MEASUREMENT OF THE CURRENT DISTRIBUTION IN ASDEX DURING LOWER HYBRID CURRENT DRIVE USING THE LI-BEAM/ZEEMAN EFFECT TECHNIQUE

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Abstract: Results are presented for an exploratory investigation into the behavior of the current density distribution during LH current drive. Indications are that the current profile broadens slightly, in contrast to a peaking of the electron temperature profile, thereby implying that the RF-driven current is not strictly coupled to Spitzer conductivity.

Diagnostic Description: The Zeeman technique /1/ yields the local pitch angle $\theta_p = \tan^{-1}(B_p/B_T)$ of the magnetic field lines, from which the safety factor q(r) and poloidal field $B_p(r)$ can be determined. As illustrated in Fig. 1, a 60 keV/0.5 mA neutral Li beam /2/ is injected into the plasma for the length of the discharge. The collisionally excited Li resonance line radiation is gathered by a lens ($\ell \sim 10^{-3}$ sr) from a volume (~1.5 x 1.5 cm) defined by the field stop image on the beam. The projection of θ_p in the plane perpendicular to the optical axis is measured by rejecting the spectrally shifted σ components of the Zeeman triplet with a Fabry-Perot interferometer, and then determining the azimuth (θ_p) of the remaining unshifted π component - which is polarized parallel to $\vec{B} = \vec{B}_p + \vec{B}_T$ - by a polarimeter /1/. A profile of $\theta_p(r,t)$ is gained by scanning the beam radially from shot to shot.

Experiment: In a double null diverted discharge (H_2, R ~ 169 cm, a ~ 39 cm, $B_T(R) \sim 21.2$ kG, $I_p = 292$ kA, $\bar{n}_e \sim 7 \times 10^{12}$ cm^{-3}) 400 kW of RF power at 1.3

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GHz is injected, from t = 0.9 - 1.5 sec, into the plasma chamber via an 8-waveguide grill which is phased so that propagating waves are radiated ($\phi = 105^{o}$, $n_{\parallel}$ spectrum peaked at ~1.8). The plasma current is sustained during this time essentially entirely by the RF as evidenced by the concomitant drop of the loop voltage U_L to zero in Fig. 2. A further consequence is the increase in $\beta_p + l_i/2$ (calculated using the equilibrium vertical field) of ~ +0.079 between t = 0.9 and 1.45 secs (OH, LH phases). The simultaneous change in $\beta_{p\perp}$ (not shown; measured by a diamagnetic loop) of ~+0.065 means, under the assumption that $\beta_p = \beta_{p\perp}$, that $\Delta l_i = l_i(LH) - l_i(OH) = +0.028$; i.e., the magnetic measurements taken alone indicate a peaking of the current profile. The electron temperature T_e is measured (perpendicular to $\vec{B}_T$) by a quasi-stationary Nd-YAG Thomson scattering system at 16 points over the vertical diameter. The two T_e traces at r = 0, 19 cm of Fig. 2 illustrate that electrons are heated preferentially in the plasma center, since the $T_e(r=19)$ curve remains constant at ~0.7 keV, whereas $T_e(0)$ goes from ~1.4 to ~2 keV.

Li-Beam Results: In Fig. 2 the experimentally measured θ_p - smoothed with a 10 ms time window - is given as a function of time for five radial points, the radius r being measured from the center of the outermost flux surface. The base lines for the $\theta_p(t)$ curves are determined by fitting the $\theta_p(r,t=0.9$ sec) profile to the value computed at the plasma edge (r=a) using the Shafranov formula for $B_p(a)$ in conjunction with $\theta_p(a) = \tan^{-1} B_p(a)/B_T$.

In the OH phase, although the I_p flat top is attained at 0.5 sec, the $\theta_p(t)$ signals for r $\leq$ 28.6 cm do not reach their plateau values until t ~ 0.75sec, which is in qualitative agreement with the time behavior of $\beta_p + l_i/2$. Further, at t = 0.5 sec, $\theta_p(r = 10.7, 19.5)$ have only ~70 % of their plateau values, with this percentage increasing to ~90 % for r = 37 cm. The failure of $\theta_p(37)$ to follow I_p closely is presently not understood, since it would be expected for θ_p near the separatrix to be relatively free of thermal or skin effects. The very weak dependence of θ (-1.9) on I_p indicates that this point is near the magnetic axis.

Switching on the RF produces a significant change in θ_p only for θ_p (10.7), which exhibits a continuous decrease until towards the end of the pulse.

Discussion: Radial profiles of $\theta_p(r)$ for the OH and LH phases are presented in Figs. 3a and 3b respectively, along with the associated (cylindrical) safety factor q curves. The vertical error bar of ± 3 mrad is approximately the peak-to-peak noise level of $\theta_p(t)$. For comparison, the θ_p and q profiles derived from $T_e(r)$ assuming Spitzer resistivity (current density $\propto T_e^{3/2}$) and a constant electric field over the radius are also plotted.

