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Report on Vertical Stability Studies during the Plasma Start-Up at ITER (Task 2.1e)

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1. INTRODUCTION

This note summarises the work performed on vertical stability studies during the plasma start up in the ITER TAC3 and TAC4 configurations. The main aim of this work is to analyse the plasma stability properties at low plasma current when the effect of vessel-blanket eddy current is substantial. The main tool used for this work is the PROTEUS code [9] in its *direct implementation* as used for the pumped divertor design. Some details of the calculation techniques and difficulties encountered are illustrated with the aim of providing the JCT with some easily reproducible and extendible work.

2. WORK ON TAC3 CONFIGURATION

The work started on the so called ITER TAC3 machine configuration. A 25 MA end of burn configuration was made available by the scenario group (P. Lomas) plus some papers summarising the proposed scenarios for the ITER null formation and current ramp-up.

It is convenient to use the evolutive part of the PROTEUS code and work backwards from a known configuration instead of trying to start from scratch and get completely new configurations. The aim was to get down with the plasma current I_p at around 5MA. This could be obtained with some difficulties that can be summarised as follows:

- The mesh given by the JCT for the TAC3 configuration was creating problems to PROTEUS. Some of the elements were not properly constructed and this often prevented the code to converge. Moreover the elements in the plasma region were quite big and this created convergence problems as well.

- The PROTEUS evolutive runs are best performed keeping a *radial* position control on the plasma that automatically calculates the vertical field current for the equilibrium. Some time was devoted to designing and tuning this control. This is routinely done to run JET cases.

- The same appears to be true for *vertical position*. This was never needed in JET configurations. The control was inserted only later on when the TAC4 geometry is used

Mesh Type	Radial Position Control	Vertical Position Control
TAC3	P3 +6 P4 +2 P5 +9	Not used
TAC4	P3 +2 P4 +2 P5 +1	P2 +25 P3 +2 P5 -1 P7 -25

Table 1. Turns Ratios Used in the Radial and Vertical Position Controllers

The introduction of these controller gives quite a robust tool that allows the run of a complete scenario keeping the plasma in a pre-programmed position. In the meantime some inner wall configurations have been developed for currents around 2 MA. All the calculations to bring the plasma down from 25 MA to 5 MA were carried out without the vessel currents ($\rho=\infty$).

It is worth noting that the controls used for the radial and vertical position in PROTEUS are constructed as follows. They act on a set of coils with a fixed turns ratio calculated to give basically vertical or radial field (respectively for the horizontal and vertical position). The turns ratios used are given in Table 1. A couple of points is then selected inside the vacuum vessel to match the plasma of a relevant equilibrium. The points are then moved during the dynamic phase of a PROTEUS run in order to position the plasma as desired. The coils are kept under voltage control, therefore the current that flows is the result of the feedback action. This kind of technique allows usually a quite robust performance of the code convergence-wise.

In order to test the growth rate calculation procedure on the ITER cases some calculations at 25 MA EOB configurations have been performed. The method for calculating the growth rate is the same used and benchmarked for JET cases.

The plasma equilibrium is perturbed by either a small change in the current profile (β_p or l_i) or by an externally perturbing radial field. This can be produced by a pair of filamentary currents positioned on the vessel top and bottom, connected in antiseries and fed with a current pulse of short duration. The plasma starts moving and after the fast vessel eigenmodes have died out it is possible to measure the growth rate of the movement of the plasma current centroid. The calculation was carried out using a total vessel-blanket resistance of $10\mu\Omega$. See figure 20.

It is worth noting that this method introduces an error when the configuration is not top-bottom symmetric. For significantly non symmetric single null configuration the vertical movement induces some net flux on the plasma and therefore the plasma current itself should change. PROTEUS does not however allow to simulate the flux conservation in the plasma and therefore we decided to keep it constant. It is however shown from JET divertor configurations experimental results that also in pure vertical instabilities (i.e. when the plasma moves because plasma growth rate is beyond the stabilisation limit) the plasma current remains constant. Fig. 21 shows a vertical instability occurred in the JET pulse 29679 during the additional heating phase.

In the ITER case, given the extremely high conductivity of the vessel-blanket structure it is also to be expected that the growth rate calculation is independent from the fact the external conductors are considered perfectly flux conserving (ideal short circuits) or open ended. The calculation shows that no appreciable difference can indeed be observed (Table 2).

	Flux Conserving Coils	Frozen Current Coils
Growth Rate (s^{-1})	1.52	1.59

Table 2. 25 MA Configuration Growth rate

3. TAC4 MESH

The JCT asked us to prepare a mesh for the TAC4 geometry and therefore the effort was diverted in this direction (fig. 1-2). The new mesh appeared to be much easier to handle. It was possible to achieve right away all the configurations calculated with the previous TAC3 mesh. A small piece of code can be made available to construct a *restart file* (containing the flux values at the mesh nodes) for a mesh given the one for a different mesh. This *restart file* is used by PROTEUS as the initial point of the Newton-Raphson iterations needed for finding a new equilibrium. The use of such restart files allows an easy storage of configuration databases and gives the possibility of reproducing long calculations with a minimal effort. For minor changes on the machine geometry, like the movement of a coil or the first wall this technique allows an easy transfer of already obtained results to the new mesh.

The essential characteristics of the TAC4 mesh can be summarised as follows:

- 3984 nodes
- 1959 elements
- full mesh

It describes the vacuum vessel and the blanket structures as massive conductors which conductance can be specified in the PROTEUS input files. A variation of this mesh which describes the passive conductors as coils is also available. The advantage is that the description of the vessel elements as coils allows the freezing of the eddy currents in the wall at specified time slices during the simulation and therefore makes possible to restart a particular run from a dynamic situation without repeating the full run.

It should however be noted that the equations in the code concerning the passive structures and coils are slightly different. In the case of the passive structures the equations take into account the field penetration times, while the current is treated as uniform in the case of coils. At the frequencies of interest, however, this small difference has no practical impact.

The TAC4 mesh describes also the divertor region tile with current carrying elements with modifiable resistivity. This feature was recognised to be important for scenario studies to check fast movements in the X-point position when fast transients are to be analysed. If the target is highly conductive the position of the X-point can be rather different. For the purpose of stability calculations however this feature quite irrelevant since the passive structure conductivity already dominates the overall behaviour.

4. START UP CONFIGURATIONS WITH TAC 4

The starting point of the approach taken here is the current ramp up shown in [1]. It is quite important to explain how the ramp-up simulations were actually carried out. The PROTEUS evolutive part is best exploited starting from a given configuration and then moving from there to obtain what is desired. Therefore the first aim was to set-up a simulation ramping the plasma current down from 5 MA to as low as possible using two different speeds. The ramp from 5 MA to 2 MA was carried out at 0.25 MA/s, while the remaining is done at 0.5 MA/s.

This allows to set up the eddy currents pattern for low plasma current configuration and then to redo the same path with an increasing plasma current.

In the set-up of the dynamic runs it is also necessary to include a fictitious radial and vertical position control in order to be able to position the plasma where it is desired without to much effort. The resulting currents in the PF coils will be therefore not identical to the one given for the reference scenario.

Calculations were repeated for the following cases:

1. **Outer wall ramp-up with eddy currents (based on M.Mastukawa's scenario [1], fig.3-7).**

2. **Outer wall ramp-up with eddy currents (based on A.Portone's scenario [2], fig.8-12).**

3. **Inner wall ramp-up with eddy currents (fig.13-17).**

4. Outer wall ramp-up without eddy currents (based on the first ramp-up scenario).

In any of the four type of runs the minimum plasma current achievable is 250 KA. This is due to the mesh element size and the fact that the flux difference between the magnetic axis and the plasma boundary is near to the numerical precision. Moreover this plasma current level represents somehow the boundary between the Townsend phase of the discharge and the tokamak plasma proper.

The presence of the eddy currents (total eddy current 1.3 MA when Ip = 2 MA) does not pose any particular problem for the code. It is also quite correct to say that main contribution of the eddy current field is to the vertical field. It is therefore quite possible to replace the eddy currents field with an outside field without changing the plasma shape significantly. This considerations make it possible to carry out the plasma simulation either starting from a higher plasma current and regressing in time or using the way forward. The eddy current total value for the two cases will be different as far as the total eddy current value is concerned, but as explained it wont affect the equilibrium shape or the stability properties. This technique simplifies substantially the task of finding a very low current equilibrium because of the mechanics of the code convergence.

Appendix 1 shows the case 1 above. At the starting point (Ip = 5 MA) the plasma is on the outside wall, vertically centred on the mid plane.

At the present moment the list of plasma configurations during the start up is available and it is possible to obtain any configuration between 0.5 MA and 5 MA.

At the same time, the start up phase was simulated using a filamentary current in order to compare the results with the previous simulation.

The following results have been obtained:

1. The magnetic field and the eddy currents produced with the two different simulations are similar. This suggests that it is possible to consider the plasma as a filamentary current without making a significant error. (Fig. 18-19)

2. The simulations show that during the first 4 seconds, where the plasma current has a derivative of 0.5 MA/s, the total eddy current reaches the value of 1.3 MA. After that period, when the plasma current reaches the value of 2 MA, and its derivative becomes 0.25 MA/s, the eddy currents drop to a value of 0.2 MA.

3. During the first period of the start up (until the plasma current reaches 2 MA) there is a magnetic field null inside the plasma region. This x point does not allow the use of the flux extrapolation method to control the plasma. (Fig. 26).

5. PLASMA STABILITY ANALYSIS

The method developed for calculating the growth rate for a flattop configuration was used for some selected plasma configurations of the ramp-up scenarios.

The plasma equilibrium is perturbed by either a small change in the current profile ($_p$ or l_i) or by an externally perturbing radial field. The plasma starts moving and after the fast vessel eigenmodes have died out it is possible to measure the growth rate of the movement of the plasma current centroid.

The simulations show that the plasma is radial unstable for all the plasma configurations with plasma current below 4 MA (fig. 23-25). The growth rate determined are in the same region 1.5 s^{-1} as for the flattop situation. The difficulty on the measurement of these growth rates is due to the fact that the plasma moves inward only for few centimetres before loosing completely its position.

Further studies show that if a radial position control is performed, as it is usually done at JET from the early phase of the pulse, the plasma does not show vertical instability (fig. 20). Only with plasma currents bigger than 4 MA and plasmas not centred on the mid-plane the plasma shows vertical instabilities with the same behaviour of the flattop configurations.

As it was said before, it is not possible to perform a radial control based on the flux extrapolation of the first order, as it is done at JET, because of the presence of the X-point on the mid plane. Moreover, due to the eddy currents and the distance of the plasma from the point where the magnetic sensors must be positioned, plasma boundary reconstruction based only on magnetic sensors could have serious problems to determine the plasma boundary and its position.

6. CRITICAL DECAY INDEX ANALYSIS

Another way to analyse the plasma vertical stability is to determine the critical decay index for some plasma configurations and then calculate the growth rates.

In order to perform this calculation a rigid plasma model was used [3],[4],[5]. This model represents the plasma as a current conserving, rigid body, inductively coupled to an array of conductors which represents the poloidal field coils and the vessel. The dynamic equation describing this model is given by:

$$\frac{d\left(\vec{\mathbf{M}}\vec{\mathrm{I}}\right)}{dt} + \vec{\mathbf{R}}\vec{\mathrm{I}} = \vec{\mathrm{V}} \qquad (1)$$

where $\vec{\mathbf{M}}$ and $\vec{\mathbf{R}}$ are the conductor mutual inductance and resistance matrices, $\vec{\mathrm{I}}$ is the conductor current vector, $\vec{\mathrm{V}}$ is the applied voltage vector.

Solving the equation above for a rigid plasma free to move only vertically and using the force balance equation:

$$\vec{\mathbf{M}}\dot{\vec{\mathrm{I}}} + \mathbf{R}\vec{\mathrm{I}} + \frac{2\mathrm{R}_0}{\mu_0 \Gamma n}\vec{\mathrm{M}}_{\mathrm{vp}}\vec{\mathrm{M}}_{\mathrm{pv}}\dot{\vec{\mathrm{I}}} = \vec{\mathrm{V}} \tag{2}$$

Here $\vec{\mathrm{M}}_{\mathrm{vp}}$ is the mutual inductance gradient vector (from plasma to conductor array), $\Gamma = ln\left|\frac{8\mathrm{R}_0}{a}\right| + \Lambda - 1.5$ is the Shafranov vertical field coefficient. The decay index, *n*, describes the average vertical field curvature.

The solution of eq. 2 consists of a set of conductor eigenmodes and eigenvalues which depends on the decay index. Moreover it is possible to determine a critical decay index which delimits a decay index values region where the plasma becomes vertically unstable. It can be easily shown, from eq. 2 that for an array of stabilising conductors n_c is given by:

$$n_c = -\frac{2\mathrm{R}_0}{\mu_0 \Gamma} Tr\left(\vec{\mathbf{M}}^{-1}\vec{\mathrm{M}}_{\mathrm{vp}}\vec{\mathrm{M}}_{\mathrm{pv}}\right) \tag{3}$$

where *Tr* indicates the matrix trace.

