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CALCULATION OF INDUCED VOLTAGES, CURRENTS, AND FORCES DUE TO PLASMA DISRUPTIONS IN THE TCV TOKAMAK, USING THE TSC CODE

F.B. MARCUS, S.C. JARDIN*, A. PEREZ, G. TONETTI

ABSTRACT

The TSC code has been used to calculate induced voltages, currents, and forces due to plasma disruptions in the TCV tokamak. The following results have been obtained:

1) Induced voltages outside the vessel near the shaping coils may reach 85 volts/turn, due to currents in the vessel.
2) The induced eddy currents in the thermal shield have a distribution $Jz=(-x/2\Pi R\eta)*(dV/dz)$. The integrated current for N sectors is $Iz=-(\Pi RT/4\eta N**2)*(dV/dz)$. This current, crossed with the toroidal field, results in forces which change direction with +-x and +-z. The integrated force in one quadrant on a 1 mm stainless steel shield with N=16 sections is 25 kilograms-force.
3) Inside the vessel, up to 1200 volts/turn at the plasma center are generated during a disruption with the given current disruption rates. This would induce up to 11 Kamps in a single turn, shorted feedback coil in the corner, and induce several hundred volts/turn in its vicinity.
4) With non-symmetric disruptions, the maximum values of induced voltages and currents are similar to the results above, but the spatial and temporal distributions are very different.
5) For a slow vertical disruption, the total vessel vertical force due to induced toroidal currents is about 17 tons.
6) Based on a model proposed for JET by F. Marcus, the estimated vertical force in TCV due to poloidal currents intersecting the wall from the plasma is 20 tons.

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne

*Plasma Physics Laboratory
Princeton University, N.J., U.S.A.

I. INTRODUCTION

Disruptions in TCV may result in both electrical and mechanical damage to coils, conducting elements, and power supplies. In these simulations, an MHD equilibrium is first calculated, then evolved in time. After an initial steady state period, the plasma temperature is dropped, and the plasma current decays with a time constant determined by the plasma ohmic resistivity and the plasma inductance. The time dependent flux and its derivative (x 2Π), the loop voltage, are observed as a function of time. For points inside the vessel, the induced voltage is determined by the plasma disruption rate and by the distance to the vessel wall. For points outside the vessel, the voltage is limited to the product of the local current induced in the wall times the local wall resistance, as well as position. For short-circuited coils, the induced voltage is very small, but the current change is significant.

II. INDUCED VOLTAGES NEAR SHAPING COILS

In Fig. 1, the vessel and coil geometry are shown, along with the position of observation points 1,2,3,4 . The coils and vessel elements are short circuited. The outside 16 shaping coils start with the necessary currents to form a 1200 KA dee-shaped plasma in MHD equilibrium. The outermost plasma surface, initially limited, later diverted, is shown for the evolution of the disruption with time.

In Fig. 2, the plasma current is shown as a function of time. The plasma pressure is maintained constant up to 0.000300 sec, i.e. 0.3 ms, so the plasma current stays constant. From 0.3 to 0.4 ms, the plasma temperature is forced to drop down to 5. eV peak. The plasma current reacts by starting to fall. From 0.4 to 0.75 ms, the plasma current decays from 1200 to 200 KA. During this time, the total vessel current is observed to rise to 1000 KA at the same rate as the plasma current decreases.

The time of thermal quench has been observed, for example in PBX, to be from 50-100 microseconds, as chosen here, but the current disruption rate in other tokamaks is at most 1 MA/ms, compared to the 2 MA/ms chosen here. However, since TCV plasmas may be very unstable, this rate is chosen to give a worst case.

In Figs. 3a, 3b, the voltages at the observation points are shown versus time. The voltages are not uniform, but depend on position. The expected average voltage is the total current times vessel resistance, which is about 50 V. The maximum observed voltage is about 85 V, and for the points at the midplane, the voltage increases on the same time scale as the total vessel current. For points at the top, the voltage reaches its (lower) maximum value in a shorter time, because the plasma initially moves away from the top (see Fig. 1).

In conclusion, voltages outside the vessel are limited because of the vessel, but the absolute values and time behaviour depend on the initial plasma current distribution and evolution. Other voltage distributions would result from different plasma forms, for example, non-symmetric plasmas.

III. EDDY CURRENTS INDUCED IN THE THERMAL SHIELD

The eddy currents induced in the thermal shield result from the attempt of the shield segments to conserve the flux that links them, which is the radial component of the total poloidal flux at the screen locations. To calculate this flux, and the induced eddy currents, we use the following equations:

Coordinates: Radial R, vertical z, along toroidal field x.

Radial field: $B(R) = (1/R) * d\Psi/dz$

Loop voltage: $V = 2\Pi * d\Psi/dt$

E field from flux: curl $E = - dB/dt$

E field and current: $E = \eta J$

To solve these equations, we make the following assumptions:

1) We assume that the shield slab height H is >> the width W, so the x path integral of curl E is << the z path integral.

2) We assume that the slab resistivity is high enough so that the L/R time constant of the slab is much less than that of the vessel, so that the slab has a purely resistive current distribution due to the induced voltage from the vessel.

By substituting J for E, and $d\Psi/dz$ for B, then V for $d\Psi/dt$, and integrating Jz along the current path in the slab, we obtain:

$$Jz = (-x/2\Pi R \eta) * (dV/dz)$$

Integrating over x to obtain the total current, we obtain, for the screen divided into N sectors:

$$Iz = -(\Pi R T / 4 \eta N^{**}2) * (dV/dz)$$

The values for disruption induced voltage as a function of z along the height of the screen are obtained as before from a TSC simulation. In Fig. 4, the geometry of the measurement points at the screen are shown. In Fig. 5, the value of the voltage at 1. msec, that is near the maximum value, is shown versus height. The maximum value of dV/dz = 100 V / m is found. This value will decay with the vessel time constant from its maximum.

As an example, if we take T = 0.001 m of stainless steel with η = 77 x 10**-8 ohm-m, a screen major radius of 0.55m, and a screen divided into N = 16 sectors, then the circulating current reaches about Iz = 220 amps. The force per length, with a local toroidal field of 2.2T, gives an I x B = 500 newtons / m, and for a length of 0.5 m, gives about 250 newtons or 25 kilograms-force of twisting force on this tall, thin slab.

In conclusion, the forces, which depend on the thickness, resistivity, and the square of the number of sectors, can be important and can influence the number of sectors chosen.

IV. DISRUPTION CURRENTS INDUCED IN INTERIOR COILS

As shown in Fig. 6, during these disruptions, the voltage at the plasma axis reaches about 1200 volts per turn. The voltage or current induced in the corner coils inside the vessel depends on their hookup, i.e. separate or in series opposition, and the power supply condition during a disruption, open circuit or short circuit.

As shown in Fig. 7, when the fast response coils inside the vessel are connected as independent and short circuited, the current increases to about 11 KA for a single turn coil at the same rate as the current in the plasma decreases. The current induced is similar to that of a comparable sized vessel element, since the inductances are similar, and the resistance is unimportant on this time scale.

As shown in Fig. 8, the voltages induced 2.5 cm away from the center of the coil can become large, especially during the initial phase when the plasma pressure drops rapidly, causing rapid plasma motion linside the vacuum vessel. Inside the coil, the voltage is limited to the resistive voltage.

V. COMMENTS ON NON-SYMMETRIC DISRUPTIONS

In the above example, the plasma initial equilibrium and disruption evolution are symmetric. However, the values obtained should represent upper limits because:

--The 1200 KA plasma had 600 KA in the upper and lower half, which exceeds the current possible in a less elongated, non-symmetric plasma in each half.

--For points outside the vessel, maximum currents and voltages depend only on the initial position of plasma current inside the vessel, if the disruption is faster than the vessel time. Even if the plasma moves vertically, the vessel conserves the flux outside as it was before the disruption.

However, there are circumstances where the disruption effects could be considerably worse:

--For coils inside the vessel, there is no delay in the arrival of disruption induced voltages, so a plasma going ideally unstable vertically could generate very large voltages at any open-circuited coil.

--If the plasma moved vertically on a time scale slower than the vessel, or disrupted at this rate, larger local currents might be induced, although the voltages would be limited by the slower disruption.

--Only axisymmetic toroidal currents are considered in this simulation.

