Extreme Shear Reversal in JET Discharges*

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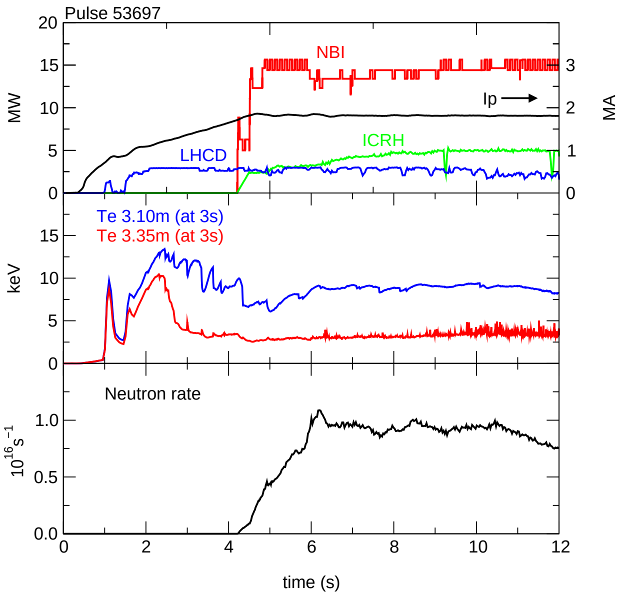

Figure 1: *Time history of plasma parameters for a typical reversed shear experiment. Note the 'sawtooth-like' collapses on the T_e signals between 2 and 4 seconds.*

Discharges in JET have been studied where a combination of fast current ramp with Lower Hybrid heating and Current Drive (LHCD) is used to produce a reversed shear q-profile, Fig. 1. The choice of a fast I_p ramp means that the current is still diffusing into the core when the main experiment starts. The diffusion process is slowed by the heating action of the LHCD which raises T_e and increases conductivity, $\eta_{||}$, [1]. The LHCD also drives a current parallel to the plasma current with an absorption radius peaked off-axis, which tends to remove current from nearby regions, further reducing the on-axis current density[2]. In this scenario a transport barrier can be established in the electron channel (eITB) which persists into the main heating phase. This is manifest as steep gradient in T_e at r/a=0.2-0.3 with a flattening of the profile inside this barrier region. Also during this phase there are periodic, 'sawtooth-like', relaxations[3] in central T_e with accompanying positive transients in outer channels from the escaping heat pulses, Fig. 1. The inversion radius of these collapses lies

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in the steep gradient part of the T_e profile.

Observations with the Motional Stark Effect (MSE) diagnostic show that the gradient in the observed projected pitch angle, γ_m, becomes zero (within error bars) over the central part of the plasma, inside the transport barrier, Fig 2. The value of γ_m in this 'flat-spot' corresponds to there being no poloidal field, comparable to the calibration conditions when the MSE heating beams are fired into the tokamak with a purely toroidal field. (This results in $\gamma_m \simeq$-1.7° due to the beam geometry.) All discharges that show the sawtooth-like collapses in T_e (indicative of an eITB) also show the flat-spot in the MSE γ_m profile.

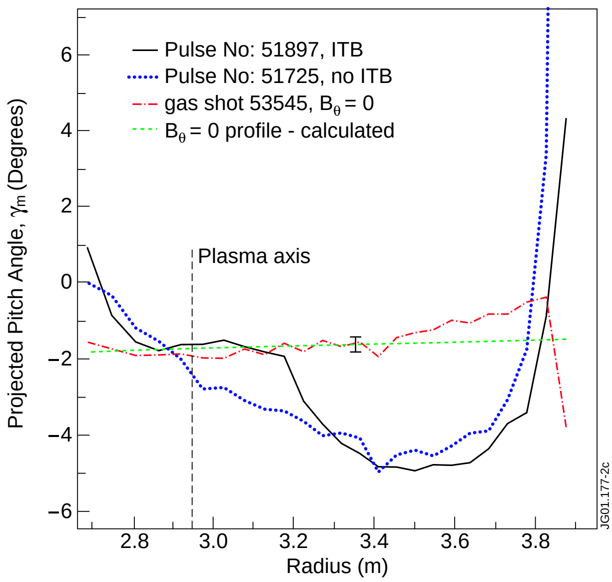

Figure 2: *Profiles of projected pitch angle, γ_m, obtained with the MSE diagnostic, showing the appearance of a flat region near the plasma axsis. This is interpreted as zero toroidal current.*

The observation of zero poloidal field indicates that the toroidal current density, $j(r)$, is also zero (Ampére's Law). An evaluation of the actual value of the central $j(r)$ depends on the accuracy of the measurements of γ_m. The biggest contribution to the error comes from the calibration of the 'zero' angle of the individual channels and this results in an uncertainty in current of $|j(0)|$<200 kA.m^{-2}. By sweeping the plasma position rapidly in radius it is possible to measure the radial variation in γ_m using a single channel of the diagnostic, Fig. 3. This technique eliminates channel-to-channel calibration uncertainties and yields $|j(0)|$<80 kA.m^{-2}. In all cases with a toroidal field of 2.6T, there are no examples of the plasma current ever reversing, Fig 4. (This result is generally true also at 3.4T, although there are two potential cases where $j(0) < 0$.) The mechanism for off-axis LHCD reducing the on-axis current is not restricted to reducing the current only to zero. This mechanism is quite capable of reversing $j(r)$ in this region and the observation that the current does not (in almost all cases) fall below zero implies that another mechanism acts to prevent such a situation. It is natural to imagine that the sawtooth-like