PROTEUS was used to determine the inductance matrix and the plasma parameters to allow the critical decay index calculation for some configuration:

Plasma Current (MA)	βp	li	Critical Decay Index	Decay Index
1	0.12	0.8	-6.1	0.42
2	0.12	0.8	-5.7	0.31
3	0.12	0.9	-5.4	0.30
4	0.13	0.9	-5.0	0.23

Table 3. Critical Decay Index

The decay index defined as:

$$n = -\frac{\mathrm{R}_0}{\mathrm{B}_{z0}}\frac{\partial \mathrm{B}_z}{\partial \mathrm{R}} \tag{4}$$

is extremely difficult to determine, because during the ramp-up, in the plasma region, the vertical field is almost uniform, this produces a magnetic field derivative which is near zero and therefore affected by some uncertainty, (the decay indexes are reported even if they are calculated with values where the numeric error could affect the results).

With these decay index values the plasma model (eq. 2) presents only negative eigenvalues. This confirms that the plasma is vertically stable.

7. CONCLUSIONS

The main results from this work can be listed as follows:

- A robust tool for the simulation of low current scenarios of ITER was set-up. This consists of a PROTEUS configuration using radial and vertical position control on a set of coils series connected with a suitable turns ratio.
- The PROTEUS mesh for the simulations of the TAC4 geometry was provided to the JCT.
- Plasma configurations with currents as low as 250 KA were successfully calculated with and without the inclusion of eddy currents in the equilibrium. The eddy currents presence does not modify substantially the equilibrium or the stability properties.
- The low plasma current configurations show the presence of an X-point on the mid plane. This points to the plasma being radially unstable in the very first phase. The presence of this X-point will make the flux extrapolation from the inner wall impossible for first order techniques. The growth rates for the radial instabilities are of the same order of magnitude of the vertical ones ($1.5s^{-1}$).
- An inner wall ramp-up scenario was developed to check whether a better behaviour could be obtained in this situation. The X-point formation on the inner wall persists and no substantial improvement was shown.
- The plasma starts to show a vertically unstable behaviour above the 4 MA plasma current.
- The growth rates calculated for these plasmas are in the $1.5s^{-1}$ region as for the flattop situation. Please note that the error bars for the estimate of vertical stability with equilibrium codes could be a factor of 23 as for example in the recent case of set measurements in divertor configuration

8. REFERENCES

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TAC4 MESH

TAC4 Mesh and the naming convention for the poloidal field coils are shown below.

In order to get an accurate determination of the plasma the element size is reduced in the plasma region and particularly near the walls and in the x-point region.

The element number is limited by computing time which PROTEUS needs to determine the flux configuration.

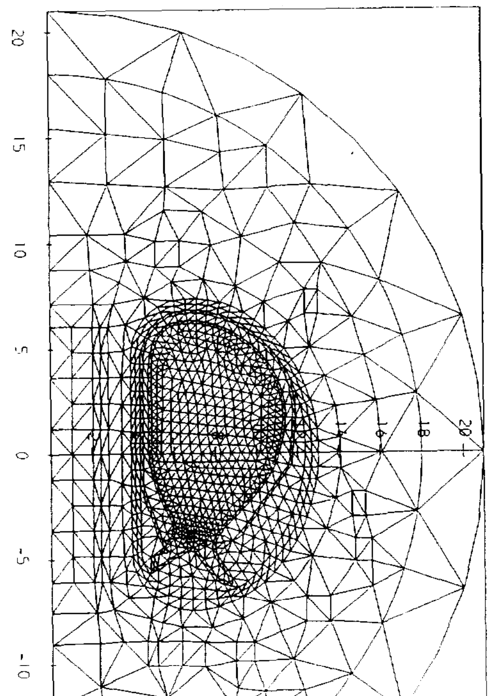


Fig. 1 TAC 4 Mesh

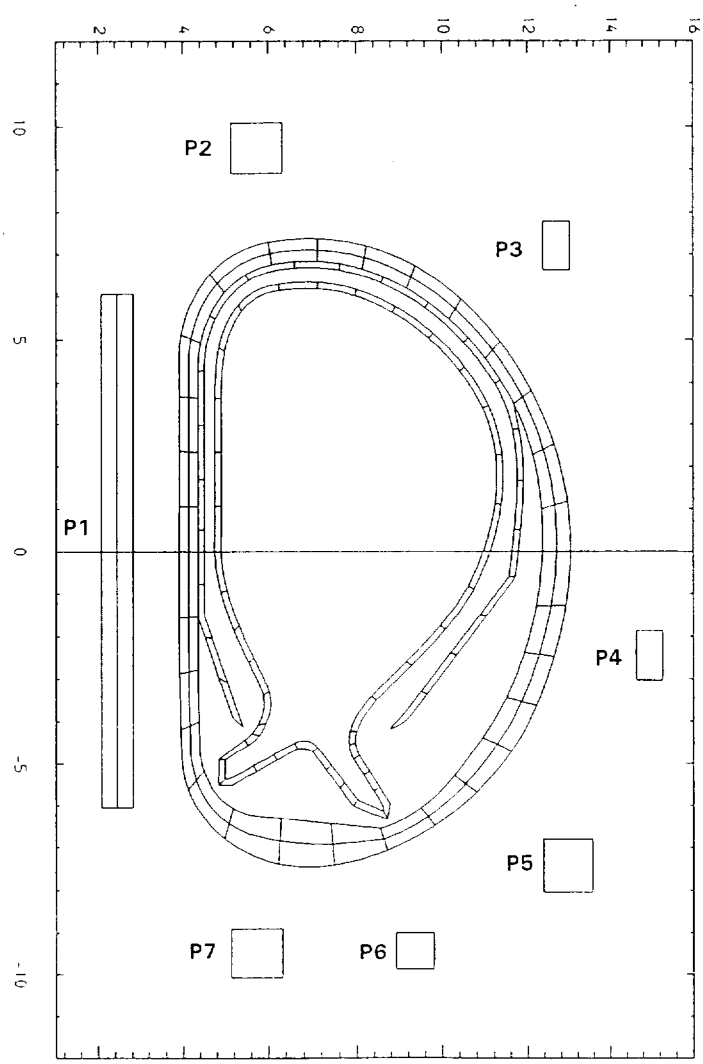


Fig. 2 Poloidal Field Coils naming convention

PLASMA RAMP-UP SCENARIO N.1

Based on the Matsukawa's paper [1], it is characterised by a fast ramp-up of the plasma current: 0.5 MA/s for the first 4 s and 0.25 for the other 12 s. The plasma changes from a filamentary plasma to an MHD plasma at 1 s when the plasma current is 0.5 MA.

In this ramp-up scenario, the breakdown is supposed to happen immediately after the start of the ramp down of the central solenoid current. This provides a scenario where there are no eddy currents during the breakdown. After the breakdown, the eddy currents increase and reach their steady state value after 1.5 s (fig. 3). This fact does not affect the plasma vertical stability studies which are performed using configurations with plasma current bigger than 0.5 MA.

Next figures (fig. 4-5) show the plasma configurations starting from 0.5 MA going up to 5 MA.

These configurations are part of an evolutive PROTEUS run where a plasma configuration is determined every 125 ms in order to obtain a complete scenario. The starting configuration (0.5 MA plasma configuration fig. 4) was determined ramping down the plasma current from 5 MA and was compared with a filamentary plasma configuration obtained using the JCT data in order to verify that the eddy currents distribution was the same in both cases. Even if, plasma configurations with lower plasma current were available (fig. 24), the PROTEUS convergency problems for this kind of configurations obliged the choose of this starting point.

In this scenario the plasma is kept well centred and with a circular shape, thanks to the two controllers which keep the plasma vertical and radial position using as control error the flux difference in two points of the vacuum chamber. One of the problem of determining this configuration was the choice of the plasma current density profile parameters in order to obtain the same li and β suggested by JCT for this scenario. As suggested by JCT the plasma current density profile is parametrized by:

$$j(r,\overline{\psi}) = j_{\varphi,0}\left[\frac{\beta_0 r}{r_0} + \frac{(1-\beta_0)r_0}{r}\right]\left(1-\overline{\psi}^{\alpha}\right)$$

where $j_{\varphi,0}$ is the toroidal current density at the magnetic axis, r_0 is the radius of the machine and the normalised flux in the plasma is defined as

$$\overline{\psi} = \frac{\psi_{axis} - \psi}{\psi_{axis} - \psi_{bound}}$$

It should be noticed that the performed vertical stability studies comprise change of β and li in order to get a wide range of cases where the calculation where performed.

In fig. 4 it could be noticed the presence of a magnetic field null on the mid plane and one on the top of the magnetic chamber. This two magnetic field null and the fact that the plasma is extremely far from the inner, top and bottom of the machine could create some problems to the plasma control if its control parameters are based on magnetic measurements. JET experience shows that plasma parameters determination (such as plasma position and plasma boundary distance from the wall) is affected by large errors when the plasma is far from the magnetic sensors.

Fig. 6-7 show the Poloidal Field coil currents behaviour during the ramp-up. It should be noticed that these current are mainly the sum of two terms: the first term tries to follow the values provided by the JCT scenario, and the second term is determined by the controllers which were implemented in order to give to the plasma the desired shape and position. The PF coils affected by this are: P2, P3, P5, and P7 for the radial field control; and P3, P4, and P5 for the vertical field control. It should be noticed that for P3 and P5 there are three different circuits which act together.

In these figures is also possible to see that the used JCT plasma configurations are mainly three: the breakdown, which is supposed to happen with small eddy currents, the 2 MA plasma configuration at 4 s, and the 4 MA plasma configuration.

