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by

B.C. Stratton, N.C. Hawkes, G.T.A. Huysmans, J.A. Breslau, L.E. Zakharov,
B. Alper, R.V. Budny, C.D. Challis, R. Deangelis, V. Drozdov, C. Fenzi,
C. Giroud, T.C. Hender, J. Hobirk, S.C. Jardin, E. Joffrin,
P.J. Lomas, P. Lotte, J. Mailloux, W. Park, E. Rachlew,
S. Reyes-Cortes, E. Solano, T. Tala,
K-D. Zastrow, and JET-EFDA Contributors

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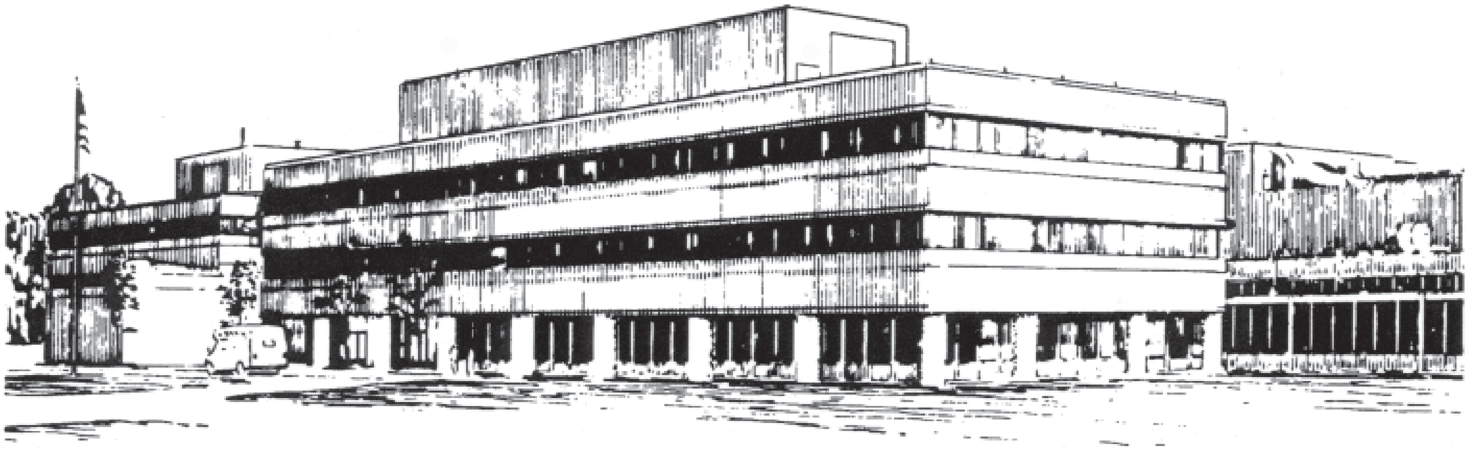

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EQUILIBRIA AND STABILITY OF JET DISCHARGES WITH ZERO CORE CURRENT DENSITY

B. C. STRATTON[1], N. C. HAWKES[2], G. T. A. HUYSMANS[3], J. A. BRESLAU[1],
L. E. ZAKHAROV[1], B. ALPER[2], R. V. BUDNY[1], C. D. CHALLIS[2], R. DEANGELIS[4],
V. DROZDOV[2], C. FENZI[3], C. GIROUD[5], T. C. HENDER[2], J. HOBIRK[6], S. C. JARDIN[1],
E. JOFFRIN[3], P. J. LOMAS[2], P. LOTTE[3], J. MAILLOUX[2], W. PARK[1], E. RACHLEW[7],
S. REYES-CORTES[8], E. SOLANO[9], T. TALA[10], K-D. ZASTROW[2], AND
JET-EFDA CONTRIBUTORS*

