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Modelling of the Current Hole in a Tokamak

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1 Introduction

A high confinement equilibrium with nearly zero toroidal current in the central region (a "current hole") has been recently observed in JT-60U [1] and JET [2]. In the case of JT-60U, the current hole was sustained for several seconds. This observation indicates the possibility of a stable non-inductive tokamak operation, which could be a promising scenario for the tokamak-reactor. The formation of the central region with very low current density, $j_{||}$, has been successfully explained as a result of the increase of the off-axis non-inductive current which reduces inductive toroidal electric field and toroidal current density in the centre [1,2]. At the same time, the stability of the current hole (shrinks in time, but maintains nearly zero $j_{||}$ in the centre with sharp gradients of $j_{||}$ at its edge) remained an unresolved issue. To address this issue, an equilibrium code based on the solution of the Grad-Shafranov equation with boundary conditions set on the inside, near the magnetic axis, was developed. Such an approach, by focussing on the inner regions of the plasma with ultra low $j_{||}$, proved useful for testing theoretical concepts for the sustainment of the current hole.

2 Equilibrium calculations of inner regions of the plasma

In JT-60U plasmas with the current hole, $j_{||}$ inside the hole is almost zero, within error bars, with a sudden rise of $j_{||}$ at its edge [1], at a radial position along the outer midplane which will be denoted as r_s in this paper. Calculations show, however, that at the edge of the current hole the safety factor q~100, implying a small positive current inside it, as shown schematically in figure 1 for a typical shot with the current hole, E36639. Although the current hole has been gradually contracting with time, a sharp transition between the almost zero $j_{||}$ region and the region of large $j_{||}$ gradients remained. This observation is counter-intuitive as one would expect a gradual smoothing out of the $j_{||}$ distribution at the edge of the current hole during the sustainment phase, when positive toroidal field E_φ diffuses into the hole.

Fig. 1 also shows constant poloidal flux (Ψ) surfaces covering the region of modelling, which ends at a certain distance outside of the current hole, where sharp pressure gradients are formed and the $j_{||}$ distribution is dominated by the Bootstrap current. The shape of the innermost magnetic surface and radial Ψ gradients ($\nabla\Psi$) along it, together with the radial dependence of Ψ on the minor radius along outer midplane ($\Psi(r)$) were specified as boundary conditions in the code (in Fig.1, the innermost surface corresponds to 5% of Ψ enclosed by the outermost surface). The dependence $\Psi(r)$ was chosen so as to create $j_{||}$ distribution along the outer midplane, $j_{||}(r)$, similar to the one observed in the experiment. The shape of the $j_{||}(r)$ profile inside the hole (with $j_{||}$ being much less than outside of the hole, resulting in q~100 at its edge) was varied in the calculations.

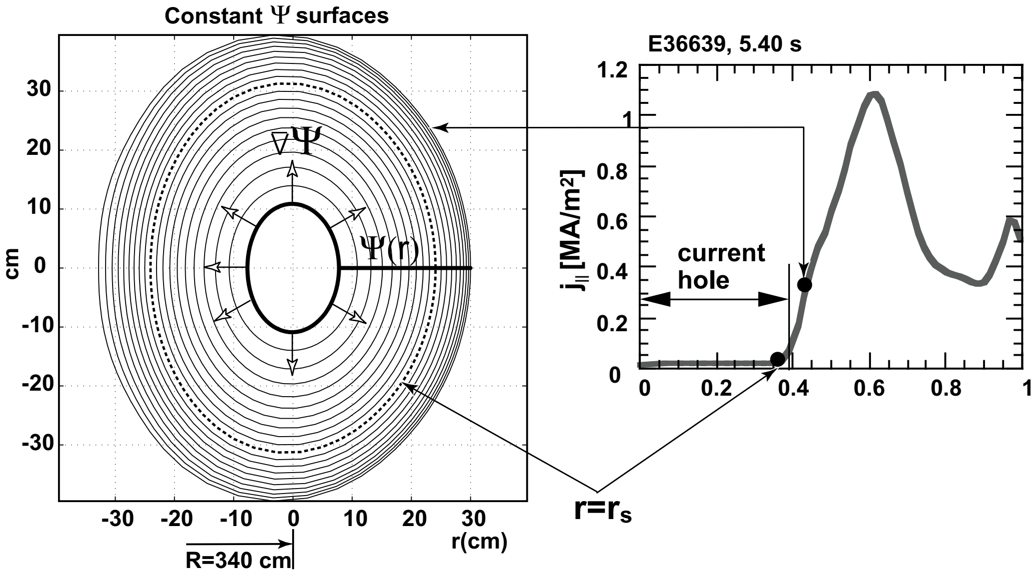

Figure 1. Parallel current density $j_{||}$ measured in the shot E36639 and the plot of constant poloidal flux surfaces (Ψ) covering the region of modelling. Boundary conditions for Ψ are specified on the innermost surface and along outer midplane.