VI. NUMERICAL CONVERGENCE OF RESULTS

It was initially found that the results were affected by the treatment of the flux at the computational boundary. An improved treatment has effectively removed this problem, leaving only very small spikes on the voltage outside the shell when the plasma inside the vessel undergoes very rapid transitions.

To check numerical convergence, the above results were run with Alfven time enhancement factors of FFAC = 40 and 5. The results shown were very similar in the two cases.

VII. EXAMPLE OF NON-SYMMETRIC DISRUPTION

A non-symmetric disruption has been produced by increasing the current disruption time to 1.0 msec by increasing the electron temperature, and an initial small upwards motion was given to the plasma. The results are shown in Figs 9-13.

In Fig. 9., we see the outermost envelope of the plasma. In Fig. 10, the flux conservation outside the vessel is shown. In Fig. 11, the relative timing for the plasma current and the vertical position of the magnetic axis are shown.

In Fig. 12, samples of the local current density induced in the vacuum vessel are shown. The strongest current is induced in the midplane, similar to the symmetric disruption results. Very different behavior is induced near the top of the vessel, where first the current goes positive, induced by current decrease in the plasma, then goes negative due to repulsion currents induced by the approach of the disrupting plasma.

In Fig. 13, these results are reflected in the local voltages induced just outside the vessel. Much larger voltages are induced near the top of the vessel than previously.

In Fig. 14, the disruption current induced in an internal coil and nearby voltages are shown for a non-symmetric disruption inside the vessel.

VIII. DISRUPTION FORCES ON THE VESSEL FROM TOROIDAL CURRENTS FROM RAPID DISRUPTIONS

In Fig. 15, we consider a disruption in which the vertical motion is faster than the current loss, which is in turn much faster than the inverse of the vessel time constant.

In Fig. 16, we show the vertical forces at 0.260 sec, with 0.84 MA plasma current remaining of the original 1.2 MA, due to induced toroidal currents only. The total force is zero within errors, but there is a strongly non-uniform distribution. Each force is in kilonewtons, calculated for each vessel element with a height (or width) of 2.5 cm.

In Fig. 17, the total forces from toroidal currents at the end of the discharge are shown. The forces are mostly implosion forces at the machine midplane, giving a pressure of about 3 ATM.

IX. DISRUPTION FORCES ON THE VESSEL FROM TOROIDAL CURRENTS FROM SLOW, NON-SYMMETRIC DISRUPTIONS

In Fig. 18, we show a slow disruption where the plasma moves and the current decreases on a time scale comparable to the vessel time constant, about 6 ms. The vertical position has changed considerably before the plasma current starts to fall significantly, which is typically the case for giving the largest net vertical force from a disruption. In Fig. 19, the vertical force around the vessel is shown at time = 2.66 ms, and the total vertical force is only -0.3 kilo-newtons. In Fig. 20, the vertical force around the vessel is shown at time = 5.5 ms, where the total vertical force is 170 kilo-newtons, or about 17 tons.

X. DISRUPTION FORCES ON THE VESSEL FROM POLOIDAL CURRENTS, BOTH SYMMMETRIC AND NON-SYMMETRIC

In the paper "Forces on the JET Vessel During Disruptions and Consequent Operational Limits," by Peter Noll, ANS 1988, Salt Lake City, the problems of poloidal currents induced in the JET vacuum vessel are discussed.

Based on discussions at JET between F. Marcus and P. Noll, a model has been proposed in JET memo PN-MEMO2/mw/TS-PSD/G, Oct. 88, in which F. Marcus suggests that:

i) after the energy quench the flow of poloidal current in the plasma is enforced (J x B = 0).

ii) the plasma resistivity is large so that there is no consservation of toroidal flux in the plasma

iii) the plasma is leaning against the wall in such a way that flux surfaces of the outer plasma zone intersect the walls. A helical current is enforced by the large loop voltage of the current quench and the poloidal current component of the intersected zone is driven through the vessel. This current establishes itself automatically to give plasma vertical force balance. There is no need to postulate a fast vertical plasma movement.

This model used for JET may be used to estimate the forces which could be present in TCV. In a non circular plasma, we have

$$Jtor/Jpol = Btor/Bpol = (a/Rq) * sqrt((1+k**2)/2)$$

which is about = 0.22 in TCV at the plasma edge.

For Itor= 1.2 MA, the average Jtor = Itor/πa**2 is 3.3 x 10**6 A/m**2, give Jpol = 0.73 x 10**6 A/m**2.

Jpol varies with radius, and the total scrape-off thickness intercepting the wall is difficult to estimate in advance. For an estimate, take Ipol/Itor approximately equal to Jpol/Jtor, giving Ipol=0.3 MA, which corresponds to a scrape-off thickness of 0.08 m.

If this current flows only in the top of the vessel, returning through the plasma, the net vertical force is F=IBL, with L = 0.5m and B = 1.43 T, which is about 0.21 x 10**6 Newtons, or about 20 tons.

If the plasma touched the entire length of the inner wall, with L = 1.5 m and B= 2.4 T, then a radially inwards force of about 100 Tons would result. This is directed in the opposite sense to the implosion force.

If the plasma has entirely disappeared, then a symmetric poloidal current will have been induced in the vessel by the disappearing poloidal current in the plasma. This current will be less than the initial plasma poloidal current, since the vessel has a larger area. The resultant force will be radially inwards, since the toroidal field is much smaller at the outer vessel wall than at the inner wall.

FIG. 1. TCV GEOMETRY AND EVOLUTION

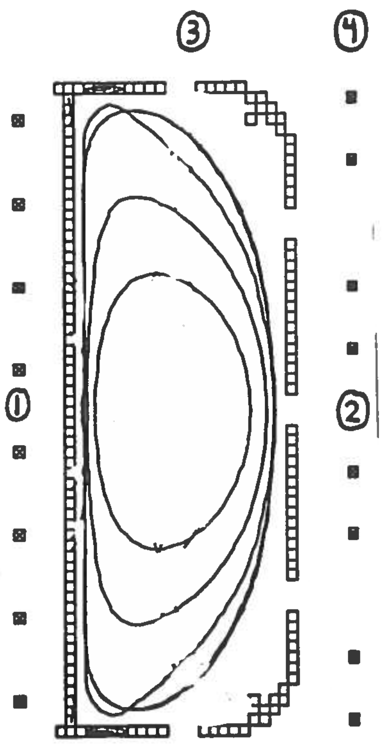


FIG. 2. PLASMA CURRENT VS. TIME

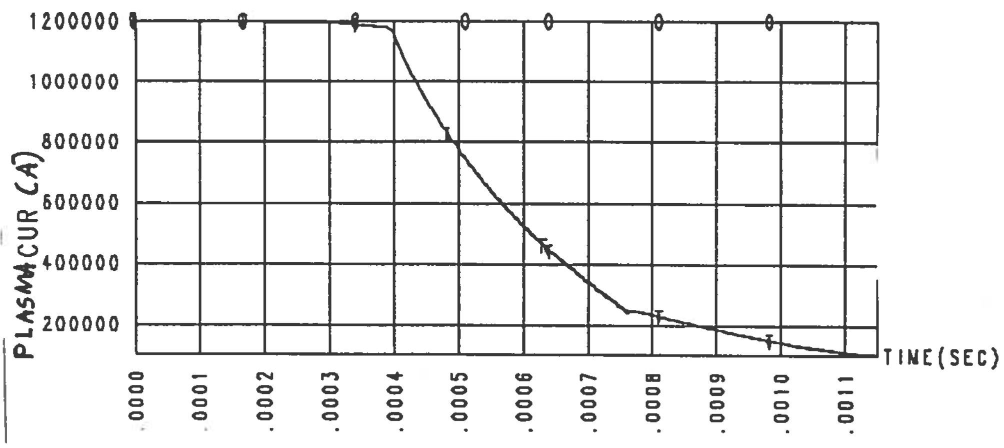
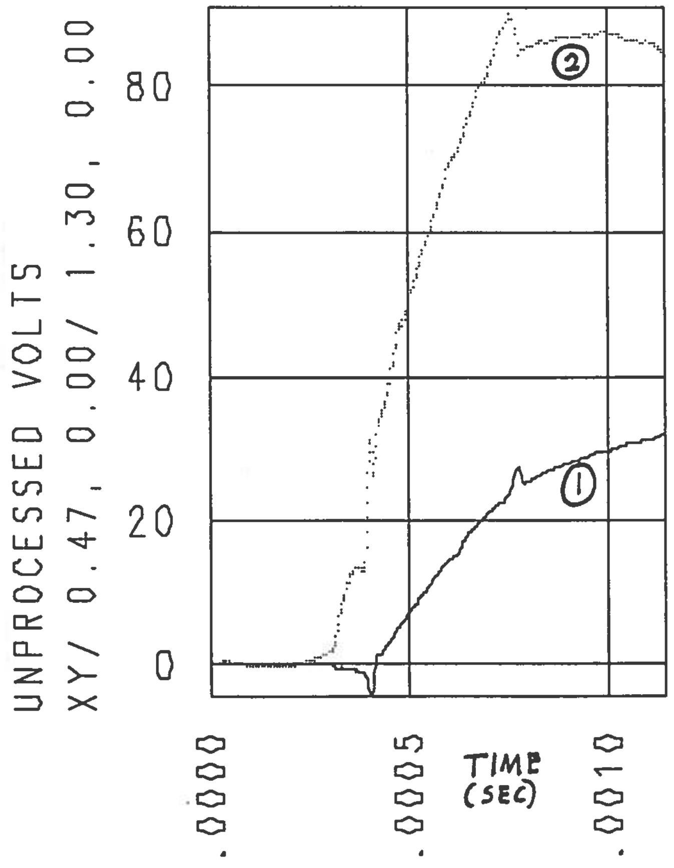


