Current profile redistribution due to internal relaxation events in extreme reversed shear JET plasmas

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1. Introduction

Reversed shear plasmas in JET, are established using a combination of LH heating and off axis current drive (LHCD), early during the ramp up phase of the discharge, also known as the prelude phase. This regime is characterised by a region near the axis with nearly zero density current. This evidence was first demonstrated from the observation of the MSE measured pitch angle γ_m [1]. Where the radial profile of γ_m exhibit a flat spot in a central region defined by $\rho \leq 0.3$, where $\rho=\sqrt{\psi_{Vol}}$ and is nearly equal to r/a on the midplane. MSE channels near the magnetic axis also probe this region. The MSE diagnostic measures the polarisation angle γ_m of the π line from the Stark splitted D_α emission as neutrals from pini1 are injected into the plasma. The relationship between the MSE measured pitch angle and the magnetic field is given by[1]

$$\tan\gamma_m = \frac{B_z A_0 + B_R A_1 + B_\varphi A_2}{B_z A_3 + B_R A_4 + B_\varphi A_5} \qquad (1)$$

Where the A_i are the geometric coefficients describing the JET geometry. In principle this relation is complex, but can be simplified near the midplane of JET, to give a simple relation between γ_m and the local pitch angle γ corrected by a geometric factor $\tan^{-1}(A_0/A_5)$, giving an offset angle of -1.7^o. This angle is carefully measured by firing pini4 into a gas filled torus for typical values of B_φ in JET discharges giving the $\gamma \cong 0^o$ calibration line. The flatspot signature coincides with the zero measured pitch angle (figure 3A, vertical red line) indicating a region of zero B_θ and consequently zero current density. This is the so called current hole, where current is excluded from this region and instead flows in a narrow skin at its boundary. An electron Internal Transport Barrier (eITB) is observed with steep gradients in T_e near the position of the current skin. In all of these kind of discharges a sawtooth-like event is present with q > 1 everywhere. This activity can occasionally be seen and is clearly influencing the MSE signals. To investigate this interference, we choose two discharges (53121 and 55604) where the high q sawtooth like event is present to study this interference, quantify its influence in the current redistribution scheme and make conclusions on the role of this activity on extreme reversed shear plasmas (ERS).

[1] The full expression includes a term involving the plasma radial electric field.

2. Experimental data

The discharge 53121, shows the eITB dynamics based on the gradient of the electron temperature (T_e') criteria (figure1A) [2], ECE signals where a large sawtooth crash (possibly a double crash) can be noticed at 3.8s (figure 1C) and the measured pitch angle signals for MSE channels 14 to 18 (figure 3C). Vertical lines are marking the time of the crashes, from here is quite clear to follow the influence of the crashes on the MSE signals for channel 14 located at 3.272 m (red line) and channel 15 located at 3.225 m (green line). All the other channels remain unperturbed. Even for these two channels the sensitivity to the event is different. While channel 14 can experience only the first crash, channel 15 is tracking two later crashes. This effect could be explained looking at the radial position of these channels (horizontal lines in figure 1A). Due the slow inward movement of the barrier channel 15 (lower line) is well inside the barrier during subsequent crashes. While channel 14 (upper line) is nearly at the edge of the barrier.

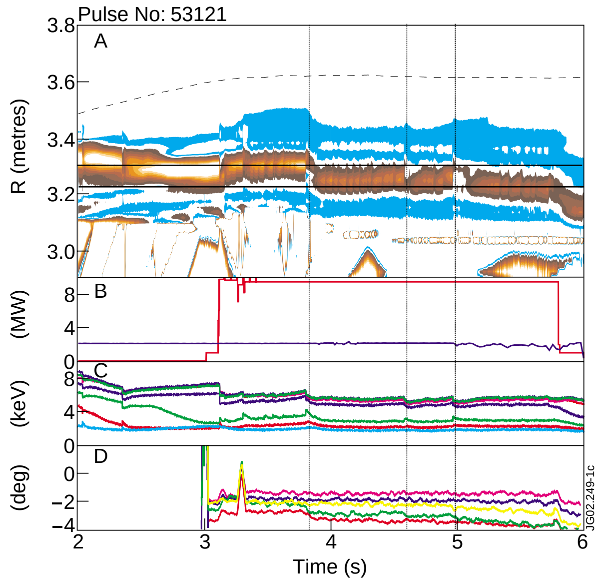

Figure 1 A) T_e' criteria showing the probability the barrier to be present at a given time and radii. **B)** LHCD (blue) and NBI powers. **C)** T_e signals from ECE.**D)** MSE measured pitch angle signals

These two channels are also at the edge of the flatspot thus reflecting the sharp change in the slope of the tanγ_m profile, this would be reflected in a steep gradient in the current profile.

