidal coordinate.

TABLE II: Characteristic data of the different field configurations.

- Standart Cases -

The curvature rating parameter (CRP) is a measure of the manufacturing expense. The values given are the average of the center filaments (cf) and of worst edges (we). \( J^* = (B_1^2 / B_2^2) \cdot (1 + (\phi / j_{\perp})^2) \) enters the stability criterion of resistive interchange modes, and is a direct measure of the reduced secondary plasma-currents.

<table>
<thead>
<tr>
<th></th>
<th>HS5V10C</th>
<th>HS5V10N</th>
<th>PKM7005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average length of one turn ( L ) [m]</td>
<td>8.04</td>
<td>8.52</td>
<td>8.63</td>
</tr>
<tr>
<td>Average coil volume ( V_c ) [m³]</td>
<td>0.304</td>
<td>0.322</td>
<td>0.326</td>
</tr>
<tr>
<td>Min. radius of curv. (cf) ( \rho ) [m]</td>
<td>0.39</td>
<td>0.43</td>
<td>0.35</td>
</tr>
<tr>
<td>Min. radius of curv. (we) ( \rho ) [m]</td>
<td>0.28</td>
<td>0.29</td>
<td>0.19</td>
</tr>
<tr>
<td>Min. dist. between filaments ( \Delta ) [m]</td>
<td>0.26</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>Min. dist. plasma-wall ( \Delta_{pw} ) [m]</td>
<td>0.11</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>Av. curv. rating param. (cf) CRP</td>
<td>0.36</td>
<td>0.22</td>
<td>0.33</td>
</tr>
<tr>
<td>Av. curv. rating param. (we) CRP</td>
<td>0.32</td>
<td>0.19</td>
<td>0.39</td>
</tr>
<tr>
<td>Stored magnetic energy ( W ) [GJ]</td>
<td>0.58</td>
<td>0.60</td>
<td>0.61</td>
</tr>
<tr>
<td>Average plasma radius ( \rho_p ) [m]</td>
<td>0.55</td>
<td>0.52</td>
<td>0.49</td>
</tr>
<tr>
<td>Rot. transform on axis ( \chi )</td>
<td>0.84</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>Well Depth ( \Delta^{\perp} ) [%]</td>
<td>-1.35</td>
<td>-1.08</td>
<td>-0.80</td>
</tr>
<tr>
<td>Current ratio ( (\rho_b / j_{\perp}) )</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Stability parameter ( J^* )</td>
<td>1.55</td>
<td>1.56</td>
<td>1.55</td>
</tr>
</tbody>
</table>
### Table 1

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$B_1$</th>
<th>$B_2$</th>
<th>$B_3$</th>
<th>$B_4$</th>
<th>$B_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>5.0</td>
<td>10.0</td>
<td>20.0</td>
<td>30.0</td>
<td>40.0</td>
</tr>
<tr>
<td>0.5</td>
<td>5.5</td>
<td>10.5</td>
<td>21.0</td>
<td>31.0</td>
<td>41.0</td>
</tr>
<tr>
<td>1.0</td>
<td>6.0</td>
<td>11.0</td>
<td>22.0</td>
<td>32.0</td>
<td>42.0</td>
</tr>
</tbody>
</table>

*Note: $B_1$, $B_2$, $B_3$, $B_4$, and $B_5$ represent different field strengths.*

---

**Figure 2:**

The figure illustrates the magnetic field distribution for different values of $\theta$. The field strength $B$ is measured in gauss (G). The field lines are shown for $\theta = 0^\circ$, $\theta = 45^\circ$, and $\theta = 90^\circ$.

---

**Figure 3:**

A contour plot showing the normalized field strength $B$ on a magnetic surface with average radius $r$. Also shown are the normalized Fourier components of the field strength $B$ with a value $\geq 1\%$ except $C_0$, which has a value of $\geq 1$. 

---

**Figure 4:**

A schematic diagram representing the magnetic configuration of a superconducting magnet. The diagram includes annotations for the magnetic field lines and the critical current density $J_c$.
FIXED POINTS AND STOCHASTICITY OF MAGNETIC FIELD LINES IN THE
BOUNDARY REGION OF HELIAS CONFIGURATIONS HS5V10N AND PKM7005

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Max-Planck-Institut für Plasmaphysik
IPP-EURATOM Association
D-8046 Garching bei München, Germany

- Measure preserving mapping
- Residues
- Structure of X- and O- points
- Ergodic region between smooth magnetic surfaces
- Results for proposed device Wendelstein 7-X (HS5V10N, PKM7005)

The vacuum fields of two Helias configurations, namely HS5V10N and PKM7005, have been investigated by analysing rational magnetic field lines of low order in the interior of the magnetic surface with $\varepsilon = 0.98$ and in the near boundary region outside of this surface.

Applying the method of measure preserving mapping, the residues of closed field lines (fixed lines), the ellipticity of $O$-type fixed lines (and the corresponding internal twist number of the islands) and the angle between the asymptotes to the hyperbola of $X$-type fixed lines are computed as functions of the toroidal angle $\varphi$. The vacuum magnetic fields are defined by a set of coils (see Contribution by J. Kisslinger to this Meeting). Some properties are given in the following table:

<table>
<thead>
<tr>
<th>HS5V10N</th>
<th>PKM7005</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{az} = 0.86$</td>
<td>$\varepsilon_{az} = 0.86$</td>
</tr>
<tr>
<td>$\varepsilon(A = 11.0) = 0.97$</td>
<td>$\varepsilon(A = 11.4) = 0.97$</td>
</tr>
<tr>
<td>$\varepsilon(A = 8.7) = 1.07$</td>
<td>$\varepsilon(A = 10.2) = 1.07$</td>
</tr>
</tbody>
</table>

$\Delta V'/V_{az}' = -1.1\%$ at $A = 11.0$
$(\langle j_t^2 / j_{||}^2 \rangle)^{1/2} = 0.75$ at axis
$(\langle j_t^2 / j_{||}^2 \rangle)^{1/2} = 0.64$ at boundary

mirror ratio $(B_1 - B_2)/(B_2 + B_1) = 4.7\%$
$(B_1, B_2$ absolute values of the magnetic field on axis at $\varphi = 0$ and $\varphi = \pi/5$)

$\Delta V'/V_{az}' = -0.8\%$ at $A = 11.4$
$(\langle j_t^2 / j_{||}^2 \rangle)^{1/2} = 0.72$ at axis
$(\langle j_t^2 / j_{||}^2 \rangle)^{1/2} = 0.66$ at boundary

mirror ratio $= 5.4\%$

stochastic edge region outside the $m/n = 5/5$ - islands
Fig. 1. Poincaré plot of the vacuum field configuration HS5V10N.

