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ABSTRACT.

This paper presents the results of some dedicated experiments performed on JET, and related simulations, that clearly demonstrate the existence in JET of a Neutral Point (NP) for density limit disruptions. It has been observed that a plasma, specially designed to be set at different vertical equilibrium position without altering the shape, moves upwards (downwards) when the disruption is triggered with the plasma below (above) the NP. The CREATE_L linearized plasma response model applied to such configurations is able to predict and explain the most significant qualitative features of the experiment.

1. INTRODUCTION

Any plasma current, position and shape controller must counteract a number of plasma disturbances – e.g. a fast plasma current quench due to a density limit disruption, or a poloidal beta drop due to a giant ELM. Such disturbances induce eddy currents in the passive structures that interact with the plasma; the imbalance of attractive forces between such currents and the plasma can cause the plasma itself to move vertically in a preferential direction (i.e. upward or downward). It can be expected that there exists a position for the plasma current centroid such that ideally this imbalance is zero and the vertical position displacement after a given time interval is zero (practically very small).

Neglecting the dynamics of the remaining stable modes, we can say that a given perturbation at a given instant t_0 excites the vertical position (axisymmetric) unstable mode with an initial vertical position displacement dz_0. This makes the plasma vertical position displacement dz evolve exponentially as

$$\delta z = \delta z_0 e^{\gamma(t-t_0)} \tag{1}$$

where g is the growth rate of the vertical position instability. We claim that the quantity dz_0 is a function of the initial plasma centroid vertical position Z_c at which the instability is excited, and that this function changes sign. Hence, we define the Neutral Point (NP) as the vertical position Z_{NP} at which δz_0 vanishes. In other words, the NP is the position of the plasma in which the unstable mode is not excited by a given perturbation, independently of γ. We note that there might be in principle a dependence also on other plasma geometrical descriptors, but in our cases the vertical position is the only parameter that is systematically and intentionally varied.

Consequently, if the plasma is initially placed exactly at the neutral point ($Z_c=Z_{NP}$), the vertical position displacement at a generic instant $t_1>t_0$ will be zero, so that the plasma apparently does not move although its growth rate is greater than zero.

In practice, we will never be able to place the plasma exactly at the neutral point, but we can argue that if the plasma is “close” to the NP then its displacement after a given time interval is “small”, as compared to a generic plasma position, since δz_0 is “small”.

In a perfectly up-down symmetric device with a perfectly up-down symmetric plasma any point lying on the z=0 axis would be neutral according to this definition. In non-symmetric configurations, like JET, the existence and location of such points is not obvious. In the past [1-3], the existence of such a neutral point has been experimentally demonstrated on JT60-U and confirmed numerically via TSC simulations. Also ASDEX-U has reported some evidence in this sense [4].

In this paper, we will describe similar experiments performed on JET, in which density limit disruptions were deliberately triggered at given instants. The simulations were carried out using the CREATE_L code [5]. In section 2 the experimental set-up is discussed, while in section 3 the experimental results and the related simulations are presented. Section 4 draws the conclusions and provides an outlook of future work.

2. EXPERIMENTAL SET-UP

The geometrical parameters of all the plasma configurations analysed are very similar, apart from the vertical position of the plasma current centroid Z_c (table I). In order to achieve this, the minor radius is quite small as compared to "high performance" configurations, and the plasma current is limited to 1.5MA; the toroidal field is chosen in order to keep the safety factor at acceptable levels. The elongation is chosen so that the expected growth rate is within the capabilities of the Vertical Stabilization (VS) system.

During one single shot, the plasma centroid was slowly ramped from the highest to the lowest vertical position, and the disruption trigger was set at a given time, in order to analyse the corresponding vertical position. The density limit disruption was provoked by puffing Argon at high pressure (800 mbar, typically injecting ~3 10^{22} electrons).

The VS system switch off was timed on the spike of the divertor H_α light, which is a reliable sign of radiative collapse. A few pulses did not have the vertical control removed, but the plasma behaviour in such cases does not differ significantly from that in the other pulses, as we will discuss in the following. Moreover, usual disruption detection actions (typically carried out to limit the vertical force acting on the vacuum vessel) were bypassed, in order not to alter PF coil currents artificially.