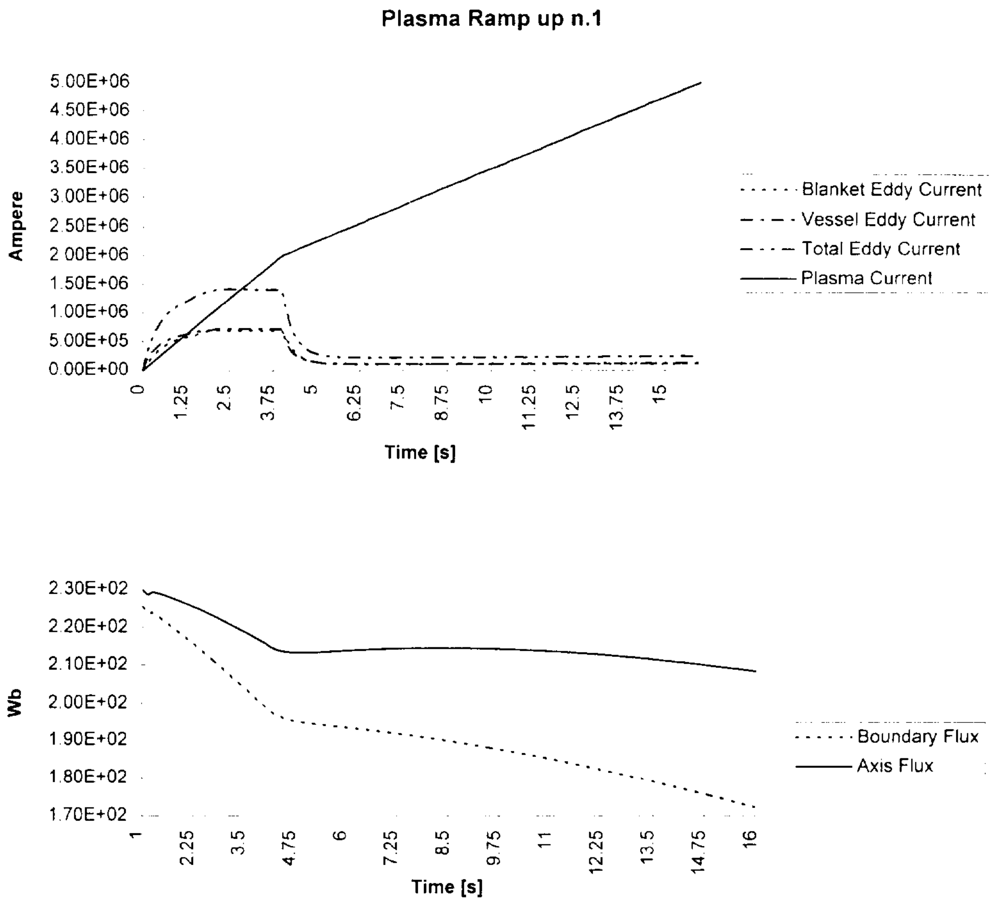


Fig. 3 Plasma ramp-up scenario n. 1

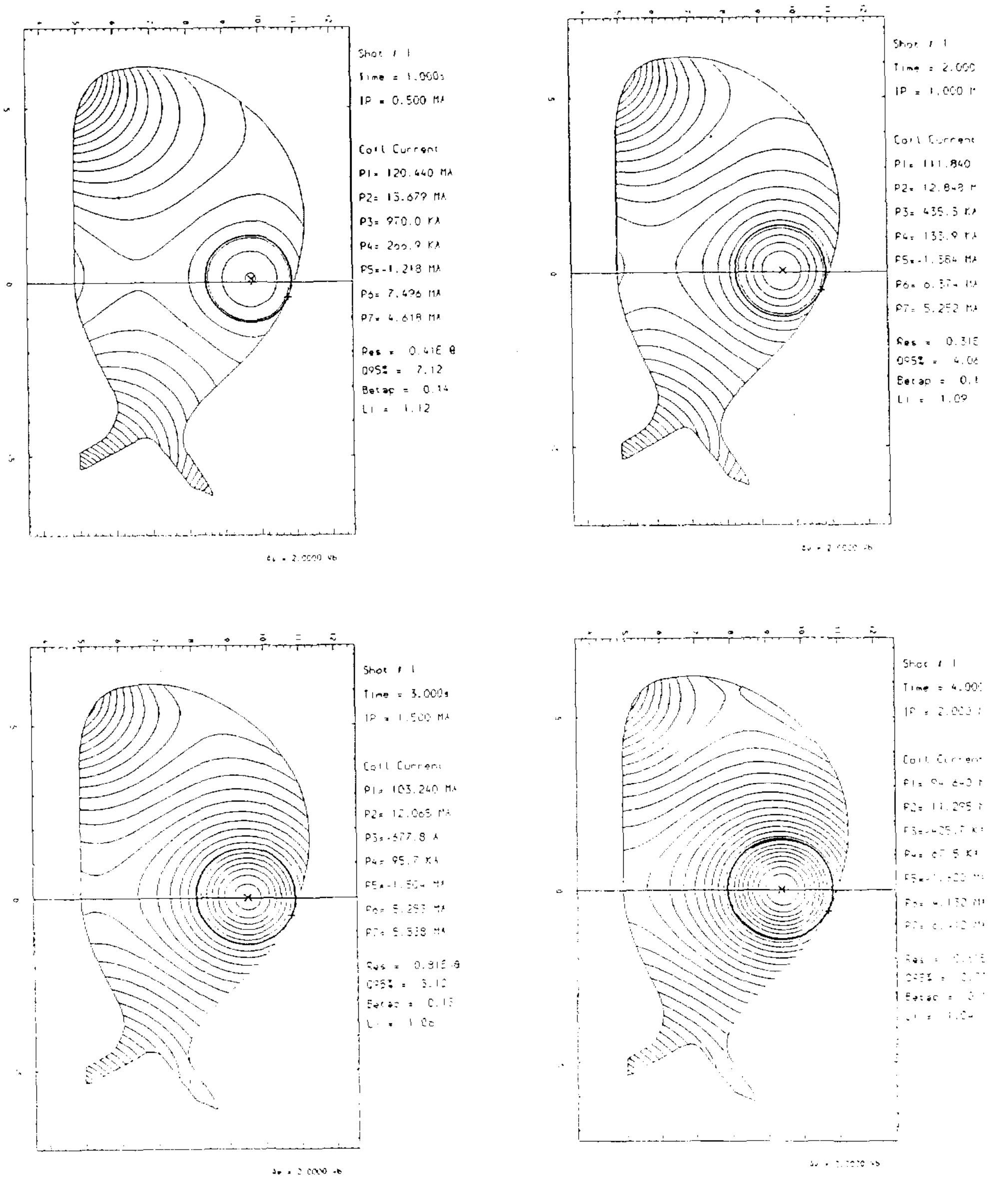


Fig. 4 Plasma ramp-up scenario n. 1

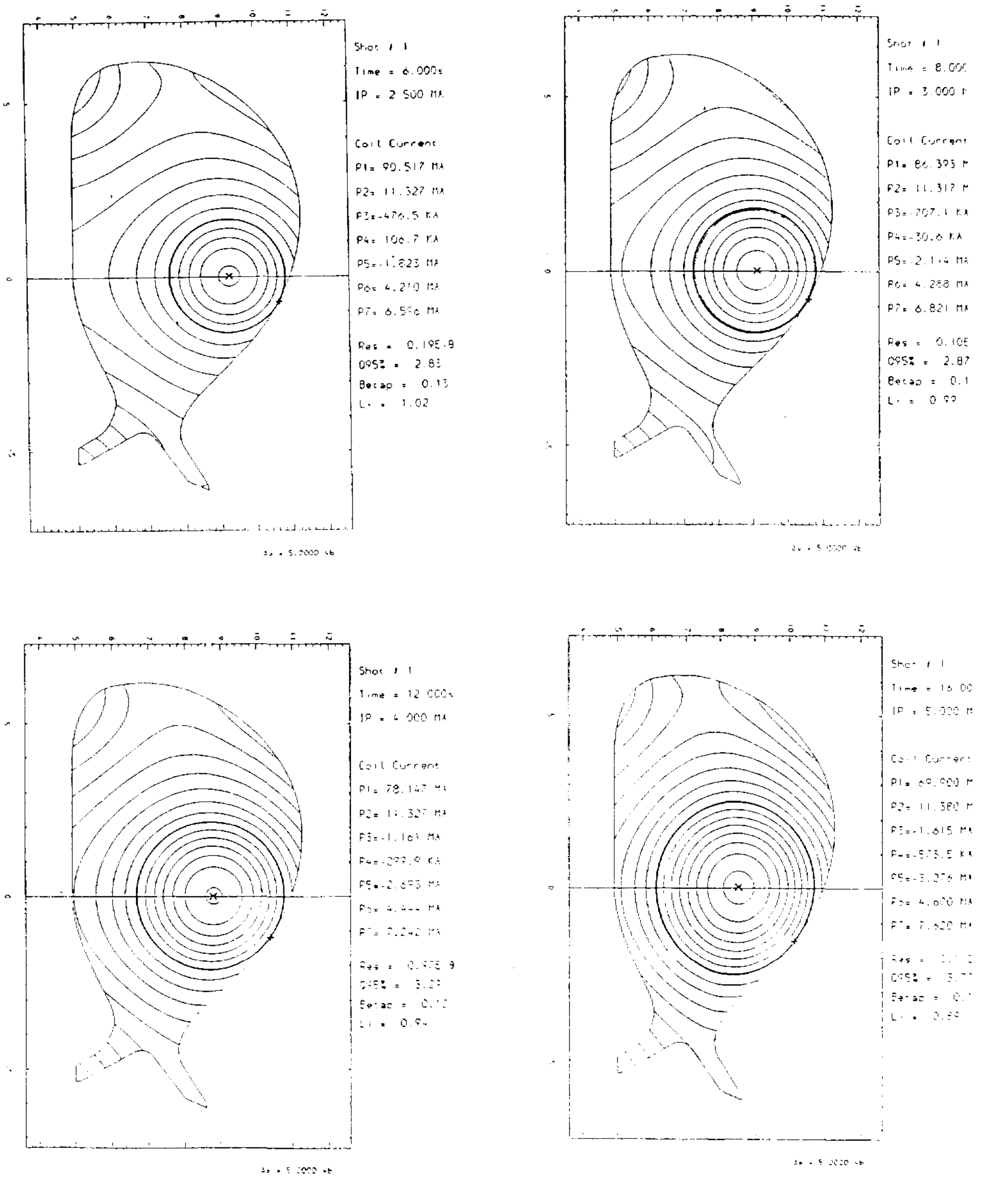


Fig. 5 Plasma ramp-up scenario n. 1

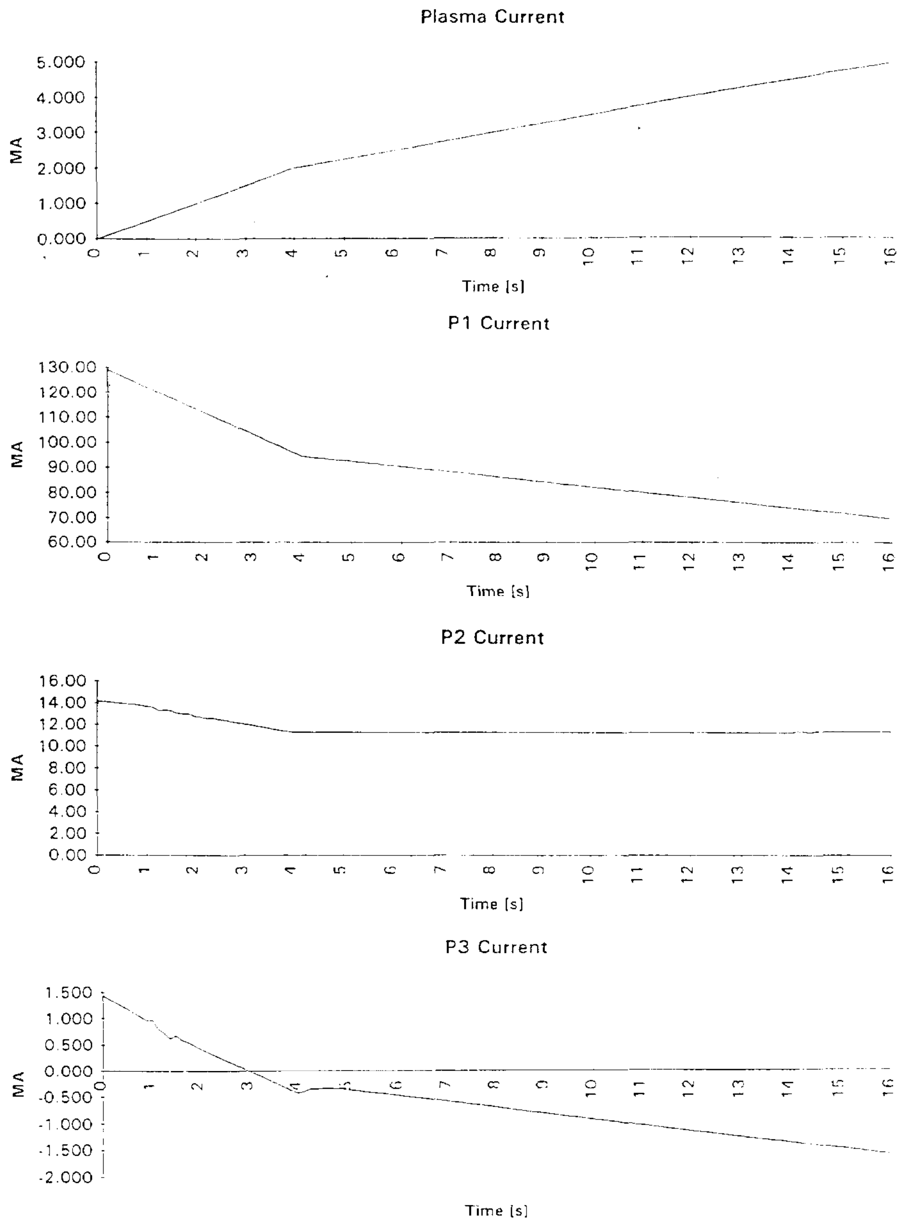
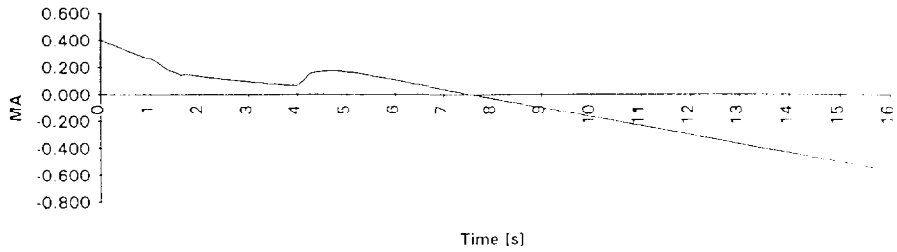
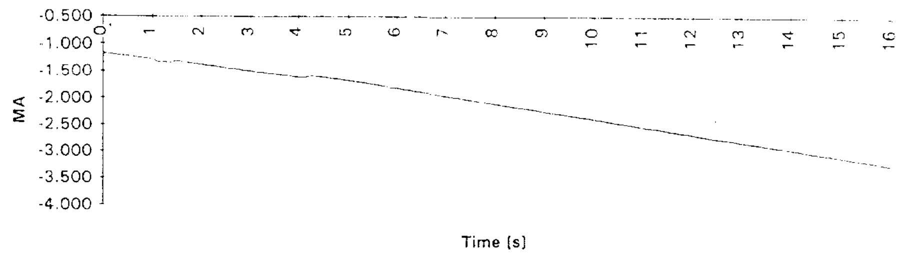


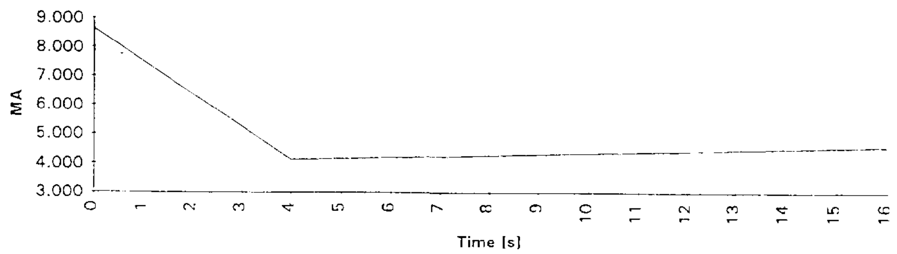
Fig. 6 Poloidal Field Coil currents for ramp-up scenario n. 1



P5 Current



P6 Current



P7 Current

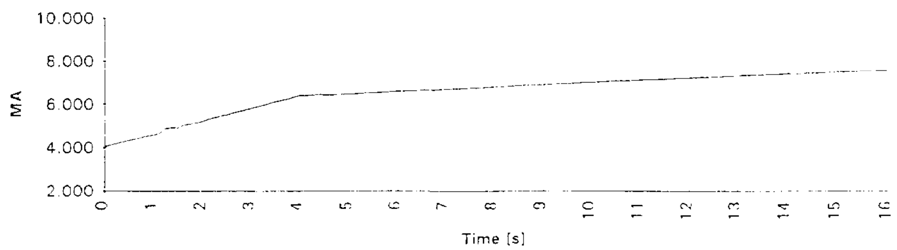


Fig. 7 Poloidal Field Coil currents for ramp-up scenario n. 1

PLASMA RAMP-UP SCENARIO N.2

This outer plasma ramp-up scenario, provided by Portone, is based on the latest studies [2]. It is characterised by a breakdown obtained 1s after the ramping down of the central solenoid current (fig. 11). The fast ramp down of the P1 coil determined very high eddy currents during the early phase of the pulse (fig. 8) even if they are supposed to be very small when the PF currents start to ramp down.

