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The Role of Magnetic Shear in the Confinement of W7-AS Plasmas

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Abstract

Magnetic shear has systematically been varied by inductive current drive in moderate β, ECR heated W7-AS discharges. Confinement is found to depend strongly on magnetic shear in the presence of high order rational values of the rotational transform. For optimum confinement, high order resonances have to be avoided in the boundary region, or shear must be sufficiently large. The observed improvement of degraded confinement with increasing shear is associated with a reduction of transport to the neoclassical level.

Keywords:
W7-AS, stellarator, magnetic shear, confinement, transport

1. Magnetic Shear in W7-AS Confinement

Shear in the magnetic field is generally expected to reduce anomalous transport by radial decorrelation of turbulent structures. In tokamaks, a synergy of improved stability at low or reversed (in the tokamak sense, *i.e.* $dq/dr < 0$) magnetic shear and $E \times B$ flow shear is supposed to give rise to the recently observed internal transport barriers[1]. In particular in stellarators, the quality of flux surfaces and their susceptibility to magnetic perturbations sensitively depends on the magnetic shear.

In Wendelstein 7-AS (W7-AS) the rotational transform ι of the vacuum field has very low shear which, at finite β, is modified by pressure driven (bootstrap- and, in W7-AS reduced but still significant, Pfirsch-Schlüter (PS)-current) and, optionally, by externally driven plasma currents. Due to the small shear, magnetic islands of considerable size may form at rational ι-values being in resonance with the major external field perturbations ("natural" $5/m$-components from the 5-fold toroidal symmetry, and 1/3- and 1/2-components from field errors)[2]. With increasing β, the sensitivity of confinement to these resonances diminishes, giving evidence of a beneficial effect of pressure induced shear [3]. Although the major resonances play a role, the detailed dependence of W7-AS confinement on the boundary value ι_a of the rotational transform cannot be explained by the external field perturbations [2]. Therefore perturbations at the higher order $\iota = n/m$ resonances may be important. Their impact will depend on the magnetic shear.

In the present study, shear has been applied by inductive current drive to ECR heated discharges at

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moderate β ($\beta_0 < 1\%$). The experiments are interpreted on the basis of ι-profiles calculated by the NEMEC equilibrium code [4], with inductive and bootstrap current profiles from the DKES code [5]. Plasma currents up to $I_p = \pm 30$ kA have been applied. They contribute $\Delta\iota_a = (\mu_0 R I_p)/(2\pi a^2 B_0)$ to the boundary transform, *i.e.* 0.007/kA for the typical parameters a=0.15 m, R=2 m and B_0=2.5 T of this study (positive currents increase the rotational transform). The NEMEC calculations show that for fixed limiter aperture the effective plasma radius changes with plasma current as $\Delta a/a = 0.004 I_p$/kA. Ohmic heating is negligible (< 10 kW) as compared to ECRH (450 kW at 140 GHz). The pulse length of 1.1 s is above the current diffusion time scale.

Figure 1 shows the dependence of energy confinement on both ι_a and I_p. The plasma energy has been derived from the diamagnetic loop signal, with a correction accounting for residual magnetic flux from large plasma currents, which is determined from the kinetic electron energy content at ι_a=0.51 (from profile integration). The electrons dominate the total energy: ion temperatures are below 450 eV compared to electron temperatures up to 2 keV. Limiter aperture and line-integrated densities are identical for all discharges, *i.e.* the plasma radius increases from 0.15 m at I_p=0 to 0.165 m at I_p=25 kA and the central densities decrease from 4 to 3.5×10^{19} m^{-3} (optimum confinement in W7-AS scales $\propto a^2 n^{0.5}$ [6]). With small net current ($I_p \leq 5$ kA) a strong dependence of confinement on the rotational transform is observed which is smoothed by increasing the current (to +15 kA) and disappears at the highest current (+25 kA). Here, the level of optimum confinement in the current free case is reached.

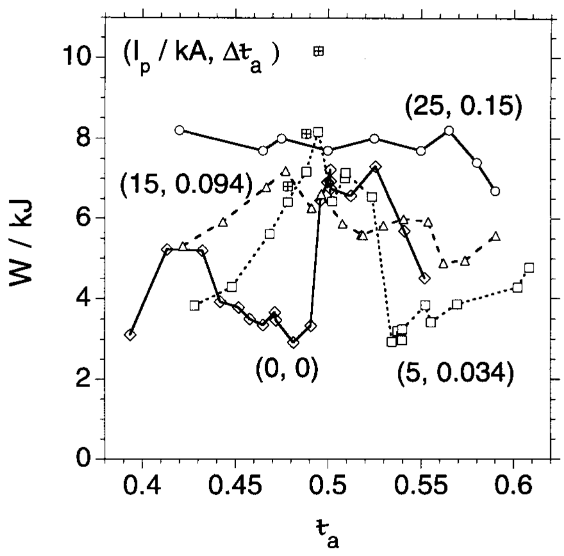

Fig. 1 Dependence of plasma energy on the boundary rotational transform for various plasma currents. For three discharges at I_p = 5 kA density control was lost and the measured energy (crossed squares) has been scaled by $n^{1/2}$ (squares)

