*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, O-5.04 (2002)*

MHD Stability of Advanced Tokamak Scenarios with Reversed Central Current: an explanation of the 'Current Hole'

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Introduction

In the advanced tokamak scenarios in JET with off-axis Lower Hybrid current drive (LHCD) during the current ramp, a relatively large central region (with a radius of ~ 20 cm) with a zero or very small toroidal current has been observed [1]. A similar phenomenon has been observed in the advanced scenarios in the JT-60U tokamak where it has been named the 'current hole' [2]. The motional Stark effect measurements (MSE) of the poloidal magnetic field show that with off-axis LHCD, the central current density reduces to zero but does not become negative. Current diffusion simulations, including the off-axis current drive, indicate that the central current is expected to become (transiently) negative in the plasma centre. The off-axis driven current induces a reversal of the electric field in the centre. This in turn drives a negative Ohmic current which can lead to a reversal of the central current density. Experimentally, however, the central current density does not become negative but appears to be 'clamped' at zero.

In this paper, the MHD stability of current profiles with a reversed central current is analysed. It is shown that the 'clamping' of the central current density can be explained by the non-linear effect of an n=0 resistive kink instability [3].

Linear MHD Stability with negative central current

For the MHD stability analysis the reduced MHD model [4] is used, initially in circular geometry. (Toroidal linear resistive MHD codes like CASTOR use a coordinate system based on the poloidal flux, which is not a valid coordinate when the central current is reversed). The current profiles considered are of the form $j(r) = j_a(1-r^4) - j_b(1-r^2)^8$. These profiles are found to be unstable to an n=0 (i.e. toroidally symmetric) resistive instability as soon as the central current density is negative. The mode, with a poloidal mode number m=1, is localised inside the q=∞ surface (where the poloidal field B_θ is zero). Their growth rate scales with resistivity as $\eta^{1/3}$ identifying the n=0/m=1 mode as a resistive internal kink mode. An n=0/m=2 and an n=0/m=3 are also unstable but with a smaller linear growth rate. The growth rates of m=2 and m=3 modes scale with $\eta^{3/5}$, characteristic for a tearing mode.

In fact, the linear MHD stability for the n=0 modes can be solved relatively easily analytically in the reduced MHD model. The analytic solutions for the n=1, m=1 internal kink modes at the q=1 surface are well known [5]. Exactly the same analysis can be applied to axi-symmetric n=0 modes by a rescaling of the equations. By replacing the approximation of the parallel wave vector close to the rational surface from $q'B_\theta/q \rightarrow B'_\theta$ in the normalisation of the equations, exactly the same solution is found for the n=0/m=1 mode as for the n=1/m=1 resistive internal kink mode. This yields for the growth rate of the n/m=0/1 mode:

$$\lambda = \eta^{1/3}\left(\frac{B'_\theta}{r}\right)^{2/3}_{r=r_q} \qquad (1) \qquad\qquad \lambda = 0.55\eta^{3/5}\left(\frac{mB'_\theta}{r}\right)^{2/5}_{r=r_q}(\Delta')^{4/5} \qquad (2)$$

where the quantities are evaluated at the rational q=∞ surface. The radial displacement of the n/m=0/1 mode is constant inside the q=∞ surface and falls to zero outside this surface.

The same normalisation can also be applied to the axisymmetric tearing modes with higher poloidal mode numbers. The resulting growth rate is given by Eq. (2). In the reduced MHD model the n/m=0/1 is always unstable in the presence of a q=∞ surface whereas the stability of the n/m=0/m depends on Δ'. For the current profiles considered, the m=3 mode is close to marginal stability, the higher m tearing modes are stable. The analytic growth rates from equations (1) and (2) agree very well with the numerically obtained values (see Fig.1).

