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# Upgrade of the Present JET Shape and Vertical Stability Controller

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## ABSTRACT.

The development of linear model of the present JET electromagnetic system has allowed the design of an optimized Plasma Shape Controller. Quite extreme plasma boundaries (elongation $k$ =1.9 and triangularity $<\delta> = 0.6$) are shown to be controllable also in the presence of large variations of the values of poloidal beta ($0.1<\beta_p<0.6$) and/or internal magnetic inductance ($0.8<l_i<1.4$). The developed model gives also an excellent simulation of the growth rate of the experimental vertical disruptions.

## 1. INTRODUCTION

The ITER reference scenario [1] relies on the capability of obtaining a high quality H mode at a volume plasma density close to the Greenwald limit. The experiments [2] so far performed on the present large Tokamaks have shown that the most important parameter, to achieve such regimes, is a plasma boundary characterized by a high triangularity. Therefore the capability of obtaining and controlling extreme plasma shaping in presence of large disturbances (e.g. giant edge localised modes [ELMs]) will be a key feature in ITER design. Of course, for this reason, it is also mandatory to use the present machines for testing the capability of optimizing the shaping controller system. The present JET Shape Controller [3] has the possibility to control a limited number of plasma geometrical parameters chosen among plasma gaps, coil currents, the *X*-Point location and the plasma centroid. The selected set of controllable parameters can be varied during a plasma discharge to accommodate the experimental needs. Eight independently supplied poloidal shaping circuits can be used to obtain the desired configuration; in addition the central core transformer is essentially dedicated to control the plasma current. However, since the action of these actuators is not totally decoupled, normally only up to 5 parameters can be easily controlled.

So far the full JET electromagnetic system has never been accurately modeled as a consequence of the non-linearity introduced by the iron core. For the purpose of designing an improved and optimized shape controller, a new iron model has been developed. This has allowed to obtain both a non linear and a linear model (by using the CREATE-L [4] approach) of the JET electromagnetic system. The second section of this paper will be dedicated to the description of the results. In the third section the design of the new Shaping Controller will be described. The performances, obtained in closed loop and simulating the plasma by the linear model, will be also described. In the last section the achieved capability of simulating the growth rate of a JET Vertical Disruption (VDE) will be shortly discussed.

## 2. THE JET MODEL

The presence of the Iron Core has, so far, made quite difficult to obtain a fully reliable model of the actual JET electromagnetic system. Therefore the first step of our work has been devoted to developing a new axisymmetric model of the Iron Core (a more complete description is also given in another contribution [5]). The new model was designed trying to fit as much as possible to the real Iron geometry. In Figure 1 we report the comparison of an experimental measurement (using one of the available pick up coils) with the value predicted by the code PROTEUS respectively using the old and the new iron model. The check was performed by a dry run where all the poloidal circuits were fed separately. In particular Figure 1 reports the case where the JET circuit named P4 is fed, which essentially provides the vertical field. The large error obtained by using the standard Iron model and the strong improvement by using the new one are evident. Once a reliable non-linear model was available it was also possible to work out the linear model of an actual plasma experimental discharge by using the CREATE-L approach [4] adapted to the features of JET. In Figure 2 some traces are shown for the selected discharge #52310: a standard H mode plasma. This discharge was selected because quite large variations of both the internal equilibrium parameters ($\Lambda = \beta_p + l_i/2$) and of the shaping parameters (elongation and triangularity) occur during plasma evolution. Moreover the discharge remains in $X$ point configuration also during the controlled plasma current decay. In particular it has to be noted that $\beta_p$ is varying by more than a factor of 6 and $l_i$ is varying by about 40% that implies a huge variation of the current density profile. The linear model was obtained at the time slice $t = 58s$ (it must be pointed out that the breakdown occurs a $t = 40s$). In Figure 3 the time evolutions of one of the worst reproduced plasma-wall gaps, obtained by using the linear model with the old and new models, are compared with the experimental data. These were obtained by giving the magnetic measurements as an input to the real time code XLOC [6]. The same procedure was followed in using the linear model: the evaluated ‘magnetic measurements’ are given as an input to XLOC and this is providing the gaps of Figure 3. It can be noted that the new linear model, with the new Iron geometry, is able to reproduce quite well the behavior of the plasma boundary during the large variation of $\Lambda$. The simulation is quite good also during the large variation of plasma current for most of the gaps, however (as shown in Figure 3) some minor discrepancy remains on a few of them. Although this residual problem is not important in the project of the new Shaping Controller, we have investigated what could be the source of the problem. A set of magnetic measurements is dedicated to evaluate the flux variation between two poloidal sections. As a consequence of the vacuum vessel ports, some of these probes have a complicated geometry, which is also making the sensor not axisymmetric. We have checked that the remaining error is essentially due to this problem and, presently, we are trying to include in the model the ‘correct’ probes geometry.