Figure 1 shows a Poincaré plot of magnetic surfaces (dots) of configuration HS5V10N at three different azimuthal planes $\varphi = 0$, $\pi/10$, $2\pi/10$ (half of a field period). Five big islands ($\varepsilon = m/n = 5/5$, $O$-type fixed points belonging to five separate closed field lines; between them the corresponding $X$-type fixed points) separate the inner region from the boundary region. The angle $\gamma$ between the asymptotes of the hyperbola at the $X$-points ($m/n = 5/5$) is about $90^\circ$ in the azimuthal planes $\varphi = 0$ and $\pi/5$ (see Fig. 2: here also the separatrix is shown which is approximated by a rational closed field line of high order, e.g. $m/n = 99/100$ or $101/100$).

The field configuration HS5V10N shows "smooth" magnetic surfaces outside the $\varepsilon = 5/5$-islands whereas the field lines of the configuration PKM7005 (see Fig. ) show stochastic behaviour in the boundary region outside of $\varepsilon = 1$-islands.

In the boundary region of HS5V10N outside of $\varepsilon = 5/5$, only fixed points of different order are shown (symbols ■, △, ▲, ○); the absolute values of the residues $R^*$ (see the following table) are smaller than one. All fixed lines start at $Z = 0$ either in the plane at $\varphi = 0$ or at $\varphi = \pi/5$. Only one fixed line with $\varepsilon = m/n = 10/9$ has been found ($|R^*| = 0.254 > 1/4$); there are no smooth magnetic surfaces with $\varepsilon \geq 10/9$.

The poloidal distribution of the fixed points is weakly concentrated on top and bottom of the bean-shaped cross section and fairly uniform in the triangular cross section.
Fig. 2. Poincaré plot of magnetic surfaces (at $\varphi = 0$ and $\pi/5$) and the separatrix which separates the $m/n = 5/5$ - islands, the interior region and the outer boundary region for which the fixed points of low order only are shown (see insert).
Residues in the boundary region of HS5V10N:

<table>
<thead>
<tr>
<th>$m/n$</th>
<th>$R_1$</th>
<th>$\varphi$</th>
<th>$R^*$</th>
<th>$\epsilon_{is}$</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/5</td>
<td>621.689</td>
<td>0</td>
<td>+0.06391</td>
<td>0.081</td>
<td>O</td>
</tr>
<tr>
<td>5/5</td>
<td>570.831</td>
<td>0</td>
<td>-0.10224</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>10/9</td>
<td>566.231</td>
<td>0</td>
<td>-0.25365</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>15/14</td>
<td>567.940</td>
<td>0</td>
<td>-0.28638</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>15/14</td>
<td>448.361</td>
<td>$\pi/5$</td>
<td>+0.23518</td>
<td>0.161</td>
<td>O</td>
</tr>
<tr>
<td>20/19</td>
<td>624.602</td>
<td>0</td>
<td>-0.17246</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>20/19</td>
<td>568.746</td>
<td>0</td>
<td>+0.16149</td>
<td>0.132</td>
<td>O</td>
</tr>
<tr>
<td>25/24</td>
<td>624.199</td>
<td>0</td>
<td>-0.08939</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

From the numbers of $R_1$ one can observe how close the fixed points are at $Z = 0$; the bulge out of the field lines on top and bottom of the bean-shaped cross section can be seen in Figure 1.

Fig. 3. Angle between the asymptotes for the $m/n = 5/5$ $X$ - type fixed point (as seen from the interior plasma region) as function of the toroidal angle $\varphi$; five field periods are shown. Because of the stellarator symmetry of the field, the first half of the curve is strictly symmetric to the second half. The angle $\gamma$ is approximately $90^\circ$ at three positions along the field line, namely on top and bottom of the bean-shaped cross section and at $Z = 0$ in the triangular cross section (see Fig. 2).

Fig. 4. Ellipticity $\epsilon$ of the $m/n = 5/5$ $O$ - type fixed point as function of the toroidal angle $\varphi$; the ellipticity is zero for a circle and approaches one for an ellipse with large values of the half-axis ratio. The smallest value of $\epsilon$ occurs at $\varphi \approx \pi/10$ (see second cross section of Fig. 1).
Fig. 5. Location of $m/n = 5/5$ fixed lines of $X$-type (left) and $O$-type (right) (five field periods). All curves are symmetric or skew-symmetric with respect to the middle plane.

Fig. 6. Ellipticity and angle between the asymptotes for various fixed points versus $\varphi$. 
Fig. 7. Ellipticity for various fixed points. Fig. 8. Location of $m/n = 25/24$ fixed line.

Residues in the boundary region of the vacuum field PKM7005:

<table>
<thead>
<tr>
<th>$m/n = \epsilon$</th>
<th>$R_1$</th>
<th>$\varphi$</th>
<th>$R^*$</th>
<th>$t_{is}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/4 = 1.250</td>
<td>625.229</td>
<td>$\pi/5$</td>
<td>-2.89754</td>
<td></td>
</tr>
<tr>
<td>5/5 = 1.000</td>
<td>574.476</td>
<td>0</td>
<td>-0.02176</td>
<td></td>
</tr>
<tr>
<td>5/5 = 1.000</td>
<td>619.345</td>
<td>0</td>
<td>+0.12265</td>
<td>0.114</td>
</tr>
<tr>
<td>10/9 = 1.111</td>
<td>620.980</td>
<td>0</td>
<td>+2.49970</td>
<td></td>
</tr>
<tr>
<td>10/9 = 1.111</td>
<td>572.574</td>
<td>0</td>
<td>-1.25562</td>
<td></td>
</tr>
<tr>
<td>10/11 = 0.909</td>
<td>615.450</td>
<td>0</td>
<td>+0.01252</td>
<td>0.036</td>
</tr>
<tr>
<td>15/13 = 1.154</td>
<td>621.108</td>
<td>0</td>
<td>32.76690</td>
<td></td>
</tr>
<tr>
<td>15/13 = 1.154</td>
<td>571.541</td>
<td>0</td>
<td>-5.58233</td>
<td></td>
</tr>
<tr>
<td>15/14 = 1.071</td>
<td>620.613</td>
<td>0</td>
<td>+1.50453</td>
<td></td>
</tr>
<tr>
<td>15/14 = 1.071</td>
<td>610.496</td>
<td>$\pi/5$</td>
<td>-1.50315</td>
<td></td>
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<tr>
<td>15/16 = 0.938</td>
<td>617.041</td>
<td>0</td>
<td>+0.01536</td>
<td>0.040</td>
</tr>
<tr>
<td>25/24 = 1.042</td>
<td>620.280</td>
<td>0</td>
<td>+1.13112</td>
<td></td>
</tr>
</tbody>
</table>

All absolute values of the residues of fixed lines with $\epsilon > 1$ are greater than one; so these fixed lines are isolated fixed lines with a stochastic neighborhood. The local shear of the mapping is large which means that a field line starting close to a fixed line moves very fast away from that fixed line. On the other hand, a fixed line with small positive residue $R^*$ is surrounded by nested magnetic surfaces (islands) and the neighboring field lines will not leave a certain bounded region.
Fig. 9 Poincaré plot of vacuum field PKM7005.