[1]Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ, 08543, USA
[2]Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[3]Association Euratom-CEA, Cadarache, F13108, France
[4]Association Euratom-ENEA sulla Fusione, CRE Frascati, Roma, Italy
[5]FOM-Institut voor Plasmafysica "Rijnhuizen", Associatie EURATOM-FOM, Trilateral Euregio Cluster, P. O. Box 1207, 3430 BE Niewgen, The Netherlands
[6]Max-Planck-Institut für Plasmaphysik, Euratom Association, 85740, Garching, Germany
[7]KTH-Physics, SCFAB, VR Association, 10691, Stockholm, Sweden
[8]Euratom/IST Association, Centro de Fusao Nuclear, 1049-001, Lisboa, Portugal
[9]Association EURATOM-CIEMAT para Fusion, CIEMAT, Spain and EFDA CSU JET, Abingdon, OX14 3EA, UK
[10]Association Euratom-TEKES, VTT Chemical Technology, Espoo, P. O. Box 1404, Finland
*See Annex 1 in J. Paméla , OV/1-4 (IAEA Fusion Energy Conference 2002)

e-mail address of main author: bstratton@pppl.gov

ABSTRACT. Injection of Lower Hybrid Heating and Current Drive (LHCD) into the current ramp-up phase of JET discharges can produce extremely reversed q-profiles characterized by a core region of near zero current density (within Motional Stark Effect diagnostic measurement errors). Non-inductive, off-axis co-current drive induces a back electromotive force inside the non-inductive current radius that drives a negative current in the plasma core. The core current density does not go negative, although current diffusion calculations indicate that there is sufficient LHCD to cause this. The clamping of the core current density near zero is consistent with n=0 reconnection events redistributing the core current soon after it goes negative. This is seen in reduced MHD simulations and in nonlinear resistive MHD simulations which predict that these discharges undergo n=0 reconnection events that clamp the core current near zero.

1. INTRODUCTION

Injection of Lower Hybrid Heating and Current Drive (LHCD) into the current ramp-up phase of JET discharges can produce extremely reversed q-profiles characterized by a core region of very small or zero current density (within Motional Stark Effect diagnostic measurement errors) and $q_{min}>1$ [1]. This phenomenon is termed the "current hole". It occurs because non-inductive, off-axis current drive in the same direction as the Ohmic current induces a back electromotive force inside the non-inductive current drive radius that decreases the core current density. T_e-profiles show the presence of an internal transport barrier (ITB) during the LHCD prelude phase. These discharges can exhibit strong ITBs and transient high performance during a subsequent high-power heating phase [2]. If the non-inductive current drive is strong enough relative to the Ohmic current, the total current could in principal be driven negative in the core. This does not happen [3], although current diffusion calculations indicate that there is sufficient LHCD to cause this. The clamping of the core current density near zero is shown to be consistent with n=0 MHD events redistributing the core current soon after it goes negative [4, 5]. Current hole discharges are also observed on JT-60U, where the off-axis current drive is due to the

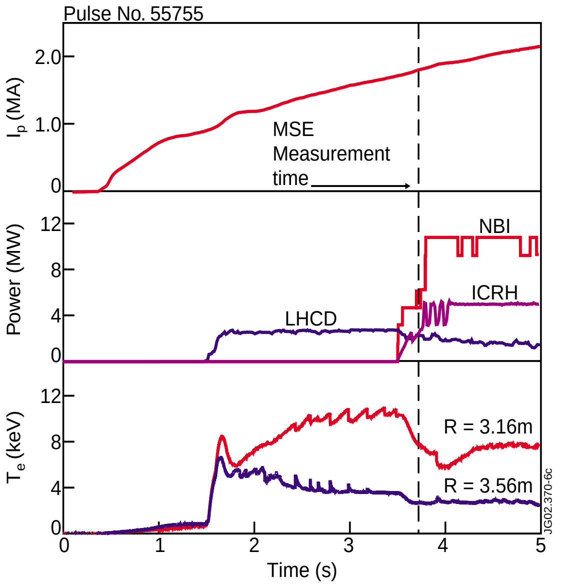

FIG. 1. Current hole discharge parameters.