FIG. 3A AND 3B. LOOP VOLTAGE AT OBSERVATION POINTS VS TIME



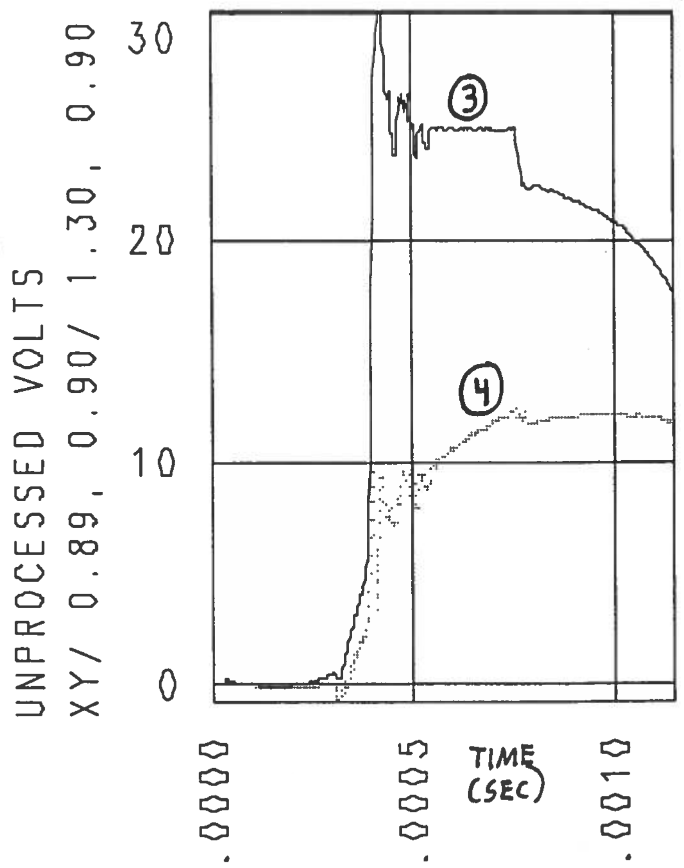


FIG 4. SCREEN GEOMETRY IN TCV

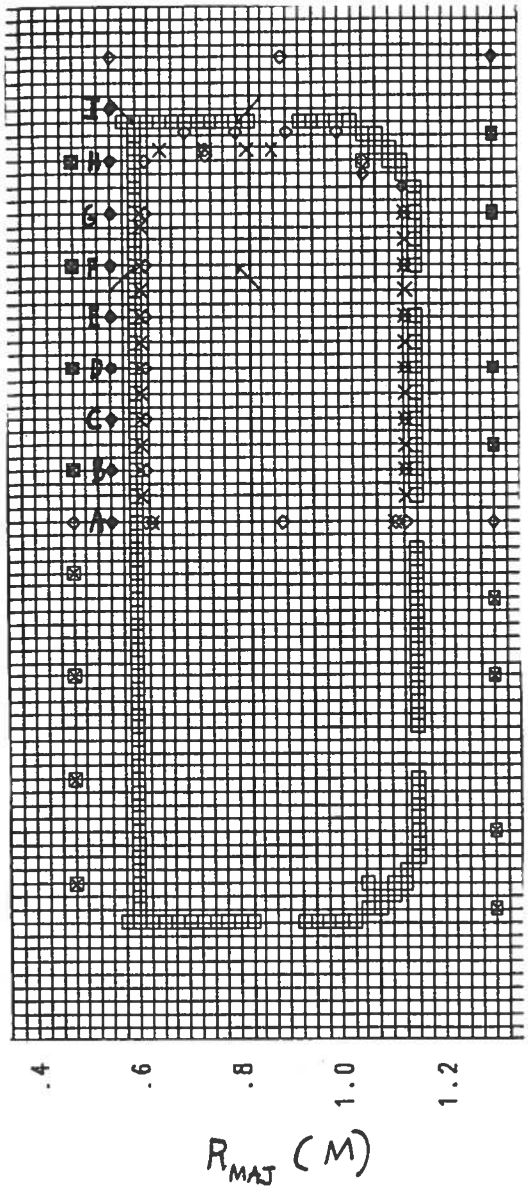


FIG. 5. DISRUPTION VOLTAGE AT 1 MS VS HEIGHT AT SCREEN

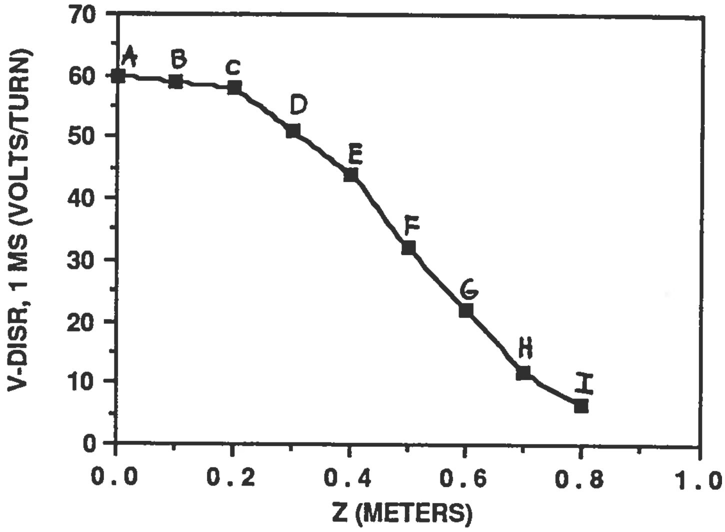


FIG. 6. LOOP VOLTAGE AT PLASMA CENTER DURING DISRUPTION

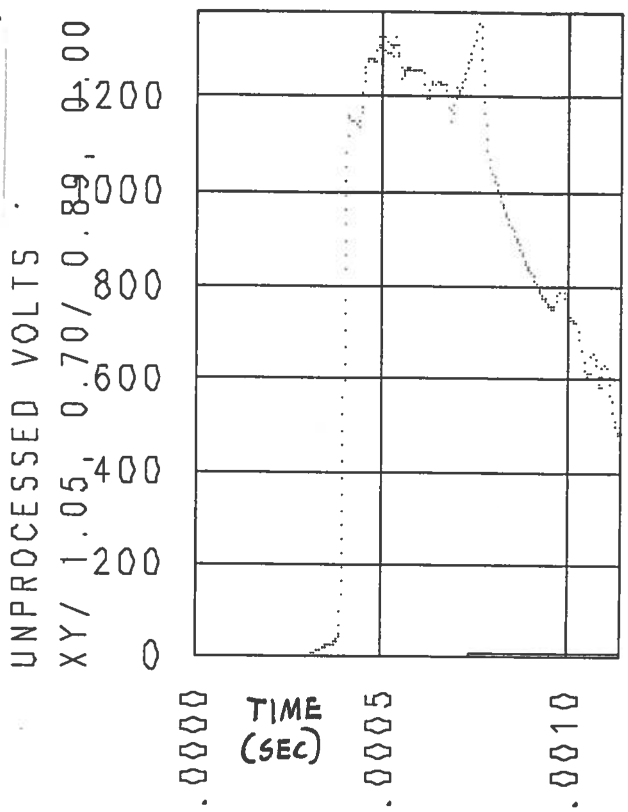


FIG. 7. CURRENT INDUCED IN FAST RESPONSE COIL INSIDE VESSEL DURING A PLASMA DISRUPTION

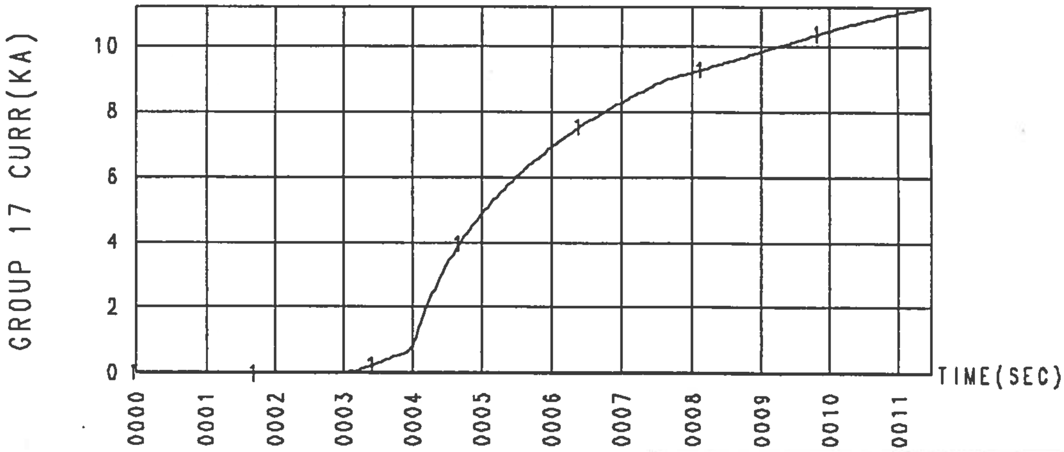


FIG. 8. INDUCED VOLTAGE INSIDE RAPID RESPONSE COIL AND AT 2.5 CM BELOW COIL CENTER

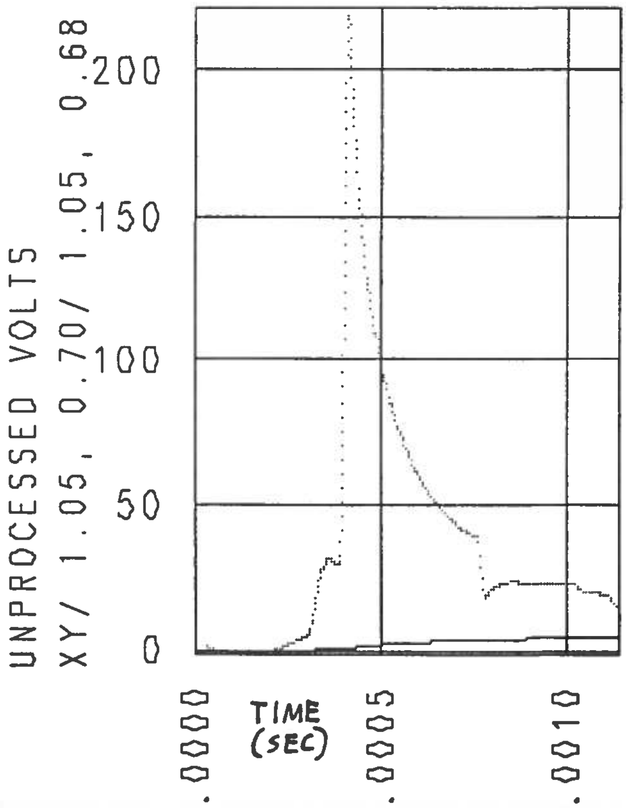


FIG 9. NON-SYMMETRIC PLASMA DISRUPTION IN TCV. CURRENT IS LOST IN 1.0 MSEC. VERTICAL GROWTH RATE IS 5000 SEC-1. NOTE THAT INNER WALL MOVED BY 2.5 CM AWAY FROM PLASMA. THE OUTER FLUX SURFACES ARE SHOWN FOR DIFFERENT TIMES.

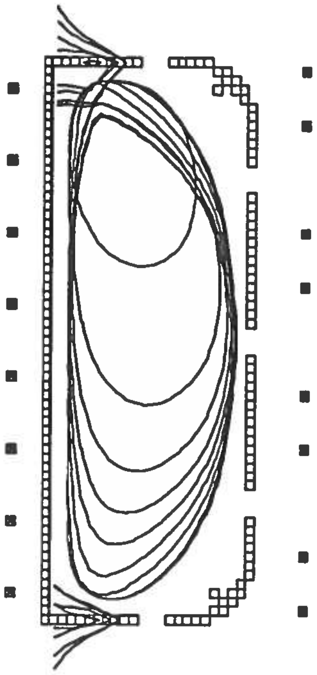


FIG. 10. MHD EQUILIBRIA AT BEGINNING AND NEAR END OF DISRUPTION. NOTE THAT FLUX SURFACES OUTSIDE THE VESSEL ARE NEARLY UNCHANGED, SINCE THE DISRUPTION TIME IS MUCH LESS THAN THE VESSEL TIME.

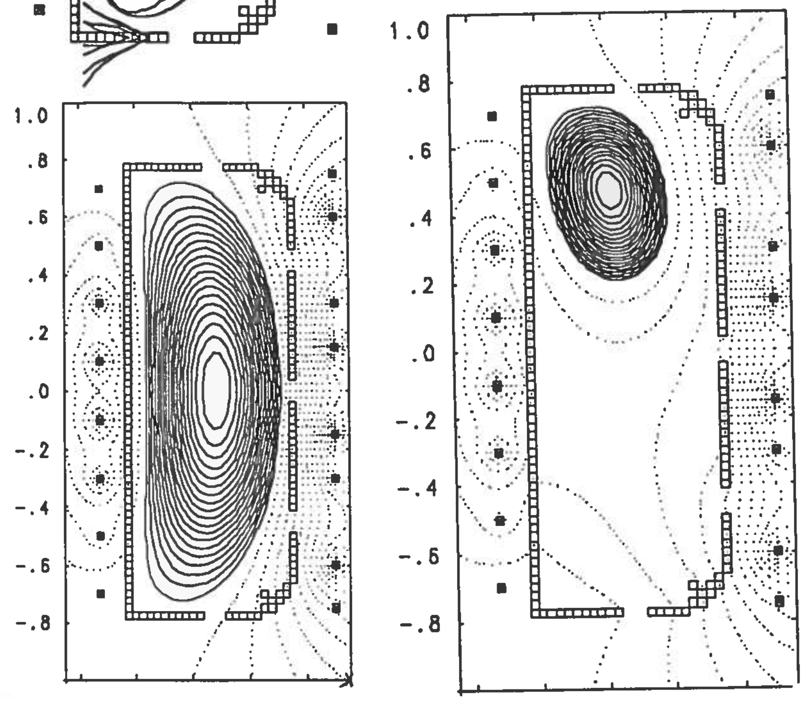


FIG. 11. IN THIS CASE, ABOUT HALF THE PLASMA CURRENT IS LOST BY THE TIME THE VERTICAL POSITION OF THE MAGNETIC AXIS Z MOVES UPWARDS SIGNIFICANTLY. ALL OF THE PLASMA CURRENT OF 1.2 MAMPS IS LOST AT 1.0 MSECS.