In Fig. 3a, although there are not enough measuring points to adequately describe q for r < 10.7 cm, the $q_{exp}(0)$ value of ~1.1 is consistent with the observed absence of sawteeth during the discharge. Moreover, there is surprisingly good agreement between the experimentally determined θ_p^{exp}, and the calculated $\theta_p^{Spitzer}$. The corresponding values of l_i are 1.18 and 1.16, respectively.

For the LH phase (Fig. 3b) there is a large difference between θ_p^{exp} and $\theta_p^{Spitzer}$ for r < 20 cm, which is reflected in l_i values of 1.15 and 1.23. $q_{exp}(0)$ is ~1.25 in contrast to a Spitzer q(0) of ~0.55. Comparison of θ_p^{exp}(LH) to θ_p^{exp}(OH) (note that for θ_p^{exp}(OH) only the points are plotted in Fig. 3b, and not a curve) reveals that current drive causes a flattening of the current distribution within r ~ 20 cm, leading to $\Delta l_i = -0.03$. This is in strong contrast to the behavior anticipated, were the current profile to continue to follow $T_e^{3/2}$, which peaks during the RF pulse due to strong central heating.

The disparity between the magnetically derived $\Delta l_i = +0.028$ (using $\beta_p = \beta_{p\perp}$) and the measured $\Delta l_i = -0.03$ suggests that $\beta_p(LH) > \beta_{p\perp}(LH)$, which would be compatible with an enhanced energy deposition by RF in the parallel electron component. In view of the uncertainties associated with the magnetic data for the small changes discussed here, no attempt at quantitatively estimating this additional parallel energy is made.

In summary, the Li-beam Zeeman diagnostic has been brought into operation on ASDEX and found - for the OH phase - to produce results in close agreement with those predicted by assuming Spitzer resistivity. During LH current drive, the current density profile appears to decouple from the bulk thermal electron population, as demonstrated by the decrease in $\theta_p^{exp}(r < 20)$ accompanied by an increase in T_e in the plasma center region.

References:

/1/ K. McCormick, M. Kick and J. Olivain, Proc., 8th Eur. Conf. on Controlled Fusion and Plasma Physics (Prague, 1977) 140
/2/ K. McCormick, et al., J. Nucl. Mater. 121 (1984) 48.

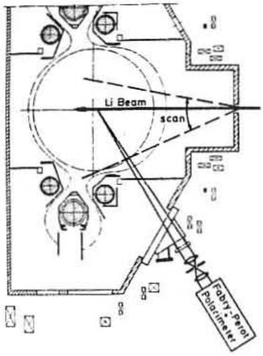

Fig. 1: Diagnostic setup on ASDEX.

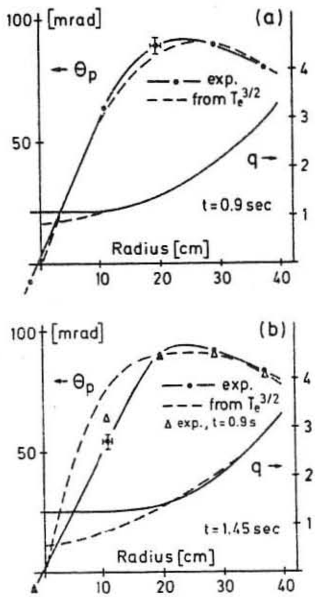

Fig. 3: Comparison between the directly measured Θ_p profiles and $\Theta_p(r)$ derived from $T_e^{3/2}$, and their associated q values for: (a) the OH phase, t = 0.9 sec, (b) during current drive, t = 1.45 sec, including the measured Θ_p (OH) points.

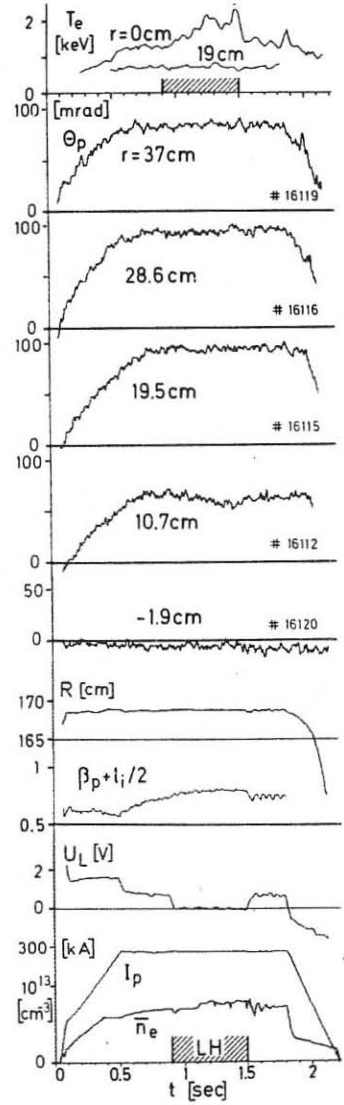

Fig. 2: Time behavior of T_e (r=0,19cm), Θ_p at five radial points, R, $\beta_p + l_i/2$, U_L, I_p and $\bar{n}_e$.