In Figure 8, magnetic surfaces of the vacuum field configuration PKM7005 are shown at $\varphi = 0, \pi/10, 2\pi/10$. The twist $\epsilon$ of the last "closed" magnetic surface is $\epsilon = 0.98$. The $m/n = 5/5$ O-points are surrounded by a narrow region of nested magnetic surfaces (islands). In the region outside the $m/n = 5/5$ islands, only fixed points of various order are shown (see insert of symbols), some of them seem to lie on "smooth" surfaces however the field lines show stochastic behavior ($|R^s| > 1$).

The poloidal distribution of the fixed points is strongly concentrated on top and bottom of the $\varphi = 0$ -plane, on bottom of the $\varphi = \pi/10$ -plane, and at outboard side ($Z = 0$) of the $\varphi = 2\pi/10$ -plane.

The fixed lines with $m/n = 15/13$ show large excursions although they start very close to the $m/n = 10/9$ -fixed line (see Table above and Fig. 11). Only one of the $m/n = 5/4$ -fixed lines (starting at $Z = 0$) exists.

The following Figures show the ellipticity and the angle $\gamma$ for various fixed points of the configuration PKM7005.
Fig. 10. Ellipticity and angle $\gamma$ as function of the toroidal angle $\varphi$ for various fixed points of vacuum field configuration PKM7005.

The last graph of Fig. 9 shows a numerical truncation problem which might occur when field lines are numerically integrated in a region where the magnetic field shows stochastic behavior. Because of the stellarator symmetry, all curves are symmetric with respect to the middle plane except the last one ($m/n = 15/13$, fixed line at $R_1 = 621.1$, outboard side) where the symmetric behavior is violated more and more for large abscissa values because of truncation errors. The other fixed line of same order ($m/n = 15/13$ at $R_1 = 571.5$, inboard side) shows the correct symmetry behavior for the same numerical parameters.

Fig. 11. $R$-coordinate of $m/n = 15/13$ fixed line.
PERTURBATION STUDIES
FOR W7-X

F. Rau

1) Proposal W7-X and
Ad-hoc Group Discussions

2) New Results

"Inselbildung" ISLAND
FORMATION

Jeder ist ein Trottel — bloß auf einem anderen Gebiet.  Punch

Symmetry breaking perturbations of vacuum fields in stellarators are
effective at rational iota values, and result in

modification of existing magnetic islands,
introduction of new islands, and
enhancement of stochasticity.

As a consequence, the aspect ratio of the "last useful" magnetic surface
rises. Such perturbations can be compensated by appropriate currents in
external trim coils, see Proc. 19th EPS Innsbruck 1992, part I, 581.

The present and earlier perturbation studies use field line tracing in
stored periodic grids. Small differences to "direct" integration exist. The
integration step size is chosen sufficiently small. The interpolation
between the grid points causes an enhanced stochasticity near
separatrices, the amount of which is hard to quantify. Results on
perturbation calculations performed for earlier W7-X coil systems are
given in the Proceedings of preceding Ringberg Workshops. In the W7-X
Proposal perturbations of the standard case of the reference coil system
HS 5-10 are treated at iota = 1 near the edge, along with the high-iota
case of HS 5-8, and are extended to the high-shear and high-iota cases
of HS 5-10 in a contribution to the Ad-hoc Subgroup "Operational Range
and Flexibility" in the procedure to get Euratom Phase I Preferential
Support. These studies are reviewed in the first part of the present
paper.
Superposing a perturbation by a homogeneous horizontal field, the field of an external dipole loop, or the tilt of one of the modular coils (modelled by 2 tilted dipole loops with the module coil current) results in similar effects: the five "natural" islands at \( \text{iota} = 1 \) are changed to one large island, the four other O-points successively vanish with increasing perturbation amplitude. At rational \( \text{iota} \)-values, thin new islands appear.

Perturbation by an external dipole loop with \( \Delta B/B \) of about 0.5% near the magnetic axis is comparable to the effect of a modular coil tilted by 0.5 cm around a vertical axis. This tilt might be comparable to a typical construction tolerance. Two sub-islands are caused at \( \text{iota} = 1 \) by an elliptic offset of the major radii of the modular coil set with an amplitude \( \Delta R = 1 \) cm, the size being similar to that caused by the tilted coil. For the high-\( \text{iota} \) case with \( \text{iota} = 5/4 \) at the edge, a rather large island with \( \text{iota} = 6/5 \) develops in HS 5-8 from the high-order element \( \text{iota} = 30/25 \) of the Farey-Tree. This resonance is absent in the high-\( \text{iota} \) case of HS 5-10, because of its stochastic edge near \( \text{iota} = 1.2 \).

For the above cases, an increase of the aspect ratio by 15 to 25% is estimated from the enhanced stochasticity near the edge and the added widths of the main induced islands.

The second part of this paper compares the edge regions of slightly different vacuum fields for three recent coil sets, labelled W7-X n1, W7-X n2 and PKM j, respectively, derived by J. Kißlinger and P. Merkel. The average field on axis is 3 T, and the main resonance near the edge is \( \text{iota} = 1 \) for the three cases. Only W7-X n1 has closed surfaces outside these islands. The second of the configurations uses rather moderate currents of 10 kA in a system of sweep coils. This enhances the stochasticity near the edge, removes the magnetic surfaces outside \( \text{iota} = 1 \), but keeps the positive shear. The third configuration has slightly negative shear near the axis.

A homogeneous perturbation field \( B_y = 1 \) mT removes the closed outer surfaces in W7-X n1. The resonance at \( \text{iota} = 20/21 \) can be seen in all three cases; the aspect ratio is increased by about 5%. Five "good" O-points of the \( \text{iota} = 1 \) islands are maintained only for W7-X n2. The perturbed system PKM j develops a minimum of \( \text{iota} \) above but near a value of 6/7, which \( \text{iota} \)-value is not present in the other two systems.