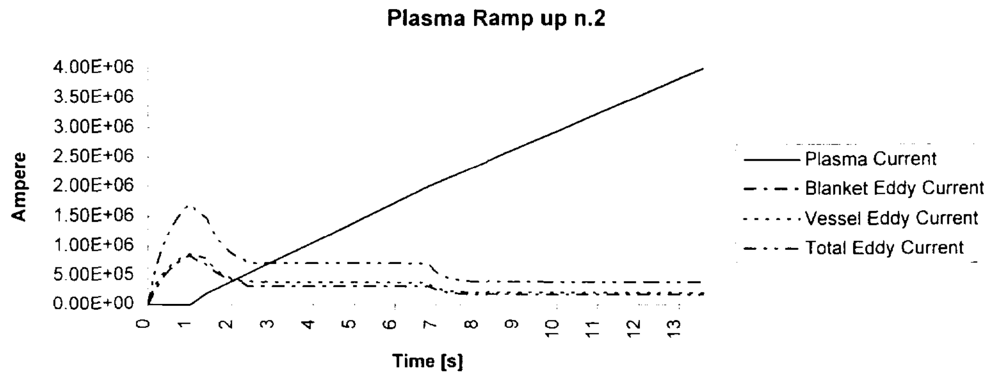
During the breakdown the eddy currents reach the value of 1.6 MA and then the lower plasma current ramp rate (0.3 MA) induces eddy currents values of the order of 0.7 MA (fig. 8).

As in the first scenario it is possible to see the two magnetic field nulls inside the vessel (fig. 9-10).

It should be noticed that the top magnetic field null is lower than in the first scenario, this causes convergency problems to the PROTEUS which, with lower plasma currents, tends to determine a plasma configuration with an X-point on the top of the vacuum chamber. It is possible to see on the 0.5 MA plasma configuration (fig. 9) that the plasma is elongated because of this reason. The attempt to push it on the outer wall provided a plasma too small and as a consequence convergency problems for PROTEUS.

In fig. 11-12, The plasma and PF coils currents are shown. The main difference is the ramp-up of the plasma current which is more uniform than in the other scenario. Moreover all the PF coil currents proposed for this scenario have higher values, especially the P7 coil current which has a completely different behaviour from the first scenario. This different behaviour could be the cause of the elongated shape of the plasma in the early phase of the ramp-up.

The P2 coil current shows quite easily the acting of the radial field controller used to keep the plasma on the mid plane. It is possible to see the change from a rigid body filamentary plasma to an MHD plasma at 2.3 s where the waveform starts to show the small steps (fig. 11).



