ON THE INFLUENCE OF ROTATIONAL TRANSFORM AND MAGNETIC SHEAR ON CONFINEMENT IN THE W7-AS STELLARATOR

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1. Introduction

Confinement in low shear stellarators is - at moderate β - known to be very sensitive to the boundary value ι_a of the rotational transform. Optimum confinement is established in narrow operation windows around low order major rationals ι_a =1/2, 1/3, etc. These regions are free from the otherwise densely spaced higher order rational ι-values [1]. In W7-AS, there is evidence that internal perturbations at such higher order rational flux surfaces cause confinement degradation by enhancing the anomalous electron energy transport. Their effect is reduced with increasing magnetic shear [2]. Although being very low in the vacuum field, magnetic shear is introduced at finite β by the intrinsic pressure driven (bootstrap, Pfirsch-Schlüter (PS)) and by externally (inductively, electron cyclotron resonance (ECR), neutral beam) driven currents.

Here, we compare experimental data from moderate density ECRH discharges in W7-AS with a simple transport model, which self consistently accounts for the mutual dependence of shear (from bootstrap and inductive current) and confinement by using an electron heat conductivity which empirically depends on the magnetic shear and the location of rational ι-values.

2. The model

In the ECR heated discharges under consideration the electrons dominate the plasma confinement. The electron temperature profile $T_e(r)$ is calculated from a simplified power balance, which neglects convective and radiation losses as well as electron-ion coupling. Guided by experimental results [2], a dependence

$$\chi_e(r,\iota,\iota') = \chi_0(r) + \Sigma\, \chi_{nm}(\iota,\iota'),\;\; \chi_0 = \exp(\Sigma c_i\,(r/a)^i)\ \mathrm{m^2/s},\;\; \chi_{nm} = \alpha_{nm}\exp(-|\iota - n/m|/\delta - \gamma\,|\iota'|\,)$$

is assumed for the electron heat conductivity χ_e. χ_0 accounts for the transport at optimum confinement, the parameters c_i being adjusted to reproduce the experimental $T_e(r)$ in the absence of resonances. The neoclassical contribution to χ_e is included in χ_0. χ_{nm} describes an additional enhancement of χ_e near a rational value $\iota = n/m$ which is damped with increasing absolute value of the magnetic shear $\iota' = d\iota/dr$. a is the minor plasma radius; the parameters

α_{nm}, δ, and γ have to be determined by comparison with experiments which vary $\iota(r)$.

The rotational transform profile $\iota(r)$ is calculated from the vacuum field and the toroidal bootstrap and inductive current densities, j_{OH} and j_{BS}. The PS current is neglected. For the bootstrap current density $j_{BS} = 0.7\, j_{BS}^{HH}$ is used, where j_{BS}^{HH} is the bootstrap current density in a circular tokamak [3]. The factor 0.7 adjusts the current to the value obtained with the DKES code [4] for optimum confinement (in the plateau regime a factor of 0.5 would be expected for a tokamak with the mean elongation of the W7-AS flux surfaces). The inductive current density profile is calculated from the tokamak neoclassical conductivity [3] and normalized such that bootstrap and inductive current add up to the given net plasma current I_p. Density and power deposition profiles, $n_e(r)$ and $P_{heat}(r)$, net plasma current and boundary value ι_a of the rotational transform are input to the model. For all conditions $Z_{eff} = 2$ and $T_e(a) = 100$ eV are used. $\iota(r)$ - and thus $\chi_{nm}(r)$ - and $T_e(r)$ are selfconsistently determined in an iteration procedure which starts with the optimum confinement profile for $T_e(r)$.