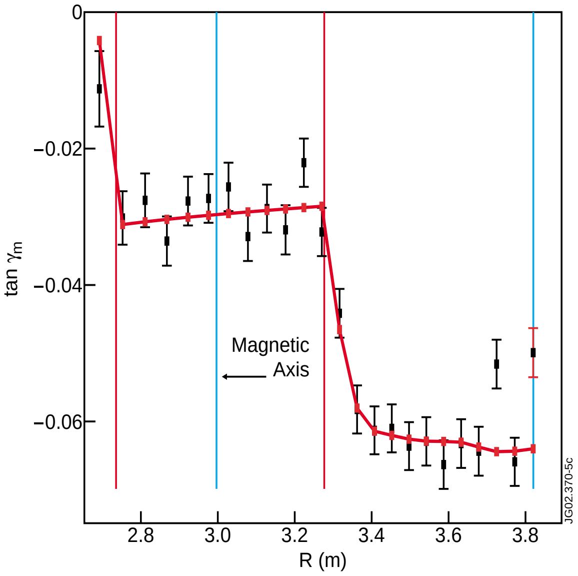

FIG. 2. MSE pitch angle profile (points) and ESC reconstruction best fit (solid line).

bootstrap current generated by neutral beam injection [6]. This paper summarizes work on JET current hole discharges with an emphasis on recent results.

2. EXPERIMENTAL SCENARIO

The time evolution of the early part of a JET current hole discharge with B_ϕ=3.45 T is shown in Fig. 1. The LHCD prelude starts at 1.5 s. It is followed by a short pre-heat phase of low-power neutral beam and ICRH injection and then a longer high-power main heating phase. The T_e time evolution shows 'high-q' sawteeth [7] that are always seen during the LHCD prelude in JET discharges with extreme shear reversal. The pitch angle profile measured by the MSE diagnostic ($\tan\gamma_m$) at 3.78 s is shown as the points in Fig. 2. For this case of only the beam viewed by the MSE diagnostic injected at the measurement time, γ_m is proportional to the magnetic field pitch angle, $\gamma=\tan^{-1}(B_Z/B_\phi)$, with an offset due to the non-zero neutral beam injection angle with respect to the midplane. Thus, the flat region in $\tan\gamma_m$ shown in Fig. 2 indicates a large region of nearly zero B_Z, or very small core current density according to Ampère's Law [3]. This is the characteristic feature of current hole discharges and it can persist for several seconds if the LHCD remains on. The effect of the radial component of the plasma electric field, E_r, on the MSE measurement is negligible at this time [3]. Measurements at the earliest time at which the beam viewed by the MSE diagnostic can be injected show that the current hole is well established by 0.75 s into the LHCD pulse [5].

3. EQUILIBRIUM RECONSTRUCTION OF CURRENT HOLE PLASMAS

Although accurate equilibrium reconstruction of current hole discharges is challenging because the poloidal flux, ψ, inside the hole region is nearly zero, reliable reconstructions have been obtained using a modified version of the EFIT code [3] and the ESC code [5, 8]. The resulting current density profiles show a strong gradient at the edge of the current hole with a narrow peak just outside it. The small current density inside the current hole is consistent with a measurement made by rapidly moving the plasma in the radial direction so that a given point in the plasma was swept across adjacent spatial channels of the MSE diagnostic [3], eliminating the effect of systematic uncertainties in the diagnostic

