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A Poloidal Field Scenario Generating Code for Use in the Design and Operation of Tokamaks

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Introduction

The calculation of energy, power, current and voltage requirements of the coils in a tokamak poloidal field system is a common design and analysis problem. The calculation of all circuit parameters, given a sufficient set of inputs, such as a program of current vs. time, along with coil dimensions, is straightforward. However, the construction of a general-purpose code is nontrivial. Several design decisions and physical insights are required, in order to program the coil currents and voltages. It is thus frequently difficult for one investigator to duplicate the design and analysis results of another, using a different code. A further, purely technical barrier, is that the display of calculated parameters in a manner that easily permits the selection of the number of turns for each coil, and the allocation of rectifiers, dump resistors and switches involves a large amount of graphics postprocessing and typesetting, which has not previously been completed.

There are also a number of important parameters that can be calculated easily by the use of circuit theory that are usually neglected, including the radial and vertical forces on each coil, before or after a disruption, at each moment in time. The purpose of the code described below is to calculate everything of any design importance that can be deduced through circuit theory, to display the results in a comprehensive, but easy to use format, and to retain enough flexibility in inputting to permit collaboration with other groups.

Method

A scenario is specified that includes the dimensions of each of the poloidal field coils, including the plasma, and the coil currents at a small number of discrete times. These are typically the beginning and ends of coil charge-up, plasma initiation, start-up, auxiliary heating, burn, plasma shutdown and coil rampdown. The scenario and coil specifications are input by hand or calculated by auxiliary algorithms.

Once the scenario is specified, three inductance matrices are specified. Both mutual and self inductances are calculated using constant current density, rather than filamentary, models, in order to have the greatest possible accuracy. Mutual inductances are calculated at positions perturbed by 0.1 mm individually in the radial and axial directions in order to calculate radial and vertical forces on the coils. The perturbed mutual inductances are used to calculate influence matrices for radial and axial force that are multiplied by the coil currents to obtain the forces at each moment of time.

Forces between the coils are simply calculated at each moment in time by precalculating an influence matrix, based on the conservation of coenergy, so that the per unit force due to 1 ampere-turn in coil 1 on 1 ampere-turn in coil 2 is simply:

$$F_{r,pu} = \frac{\delta M_{12}}{\delta r}$$

$$F_{z,pu} = \frac{\delta M_{12}}{\delta z}$$

where the average hoop tension in the coil is related to the fictitious radial force, as:

$$F_T = \frac{F_r}{2\pi}$$

In order to calculate currents and forces in the coils after disruptions, the simplifying assumption is made that the coils are connected to low impedance power supplies. In the short circuit limit, the coil currents will change passively so that the flux linkage of each coil is conserved. A matrix inversion is performed to calculate the per unit changes in each coil due to a change in plasma current that satisfy this criterion. The flux-conserving currents in each coil due to disruptive disappearance of the plasma current are then calculated using this influence matrix at each moment of time in the scenario. The radial and axial force influence matrices are then used to calculate the forces on each coil at each moment of time, following a flux-conserving disruption. The radial force is converted to an average tensile stress over the winding pack cross section, while the axial force is converted to an average axial compression stress over the coil bearing area. Each case requires confirmation by more sophisticated analysis, but it has been our experience that average hoop stresses above 200 MPa will require the addition of steel reinforcement to the winding pack or case.

Guidance is given to the selection of power supplies by monitoring when each coil's current and voltage have the same polarity, and recording the maximum individual voltage and current for each polarity. Note that the product of the maximum voltage and current is invariably higher than the maximum instantaneous power needed from the power supplies, since the current and voltage maxima usually do not occur at the same time. Periods of regenerative power flow are also monitored, in order to aid in the design of switches and dump resistors or to check for inverter commutation failure.

The energy requirements for the system and for each individual coil are determined merely by monitoring the power flow through the coil terminals. Therefore, when the power flow is regenerative (negative), the code calculates a reduction in the instantaneous energy requirement. If the code is used to calculate the rotational stored energy requirements for the system, this output will always be optimistic, since not all of the regenerated power can be returned to the coils' energy source. Thus a diagnostic parameter called "Dump Energy" is calculated and displayed. This is the sum of the integrated regenerative power flow through each pair of coil terminals. The parameter physically corresponds to the energy ratings of dump resistors, if all of the negative coil power were dissipated in dump resistors. If the calculation of "Dump Energy" is added to the calculation of energy required, upper and lower bounds can be calculated for the actual energy drawn from a source.

Worked Example

An interesting worked example is the limiter discharge, as of March 1986, for the Compact Ignition Tokamak (CIT) device [TH86]. This poloidal field system provides a 9 MA plasma current for a 3.0 s ignited burn. All of the graphics and tabulated output of the code are included in the Appendix. Selected features of the output are discussed in the text.

Table I shows the positions, maximum ampere-turns and turns in each one of the PF coils. Coils above and below the equator are routinely tabulated, in order to avoid confusion or to handle the infrequent design case of an asymmetric system (e.g. Intor, Alcator DCT). Table II shows the peak current density over the winding pack envelope, maximum temperature, maximum energy and peak power required by the coil. The latter two values are the sums of dissipative and magnetic energies, thus representing the peak requirements for stored energy sources and power supplies. Table III shows the peak positive and negative current and positive and negative voltage requirements of each coil. These are not the power supply ratings. The peak positive voltage frequently, even usually, occurs when the current is negative and vice versa. Since the instantaneous power flow is negative at that moment, a power supply is not required, and the coil can dump energy into a resistor, if desired. The values in Table III, then, are used primarily for the design of bus, ground insulation and switch circuits. Power supply requirements are listed in Table IV. During each moment of time, the emulator monitors whether the current and voltage have the same polarity, then divides the scenario for each coil into time intervals that have to be provided for by positive current power supplies, negative current power supplies or neither. Notice that the power ratings listed in Table IV are typically much larger than the peak power flowing instantaneously through the coils, being the product of the peak current and peak voltage during the entire period that current and voltage have the same polarity. Thus the power requirement tabulated is essentially the product of the no load voltage-full load current product that typifies the power supply requirement for each coil. Table V lists the volt-second contributions of each coil to the plasma, which is a source of physical insight for redesigning the coils or the scenarios.

System requirements as a function of time are illustrated in Figures 1-7. Each total system requirement is usually illustrated in two different formats, showing the individual contributions of each coil pair and showing the individual contributions of the magnetic and resistive components of power or energy. As shown in Figure 1, the resistive energy requirements of the PF system are higher than the magnetic requirements. The peak total energy requirement of the PF system is 1283 MJ, so the pulsed energy source must be capable of delivering that much energy to the load. The final dissipated energy of the PF system is 990 MJ, so the cryogenic system must remove that much energy from the coils between pulses. As shown in Figure 2, the dominant energy requirement for the CIT PF system comes from the outermost coil, EF3, that provides most of the plasma's vertical field. This is a typical situation, since the outermost coil always has the largest major radius and is usually the most efficient in providing vertical field on axis. The energy that flows through the coil terminals, however, is always less than the actual energy that an energy source must provide, because when magnetic energy leaves the coils, it is not returned to the energy source with 100 % efficiency. In particular, during plasma initiation, most or all of the regenerative energy flow through the coil terminals is dumped in external resistors. A diagnostic of the system dump energy is included in Figure 3. This is simply the sum of all the energy that could be either returned to the line or dumped from each coil, whenever its power flow is negative. A typical approach to source design is to assume that all of the dump energy during the initiation and start-up period, must be provided by the generator, while the 'dump energy' from the shutdown period can be returned to the line or provided over a long enough period to constitute a negligible load. As seen in Figure 3, the total dump energy is - 557 MJ, of which - 270 MJ is dumped during the start-up period. If the start-up dumped energy is charged to the generator, then it must provide 1553 MJ to the PF load during a plasma discharge.

Power flow through the system is shown in Figures 3-7. Figure 3 shows the instantaneous power flow through all of the PF coils. The curve is dominated by the large regenerative power flow due to plasma initiation, and, therefore, makes all the positive powers somewhat difficult to read. Therefore, additional curves, labeled 'line power' are included, that only count and sum the positive power flows in each coil. As seen in Figure 4, the peak line power of 429 MVA, like the energy, is dominated by the outside PF5 coil at the end of plasma current rampup, so the dominant power requirement of the system is simply ramping the vertical field to its final value. There are three secondary power peaks at the end of coil precharge, auxiliary heating and end of burn. As seen in Figure 5, the resistive coil losses are climbing rapidly at the end of burn, so there is probably not much to be gained ramping the plasma more slowly. However, the peaks are sufficiently separated that an additional 0.5-1 second of ramp might lower the peak line power by 50 MW or so. Other tradeoffs that would be created, as shown later would be the final temperature of OH2, the hottest coil in the PF system, vs. the more difficult to evaluate benefits of being permitted to take longer to establish the final plasma.

Figure 6 shows the history of the plasma loop voltage and the contributions of each pair of PF coils, confirming that 30 V are available for plasma initiation. Figure 7 shows the history of the volt-second linkage to the plasma, confirming that the specified 26 V-s have been satisfied by the PF system. The large contribution by the outside PF5 coil is striking. However, since the positive current polarity coil, PF4, used for elongating the plasma, subtracts a large number of volt-seconds, the contribution from the two central solenoid coils, PF1 and PF2, is still half the total swing.

Figures 8-11 display circuit and force scenarios for the upper OH1 coil. The scenario code generates total displays of all circuits for each one of the coils individually. The code automatically checks for symmetry. If the system is asymmetric, as in a recent simulation done for INTOR, four pages of curves apiece were generated for each of nine asymmetric coils, above and below the equator. If symmetry is satisfied, only the four coils above the equator are displayed. The designer has to keep this in mind when deciding whether to connect mirror image coils in series, parallel, or independently. Figure 8 displays the ampere-turns, volts/turn, power flow and energy vs. time for OH1, U. Note that the power flow curve displays not only the bipolar power requirements, but also the positive and negative power supply requirements. Both resistive and inductive contributions to energy and power are displayed. Figure 9 displays the conductor current, terminal voltage, flux linkage and coil temperature vs. time. Note that the flux linkage is the flux linking the coil, not the coil contribution to the plasma. For inertially-cooled coils, the temperature rise is frequently the dominant feasibility issue of the PF design. The rise of OH1 to 292 K is substantial, but within the allowable final temperature specification of 370 K.

The radial and axial force vs. time are displayed in Figure 10. The 'radial force' is really the product of the average coil circumference and the radially outward force per unit circumference, the actual integral of this force being zero. The average hoop tensile stress in the winding pack is this force divided by 2π times the area of the winding pack. When this average force exceeds 200 MPa, reinforcement of the copper is frequently found to be necessary. The axial force vs. time is the vertical bearing force on the top or bottom of the magnet. The average stress is this force divided by the cross-sectional axial bearing area of the winding pack. If the vertical force peaks somewhere other than the magnet end, then there will be no particular relation between the peak and average axial stresses. Whenever any coil has moderately high average stresses, the peak stresses are calculated, using E. Bobrov's three-dimensional closed-form solution to the stresses in a solenoid, using a fully anisotropic model of an equivalent composite winding pack [BO84].

Figure 11 shows the pre- and post-disruption current and radial force in OH1, U, assuming that all the PF coils are flux-conserving (i.e., short-circuited). Although the plasma had a demagnetizing effect on the OH1 field, the overall effect is a decreased OH1 current, so that the change in the bursting force on OH1 is negligible at all times during the scenario. Note that disruption forces are given at every moment of time, so that what is being calculated is not a single scenario, but a series of hypothetical events, since a disruption might occur at any time, during a pulse.

Conclusions

A simple poloidal magnet scenario emulator has been constructed for use in the design and evaluation of tokamaks. This code has proven to have a wide utility, being used both in the design and planning of laboratory experiments, such as Alcator C-Mod at M.I.T., analysis of behavior on existing machines , such as Alcator C, and design and planning of national and international 'flagship' demonstration tokamaks, such as CIT and INTOR. The code is a simple time integrator that allows the designer and analyst to calculate all parameters that can be deduced by circuit theory, including power, energy, voltage, current, and force.

A worked example has been presented from the CIT design, illustrating something of the extent of the analysis on that machine, along with some discussion of design problems and tradeoffs suggested by the results of PF system emulation. A complete set of code output for the CIT limiter discharge is included in the Appendix.

Acknowledgments

Special thanks are owed to A.M. Dawson for the preparation of this report.

References

[BO84] E.S. Bobrov, "Electrically conducting orthotropic cylindrical shell in axial and radial magnet fields," in The Mechanical Behavior of Electromagnetic Solid Continua, ed. G.A. Maugin, Proc of the IUTAM-IUPAP Symposium, Paris, France, 4-7 July, 1983, Elsevier Science Publishers (North-Holland), 1984

[TH86] R.J. Thome et al. "Poloidal field coil system design for the Compact Ignition Tokamak: Status Report." M.I.T. Plasma Fusion Center Research Report PFC/RR-86-11, April, 1986

Table I

CIT-L System Winding Pack Dimensions

Coil	R	Z	R_1	R_2	Z_1	Z_2	NI	n_{turns}
	(m)	(m)	(m)	(m)	(m) (m)	(MAT)	()	
OH1,U	0.383	0.184	0.259	0.507	0.000	0.368	7.000	200.0
OH1,L	0.383	-0.184	0.259	0.507	-0.368	0.000	7.000	200.0
OH2,U	0.383	0.684	0.259	0.507	0.368	1.000	12.600	160.0
OH2,L	0.383	-0.684	0.259	0.507	-1.000	-0.368	12.600	160.0
EF1,U	1.050	1.748	0.910	1.189	1.518	1.979	7.660	300.0
EF1,L	1.050	-1.748	0.910	1.189	-1.979	-1.518	7.660	300.0
EF2,U	2.050	1.680	1.887	2.213	1.517	1.843	4.220	112.0
EF2,L	2.050	-1.680	1.887	2.213	-1.843	-1.517	4.220	112.0
EF3,U	2.510	0.955	2.351	2.670	0.795	1.115	7.100	160.0
EF3,L	2.510	-0.955	2.351	2.670	-1.115	-0.795	7.100	160.0

Table II

Current Density, Temperature, Energy and Power

Coil	$J_{env,pk}$ (MA/m^2)	T_{max} (K)	$E_{pk,req}$ (MJ)	P_{max} (MW)
OH1,U	76.701	292.358	116.791	34.715
OH1,L	76.701	292.358	116.791	34.715
OH2,U	80.390	300.559	207.244	52.526
OH2,L	80.390	300.559	207.244	52.526
EF1,U	59.556	95.636	84.585	53.247
EF1,L	59.556	95.636	84.585	53.247
EF2,U	39.708	95.568	36.884	9.223
EF2,L	39.708	95.568	36.884	9.223
EF3,U	69.771	139.789	348.497	133.600
EF3,L	69.771	139.789	348.497	133.600

Table III

Peak Currents and Voltages on PF Coils

Coil	$I_{cond,max}$ (kA)	$I_{cond,min}$ (kA)	$V_{term,max}$ (kV)	$V_{term,min}$ (kV)
OH1,U	29.300	-35.000	0.606	-2.786
OH1,L	29.300	-35.000	0.677	-2.702
OH2,U	78.750	-59.125	0.667	-1.938
OH2,L	78.750	-59.125	0.572	-2.062
EF1,U	25.533	-8.200	2.085	-9.196
EF1,L	25.533	-8.200	2.085	-9.196
EF2,U	37.679	-22.054	0.716	-0.156
EF2,L	37.679	-22.054	0.716	-0.156
EF3,U	5.750	-44.375	3.529	-12.986
EF3,L	5.750	-44.375	3.529	-12.986

Table IV

Positive and Negative Power Supply Requirements

Coil	I_{+PS} (kA)	V_{+PS} (V)	P_{+PS} (MVA)	I_{-PS} (kA)	V_{-PS} (V)	P_{-PS} (MVA)
OH1,U	29.30	605.86	17.75	-35.00	-991.85	34.71
OH1,L	29.30	676.69	19.83	-35.00	-1699.02	59.47
OH2,U	78.75	667.00	52.53	-59.13	-862.22	50.98
OH2,L	78.75	572.14	45.06	-59.13	-721.88	42.68
EF1,U	25.53	2085.40	53.25	-8.20	-2216.50	18.18
EF1,L	25.53	2085.40	53.25	-8.20	-2216.50	18.18
EF2,U	37.68	288.90	10.89	-22.05	-156.17	3.44
EF2,L	37.68	288.90	10.89	-22.05	-156.17	3.44
EF3,U	5.75	598.59	3.44	-44.38	-3389.14	150.39
EF3,L	5.75	598.59	3.44	-44.38	-3389.14	150.39