## 3. THE NEW PLASMA SHAPING CONTROLLER

The availability of a reliable linear model allowed to the design a new and optimized Shaping Controller. Without going into the details of this new controller (reported in another contribute to this Conference [7]), here we will describe the general features and the expected performance of the new controller estimated using the CREATE-L model to simulate the closed loop plasma behavior.

The new Controller consists of three nested loops. The inner one provides an active decoupling among the coil and the plasma currents. The second loop consists of a set of SISO controllers, which should guarantee the coil current values commanded by the external loop, and the desired plasma current behavior by means of the central core transformer. Finally, the outer loop will control the plasma boundary, by using a fully MIMO logic, so as to guarantee the requested shape. A set of $N$ gaps (where $N$ is ranging up to 100) will be used to characterize the Plasma Boundary. The corresponding reference time traces will be obtained by interpolating a number of plasma equilibriums calculated in selected time instants by using a predictive plasma equilibrium code. In order to control such a high number of geometrical parameters using just 8 coil currents, an approach based on the singular value decomposition is used: in particular a limited number of suitable linear combinations of these parameters is controlled. Although in the JET tokamak 8 circuit currents are available, the design approach has shown that only 5 of them are really independent. During a discharge the Controller will choose the most suitable set of five independent circuits by using several different criterions: for instance taking care that all the coil currents are far from the maximum allowed value.

The first attempt of controlling the plasma shape was performed by simulating the JET discharge #52310. The Controller task was to keep the Plasma Boundary fixed using as reference Boundary the one at $t = 58s$. The disturbances causing the shaping movements were the time variations of $\beta_p$ and $l_i$ registered during the shot (see Figure 2). In spite of the large variations of the plasma current profile parameters, the matching between the reference shape and the controlled one was satisfactory all over the simulated time interval, with a maximum error on the gaps location below 3 cm. It is worth noting that in the actual experiment (with the present controller) the error on the gaps was more than twice.

A large number of tests have been performed with different plasma shapes and with several experimental scenarios like, for instance, an Advanced Tokamak scenario with reversed magnetic shear. As an example we report the case of Figure 4, referred to a plasma with the following parameters $I_p = 1.6$MA, $\beta_p = 1.6$, $l_i = 0.83$, $K = 1.9$, $<\delta> = 0.59$. In this simulation we assumed that $\beta_p$ and $l_i$ vary with the same time behavior registered during the experimental discharge #52310 (see Figure 2). Figure 5 shows the nominal extreme plasma equilibrium and the worst perturbed configuration occurring after $2s$. In addition Table I shows the maximum displacements of the gaps occurred during the simulation. The average error is about 2.5cm, with a maximum of about 6cm. Once again simulations performed using the present JET Shaping Controller, showed that the maximum error on the plasma shape is more than twice.

**Table I**

| | *Sim (cm)* | | *Sim (cm)* |
|---|---|---|---|
| LOG | 3.1 | GAP3 | 2.8 |
| ROG | 1.2 | GAP4 | 2.3 |
| ZUP | 2.7 | GAP6 | 0.8 |
| RIG | 2.6 | GAP7 | 2.7 |
| TOG1 | – | RX | 0.8 |
| TOG2 | 3.0 | ZX | 3.3 |
| TOG3 | 2.8 | ZSI | 2.1 |
| TOG4 | 2.2 | ZSO | 5.7 |
| TOG5 | 2.1 | ZC | 2.0 |
| GAP2 | 1.7 | | |