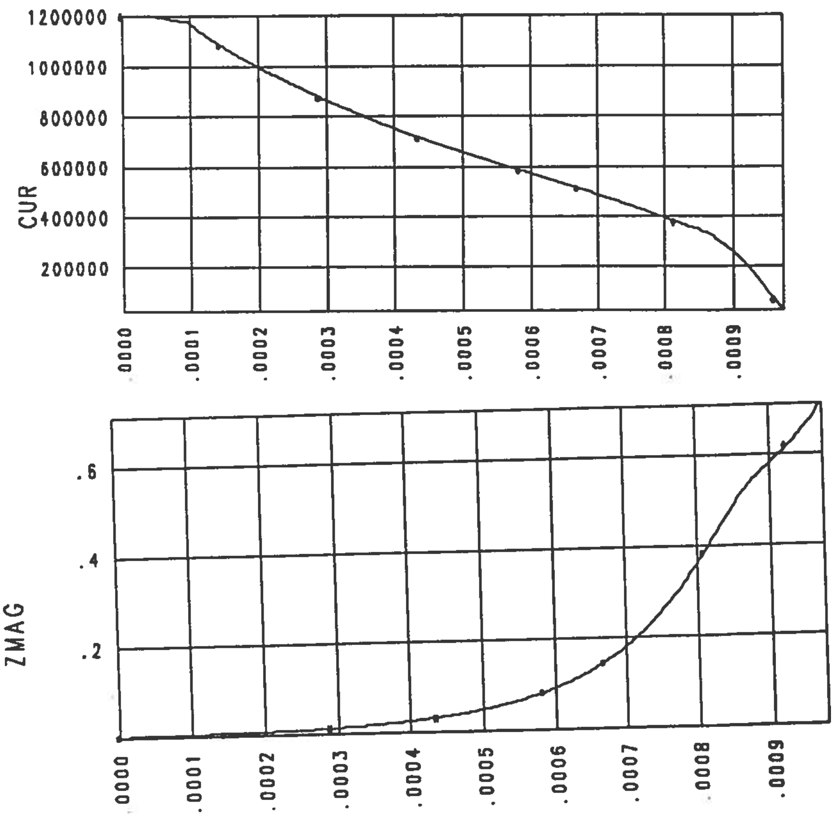


FIG. 12 TIME-DEPENDENT CURRENTS, INDUCED IN VACUUM VESSEL SEGMENTS 2.5 CM LONG, BY NON-SYMMETRIC DISRUPTION OF 1200 KAMPS LASTING 1.0 MSECS. AT MIDPLANE AND BOTTOM, POSITIVE CURRENTS ARE INDUCED BY PLASMA CURRENT DECREASING AND MOVING AWAY. ON THE TOP, REPELLING CURRENTS ARE ALSO INDUCED.

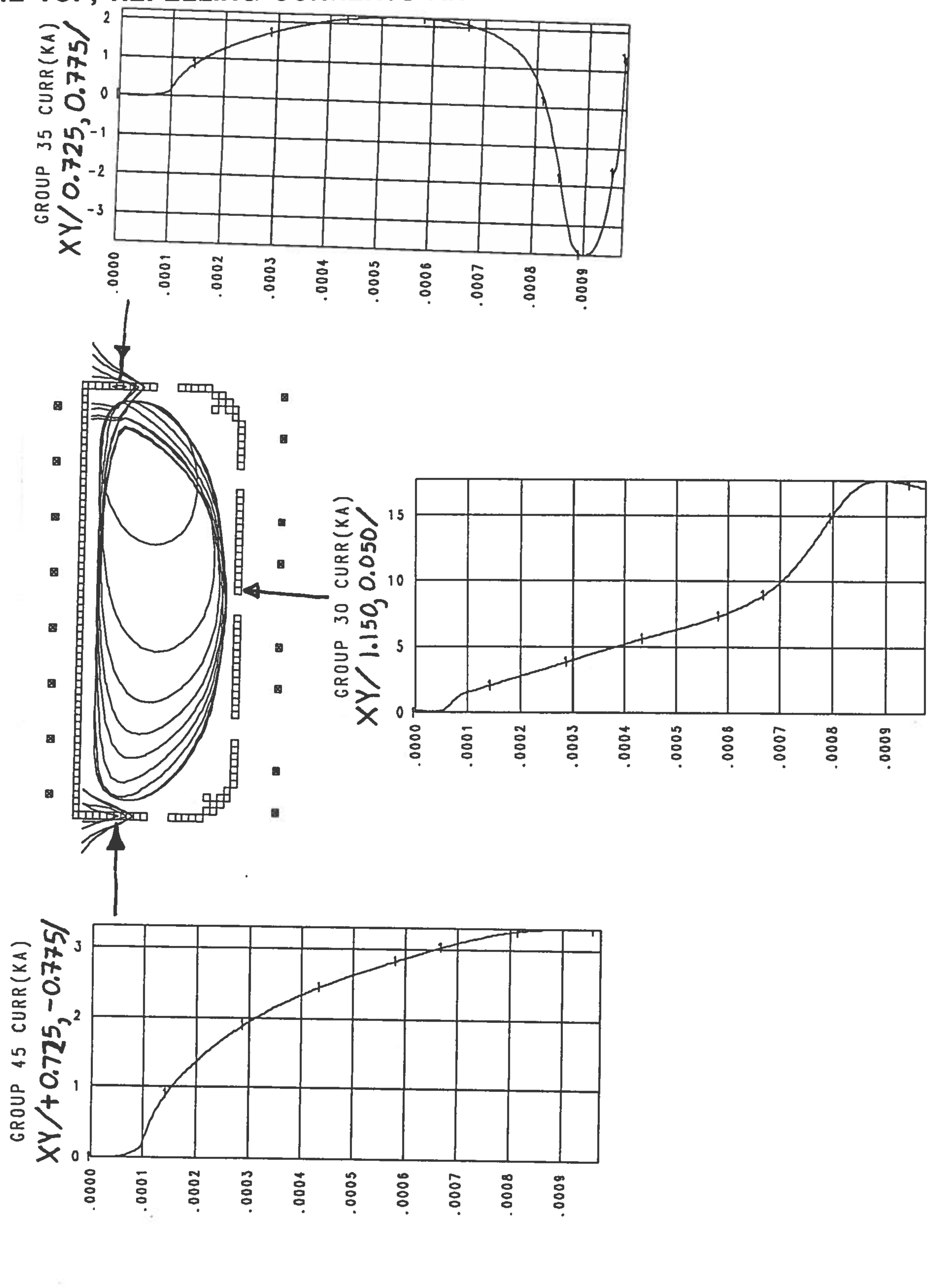


FIG. 13 INDUCED VOLTAGES OUTSIDE THE VESSEL BY THE DISRUPTION ARE SIMILAR TO THE SYMMETRIC DISRUPTION RESULTS FOR POINTS NEAR THE MIDPLANE. FOR POINTS ABOVE THE VESSEL, VOLTAGES ARE MUCH LARGER, ESPECIALLY NEAR THE AXISYMMETRIC GAP.