Therefore we would prefer as reference system for the work towards Euratom Preferential Support Phase II the parameter field W7-X n, with the vacuum field topologies W7-Xn1 ... Xn5 having \( \text{iota} = 1 \) at the edge, and Xn6 and Xn7 with high and low \( \text{iota} \), resp.
Modular coil system of Wendelstein VII-X and position of current loops used for perturbation studies.

We apply either:
- homogeneous fields \( B_x \) or \( B_y \),
- dipole field of one outside loop for \( M = 1 \) perturbation,
  typically placed at some \( y \)-value,
- dipole fields of two loops at the position of module coil No 13, i.e. at \( y \approx 5.5 \) m, in order to model a tilt of this coil around a vertical axis.

\( M = 2 \) perturbations are done either by an elliptical offset of the major radii of all modular coils, or by two external dipole loops.

\[ \phi = 36^\circ \]

Standard case of Wendelstein VII-X. Top part: unperturbed configuration, middle and lower parts: external dipole perturbation with relative amplitudes \( B_x / B = 0.16 \) and \( 0.47 \% \), respectively.
Perturbed fields at $\epsilon = 1$. Top part: modular coil No 13 tilted by 0.5 cm around a vertical axis, modelled by two tilted dipole loops. One main X-point indicated. Lower part: elliptic offset of the radial position of all modular coils with an amplitude of 1 cm; two main sub-islands. Note: for both types of perturbation a large number of thin islands exists inside $\epsilon = 1$, as exemplified in the upper part. Between them there are closed surfaces, see lower part of the figure. A total increase of the aspect ratio of about 15% is estimated for either perturbation.
Earlier Coil Set HS 5-8

high-iota case

at iota = 5/4

unperturbed

M = 1 Perturbation

Edge vacuum fields of HS 5-8 with $R = 6.5$ m and $\epsilon = 5/4$. Top part: unperturbed configuration, several high-order elements of the Farey-tree with $\epsilon = 5/5$ and $5/4$ as basis, and closed magnetic surfaces with increasing ergodicity towards the edge. Lower part: external dipole perturbation with relative amplitude $B_d/B = 0.3\%$ at $y = 6.5$ m. The resonance 30/25 degenerates to 6/5 and causes a substantial width of this island. The new islands at $\epsilon = 7/6$ and 8/7 are rather thin. A total increase of the aspect ratio between 15 and 25% is estimated.
High-iota Case of HS 5-10
at iota = 5/4
unperturbed

Two Dipole Loops at Position of Coil #13
5/4 islands are nearly unchanged
new islands are thin,
e.g. iota = 7/6 or 12/11.

No stochasticity if edge field lines are intercepted
by first wall or by tentative target plates
which intersect the 5/4 islands.

Long Connection Lengths to First Wall
R_{start} = 592 \quad \Rightarrow \quad L_{wall} = 9.4 \text{ km} = 260 \text{ toroidal transits}
NEW COIL SYSTEM
HS 5-10 N, unperturbed
Standard Case W7-X n1

FFR0112  FFR0123
FFR0111

Farey tree : 5/5
5/4 => 10/9 = 1.11111 5/6 => 10/11 = 0.90909
10/9 => 15/14 = 1.07143 10/11 => 15/16 = 0.93750
15/14 => 20/19 = 1.05263 15/16 => 20/21 = 0.95238
20/19 => 25/24 = 1.04167 20/21 => 25/26 = 0.96154
25/24 => 30/29 = 1.03448 25/26 => 30/31 = 0.96774
30/29 => 35/34 = 1.02941 30/31 => 35/36 = 0.97222
35/34 => 40/39 = 1.02564 35/36 => 40/41 = 0.97561

IOTA

W7 - X n1 STANDARD CASE
no current in sweep coils
inner surfaces, iota < 1
iota = 0.986 at r = 50.3 cm

0.86 0.9 0.92 0.94 0.96 0.98

0 20 40 r (cm) 60

IOTA vs Minor Radius
W7-X n2
Sweep Coils ⇒ Stochastic Edge
$R_{\text{start}} = 601$ ⇒ $r = 50.3 \text{ cm}$
iota = 0.982

Smooth Inner Surfaces

FFR0157
frr:w7x.n2 HSSV10N DAT5v10n
SP5v10n3 IPO2 -10+10+10-10kA $m=5$ unpert.
For \( \iota < 1 \): W7-X n2 has same positive shear as W7-X n1.
This is different in Configuration PKM j by P. Merkel MIN iota

outside iota = 1 stochastic

$IOTA$

$IOTA$ vs Minor Radius

PKM j, interpol. grid

MIN iota

$r$ (cm)
Perturbation $B_y = 1 \text{ mT}$ at $<B>=3 \text{ T}$

Main island $\text{ iota}=1$

3 "good" O-Points $\text{ iota}=20/21$ is seen

5 "good" O-Points

Many thin islands and smooth surfaces

$iota_{\text{min}}$ approx $6/7$

$iota = 20/21$

Therefore we would prefer as reference system for the work towards Euratom Preferential Support Phase II the parameter field W7-X n, with the vacuum field topologies W7-Xn1 ... Xn5 having $iota = 1$ at the edge, and Xn6 and Xn7 with high and low $iota$, resp.
COMPARISON OF W7-X COIL CONFIGURATIONS IN VIEW OF FORCES AND STRESSES

E. Harmeyer

- Field and force distributions in the coils
- Net coil forces in the coil arrangement
- Mechanical stress analysis:
  - Standard case HS5-10.N
  - Boundary conditions
  - Ring support structure

5th Workshop on Wendelstein 7X May 1992

Abstract

The calculations of magnetic fields and the forces concentrate on the standard cases of the S-period coil configurations HS5-I0N and HS-PKM. The latter was derived from the data set PKMT905. Magnetic fields and forces are obtained by the EFFI code. Mechanical stresses and strains are computed using the SAPV(2) and ADINA programme systems.

The coil systems consist of 5 different modular non-planar coils and 2 additional planar coils per half field period. Because of the local coil curvatures and the slightly helical arrangement of the coils the magnetic forces in the coils are inhomogeneously distributed. The magnetic force density averaged over the cross-section of the coils consists of a radial and a lateral component which vary along the circumference of the coils. The volume integral of the magnetic force densities yields different forces for each coil. The comparison of the coil systems HS5-I0N and HS-PKM shows that the configuration HS-PKM is subjected to higher values of the magnetic field at the coils and the magnetic forces in the coils. This is mainly due to the larger toroidal excursions and the smaller radii of curvature of these coils. Also the local mutual vicinity of the coils in the HS-PKM configuration is relevant in this context.

