3 MW Neutral Injection into the Stellarator Wendelstein7-AS
- Heating efficiency at high-beta operation -

F.-P. Penningsfeld, J. Geiger, W. Ott, E. Speth, W7-AS Team, NI Team

Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany

Abstract

With 3 MW of neutral power and a new non-resonant RF method of plasma start-up, W7-AS is now equipped for the investigation of high-β plasmas over a wide range of magnetic fields ($0.5 < B_0 < 2.5$ T). With full beam power, a maximum central beta of 4% at 1.27 T was obtained, however the aim of hitting the beta limit, expected at about 4.5%, by lowering the magnetic field, was not reached. In contrast to Lackner-Gottardi scaling, where $\beta \propto n^{0.6} P^{0.4} B^{-1.2}$ can be expected, no increase in $<\beta>$ was seen even at reduced B despite constant neutral input power. In this paper it is shown, that one of the reasons for this behaviour is a degradation of the heating power with decreasing magnetic field; not due to transmission or reionisation losses of the neutral beams, but due to increasing fast ion orbit losses with decreasing magnetic field.

Introduction

The power level of Neutral Beam Injection (NBI) into the W7-AS Stellarator has been increased from 1.5 to 3.0 MW in order to extend the accessible range of plasma parameters in this device. The beta values achieved at 1.5 MW were about a factor 2 below the equilibrium limit. Furthermore, since the energy confinement time in W7-AS scales favourable with density and the maximum density obtained increases with power, this was an additional incentive for upgrading the beam power.

Therefore, the number of ion sources was increased from 4 to 8 which doubled the available neutral power. Experiments with the upgraded power began in spring 1995. The extended parameter regimes are still being explored. This paper reports the present status.

In an attempt to understand the experimental findings, the computations of the heating efficiency had to be repeated and extended because the plasma limiters have been changed to inner limiters and the magnetic field range of NI discharges was widened up by start-up with 900 MHz RF. The variations of the flux surfaces with increasing β became much stronger than earlier [1]. The vacuum magnetic field configuration as used previously was therefore no longer appropriate for the computation of the beam deposition in the plasma. A series of FAFNER runs [2] with finite-beta plasma configurations and variations of the magnetic field had to be done. The main results are a somewhat more favourate heating efficiency at low plasma densities than earlier and a strong reduction of the heating efficiency for low magnetic field operation.

Status of the 3MW Neutral Injection on W7AS

Total and neutral power of 45 kV H^0-beams delivered into the torus were measured by a reinstalled calorimeter inside the torus for one box. The results confirm the estimated power transmissions per source for not fully optimized divergence and beam steering. Comparison of single source operation with and without magnetic field of W7-AS show a reduction by reionization of about 12% mainly caused by high pressure in the front part of the NI-box, not in the duct itself. It was confirmed, that a common operation of all sources over 0.3 s, limited by the inertial calorimeter plate, does not show beam blocking.

NI heating efficiency for $\beta > 0$ in W7-AS

Two motivations lead to a resumption of calculations with FAFNER to update the heating profiles of NBI in W7-AS: the change of the limiter geometry and the high Shafranov shift due to the higher beta values obtained. The variations between vacuum field and finite beta equilibrium flux surfaces, as shown in fig.1, are dominated by the large increase of the plasma cross section and by the Shafranov shift of about 7.5 cm in the $\phi = 0^{\circ}$ plane for highest beta obtained up to now [1]. Lower and upper limiter used in earlier campaigns were removed and the plasma now is only controlled by the inner limiter and the vertical field. To clarify the effect of these modifications on the global NI heating efficiency, especially as function of the magnetic field strength and target density, the Monte-Carlo code FAFNER [2] was used, not only in 3D guiding centre but also in real orbit calculation at very low fields, where the gyro radius of fast ions starting nearly parallel to B (pitch angle of the starting ions is in the range of $22^{\circ} < \gamma < 35^{\circ}$) becomes greater than the |grad p| - region of typical 2-3 cm in the outer part of high density NI discharges.

