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INTRODUCTION

Experimental observations in JET indicate that type I ELMs are associated with rapid movements of strike points [1,2]. In [2] strike positions are identified with 2 different diagnostics: as the position with maximum ion saturation current, measured with divertor target Langmuir probes, and as the position of highest temperature and/or heat flux measured with an infrared camera. The apparent strikes often shift as much as 20cm in 100 μs or less (limit of temporal resolution), but in the next data point the strikes settle nearer their original position, displaced toward the plasma centre by 2-5cm from the pre-ELM position.

In an H-mode plasma strong edge pressure gradients indicate the likely presence of non-zero current density at the separatrix. This means that at the X-point there is a flux tube with toroidal current, which we assume to be parallel to the core plasma current. A new instability mechanism for the plasma can then be considered: if the X-point current carrying flux tube is displaced towards the private flux region, it will be accelerated further in that direction, as the attractive j×B force from the core plasma decreases while the force from the divertor coils increases. The X-point flux tube would then tear, opening up the separatrix. Transiently, a new X-point would form, closer to the core plasma, as the externally imposed diverting fields are increased by the field produced from the detached current carrying flux tube. Plasma would flow along previously closed field lines, both in public and private scrape-off layer flux regions. As the current in the private region reaches the targets, it would dissipate, leading to yet another new equilibrium, with a new X-point forming at an intermediate position between the previous two.

1. THEORETICAL CONSIDERATIONS ON SEPARATRIX STABILITY:

Most studies of plasma MHD stability begin from a given equilibrium, which is then perturbed to explore some parameter of interest. Typically, the last closed flux surface is assumed not to have an X-point, and it is held constant. In consequence, it is not surprising that separatrix instability has not been studied so far.

In an study of X-point interchange stability [3] it was assumed that the local current density is zero. Typically, equilibrium reconstruction indicates that this is not the case in diverted H-mode plasmas with high edge temperature (i.e., the type I regime).

As in most older articles, studies of doublet configurations typically used monotonically decreasing current density profiles, although even in that case criticality of a separatrix was identified [4]. Vertical instability of current-carrying X-point, and strike movements:

We consider the stability of a current carrying filament in a diverted plasma in a magneto-static model of the tokamak. The divertor is represented by straight circular coils of radius 0.1m, placed at (R,Z) = (±0.2, ±2.0) and (±0.3,±1.8) (metres), divertor target tiles are assumed to be vertical, at R = ±0.2m, plasma centre at R = 0. Initially the double null plasma is modelled as a straight circular coil of radius 0.5m, immersed in the divertor field, leading to an X point height of Z_X = ±1.47 m, and strikes at Z_S = ±1.618m, as shown in Fig.1. At the X-point the force on a current filament would be zero, such equilibrium is vertically unstable. There is a secondary null at $Z_{X2} = \pm1.77$m, forces on a filament here would again be zero, this equilibrium is vertically stable, and horizontally unstable. Removing 5% of the plasma current and placing it in 2 filaments (1cm radius) placed at $\pm Z_f$, above and below the plasma centre, leads to a displacement of the strike points, as shown in Figs. 2 and 3. As the X-point is approached from inside, the strikes are pushed away from the plasma centre, "down". Beyond a critical value, strikes are swept "up". For $Z_s = Z_{X2}$, the highest strike position is reached, equivalent to a "peeled" plasma with extra divertor current. Whenever current in the private flux region dissipates, strikes would move to "peeled" position without extra divertor current, $Z_s = \pm1.60$m. About 10cm of the divertor target area are swept in this process. Qualitatively, this is what we expected. Quantitatively, the effect is overestimated, as it is unlikely that as much as all of the current lost from the plasma at an ELM (estimated 5%) would appear in the private flux regions after separatrix breakage.

However simple, this model indicates that if current filaments were to be displaced from the main plasma towards the divertor coils, they would "fall" vertically in a fast time-scale until the secondary X-point is reached. There the filaments would drift horizontally towards inner or outer target plates. It inspires us to study in more detail the magnetic topology in the divertor region. It also indicates that strike point behaviour may well differ if a dome is placed just below the X-point (JET septum plasmas).

Realistic tokamak geometry and current profile details may well alter quantitative results. In that case, we would search for an equivalent instability associated not with filament displacements, but with progressive transfer of current density from plasma core to edge, as probably occurs when pedestal pressure gradients, and associated toroidal current density, increase before an ELM.