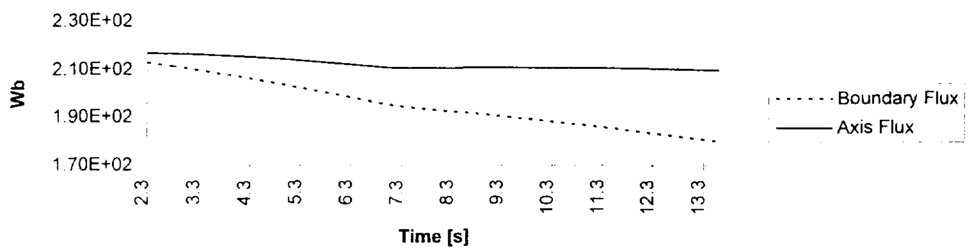


Fig. 8 Plasma ramp-up scenario n. 2

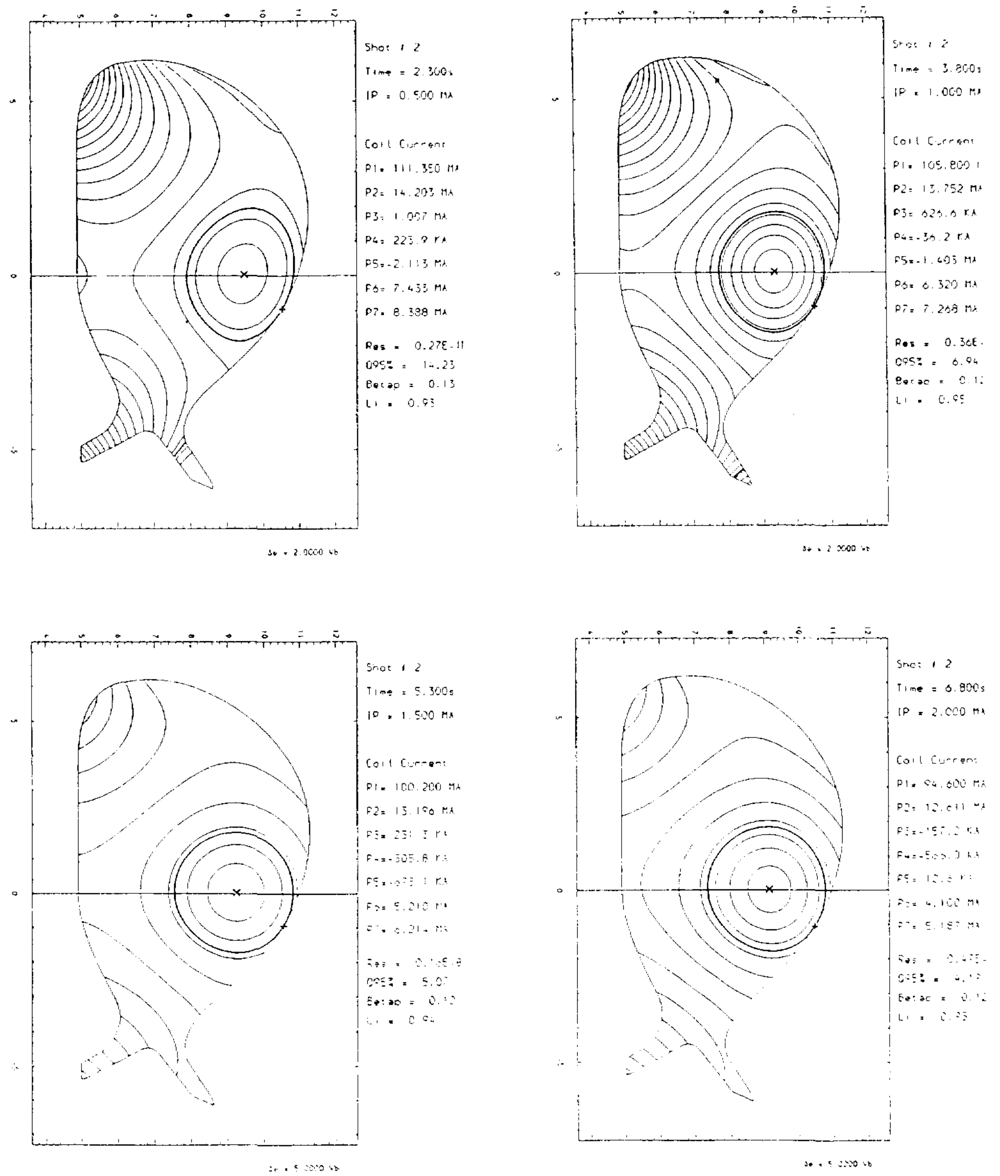


Fig. 9 Plasma ramp-up scenario n. 2

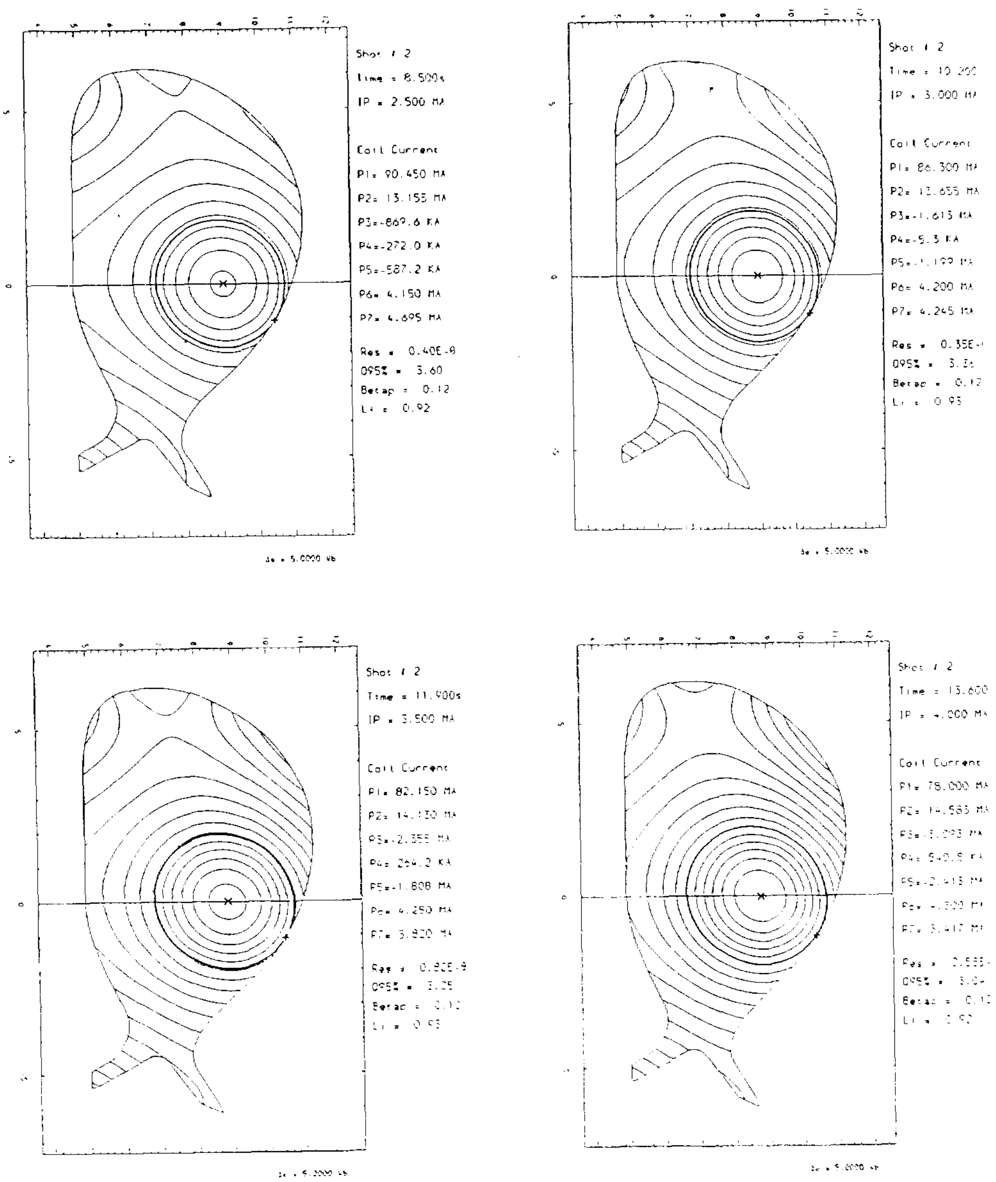


Fig.10 Plasma ramp-up scenario n. 2

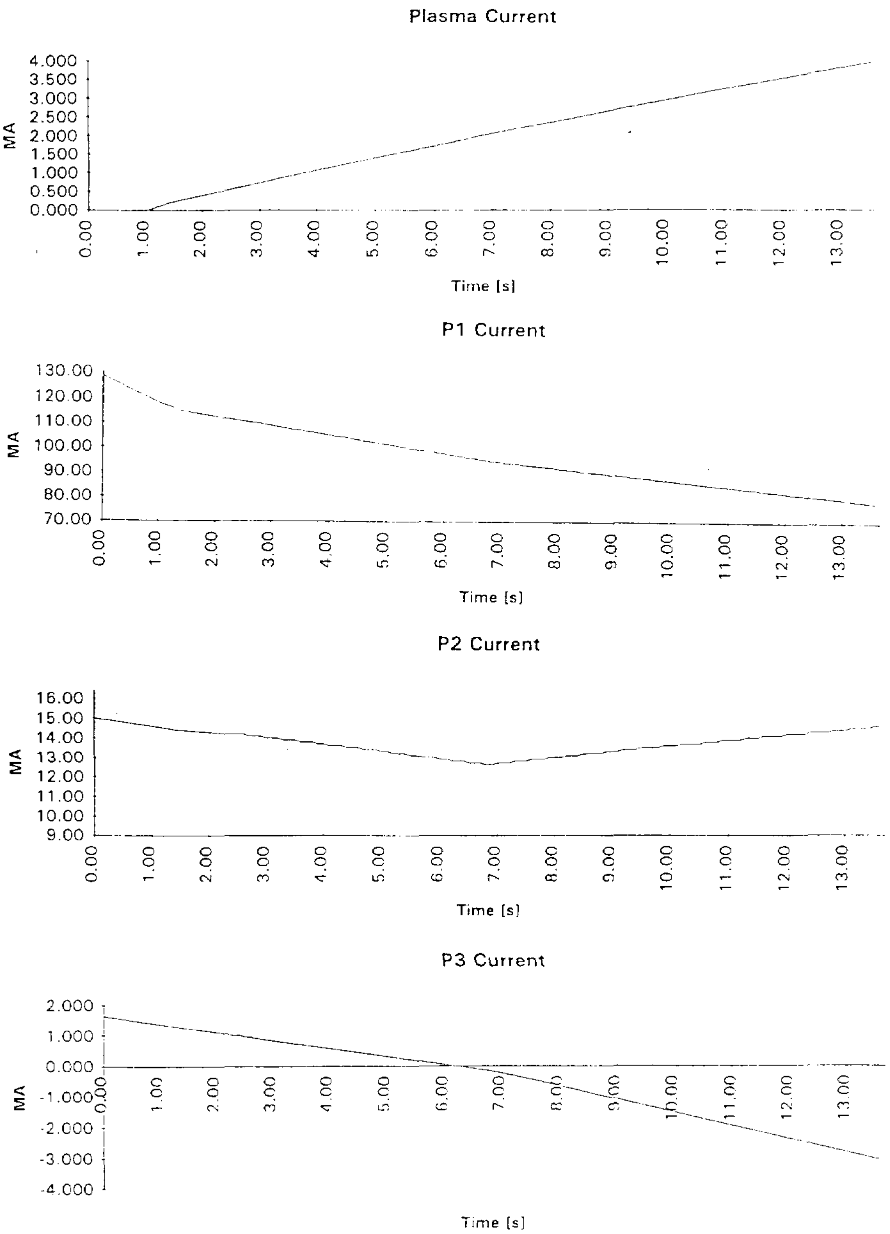


Fig. 11 Poloidal Field Coil currents for ramp-up scenario n. 2

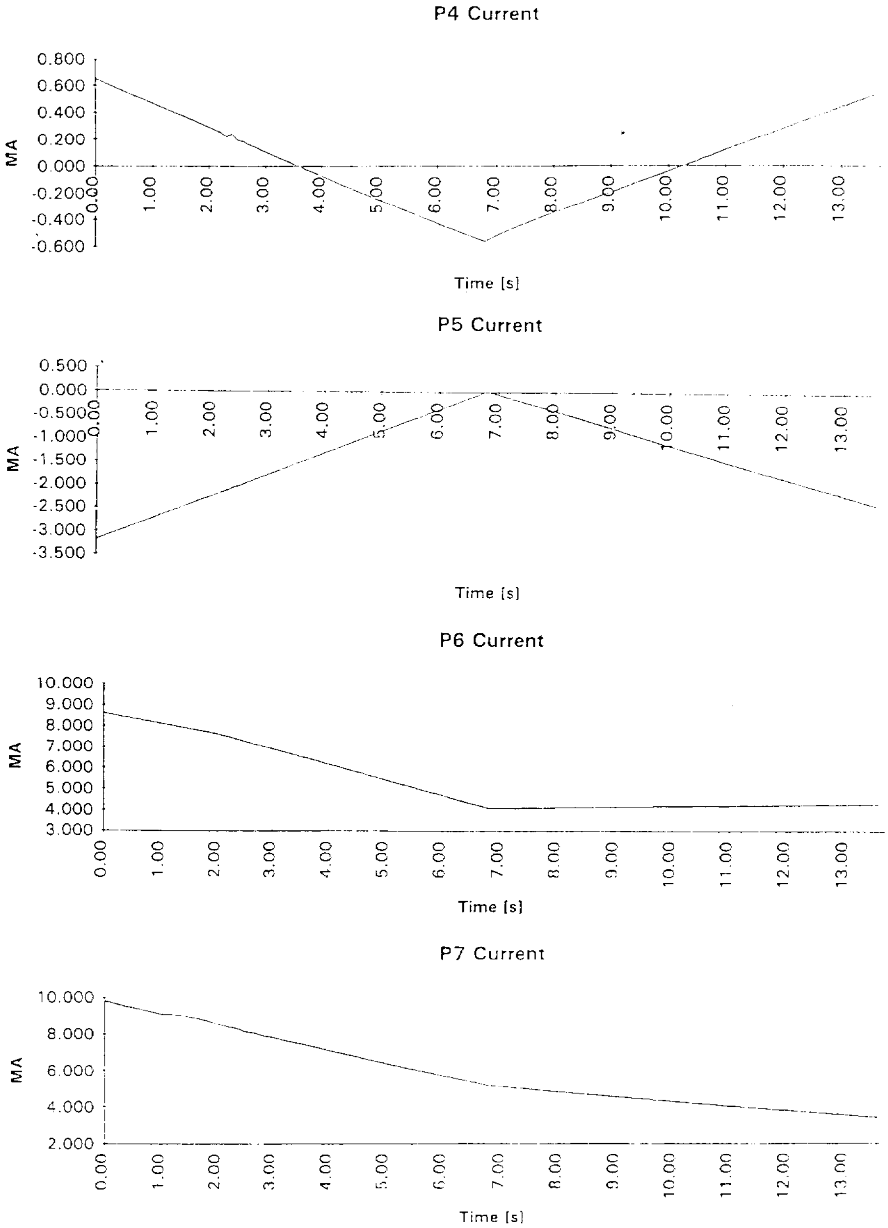


Fig. 12 Poloidal Field Coil currents for ramp-up scenario n. 2

PLASMA RAMP-UP SCENARIO N.3

This inner wall scenario was elaborated only for vertical stability studies. Therefore, the breakdown phase was not studied. The plasma configurations start from 1 MA plasma current configurations (fig. 14) and go to 5 MA. The poloidal field currents are based on the PF currents provided for the first scenario, even if in this case the term which belongs to the controllers is different and affects the total value considerably.

This scenario is characterised by very high values of eddy currents (fig. 13), which are determined by the higher current values of P2 and P7 (fig. 16-17). They are used give to the plasma a more circular shape. In fact the strange shape of the plasma at 1 MA is due to the P1 current which pushes outwards and squeezes the plasma (fig. 14-15). Also the P3, P4 and P5 currents, used to keep the plasma on the inner wall, are higher than in the previous scenarios and especially the P4 current, which changes its sign for the first period, has a completely different behaviour.

It should be noticed that also in this case there is the presence of a top and a bottom magnetic field null (fig. 14) during the first 3 s. Then, when the plasma reaches the 2 MA value the bottom magnetic field null disappears from the vacuum chamber (fig. 15); nevertheless the top magnetic field null is still present.

