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ABSTRACT.
Abstract. In this paper we show that the effect of the saddle currents in the rigid sectors slows down the vertical instability of JET elongated plasmas by a factor of about two with respect to estimates based on pure axisymmetric models. This significantly improves the agreement between the theoretical predictions and the experimental results. The CREATE-L model taking into account the 3D effects of the eddy currents has been applied to various JET pulses; the growth rates have been estimated within an accuracy of 5% for plasmas with a growth time longer than 2ms. This model can be used for JET and extended to ITER-FEAT to provide a reliable test bed for assessing the performance of the vertical control system, and give an estimate of the loads on the structures during VDEs and plasma disruptions.

1. INTRODUCTION

During JET operation a number of pulses are terminated by vertical displacement events (VDEs), caused by the loss of stability of the closed loop system for elongated plasma configurations. At present the JET con-troller adapts the control parameters, adjusting the gains on the basis of the measured amplifier switching fre-quency, which is related to the growth rate [1]. The alternative approach, i.e. using a model based controller, requires the model to accurately predict the growth rate. However so far to our knowledge, the predictions of the growth rate for most elongated JET configurations were either overestimated or adjusted using ad hoc axisymmetric models tuned empirically.

In this paper we provide a possible explanation of such disagreement and, more importantly, we propose a model able to reliably predict the growth rate of the elongated configurations that are desirable in the next JET campaigns to increase the machine performance. In particular, we demonstrate that the presence of saddle currents in the vessel, disregarded in purely axisymmetric models, substantially slows down the vertical instability.

The paper is organized as follows. Section 2 deals with the description of the 2D axisymmetric model used. This model was corrected taking into account the 3D effects of the eddy currents described in Section 3. The choice of the experimental pulses to validate the proposed approach is discussed in Section 4, while in Section 5 a comparison of the numerical predictions of the growth rates with experimental results is carried out. Finally, Section 6 draws the conclusions.

2. ASSUMPTIONS FOR THE 2D AXISYMMETRIC MODEL

We assume the model of JET illustrated in Fig. 1, including an equivalent axisymmetric model of the magnetic circuit, the poloidal field coils connected by a voltage driven circuitry with ten independent currents, an equivalent 2D axisymmetric model of the vacuum vessel, and the conducting plates (passive Mark II divertor structure) located in the vicinity of the divertor coils (i.e., the poloidal field coils inside the vacuum vessel) [2].

The JET vessel consists of 32 toroidal rigid sectors connected by cylindrical resistive bellows

(see Fig. 2). To take account of this, the equivalent axisymmetric model of the vessel has an enhanced cross-section of $1.75m^2$, with an equivalent resistivity that is a function of the r co-ordinate [3] ($\eta = A_\eta + B_\eta/r$, with $A_\eta = 6.77\mu\Omega m$ and $B_\eta = 120.6\mu\Omega m^2$, except two conducting inserts at r = 1.695 m, z = ±.:189m). The resulting torus resistance of the vessel is 320μΩ for a uniform current density distribution. The overall cross-section of the plates located in the vicinity of the divertor coils (passive Mark II divertor structures) is $0.0878\ m^2$, their resistivity is uniform, and the overall torus resistance (for a uniform current density distribution) is 750μΩ.
The iron cross section is shown in Fig. 1. As suggested in [4], the equivalent axisymmetric geometry is obtained by the real 3D shape preserving the plasma-facing-side of the limbs and keeping the same reluctance as the 3D magnetic circuit. Though the magnetic circuit is made of several different iron materials, we assume one single magnetic characteristics (Fig. 3). A deep analysis has shown that taking into account different permeability regions does not substantially improve the agreement with experimental data [5].

As for the plasma current density profile, we assume that it is a function of four parameters (λ, β_0, α_m, and α_n) that can be associated with the physical quantities Ip (plasma current), β_p (poloidal beta), l_i (internal induc-tance), and q_0 (safety factor at magnetic axis):

$$J\phi = \lambda[\beta_0 r/R_0 + (1-\beta_0)R_0/r]\ (1-\bar{\psi}^{\alpha_m})^{\alpha_n} \tag{1}$$

with $\bar{\psi} = (\psi - \psi_a)/(\psi_b - \psi_a)$, ψ_a being the flux per radian at the plasma magnetic axis; ψ_b the flux per radian at the plasma boundary; R_0 a reference length, e.g. the major radius of the vacuum chamber. We assume the values of p and li to be frozen during the vertical motion.