Table V

Volt-second Contributions of Each PF Coil

Coil	$VS_{end,start-up}$ (V-S)	$VS_{end,flattop}$ (V-S)
OH1,U	1.384	-1.654
OH1,L	1.384	-1.654
OH2,U	1.969	-1.478
OH2,L	1.969	-1.478
EF1,U	2.067	-0.664
EF1,L	2.067	-0.664
EF2,U	-1.498	2.560
EF2,L	-1.498	2.560
EF3,U	0.906	-6.994
EF3,L	0.906	-6.994
Total	9.657	-16.461

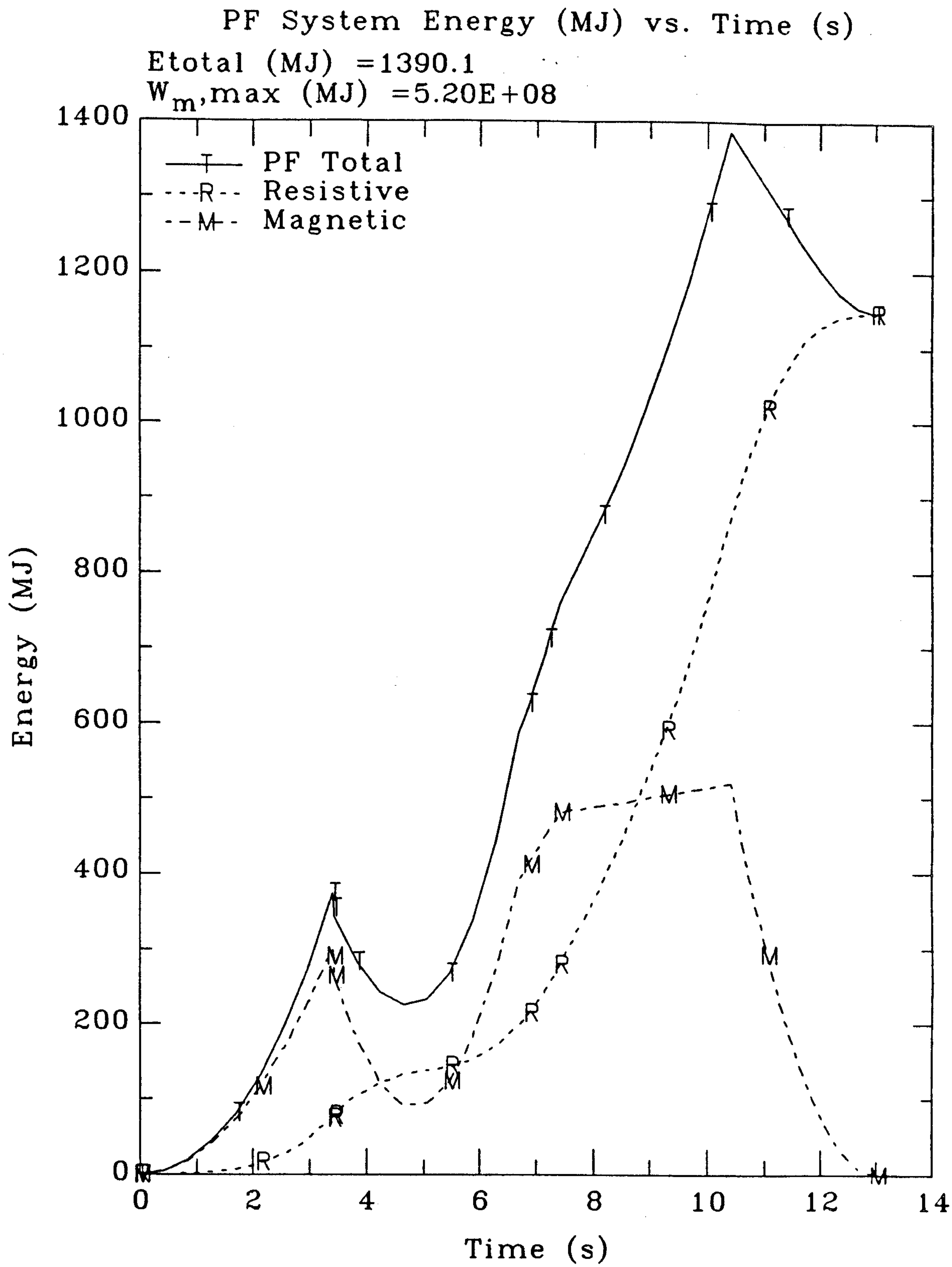


Figure 1 – CIT Limiter Discharge: System Energy Requirement vs Time

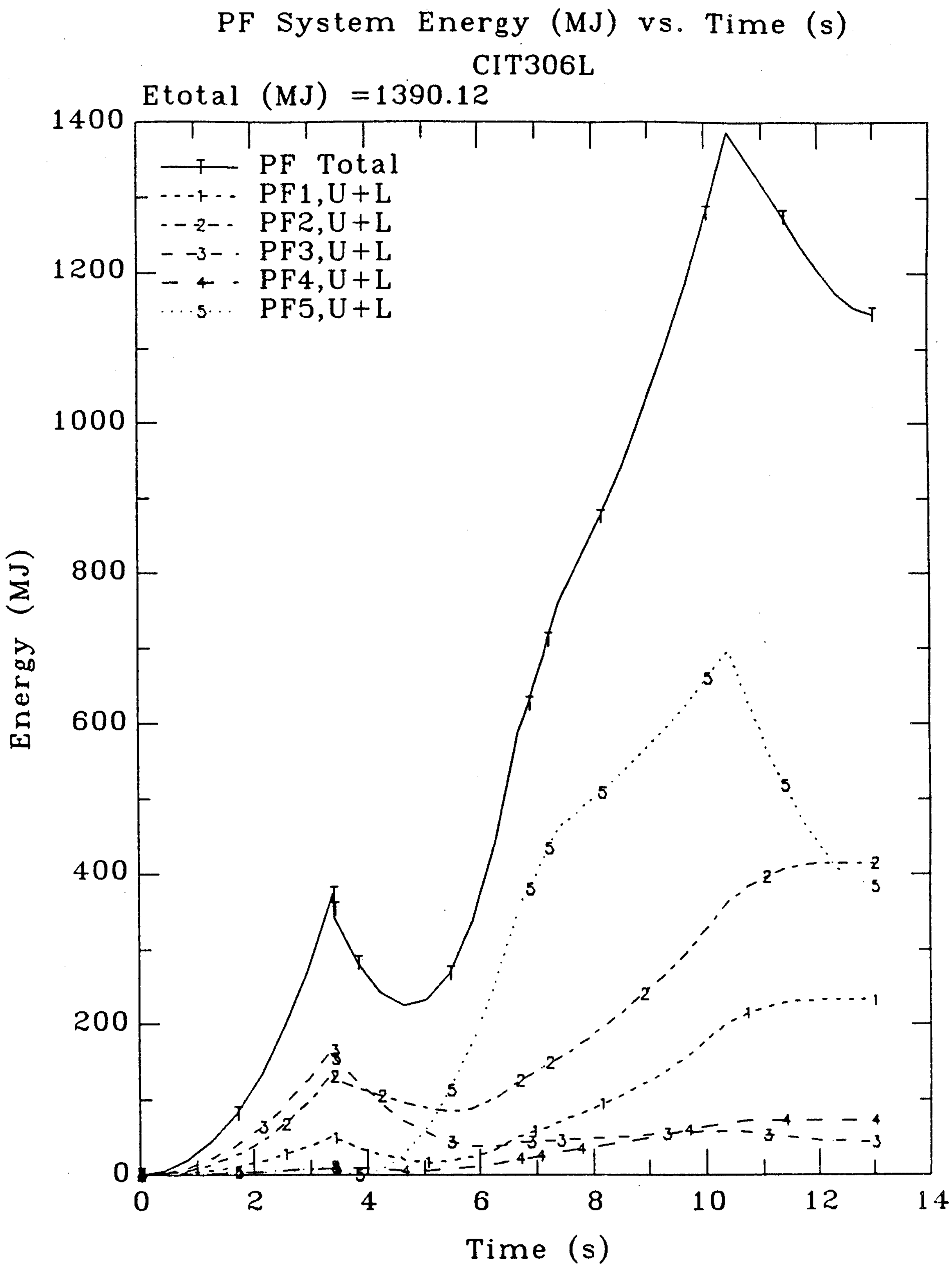


Figure 2 – Total PF System and Individual Coil Energy Requirements vs Time

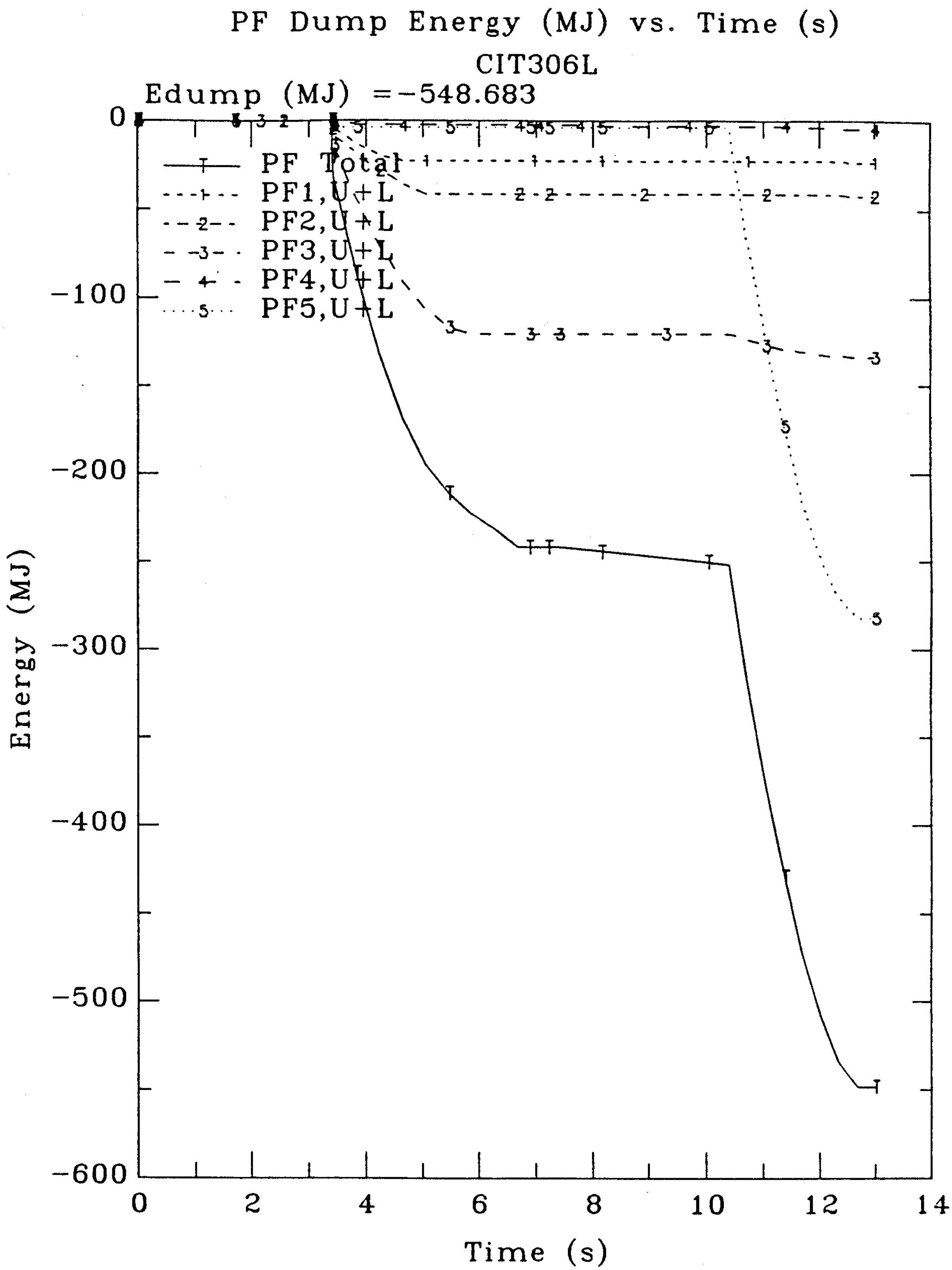


Figure 3 – Additional Energy Requirements if Regenerative Energy is not Returned to Source

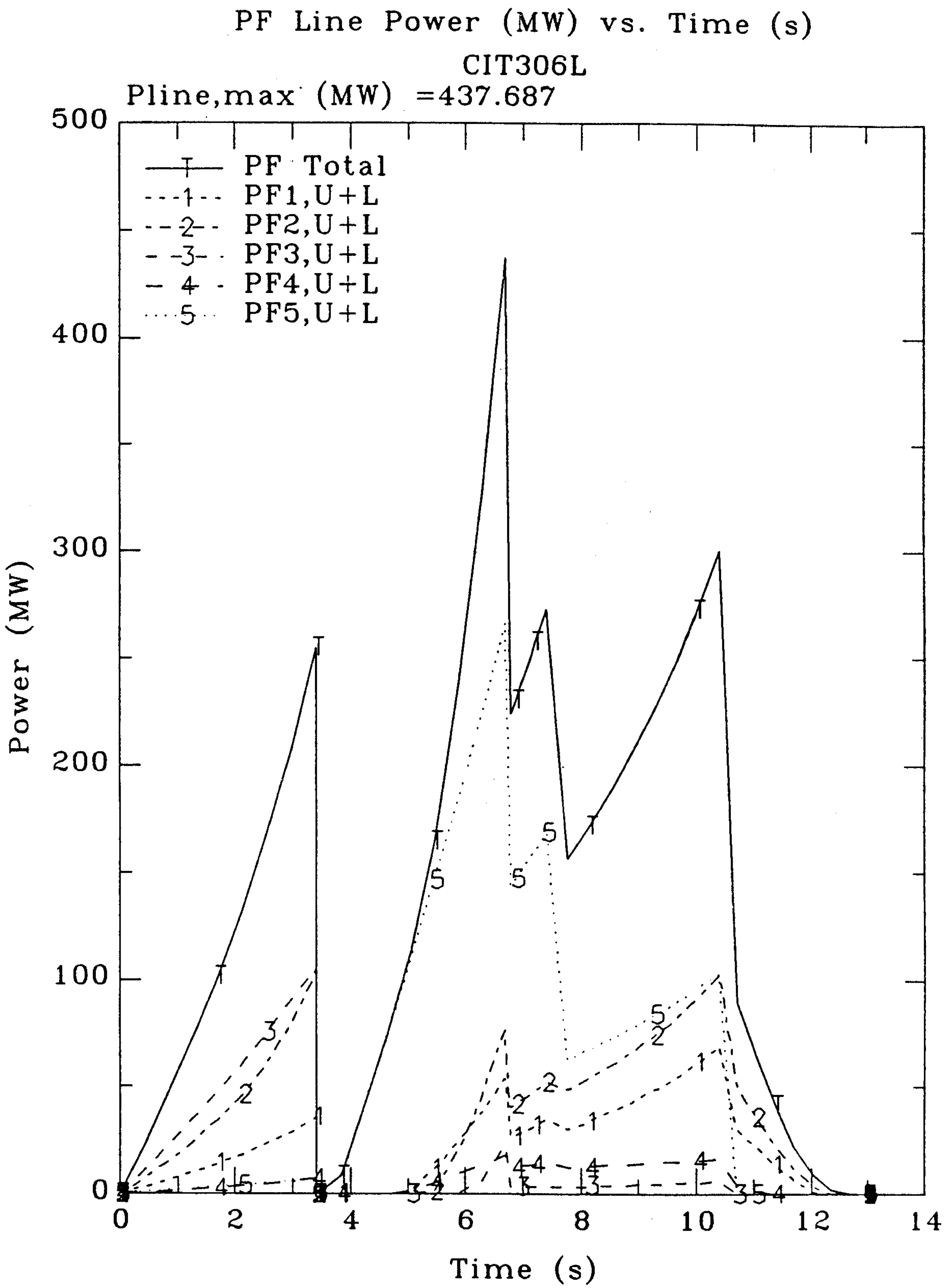


Figure 4 – Individual Power Supply and System Line Power Requirements (MW) vs Time(s)