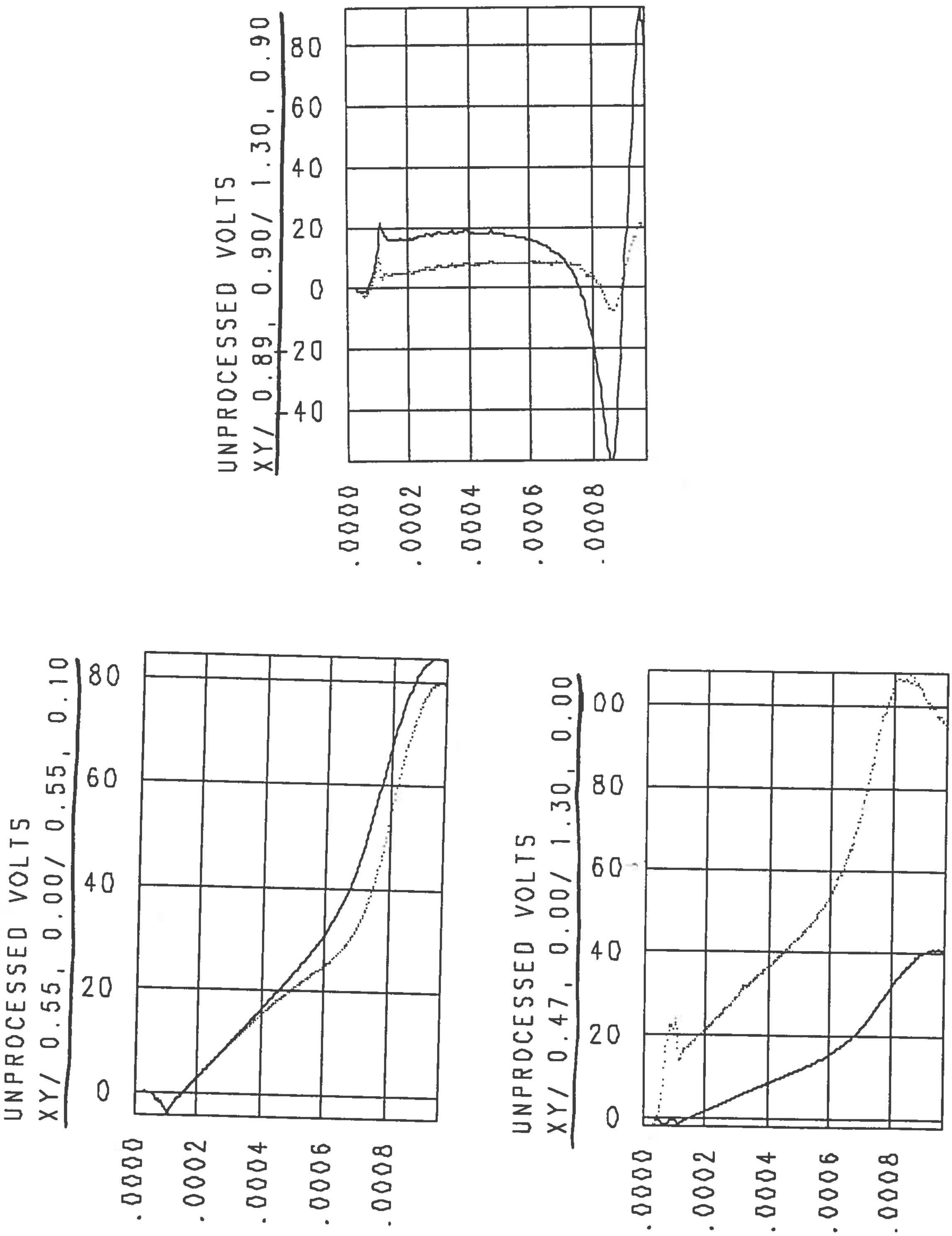


FIG 14 DISRUPTION-INDUCED CURRENTS, VOLTAGES

--IDEALLY STABLE EQUILIBRIA CAN BE STABILIZED BY RAPID COILS INSIDE THE VESSEL

--IN THE ABSENCE OF THIS CONTROL, THE PLASMA GOES VERTICALLY UNSTABLE, AND CAN INDUCE LARGE CURRENTS OR VOLTAGES AT THESE COILS

--BELOW IS AN EXAMPLE OF A PLASMA WHICH DISRUPTS. THE FEEDBACK IS OFF, AND THE PLASMA TE IS DROPPED TO 10 EV TO SIMULATE A DISRUPTION.

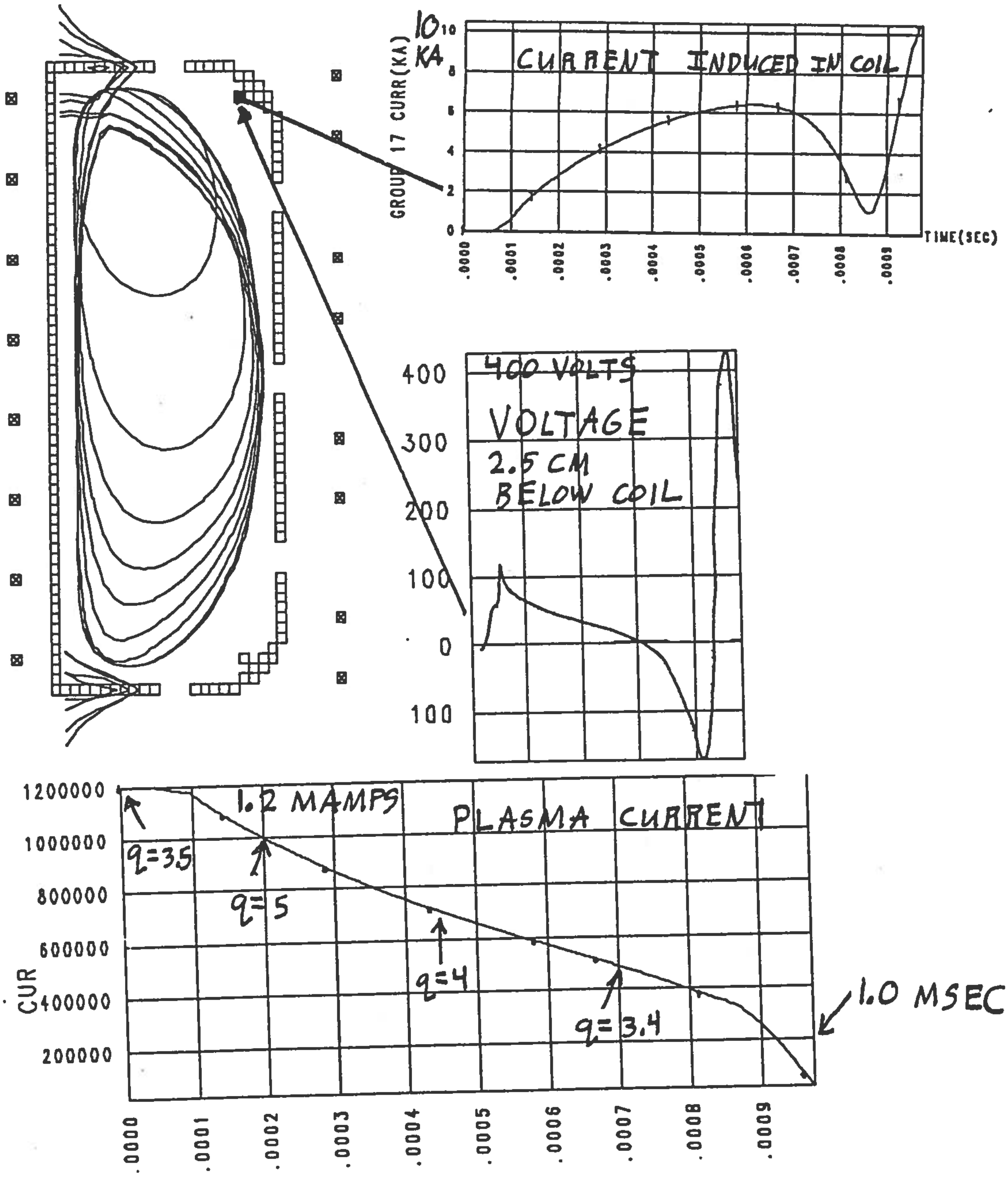


FIG. 15. DISRUPTION FORCES ON VESSEL

--AS DISCUSSED PREVIOUSLY BY P. NOLL FOR JET RESULTS, VESSEL FORCES RESULT FROM:

1) TOROIDAL CURRENTS INDUCED IN VESSEL

2) AN ADDITIONAL FORCE, FOR EXAMPLE, FROM INDUCED POLOIDAL CURRENTS

--HERE WE GIVE AN EXAMPLE OF A NON-SYMMETRIC DISRUPTION WHERE THE VERTICAL MOTION IS FASTER THAN CURRENT LOSS.