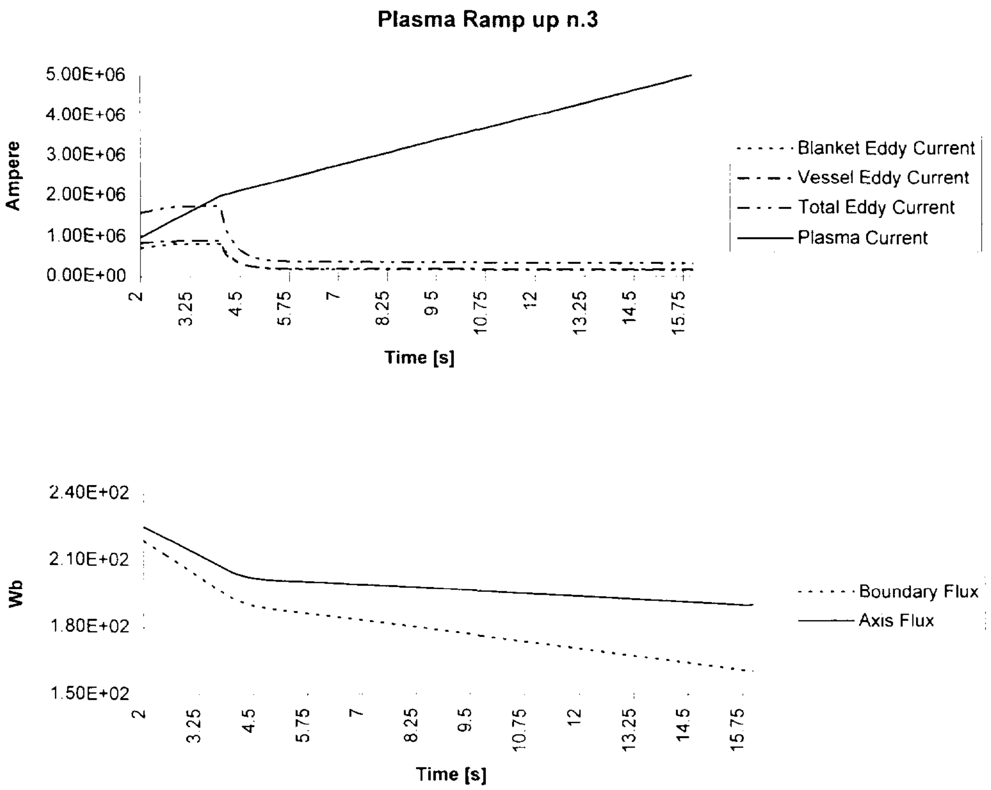


Fig. 13 Plasma ramp-up scenario n. 3

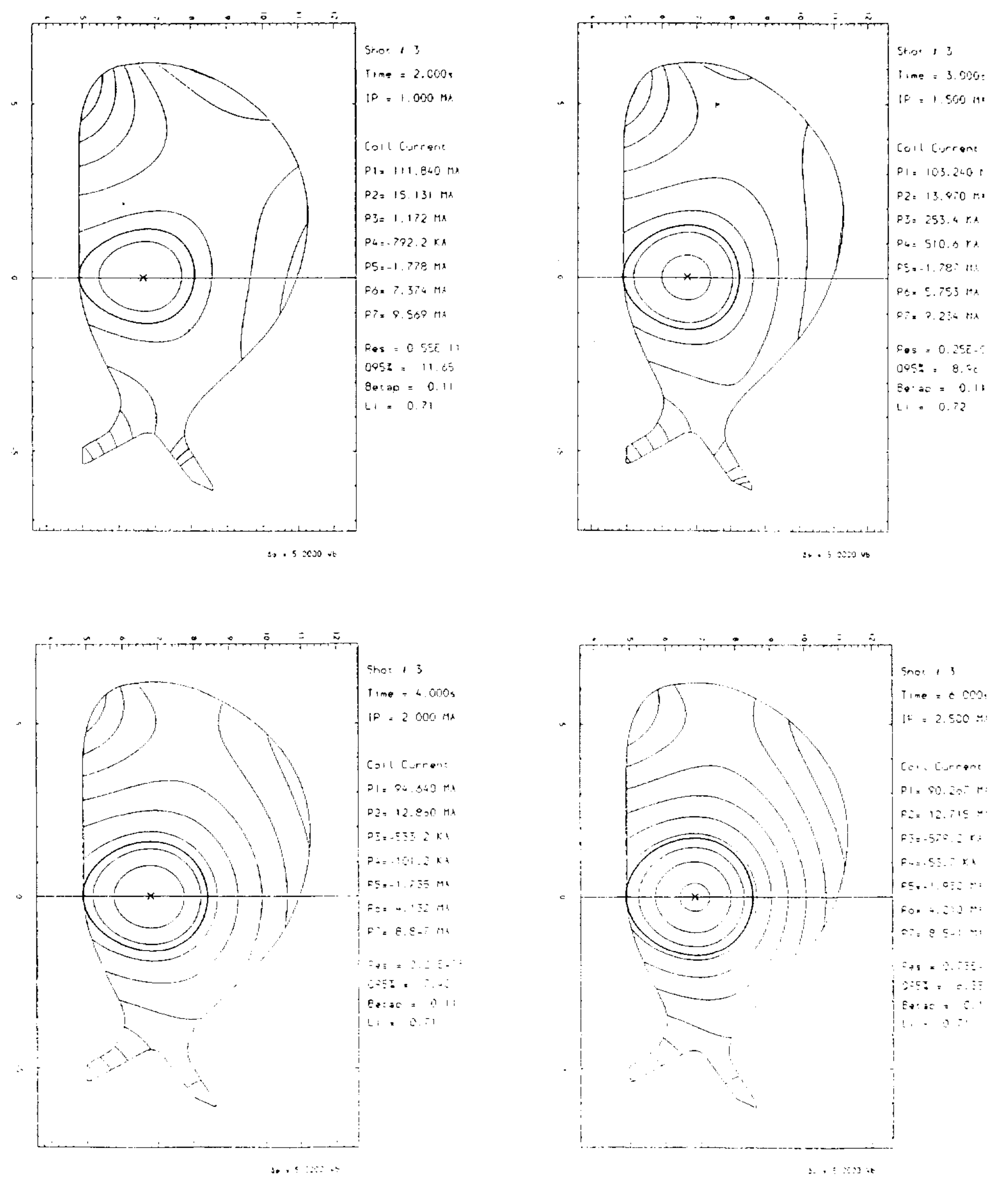


Fig. 14 Plasma ramp-up scenario n. 3

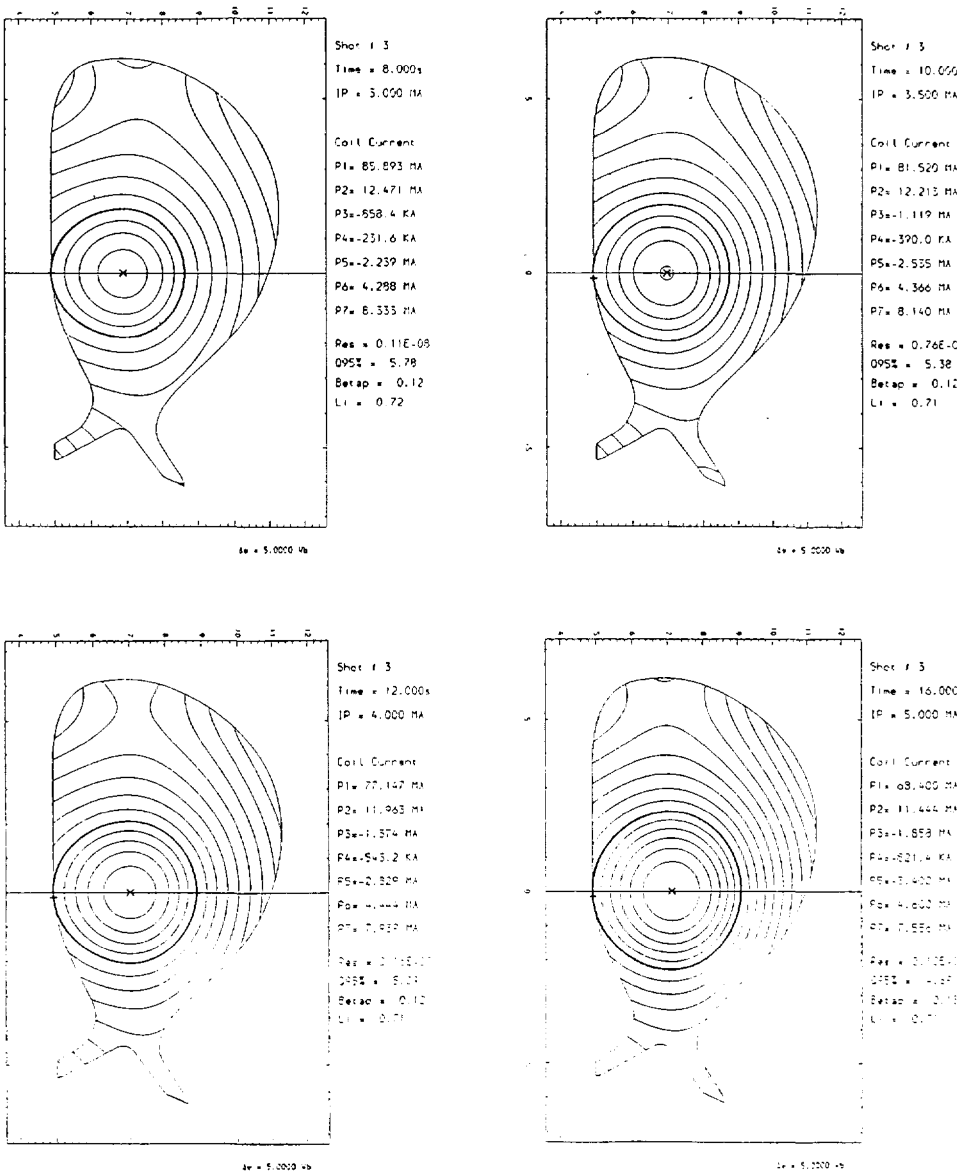


Fig. 15 Plasma ramp-up scenario n. 3

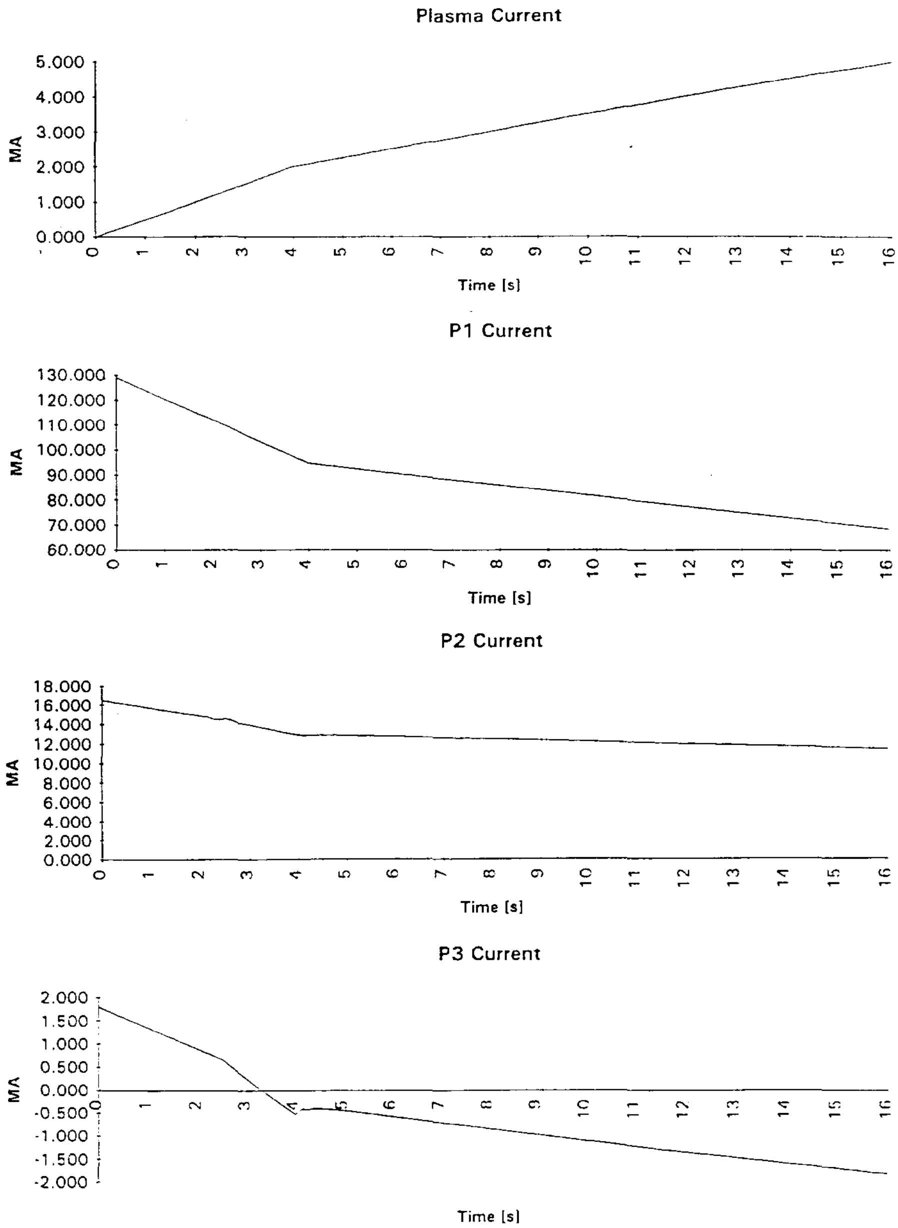


Fig. 16 Poloidal Field Coil currents for ramp-up scenario n. 3

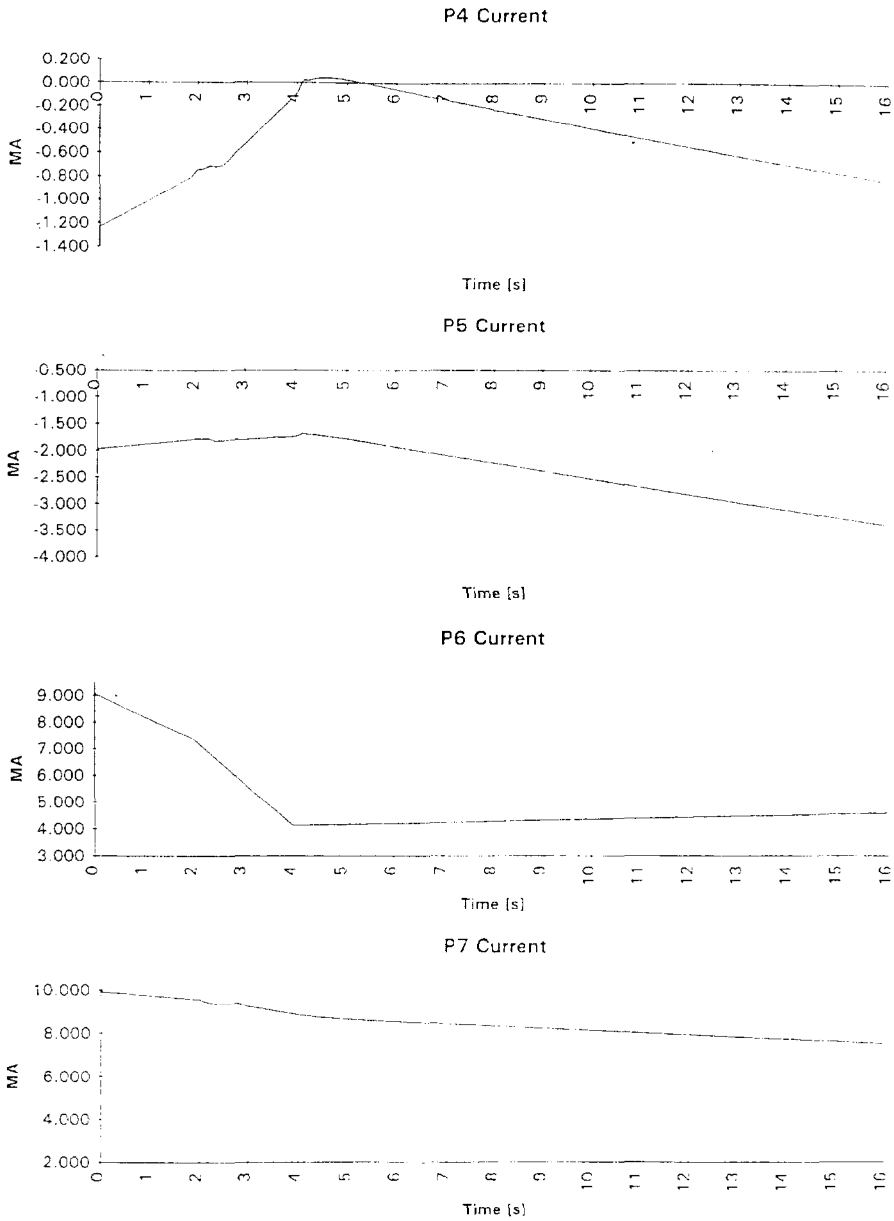
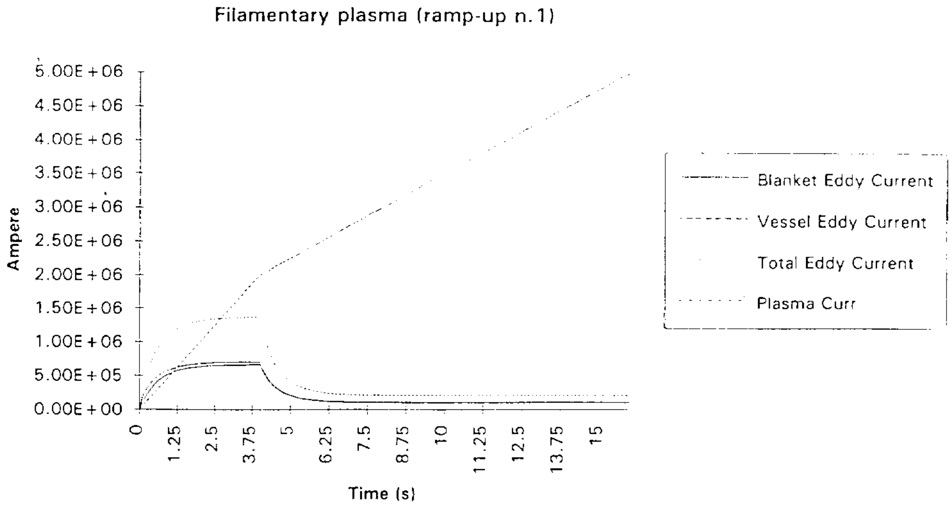


Fig. 17 Poloidal Field Coil currents for ramp-up scenario n. 3

FILAMENTARY AND MHD PLASMA

Fig. 18 shows the eddy currents generated by a filamentary plasma ramp-up and a MHD plasma ramp-up. If the plasma is not allowed to move fast the behaviour of the two eddy currents depends mainly by the PF coil currents and by the plasma current itself.