3. EXPERIMENTAL RESULTS AND PRELIMINARY MODELLING

On the basis of the NP definition given above, and assuming that the growth rate does not significantly vary among the configurations analysed, we evaluate the existence of the NP by plotting (Fig.1) the vertical position displacement (dz_p) of the plasma current centroid after a given time interval (3ms) from the H_α spike, as a function of the initial plasma vertical position (as measured by the VS system).

The quantity dz_p depends almost linearly on the initial vertical plasma position, and changes sign around $Z_c \approx 20$cm. This means that all the configurations with $Z_c > 20$cm moved downwards after the excitation of the vertical instability, while all the configurations with $Z_c < 20$cm moved upwards. Configurations with $Z_c \approx 20$ cm went either up or down. Therefore, we define the Neutral Point position for the configurations analysed as $Z_{NP} = 20$cm.

The actual switch-off of the VS system does not seem to affect dramatically the results; however, in the following we will focus our attention on the shots (reported in table I) in which the VS system was actually disabled.

In order to simulate the plasma behaviour we must understand the perturbation that excites the unstable mode. With reference to Pulse No: 55170, from Fig.2 we notice that just after the H_a spike Z_c has an initial increase, whose origin is not fully understood yet, which could be due to a spurious "kick" of the VS system just before its switch off. Immediately after, a sudden I_p increase (in amplitude) occurs, that is quickly recovered, and afterwards, an almost linear decrease of the plasma current takes place.

We claim that the sudden increase in plasma current is due to a sudden drop of the plasma internal inductance l_i, that in turn is due to a current profile flattening related to impurity penetration. Indeed, if we assume that the plasma evolves keeping roughly constant the quantity $l_i\ I_p^{\alpha}$ ($\alpha=1$ corresponds to flux conservation, a=2 to energy conservation), we have that (the suffix "0" stands for reference quantities):

$$\delta\left(l_i I_p^{\alpha}\right)=0 \quad \Rightarrow \quad \frac{\delta I_p}{I_{p0}}=-\frac{1}{\alpha}\frac{\delta l_i}{l_{i0}} \tag{2}$$

so that an instantaneous drop $\delta l_i<0$ causes a plasma current perturbation such that $\delta I_p/I_{p0}>0$.
On the basis of these considerations, we assume that the instability is excited by the simultaneous variations of plasma current and of internal inductance. We also assume that the variations of poloidal beta produce a negligible effect, since its starting value is very low.

We can expect that this perturbation of I_p and l_i would tend to move the plasma mainly radially; due to the up-down asymmetry of the equilibrium field and of the currents induced in the passive structures the plasma vertical position will be perturbed. Our goal is to find out the sign of the vertical position perturbation.

In order to do this, we use the CREATE_L linearized plasma response model [5], systematically validated in the past on smaller tokamaks in air [6]. This model gives a linearized approximation of the non-linear plasma response around a reference equilibrium configuration. The plasma is assumed to be axisymmetric, in equilibrium at each instant, and described by a small number of global parameters. The effects of plasma mass and finite conductivity are neglected.

The CREATE_L model has been used for all the shots reported in Table I. The resulting growth rates vary only of about ±15% around a mean value of about $480s^{-1}$, which is consistent with the experimental observations of vertical forces acting on vessel.

We feed the CREATE_L model using a perturbation $dl_i(t)$ that provides the best agreement with the experimentally observed $\delta I_p(t)$. This (Fig.3) is close (in terms of amplitude of the drop) to the variation of the experimental estimation of the quantity $2^*\delta\Lambda$ ($\Lambda=\beta_p+l_i/2$), that is a good estimate of l_i variations, provided that the effect of variations of β_p is negligible.

We notice from Fig.4 that the time behaviour of Z_c is correctly reproduced qualitatively. The main features of the vertical movement are the following.

a) The I_p spike makes the plasma suddenly move down both in the model and in the experiment, although the amplitude of the movement is clearly too high in the model. This discrepancy has a number of possible explanations: either a measurement error (the I_p spike is overestimated, or the Z_c spike is underestimated) or a prediction error (nonlinear effects due to the huge modelled movements and plasma current excursions).

b) After this fast downwards movement, the plasma moves upwards both in the experiment and in the model. Hence, the model is able to successfully reproduce the direction of the overall plasma movement.