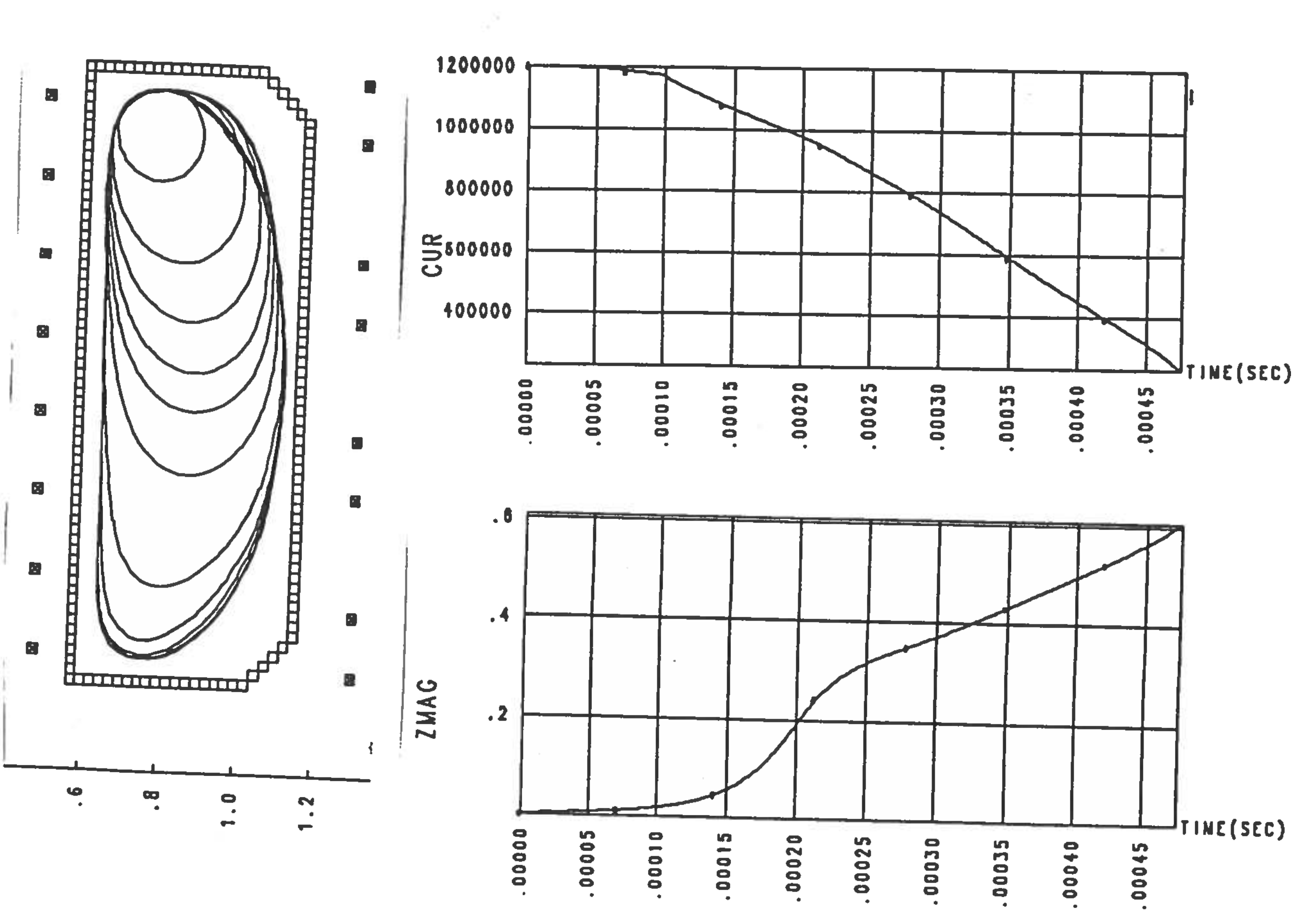


FIG. 16 VERTICAL FORCES AT 0.260 SEC, WITH 0.84 MA PLASMA CURRENT REMAINING OF ORIGINAL 1.20 MA, DUE TO INDUCED TOROIDAL CURRENTS ONLY