Our physics picture of $j_{||}$ and pressure (p) distribution in the plasma centre is illustrated in figure 2. Inside the current hole, the pressure profile is flat (supported by experiment [1]) due to confinement degradation related to low poloidal fields B_θ. In our calculations, we assumed that a certain critical value of B_θ is required to ensure plasma confinement. Due to zero pressure gradients inside the current hole, only small Ohmic plus externally driven currents (j_{ex}) exist there (these two currents are not separated in the code). Thus, in this region the total toroidal current density j_{tor}, obtained from the Grad-Sharfanov equation under the condition of $\nabla p=0$, coincides with j_{ex}. The j_{ex} profile is not necessarily flat (despite being shown flat in Fig.2). The confinement region, owing to the rising B_θ, starts at the edge of the current hole. The pressure gradient gradually builds up giving rise to the Pfirsh-Schlüter (j_{ps}) and Bootstrap (j_{bs}) currents. The j_{ex} is exponentially extrapolated outward from the edge of the current hole, $r=r_s$, and the sum ($j_{ps}+j_{bs}$) is then calculated so as to feel the gap between the total current density j_{tor}, obtained from the Grad-Sharfanov equation, and j_{ex}. Finally, the sum ($j_{ps}+j_{bs}$) is split into individual current densities j_{ps} and j_{bs} using their theoretical ratio at the outer midplane. These two current densities can be easily separated from each other owing to their different dependencies on the major radius R, within the same magnetic surface.

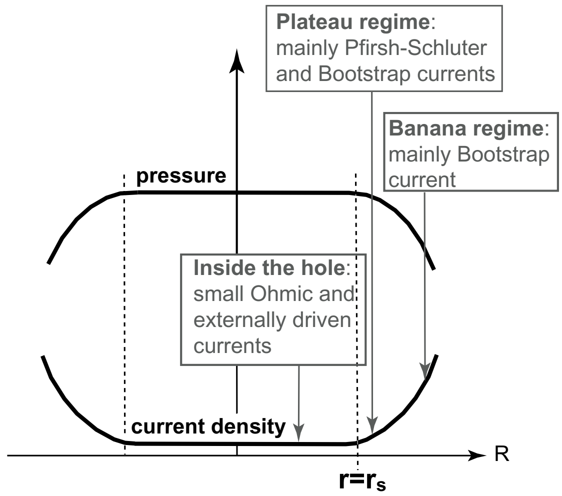

Figure 2. Illustration of the physics picture of pressure and $j_{||}$ distribution

3 Results of calculations

We assumed the plasma parameters at the edge of the current hole measured in experiment for the shot E36639, t=5.4s [1]: toroidal field B_t=3.7 T, plasma current I_p=1.35 MA, electron and ion temperatures T_e=5.5 keV and T_i=8 keV respectively, plasma density $n_e=2.7\times10^{19}m^{-3}$, Z_{eff}=3, and the estimated value of safety factor at $r=r_s$, q_{rs}=100. According to the experiment, both density and temperature profiles are flat inside the current hole [1]. Just outside of the current hole, $T_{e,i}$ continue to be flat for a few cm, while the n_e gradient starts to develop. We therefore assumed in the calculations that the pressure gradient is due entirely to the gradient in density inside the region of modelling.

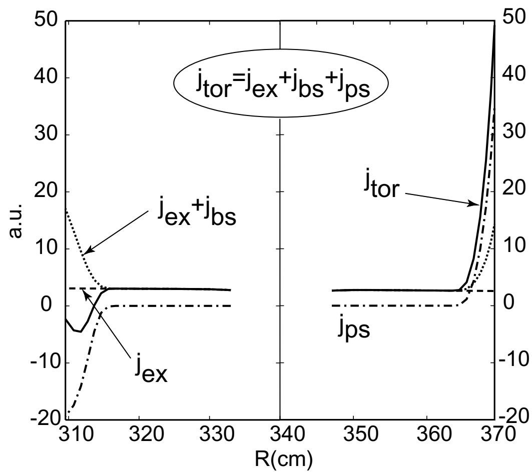

Figure 3. Distribution of current densities along the midplane for the case of flat Ohmic+External (j_{ex}) profile inside the current hole.

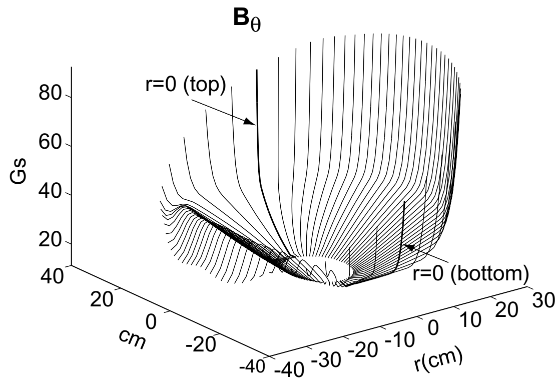

Figure 4. Distribution of the poloidal field for the case shown in Fig. 3.

