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Ignitor Scale-Up Studies (DIGNITOR)*

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Abstract

An analysis of a scaled-up version of IGNITOR (to a major radius of 2.16 m) is discussed. The design, referred to as DIGNITOR, is a direct extrapolation of IGNITOR. The consequences from the increased size are discussed (mainly due to decreased temperature excursions). A summary of comprehensive calculations of the stresses (documented in an accompanying paper) are presented. The case of a divertor plasma configuration is analyzed. The implications of a CIT-like vacuum vessel are also discussed.

Introduction

The purpose of the work was to study the implications of increasing the size of the IGNITOR device [1] to a size comparable to the CIT. We will refer to the extrapolated device as DIGNITOR. Previous work (done for the IGNITOR design in 1988) calculated the reactions to the Lorentz, mechanical and thermal loads of the toroidal and poloidal field systems; fine-tuned the equilibrium; and studied the sensitivity of the stresses to non-ideal conditions (non-zero gaps, moduli variations, preloading variations, etc) [2]. The previous work showed that the IGNITOR configuration was relatively robust to non-ideal conditions [2].

IGNITOR uses a magnet design (bucking and wedging) that maximizes the magnetic field for a given coil stress level. In bucking and wedging the radial loads of the toroidal field coil are supported by both the toroidal field coil (wedging) and by a poloidal field coil/bucking post (bucking). In IGNITOR the wedging takes about 30% of the radial loads and bucking takes the remaining 70%. The inplane stresses are minimized for this distribution of loads [4], although the minimum is insensitive to distribution of the radial loads (due to the presence of the vertical loads). The wedging, however, is necessary to support the out-of-plane loads. If there is not enough wedging, shear carrying capacity between the turns of the toroidal field coil would not be sufficient to support the out-of-plane loads. This concern was addressed at length in the previous study and it was found that the IGNITOR configuration was indeed robust to the non-ideal conditions studied. No structural failure conditions were found. Substantial gaps (of the order of 1 mm) could be tolerated.

In this report we present results of extensive calculations of the plasma equilibria, for the scenarios indicated in Table I.

In this report only a summary of the stress calculations are presented for the case of full current (18.5 MA). This case results in the largest loads, and backing away from it (i.e., reducing the plasma current while holding the toroidal field constant) will result in a more benign stress situation. Extensive details of the stress calculations are presented in an accompanying paper [3].

We did not deal with the issues of the vacuum vessel and the first wall of DIGNITOR. Instead we chose to look at a range of vacuum vessels determined from either scaling up the IGNITOR vacuum vessel/first wall or using the CIT vacuum vessel/first wall. We have not calculated the disruption loads for DIGNITOR.

The first column shows the parameters of CIT. The first DIGNITOR column corresponds to a DIGNITOR plasma with 18.5 MA and with a IGNITOR-like vacuum vessel (directly scaled from the IGNITOR). The plasma current was adjusted in order to operate at a value of q ($\sim 5B_T a^2 \kappa / I_p R$) comparable to that of CIT. The second case corresponds to a divertor plasma, with an x-point at the location of the first wall (also with a IGNITOR-like vacuum vessel). The last column corresponds to a divertor with a CIT-like vacuum vessel (TF-plasma gap equal to that of CIT).

Figure 1 shows the IGNITOR geometry. We have scaled the major radius to 2.16 m. There are large compression rings on the outer leg of the device, both at the top and bottom. The purposes of these rings are to decrease the vertical load of the throat and to provide sufficient hoop stresses in the region near the top and bottom of the inner leg to react the out-of-plane shears in these regions. There is a bucking post through the center of the OH transformer. The bucking post supports of OH transformer and toroidal field coil when the inwardly directed radial load of the TF solenoid is larger than the outwardly directed OH load. Also, it is designed to carry some vertical load through a preload.

When scaling the size of the device (at constant magnetic field), the current densities (j) in the magnets scale as the inverse of the scaling constant $\lambda = R_{DIGNITOR}/R_{IGNITOR}$ (in this case, $\lambda = 1.76$). The volumetric heating rate then scales as λ^{-2} . For constant temperature excursions (which varies and $j^2 \times \tau$), then the characteristic times (start-up, flat-top, ramp-down) scale as $\tau \sim \lambda^2$. The relative current penetration and the temperature excursions would be the same for both IGNITOR and DIGNITOR if these scaling rules are utilized.

In this work, however, we have assumed a flat top time of 7 s, the same as CIT. This results in much lower temperature than both CIT and IGNITOR at the end of pulse and much lower power supply and stored energy requirements than

CIT. Releasing the temperature constraint can be used to the advantage of DIGNITOR power supply equipment, by decreasing the ramp-up times or increasing the pulse length. We have, indeed, assumed slower ramp-rates than a straight scale-up of IGNITOR ($\tau \sim \lambda^2$). The temperature excursions of both the toroidal and the poloidal field system, however, are still small.

In section II of this report the equilibria for a limiter and several divertor cases are presented. Calculation of the PF scenario (temperature, energy and power of the toroidal field and poloidal field systems) are also shown.

Section III shows the results for the electrical/thermal parameters for the toroidal field coil.

Section IV summarizes the results from the stress calculations.

Section V extrapolates the results to other interesting regions of parameter space, including divertor operation. Limits of pulse length, implication of a more CIT-like vacuum vessel, and other tradeoffs will be performed parametrically in this section.

Section VI briefly discusses some of the impacts on physics of a CIT-sized IGNITOR.

Finally, section VII summarizes the results.

II. Equilibria and PF considerations

The equilibria that was used for the analysis of the standard DIGNITOR plasma was scaled from the IGNITOR equilibria. The IGNITOR equilibria is shown in Figure 2. The currents in the PF coils for DIGNITOR (with 18.5 MA plasma current), the energy stored and dissipated, and the resistive and inductive power and the coil temperatures are shown in Figure 3. The temperature excursions are small, with the maximum temperature in the PF coil system (in PF1) of 125 K. The toroidal field coil and the central solenoid are started at 50 K.

The summary of the energy and power of the poloidal field system for this case are shown in Table II. The energy and power requirements are less than those

for CIT.

The case of a divertor was analyzed next. We have done preliminary optimization of a divertor configuration for such a machine. However, due to the low elongation, we have found that it is very hard to pull the x-point. The best results that we have obtained are shown in Figure 4. The size of the coils is proportional to the current that they carry. The current of the divertor coil (PF5) is 12.9 MA. Figure 5 shows the PF coil temperature, the inductive and resistive PF system power, the stored and dissipated energy and the coil temperatures. There is substantial temperature excursion of PF5. Since this coil is relatively out of the way, it would be possible to increase its size to decrease the current density and the temperature rise. We have not done this in this work. Substantial decreases in the energy could be obtained by increasing the size of PF5.

The flux linkage between the PF system and the plasma has been decreased for the divertor cases, in order to take into account the diminished plasma flux requirements due to the lower plasma current.

We have investigated the possibility of running a divertor discharge and accomodating a more CIT-like vacuum vessel. The main parameters are shown in the last column of Table I. The plasma minor radius has been reduced by about 9 cm (to 0.69 m). This would allow use of CIT vacuum vessel and gaps. The possible need for a thicker vacuum vessel due to larger fields and currents (and therefore, disruption loads) has not been included, since we have not calculated the disruption loads for DIGNITOR. Any comparison with CIT should be done cautiously.

The resulting plasma equilibrium is shown in Figure 6. The plasma current is decreased to 15 MA, corresponding to $q = 1.65$. The current in the divertor coil (PF5) has been dramatically decreased. This is because of the increased plasma elongation. There is a large corresponding decrease of the energy, power and temperature excursion of the coils, as shown in Figure 7. Table II contains the results for the divertor case.