The time evolution of all currents (PF coil currents, eddy currents in the passive structure, and plasma current) is determined by the linearized perturbed equilibrium CREATE-L plasma response model [6]. This model is the result of a linearization of the standard MHD equilibrium equations: the inertial terms are neglected and a quasi-static evolution through plasma equilibria around a reference configuration is assumed. The CREATE-L model has been extensively validated in the past on TCV [7], FTU [8], RFX [9].

3. 3D CORRECTIONS

The results presented in this paper will show how the non-axisymmetric effects in the metallic structures strongly affect the vertical instability of the plasma. In a purely axisymmetric model, the presence of bellows separating the rigid sectors is usually accounted for by simply enhancing the equivalent toroidal vessel resistivity as discussed in the previous section. With this assumption, a sudden displacement of the plasma causes the growth of purely axisymmetric currents whose time constants are rather fast due to the relatively high toroidal axisymmetric resistivity. In fact, we can expect that currents on a slower time scale arise only in rigid sectors due to their relatively low resistivity. These saddle currents may have a stabilizing effect on the plasma which is investigated in the following.

In order to perform our analysis a 3D modelling of the vessel is required. In the past a method for the simulation of the time evolution of fusion plasmas in the presence of eddy currents induced in 3D structures was developed and applied to ITER [10]. This method considered the plasma to be 2D axisymmetric, and the inter-action between the plasma and the external currents was assumed to occur via the magnetic field averaged over the toroidal angle. The average poloidal field was computed by means of a 2D axisymmetric differential FEM formulation in terms of the poloidal magnetic flux, whereas the currents induced in 3D non-magnetic structures were cal-culated via an integral edge-element formulation in terms of a two-component current density vector potential.

However, the application of such technique to JET is not immediate. The presence of the iron core prevents application of superposition as well as the use of the non-magnetic eddy current formulation. In principle, this problem might be overcome via linearization of the B-H curve around the equilibrium configuration and inclusion of the magnetization in the 3D eddy current formulation. Unfortunately, a good 3D model of both iron core and vacuum vessel would require too large CPU resources when using integral formulations. For this reason, we decided to follow the approach presented in [11], approx-imating the quasi-axisymmetric JET vessel by means of an equivalent set of axisymmetric conductors connected to a fictitious external electric network.

The vessel is discretized in a number of axisymmetric conductors carrying uniform currents. Each of these conductors is located at a fixed poloidal location. With reference to Fig. 4, I_{ai} represents the axisymmetric currents flowing at the *i*-th location of the poloidal plane in both rigid sectors (with toroidal resistances R_{rsi}) and bellows (with toroidal resistances R_{bi}). I_{si} represents the saddle current flowing in rigid sectors and in the poloidal path connecting two adjacent poloidal locations (characterized by a poloidal resistance R_{si}). These saddle currents provide no contribution to the total toroidal current. The inductive terms of the toroidal paths of both I_{ai} and I_{si} are automatically taken into account by the field for-mulation of CREATE-L. As for the poloidal paths of the I_{si}, suitable inductances L_{si} must explicitly be added to the model. The poloidal resistance R_{si} and inductance L_{si} are supposed to scale with the distance d_i between two adjacent poloidal locations; approximate expressions (based on simplifying assumptions on both poloidal and partial toroidal paths of the induced currents) are:

$$Rrs_i = k_r d_i \eta_b / (l_b \delta_b) \quad (2)$$

$$Lrs_i = k_l N_b d_i \mu_0 / (4\pi) \quad (3)$$

where $\eta_b = 135\mu\Omega m$ is the actual bellow resistivity, $\delta_b = 4mm$ is the actual thickness of the bellows, $l_b = 490mm$ is the developed length of a single bellow (equal to the gap, 120mm, between two adjacent rigid sectors multiplied by the corrugation), $N_b = 32$ is the number of bellows. k_r and k_l are two non-dimensional coefficients to be calibrated on the experimental data.