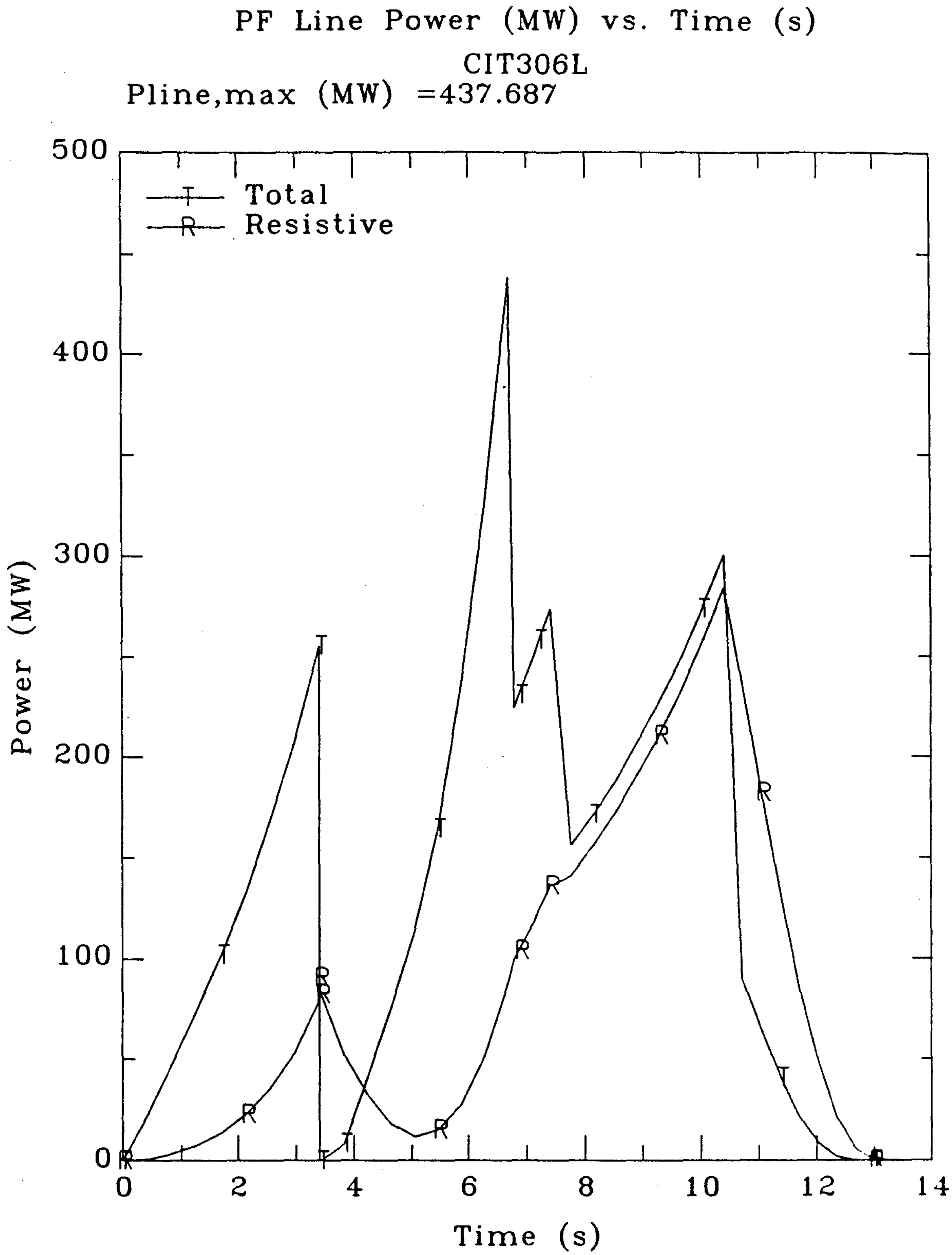


Figure 5 – System Line Power: Resistive, Magnetic and Total (MW) vs Time (s)

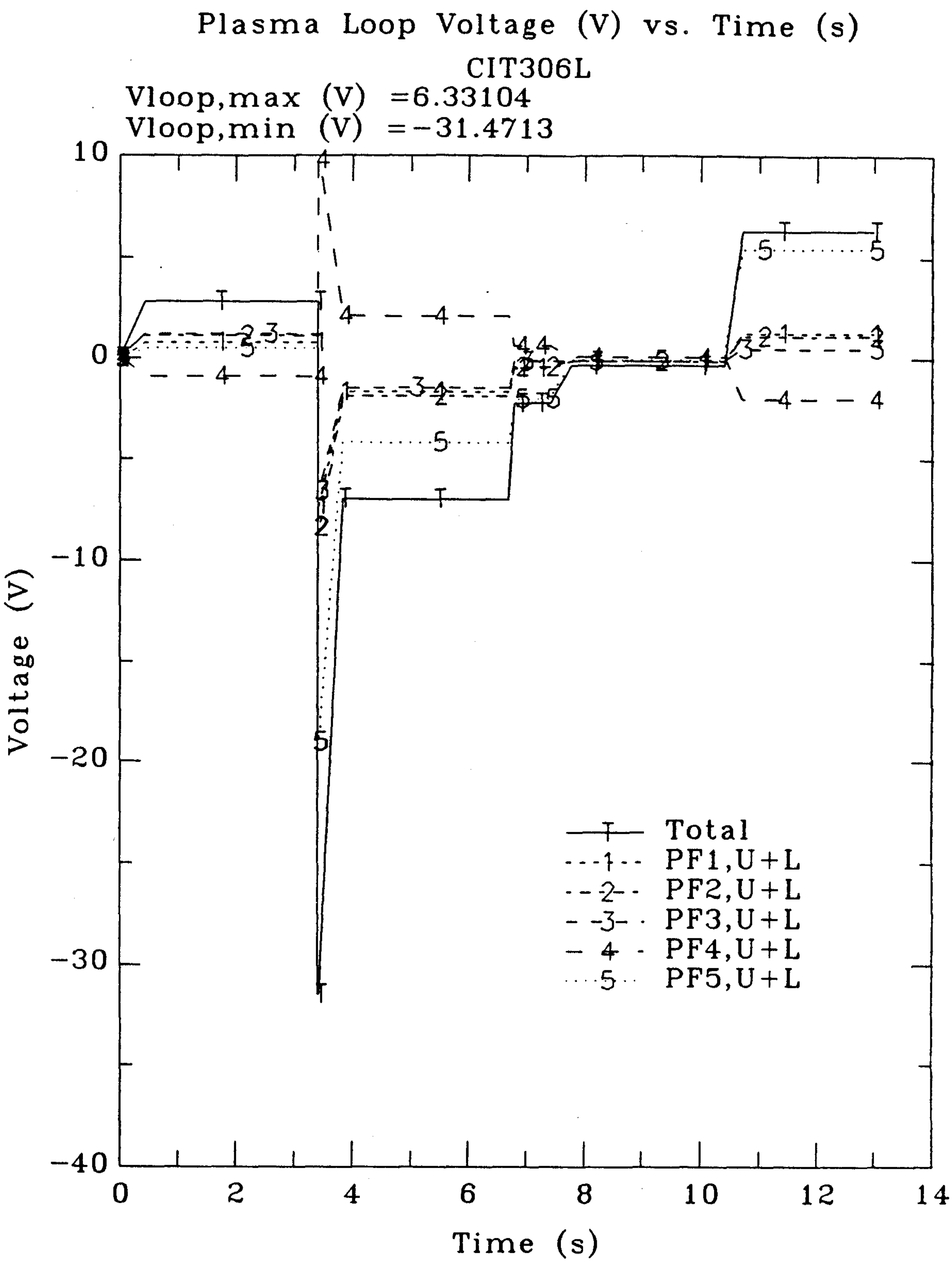


Figure 6 – Contributions of Individual PF Coils to Plasma Loop Voltage (V) vs Time (s)

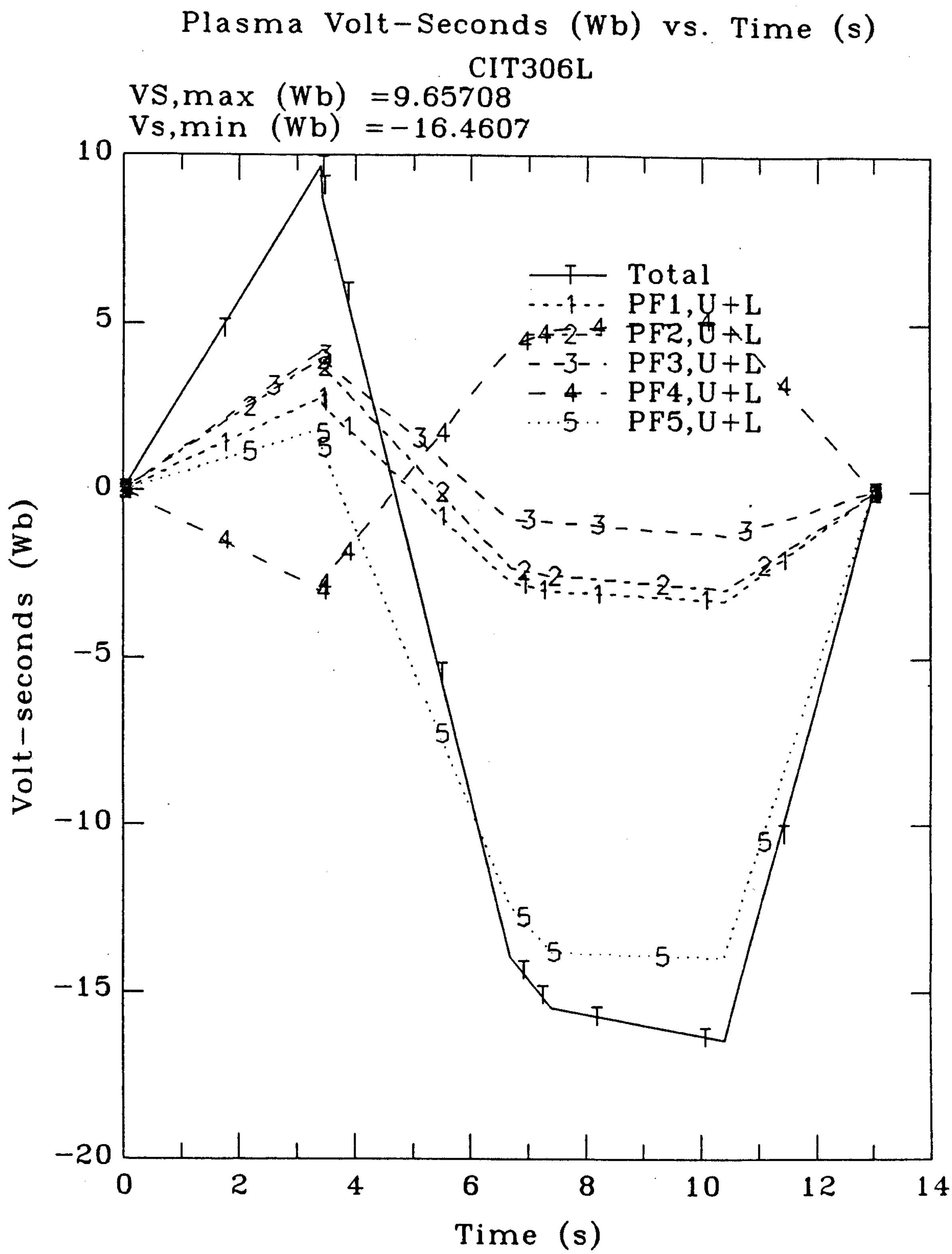


Figure 7 – Contribution of Individual PF Coils to Plasma Volt-Seconds (Wb) vs Time (s)

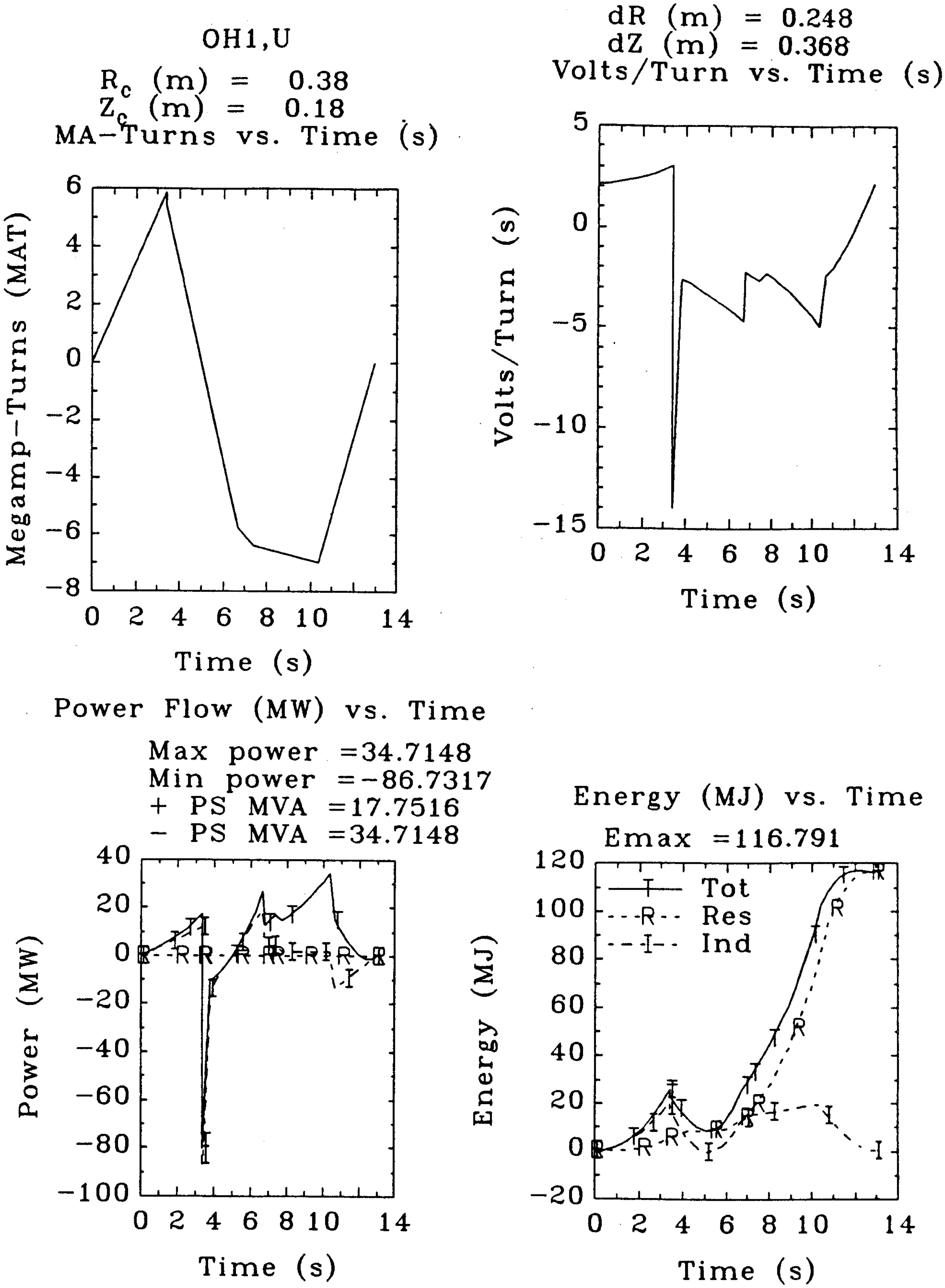


Figure 8 – Ampere-Turns (MAT), Volts/Turn (V), Power (MW), and Energy (MJ) vs Time (s) for Upper OH1 Coil