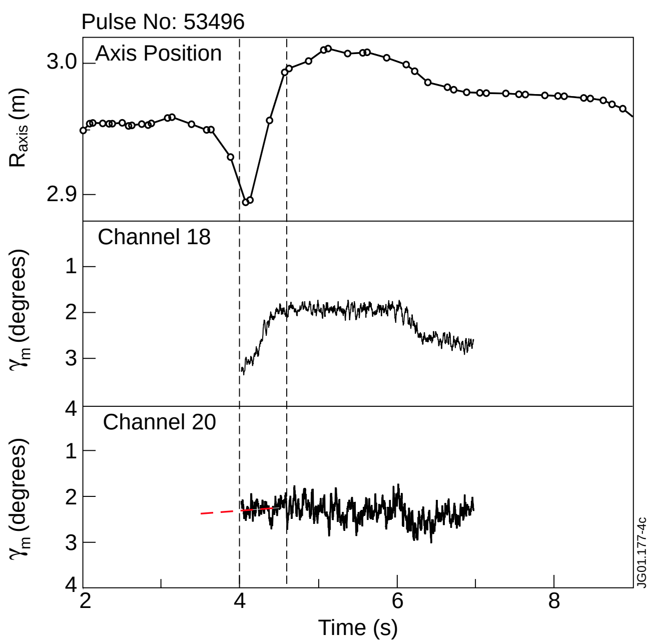

Figure 3: *The plasma is moved radially by 10 cm between 4.0—4.6 s. Channel 20 remains in the region of zero poloidal field during the entire sweep and records no change.*

collapses in T_e play a role in such a mechanism; since the sawtooth collapses redistribute energy across the transport barrier it is likely that they also redistribute current density.

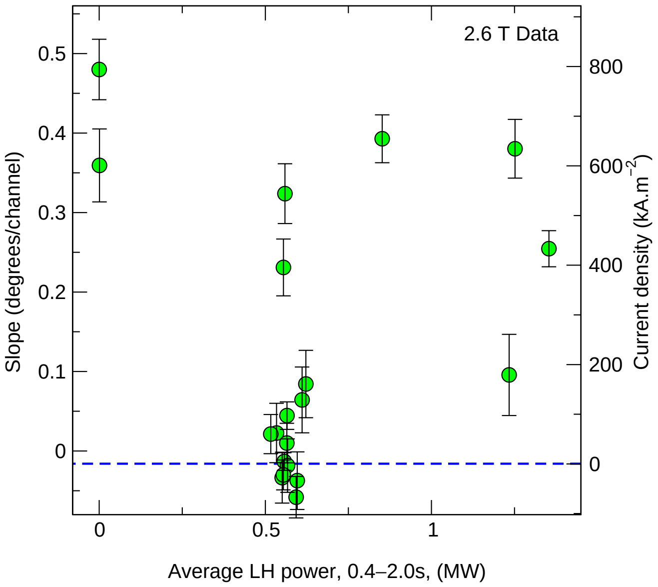

Figure 4: *Slope of the flat region in the γ_m profiles for a number of discharges. There is evidence that the axis current, although reduced to zero, is never driven below zero.*

The MSE measurements of γ_m are known to be affected by E_r, the plasma radial electric field[4]. We estimate this contribution from the terms of the radial force balance equation, using toroidal rotation from carbon impurity ions measured using charge exchange spectroscopy. Only during the full power heating phase, with the appearance of an ion ITB, does the toroidal rotation term become large enough to influence the MSE measurements. The data discussed here do not include these conditions, but a correction for the effect of toroidal rotation is routinely applied. (The pressure gradient term is significantly smaller than the toroidal rotation term and is ignored.) Calculations of the poloidal velocity from neoclassical theory[5] give a very small contribution to E_r. Measurements with the new poloidally viewing core charge