4. EXPERIMENTAL ANALYSIS

We considered a number of JET pulses aimed at testing the plasma behavior during VDEs [12]. In these pulses, characterized by various values of elongation and triangularity, vertical instabilities were deliberately trig-gered at a preprogrammed time instant, e.g. switching off the vertical control system and (possibly) applying a radial field to the plasma (kick-up or kick-down). In this way, the fast acquisition system could be activated in the time window of interest to obtain the highest level of relevant information.

In all cases examined in this work, after the switch-off of the vertical stabilization, on the time scales of interest, the plant is supposed to exhibit its open loop unforced dynamic behavior as the voltage applied to the radial field circuit is zero. Since the elongated plasmas are vertically unstable, all the examined discharges are terminated by VDEs, even in the absence of a deliberately applied triggering action.

For our analysis we focus on three different shots: Pulse No: 49591, Pulse No: 54283, and Pulse No: 54839. This choice is motivated by the observation that the three shots exhibit substantially different growth rates, as we will show in a while, representative of the range of possible different growth rates of JET configurations.

In order to estimate the experimental growth rate, we consider the following variables:

- I_{FRFA}: current in the radial field circuit;
- $d(Z_pI_p)$=dt: time derivative of the vertical plasma current moment estimate;
- Z_p: estimated vertical position of the plasma current centroid;
- I_{MK2}: estimate of the total passive current in the Mark-II divertor structure.

These quantities can be measured in a number of different ways, with slightly different results. The measurements used here are those computed by the JET vertical stabilisation system.

In principle, any combination of signals excited by the unstable mode could be used to estimate the growth rate. We selected the above quantities because of their fast sampling rate and/or their strict correlation with the vertical plasma dynamics.

The estimates of the experimental values of the growth rate have been obtained by fitting the time evolution of each signal, say s(t), with the nonlinear regression:

$$s(t) = \alpha_0 + \alpha_1 e^{\gamma(t - t_0)} \tag{4}$$

in a suitable time interval (t_0, t_f).

The initial time t_0 has to be chosen after switch-off of the vertical stabilization system and possibly after the decay of all stable dynamics induced by the triggering action (if present).

The final time t_f is selected before the rise of significant nonlinear effects. For instance, it must be chosen before the contact between plasma and wall, which yields a change of the plasma configuration and in some cases gives rise to halo currents. Indeed, in all examined discharges, we

observed a discontinuity in the time derivative of the plasma vertical current moment after a time extent roughly proportional to the estimated growth time $1/\gamma$.
The parameters α_0, α_1 and γ are estimated via least square minimization of the residuals:

$$\in = s_i - \alpha_0 - \alpha_1 e^{\gamma(t - t_0)}, \qquad i = 1,...,n \tag{5}$$

where n is the number of time instants t_i in $(t_0; t_f)$ at which the signals $s_i = s(t_i)$ are available.
To get an indication on the accuracy of the fitting, we can refer to the coefficient of determination, defined as:

$$R^2 = 1 - \sigma_\in{}^2 / \sigma_s \tag{6}$$

where and ˙s are the variances of residuals and signals, respectively. This coefficient measures the fraction

of the variability in the signal that is taken into account by the exponential fitting (4). As it is apparent from Table 1, this coefficient is close to 1 in most cases.

Fig. 5 reports the results of the nonlinear fitting obtained for $d(Z_pI_p)/dt$ in both linear and logarithmic scales for Pulse No's: 49591 and 54839. It appears that in the initial phase of the VDE the exponential growth is hidden by the presence of other stable modes that have not yet decayed and by quantization error.

As error bars for the growth rates, we assume the values for which the variance of the residuals is a factor of $\sqrt{2}$ larger than the fitted variance:

$$\sigma_\in| /_{\gamma+\Delta\gamma} = \sqrt{2}\, \sigma_\in|_\gamma \tag{7}$$

In Table 1 we report the results of the growth rate estimates for the three shots under consideration, obtained from the fitting on the different signals enumerated above. It should be noted that the estimates from the different measurements are consistent within statistical uncertainties. Taking into account the error bars and the coefficients of determination of the various signals, we assume that the estimates provided by $d(Z_pI_p)/dt$ (e.g. the first row of Table 1) are the most reliable.