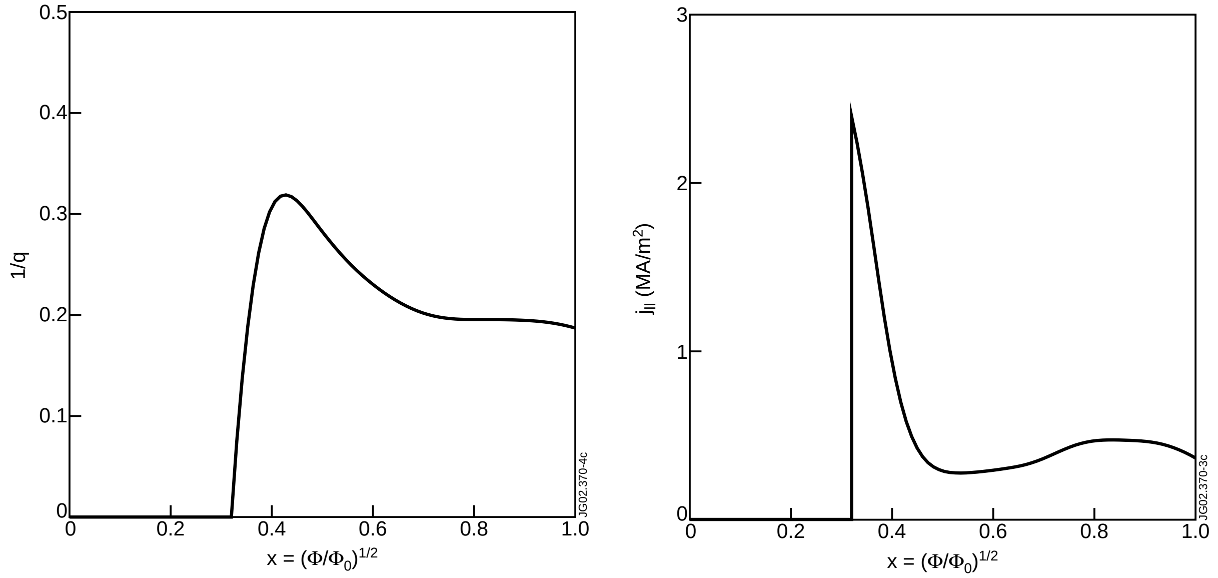

FIG. 3 $\bar{\iota}=1/q$ profile (left) and $j_{||}$ profile (right) from ESC reconstruction of current hole discharge shown in figures 1 and 2.

calibration. Assuming constant current density inside the current hole, this measurement yields a small core current density of 0.08±0.025 MA/m^2 compared to the off-axis peak value of ~1 MA/m^2.

The ESC code uses a free-boundary solver constrained by the measured coil currents and magnetics data to determine the plasma boundary; a fixed boundary solver constrained by the MSE pitch angle measurements then determines the magnetic geometry and the current density profile [5]. The flux surfaces are labeled by the variable $x=(\Phi/\Phi_0)^{1/2}$, where Φ is the toroidal flux and Φ_0 is the total value through the plasma cross section. A standard ESC reconstruction of a current hole discharge with small finite core current is shown in ref. 5. Recently, ESC has been modified to include a current hole model in which the current density is identically zero and the pressure profile is flat over a specified region in the plasma core. (The observed pressure profile is often flat inside the current hole within temperature and density profile measurement errors [3].) This model is a good approximation because little (1% or less) of the total current flows in the hole region. It has been used to reliably reconstruct a number of current hole discharges. The solid red line in Fig. 2 shows that such a reconstruction with the radius of the current hole set to x=0.33 (indicated by the vertical red lines in Fig. 2) reproduces the MSE pitch angle measurements within the error bars. (The small positive slope in the calculated $\tan\gamma_m$ inside the current hole is due to the change in the neutral beam injection angle with respect to the midplane across the diagnostic field of view.) Profiles of the rotational transform, $\bar{\iota}\equiv\partial\psi/\partial\Phi=1/q$, and parallel current density, $j_{||}$, are shown in Fig. 3. The narrow peak in $j_{||}$ at the edge of the current hole region arises from the sharp change in $\tan\gamma_m$ at the edge of the flat region seen in Fig. 2.