The magnetic forces of the coils are supported by a scheme of mutual support. The programme system SUPPORT subdivides the coils and generates the elements of the coil housing and of the mutual support. Local reinforcement of the structure in radial and lateral direction as well as trapezoidal elements are possible. Also the boundary elements can be defined with this code. In order to check the validity of the chosen boundary conditions two different arrangements of one field period have been defined, utilizing the helical symmetry of the field period. The first case comprises coils 4 to 5, and the second case coils 1 to 10.

In a further step the mutual support system has been reinforced by a ring support structure similar to that already proposed during the 2nd Workshop on W VII-X in 1988 (see Proceedings of this workshop, pp 318-319). This leads to a further stiffening of the support system.
Cell configuration HS-10N: One field period, Coils 1 to 10, 21 to 24

Cell configuration HS-PKM: One field period, Coils 1 to 10, 21 to 24

HS-10N: Local radius of curvature of coils 1-10.

HS-PKM: Local radius of curvature of coils 1-10.

\[ |B|_{max} = 5.7 \, T \]

HS-PKM: Magnetic field distribution at the inner side of coil 1.

\[ |B|_{max} = 6.1 \, T \]

Coil configuration HS10.N, \( r_s = 0.66 \):
Net coil forces in radial and vertical direction.


\[ j_c = \frac{Q_{MA}}{A} \]

HS-PKM: Magnetic force density in radial and lateral direction, coil 3.

\[ j_c = \frac{Q_{MA}}{A} \]

Coil configuration HS-PKM, \( r_s = 0.66 \):
Net coil forces in radial and vertical direction.
Mutual Coil Support for H55-10N.

Coil configuration H55-10N, $B_0 = 3$ T, standard configuration:
Displacement plot

Coil configuration H55-10N, $B_0 = 3$ T, standard configuration:
Displacement plot
HSS-10.N: Tangential stress $\sigma_x$, orthotropic coil data.

HSS-10.N: Shear stress $\sigma_y$, orthotropic coil data.

HSS-10.N: Tangential stress $\sigma_z$, orthotropic coil data.

HSS-10.N: Shear stress $\sigma_z$, orthotropic coil data.

HSS-10.C: Equivalent stress $\sigma_{eq}$, coil 49, without ring structure.

HSS-10.C: Equivalent stress $\sigma_{eq}$, coil 49, with ring structure.
TABLE I
Characteristic data of different HELIAS configurations.

- Standard Cases -

<table>
<thead>
<tr>
<th></th>
<th>HS5-10.C</th>
<th>HS5-10.N</th>
<th>HS-PKM (PKM7005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average major radius</td>
<td>$R_0$ [m]</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Average coil radius</td>
<td>$r_c$ [m]</td>
<td>1.14</td>
<td>1.25</td>
</tr>
<tr>
<td>Radial coil height</td>
<td>$t$ [m]</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Lateral coil width</td>
<td>$w$ [m]</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Average coil volume</td>
<td>$V_c$ [m$^3$]</td>
<td>0.304</td>
<td>0.322</td>
</tr>
<tr>
<td>Total coil volume</td>
<td>$n \cdot V_c$ [m$^3$]</td>
<td>15.2</td>
<td>16.1</td>
</tr>
<tr>
<td>Min. radius of curvature</td>
<td>$\rho_c$ [m]</td>
<td>0.23</td>
<td>0.29</td>
</tr>
<tr>
<td>Av. curvature rating parameter</td>
<td>CRP</td>
<td>0.36</td>
<td>0.22</td>
</tr>
<tr>
<td>Min. dist. between centr. filaments</td>
<td>$\Delta_{cf}$ [m]</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Min. distance coil-wall</td>
<td>$\Delta_{cw}$ [m]</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Min. distance plasma-wall</td>
<td>$\Delta_{pw}$ [m]</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>Coil number total / per FP</td>
<td>$n/np$</td>
<td>50/10</td>
<td>50/10</td>
</tr>
<tr>
<td>Total coil current</td>
<td>$I_c$ [MA]</td>
<td>1.76</td>
<td>1.74</td>
</tr>
<tr>
<td>Overall current density</td>
<td>$j_c$ [MA/m$^2$]</td>
<td>46.6</td>
<td>46.0</td>
</tr>
<tr>
<td>Total inductance (one-turn)</td>
<td>$L$ [$\mu$H]</td>
<td>375.</td>
<td>400.</td>
</tr>
<tr>
<td>Induction on axis</td>
<td>$B_o$ [T]</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Max. induction at coil</td>
<td>$B_m$ [T]</td>
<td>6.1</td>
<td>5.7</td>
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<tr>
<td>Rotat. transform on axis</td>
<td>$r_s$</td>
<td>0.84</td>
<td>0.86</td>
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<tr>
<td>Rotat. transform on boundary</td>
<td>$r_b$</td>
<td>0.99</td>
<td>0.99</td>
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<tr>
<td>Average plasma radius</td>
<td>$r_p$ [m]</td>
<td>0.53</td>
<td>0.52</td>
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<tr>
<td>Average force density</td>
<td>$(f)$ [MN/m$^3$]</td>
<td>75.</td>
<td>71.</td>
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<tr>
<td>Local max. force density</td>
<td>$</td>
<td>f</td>
<td>_{lm}$ [MN/m$^3$]</td>
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<tr>
<td>Max. net force (one coil)</td>
<td>$F_{res}$ [MN]</td>
<td>3.6</td>
<td>3.0</td>
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<tr>
<td>Virial stress</td>
<td>$\sigma_V$ [MPa]</td>
<td>37.5</td>
<td>37.7</td>
</tr>
</tbody>
</table>
Technical Evaluation of W 7-X Coils

J. Sapper

For the W 7-X confinement system two slightly different coil sets are being discussed. The performance of the coil sets, labelled HS5 V10N and PKM 7005 is described elsewhere in this report. It was the task to find out whether any technically dominating properties are existing in one of the coil sets which lead to better conditions for the practical realization. For the analysis, six parameters, listed in Table I, have been considered. The result is that both coil sets are feasible, but the HS5 V10N has to be preferred from technical and financial points of view.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HS5 V10N</th>
<th>PKM 7005</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature Radius Parameter</td>
<td>0.22</td>
<td>0.34</td>
<td>averaged for 5 coils, central filaments</td>
</tr>
<tr>
<td>Assembly techniques</td>
<td>no difference</td>
<td>no difference</td>
<td></td>
</tr>
<tr>
<td>NBI-Port</td>
<td>feasible as required</td>
<td>reduced geometry</td>
<td>AUG-beamline</td>
</tr>
<tr>
<td>Ports, through-ports</td>
<td>no difference</td>
<td>no difference</td>
<td></td>
</tr>
<tr>
<td>Space for structure</td>
<td>complex</td>
<td>very complex</td>
<td></td>
</tr>
<tr>
<td>Coil housings</td>
<td>see: CRP</td>
<td>see: CRP</td>
<td>has to be preferred from technical and financial point of view</td>
</tr>
</tbody>
</table>

TABLE I  Technical Evaluation of W 7-X Coil Sets
Fig. 1: Modular/sectional assembly
Ueberschneidung 20 mm.
Bei beiden Gehaeusen muss die Wandstaerke teilweise von 40 auf 20 mm reduziert werden.