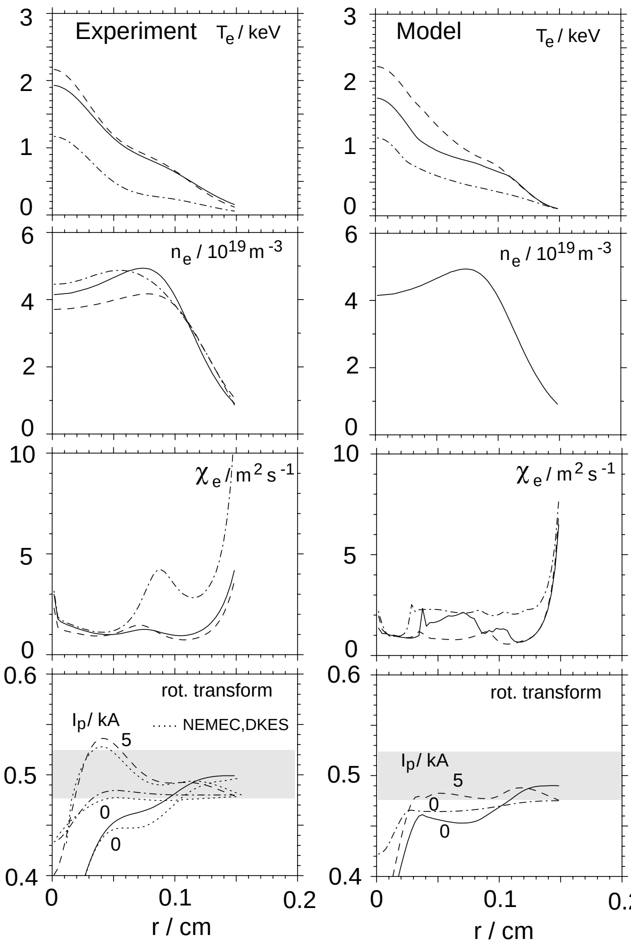

Fig. 1. Radial profiles of electron temperature, density and heat conductivity and profiles of the rotational transform for plasma currents of 0 and 5 kA and ι_a = 0.480 and 0.495. The shaded areas indicate the ι-range which is free from resonances with $m \leq 20$. Left: experiment. Right: model.

3. Results

Experimentally, the dependence of confinement on the boundary value of the rotational transform and the net plasma current has been investigated in stationary discharges heated by 450 kW ECRH at central densities $n_e \approx 4 \times 10^{19}$ m^{-3} (B = 2.5 T, R = 2 m, a = 0.15 m, $\beta_0 \leq 0.6\%$, for details see [2]). In the model, rational values up to m = 20 and the following set of parameters have been used: $c_0 = -0.1$, $c_2 = -1.0$, $c_6 = 2.0$, other $c_i = 0$, $\delta = 0.004$, $\gamma = 1.1$ m, and $\alpha_{nm} = 1.1\, g_{nm}^{-1}$ m^2/s. g_{nm} is the degeneracy of a n/m value, i.e. every rational number is counted only once.

Radial profiles are shown in Fig. 1 at selected values of ι_a and I_p which yield optimum and degraded confinement near ι_a = 1/2. At least at the outer radii, $r/a > 0.5$, the model reproduces the experimental profiles quite well. The T_e-profile flattens when $\iota(r)$ lies in the zone with densely spaced resonances, and becomes steep otherwise. A single density profile was

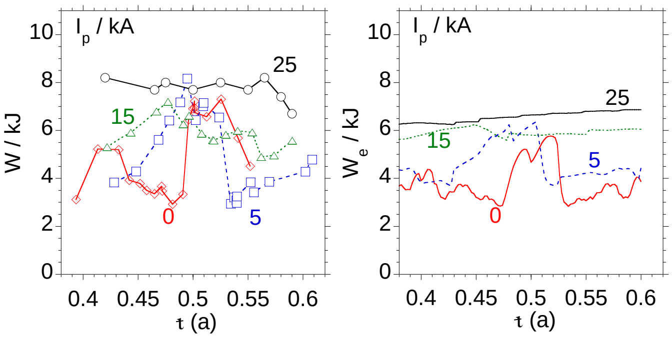

Fig. 2. Dependence of plasma energy (experiment, left) and electron kinetic energy (model, right) on the boundary value of the rotational transform for various plasma currents.

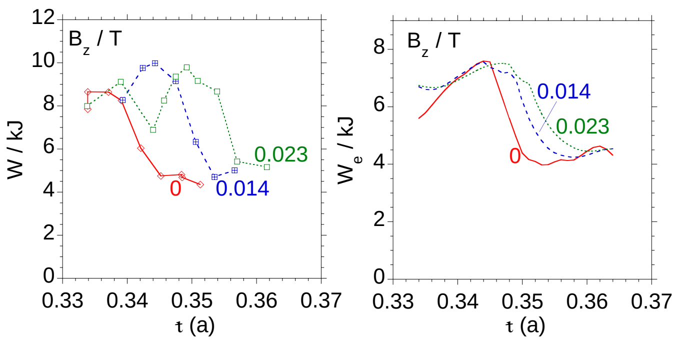

Fig. 3. Dependence of plasma energy (experiment, left) and electron kinetic energy (model, right) on the boundary value of the rotational transform for various values of the vertical magnetic field (I_p = 0).