	Pulse No: 49591	Pulse No: 54283	Pulse No: 54839
$\frac{d(Z_pI_p)}{dt}$	**775 ± 11.0**	**410 ± 7.8**	**136 ± 4.5**
Z_p	891 ± 23.1	340 ±33.0	134 ± 4.5
I_{MK2}	910 ± 21.0	675 ±39.7	120 ±12.6
I_{FRFA}	N.A.	N.A.	135 ± 4.0

a. $\gamma (s^{-1})$

	Pulse No: 49591	Pulse No: 54283	Pulse No: 54839
$\frac{d(Z_pI_p)}{dt}$	**4.63**	**3.60**	**2.30**
Z_p	9.80	12.90	2.36
I_{MK2}	9.40	20.60	5.30
I_{FRFA}	N.A.	N.A.	2.20

b. $\sigma_\in/\sigma_s$

JG03.125-9c

Table 1. Analysis of the experimental data: a. estimates of the growth rates γ;b. values of $\sigma_\in/\sigma_s$ (ratio between the variance of the residual error and the variance of the signal). The error bars are determined by the values of for which the variance of the residuals is increased by a factor of √2; N.A. stands for the cases in which the error bars are larger than 100%

5. SIMULATION RESULTS

In all cases described in the previous sections, we have derived the linearized plasma response models at a time instant immediately before the triggering of the vertical instability, using the CREATE-L code including the saddle current described above. We have then calculated the growth rate, i.e. the unstable eigenvalue of the dynamic matrix, for various values of the correction factors k_l and k_r introduced in Section 3. The results reported in Table 2 show that an adaptation of k_l and k_r is not strictly needed, as the choice of $k_l = k_r = 1$ provides good predictions in a rather large range of growth rates. On the other hand, the purely axisymmetric model without 3D corrections, obtained in the limit $k_l \rightarrow \infty$ and $k_r \rightarrow \infty$, provides rather pessimistic estimates of the growth rates, about twice as high as the experimental values.

The predictions obtained retaining the 3D corrections (with $k_l = k_r = 1$) are in very good agreement (within an error of about 4%) with the experimental estimates for moderate plasma growth rates (e.g. Pulse No's:54283 and 54839 and other pulses not reported in this paper). On the other hand, for Pulse No: 49591 (and other similar pulses analyzed) characterized by a high growth rate, the agreement is less satisfactory (error of about 13%). The reasons for the worsening of the growth rate predictions for this kind of pulses seem to be the following.

k_l	k_p	γ prediction Pulse No: 49591 $\gamma_{exp} = 410$	γ prediction Pulse No: 54283 $\gamma_{exp} = 410$	γ prediction Pulse No: 54839 $\gamma_{exp} = 136$
1	1	674	414	142
0	0	185	115	44
		1130	791	314
10	1	1029	684	243
1	10	887	595	239
2	1/2	791	481	148
1/2	2	643	416	160

JG03.125-8c

Table 2. Growth rate predictions $\gamma(s^{-1})$ provided by the CREATE-L model for various values of k_l and k_r compared to their experimental values γ_{exp} (s^{-1}) reported in Table 1.

i) For high growth rates the exponential fitting of the experimental traces is harder, due to the limited duration of the transient before the plasma hits the wall.

ii) Plasma triangularity increases the radial gradient of the field index and hence the sensitivity of the plasma response to the radial position of the plasma. Therefore, small changes of poloidal beta or internal inductance may yield large variations of the growth rate of the linearized model [13].

iii) Significant nonlinear effects may take place if the field index undergoes large variations throughout the trajectory of the plasma current centroid [14], [15].

To analyze the influence of nonlinear effects, we have calculated the equilibrium configurations and derived the linearized models at various time instants during the VDE of Pulse No: 54283. The relatively long duration of this event allows us to make a fair comparison between model predictions and experimental data. During the early phase of the VDE, the magnetic field that keeps the plasma in equilibrium is due not only to the PF circuits but also to the eddy currents induced in the passive structures. Since these currents are not directly measurable, assuming that all the stable modes have decayed, we superpose to the initial equilibrium currents an eddy current distribution obtained by a time evolution on the growth mode. The scaling factor of the eddy currents on the unstable mode can be obtained calculating the amplification factor of any measurable quantity (e.g. the vertical current moment or vertical displacement).

The results of the simulations are shown in Fig. 6. We observe that during the VDE, before the plasma-wall contact, the growth rate slightly increases as a consequence of the elongation increase due to a field index change.