2. TOROIDICITY EFFECTS

When toroidal effects are taken into account, the toroidal plasma current density in a tokamak equilibrium is given by $j_t = Rp' + FF'/R$, where p is the pressure, F the poloidal current density, and prime is the poloidal flux derivative, $p' = dp/d\Psi$. As p and F are flux functions, if F' has opposite sign to p' (diamagnetism), in the high field side the toroidal density reverses. This is common in H-mode plasmas, near the edge, as was pointed out in [5]. Figure 5 shows a JET reconstructed equilibrium, just before an ELM, in which the region with negative current density is marked in red. The variation of jt, Rp' and FF'/R along° the lower half of the separatrix is shown in Fig.6. Increasing $\beta_{poloidal}$ and triangularity increases diamagnetism and reduces the toroidal current density at the X-point, increasing the stability of the current-carrying X-point. At extreme triangularity and $\beta_{poloidal}$, the toroidal current density at the X-point might reverse, thereby completely modifying its stability conditions (from "pulled" to "pushed" field null).

The toroidal negative current in the HFS may itself de-stabilize the separatrix, as opposing currents repel each other, and might contribute to peeling of the outer surfaces.

CONCLUSIONS

Experimental observations are compatible with the hypothesis that an ELM is a peeling of flux surfaces near the boundary, which open into the scrape-off layer, and the formation of a new separatrix, inside the previous one. In the transitional phase, the strike points may sweep a large area while current that became trapped in the new private flux region drifts and dissipates. The stability of a current-carrying X-point may play a role in ELM dynamics, as shown with a simplistic model. Toroidicity effects may relate $\beta_{poloidal}$ and triangularity to X-point stability. Separatrix instability could provide an ELM trigger.

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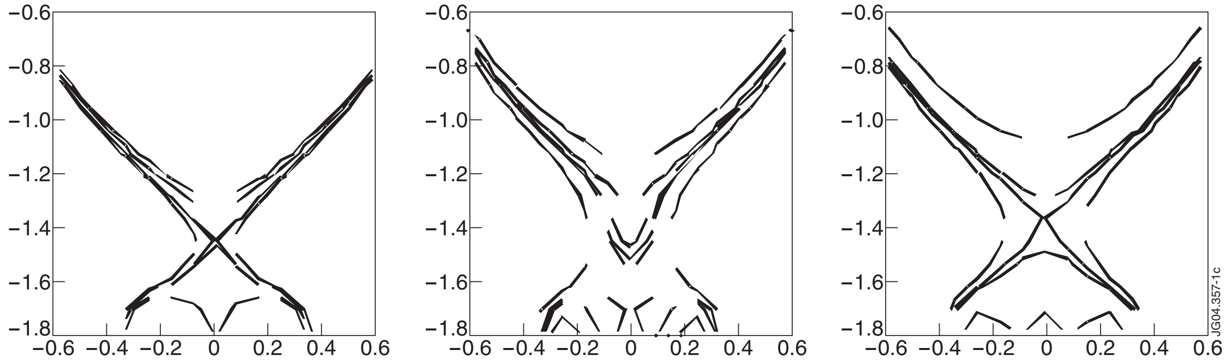

Figure 1: (a) Plasma, no filament (b) Filaments at Zf= ±1.4 m. (c) Filament at Zf=±1.77 m

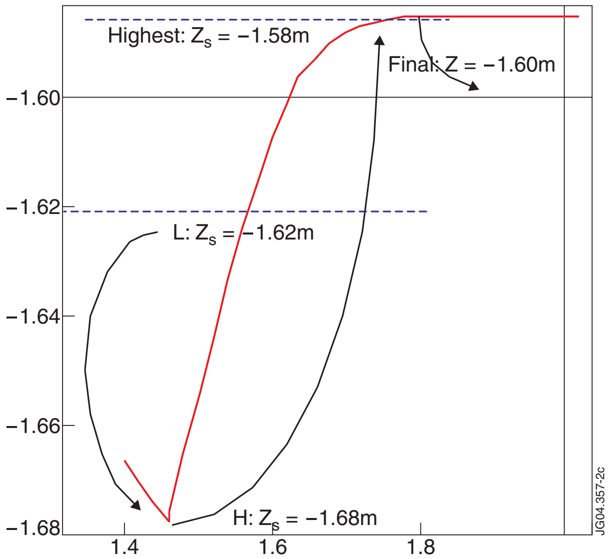

Figure 2: Strike position vs. filament position: from L-mode to H-mode, to extra high, to final.