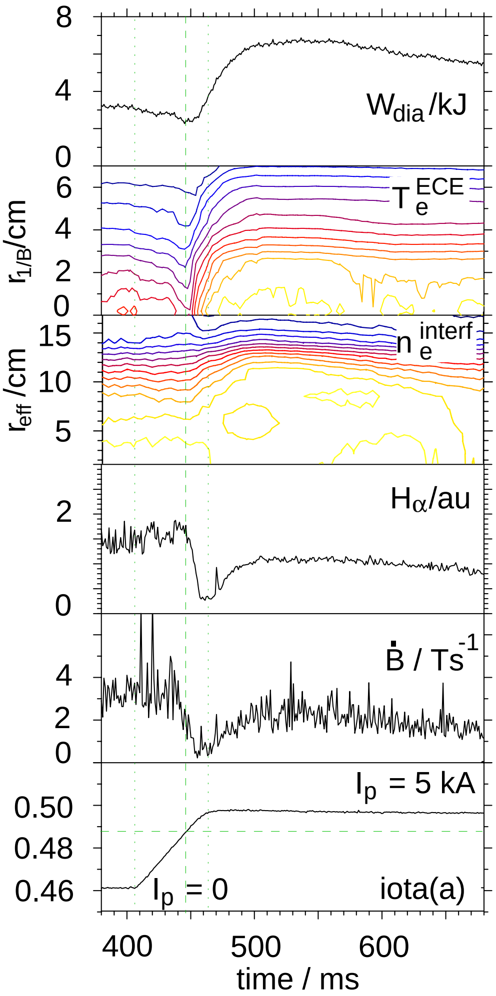

Fig. 4. Time traces of plasma energy, H_α light, magnetic fluctuations and boundary rotational transform, and time evolution of temperature (from ECE) and density (from interferometry) profiles during a transition from degraded to optimum confinement induced by a current ramp.

used since the measured density profiles change only slightly (in the experiment the line averaged density was kept constant by feedback control). To calculate $\iota(r)$, the tokamak approximation has been used for j_{BS} and j_{OH} in both cases, experiment and model. ι-profiles calculated with j_{BS} and j_{OH} from the DKES code [4] and PS currents from the NEMEC code [5] are given for reference. The observed dependencies of global confinement are qualitatively reproduced for a wide range of ι_a and I_p by the model as well (Fig. 2).

The model can also account for details of confinement near ι_a = 1/3 (Fig. 3, a = 0.17 m, $n_e \approx 8 \times 10^{19}$ m^{-3}). The shift of the optimum confinement zone to larger ι_a-values with a vertical magnetic field B_z arises at least partly from the positive shear which is introduced at the boundary by the vertical field. Note, that these discharges have higher densities and some assumptions of the simple model may no longer be valid, e.g. the smallness of electron-ion coupling and PS currents.

Along with improved confinement, a reduction in the measured fluctuation level is observed when the rotational transform is moved into a resonance free region. Figure 4 shows a transition which is induced by a plasma current ramp from $I_p = 0$ to 5 kA. As soon as ι_a comes into the resonance free region, confinement improves by a persistent steepening of the T_e-gradient, while the n_e-profile steepens transiently and then relaxes slowly to its initial form. Comparing the stationary phases before and after the transition, the level of H_α light indicates improved particle confinement, which is compensated by a reduced gas puffing rate. The reduction of the fluctuation level is seen from the H_α light, microwave scattering and Mirnov probes. The frequency spectra of density (Fig. 5) and magnetic fluctuations narrow significantly.

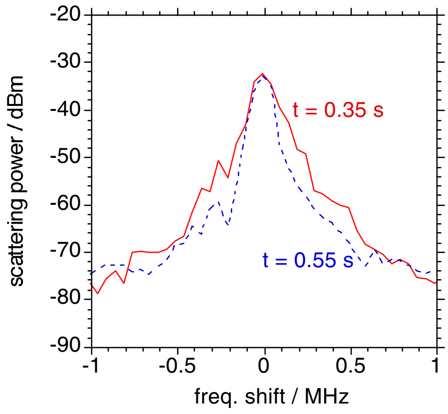

Fig. 5. Microwave scattering spectra before and after the transition for the discharge in Fig. 4.

Another way to obtain good confinement even in the presence of resonances is to provide sufficient magnetic shear in the boundary region, e.g. by an inductive current (see the 25 kA curve in Fig. 2, the bootstrap current is of the order 7 kA for optimum confinement). Although the temperature gradient strongly increases with shear [2], a clear correlation between magnetic shear and the observed fluctuations has not yet been found.

4. Conclusions

In spite of its simplicity, the presented model reproduces the basic dependencies of confinement on rotational transform and plasma current induced shear in moderate β, ECR heated W7-AS plasmas. The qualitative agreement with experimental results over a wide range of parameters (ι_a, I_p, B_z) gives strong support to the hypothesis that electron energy transport is enhanced in the presence of higher order rational values $\iota = n/m$ with $m \leq 20$ of the rotational transform and that these perturbations are reduced by magnetic shear. For optimum confinement such resonances have to be avoided at least in the boundary region, i.e. ι_a must be set to the resonance free regions near $\iota_a = 1/2$, 1/3, etc, or shear must be sufficiently large, i.e. $\iota' \geq o(\gamma^{-1} \approx 1\ \mathrm{m}^{-1})$, which is achieved with an inductive plasma current.

In the absence of higher order resonances the measured level of density and magnetic fluctuations reduces significantly. Their mode structure could not be identified yet and it is still not clear which kind of perturbations/instabilities enhance the electron transport.

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