Figure 6 also shows that according to the CREATE-L model the plasma hits the wall after a displacement of about 11.5cm. This is in fair agreement with the experimental observation of $d(Z_pI_p)/dt$, which has a jump at time t_c = 24:0146s (contact time, see Fig.7). The jump takes place in correspondence of a displacement of about 12 cm. This value is calculated on the basis of a numerical integration of the $d(Z_pI_p)/dt$ signal. Indeed the plasma-wall contact is expected to yield a discontinuityin the plasma response model, which passes from a diverted configuration to a limited one, with a reduction in the growth rate of about 7%.

A simple model for the simulation of the nonlinear effects due to the plasma-wall contact can be obtained under the following hypotheses which have been verified a *posteriori*.

i) The time evolution before and after the contact time tc can be obtained with a good accuracy using the plasma response models derived around a number of equilibria calculated on the linearised trajectory. We denote as γ^+ (t) and γ^-(t) the predicted growth rate time behaviors for $t > t_c$, and $t < t_c$ respectively.

ii) The vertical plasma current moment Z_pI_p is continuous at time tc and the eddy current distribution along the growth mode is almost unchanged when passing from diverted ($t = t_c^-$) to limited ($t = t_c^+$) configuration.

iii) The value of dZ_pI_p/dt (tc^-) can be successfully predicted by the model while the value of $dZ_pI_p/dt(t_c^+)$ can be calculated as $dZ_pI_p/dt(t_c^+) = dZ_pI_p/dt(t_c^-)\gamma^+(t_c^+)/\gamma^-(t_c^-)$.

Under these hypotheses the time evolution of dZ_pI_p/dt around $t = t_c$) can be modeled as

$$dZ_pI_p/dt(t) \cong dZ_pI_p/dt(t_c^-)e^{\gamma-(t_c^-)\bullet(t-t_c)} \qquad \text{for } t < t_c \qquad (8)$$

$$dZ_pI_p/dt(t) \cong dZ_pI_p/dt(t_c^+)e^{\gamma+(t_c^-)\bullet(t-t_c)} \qquad \text{for } t < t_c \qquad (9)$$

Figure 7 shows the time behaviour of dZpIp=dt. The circles represent the experimental evolution. The solid line refers to a fully predictive model, assuming the value of contact of $dZ_pI_p/dt(t_c^-)$ to be consistent with the vertical displacement expected at the contact time obtained by integrating equation 8.

This simple model neglects the rise of halo currents in the passive structures. Therefore, further studies are needed to obtain a good description of the plasma behav-ior after the contact. Nevertheless it allows us to predict the value of the plasma displacement at the contact time and to explain the jump in the plasma vertical velocity.

6. CONCLUSIONS

In this paper we have shown that the effect of the saddle currents in the rigid sectors slows down the vertical instability of a JET elongated plasma by a factor of about wo with respect to estimates based on pure axisymmetric models. The CREATE-L model taking into account the 3D effects of the eddy currents has been applied to various JET pulses where, without further calibrations, the growth rates have been estimated within an accuracy better than 5% for moderately high growth rates (up to about $400s^{-1}$). Slightly less satisfactory results (about 15% accuracy) have been obtained for higher growth rates (around $700s^{-1}$). A discussion of reasons for this loss of accuracy has been carried out. The model developed in this paper can be used for JET (and extended to ITER-FEAT) to provide a reliable test bed for assessing the performance of the vertical control system, and give an estimate of the loads on the structures during VDEs and plasma disruptions. Future developments are advisable in several directions. First of all, the proposed model could be used to predict the closed-loop behaviour of the system (i.e. with the vertical stabilization system active), e.g. in the presence of disturbances like ELMs. This could help also in understanding more deeply the relationship between the vertical stabilization controller behaviour (in terms of switching frequency) and the actual growth rate. The availability of such a model could also allow a partial redesign of the vertical stabilization controller itself. From the modelling point of view, a very interesting area of development could be related to a deeper study and understanding of all the phenomena that arise when the plasma hits the wall, primary the halo current evolution.