III. Toroidal field coil: temperature and energy considerations

The model used to calculate the toroidal field temperature, the Lorentz loads, the energy and the power requirements was designed such that the model nodal points corresponds to the nodal points in the FEM analysis.

The power, energy requirements and maximum temperature for the toroidal field coil are shown in Figure 8. The temperature excursions in the toroidal field coil are also substantially smaller than for both IGNITOR and CIT.

In order to provide larger radial loads during the startup (when the toroidal field coil is not fully charge but the OH transformer is), we investigated charging the toroidal field magnet earlier. At start-up, the current in the toroidal field coil was increased by 22%. This has the additional advantage that the toroidal field coil is more constant during the plasma start-up phase, simplifying the plasma heating if resonant waves are used. The net effect is an increase in temperature of about 10 K, with a corresponding increase of TF power of about 50 MW.

IV. Stress summary

In this section, a summary of the stress calculations for DIGNITOR is presented. The full details are given in another report [3].

The stress calculations were performed for a plasma current of 18.5 MA and a toroidal field of 12 T. Qualification of this level of operation would qualify some family of lesser loading with the provision that OH and TF loading was either sufficiently reduced or was matched as in the fully loaded case.

It has been suggested that the allowable for externally supported coils (such as the ones in DIGNITOR) be $0.75 \sigma_y$, where σ_y is the yield stress. The yield stress is temperature adjusted.

The maximum average stress in the TF is about 233 MPa at both beginning of flat top (BOFT) and end of flat top (EOFT). This is slightly above 2/3 of yield $\sigma_y = 340$ MPa (close to the allowable for not-confined coils). The OH coil sees a maximum of 250 MPa average stress or 0.67 of yield ($\sigma_y = 370$ MPa at 60 K).

Again, the OH transformer is below the allowable for confined coils and close to the allowable for not-confined coils.

In table III the limiting peak stresses are shown and are compared with yield.

The toroidal field packing fraction is 90%, while the central PF transformer is 80%.

Like IGNITOR, DIGNITOR employs two preload mechanisms, the large outer shrink ring and second, the center tiebolt (shown in Figure 1). The Tiebolt also serves as a bucking post when the TF loads over-come the OH loads and put the machine core in radial compression. DIGNITOR has benefitted from the scale-up in terms of the lower temperatures of the coils. Active control of the tiebolt preload is not needed in DIGNITOR to relieve end-of-pulse compressive stresses. The preloads assumed for the precompression systems are 90 MN for the tiebolt load and 1600 MN for the total ring radial load.

The tiebolt produces only a small percentage of the vertical pre-compression. The ring load is large, but radial pressures to achieve these large loads are modest, approximately 50 MPa (7 kpsi) average. This would allow for many jacking schemes such as the wedge type jacks used in IGNITOR or freezable hydraulic bladders.

Next the issue of fatigue of the magnets is addressed. Equivalent alternating stresses of approximately 200 MPa have been calculated based on a proposed multiaxial fatigue model [3]. Equivalent mean stresses were compressive and thus will improve fatigue behavior over that predicted from a conventional $R=-1$ S-N diagram. But based on this type of diagram, the number of cycles of the coils would be over 10000 cycles. This is based on mean performance characteristics, with reasonable credit taken for the better performance of the cold-worked coppers, and improved liquid nitrogen fatigue life. More tests of the specific material chosen for the coils would be appropriate to quantify the statistical uncertainty in fatigue performance. This evaluation is exclusive of initial flaw/crack propagation effects, and detailed fracture mechanics calculations are also needed to allow a reasonable inspection program. These calculations have not yet been performed.

The fatigue life will be affected by microplasticity during repeated load cy-

cles (cyclic softening). This has the effect of reducing the yield stress in work hardened copper. In DIGNITOR, stresses remain within the elastic region of the stress-strain curve throughout the machine. Cyclic softening will not be an issue for all but the most highly stressed areas. Without detailed stress strain curves for liquid nitrogen temperatures it is difficult to assess the possibility of noticeable cyclic softening. The more highly stressed areas typically represent small percentages of the total coil volume and thus would behave as strain controlled regions with constraint provided by increases in stress in low stress regions. For a tokamak design like DIGNITOR, which utilizes external structure, the effect of small amounts of cyclic softening and creep would be to make stresses more uniformly distributed and increase the load share taken by other regions of the coil and the external structure. External structures will be made from materials which do not exhibit cyclic softening.

The shear capacity of a TF inter-plate bond is a function of face compression. Based on assumed performance of insulator shear capacity, and the wedge pressures in the TF, the calculated shear capacity is larger than the shear stress. The minimum excess shear capacity is near zero near the intended design boundary between wedged and the the unwedged region of the TF horizontal leg. In this region the out-of plane loads are taken by C-Clamp wedges in between the TF legs. At the equatorial plane, at EOFT, on the plasma side of the TF, the peak torsional shear stress is 49.8 MPa. The hoop wedge pressure is 180 MPa and the bond strength without compression is 13.8 MPa. The shear capacity is $.3 \times 180 + 13.8 = 67.8$ MPa. In a manner similar to the TF shear stress evaluation, the shear stresses in the OH can be calculated and compared with the shear capacity. Typical results are shown in Table IV.

V. Discussions

In this section we summarize the work of the previous sections and speculate about the implications of using a more CIT-like vacuum vessel.

As defined by the parameter $q = 5B_T a^2 \kappa / I_p R$, the DIGNITOR configu-

rations that we have analyzed have comparable q 's to CIT, as shown in Table I.

The case of the DIGNITOR small divertor plasma has comparable distance between the plasma and the toroidal field coil and CIT. Therefore it is possible to fit in a CIT-like vacuum vessel and first wall.

We have briefly studied the out-of-plane loading on the toroidal field coil in the small divertor configuration of DIGNITOR (last column in Table I). This was done to explore whether divertor operation resulted in larger shears. However, in part because the plasma current is substantially decreased in the case of the divertor, the induced shears are smaller in the case of the divertor than in the case of the 18.5 MA non-diverter plasma. Since the toroidal field has been kept at 12 T, the shear capacity is not changed. Details of these calculations can be found in the accompanying report [3].

Table V summarizes the energy, power and temperatures of the poloidal field system for the designs shown in Table I. These numbers are substantially smaller than those for CIT, mainly due to the increased copper content in the throat (for both TF and PF systems).

The flat-top time in Table V is 7 s with the exception of the last column, where it has been increased to 10 s. Increasing the pulse length requires additional energy and larger temperatures at the end of the pulse (the power is mainly determined by start-up consideration). We have not calculated the stresses for the longer pulse option. However, since the temperatures are still relatively low for the case of the small divertor, it is expected that for moderate increments of the flat top time the stress distribution will not change.

VI. Physics

The ignition margin based on Goldston scaling for tokamaks of similar elongation and q 's is

$$I.M. \sim B^2 a^{1.26} R^{0.5}$$

where $I.M.$ is the ignition margin (a measure of $n\tau$), B is the toroidal field, a is

the minor radius and R is the major radius.

In making relative comparisons between DIGNITOR and CIT, the Goldston scaling is the most pessimistic. This is because the other scalings have positive toroidal field and density scaling that would be to the advantage of DIGNITOR. To compare CIT and DIGNITOR we take the CIT-like device listed in Table I. Using these versions of small-divertor for DIGNITOR and CIT from Table I, DIGNITOR (with elongation of 2) would have 1.5 times larger margin than CIT. However, the DIGNITOR transformer is capable of driving up to 18.5 MA so that if operation at lower q or slightly larger minor radius is possible, then DIGNITOR would have up to 1.9 times the ignition margin of CIT.