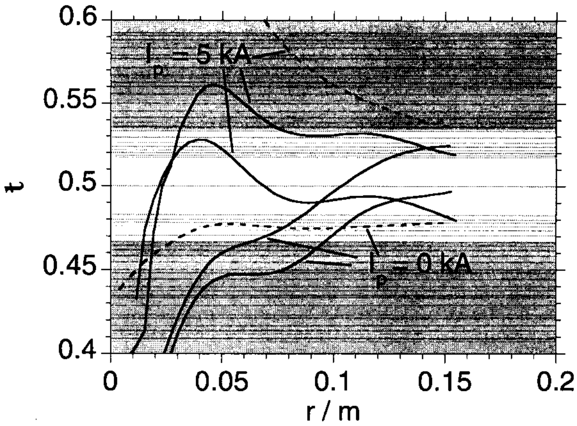

Fig. 2 Calculated ι-profiles for discharges with net plasma current as indicated (full lines: optimum confinement; dashed lines: degraded confinement). Rationals n/m, $m \leq 30$, are given for reference (horizontal lines; the shaded area covers the range of rationals with $m \leq 15$).

2. Confinement at Moderate Shear

For the discharges of Fig. 1, degraded confinement is associated with a very flat electron temperature profile at larger radii (r > 0.05 m), whereas for good confinement, a strong T_e-gradient extends to the edge. The density profiles are similar for all discharges. Figure 2 shows the calculated profiles of the rotational transform for low current discharges (I_p=0 and 5 kA) at selected ι_a-values close to 1/2, where the sensitivity of confinement to ι_a is strongest. The rational values $\iota = n/m$ up to m=30 are given for reference. The close vicinity of ι=1/2 is free from such resonances (see also Ref. [7]). The calculated bootstrap current reaches up to 7 kA in case of optimum confinement, but only up to 2 kA for degraded confinement. For low confinement with small bootstrap current (dashed lines in Fig. 2), shear is basically determined by the inductive current, *i.e.* remains low if no net current is imposed. For good confinement (full lines in Fig. 2), both low or moderate shear may result from the combination of inductive and bootstrap current density profiles.

The analysis gives evidence that confinement in W7-AS essentially depends on magnetic shear and resonant ι-values in the outer plasma region: for optimum confinement $\iota(r)$ has to be in the "resonance-free" region (*e.g.* ι_a=0.48 at I_p=5 kA), or shear has to be sufficiently large in the presence of high order n/m-resonances of the rotational transform (*e.g.* ι_a=0.495 at I_p=0). In contrast, degraded confinement is associated with low shear in the presence of such resonances (*e.g.* ι_a=0.48 at I_p=0). With respect to the maximum m-number which determines the width of the "resonance-free" region, the experimental ι_a-values for the onset of confinement degradation below ($\iota_a \approx 0.49$) and above ($\iota_a \approx 0.53$) ι_a=1/2 are not consistent. However, since at present we do not know which specific perturbations at the high order rational surfaces enhance transport, there is no *a priori* reason for such a symmetry. Furthermore, the rather strong natural 5/9 perturbation will be important as well for $\iota_a \geq 0.53$. It gives rise to magnetic boundary islands which cannot be accounted for by the NEMEC code.

3. Proceeding to High Shear

If, for ι_a=0.51, the net current is increased from 5 to 7.5 kA, optimum confinement strongly degrades, probably because $\iota(r)$ is raised with low shear into the upper "resonance" region (Fig.3; here, the variation of plasma radius with current is compensated by proper adjustment of the limiter aperture). Confinement recovers, when shear is increased by higher currents. For ι_a=0.42, confinement improves continuously with currents of both sign. In the low density case included in Fig. 3 from a previous study, the stagnation with high negative currents is attributed to the approach of very small central ι-values [8].

It is obvious, that the effect of magnetic shear on local transport can at best be assessed from the degraded situation at ι_a=0.42, which is free from effects related to the "resonance-free" zones. Figure 4 shows the radial profiles of electron temperature and heat conductivity (from power balance analysis) for discharges with plasma currents of 0, ±10, and +25 kA. With increasing shear a continuous steepening of the T_e-gradient is observed at the boundary independent on the sign of shear. In this region (0.08 to 0.14 m) the heat conductivity decreases by a factor of up to 5. As compared to neoclassical transport, the experimental χ_e is anomalous over the whole plasma cross section for I_p=0, neoclassical in the very center for ±10 kA, and neoclassical up to $r/a \leq 0.7$ for +25 kA. Only at the very plasma edge transport remains strongly anomalous. Thus, with increasing shear, the region dominated by neoclassical transport continuously expands towards the boundary due to the increase of neoclassical transport with temperature and a simultaneous strong reduction of anomalous transport. The results are consistent with those of Ref. [8] (low density in Fig. 3, $T_e \leq 4$ keV) where χ_e decreased by a factor of up to 2. At the higher collisionality of the present study neoclassical