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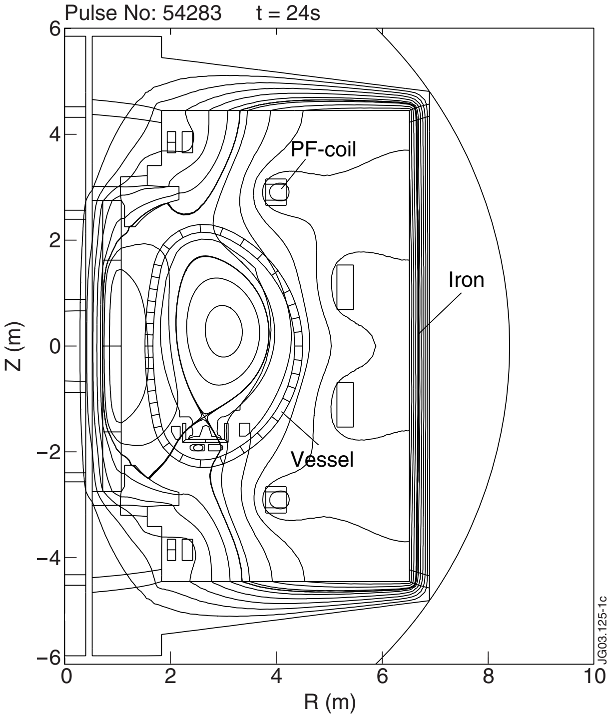


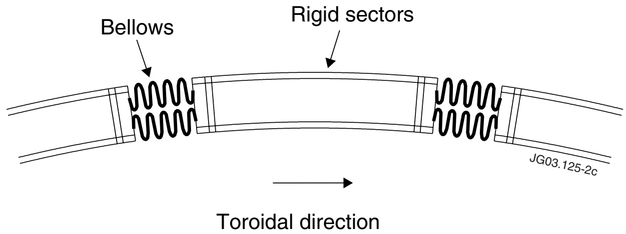
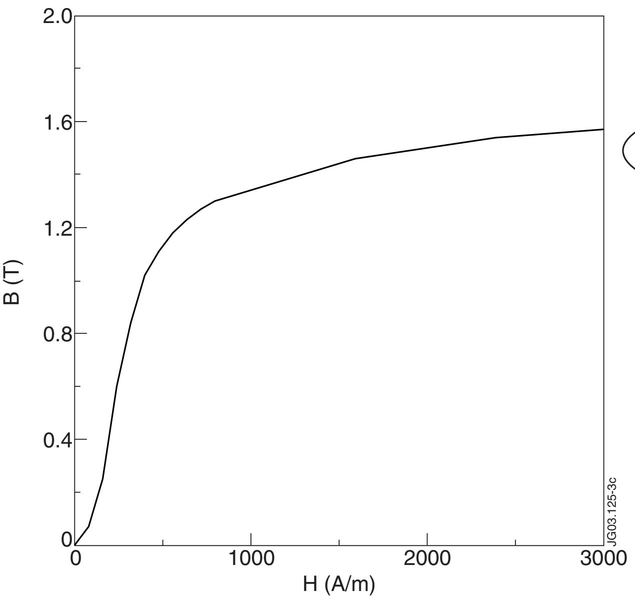


Figure 1: Equivalent axisymmetric model of JET. Equilibrium conditions: Pulse No: 54283 at t = 24s toroidal direction bellows rigid sectors.

Figure 2: Schematics of the cross section of the JET vessel in the outer part of the equatorial plane.



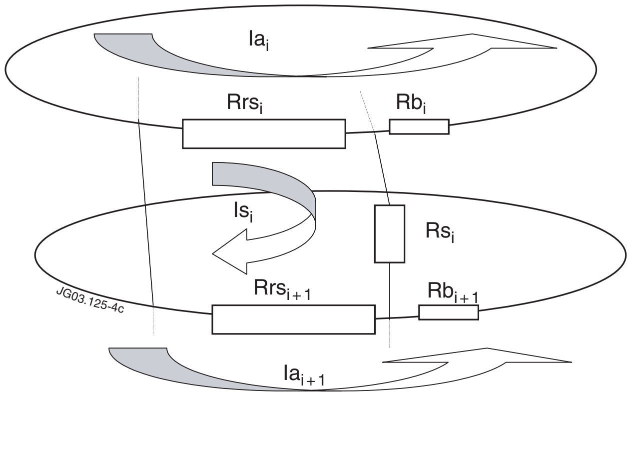


Figure 3: B-H curve of the magnetic material: single material curve provided by JET and used in the 2D axisymmetric calculations.