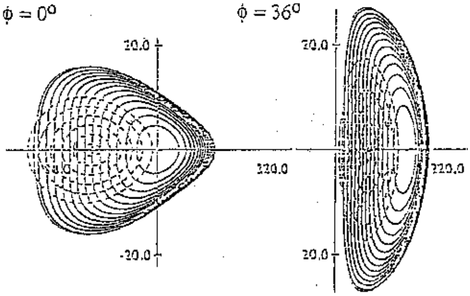


fig. 1: Comparison of vacuum field (dashed) and finite beta equilibrium flux surfaces at the toroidal angles $\phi = 0^{\circ}$ and $\phi = 36^{\circ}$

The calculations use the measured density and temperature profiles with $n_e(0) = 1.8*10^{20}$ m^{-3}, $T_e(0) = 350$ eV with full beam power, where the obtained $<\beta>$ was 1.8%. For density and temperature scans, these central values are scaled. The results for the global NI heating efficiency as a function of the line density $\int ndl$ for co and counter beams of inner and outer sources for 1.25T are shown in fig.2a. The maximum beta obtained corresponds to $\int ndl = 0.64*10^{20}$ m^{-2}.

Fig.2b shows the corresponding results for the vacuum field (β=0 , B = 1.25T) as used before, including the inner limiters, but using a fixed radial position. This radial position corresponds to a beta value of about $<\beta> \approx 0.75\%$ of the new data set. Therefore, the differences between both results are low ($< 10\%$ for $\int ndl > 0.3*10^{20}$ m^{-2}).

For lower line densities the results differ somewhat more, depending on the source position, because the target plasma moves to the inner limiters and shrinks in diameter typically by a factor of 1.5 (see fig.1 also).

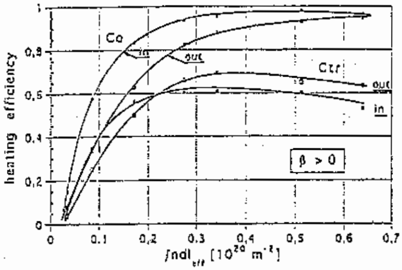


fig2.a: heating efficiency as function of line density using flux surfaces of the corresponding beta for all types of NI sources .

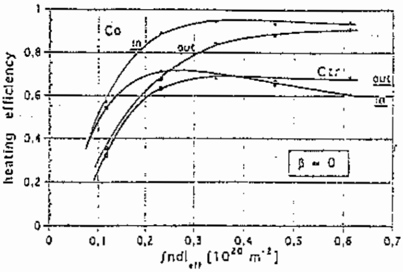
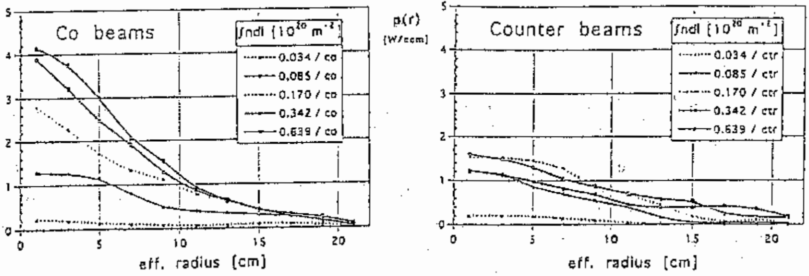


fig.2b: heating efficiency versus ∫ndl for β=0 as used up to now with the effect of inner limiter; (n,T)-profiles in both cases are similar

The radial heating profiles for co and counter beams (each 1.5 MW neutral power) obtained by FAFNER in guiding center approximation are shown in fig.3. For $\int ndl > 0.10*10^{20}\ m^{-2}$ the counter beams deliver only half of the power of the co beams in the inner plasma region with $r/a \leq 0.3$. The high beta studies done so far, show a central heating power of about 5.4 W/cm^3 (co + counter) in a wide density range of $0.34 < \int ndl < 0.64\ [10^{20}\ m^{-2}]$.

fig.3: NI/W7AS heating profiles p(r) for various line densities including Shafranov shift. left (right) side shows the contribution of all four co (counter) beams (each for 1.5 MW).