Fig. 2: Modular assembly, local interference
Fig. 3: Modular assembly
Spulensatz hs5v10n

Fig. 4: NBI-port, collision check
Fig. 5: NBI-port, collision check

Spulensatz pmga7005
Figs. 6; 7: Θ-Φ developments of coil sets, structure and ports (dotted lines are set PKM 7005).
Neutral Injection into W7X
F.-P. Penningsfeld

Abstract

According to the actual design of W7X the accessibility for NI-heating has been checked and beam absorption and heating efficiency are studied using theoretically estimated plasma parameters. The application of ASDEX-Upgrade NI-boxes, each housing four PINIs, is planned. An overview of this NI- system is given in report IPP 2/302, 1989. Each box delivers 6 MW neutral power for 55 kV H\textsuperscript{0} or 9 MW for 65 kV D\textsuperscript{0}. An interesting alternative could be a 100 kV D\textsuperscript{0} beam (7 MW per box) now developed for the second AUG- injector.

The study of the transmission of the port hole geometry shows that injection angles $\alpha_{ni}$ up to 20° are possible in CO and COUNTER direction. Furthermore the port holes allow to follow the vertical displacement of the plasma axis with respect to the midplane of the NI-boxes to realize optimal beam plasma intersections.

The Monte-Carlo code FAFNER\textsuperscript{1} is used to simulate the neutral beam absorption and heating efficiency. Assuming standard $n_e$- and $T_e$-profiles ($n_e(0) = 1.5 \times 10^{20}$ m\textsuperscript{-3}, $T_e(0) = 2.5$ keV) it is shown that total losses are reduced by a factor of two for an injection angle $\alpha_{ni} = 20^\circ$ compared to radial injection. For this standard discharge the typical heating profile (12 MW H\textsuperscript{0}, two NI-boxes) is shown. The dominant power losses (about 18 \%) are caused by charge exchange of fast ions with neutral background particles assuming a neutral density $n_0$ of $10^8$ cm\textsuperscript{-3} in the center and $10^{10}$ cm\textsuperscript{-3} at the plasma edge. This fact is dominated by the long slowing down time due to the assumed high electron temperature.

Furthermore the simulation of CX-losses in FAFNER\textsuperscript{1} was improved by introduction of a new method to calculate the local $n_0(R,\phi,z)$ corresponding to the actual $n_e$-profile. In a first example it is seen, that the central neutral density varies by a factor of 8 to 10 around the torus due to the absolute penetration length of cold neutral particles.
Neutral Injection into W7X

F.-P. Penningsfeld

Abstract:

**actual concept:**

Application of LPNI Asdex-upgrade

According to plans for the ASDEX Upgrade project the application of ADEX-UPGRADE is scheduled. The project is seeking the transfer of the basic injection scheme and an overview of the applied injectors to W7X. The design requires an additional scheme for the injection of deuterium and tritium into the plasma.

- **55 keV H\(^\circ\):** 6 MW per box
- **65 keV D\(^\circ\):** 9 MW per box
- **100 keV D\(^\circ\):** 7 MW per box

**main question:**

Is the actual W7X - concept accessible for NI-heating?

- geometry
- heating profiles / FAFNER 1
- losses by charge exchange

Furthermore, the simulation of CX-losses in FAFNER 1 was improved by

Introduction of a new model to calculate the local power deposition and the total heating power. A new example is seen that the central neutral density varies by a factor of 8 to 1 around the plasma.
the port diameter of 40 cm allows injection angles up to \( \alpha_{NI} = 20^\circ \);
the vertical elongation of the port allows the box midplane to follow the
vertical movement of the plasma axis.

Box position for injection angle \( \alpha_{NN} = 20^\circ \). At least two boxes are
necessary to cancel co and counter injection effects. Therefore two types
of NI-port are necessary corresponding to the toroidal angles
\(+7.7^\circ + m \cdot 72.0^\circ\) and \(-7.7^\circ + m \cdot 72^\circ\) to allow equivalent beam injection.
Neutral beam cross section in the duct region

55 keV H⁰
6 MW per box / 4 sources
beam divergence 1°

P_{\text{max}} = 14.5 \ kW/cm²

W7X/NL-port
horizontal broadness vs injection angle

D_{eff} [cm]

outer part

inner part

center

typical beam cross section

injection angle [degree] \( \alpha_{W1} \)
vertical position of the plasma axis is followed by the midplane of Ni-box

**Example:** injection angle $\alpha_{NI} = 20^\circ$

$\Phi = 0^\circ$  
$\Phi = 12^\circ$

- beam-plasma intersection at $\Phi = 10^\circ$
- $z_{box} \approx 26 \text{ cm}$ necessary

**NI-simulation using FAFNERI**

**NI-W7X / assumed temperature and density profiles**

\[ T_e(0) \text{ (eV)} \]
\[ n_e(0) \text{ (10^20 m}^{-3}) \]

**NI-W7X / beam absorption vs. line density**

source $2 / CO$

$H^+ : H_2^+ : H_3^+ = 80 : 15 : 5$

$\alpha_{NI} = 20^\circ$
**Variation of the magnetic field strength**

Example for equivalent sources in CO resp. COUNTER direction

<table>
<thead>
<tr>
<th>Source 1 / CO</th>
<th>Source 3 / COUNTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e(0) = 2.5$ keV</td>
<td>$T_e(0) = 2.5$ keV</td>
</tr>
<tr>
<td>$n_e(0) = 1.5 \times 10^{20} \text{m}^{-3}$</td>
<td>$n_e(0) = 1.5 \times 10^{20} \text{m}^{-3}$</td>
</tr>
</tbody>
</table>

**Target plasma:** standard profiles for $T_e(na)$ with peak values

$T_e(0) = 2.5$ keV

$n_e(0) = 1.5 \times 10^{20} \text{m}^{-3}$

**Main result:** shine-through losses can be reduced by a factor 2 at $\theta = 20^\circ$.

**Note:** neutral density profile used for CX-loss calculation in FAFNER1 is not realistic up to here: the neutral density at the plasma edge is assumed to be $n_e(a) = 10^{10} \text{cm}^{-3}$ with 2 decades relative decay towards the axis.