In order to understand more deeply the vertical position movement, we analyse the excitation of the unstable mode. We calculate the unstable eigenvector $\mathbf{v}_{unst}$ of the dynamic matrix of the linearized model, and we evaluate the projection of the state of the system over $\mathbf{v}_{unst}$. This projection tells us how we are exciting the unstable mode. The result is that during approximately the first 2ms after the H_a spike the unstable mode is excited in the downwards direction, while after the I_p spike the unstable mode is excited in the upwards direction, consistently with the experiment. Therefore, we can conclude that the perturbation that in fact excites the upward instability is the I_p spike plus its subsequent diminution.

Similar results will also hold for the other shots. In all cases (but Pulse No: 55176) the CREATE_L model is able to correctly reproduce the direction of movement due to the density limit disruption, hence justifying the rather unexpected result that all configurations with a “high” vertical position (Z_c>Z_{NP}) moved downwards, while all configurations with a “low” vertical position (Z_c<Z_{NP}) moved upwards. The reason why the model is not able to reproduce the direction of the movement is Pulse No: 55176 is that the plasma is located very close to the neutral point, so that the plasma could move either upwards or downwards with almost equal probability.

CONCLUSIONS AND FUTURE WORK

A number of dedicated experiments have been carried out at JET, clearly demonstrating the existence of a Neutral Point for density limit disruptions. A simulation tool which is able to qualitatively reproduce the experimental behaviour for all the configurations not located at the NP has been developed, hence confirming the position of the NP.

The main points that will be addressed in our future activity are the following. From the experimental point of view, the dependence of the NP location on the plasma configuration and the effects of different perturbations (e.g. ELMs) should be investigated. From the modelling point of view, further refinements need to be explored (e.g. the input constraints on the model) to improve the quantitative agreement; moreover, the reliability of the magnetic measurements should be assessed, possibly comparing with non-magnetic measurements (e.g SXR).

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Pulse No:	I_p (MA)	β_p	1_i	Z_c (cm)	R_c (m)	κ	upper δ	lower δ
55170	1.48	0.18	1.15	9	2.79	1.65	0.15	0.19
55171	1.48	0.18	1.14	15	2.79	1.65	0.15	0.19
55173	1.52	0.19	1.18	36	2.78	1.66	0.14	0.18
55174	1.49	0.18	1.14	27	2.78	1.66	0.14	0.19
55175	1.49	0.19	1.13	24	2.78	1.66	0.14	0.19
55176	1.49	0.18	1.13	20	2.78	1.66	0.14	0.19
55177	1.49	0.18	1.13	14	2.78	1.65	0.14	0.18

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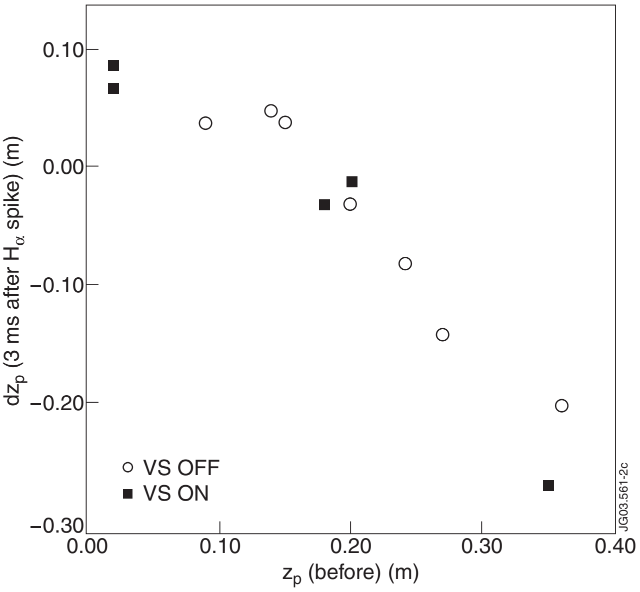
Table I. Various plasma configurations analysed