4. SIMULATION OF CURRENT HOLE EVOLUTION

Theory shows that tokamak equilibria with a core region of zero current density and $\nabla p=0$ can exist, but that no equilibria exist if the core current density is negative or $\nabla p\neq 0$ [9]. Two MHD simulations of current hole discharges offer an explanation for the observed clamping of the core current density near zero: 1) reduced non-linear MHD simulations, initially in cylindrical geometry [4] and recently including toroidal effects [10], show that a plasma with negative core current is unstable to n=0 resistive internal kink instabilities which lead to redistribution of the core current to prevent it from becoming negative;

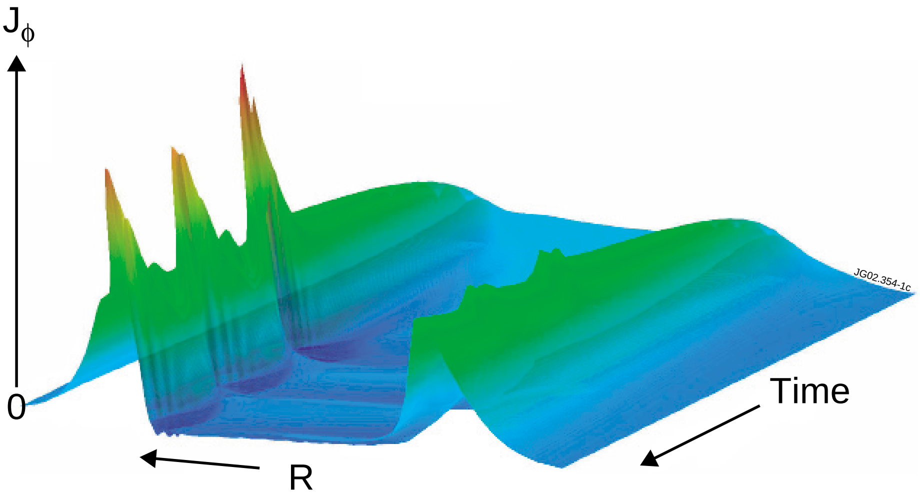

FIG. 4. 2-D Nonlinear resistive MHD simulation of current density in midplane showing repetitive clamping of core current density near zero.

and 2) full 2-D and 3-D nonlinear resistive MHD simulations in toroidal geometry with both a circular plasma cross-section and the experimental shape predict that these discharges undergo n=0 reconnection events (axisymmetric sawteeth) which clamp the core current near zero when $\bar{\iota}=0$ at some point in the plasma [5].

Nonlinear resistive MHD simulations of the initial formation of the current hole and several axisymmetric sawtooth periods afterwards have been performed using the M3D code [5, 11]. Fig. 4 shows the predicted time evolution of the current density profile in the midplane from a 2-D simulation. The core current density falls initially and then clamps near zero due to an axisymmetric sawtooth that occurs when the core current density becomes sufficiently negative that an $\bar{\iota}=n/m=0$ surface enters the plasma. The sharp peaks in the current density at the edges of the hole are due to the current sheet associated with the reconnection process. After the initial reconnection is complete, the process repeats several times if the LHCD remains on. The clamping of the core current density due to axisymmetric sawteeth is also seen in recent 3-D M3D code nonlinear resistive MHD simulations. The reconnection event is primarily m=1 but with a significant m=2 component in simulations done with the experimental plasma cross-section. The essential features of the reconnection process are most easily seen in a simulation done with a circular cross section. Fig. 5 shows the evolution of $\psi(R, Z)$ during an axisymmetric sawtooth period; the magnetic island structure is similar to that of conventional (n=1) sawteeth [5]. However, the axisymmetric sawteeth have the same symmetry as the equilibrium and should therefore be viewed as being due to a transient loss of conditions required for a normal equilibrium with nested flux surfaces [5].