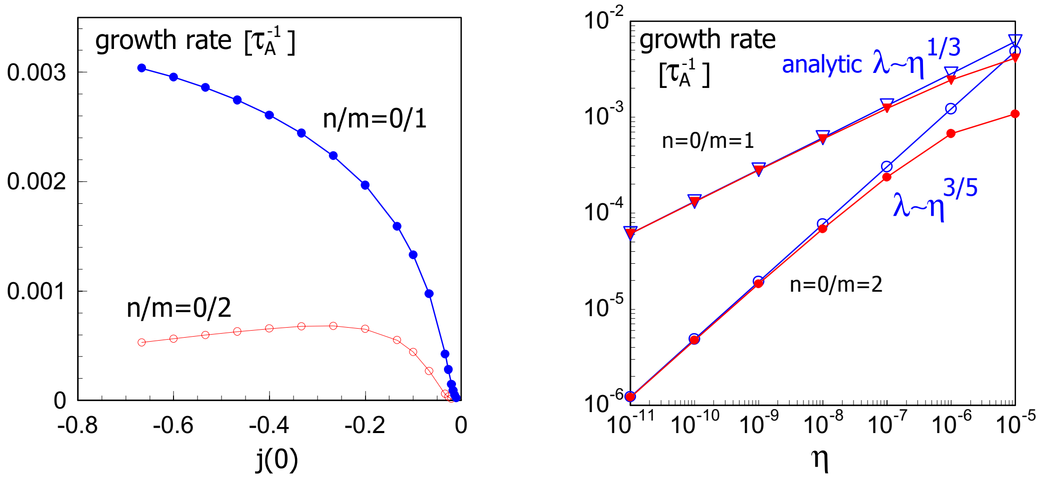

Fig.1 *Linear growth rates of the n=0/m=1 and n=0/m=2 modes as function of central current density (left) and as function of resistivity (right), included are the analytic growth rates (open symbols).*

Non-linear evolution

To establish the influence of the MHD instabilities on the evolution of the current profile, the non-linear reduced MHD equations are evolved to model a current ramp phase. A feedback on the poloidal flux at the boundary is used to follow a prescribed linear rise of the current up to the steady state value. The off-axis driven (non-Ohmic) current is given as a radial profile, constant in time, localised between 0.2 < r/a < 0.7. The time scales involved differ by many orders of magnitude. In JET, for example, a typical current ramp takes several seconds whereas the MHD instabilities need to be resolved on the Alfvén time scale which is ~2×10^{-7} s. This implies a large number (~10^7) of time steps in the numerical simulation of a current ramp. By increasing the resistivity with respect to the experimental values and adjusting the current ramp rate accordingly, the time scales can be shortened.

Solving only the n=0 and m=0 harmonics yields the evolution of the current profile without the MHD instability (see Fig.2a). In this case the central current becomes negative soon after the off-axis current drive is switched on at t = $4\text{x}10^5$ τ_A. Eventually, the current on axis becomes positive due to the continuing increase of the Ohmic current.

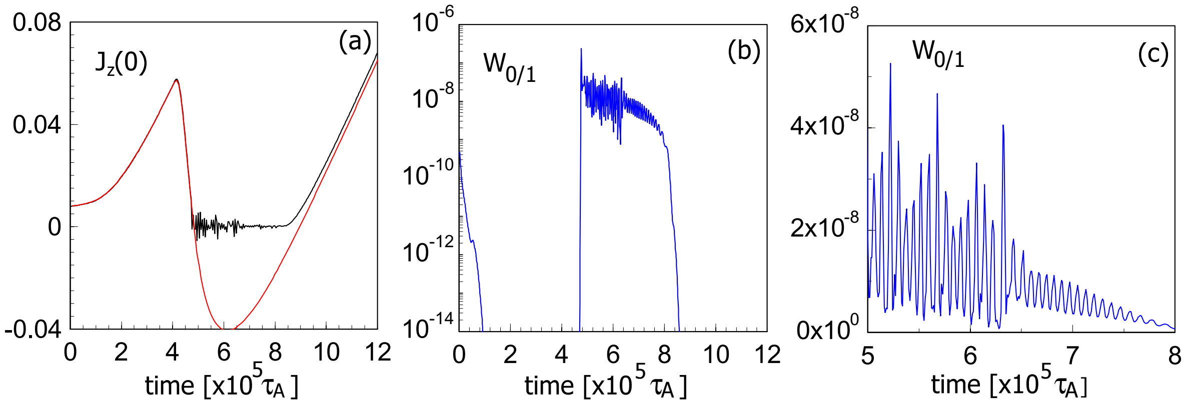

Fig.2 **(a)** *Comparison of the time evolution of current density on axis with and without MHD activity.* **(b+c)** *The amplitude of the m=1 mode showing a periodic behaviour. (The resistivity on axis is $2\text{x}10^{-7}$.)*

Including the m=1 harmonic shows the influence of the m=1 resistive kink mode on the evolution of the central current density (see fig. 2). Initially, the mode start to grow exponentially when the q=∞ surface enters the plasma. The flow pattern of the m=1 mode corresponds to a 'rigid' movement of the plasma core towards the q=∞ surface. This induces a very large, radially localised current sheet at the q=∞ surface (on the side where the core runs into the q=∞ surface) and a reconnection of the poloidal flux. The result of the instability is a current profile which is completely flattened to zero in the plasma centre. The edge of the central region of zero current density is marked by a very large current gradient (see Fig.3). The central pressure profile also shows a flattening. After the initial flattening, the amplitude of the m=1 mode shows a periodic oscillation of growth and decay (see Fig.2c). The m=1 mode tends to remove the q=∞ surface after which the mode decays. However, the off-axis current drive continues to reduce the central current density. As the q=∞ surface is reintroduced the mode starts to grow again. The periodically recurring reconnections of the m=1 mode keep the central current density close to zero. The frequency of the cycle decreases with decreasing resistivity (f ~ $\eta^{0.6}$), its amplitude increases with the amplitude of the off-axis driven current.