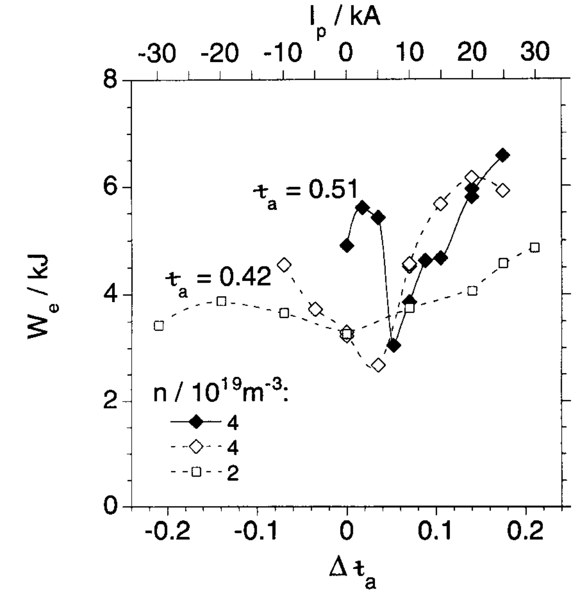

Fig. 3 Dependence of the electron kinetic energy content on plasma current for ι_a=0.51 and ι_a=0.42.

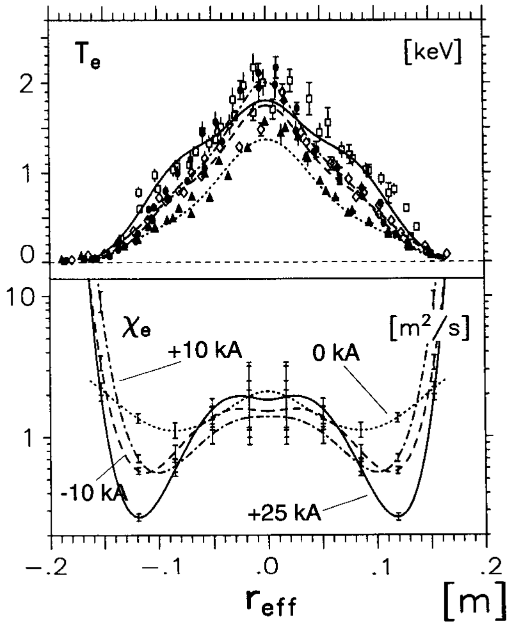

Fig. 4 Measured T_e-profiles and χ_e-profiles from power balance for discharges at ι_a=0.42 for various plasma currents.

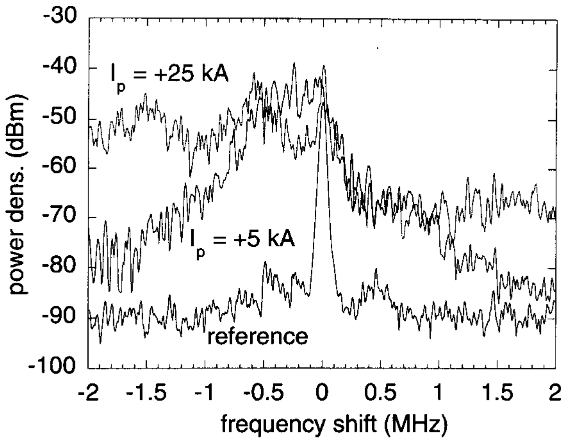

Fig. 5 Reflectometry spectra from discharges with plasma currents of 5 and 25 kA at ι_a=0.42. The spectrum from wall reflection without plasma is given for reference.

transport is significantly smaller, and the observed improvement by reduction of anomalous transport with increasing shear is more pronounced.

Reflectometry spectra indicate significant systematic changes of plasma turbulence with increasing magnetic shear (Fig. 5). A broadening and a large red-shift in the spectra is observed. In addition, the coherent peak of the unshifted mm-wave carrier, which cannot be observed for reflection in the low-shear plasma, reappears. These features gradually strengthen with the magnitude of shear and are independent of its sign. The quantitative interpretation of reflectometry spectra is difficult, since the propagation and k-spectra of the turbulence and the specific antenna-plasma geometry influence the spectrum of the reflected and backscattered mm-wave. However, the observed broadening and frequency shift would be consistent with a decrease of the turbulence scale length and an increasing plasma rotation in the electron diamagnetic drift direction, respectively. Unfortunately, direct spectroscopic measurements of the plasma rotation which could support this hypothesis are not available for these discharges.

4. Summary

Confinement in W7-AS at moderate β is found to be strongly related to high order rational values of the rotational transform and to the magnetic shear. For optimum confinement, these resonances have to be avoided in the boundary region or shear must be sufficiently large if they are present. Therefore, with moderate plasma current (up to the order of the bootstrap current) the boundary rotational transform has to be adjusted to the narrow "resonance-free" region close to the major resonances 1/2 and 1/3. With ι_a in the "resonance" region, confinement degrades strongly since shear remains low. So far it is not clear which specific perturbations at the high order rational surfaces enhance transport and are stabilized or decorrelated by the magnetic shear. Increasing the shear with higher plasma current for a degraded situation continuously improves confinement back towards the optimum. Transport analysis indicates a strong reduction of transport to the neoclassical level. The effect is independent of the sign of shear.

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