The distribution of the total toroidal current density, j_{tor}, and its constituents along the midplane for the case of a flat j_{ext} profile inside the current hole are shown in Fig.3. Just outside of the current hole, j_{tor} is dominated by the Pfirsh-Schlüter (j_{ps}) current density, with the plasma being in the Plateau collisionality regime. Since the Pfirsh-Schlüter curent has an opposite (negative) sign on the inboard (high field) side of the plasma, it drives the total current density negative there. Negative j_{tor} on the inboard results in the drop of B_θ just outside of the current hole (Fig. 4), prompting the formation of a local X-point. Such a solution seems unrealistic: we relate the absence of confinement inside the current hole with low B_θ, which is below a certain critical value. Falling B_θ on the inboard side, with the X-point formation, implies that either the size of the current hole is wider than was assumed in the calculations, or such a regime does not exist for the given plasma parameters and j_{ext} profile. Increasing j_{ext} with radius (making it profile hollow) inside the current hole was found to alleviate the problem of falling B_θ, resulting in a realistic solution with a monotonic B_θ distribution.

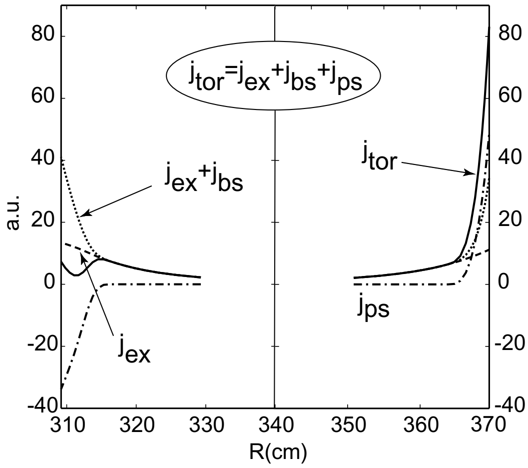

Figure 5. Distribution of current densities along the midplane for the case of rising Ohmic+External (j_{ex}) profile inside the current hole.

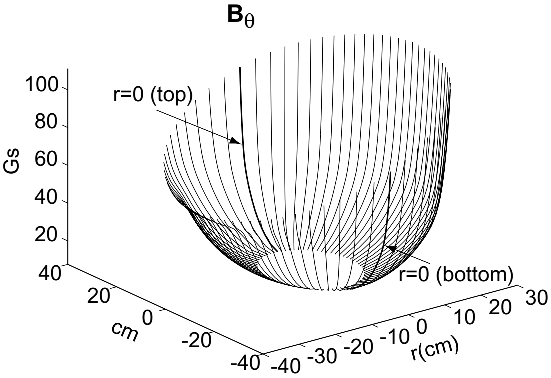

Figure 6. Distribution of the poloidal field for the case shown in Fig.5.

Figure 5 corresponds to a sufficiently hollow j_{ext} profile, where the negative j_{tor}, as well as the B_θ drop on the inboard side, have been completely eliminated. By hollowing the j_{ext} profile inside the current hole, its magnitude at the edge of the current hole has been effectively increased. This is due to the fact that the total toroidal current contained inside the current hole was fixed in our calculations, since we fixed the safety factor, q=100, at r=r_s. The results, therefore, point to the stabilizing role of either Ohmic or externally driven current densities at the edge of the current hole, necessary for the very existence of such a structure.

4 Conclusions

It is shown that the stability of the current hole, with almost zero $j_{||}$ inside the hole and sharp radial $j_{||}$ gradients at its edge, can be explained by assuming that the plasma confinement requires a certain minimum of the poloidal field B_θ. This critical B_θ is reached at the edge of the current hole. The code separates current density into Ohmic + externally driven (j_{ext}), Bootstrap (j_{bs}) and Pfirsh-Schlüter (j_{ps}) currents. The latter was found to dominate at the edge of the current hole. The experimentally observed sharp $j_{||}$ rise at a certain radius is thus attributed mostly to the Pfirsh-Schlüter contribution (which is continued by the Bootstrap current at more outward positions, in the region of sharp ∇p). Large j_{ps} can force a negative net $j_{||}$ on the inboard side of the edge of the current hole, resulting in an unrealistic solution with B_θ falling just outside of the current hole on the inboard, prompting the formation of a local X-point. To obtain a realistic solution with monotonically rising B_θ, j_{ext} must be sufficiently large at the edge of the current hole, to compensate (together with j_{bs}) for the negative j_{ps} on the inboard.

References

[1] Fujita T et al, Phys. Rev. Lett. 87 (2001) 245001.
[2] Hawkes N C et al., Phys. Rev. Lett. 87 (2001) 115001.