Because of the inertial cooling of the coils, the pulse length of this class of ignition devices is limited. In CIT the flat top pulse length is limited to about 7 seconds. In DIGNITOR the flat top pulse length is about 15-20 seconds (depending on the level of neutron power heating the magnet). For DIGNITOR, the energy confinement time is estimated ~ 0.7 seconds. With 20 MW of heating power, DIGNITOR is expected to be heated in about 3-4 seconds. The 10-20 seconds flat top therefore gives adequate time to explore the ignited domain. We have not calculated the stress distribution in DIGNITOR for the case of longer pulse lengths.

VII. Conclusions

This work has studied the possibility of using the DIGNITOR magnet configuration for a CIT-size device. We have not found any failure mechanism due to non-ideal behaviour for the magnet. The stresses in the toroidal field coil are below yield and below the allowables for a fully confined coil. The shear carrying capacity is sufficient for a performance level of the insulation and bonding strength consistent with that proposed for CIT. And the low temperature excursions of the coil remove the need for dynamically loading of the tiebolt. The result is a machine with at least 50% more ignition margin, lower power supply and stored energy requirements, longer pulse length (up to 20 seconds at full field), sufficient number of pulses and appropriate diagnostic access.

References

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- [3] P.H. Titus et al., "Structural Analysis of the DIGNITOR Reactor," MIT Plasma Fusion Report, to be published.
- [4] D.B. Montgomery, J. Chen and H. Becker, "Structural Support and Conductor Configurations for CIT", CIT Engineering Report G-870810-PPL-01-ER.

Table I
Scaled Ignitor (Jan, 1989) by 1.76 (linear dimension)

	CIT	DIGNITOR	DIGNITOR (large divertor)	DIGNITOR (small divertor)
Major radius (m)	2.16	2.16	2.16	2.16
Minor radius (m)	0.66	0.78-0.80	0.78-0.80	0.69
Toroidal field (T)	10	12	12	12
Plasma current (MA)	12	18.5	16.4	15.1
Elongation	2(95%)	1.8	1.6(95%)	1.85(95%)
$q (5B_T a^2 \kappa / I_p R)$	1.68	1.64	1.65	1.62
flat top (pulse length) (s)	7	7	7	7
max flat top † (s)	7	20	20	20
TF-plasma gap (m)	0.17	0.081	0.081	0.17
Port size (m × m)	0.37×1.02	0.47×1.4		

† Determined by maximum temperature excursion.

Table II
DIGNITOR PF SYSTEM PARAMETERS

	Large Divertor 16.4 MA	Small Divertor 15.1 MA	Limiter 18.5 MA
Maximum Energy Stored and Dissipated			
Time of Max. Energy (s)	19.3	27.7	19.3
Stored Energy (MJ)	1634	1165	1305
Dissipated Energy (MJ)	2394	1084	1280
Total Energy (MJ)	4028	2250	2585
Max. Stored Energy (MJ)	1634	1421	2430
Max. Dissipated Energy (MJ)	3646	1375	1690
Peak Power			
Time of Peak Power (s)	12.3	20.7	5.4
Magnetic Power (MW)	530	225	615
Resistive Power (MW)	156	70	82
Peak Power (MW)	686	295	605
Flux Swing			
Start-Up Flux (V-s)	35.5	35.5	47.6
EOFT Flux (V-s)	-41.6	-41.6	-43.2

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Major radius (m)	2.16	2.16	2.16	2.16
Minor radius (m)	0.66	0.78-0.80	0.78-0.80	0.69
Toroidal field (T)	10	12	12	12
Plasma current (MA)	12	18.5	16.4	15.1
Elongation	2(95%)	1.8	1.6(95%)	1.85(95%)
q ($5B_T a^2 \kappa / I_p R$)	1.68	1.64	1.65	1.62
flat top (pulse length) (s)	7	7	7	7
max flat top † (s)	5	20	20	20
TF-plasma gap (m)	0.17	0.081	0.081	0.17
Port size (m × m)	0.37×1.02	0.47×1.4		

† Determined by maximum temperature excursion.

Table III
DIGNITOR Stress Levels Evaluated With Respect to Yield

Time	Location	Von Mises Stress (MPa)	Temp (K)	Yield Stress (MPa)	F.S Based on Yield
PRECHARGE	OH I.D. (PF1)	300	58.9	374	1.25
EOFT	TF Nose Equatorial Plane	284	95	367	1.29
EOFT	TF Plasma Side Equatorial Plane	212	167	335	1.58

Table IV
DIGNITOR OH Shears Stress Levels Evaluated With Respect
Shear Carrying Capability

Time	Location	Total Shear (MPa)	Inter-pancake Shear capacity (MPa)
BOFT	T1 Top	12	21.6
BOFT	T1 Mid Height	25.57	46.8
EOFT	T1 Mid Height	29.7	48.3
EOFT	T1 Equator	31	49.8

Table V
Power, energy and temperature for several
DIGNITOR plasmas scenarios

	limiter	large divertor	small divertor	small divertor
Flat top (s)	7	7	7	10
Plasma current (MA)	18.5	16.4	15.1	15.1
PF power (MW)				
pre-start up	650	400	400	400
end of start up	550	650	470	470
PF energy (GJ)	2.6	4.0	1.95	2.5
PF peak temperature (K)	125	360(PF5)	115	155
TF power (MW)	450	450	450	450
TF energy (GJ)	6.2	6.2	6.2	6.9
TF temperature (K)	180	180	180	190