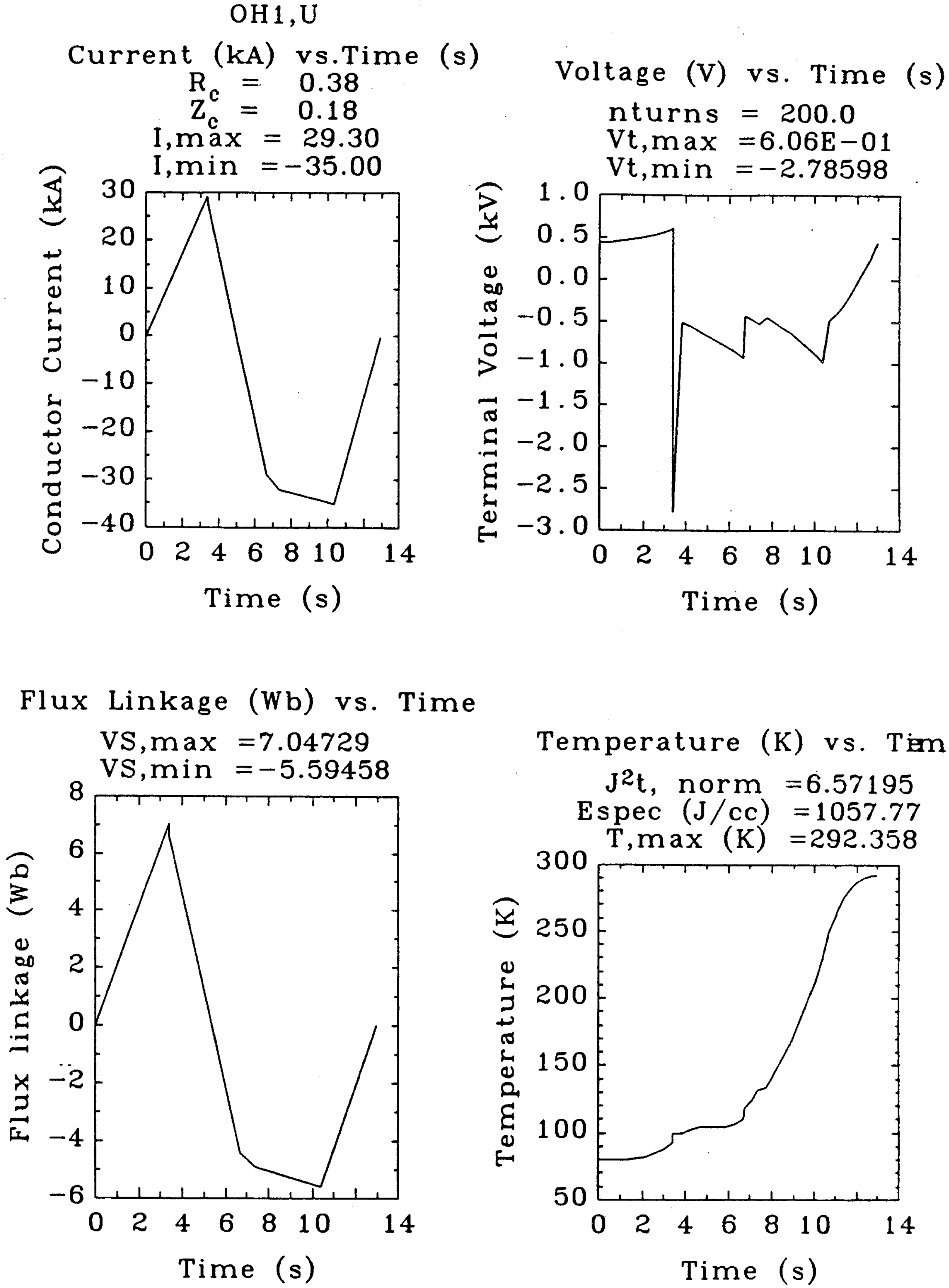
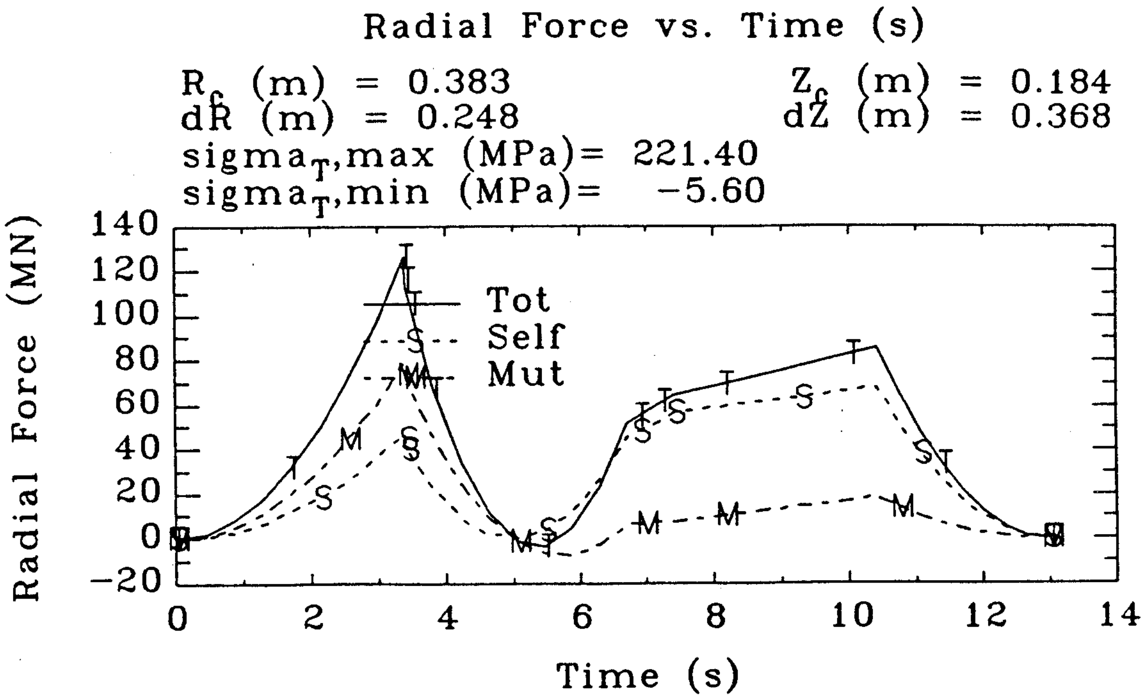


Figure 9 – Conductor Current (kA), Terminal Voltage (kV), Coil Flux Linkage (Wb), and Temperature (K) vs Time (s) for Upper OH1 Coil



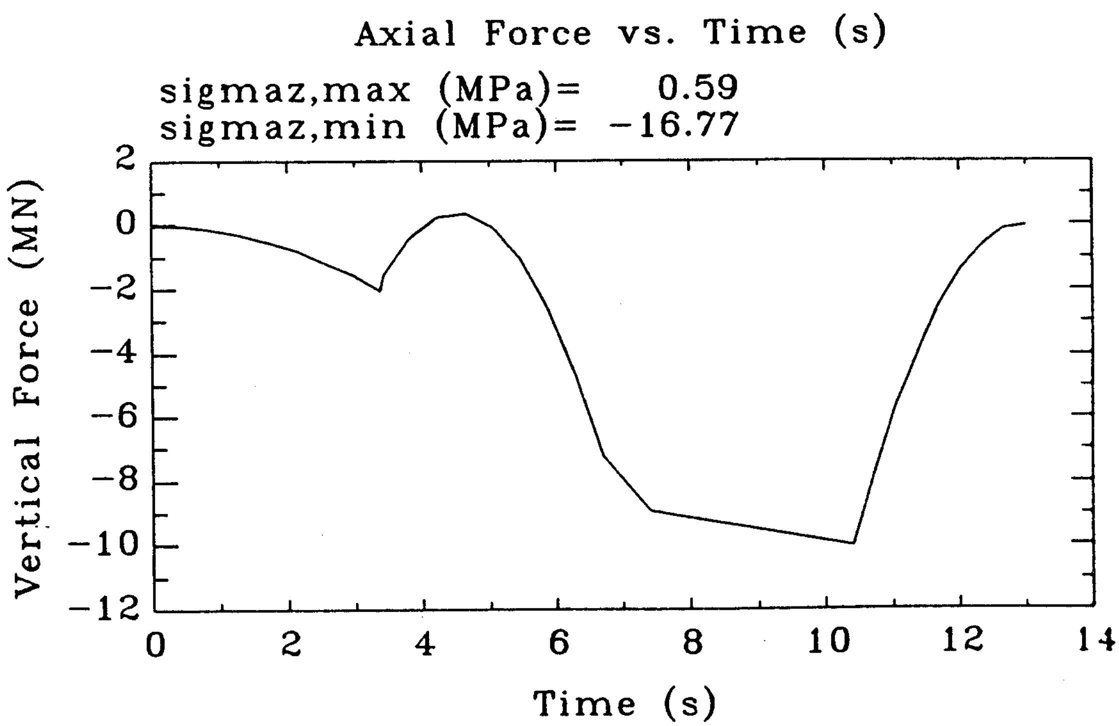


Figure 10 – Radial and Axial Force (MN) vs Time (s) on Upper OH1 Coil

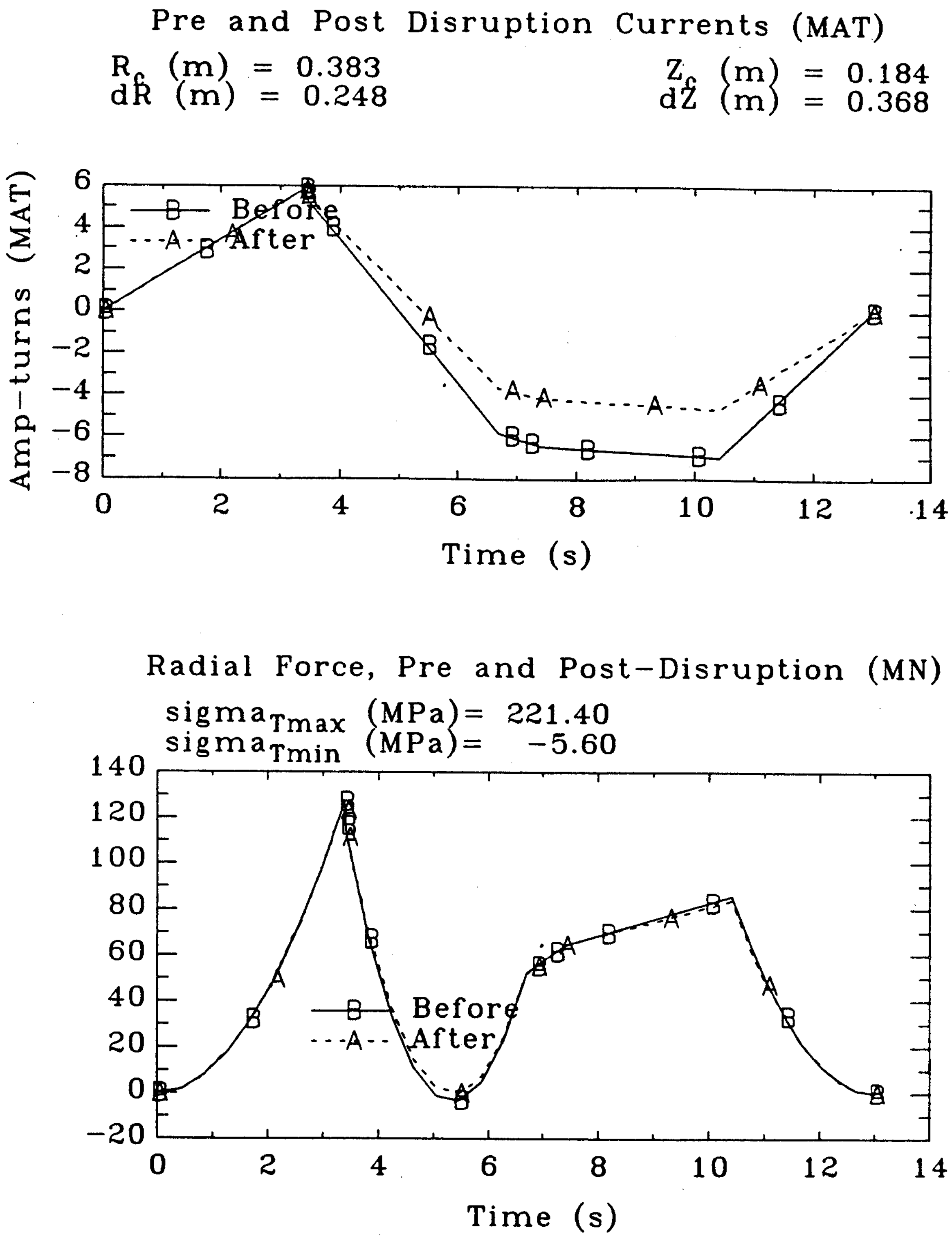


Figure 11 – Current (MAT) and Radial Force (MN) Before and After Hypothetical Plasma Disruptions at Each Point in Time, Conserving Flux in PF Coils

Appendix

Sample Output of PF Scenario-Generating Code

CIT306L System Winding Pack Dimensions

Coil	R	Z	R_1	R_2	Z_1	Z_2	NI	n_{turns}
	(m)	(m)	(m)	(m)	(m) (m)	(MAT)	()	
OH1,U	0.383	0.184	0.259	0.507	0.000	0.368	7.000	200.0
OH1,L	0.383	-0.184	0.259	0.507	-0.368	0.000	7.000	200.0
OH2,U	0.383	0.684	0.259	0.507	0.368	1.000	12.600	160.0
OH2,L	0.383	-0.684	0.259	0.507	-1.000	-0.368	12.600	160.0
EF1,U	1.050	1.748	0.910	1.189	1.518	1.979	7.660	300.0
EF1,L	1.050	-1.748	0.910	1.189	-1.979	-1.518	7.660	300.0
EF2,U	2.050	1.680	1.887	2.213	1.517	1.843	4.220	112.0
EF2,L	2.050	-1.680	1.887	2.213	-1.843	-1.517	4.220	112.0
EF3,U	2.510	0.955	2.351	2.670	0.795	1.115	7.100	160.0
EF3,L	2.510	-0.955	2.351	2.670	-1.115	-0.795	7.100	160.0

Coil	$J_{env,pk}$	T_{max}	$E_{pk,req}$	P_{max}
	(MA/m^2)	(K)	(MJ)	(MW)
OH1,U	76.701	292.358	116.791	34.715
OH1,L	76.701	0.000	0.000	0.000
OH2,U	80.390	300.559	207.244	52.526
OH2,L	80.390	0.000	0.000	0.000
EF1,U	59.556	95.636	84.585	53.247
EF1,L	59.556	0.000	0.000	0.000
EF2,U	39.708	95.568	36.884	9.223
EF2,L	39.708	0.000	0.000	0.000
EF3,U	69.771	139.789	348.497	133.600
EF3,L	69.771	0.000	0.000	0.000

Volt-second Contributions of Each PF Coil

Coil	$VS_{end,start-up}$ (V-S)	$VS_{end,flattop}$ (V-S)
OH1,U	1.384	-1.654
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OH2,L	1.969	-1.478
EF1,U	2.067	-0.664
EF1,L	2.067	-0.664
EF2,U	-1.498	2.560
EF2,L	-1.498	2.560
EF3,U	0.906	-6.994
EF3,L	0.906	-6.994
Total	9.657	-16.461

Currents in PF Coils after Flux-Conserving Disruptions

Coil	EOS I_{pre} (MA)	EOS I_{post} (MA)	EOB I_{pre} (MA)	EOB I_{post} (MA)
OH1,U	-6.093	-3.868	0.000	0.000
OH1,L	-6.093	-3.868	0.000	0.000
OH2,U	-7.790	-5.776	0.000	0.000
OH2,L	-7.790	-5.776	0.000	0.000
EF1,U	-1.609	-1.164	0.000	0.000
EF1,L	-1.609	-1.164	0.000	0.000
EF2,U	3.774	4.046	0.000	0.000
EF2,L	3.774	4.046	0.000	0.000
EF3,U	-6.658	-6.026	0.000	0.000
EF3,L	-6.658	-6.026	0.000	0.000
Total Δ I		2.941		1.470