--TOTAL FORCE IS ZERO WITHIN ERRORS, BUT STRONGLY NON-UNIFORM DISTRIBUTION

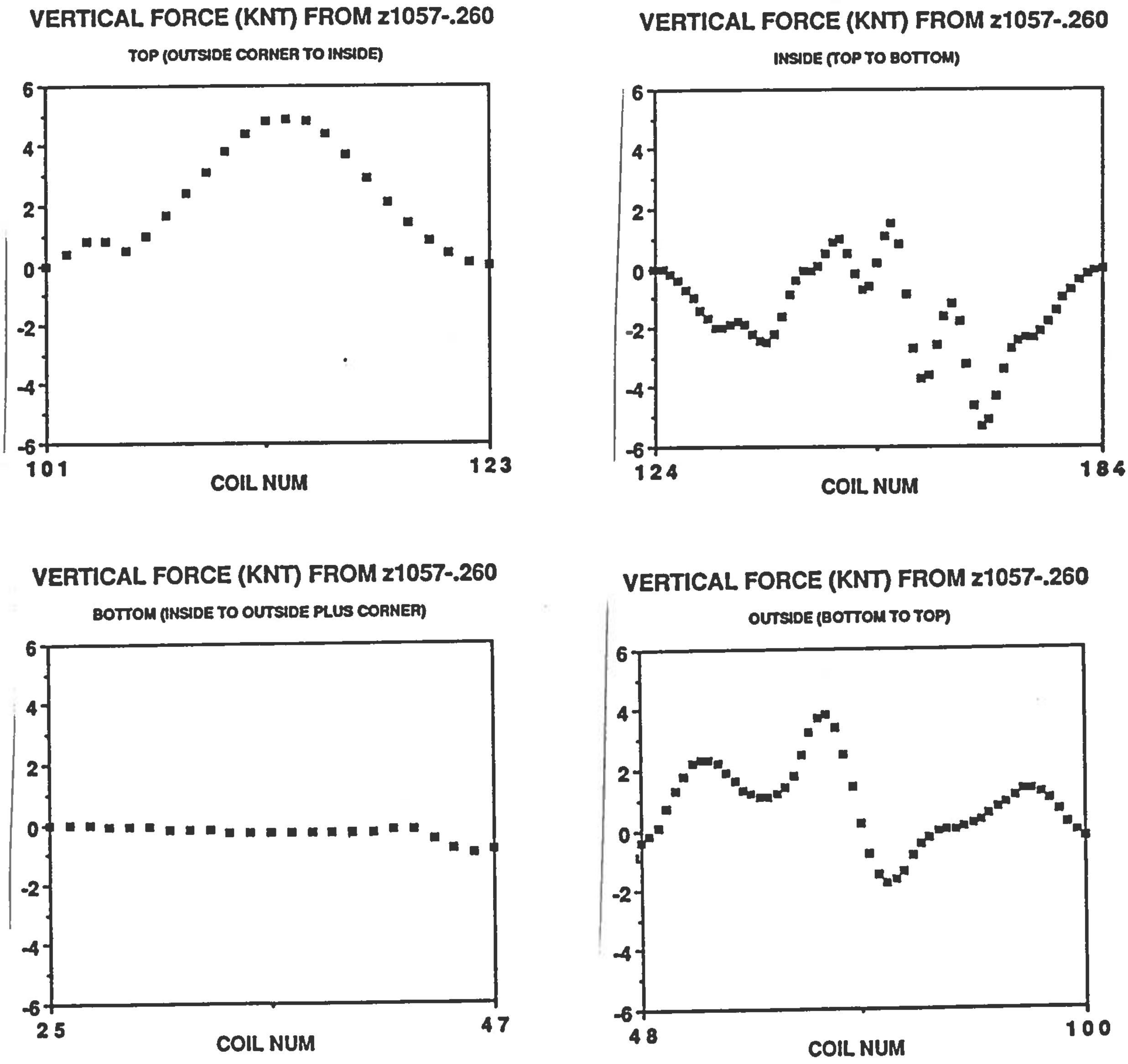


FIG. 17. TOTAL FORCES FROM TOROIDAL CURENTS AT END OF DISCHARGE

--THE FORCES ARE MOSTLY IMPLOSION FORCES AT THE MACHINE MIDPLANE, GIVING A PRESSURE OF ABOUT 3 ATM

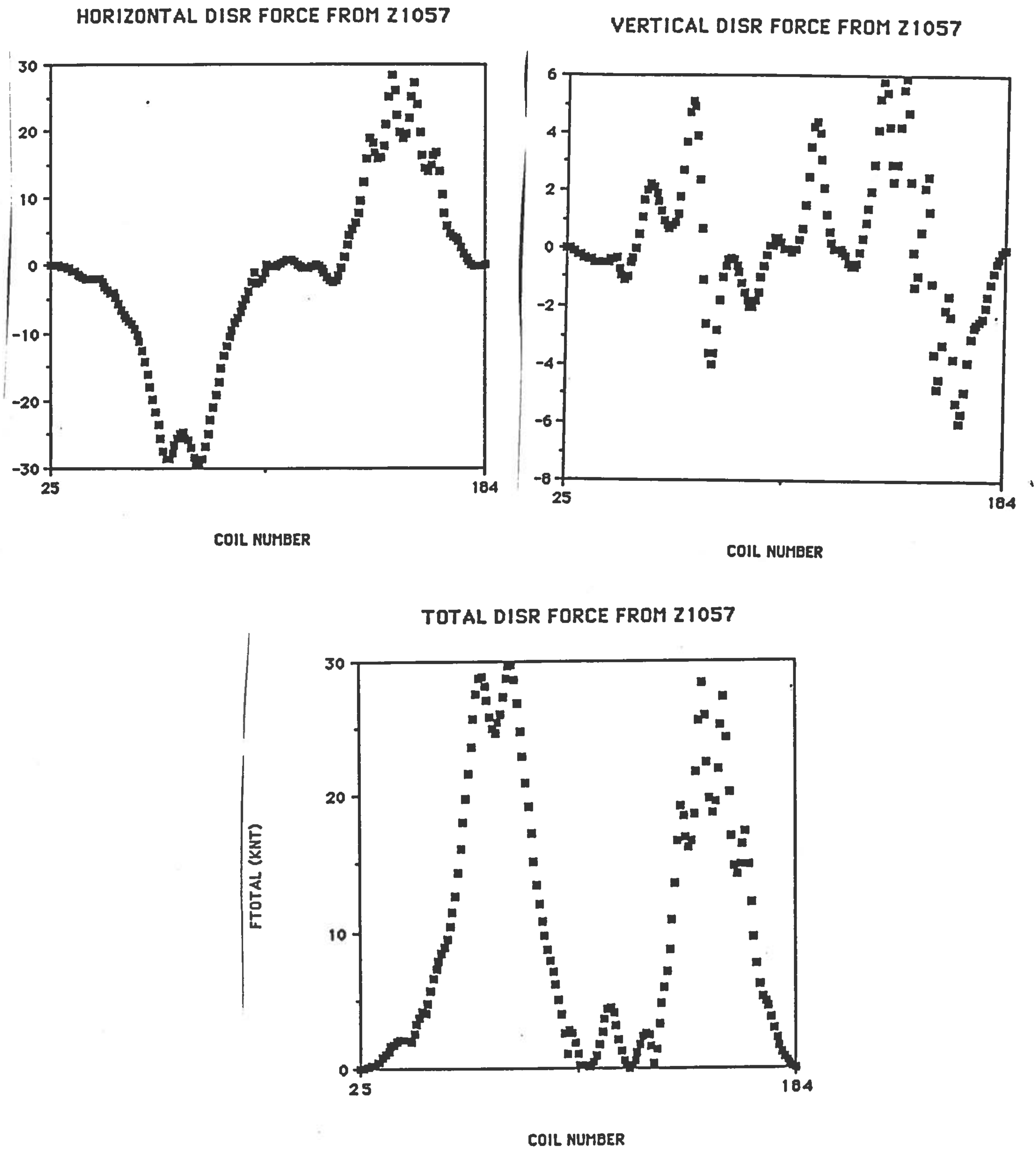


FIG. 18. SLOW, NON-SYMMETRIC DISRUPTION IN WHICH THE PLASMA MOVES AND THE CURRENT DECREASES ON A TIME SCALE COMPARABLE TO THE VESSEL TIME CONSTANT