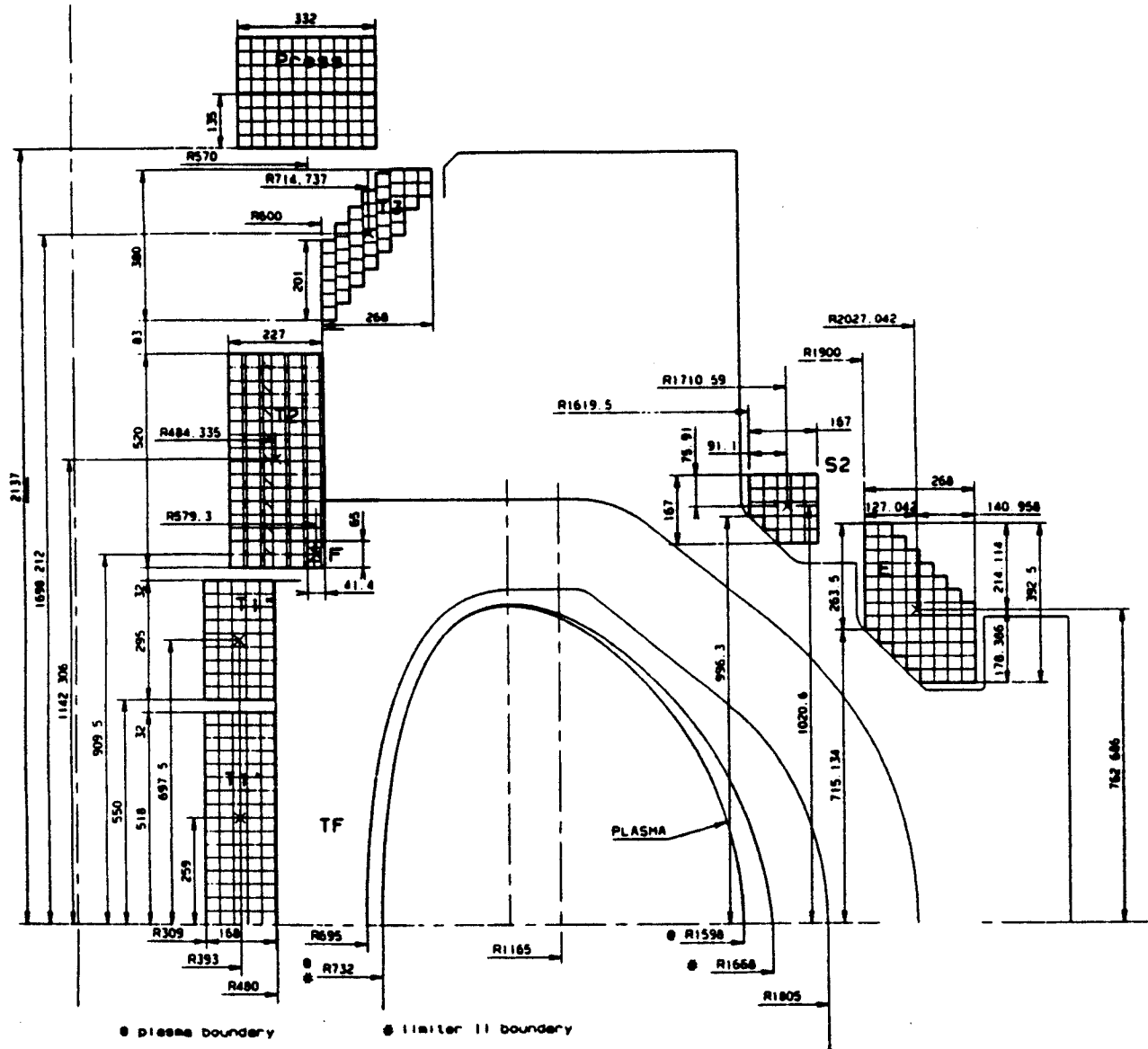


Fig 1 Elevation view of IGNITOR design; from reference [1]

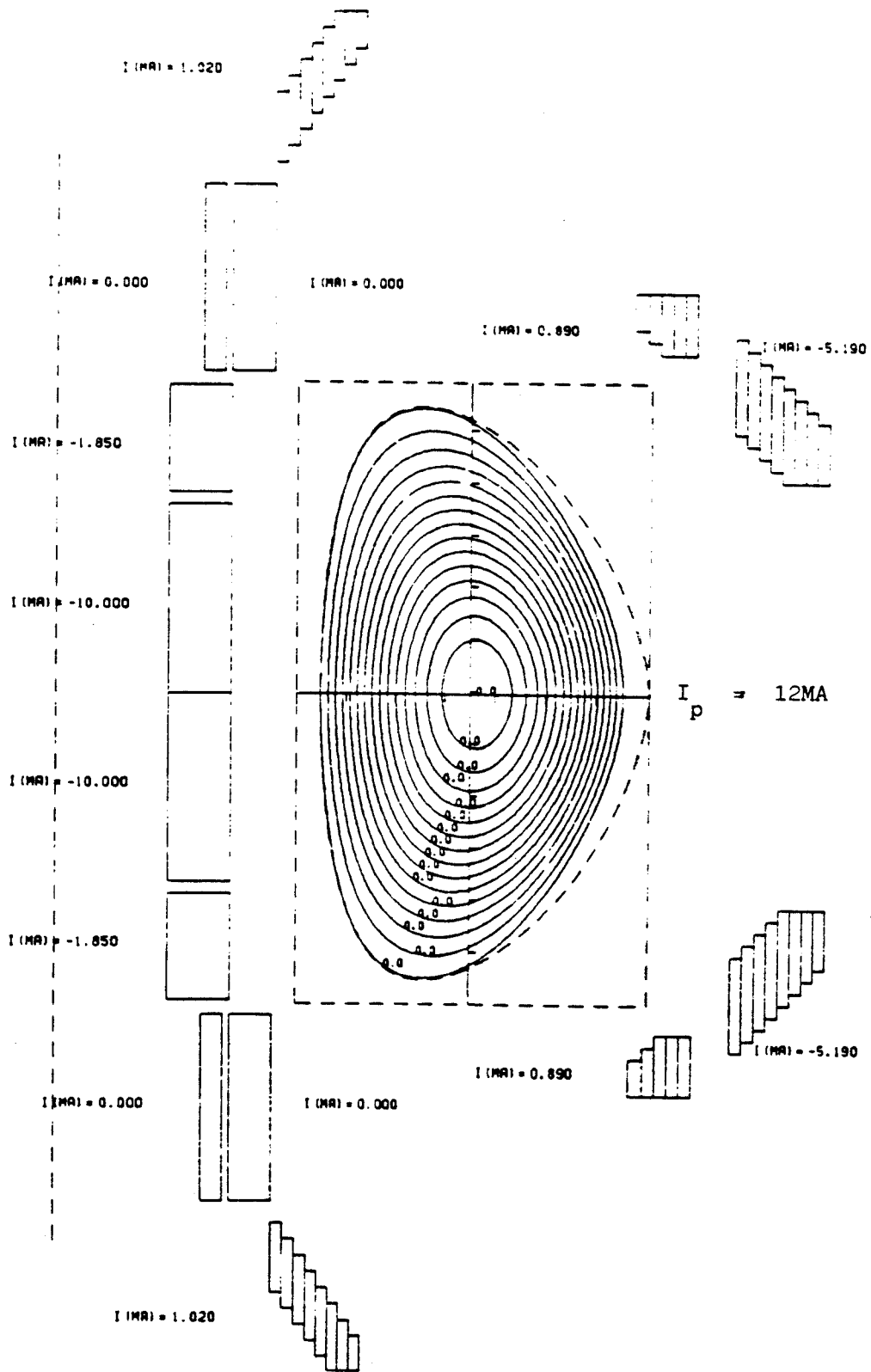


Fig 2 IGNITOR Equilibria, high beta.