Scaling of 2-D nonlinear resistive MHD simulations done at values of the Lundquist number in the range 1×10^3 to 2×10^4 to experimental values of $\sim 1 \times 10^8$ yields an estimated axisymmetric sawtooth period of ~0.01 s, similar to the period of several milliseconds predicted by the reduced MHD simulations [4]. These events have not yet been observed in the MSE γ_m measurements. This is consistent with the prediction that the periodic changes in the core current density that follow the initial core current clamping near zero are small. Observation of the axisymmetric sawteeth using other diagnostic techniques is difficult because their n=0 character implies that their frequency independent of the toroidal flow speed. The axisymmetric sawteeth are distinct from the high-q sawteeth shown on the T_e traces in Fig. 1, which are believed to be n=1 double-tearing modes [7].

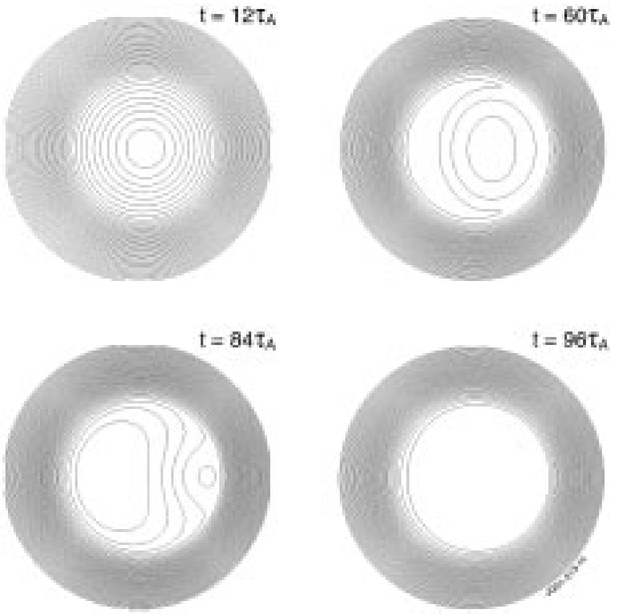

FIG. 5. Poloidal flux map, $\psi(R, Z)$, at four times in axisymmetric sawtooth period from M3D simulation with circular plasma cross section.

5. CONCLUSIONS

Significant progress has been made in the experimental characterization and theory of current hole plasmas. The challenge now is to experimentally determine if the predicted axisymmetric sawteeth are responsible for the observed core current clamping. Understanding the physics of the current hole is important not only for interpretation of present experiments but also to enable accurate predictions of current profile evolution in future devices with strong non-inductive current drive. If clamping of the core current density near zero can be relied on to prevent the core current from going negative during the non-inductive current build-up phase, it may be possible to raise the current much more rapidly than presently believed [12].

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REFERENCES

1. Hawkes, N. C., et al., Phys. Rev. Lett. **87** (2001) 115001-1.
2. Challis, C. D., et al., Plasma Phys. Control. Fusion **44** (2002) 1031.
3. Hawkes, N. C., et al., Plasma Phys. Control. Fusion **44** (2002) 1105.
4. Huysmans, G. T. A., et al., Phys. Rev. Lett. **87** (2001) 245002-1.
5. Stratton, B. C., et al., Plasma Phys. Control. Fusion **44** (2002) 1127.
6. Fujita, T., et al., Phys. Rev. Lett. **87** (2001) 245001-1.
7. Hender, T. C., et al., Plasma Phys. Control. Fusion **44** (2002) 1143.
8. Zakharov, L. E., and Pletzer, A. Phys. Plasmas **6** (1999) 4693.
9. Chu, M., and Parks, P. B., 'On Tokamak Equilibria with Zero Current or Negative Central Current Region' to appear in Phys. Plasmas (2002).
10. Huysmans, G. T. A., et al., 'MHD Stability of 'Current Hole' Plasmas', Joint Varenna-Laussane Workshop on the Theory of Fusion Plasmas (2002).
11. Park, W., Phys. Plasmas **6** (1999) 1796.
12. Jardin, S. C., Nucl. Fus. **40** (2000) 1101.

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