## 4. VERTICAL STABILITY ANALYSIS

So far the available equilibrium codes were not able to reproduce the growth rate of the JET vertical instability. The development of the improved Electromagnetic system has also allowed to investigate this point. The JET Vacuum Vessel is composed of several toroidal rigid sector joined by bellows with higher electrical resistivity. As a consequence, on the time scale of a VDE, the eddy currents flowing in the vacuum vessel must be represented by a toroidal current and by a set of saddle currents flowing on each rigid sector [8]. Once the effect of all these passive currents was included in the previously described model we have been able to accurately reproduce the fast plasma movement during all the analyzed experimental JET VDE.

## 5. CONCLUSIONS

The development of an excellent, both non-linear and linear, JET electromagnetic model allowed to design a new optimized Plasma Shaping Controller. One of the project constraints was the capability of exactly reproducing the main features of the present Controller: this condition has been satisfied and a strongly improved flexibility has been introduced. The performances of the new Controller have been tested by simulating the closed loop both on standard JET plasma discharges and on planned Extreme plasma Shaping. The obtained performances are up to a factor of 2 better than those achievable by the present controller.

Finally an optimized modeling of the passive structures allowed to reproduce the experimental growth rate of a VDE. This will make possible to improve the closed loop of the present VDE Controller.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] R. Aymar, V. Chuyanov, M. Huguet, *et al.*, (2001). ITER-FEAT: The Fut. Inter. Pl. Burning Exp.- IAEA, Vienna. Proc of the 18th Fus. En. Conf 2000, October 2000, OV/1, CD ROM ISSN 1562-4153 ITER.

[2] J. Ongena, W. Suttrop, M. Becoulet, *et al.*, Plas. Phys. And Contr. Fusion **43** (2001) 11-30.

[3] M. Garribba *et al.*, Fusion Technology 1994, pp. 747–750.

[4] R. Albanese, F. Villone, Nucl. Fusion **38** (1998) 723.

[5] R. Albanese, G. Calabrò, M. Mattei, F. Villone, *Plasma Response Models for Current, Shape and Position Control in JET*, to be presented at the 22nd SOFT, Helsinki (2002).

[6] F. Sartori, A. Cenedese, F. Milani, *JET real-time object-oriented code for plasma boundary reconstruction*, to be presented at the 22nd SOFT, Helsinki (2002).

[7] G. Ambrosino, M. Ariola, A. Pironti, F. Sartori, *A New Shape Controller for Extremely Shaped Plasmas in JET*, to be presented at the 22nd SOFT Helsinki (2002).

[8] R. Albanese, M. Mattei, F.V illone, *Prediction of the Growth Rates of VDEs in JET*, submitted to Nuclear Fusion.

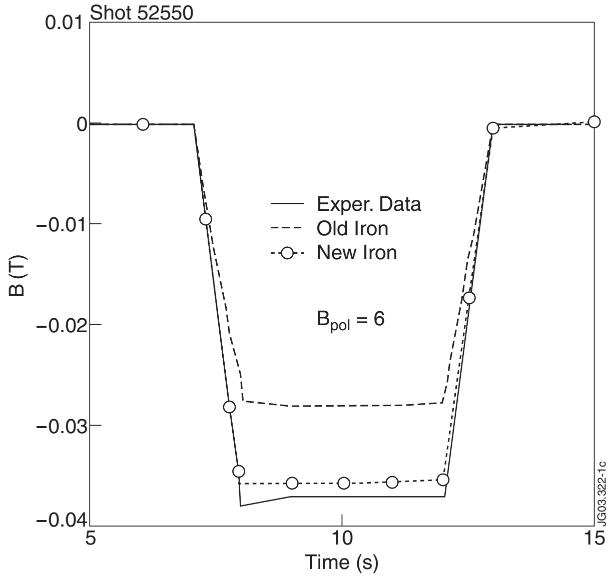

*Figure 1: The magnetic field 'measured' by the JET pick-up coil N. 6, by feeding only the P4 circuit: essentially providing a vertical field. The experimental data is compared with the simulated one by using two different Iron core models.*