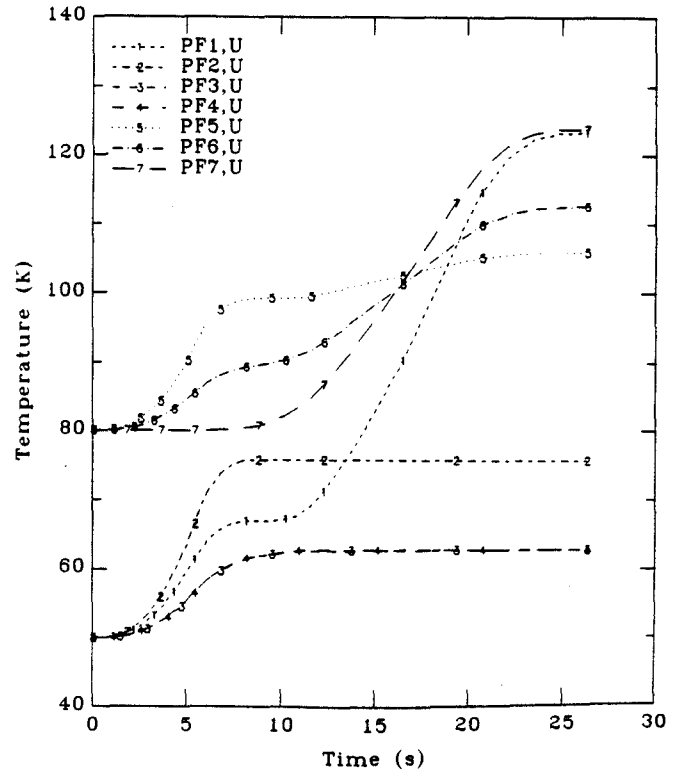
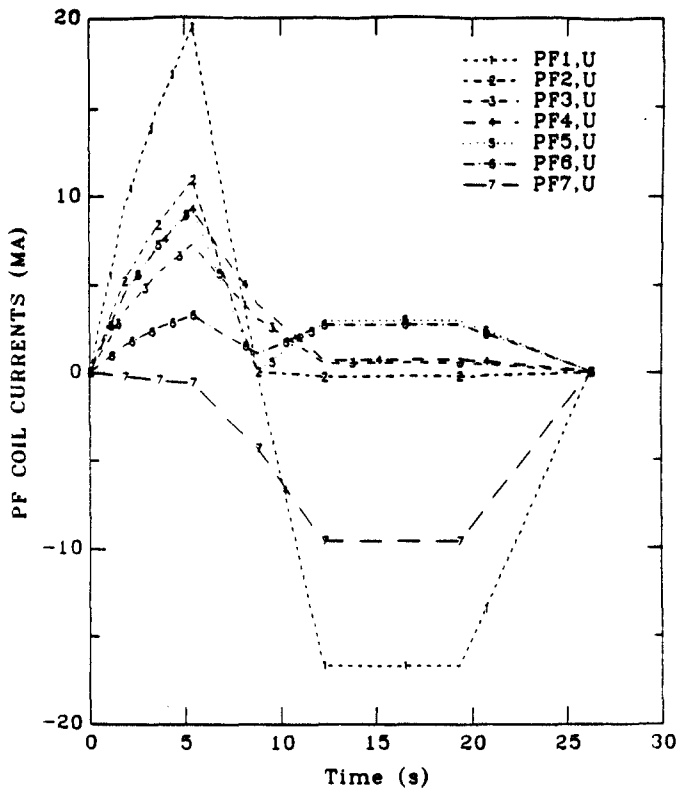
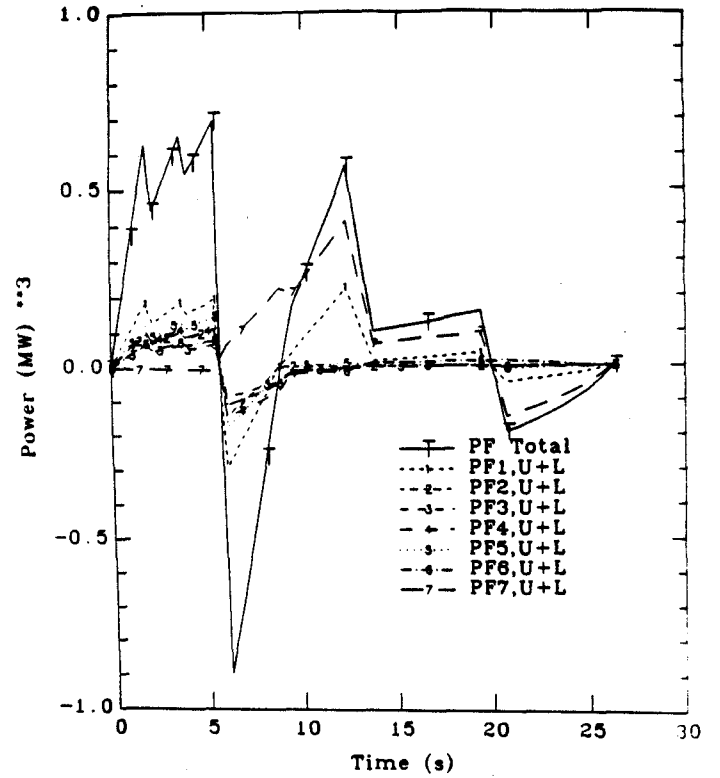
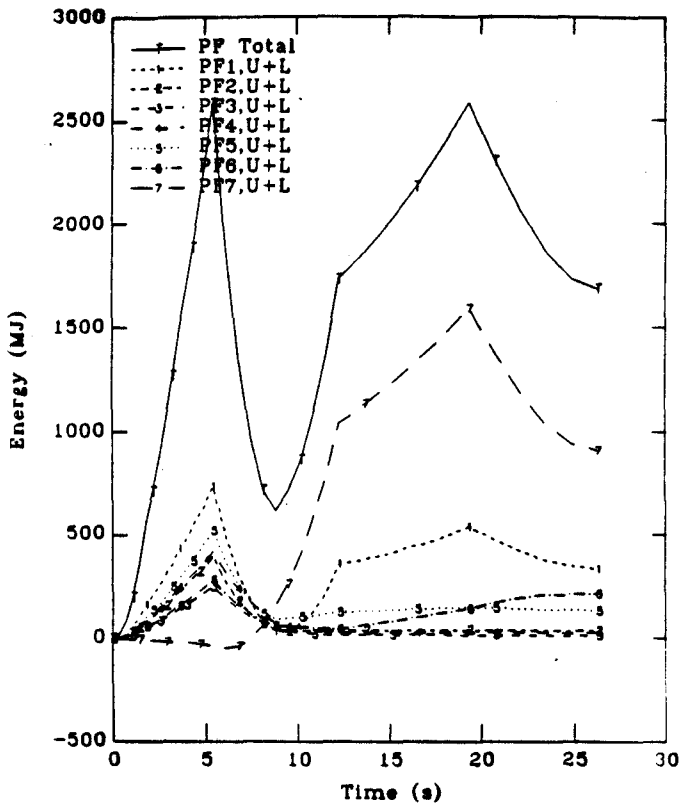


Fig 3 Total energy, total power, coil currents and coil temperature for DIGNITOR. 18.5 MA, high beta.