Shot 55604 shows another example where sawtooth-like behaviour is observed. In this case LHCD and ICRH heating are used with pini1 only to allow MSE measurements. This makes possible to study high q sawtooth between 3.8s and 4.5s. At these times the crashes have weakened. The particular dynamics of the eITB makes possible channel 16 at 3.177 m (blue line in figure 2d) to experience the effect of the crashes at later times. For channel 14 and 15 the effect of crashes is obvious and notably persists after the end of the LHCD period, following the decay of the barrier.

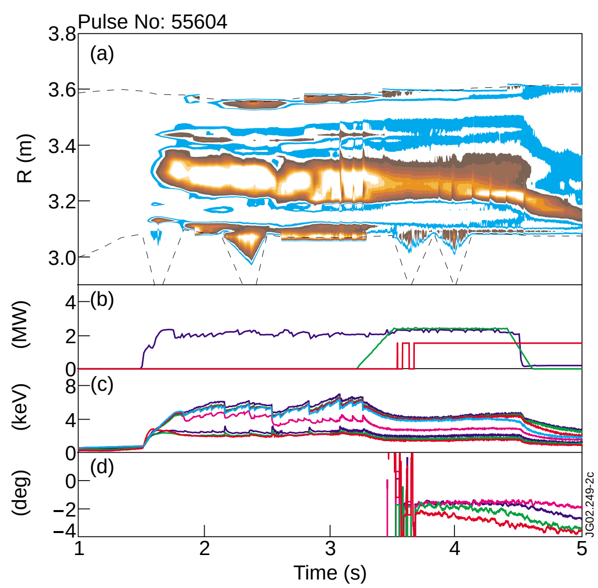

Figure 2 a) T_e' criteria showing the probability the barrier to be present at a given time and radii. **b)** LHCD (blue), ICRH (green) and NBI (pini 1 only, red) powers. **c)** T_e signals from ECE. **d)** MSE signals

3. Current density rearrangement

To study the redistribution of the toroidal current density during the crashes, we used a non-perturbative technique in solving the Grad-Shafranov equation for a fixed magnetic configuration. In this way magnetic equilibrium reconstructions were made before and after the crash (53121), or during a sequence of crashes (55604). In both cases magnetic data from coils and probes were kept constant during EFIT runs. This procedure makes sure that any changes to the current density profiles are coming only from MSE measurements. In the Grad-Shafranov equation J_φ is defined by two flux functions $p'(\psi)$ and $FF'(\psi)$. Being constructed by a superposition of basis functions either polynomials or cubic splines. Figure 3 shows the results for the crash at 3.8s in #53121, using polynomials of order 6 and 4 for FF'' and p'. Figure 3A indicates the flatspot signature in the MSE data, the perturbation due to the crash and respective modifications in the safety factor profiles leading to a current hole (figure 3C).

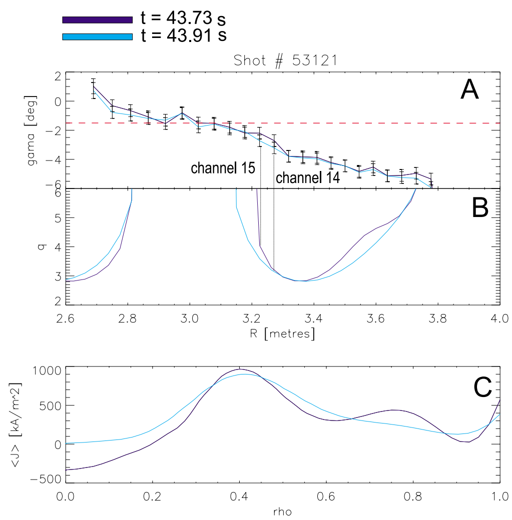

Figure 3 A)MSE measured pitch angle profiles. **B)** safety factor profiles. **C)** J(r/a)

From here we can conclude that a large high q sawtooth crash is possibly preventing the current from going negative and clamping it to zero[3,5].

Moreover, a broadening of the current density profile after the crash can be observed, as have been pointed out in [4].

Applying the same technique to the sequence of collapses mentioned above and observed in 55604, we can follow the time evolution of J(r/a) as shown in figure 4.