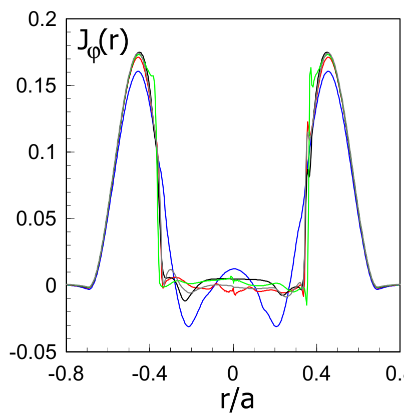

Fig.3 *The current profile just before the onset of the m=1 mode and at several times during the oscillation.*

The influence of ellipticity on the axi-symmetric MHD modes in the current hole has been studied using a new 2D hp-adaptive finite element code. The fully implicit time evolution allows very large time steps, local refinements of the finite elements facilitate high resolution fully non-linear simulations of the formation of the current hole. For a circular plasma shape, the full non-linear results are very similar to the quasi linear calculations using the m=0 and m=1 harmonics. At an ellipticity of E=1.2 and a resisitivity of $\eta=10^{-6}$ the most unstable mode is, as for a circular plasma, the n=0/m=1 resistive kink mode. Increasing the ellipticity to E=1.5 (at $\eta=10^{-6}$) the most unstable mode changes to an n=0/m=2 mode (see Fig.4). The dynamical behavior of the m=2 mode does not show the periodic oscillations of the m=1 mode. Instead the m=2 mode saturates at a constant amplitude. As the m=1 mode, the m=2 mode leads to a flattening of the central current density to zero. In view of the different scaling of the linear growth rates with resistivity (see Eq. 1, 2), the m=1 mode is expected to become the dominant mode at lower values of the resistivity.

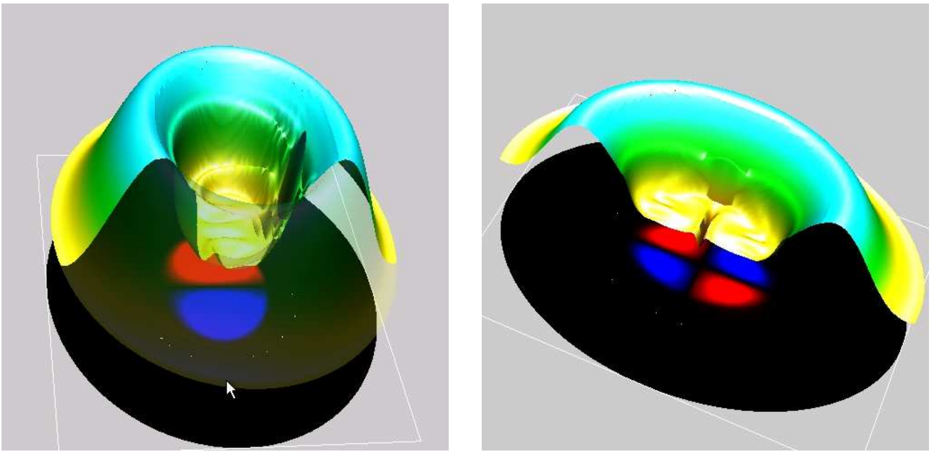

Fig.4 *The current profile at ellipticity E=1.2 with an m=1 mode structure (left) and at E=1.5 with an m=2 mode (right). The resistivity is* $\eta=10^{-6}$*. The bottom plane shows the plasma flow (vorticity).*

Conclusions

No MHD instability has yet been observed directly in the current hole. This is made more difficult by the central localisation of the mode and its axisymmetric mode structure. However, the effect of the axi-symmetric resistive kink mode on the evolution of the current profile provides an explanation for the absence of (negative) current inside the ‘current hole’.

Acknowledgement

This work was conducted under the European Fusion Development Agreement.

References

[1] N.C. Hawkes et al., Phys. Rev. Lett. 87, 115001 (2001).
[2] T. Fujita et al., Phys. Rev. Lett. 87, 245001 (2001).
[3] G. Huysmans et al., Phys. Rev. Lett. 87, 245002 (2001).
[4] R.D. Hazeltine et al., Phys. Fluids, **30**, 3204 (1987).
[5] D. Biskamp, ‘Non-linear MHD’, Cambridge University press, Cambridge (1993).