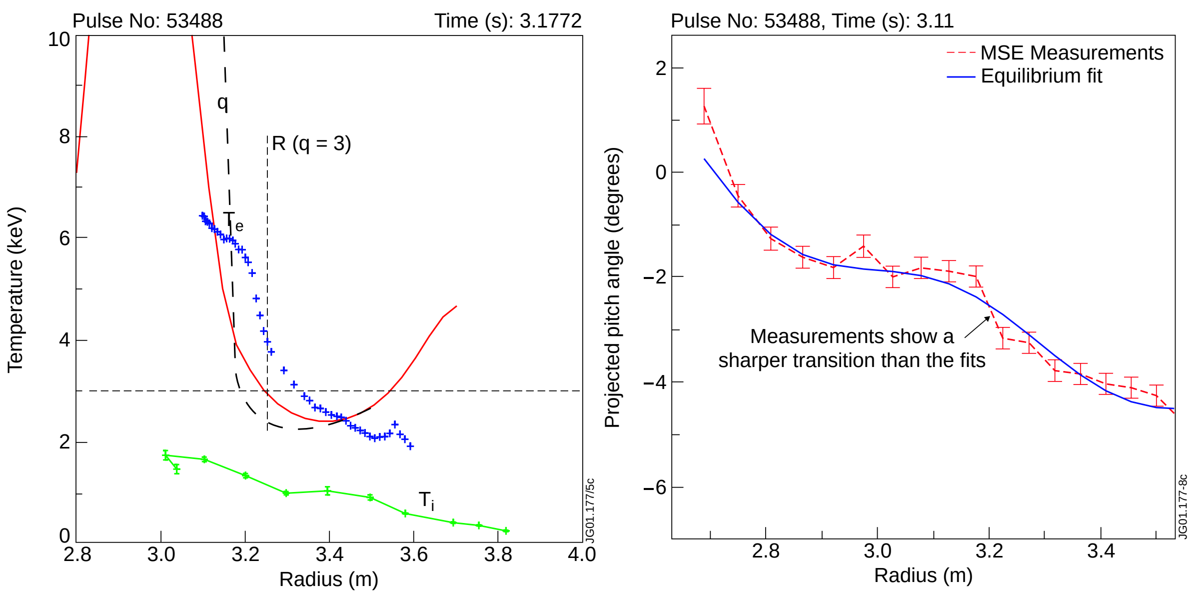

Figure 5: *(a) Equilibrium solution obtained with the* EFIT *code, constrained by the MSE data (using a flux-map obtained without the MSE data) during the LHCD phase. (b) The fit of the measurements does not reproduce the abrupt transition in γ_m at 3.2 m. This indicates that the profile in (a) is steeper in the negative shear region, with a more abrupt transition to low shear, as indicated by the dashed line sketched in figure (a).*

exchange diagnostic[6] (including a correction for cross-section effects[7]) suggest higher poloidal velocities, but still not large enough to affect the conclusions.

A profile of toroidal current density with a large region of zero current at the axis poses severe difficulties for the reconstruction of the magnetic equilibrium. The solution of the Grad-Shafranov equation depends on the existence of flux-surface quantities (p' and ff'), yet in the zero-current case flux surfaces do not exist. As a work-around to this problem we use a flux surface geometry obtained from EFIT using only external magnetics measurements. With only these measurements EFIT has little information about the internal details of the current profile and therefore yields $j(r < 0.3)$ above zero with the existence of flux surfaces. EFIT is then re-run with the MSE measurements included, but with the old flux-map, yielding an extremely good approximation to the exact Grad-Shafranov solution, Fig 5(a). During the time the LHCD is applied the transition, in radius, from zero current to a significant current density is very abrupt and this feature is not well described by the rational polynomials we presently use in EFIT, Fig 5(b). The true q-profile in Fig 5(a) will therefore be far steeper in the vicinity of the eITB, as illustrated with the dashed line. It is therefore impossible to distinguish the effect of rational q-values from that of steep negative shear, since both these features are present in the q-profile at the position of the eITB.

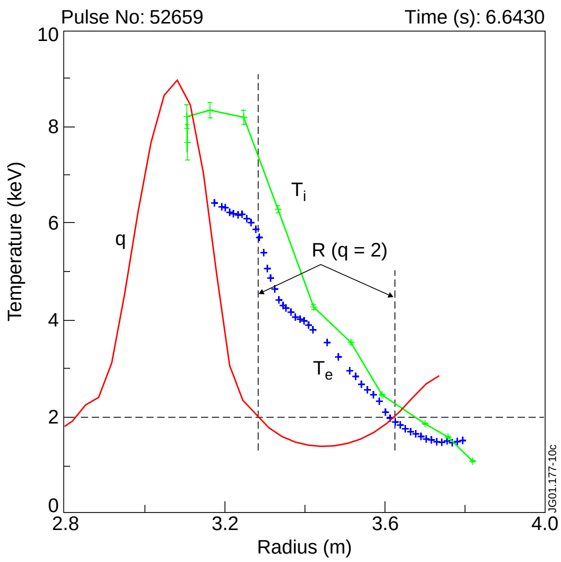

Figure 6: *After the LHCD has been switched off the current profile starts to relax to a less extremely reversed shear profile. During this period the fit to the MSE measurements is better and the q-profiles obtained more reliable. Under these circumstances there is frequently good correlation between the positions of integer q-surfaces and the radii of ITBs.*

After LHCD is turned off and NBI heating applied the abrupt transition in the current profile is eroded (both current diffusion and NBI on-axis co-current drive play a role). As the q-profile relaxes from its extremely reversed initial configuration it becomes possible to identify individual rational-q surfaces in the positive and negative shear regions. There is frequently very good correlation between the location of the rational surfaces and the location of the transport barriers, in both ions and electrons and in both positive and negative shear, Fig 6.

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