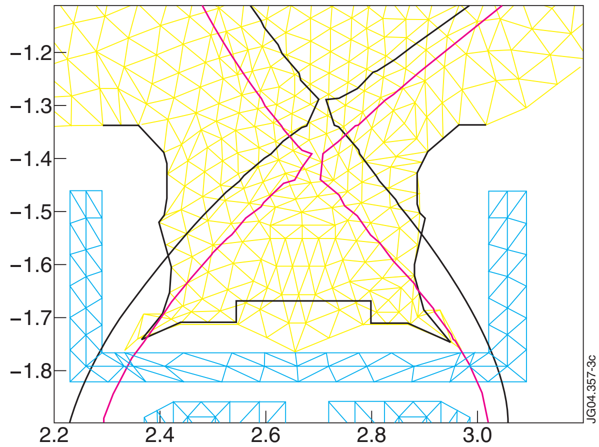

Figure 3: JET equilibrium reconstruction: before peeling (magenta); after peeling, with extra divertor current

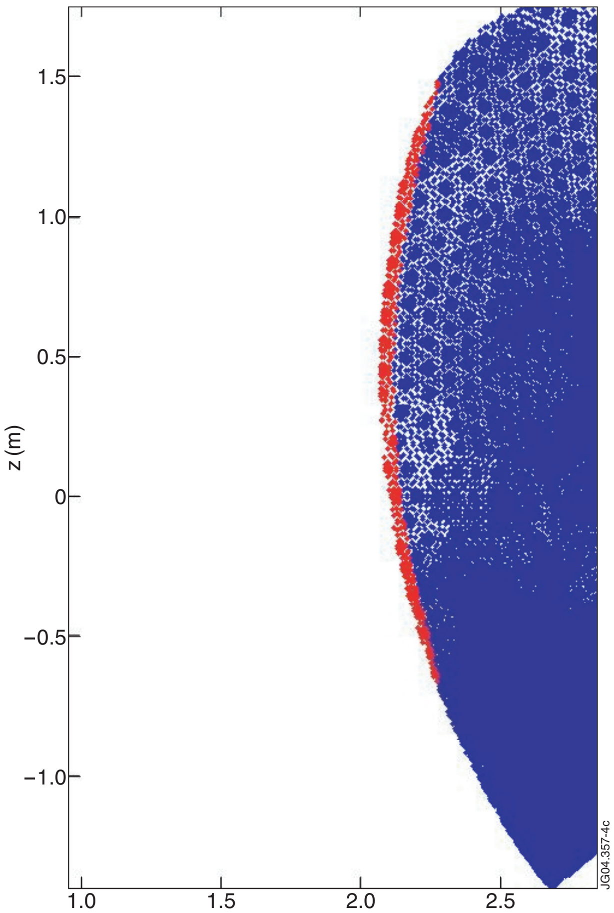

Figure 4: Reconstructed equilibrium, region with negative current density marked in red; JET 58837, 61.4 s

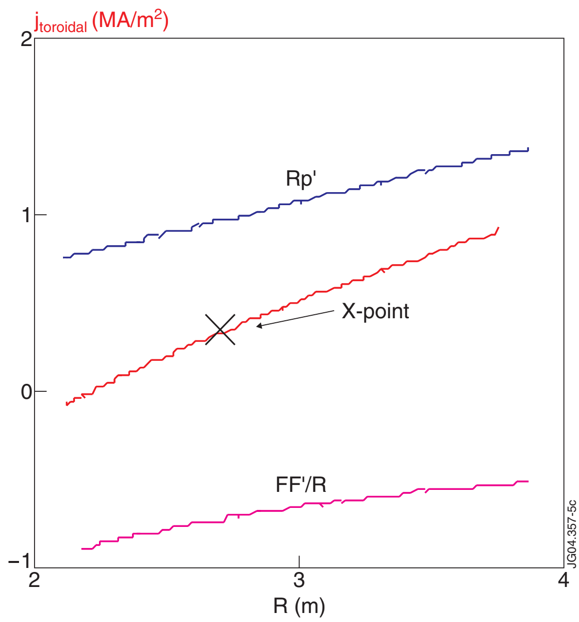

Figure 5: Toroidal current density along bottom half of separatrix, and its two components