**Main result:** no significant reduction of the heating efficiency at half field operation.

**Simulation of CX-losses in FAFNER1**

**Realme of dominant CX-losses:** $t_{cx} \approx t_{sd}$

$t_{cx} = \frac{1}{\langle n_0 \sigma v_{cx} \rangle}$

$t_{sd} = 0.012 \left( \frac{m_p}{m_n} T_e^{3/2} \right) / (n_e T_e)$

**Problem:** neutral gas penetration in toroidally asymmetric plasma cross sections

**First iteration:**

estimate local neutral gas density $n_e(x)$ by integration of the actual electron density along the "short way" from point $x$ to the plasma edge using the local direction of grad $\nabla$ and typical cross sections for the penetration of cold gas neutrals (here for first test: $c = 1.0 \times 10^{14} \text{cm}^{-2}$ assumed):

$$n_e(x) / n_e(a) = \exp \left( - \int_{a}^{x} n_e(l) \, dl \right)$$
NI-W7X/ FAFNER1 with 3D-simulation of neutral density effect of CX-losses

Neutral density on the edge [10e10 cm-3]

CX-losses for increasing neutral gas density no(a)

Source2 / co

Ne(0) = 0.5 [10e20 m-3]
Te(0) = 2.5 [keV]
NI-W7X
estimated neutral density profiles at PHI = 0°

radius density [10^10 cm^-3]

PHI = 0°

Radius [cm]

NI-W7X
estimated neutral density profiles at PHI = 36°

radius density [10^10 cm^-3]

PHI = 36°

Radius [cm]
Heating Efficiency of NI

J. Junker

Ringberg 21.-22.5.1992

- Competition between slowing down and charge exchange
- Stationary power loss of fast ions
- Total heating power and CX losses

Abstract

For the injection of a neutral beam into the W7-X plasma the power going to the ions, to the electrons, and the power lost by charge exchange (cx) collisions is investigated. From the plasma center to the plasma edge the time constant for slowing down rises from ≈0.2 to ≈40 times the time constant for cx losses. The stationary solution of the Boltzmann equation for a monoenergetic source of high energetic ions by injection of neutrals, prompt loss of cx neutrals, and assuming that the rate coefficient for cx collisions is independent of the particle energy leads to closed expressions for the heating efficiencies of the ions and the electrons, and the cx losses. For plasma parameters from the transport calculations TEMPL, Te=5keV, Ti=4.3keV, ne=ni=1.5E20m-3, and taking a neutral particle density of 1E16m-3 at the wall and 1E14m-3 at the plasma center with an energy of 1keV the volume integrated efficiencies are Pl:Pe:Px=46:13:41% for 65keV deuterium injection and =41:23:36% for 55keV hydrogen injection into a deuterium plasma.
Thermalization of fast ions in a D-plasma
ion energy 50 keV, electron-, deuteron-density 1E20 m⁻³

![Graph showing time constants for slowing down](image)

The time constants for the initial energy loss by collisions with plasma-electrons and -ions are in the order of 0.02 s.

Energy loss of fast ions in a D-plasma
ion energy 50 keV, electron-, deuteron-density 1E20 m⁻³, neutral particle density 1E15 m⁻³.

![Graph showing time constants for slowing down and charge exchange](image)

Protons (H→e,D) slow down (up to 2x) faster than deuterons (D→e,D).
Deuterons (D⁺→D) get lost 2x faster than protons (H⁺→D) by charge exchange.

For deuteron injection charge exchange losses are most important.
Time constants for W7-X parameters

<table>
<thead>
<tr>
<th></th>
<th>Deuterium Injection</th>
<th>Hydrogen Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T$</td>
<td>$n$</td>
</tr>
<tr>
<td>Center:</td>
<td>5.0 keV</td>
<td>1.0E20 m-3</td>
</tr>
<tr>
<td>Gradient:</td>
<td>2.5 keV</td>
<td>5E20 m-3</td>
</tr>
<tr>
<td>Edge:</td>
<td>1.0 keV</td>
<td>2E20 m-3</td>
</tr>
</tbody>
</table>

- In the plasma center fast particles slow down.
- From the gradient region outwards $\chi$ losses dominate.
- For D injection the relative importance of $\chi$ losses is about 4x higher than for H injection.

Evaluation of the stationary power loss of fast ions

- Boltzmann equation $\partial f(v)/\partial t = L(f(v))$.
- Landau’s collisional operator for Coulomb interaction $L(f(v))$.
- Assumptions and approximations:
  - monoenergetic ions into a Maxwellian plasma, $F(v-v_0) = \delta(v-v_0)/4\pi v_0^2$.
  - fast ion velocity between thermal electron velocity and thermal ion velocity, $v_0 < v << v_i$.
  - velocity diffusion neglected compared to particle deceleration, constant rate coefficient for $\chi$ collisions, $\sigma v = \text{const.}$
  - Stationary distribution function for decelerating ions $f(v)$.
  - Stationary energy transfer to the plasma constituents and $\chi$ losses.

- Radial distribution of electron temperature, ion temperature, electron density, and neutral density.

- Volume integrated stationary heating power of the ions, the electrons, and $\chi$ losses.
The fractional heating power to the ions, the heating power to the electrons, and the CX-losses are:

\[
\sum_i \eta_i = 2 \lambda^{3/2} \int_0^1 g(u, \lambda, \mu_o) \, u \, du
\]
\[
\eta_e = 2 \int_0^1 g(u, \lambda, \mu_o) \, u^4 \, du
\]
\[
\eta = \frac{3}{2} \mu_o \eta_e
\]

where

\[
g(u, \lambda, \mu_o) = \frac{(\lambda^{3/2} + u^3)^{\mu_o-1}}{(\lambda^{3/2} + 1)^{\mu_o}}
\]

\[
\mu_o = \nu \tau_o \quad \text{ratio of CX - losses to electron heating}
\]

\[
\lambda = \frac{E_1}{E_o} \quad \left\{ \begin{array}{l}
\lambda < 1 \quad \text{heating of electrons} \\
\lambda > 1 \quad \text{heating of ions}
\end{array} \right.
\]

\[
\tau_o = \frac{\sqrt{\pi}}{4} \frac{m_e}{m_\alpha} \left( \frac{v_e}{v_o} \right)^3 \tau \quad \text{time scale for energy exchange betw. injected ions and electrons}
\]

\[
E_1 = 14.8 \, T_e \, A_\alpha \left( \sum_i \frac{Z_i^2 \, n_i}{A_i \, n_e} \right)^{2/3} \quad \text{critical energy for equal electron and ion heating}
\]
Particle velocities

The velocity of 50 keV neutrals is well between the thermal electron and the thermal ion velocity for temperatures from 1 to 5 keV.