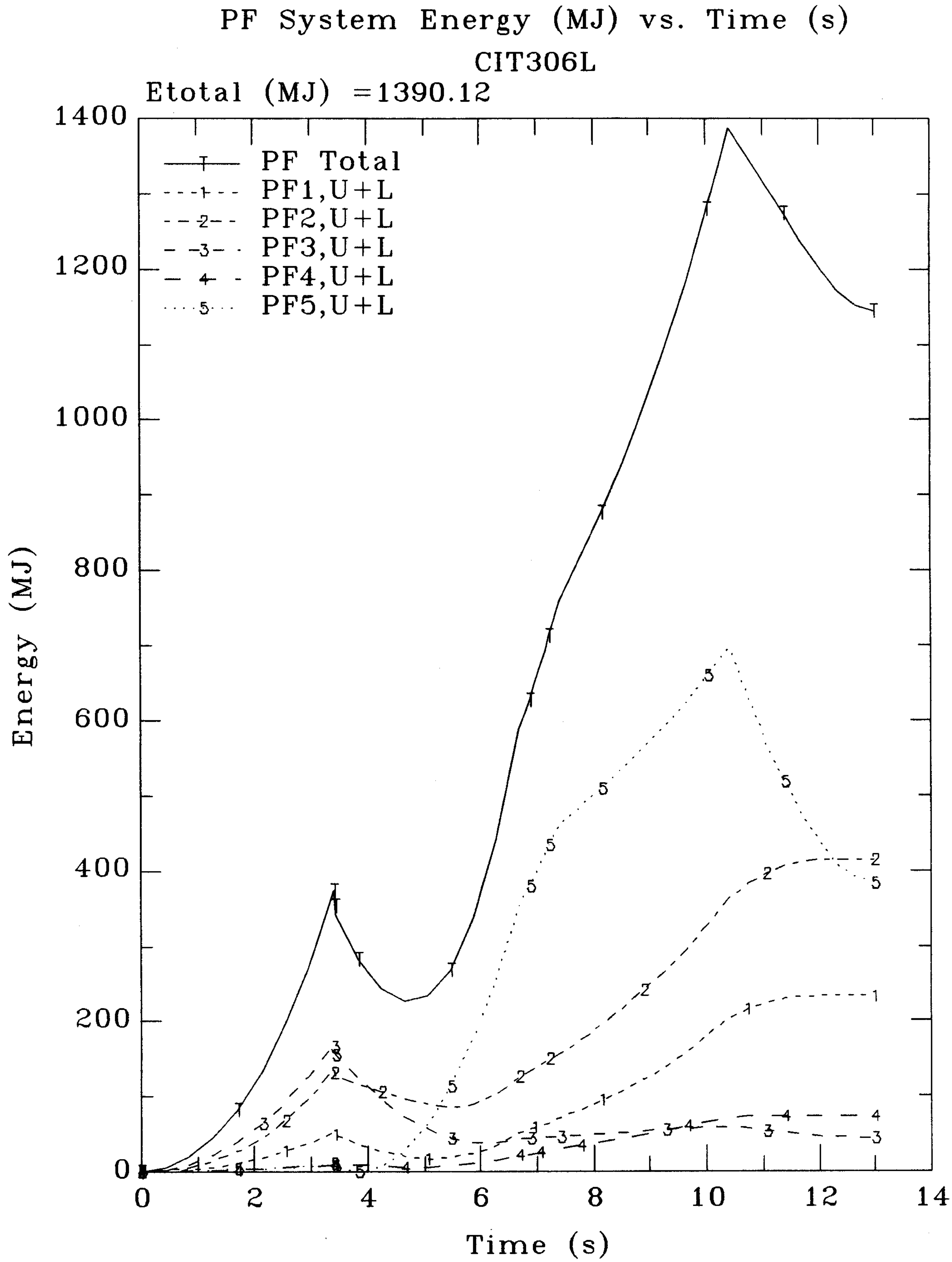
Peak Currents and Voltages on PF Coils

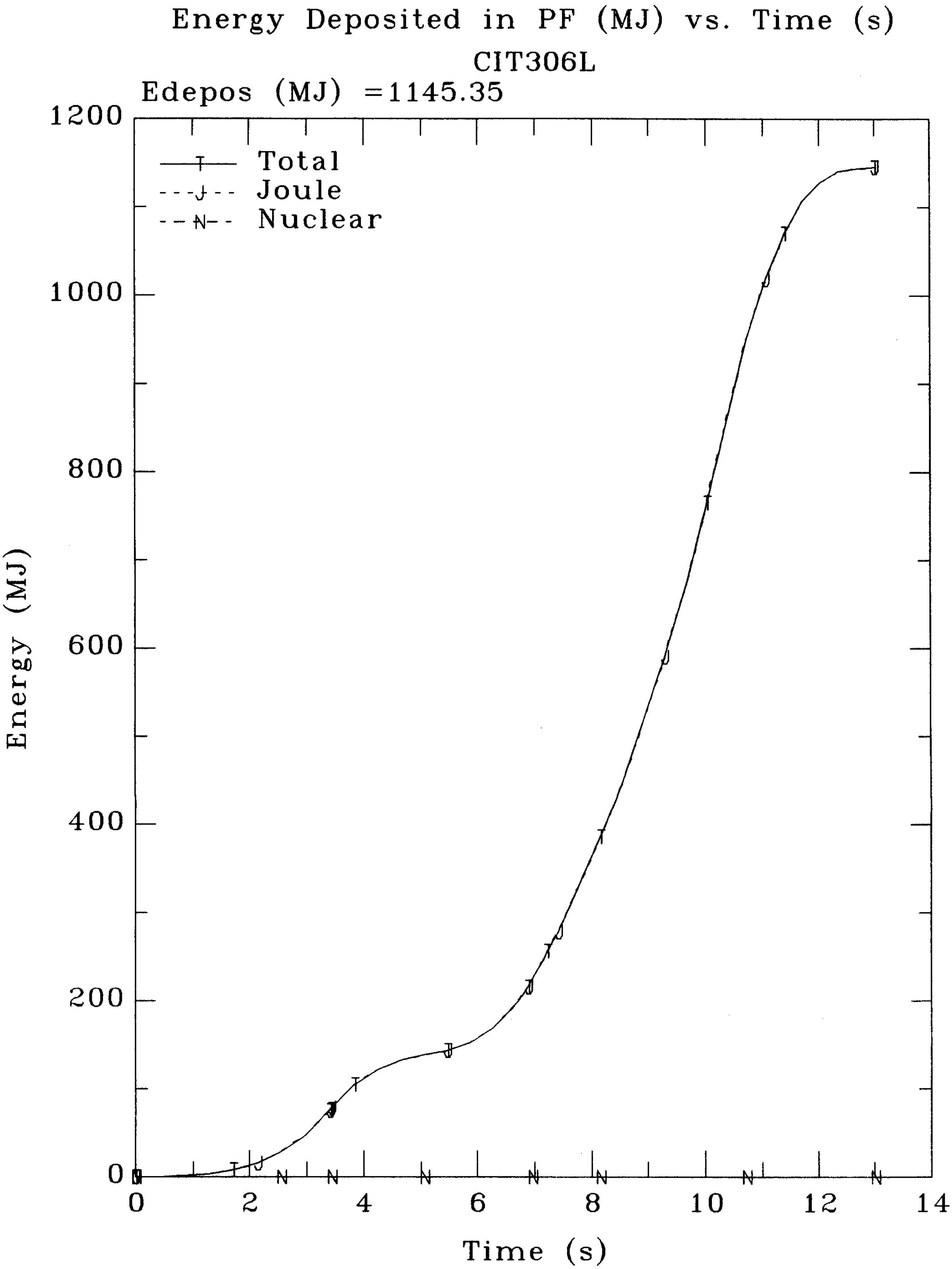
Coil	$I_{cond,max}$ (kA)	$I_{cond,min}$ (kA)	$V_{term,max}$ (kV)	$V_{term,min}$ (kV)
OH1,U	29.300	-35.000	0.606	-2.786
OH1,L	29.300	-35.000	0.677	-2.702
OH2,U	78.750	-59.125	0.667	-1.938
OH2,L	78.750	-59.125	0.572	-2.062
EF1,U	25.533	-8.200	2.085	-9.196
EF1,L	25.533	-8.200	2.085	-9.196
EF2,U	37.679	-22.054	0.716	-0.156
EF2,L	37.679	-22.054	0.716	-0.156
EF3,U	5.750	-44.375	3.529	-12.986
EF3,L	5.750	-44.375	3.529	-12.986

Positive and Negative Power Supply Requirements

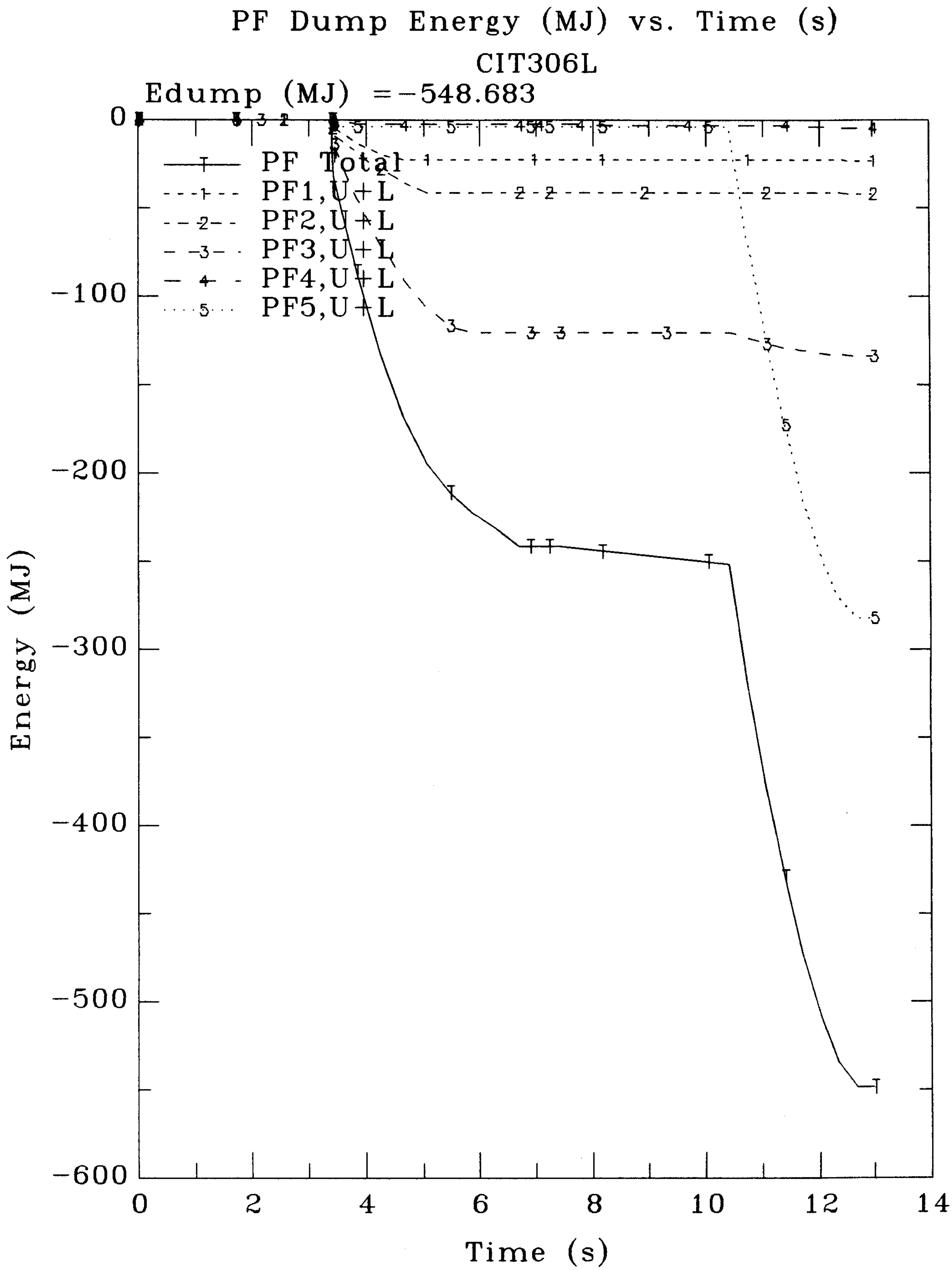
CIT306L

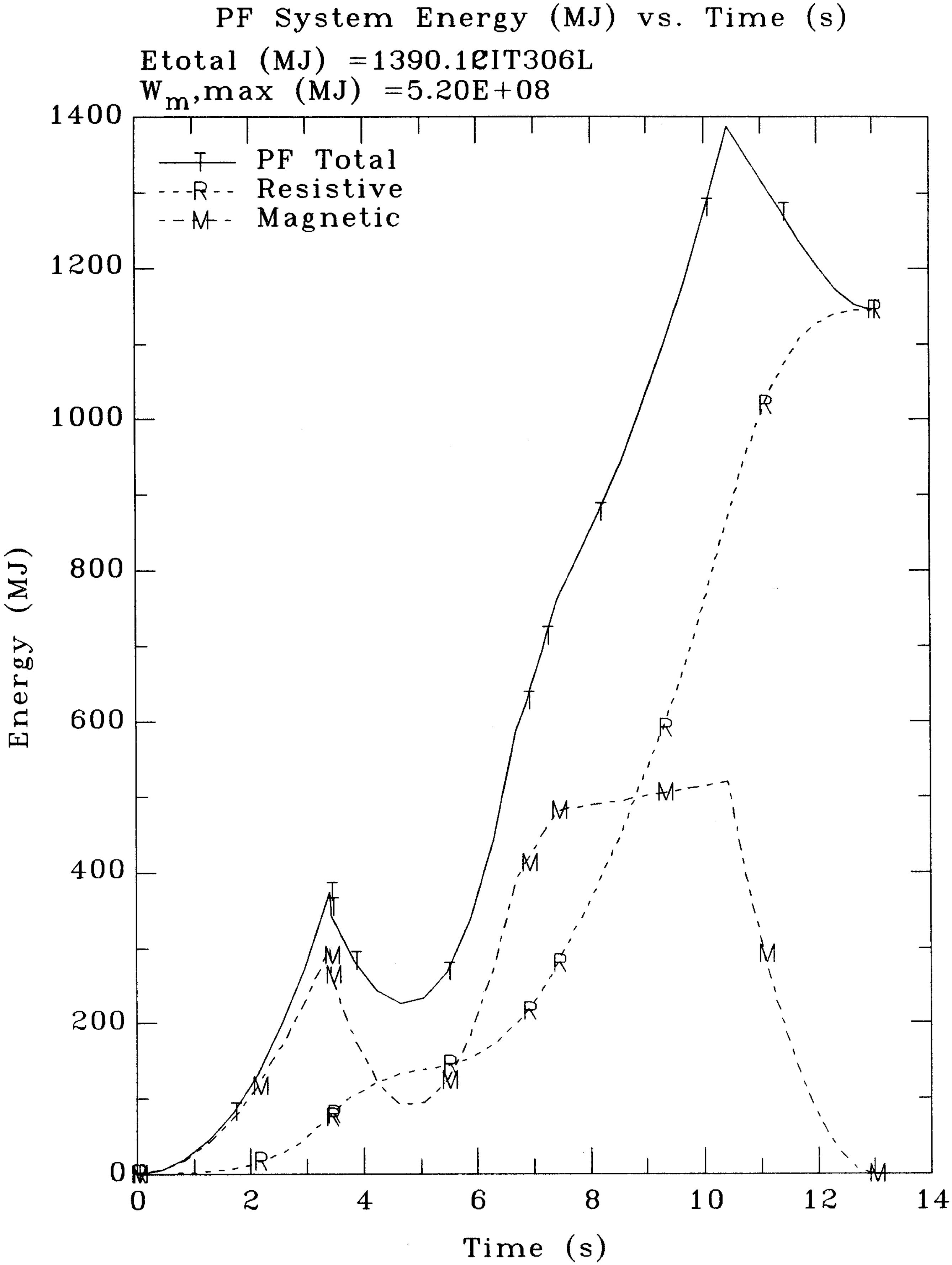
Coil	I_{+PS} (kA)	V_{+PS} (V)	P_{+PS} (MVA)	I_{-PS} (kA)	V_{-PS} (V)	P_{-PS} (MVA)
OH1,U	29.30	605.86	17.75	-35.00	-991.85	34.71
OH1,L	29.30	676.69	19.83	-35.00	-1699.02	59.47
OH2,U	78.75	667.00	52.53	-59.13	-862.22	50.98
OH2,L	78.75	572.14	45.06	-59.13	-721.88	42.68
EF1,U	25.53	2085.40	53.25	-8.20	-2216.50	18.18
EF1,L	25.53	2085.40	53.25	-8.20	-2216.50	18.18
EF2,U	37.68	288.90	10.89	-22.05	-156.17	3.44
EF2,L	37.68	288.90	10.89	-22.05	-156.17	3.44
EF3,U	5.75	598.59	3.44	-44.38	-3389.14	150.39
EF3,L	5.75	598.59	3.44	-44.38	-3389.14	150.39