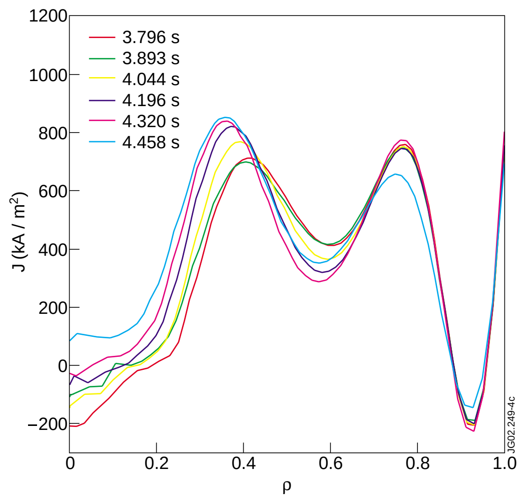

Figure 4 Time evolution of J(r/a)

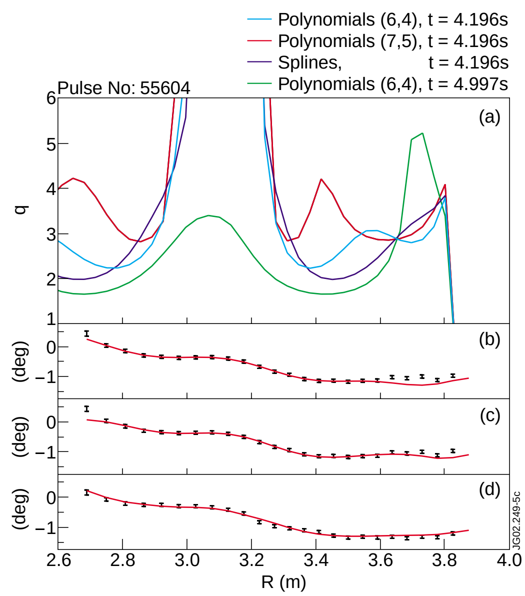

Figure 5 A) q profiles usinge either polynomials or splines (blue) **B)** fitted data (6,4) **C)** fitted data (7,5) **D)**fitted data (splines)

This example confirms the effect of crashes on the current rearrangement, a number of weak crashes have a global effect of a single large crash. Here conclusions are basically the same as in the previous case. A small drift is observed in the off-axis peak. Should be remarked that figure 4 is a nice a complement to results reported in [5], where time evolution of J(r/a) over the LHCD pulse during the current ramp up, were predicted using a simple current diffusion model in cylindrical geometry. Figure 5 shows the results of the analysis using polynomials of order (6, 4) and (7, 5) for the flux functions (*FF''*, *p'*). These results are to be compared with result using splines. From here it is clear that the fit to the measurements is excellent when using high order polynomials. On the other hand, fitting with splines is still good but not very adequate in this case, particular for channels 14 and 15.

4. MHD analysis

Analysis of magnetic pick-up coils shows that a high q sawtooth crash is usually followed by a postcursor oscillation [4]. The actual mode that causes the crash is difficult to identify, since precursor oscillations are very fast and not clearly seen when analysed with standard FFT techniques. Mode number identification of the postcursor and other modes (table 1) observed around the crash give some indication of q rational surfaces present before and after the crash. the mode number analysis is performed using magnetic pick-up coils at different toroidal and poloidal locations. The mode localisation can be obtained using cross-correlation analysis with ECE and SXR signals, indicating the position of the q surfaces associated with each mode. The use of ICRH in discharge 55604 lead to destabilisation of a wide range of high frequency modes (f=50-125khz) with mode numbers n>1 (see fig. 6 in the lower frequency range two continuous n=1 modes are observed.

t = 4.26 sec		
f (kHz)	n	m
11	1	6
21	1	3-4
55	2	8
91	3	8-9
t = 4.3 sec		
f (kHz)	n	m
60	2	6

Table 1 mode analysis from magnetic coils

The 8-9/3 mode can be identified as Alfven cascades (3.6 m) excited by ICRH and measured by high resolution pick-up coils (figure 6), indicating that q_{min} is crossing a rational surface. From this point is not clear if the structure showed in figure 5A (red curve) is physical or correspond to a numerical artifac arising from the use of higher order polynomials.

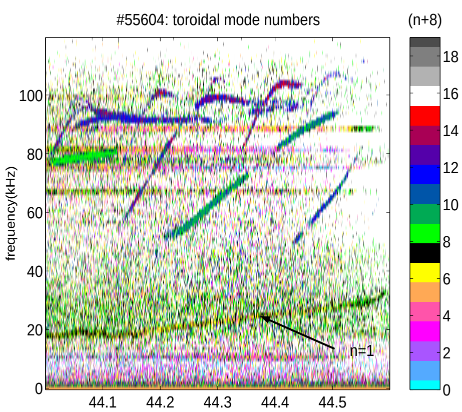

Figure 6 spectrograms from fast magnetic pick-up coils

5. Conclusions

The sensitivity of the MSE system to MHD activity, namely to the high q sawteeth has been established. Magnetic equilibrium reconstruction for two different ERS scenarios showed the effect of the high q sawtooth is prevent the current density goes negative and clamping it to zero. The problem of using high order polynomials or splines in fitting the experimental data in this scenario has been addressed. MHD analysis revealed the presence of higher frequency events whose locations would allow to speculate in principle about the nature of structures appearing in the calculated q profiles. These subjects require further investigation.

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