Figure 4: Schematization of the vessel currents.

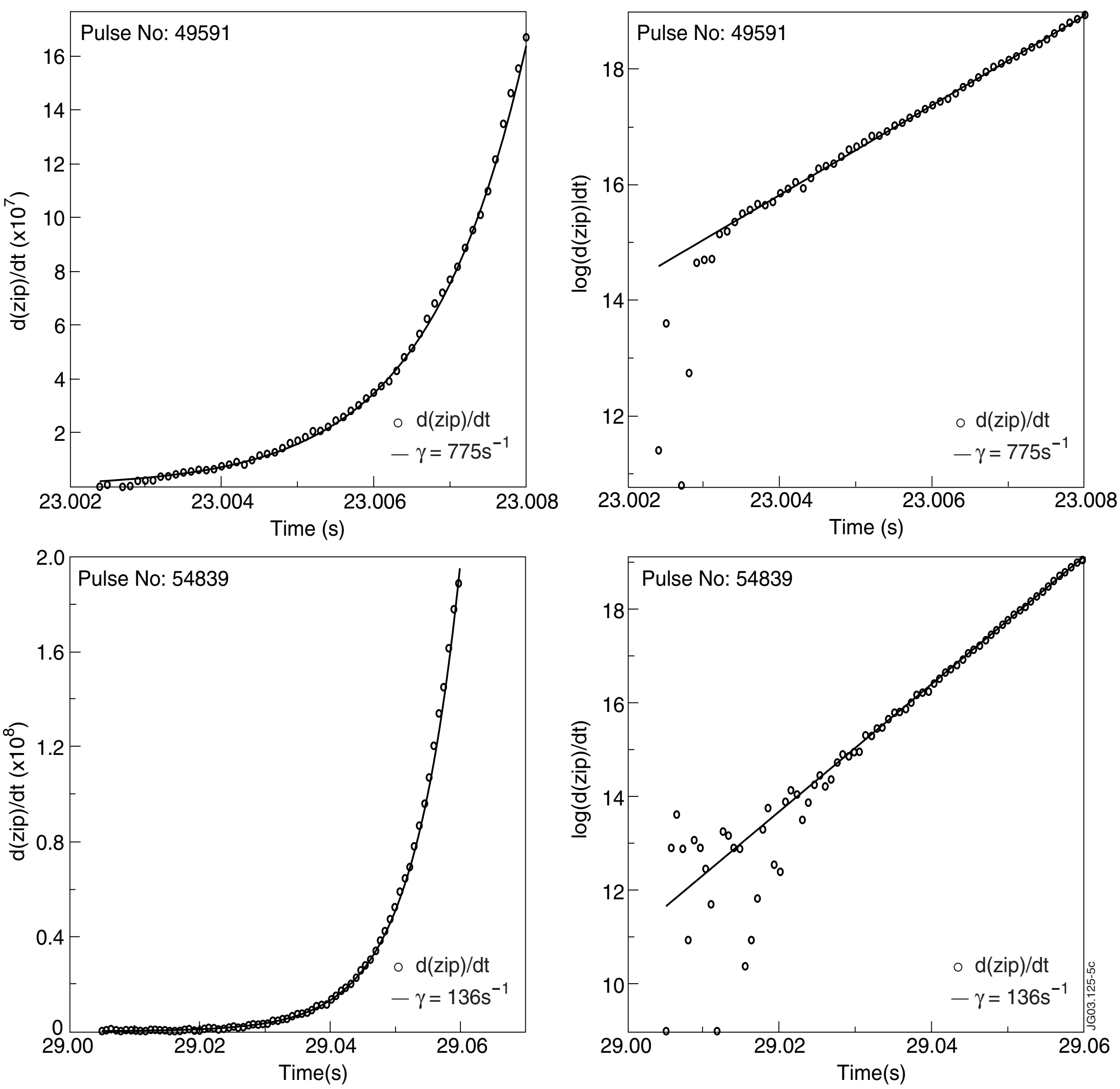
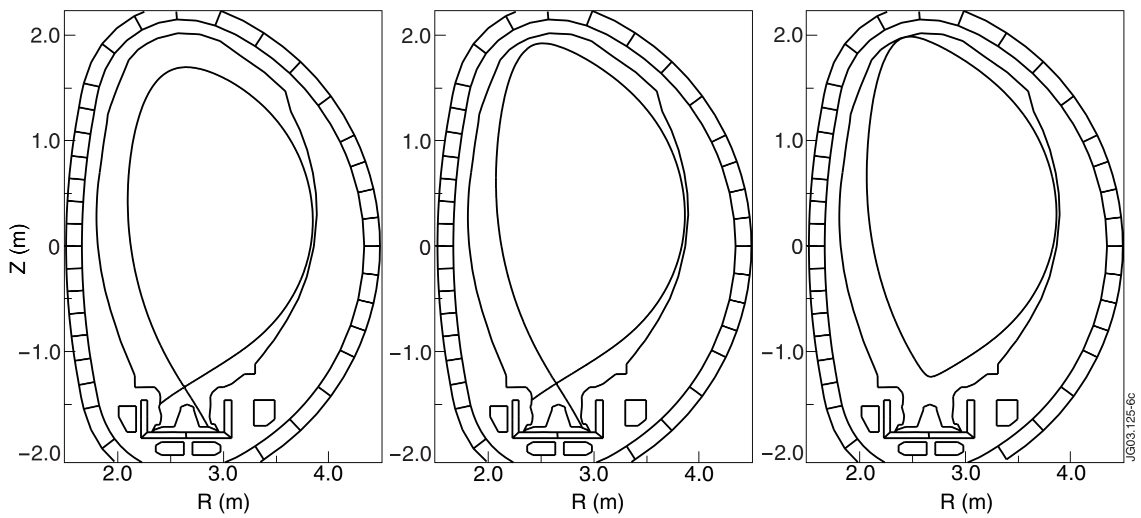


