BOOTSTRAP CURRENT AND BALLOONING STABILITY IN ASDEX L AND H PLASMAS

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ABSTRACT: The effect of bootstrap and neutral-beam-driven currents on the loop voltage, toroidal current density and ideal ballooning stability was investigated in various phases of H discharges by computer simulations. It is found that the loop voltage computed with neoclassical resistivity is only compatible with the measurements if Ohmic, bootstrap and beam-driven currents are included. The sum of the bootstrap current (100 kA with broad profile) and beam-driven current (50 kA with peaked profile) reaches 47 % of the plasma current. The field diffusion effect connected with all contributions is assessed by inclusion of these currents in the B_p diffusion equation. The main effect is the adjustment of the total current density to the broader electrical conductivity profiles in the H phase on the resistive diffusion time scale of about 400 ms. The broadening due to the bootstrap current is comparatively small, so that the ideal ballooning stability is scarcely modified by this current.

INTRODUCTION: Evidence of bootstrap currents in tokamaks was recently reported from TFTR /1/ and JET /2/. The present paper explores the bootstrap and neutral-beam-driven currents, the total current density and the ideal ballooning stability in L and H plasmas of ASDEX. The simulations are carried out by modified versions of the BALDUR predictive transport code /3, 4/. Local, empirical electron heat diffusivities χ_e, diffusion coefficients D and inward drift velocities v_{in} are used to describe the anomalous energy and particle fluxes /5, 6/.

COMPUTATIONAL MODEL: The bootstrap current density is computed from an expression /7/ valid in the banana regime since in high power injection-heated ASDEX plasmas both the electrons and the ions are collisionless ($\nu_{*e} < 1$, $\nu_{*i} < 1$):

$$j_{bs} = c\ \varepsilon^{1/2}\ B_p^{-1} \left[K_{13} \left(- \frac{\partial p_e}{\partial r} - \frac{n_e}{n_i}\frac{\partial p_i}{\partial r} + \frac{1.17}{1+\nu_{*e}^2\varepsilon^2}\, n_e \frac{\partial T_i}{\partial r}\right) + (2.5\ K_{13} - K_{23})\ n_e \frac{\partial T_e}{\partial r} \right] \qquad (1)$$

Here, c is the speed of light, $\varepsilon = r/R_o$ and K_{13} and K_{23} are dimensionless transport coefficients.

The build-up of bootstrap and beam-driven currents induces return currents in the plasma which decay on the resistive time scale. This field diffusion effect is assessed by including

$$E_t = \eta\ (j - j_{bs} - j_{bd}) \qquad (2)$$

in the diffusion equation for B_p, where η is the neoclassical resistivity and E_t is the toroidal electric field induced by the OH circuit and by the bootstrap (j_{bs}) and beam-driven (j_{bd}) currents.

Ideal ballooning stability is analysed by the transport code which evaluates the local criterion /8/

$$-\frac{2\,R_o q^2}{B_t^2}\left(\frac{\partial p}{\partial r}\right)_c = f(s) \qquad (3)$$

where $(\partial p/\partial r)_c$ is the critical pressure gradient and f(s) is a known function of the dimensionless shear $s = (r/q)\partial q/\partial r$. In the pressure gradient both the thermal pressure and the anisotropic beam pressure are taken into account, the beam contribution being derived from fast ion guiding centre distributions.

CURRENT PROFILES AND BALLOONING STABILITY: An H discharge with $\bar{n}_e = 3.3 \times 10^{13}$ cm^{-3}, I_p = 320 kA, B_t = 1.85 T and neutral co-beam power P_{NI} = 3.45 MW ($H^o \rightarrow D^+$) is analysed (see Fig. 1). The L-to-H transition occurs at t = t*. Transport is simulated in the whole plasma, including the scrape-off layer and the steep gradient zone (width $\Delta \simeq 2.5$ cm) close to the separatrix during the H phase. The transport model applied /9,10/ yields a good fit to the measured n_e, T_e and T_i profiles and β_p^{dia}. Neoclassical resistivity and uniform Z_{eff} = 2 are assumed in the computations.

The time evolution of the loop voltage is shown in Fig. 2. Obviously, the loop voltages calculated with Ohmic, bootstrap and beam-driven currents included come close to the measurements while those with Ohmic current only do not.

The current distributions in the L and H phases are given in Figs. 3 and 4, respectively. Broad profiles are found for the bootstrap current, whereas the beam-driven current is peaked like the Ohmic one. The bootstrap and beam-driven currents in the L phase are I_{bs} = 63 kA and I_{bd} = 57 kA, respectively. During the H phase I_{bs} = 100 kA and I_{bd} = 50 kA are obtained. Their sum reaches 47 % of the total current. Since the resistive time scale for current redistribution is $\tau_{res} \approx 400$ ms, very little diffusion occurs between Figs. 3 and 4. Near the separatrix, however, skin times are much shorter, so that the hump on $j_{bs}(r)$ due to the steep pressure gradient in the zone Δ becomes visible on the total current profile.