Next figure (fig. 19) compares the magnetic configuration produced by the two different plasmas. It can be noticed that the flux lines shape is the same outside the plasma. Therefore it is possible to use a filamentary plasma model to study the plasma behaviour at low plasma current and when the plasma is small.



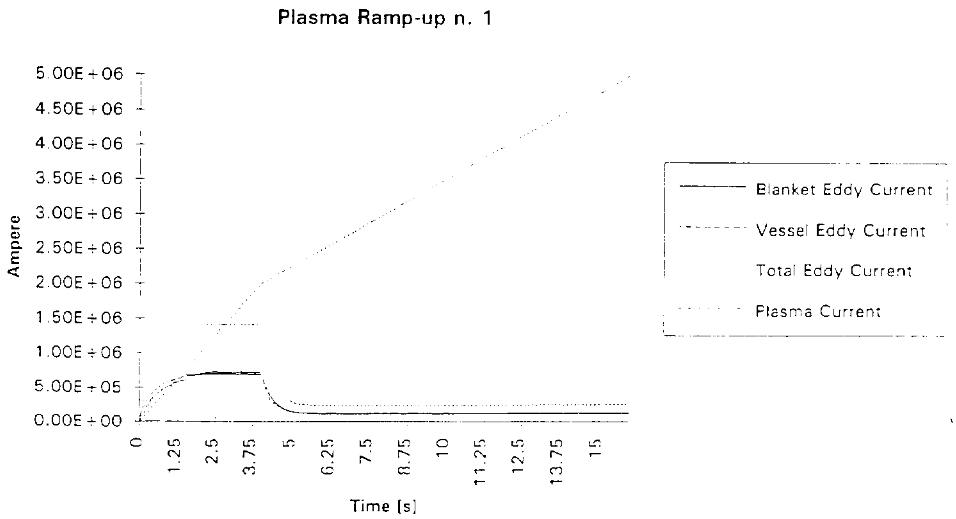


Fig. 18 Eddy currents produced by a filamentary and a MHD plasma

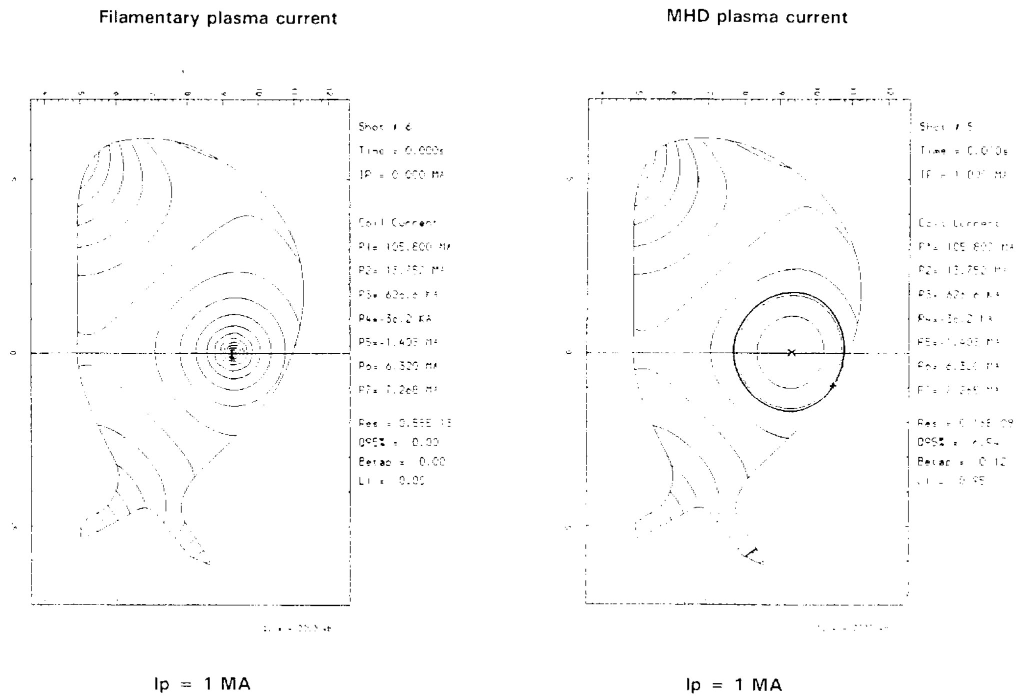
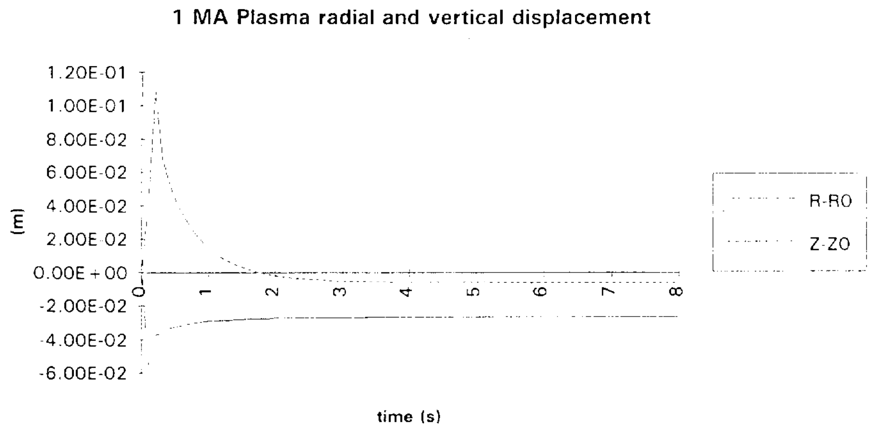


Fig. 19 Comparison between a filamentary and a MHD plasma magnetic configuration

'PLASMA VERTICAL STABILITY

When the plasma radial position is controlled, for small currents, the plasma is vertical stable. The fig. 20 shows that a radial field perturbation does not destabilise the plasma which reaches a different but stable configuration in one case and the same configuration for the other. Even l_i and β_p perturbations do not destabilise the plasma.



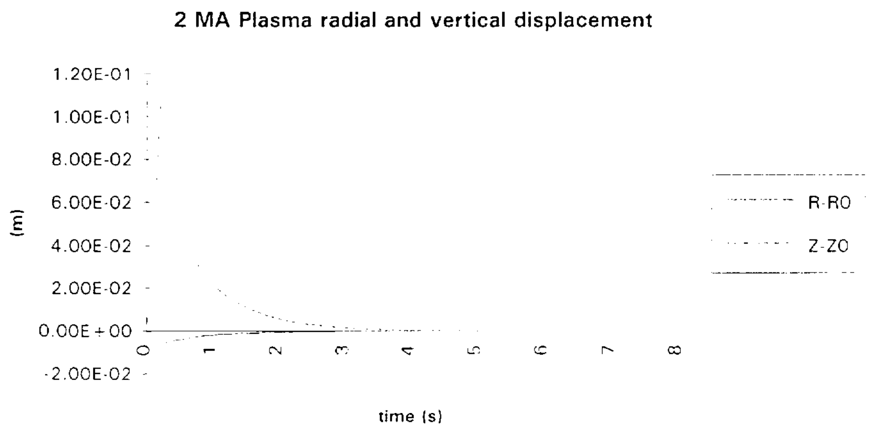


Fig. 20 Plasma vertical stability (the plasma radial control is performed)

EXPERIMENTAL DATA

JET experiments show that during a disruption the plasma moves vertically keeping its radial position and plasma current constant.

In this case (pulse n.29679) the plasma moved vertically 1 m before the plasma radial position and current show an appreciable variation.

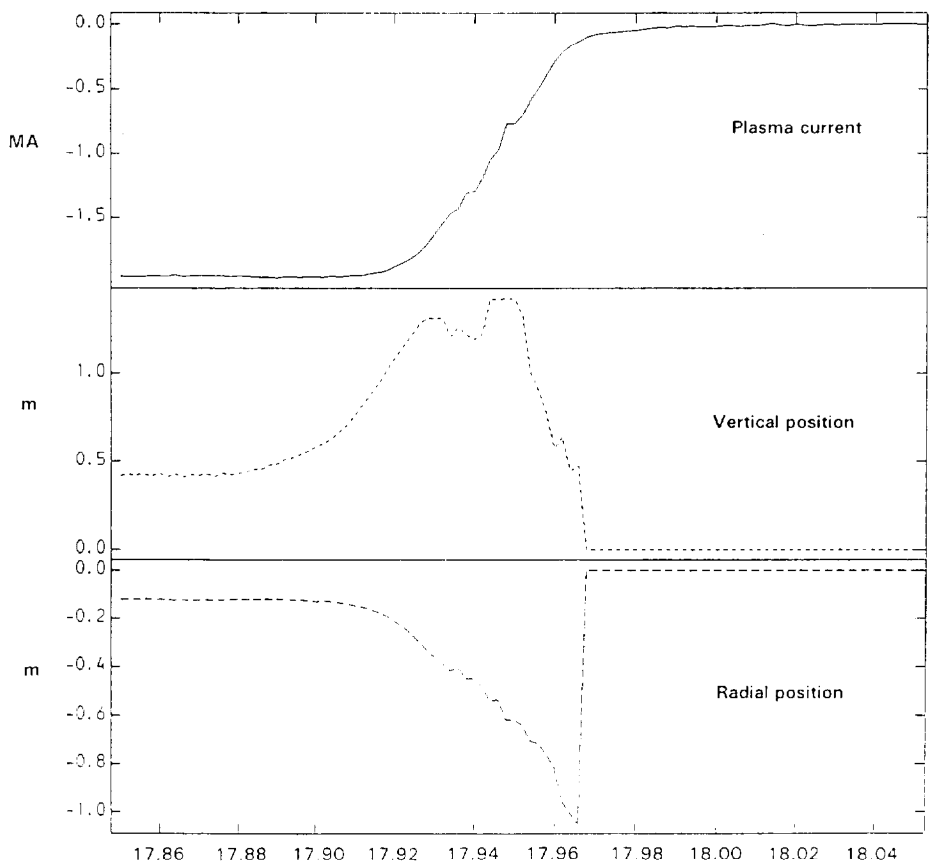


Fig. 21 JET Experimental data

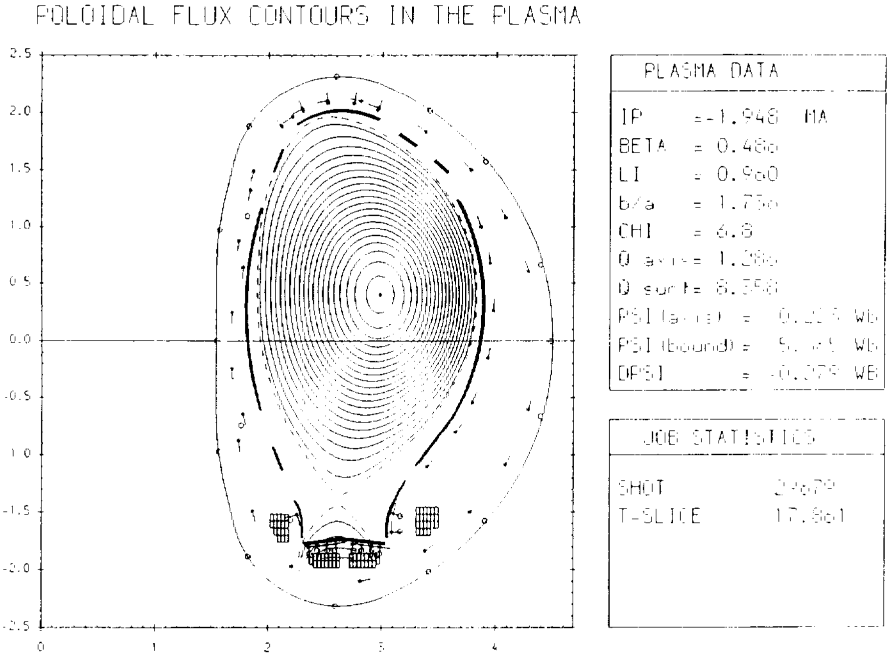
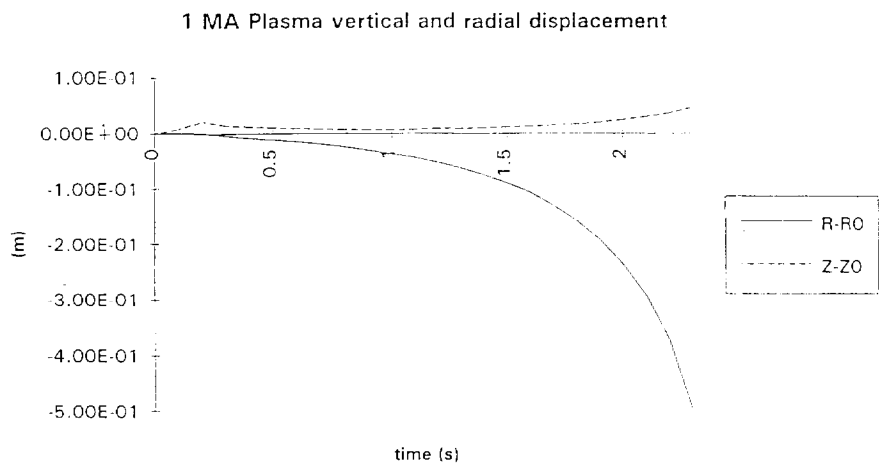