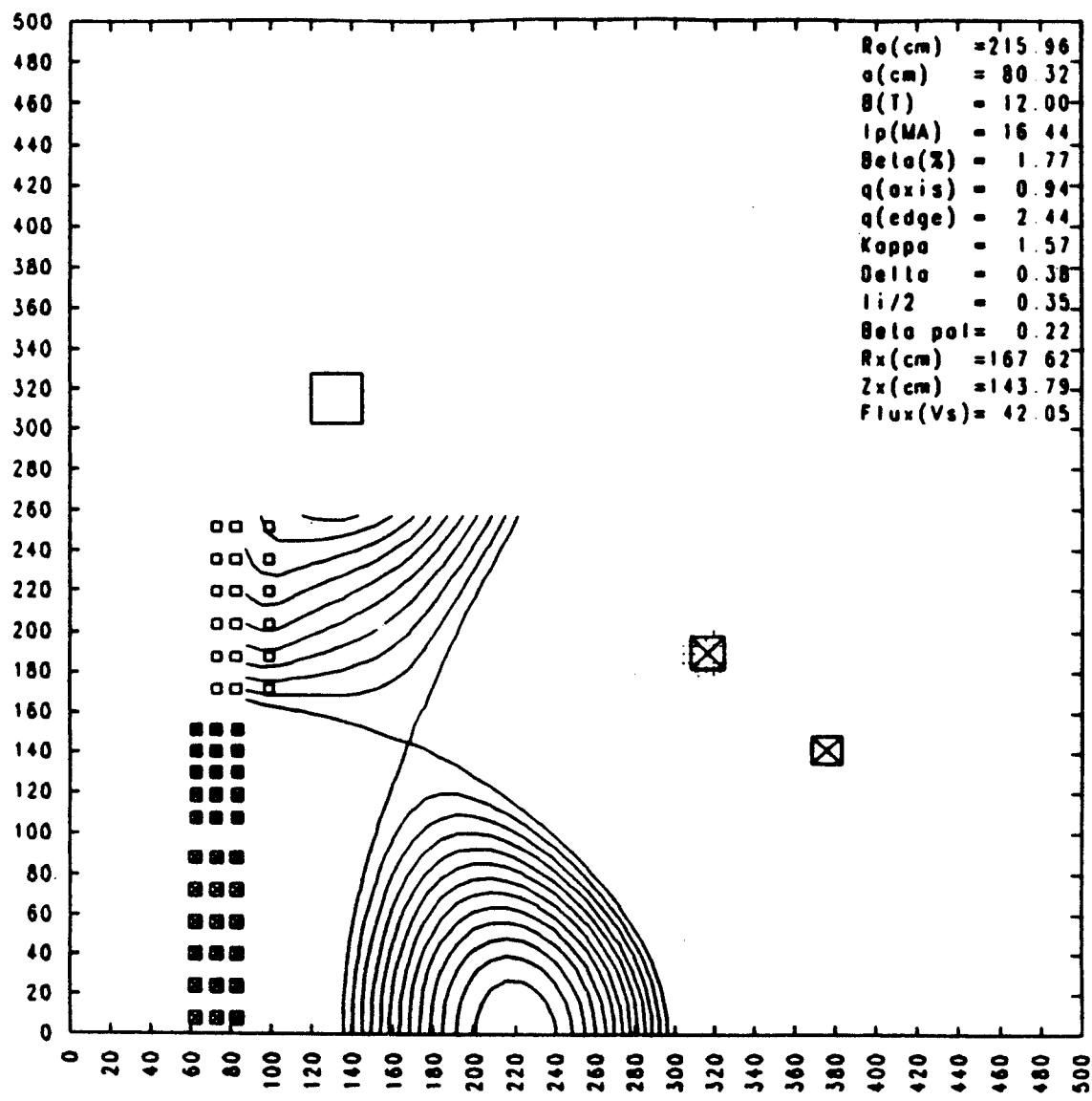


Fig 4 Equilibria for DIGNITOR
with divertor.
16.4 MA plasma current

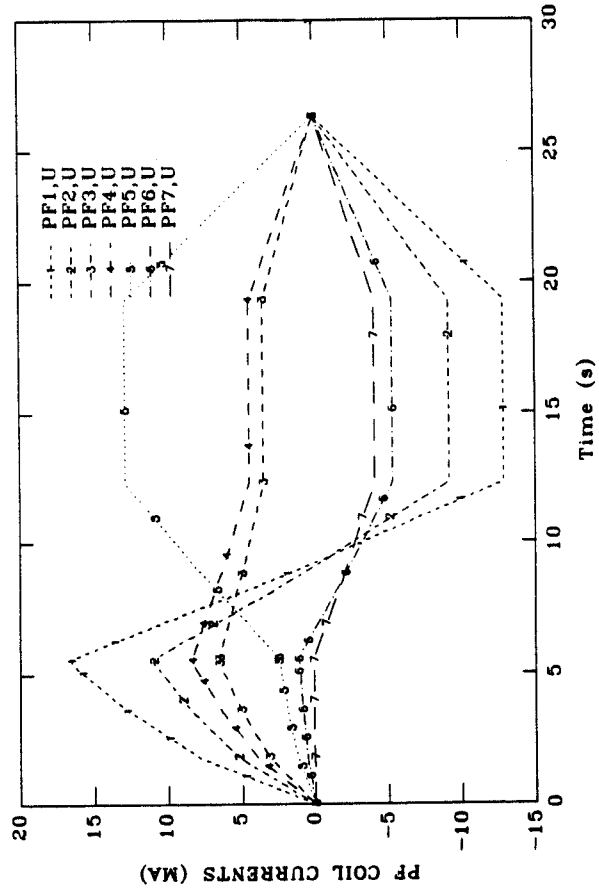
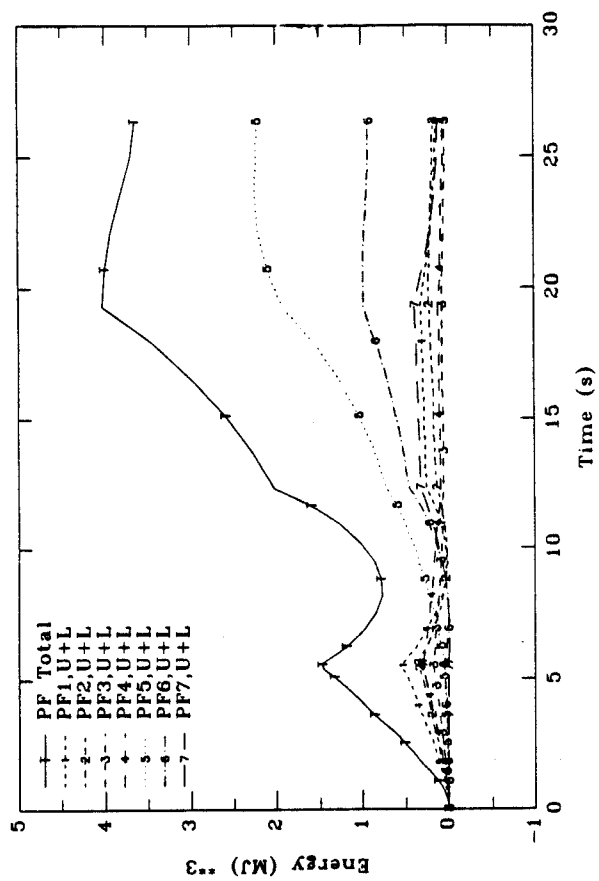
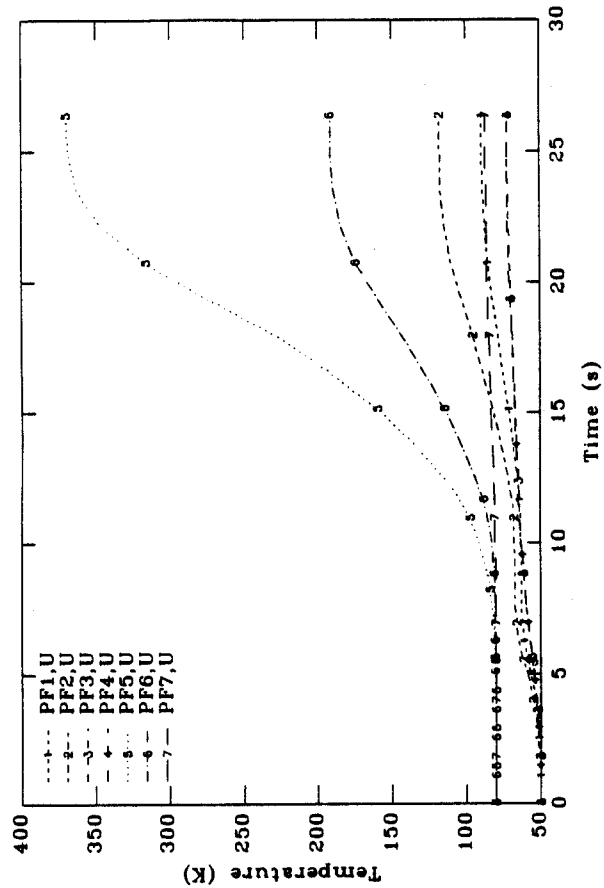
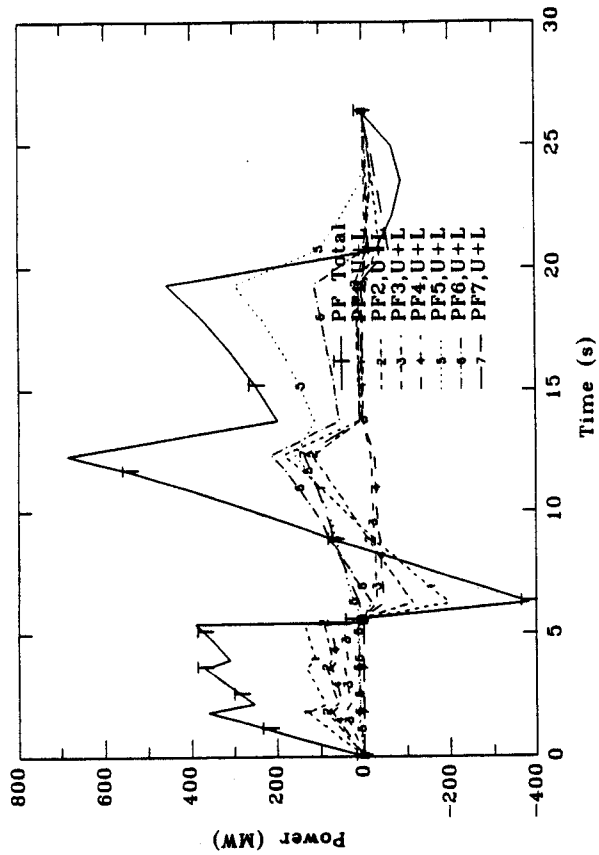


Fig 5 Total energy, total power, coil currents and coil temperatures for large DIGNITOR divertor. 16.4 MA plasma current.