PF System Energy (MJ) vs. Time (s)
CIT306L
Etotal (MJ) =1390.12
PF Total
PF1,U+L
PF2,U+L
PF3,U+L
PF4,U+L
PF5,U+L
Energy (MJ)
Time (s)
0
200
400
600
800
1000
1200
1400
2
4
6
8
10
12
14

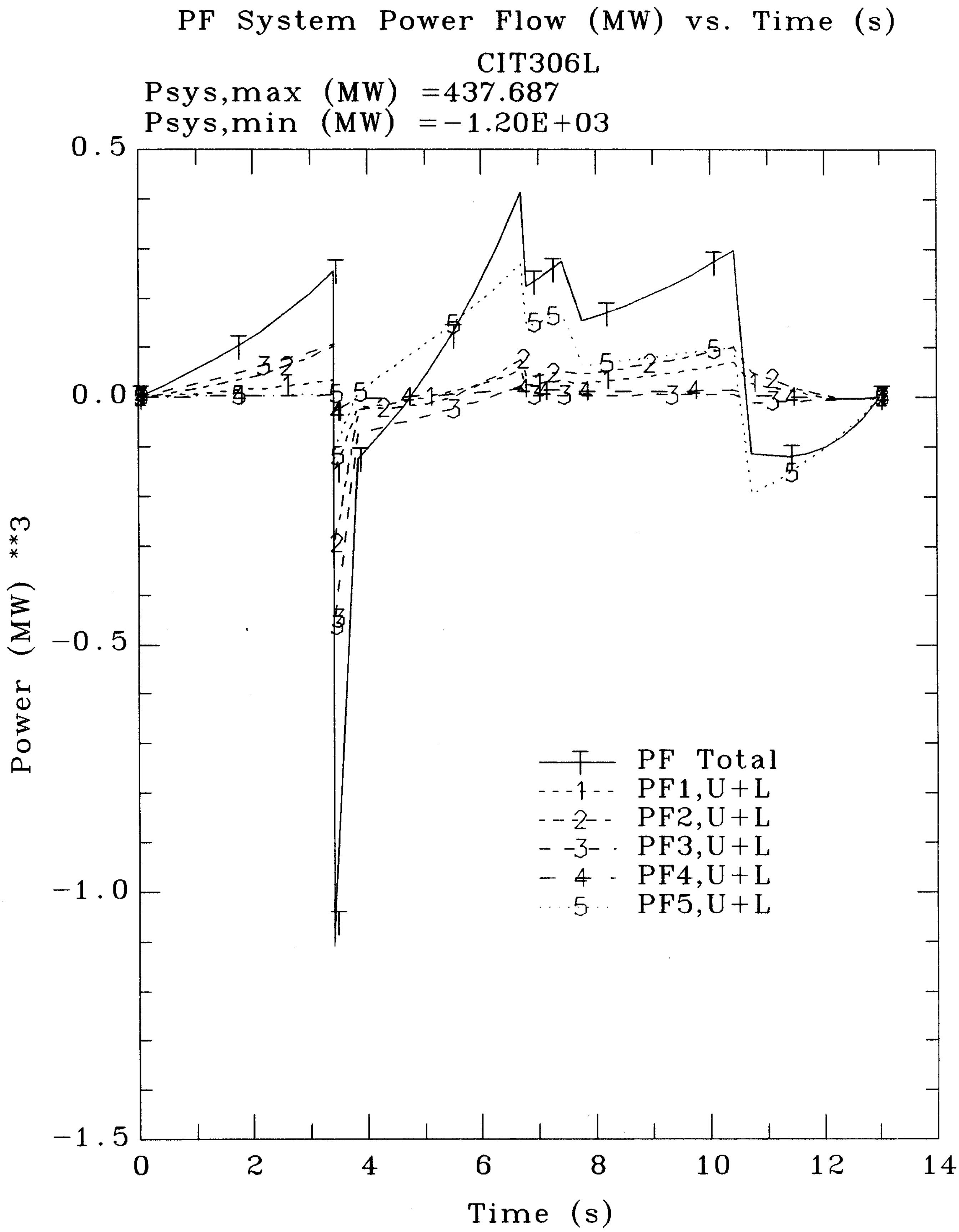


Energy Deposited in PF (MJ) vs. Time (s)
CIT306L
Edepos (MJ) =1145.35
Total
Joule
Nuclear
Energy (MJ)
Time (s)
0
200
400
600
800
1000
1200
0
2
4
6
8
10
12
14

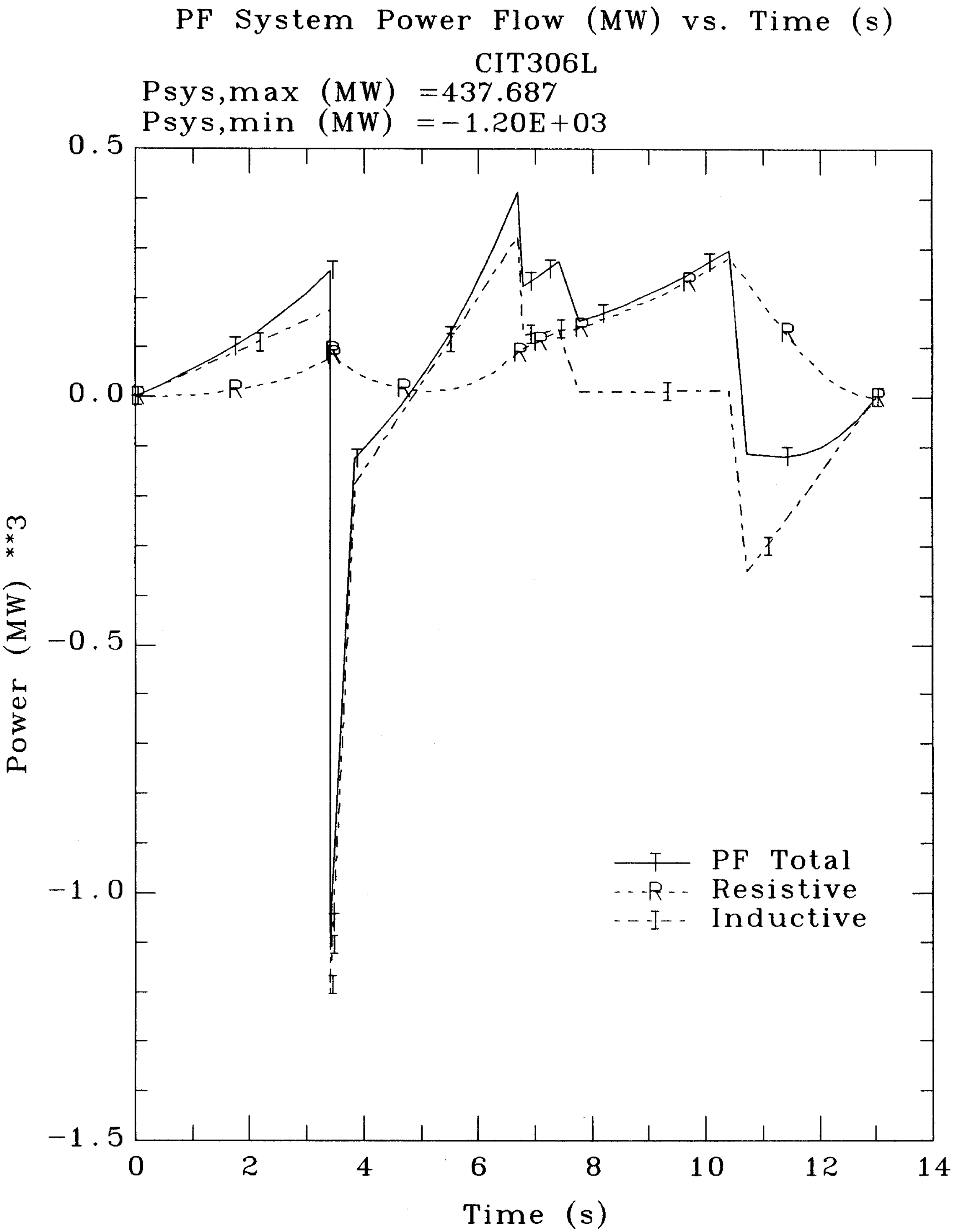

PF Dump Energy (MJ) vs. Time (s)
CIT306L
Edump (MJ) =−548.683
PF Total
PF1,U+L
PF2,U+L
PF3,U+L
PF4,U+L
PF5,U+L
Energy (MJ)
Time (s)
0
−100
−200
−300
−400
−500
−600
0
2
4
6
8
10
12
14

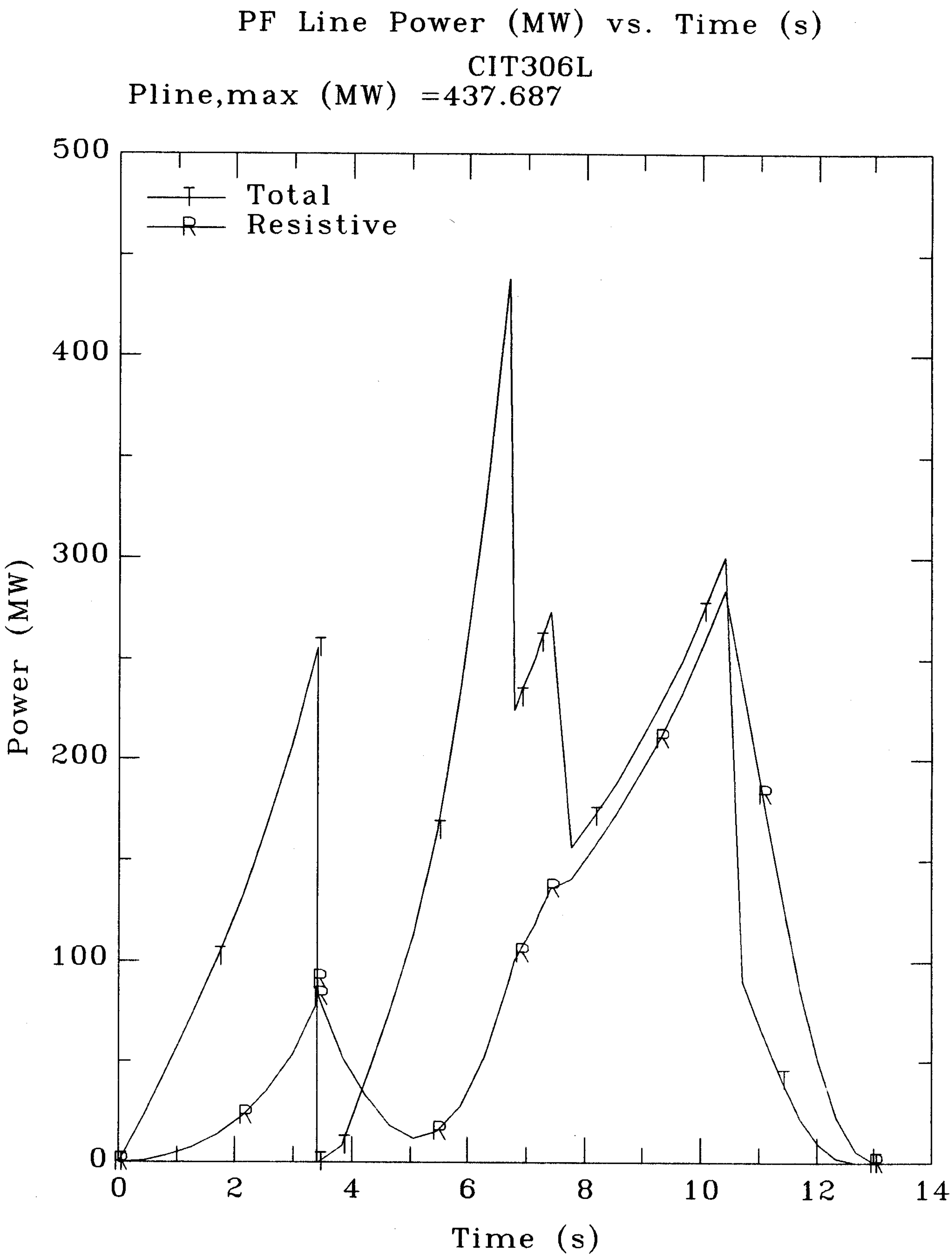


PF System Energy (MJ) vs. Time (s)
Etotal (MJ) =1390.1ℓIT306L
Wm,max (MJ) =5.20E+08
PF Total
Resistive
Magnetic
Energy (MJ)
Time (s)
0
200
400
600
800
1000
1200
1400
0
2
4
6
8
10
12
14