Figure 5: Exponential fitting of d(Z_pI_p)/dt in linear and logarithmic scales for the estimation of VDE growth rates in JET Pulses No's: 49591 Submitted to Nuclear Fusion, Vol. TBD, No. TBD (2002)



$\Delta Z_c = 0$
$\gamma = 414s^{-1}$
(diverted configuration)

$\Delta Z_c = 9.9$
$\gamma = 462s^{-1}$
(diverted configuration)

$\Delta Z_c = 12.3$
$\gamma = 421s^{-1}$
(limited configuration)

Figure 6: Simulation of non linear effects: plasma equilibrium configurations and predicted values of the growth rates at various phases of the VDE of Pulses No: 54283 ($\gamma_{exp} = 4\times10s^{-1}$): a) equilibrium configuration at t_0 ; b) equilibrium configuration in correspondence of a vertical displacement of about 10cm; c) equilibrium configuration in correspondence of a vertical displacement of about 12cm

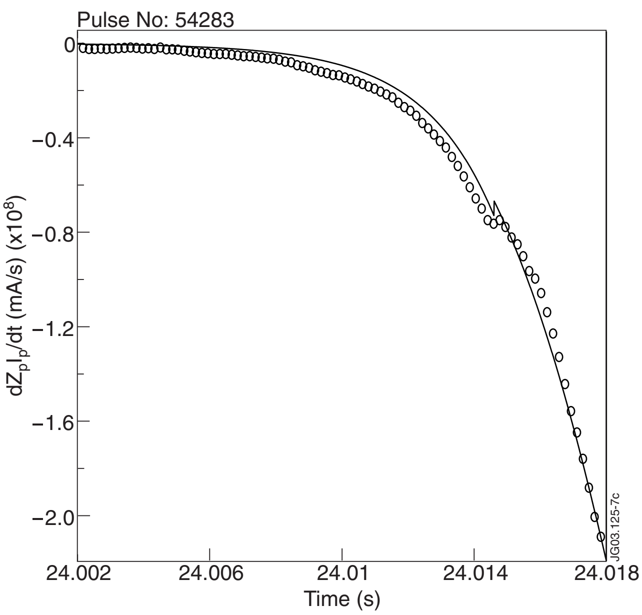


Figure 7: Non linear effects in the VDE of Pulses No: 54283. Time derivative of the plasma current moment: the continuous line represents the simulated time behaviour obtained assuming $d(Z_pI_p)/dt(t_p^-)$ to be fixed to the experimental value. The circles represent the experimental trace. Notice that the plasma moves upwards since the plasma current is negative.