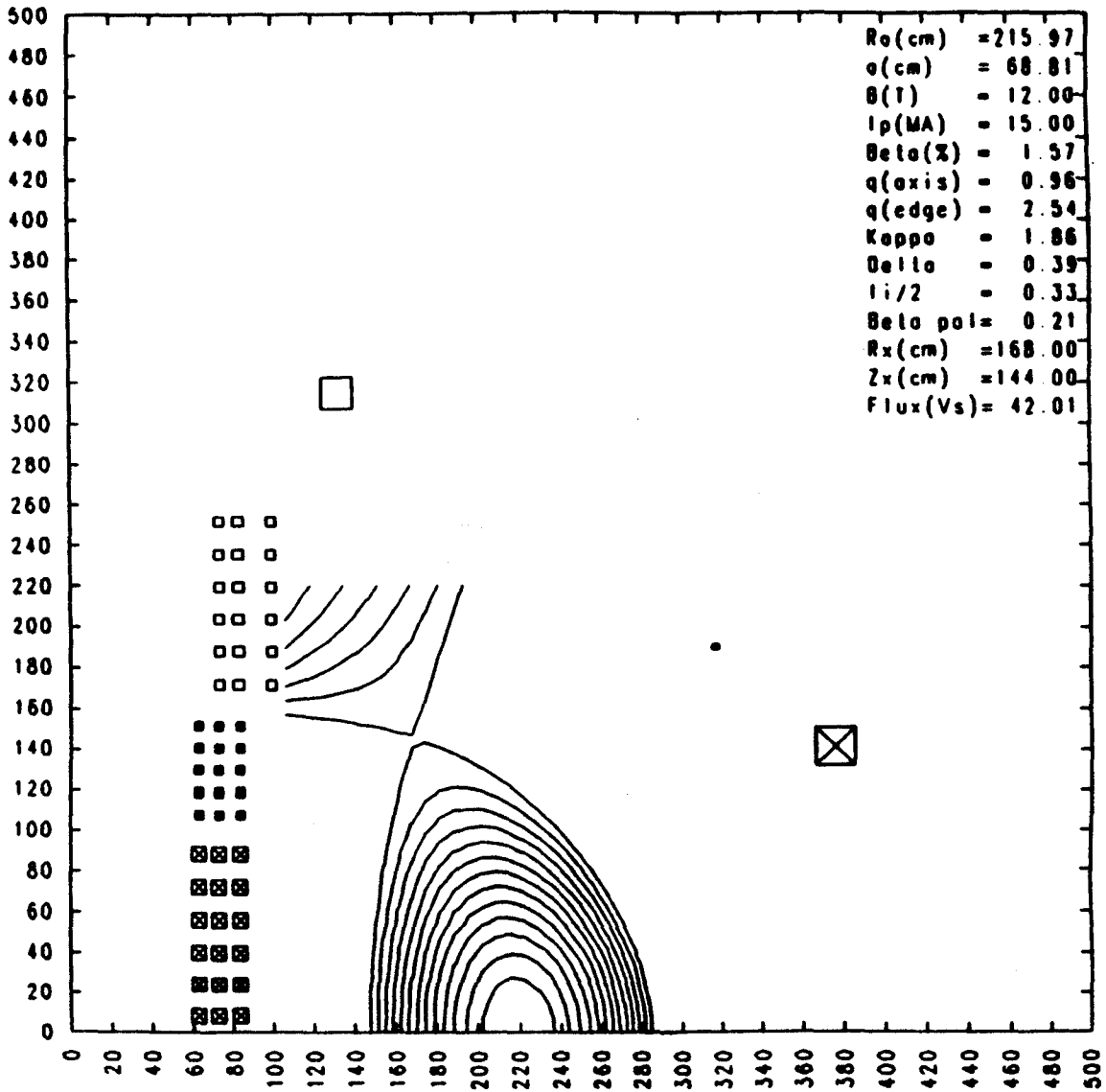


Fig 6 Equilibria for small divertor in DIGNITOR. 15.1 MA plasma current

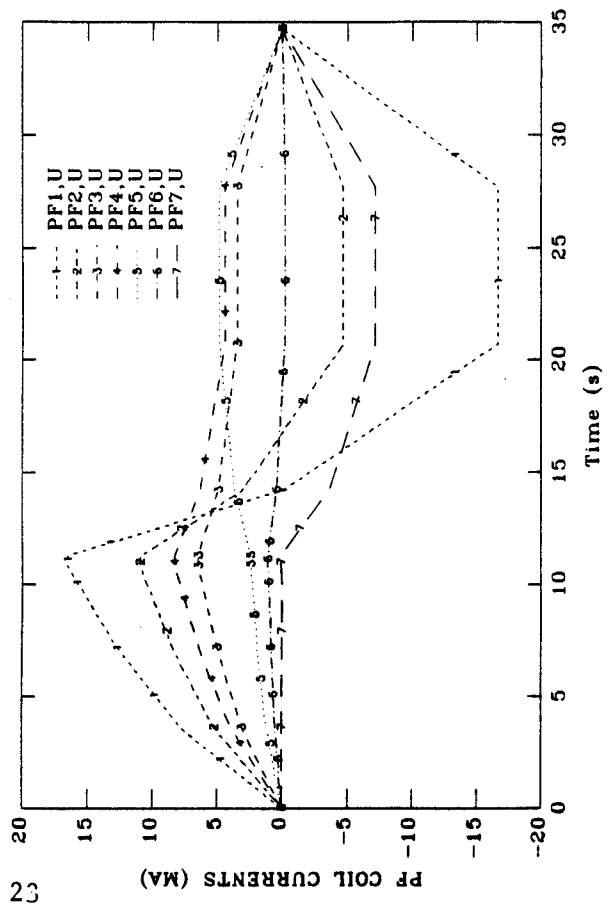
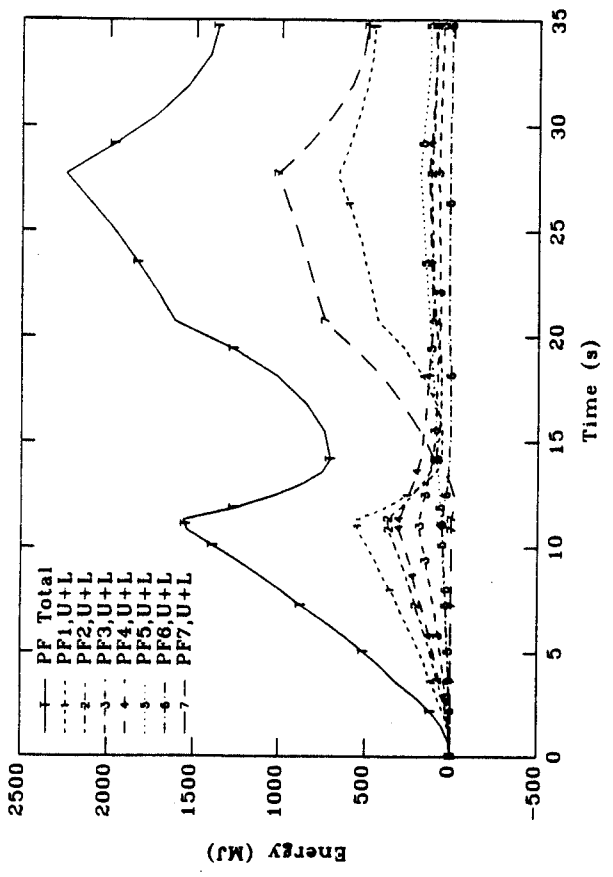
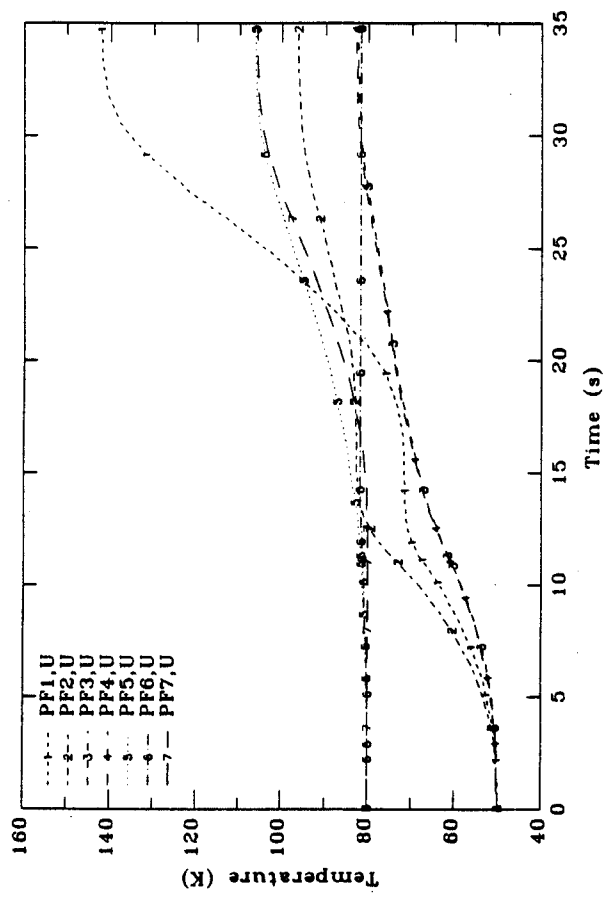
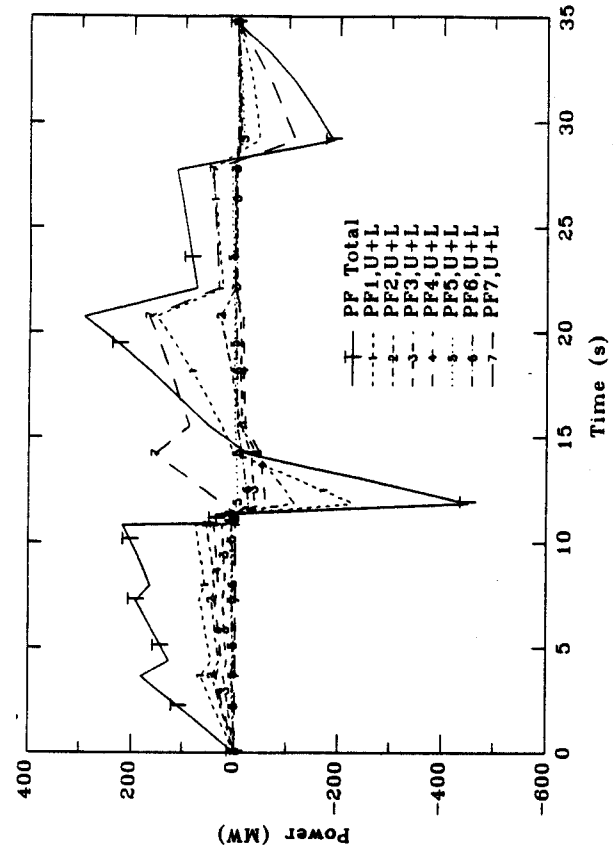