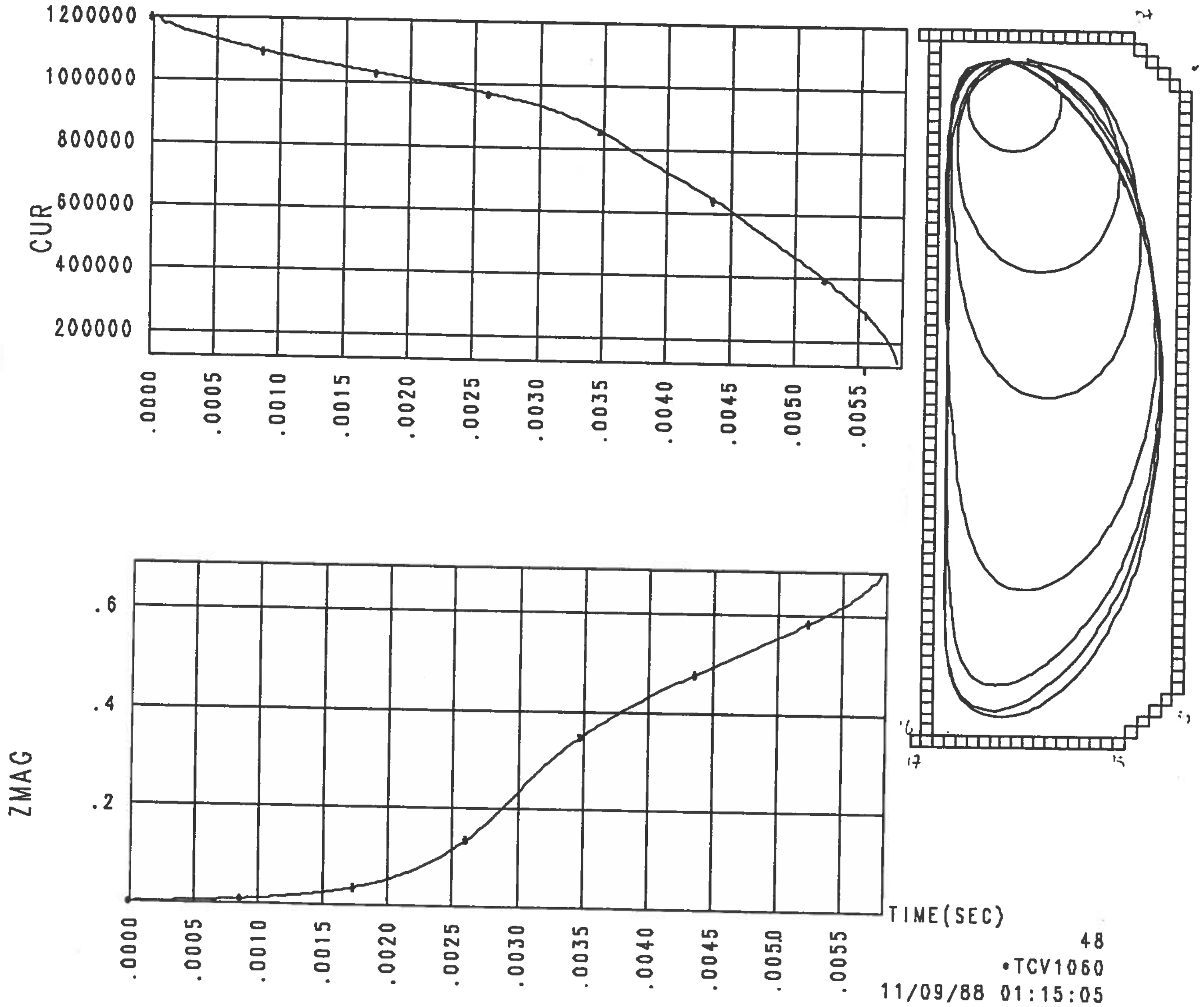


FIG. 19. VERTICAL FORCE AROUND THE VACUUM VESSEL FOR SLOW, NON-SYMMETRIC DISRUPTION AT TIME 2.66 MSEC. THE TOTAL NET VERTICAL FORCE IS ONLY -0.3 KILONEWTONS

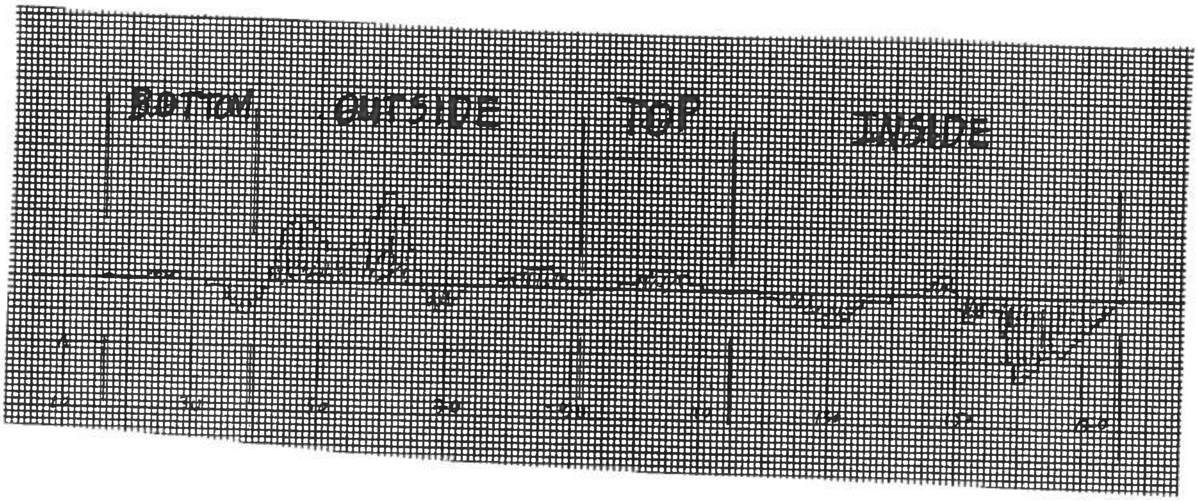


FIG. 20. VERTICAL FORCE AROUND THE VACUUM VESSEL FOR SLOW, NON-SYMMETRIC DISRUPTION AT TIME 5.5 MSEC. THE TOTAL NET VERTICAL FORCE IS 170 KILONEWTONS, OR ABOUT 17 TONS.