Fig. 22 JET Experimental data: the magnetic configuration before the disruption

PLASMA RADIAL INSTABILITY

The fig. 22-23 show the displacement of a plasma when all the poloidal field coils are short circuited. After the first period (0.3 s) where the plasma is perturbed by a radial field, it is possible to notice that the plasma moves back to its vertical position. At the same time the radial position is lost and the plasma moves to the inner wall. For plasma of 1.0 and 2.0 MA current it was possible to determine the radial growth rate which is comparable to the vertical one for flat top configurations (1.5 s^{-1}).

For plasma with current higher than 3 MA (fig. 23) the plasma starts to move also vertically. This does not allow any growth rate calculation.



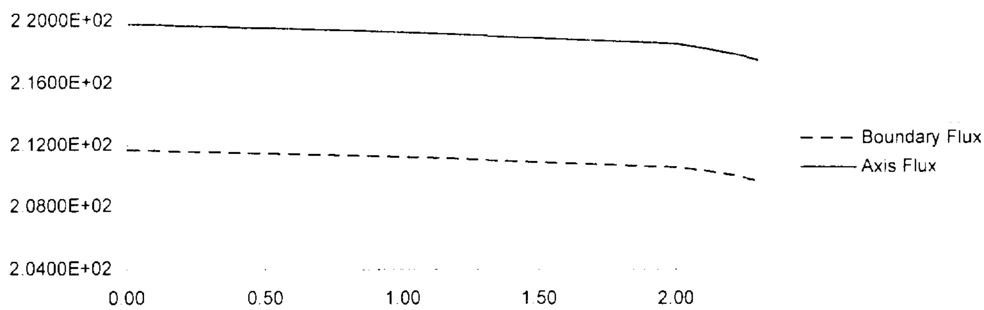


Fig. 23 Plasma radial instability (the plasma radial control is not performed)

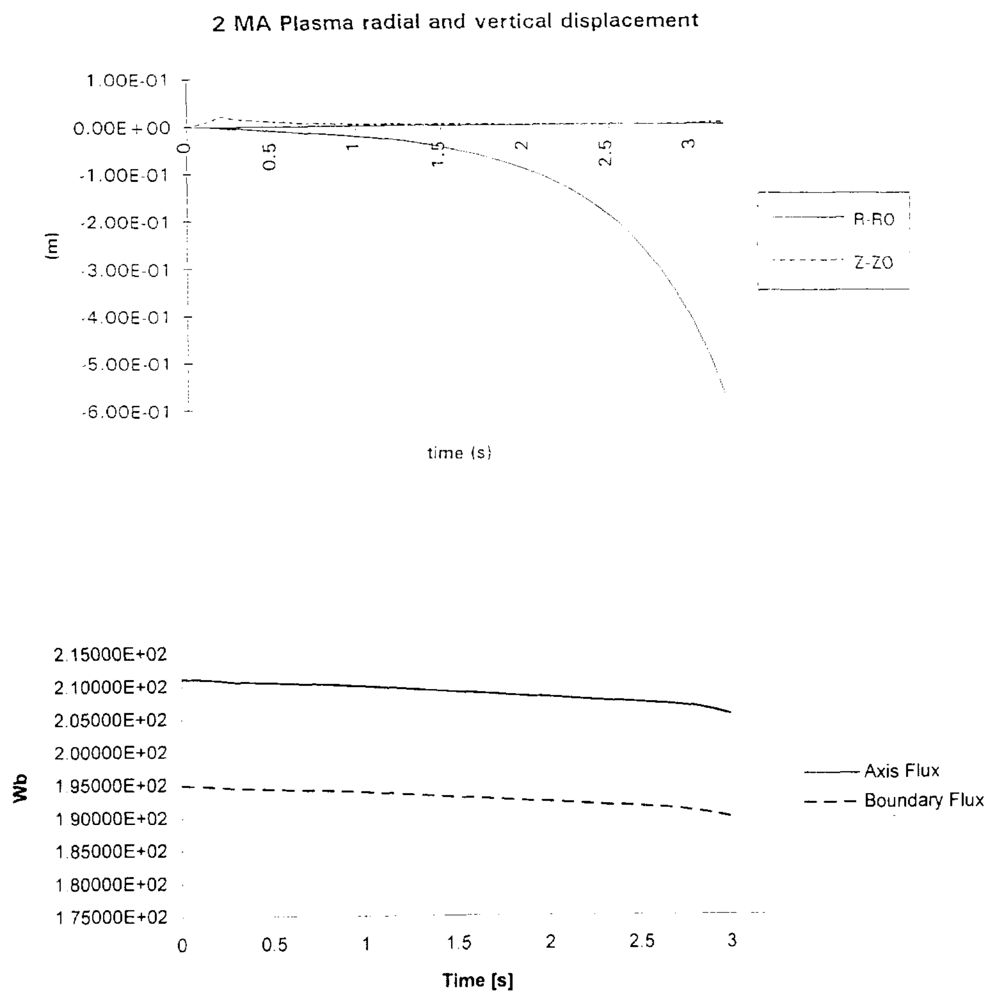
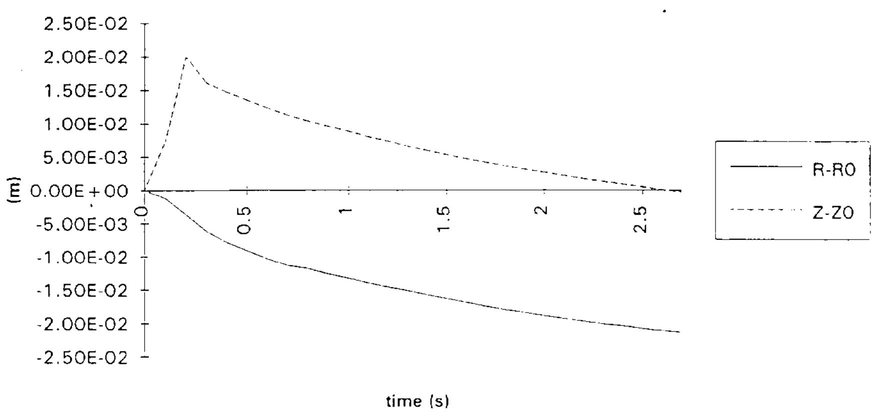


Fig. 24 Plasma radial instability (the plasma radial control is not performed)

4 MA Plasma radial and vertical displacement



3 MA Plasma radial and vertical displacement

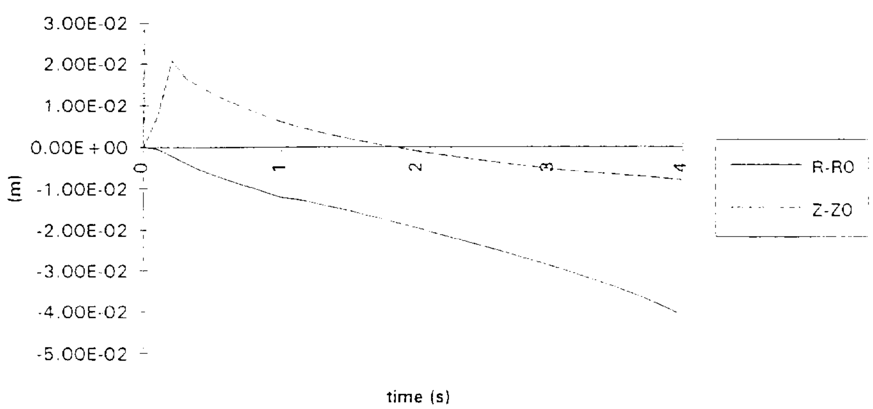


Fig. 25 Plasma radial instability (the plasma radial control is not performed)

MAGNETIC FIELD NULL ON THE MID PLANE

The presence of the magnetic field null on the mid plane could cause serious problems for a radial position control based on flux extrapolation as it is performed at JET.

This figure shows some examples of configurations where the magnetic null is present. As it was said before, the size of the plasma compared to the vacuum chamber and the presence of the magnetic field null on the middle plane and on the top, could create some problems to the control measurements based on boundary reconstruction code which uses only magnetic signals.

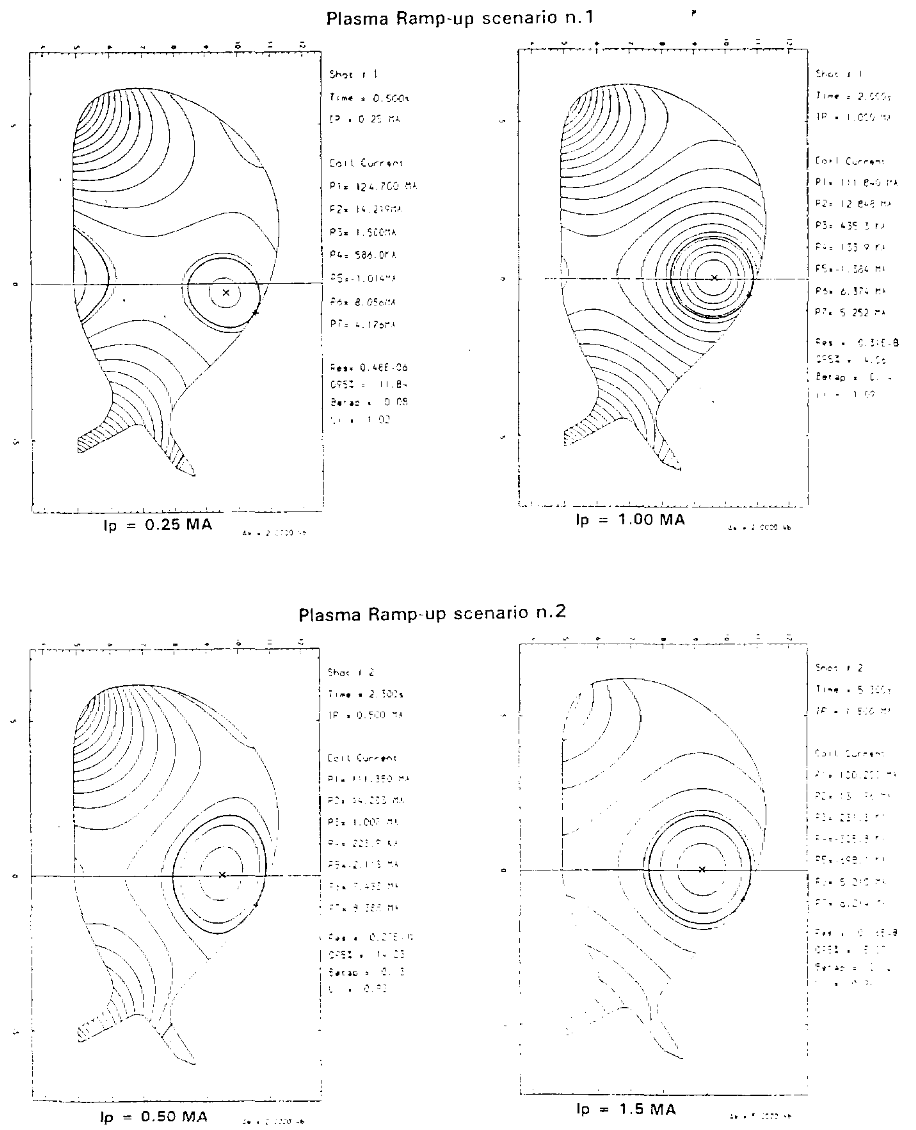


Fig. 26 Magnetic field null on the mid plane during the early phase of the ramp-up.