Results of real orbit calculations for low field operation

When the magnetic field strength is lowered, $<\beta> \propto n^{0.6}\ P^{0.4}\ B_0^{-1.2}$ should increase as long as plasma heating power P and confinement are not deteriorated. However, the B_0- dependence of the heating efficienciy η shows a strong drop at about 0.5 T for co beams and at ≈1.0 T for counter beams (see fig.4). The calculations were done for a fixed target density of

$n_e(0) = 1.0*10^{20}$ m^{-3} and temperature of $T_e(0) = 350$ eV using real orbit calculations for the first toroidal orbit of each particle.

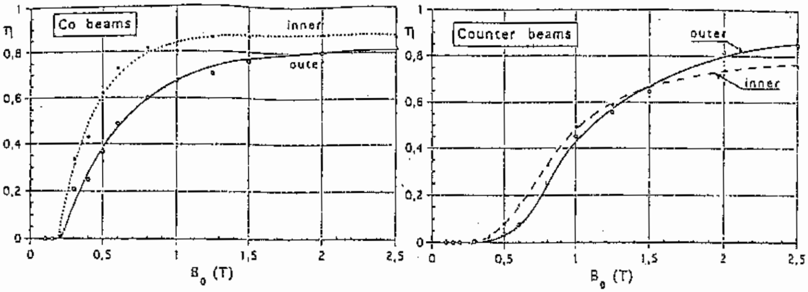


fig.4 : Heating efficiency for NI/W7AS as function of the magnetic field B_0 for inner and outer sources of co and counter beams with real orbit calculation for the first toroidal orbit.

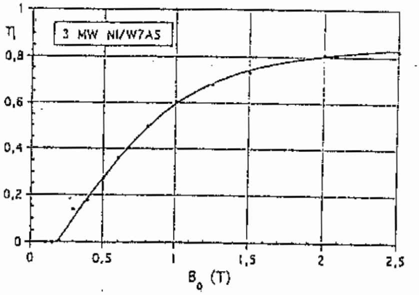


fig.5: heating efficiency for all 8 sources of NI / W7-AS for same target as used in fig.4

The heating efficiency of all 8 sources together (4 co and 4 counter beams) as a function of the magnetic field B_o is shown fig.5 for the same target conditions. Below 1T the NI-heating drops strongly and reduces $P = \eta(B_0) * 3.0$ [MW] from ≈ 2.2 MW at 1.25 T to 1.0 MW at B_0≈ 0.6 T. These M-C-results are in good agreement with a newly published paper on orbital aspects at low field in CHS [3]. The dependence $\eta = \eta(B)$ as shown in fig.5 explains at least qualitatively that no increase of <β> was found when the field strength was lowered (see also [4]).

Up to now the real orbit calculations were done without a radial electric field, because for B > 1.0 T no essential effects were seen in earlier calculations [5]. But at low magnetic field operation a strong radial E-field may influence the orbits again. A study of this effect is under way.

References

[1] *R.Jaenicke et al.*, High power heating experiments on the Wendelstein 7AS Stellarator, Plasma Phys.&Contr.Fus., **37**, A163, 1995

[2] *F.-P. Penningsfeld* : NBI studies for W7-AS using the 3D computer code FAFNER 11th Conf. on Contr.Fus.&Plasma Phys., vol **7d**, part II, pp323, Aachen, Sept. 1983

[3] *S.Murakami et al.*, Orbital aspects of reachable β values in NBI heated HELIOTRON / TORSATRONS, Nucl.Fus., **36**,no3,letters pp359, 1996

[4] *J.V. Hofmann et al., Stellarator optimization studies in W7-AS, TL of this conference*

[5] *A.Teubel, F.-P. Penningsfeld* Influence of the electric field on the heating efficiency in W7-AS, Proc.19th EPS. Conf.Plas.Phys., **16c**, part 1, p 537, 1992