Fig 7 Total energy, total power, coil currents and coil temperatures for small DIGNITOR divertor. 15.1 MA plasma current.

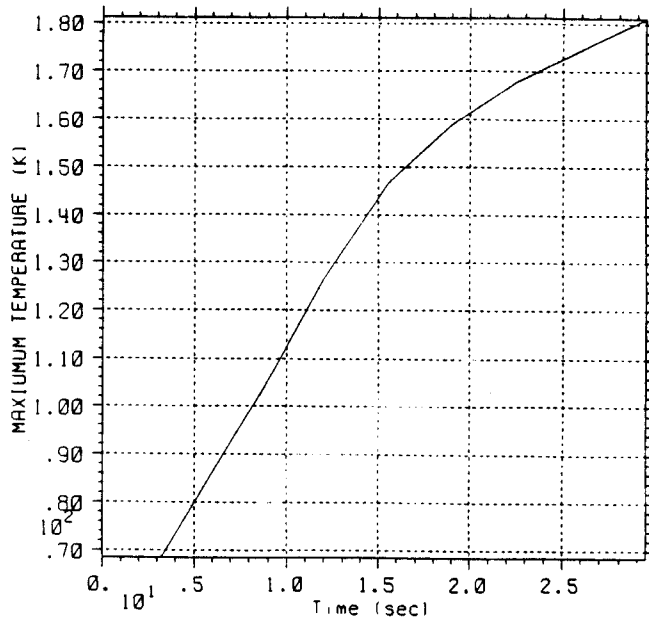
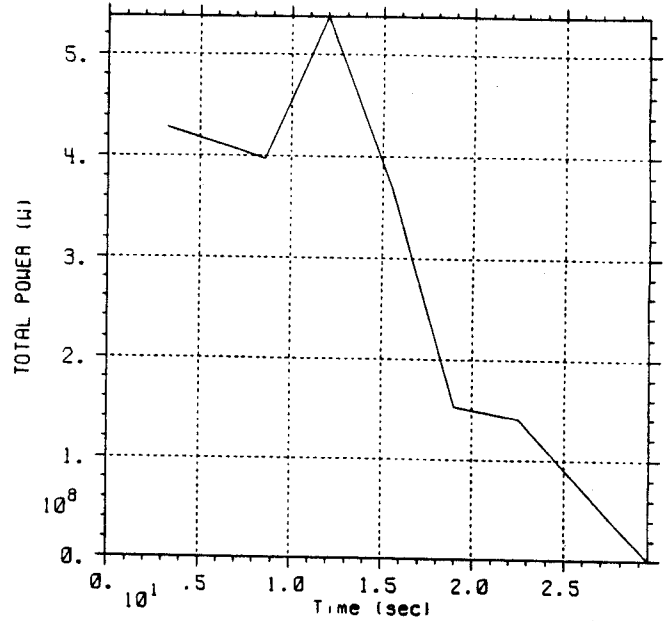
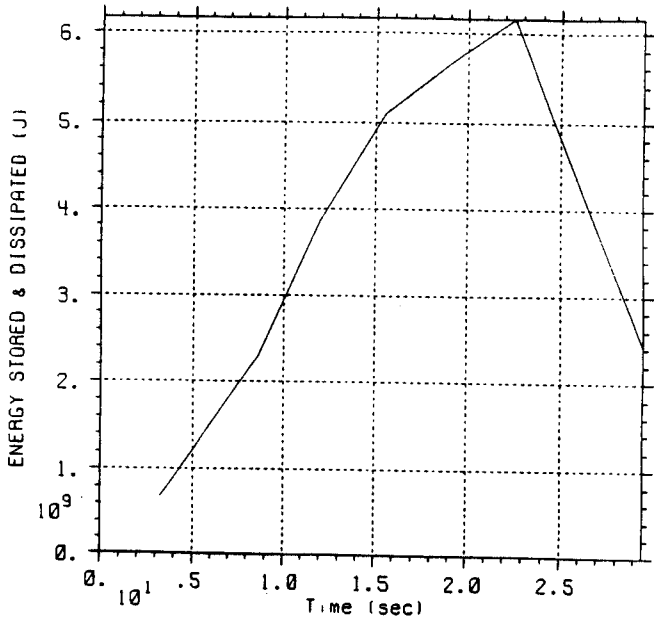


Fig 8 Total energy, total power and maximum temperature of TF coil. 12 T field at 2.1 m.