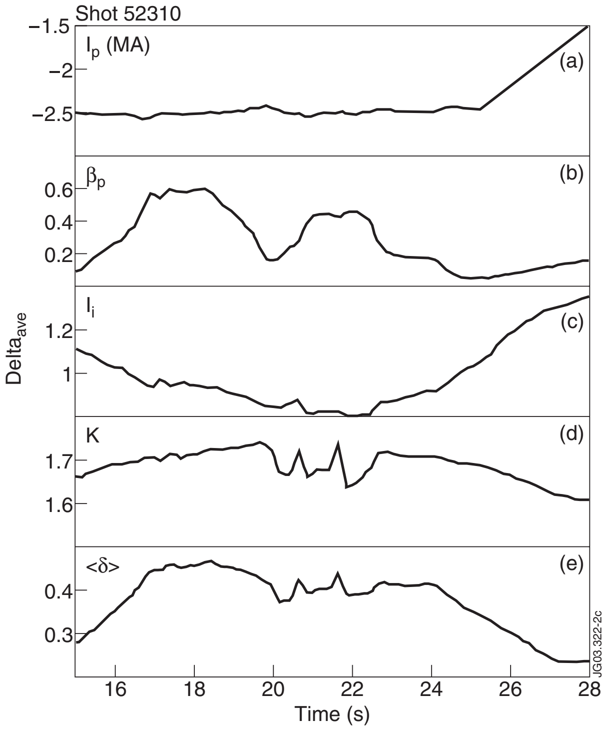

*Figure 2: Time traces of some experimental data of pulse # 52310. a) Plasma Current; b) Poloidal Beta; c) Internal Magnetic Inductance; d) Plasma Elogation; f) Averaged Triangularity.*

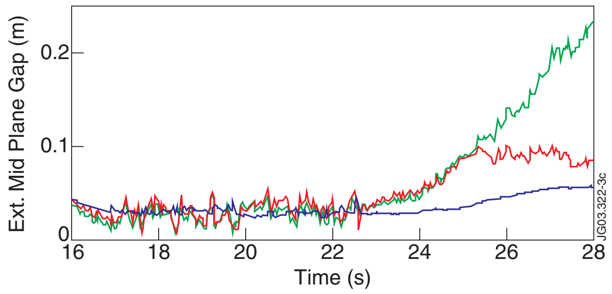

*Figure 3: Time evolution of the external midplane gap. The experimental value is compared with the traces simulated by using the linear model with two different Iron core models.*

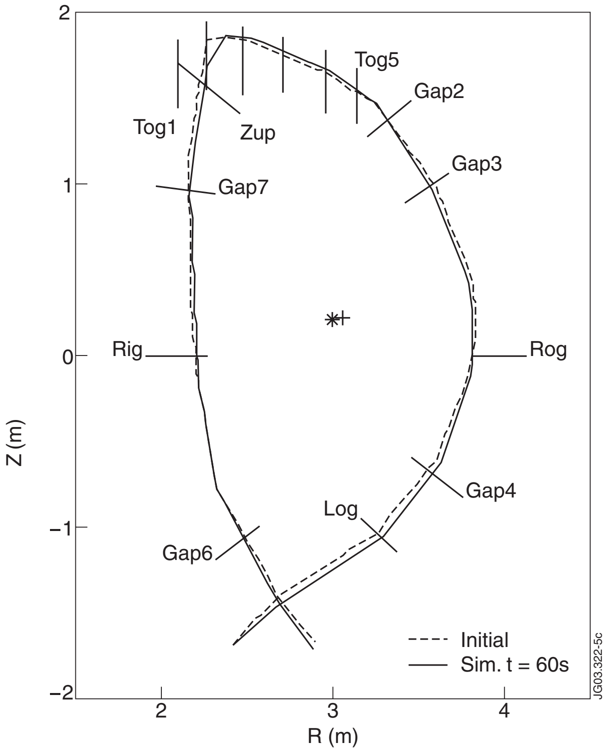

*Figure 4: The dashed curve is the reference boundary. The continous line is the controlled boundary after 2 sec. The disturbances are the time evolution of $\Lambda$ of Figure 2.*