Figure 5 illustrates that the current distribution in the H phase is broader than that in the Ohmic phase. On time scales much shorter than τ_{res}, the current profile in the hot plasma is left almost unchanged by the non-Ohmically driven currents. The simulation of another H discharge has shown that the current density mainly adjusts to the broader electrical conductivity profiles in the H phase on the scale $\tau_{res} \approx 400$ ms. The broadening due to the bootstrap effect is found to be comparatively small.

Including Ohmic, bootstrap and beam-driven currents in the ballooning stability analysis yields the results presented in Fig. 6, where the pressure gradient normalized to the critical value from Eq. (3) is plotted versus the radius. In the case with Ohmic current alone results differing by just a few per cent are obtained. This is due to the almost identical j, q and s profiles in the two cases. During the L phase the pressure gradient is everywhere below 40 % of the critical value. The edge plasma is found to be ideal ballooning stable even if bootstrap and beam-driven currents are taken into account. The steep pressure gradient in the zone Δ during the H period drives the edge plasma close to marginal stability.

Ballooning stability was also analysed in the phase prior to reaching of the beta limit, i.e. before the onset of additional transport losses. It is found that ideal ballooning stability at the β limit is modified very little by the bootstrap and beam-driven currents. It is thus concluded that the earlier results based on Ohmic current profiles /11/ are still valid.

References

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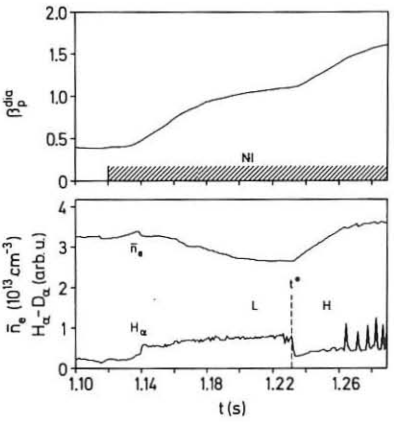

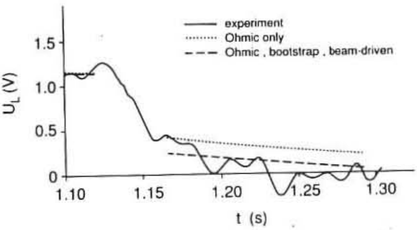

Fig. 2: Time development of measured loop voltage U_L compared with predictions from driven current models.

Fig. 1: Line-averaged density $\bar{n}_e$, H_α intensity and β_p in an H discharge with I_p = 320 kA, B_t = 1.85 T, P_{NI} = 3.45 MW ($H^0 \rightarrow D^+$).

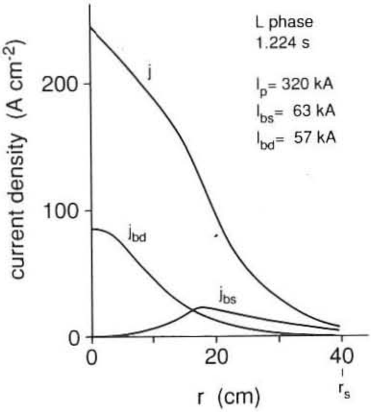

Fig. 3: Profiles of bootstrap j_{bs}, beam-driven j_{bd} and total current density j in the pre-transition L phase.

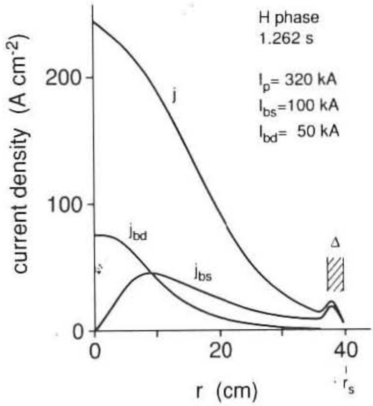

Fig. 4: As in Fig. 3, but in the ELM-free H phase.

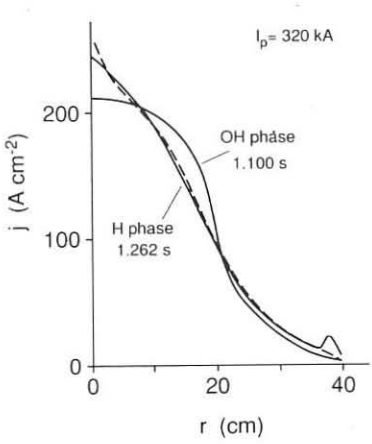

Fig. 5: Evolution of current profile with Ohmic, bootstrap and beam-driven currents (solid curves) and with Ohmic current only (dashed curve).

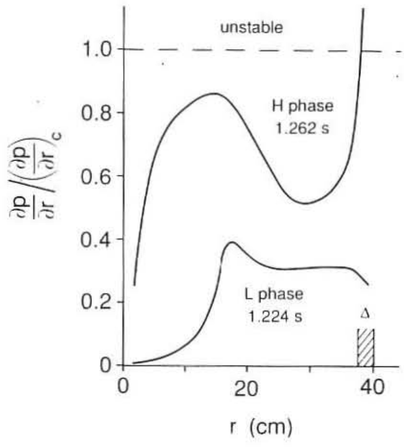

Fig. 6: Normalized pressure gradient versus radius with Ohmic, bootstrap and beam-driven currents included.