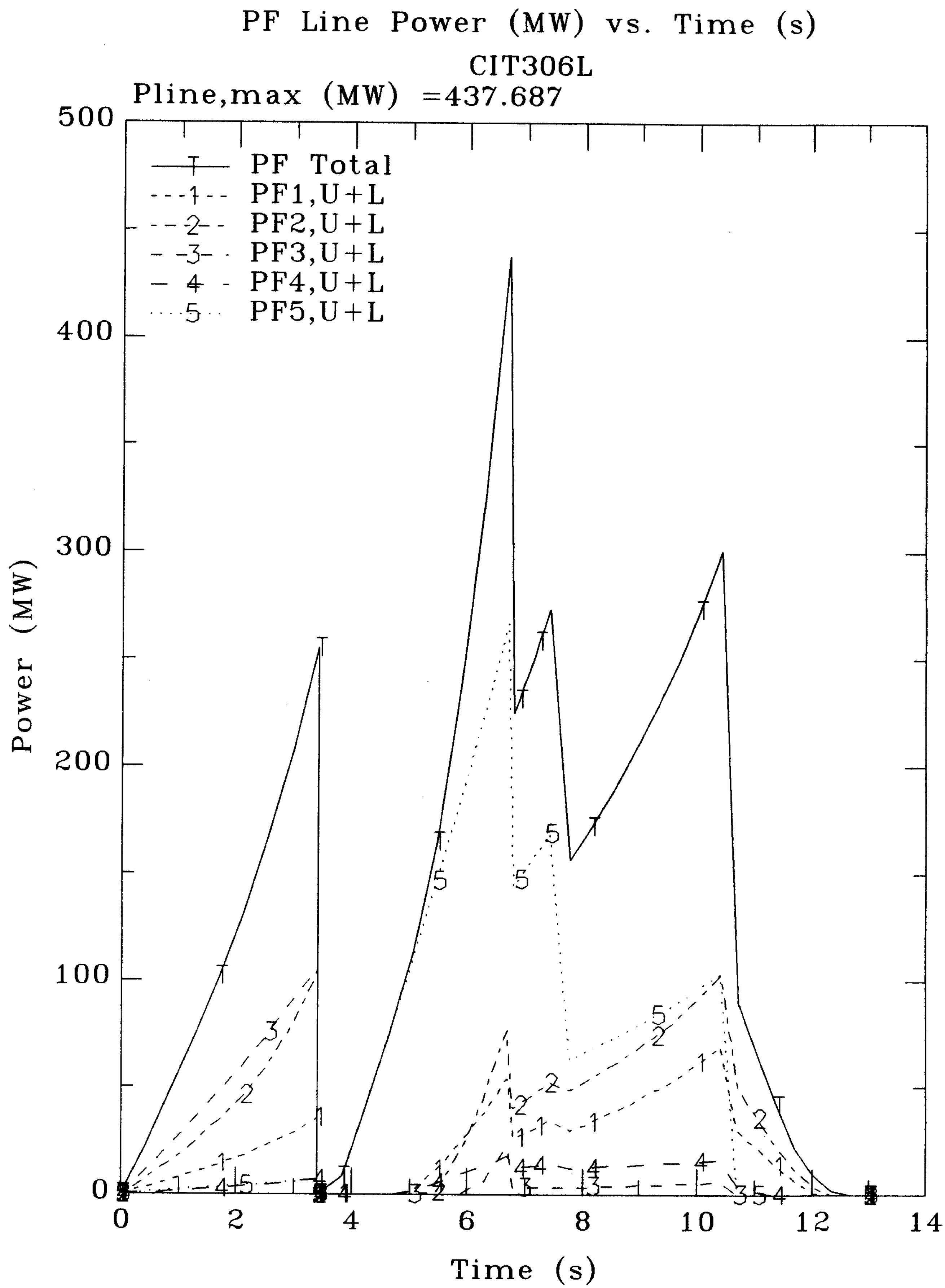


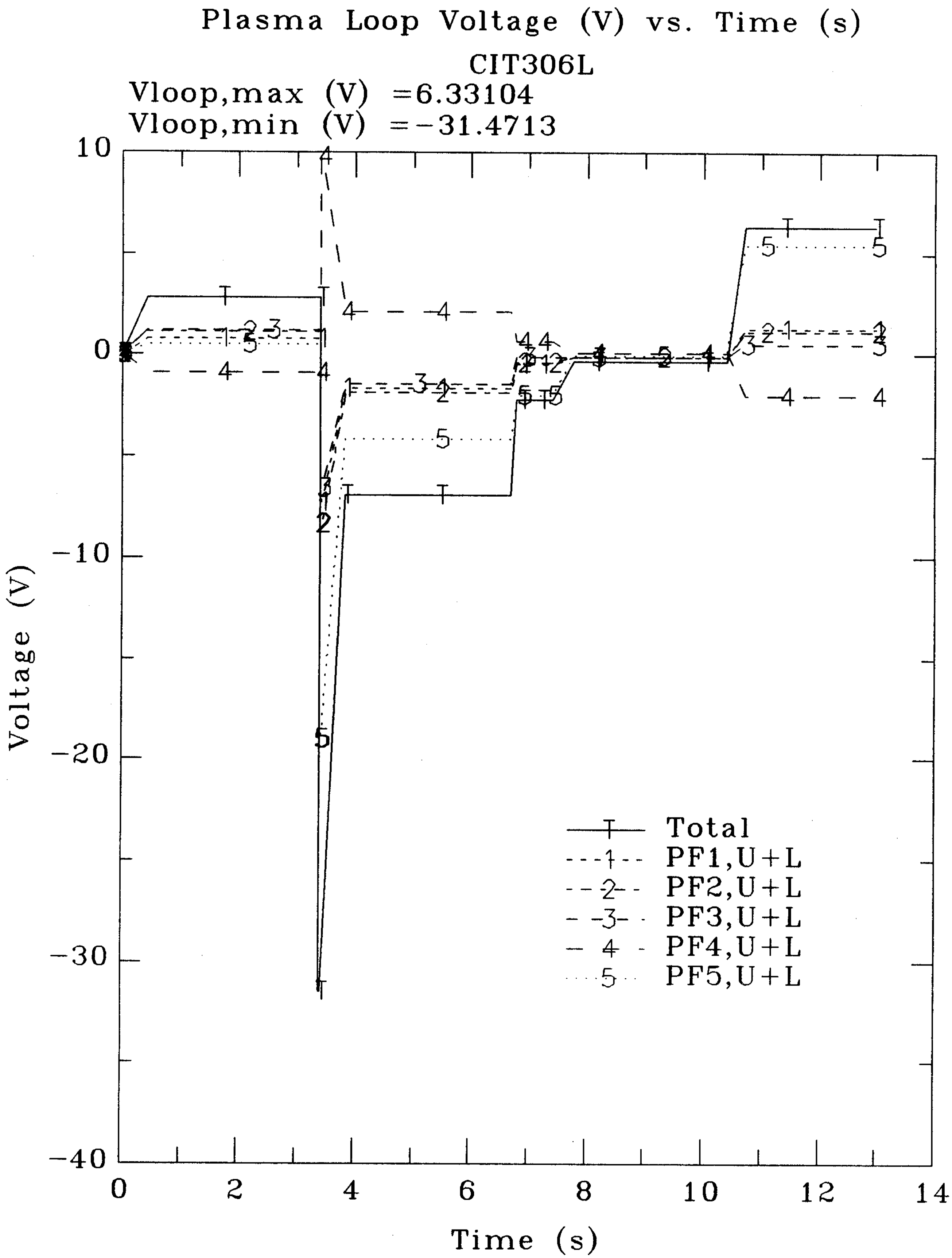
PF System Power Flow (MW) vs. Time (s)
CIT306L
Psys,max (MW) =437.687
Psys,min (MW) =-1.20E+03
Power (MW) **3
Time (s)
0.5
0.0
-0.5
-1.0
-1.5
0
2
4
6
8
10
12
14
PF Total
PF1,U+L
PF2,U+L
PF3,U+L
PF4,U+L
PF5,U+L

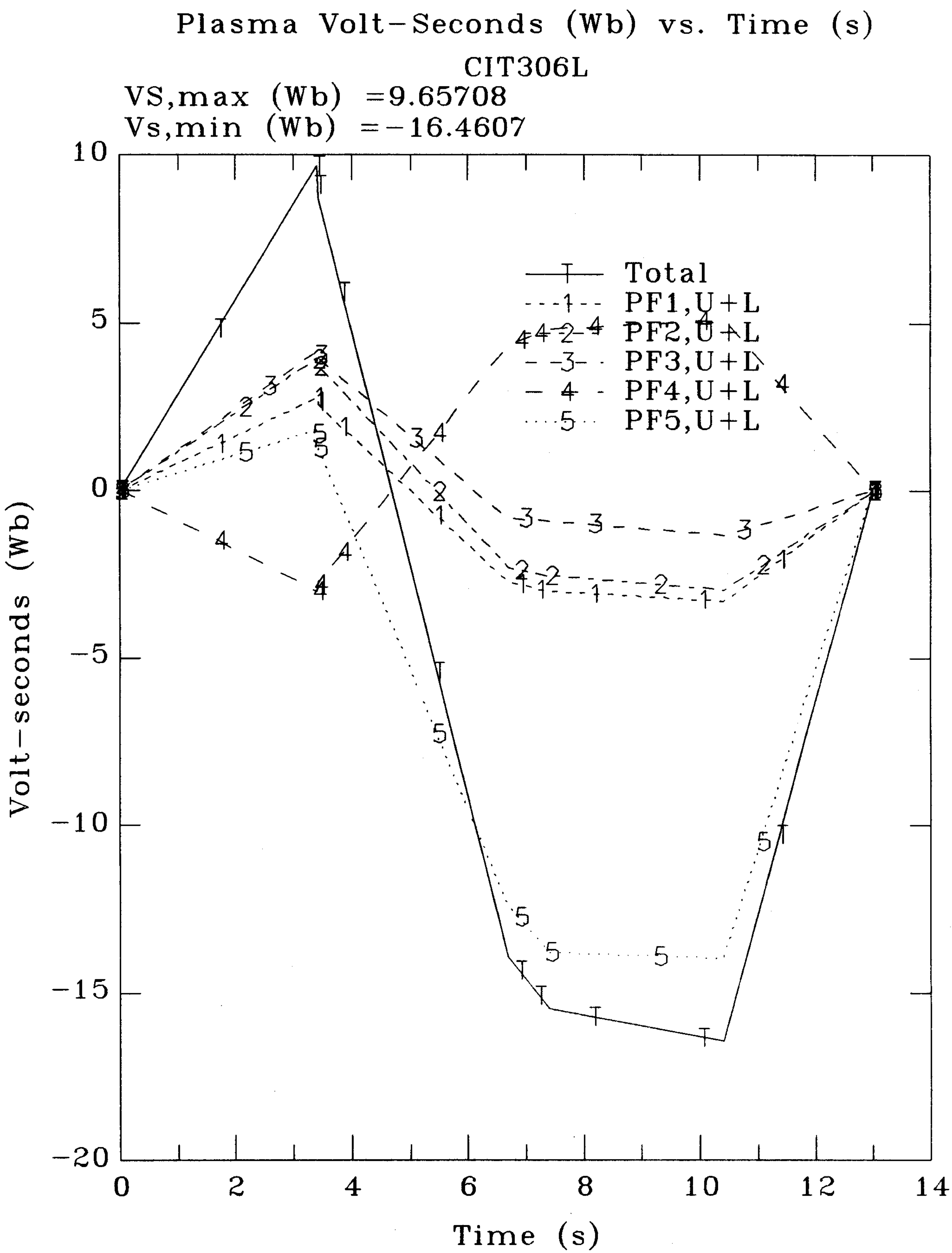

PF System Power Flow (MW) vs. Time (s)
CIT306L
Psys,max (MW) =437.687
Psys,min (MW) =-1.20E+03
Power (MW) **3
Time (s)
0.5
0.0
-0.5
-1.0
-1.5
0
2
4
6
8
10
12
14
PF Total
Resistive
Inductive



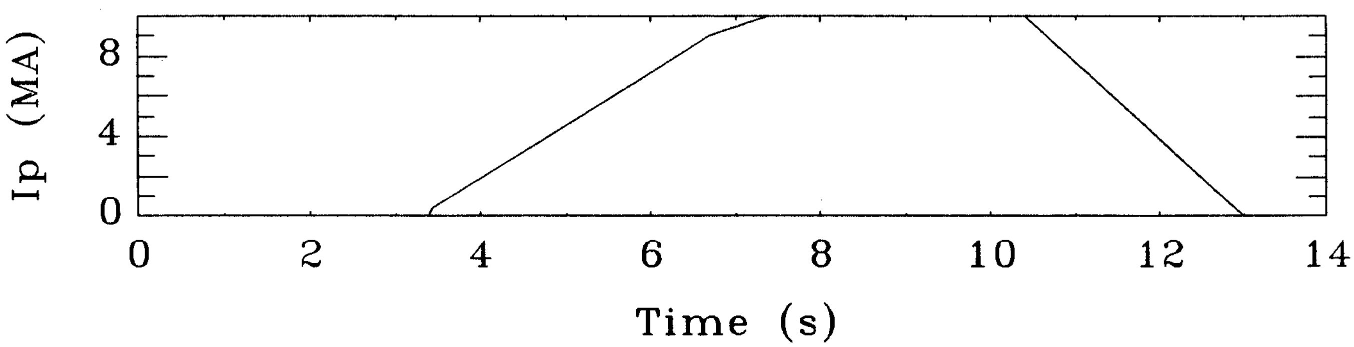
PF Line Power (MW) vs. Time (s)
CIT306L
Pline,max (MW) =437.687
Total
Resistive
Power (MW)
Time (s)
0
100
200
300
400
500
0
2
4
6
8
10
12
14


PF Line Power (MW) vs. Time (s)
CIT306L
Pline,max (MW) =437.687
PF Total
PF1,U+L
PF2,U+L
PF3,U+L
PF4,U+L
PF5,U+L
Power (MW)
Time (s)
0
100
200
300
400
500
0
2
4
6
8
10
12
14

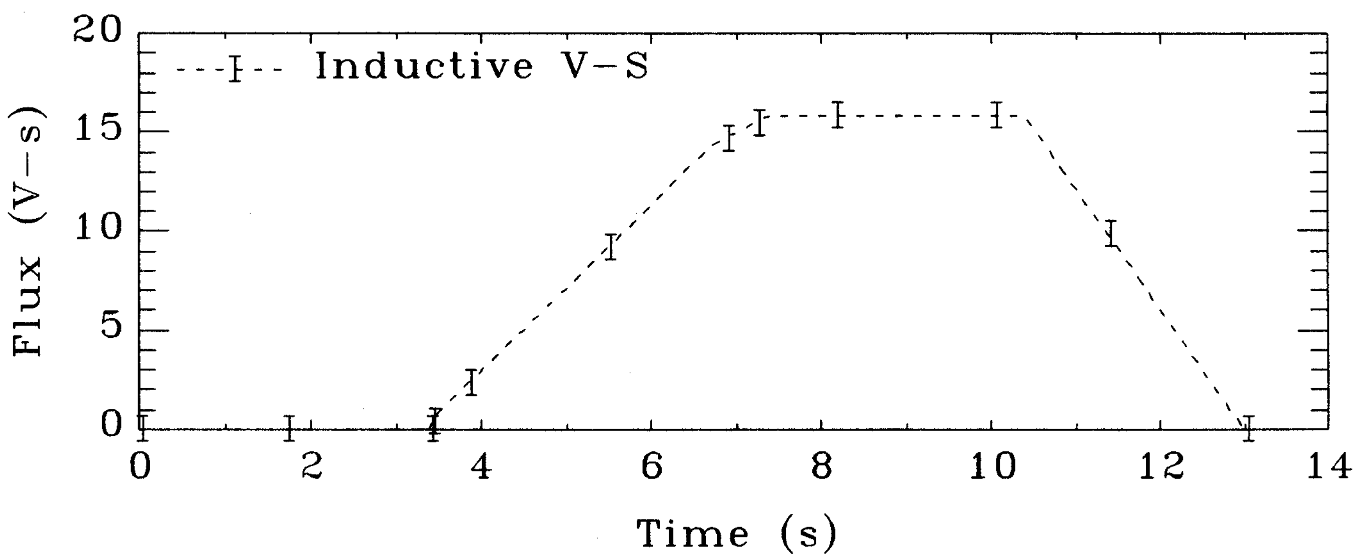

Plasma Loop Voltage (V) vs. Time (s)
CIT306L
Vloop,max (V) =6.33104
Vloop,min (V) =-31.4713
Voltage (V)
Time (s)
Total
PF1,U+L
PF2,U+L
PF3,U+L
PF4,U+L
PF5,U+L

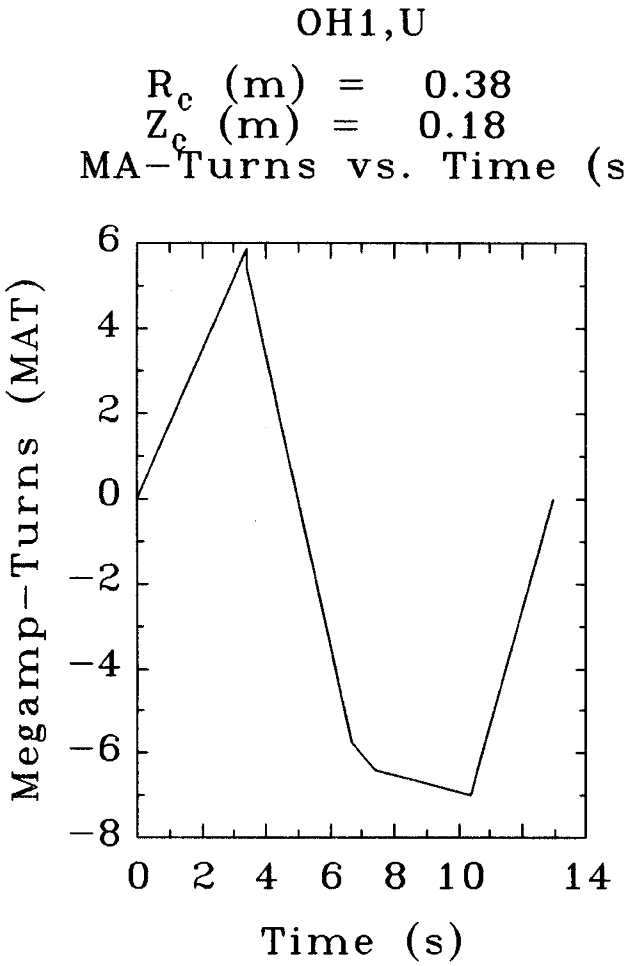

Plasma Volt-Seconds (Wb) vs. Time (s)
CIT306L
VS,max (Wb) =9.65708
Vs,min (Wb) =-16.4607
Total
PF1,U+L
PF2,U+L
PF3,U+L
PF4,U+L
PF5,U+L
Volt-seconds (Wb)
Time (s)
10
5
0
-5
-10
-15
-20
0
2
4
6
8
10
12
14