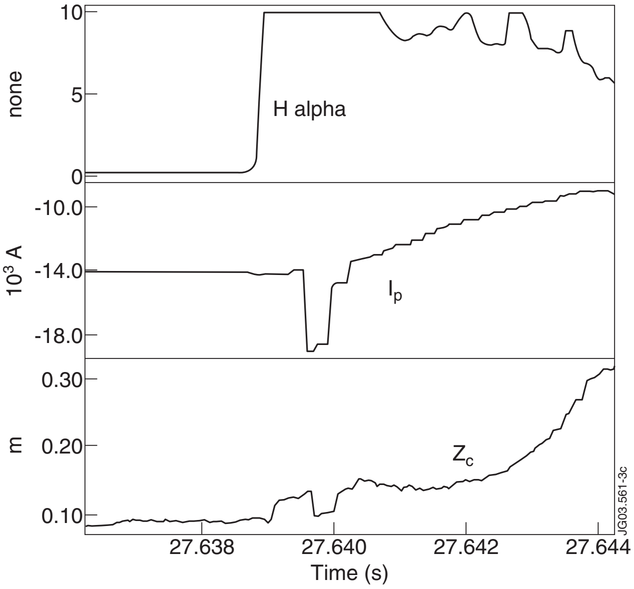
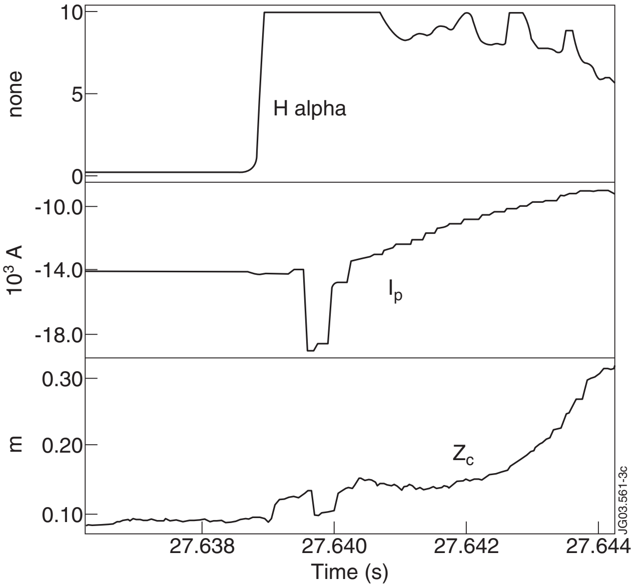


Figure 1: Vertical position displacement as a function of the starting vertical position.

Figure 2: Various plasma quantities for Pulse No: 55170. From top to bottom: H_α, plasma current, plasma centroid vertical position.



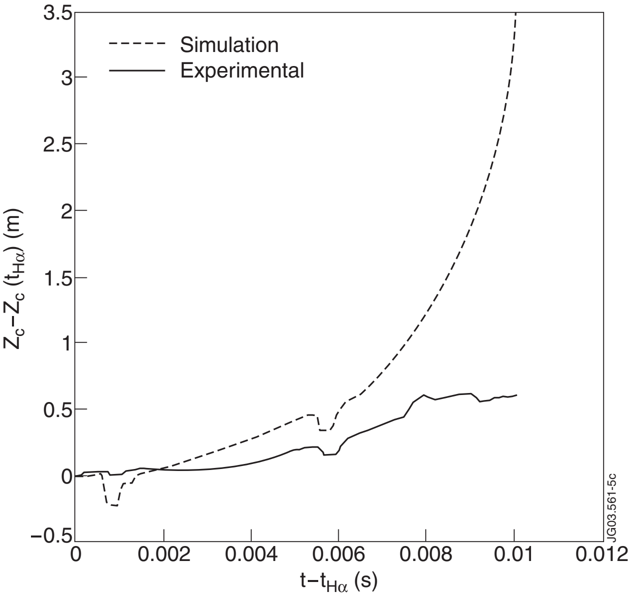


Figure 3: Time behaviour of experimental and simulated l_i perturbation.

Figure 4: Experimental and simulated vertical position evolution.