Decay of neutral density for pure absorption.

Comparison of different angular density distributions at the wall.

The cos-distribution decreases to almost 10 times lower values at the plasma center compared to the unidirectional distribution.
Temperature and density profiles

Electron temperature 5 keV, ion temperature 4.3 keV, electron density 1.5E20 m⁻³
Neutral density: 1E10 at the wall, 1E8 at the plasma center, neutral energy: 1 keV

Integrated power profiles

Electron temperature 5 keV, ion temperature 4.3 keV, electron density 1.5E20 m⁻³
Neutral density: 1E10 at the wall, 1E8 at the plasma center

65 keV D¹⁺ -> D plasma

where

\[ g(u, \lambda, \nu_a) = \frac{\lambda^{3/2} + u^2}{\lambda^{3/2} + 1} \mu_a^{-1} \]
Heating power and cx loss

electron temperature: 5 keV, ion temperature: 4.3 keV, electron density: 1.5E20 m\(^{-3}\)
near neutral density: 1E10 at the wall, 1E8 at the plasma center

55 keV H\(^{0}\) -> D plasma

\[ P_i : P_e : P_{cx} = 41 : 23 : 36\% \]

- Electron heating is more than 1/2 of ion heating.
- CX losses are still substantial.

65 keV D\(^{0}\) -> D plasma

\[ P_i : P_e : P_{cx} = 46 : 13 : 41\% \]

- Electron heating is only 1/3 of ion heating.
- CX losses are dominant.
Integration of ion plasma

Electron loss is more than 1/2 of ion loss

Electron loss is less than 1/3 of ion loss

Electron loss is less than 1/4 of ion loss
Two different advanced stellarator configurations of the linked mirror type (LIMAS) are presented which differ in the magnetic mirror ratio and twist on magnetic axis. The vacuum fields are given analytically by a finite set of Dommaschk potentials. The magnetic field properties weighed in the optimization procedure are: the residue \( R^* \) of two reference fixed lines which start at \( Z = 0 \) in the two symmetry planes and have the same value for the twist \( \varepsilon \); the associated aspect ratio \( A \), the difference \( \Delta F \) of the magnetic flux \( F = \int A \cdot dx \) between these two closed field lines belonging to the same rational \( \varepsilon \)-value (\( A \) is a vector potential, \( x \) is the radius vector, the line integral is performed over each of the fixed field lines), the deficit of the Hamada condition that \( \int dl/B \) should have the same value for these fixed lines, the specific volume \( V' \), the measure \( (j^2/\tilde{j}^2)^{1/2} \) of the F"{u}rsch-Schl"{u}ter current density, and the deviation of contours of \( B \) from contours of \( U \) (\( U \) scalar potential).

CONFIGURATION ASC117

\[ \varepsilon_{az} = 0.47, \quad \varepsilon_8 = 0.62, \]
\[ M = 5 \text{ field periods} \]
\[ A = 11.8 \]
well \( \Delta V'/V_{az} = -1.80\% \),
\[ (j^2/\tilde{j}^2)^{1/2} = 0.95 \]
mirror ratio \( (B_2 - B_1)/(B_2 + B_1) = 14.6\% \) at axis and
22\% at the boundary,
\( B_1, B_2 \) absolute values of the magnetic field
at \( \varphi = 0 \) and \( \varphi = \pi/5 \), resp
$\varepsilon e_{p'} = 3.45/\%$

$D^*$ vs. $L^*$ graphs for different values of $\beta = 0$, $A = 20$, $Q = 100$, $P = 0.5$, and $ZOL\text{-MAX}\text{, JASC1170}$.

$D^*$ vs. $L^*$ graphs for different values of $\beta = 0$, $A = 20$, $Q = 100$, $P = 0.5$, and $ZOL\text{-MAX}\text{, JASC1170}$.

$D^*$ vs. $L^*$ graphs for different values of $\beta = 0$, $A = 20$, $Q = 100$, $P = 1$, and $ZOL\text{-MAX}\text{, JASC1170}$.

$D^*$ vs. $L^*$ graphs for different values of $\beta = 0$, $A = 20$, $Q = 100$, $P = 6$, and $ZOL\text{-MAX}\text{, JASC1170}$.

$D^*$ vs. $L^*$ graphs for different values of $\beta = 0$, $A = 20$, $Q = 100$, $P = 2$, and $ZOL\text{-MAX}\text{, JASC1170}$.
Transport coefficients for electrons and deuterons in ASC117.
$c_{ax} = 0.55, \quad c_{b} = 0.68, \quad c_{sep} = 0.71$

$M = 5$ field periods

$A = 12.0$

well $\Delta V'/V'_{ax} = -1.63\%$

$(j_{/1}^2/j_{/1}^2)^{1/2} = 0.58$ at axis

$= 0.97$ at boundary

mirror ratio \(\frac{B_{2} - B_{1}}{B_{2} + B_{1}}\) =

17.6\% at axis and

26\% at the boundary,

$B_{1}, B_{2}$ absolute values

of the magnetic field

at $\varphi = 0$ and $\varphi = \pi/5$, resp.
Contours of $|B|$ on magnetic surfaces.

$|B|$ as function of toroidal angle $\varphi$. 

$A = 24.2$

$A = 17.7$

$A = 14.2$

$A = 14.3$
Fig. Parallel current density versus rotational transform for various vacuum field configurations.
ASC620:
\[ \rho = 0.5, \quad R_o = 5.5 \, m, \]
\[ B_o = 2.5 \, T, \]
\[ T = 3 \, keV \, Electron \]
\[ \Phi_o/E_o = 0 \]
Axisymmetric:
Hazeltine-Hinton \* 0.3

ASC620:
\[ \rho = 0.5, \quad R_o = 5.5 \, m, \]
\[ B_o = 2.5 \, T, \]
\[ T = 3 \, keV \, Electron \]
\[ \Phi_o/E_o = 1 \]
Axisymmetric:
Hazeltine-Hinton \* 0.3

ASC620:
(ZOL:Max.JASC1170)
\[ \beta = 0, \quad A = 20, \]
\[ Q = 100, \quad P = 1 \]
\[ \epsilon_{eff} = 4.2 \% \]