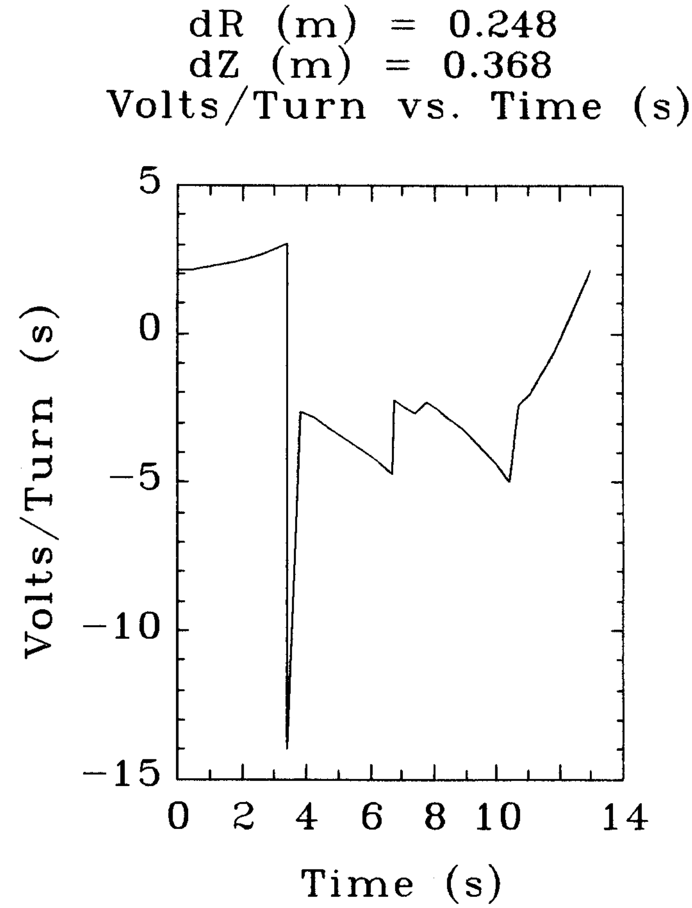
Plasma Current (MA) vs. Time (s)
CIT306L
I_p (MA) =10

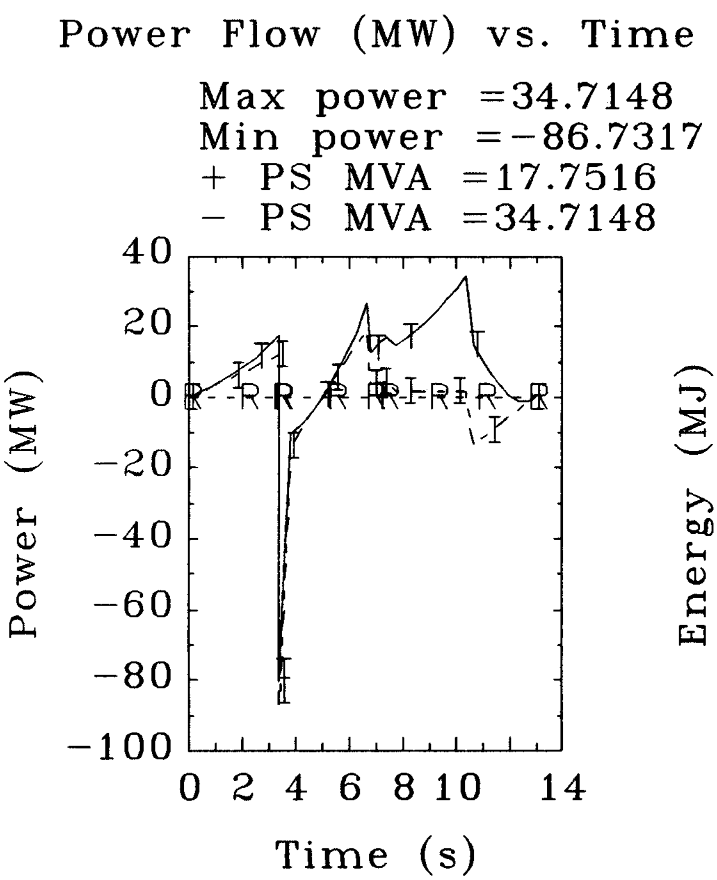


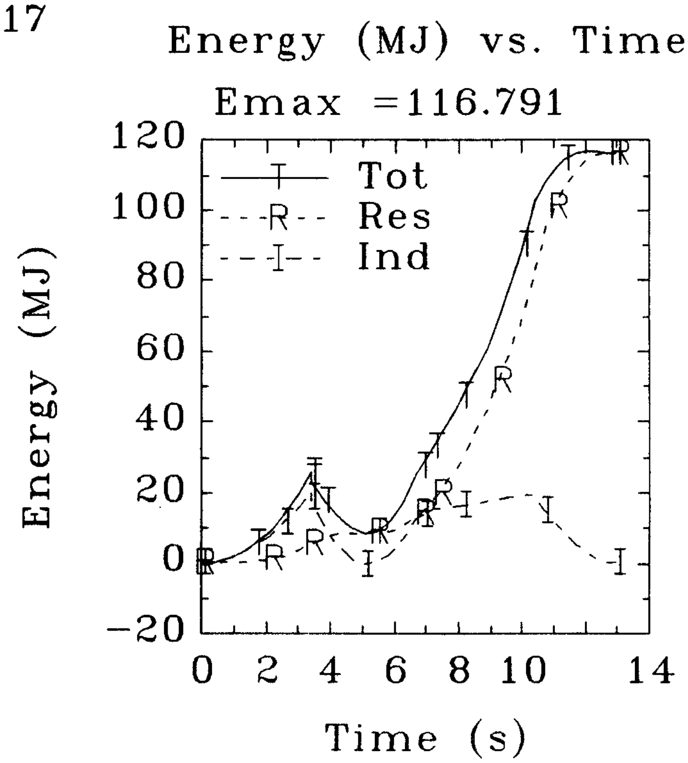
Plasma Volt-Seconds vs. Time (s)

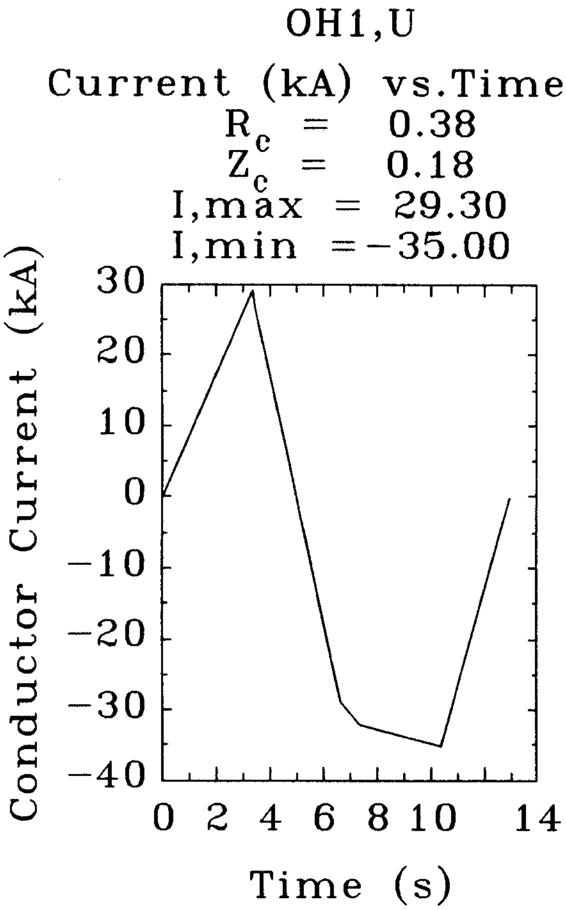


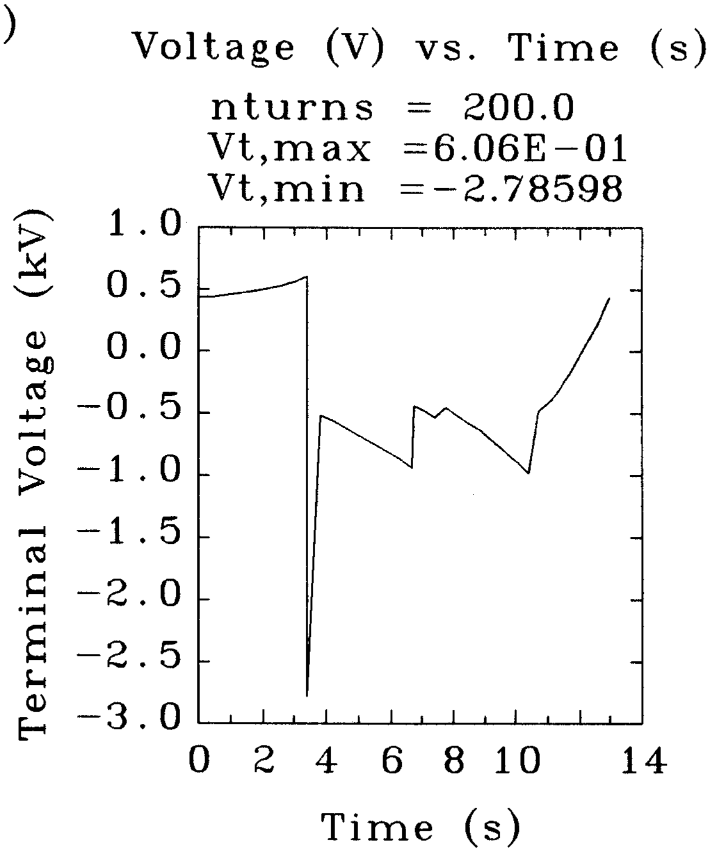

OH1,U
R_c (m) = 0.38
Z_c (m) = 0.18
MA-Turns vs. Time (s)
Megamp-Turns (MAT)
Time (s)

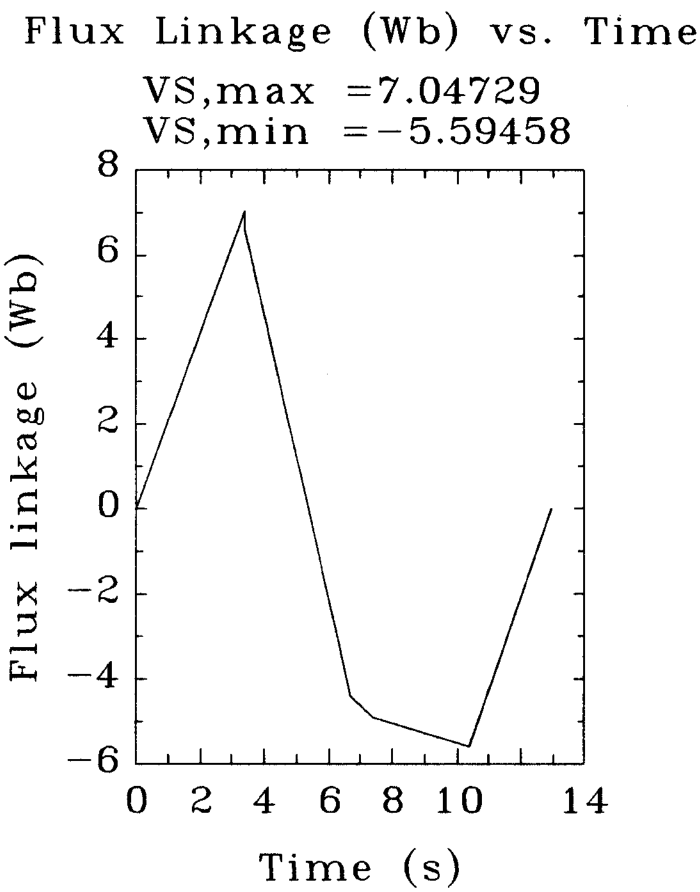

dR (m) = 0.248
dZ (m) = 0.368
Volts/Turn vs. Time (s)
Volts/Turn (s)
Time (s)

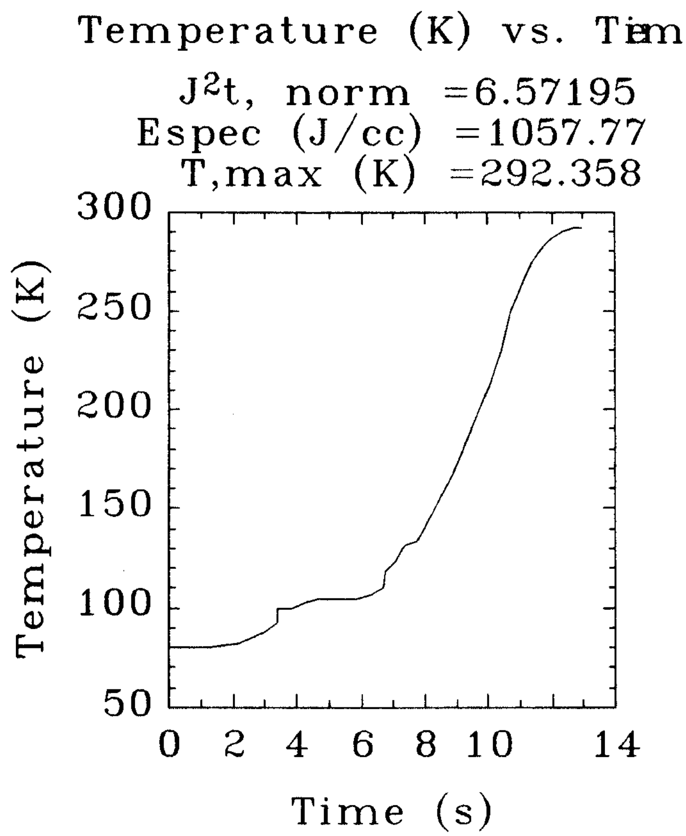

Power Flow (MW) vs. Time
Max power =34.7148
Min power =-86.7317
+ PS MVA =17.7516
- PS MVA =34.7148
Power (MW)
Time (s)

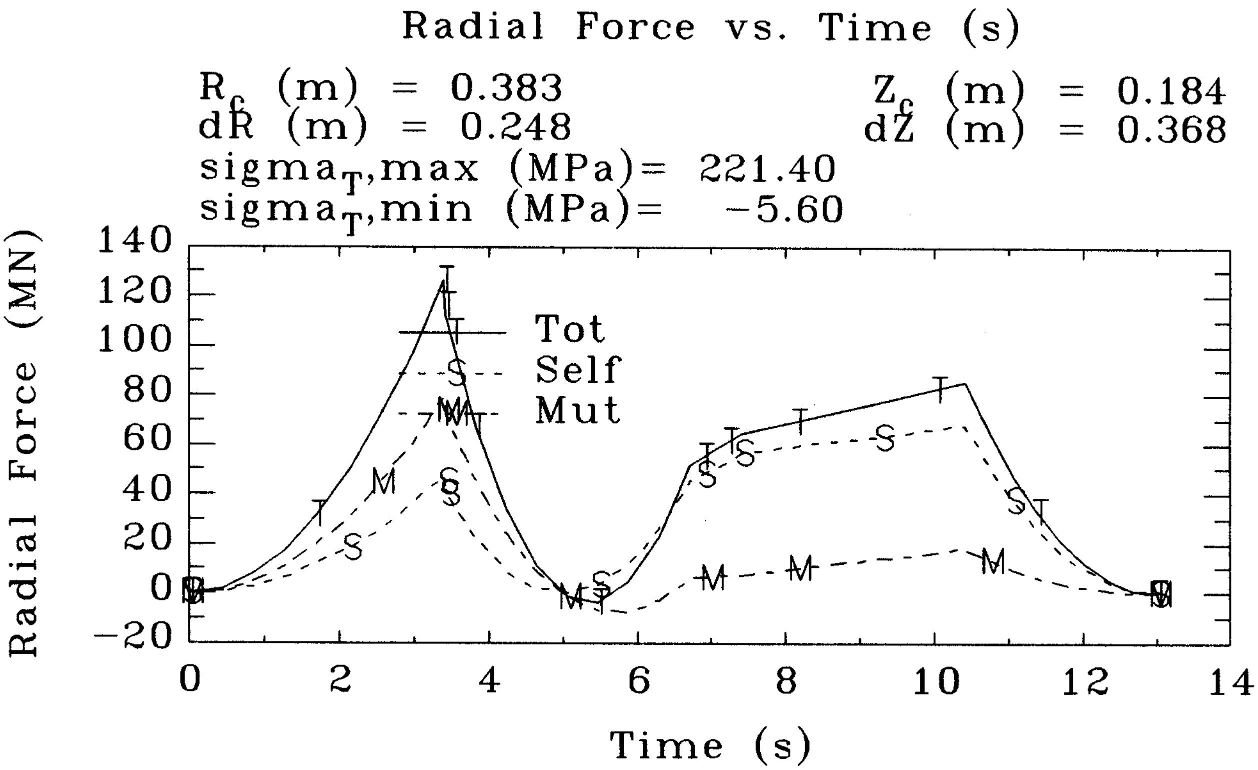

Energy (MJ) vs. Time
Emax =116.791
Tot
Res
Ind
Energy (MJ)
Time (s)

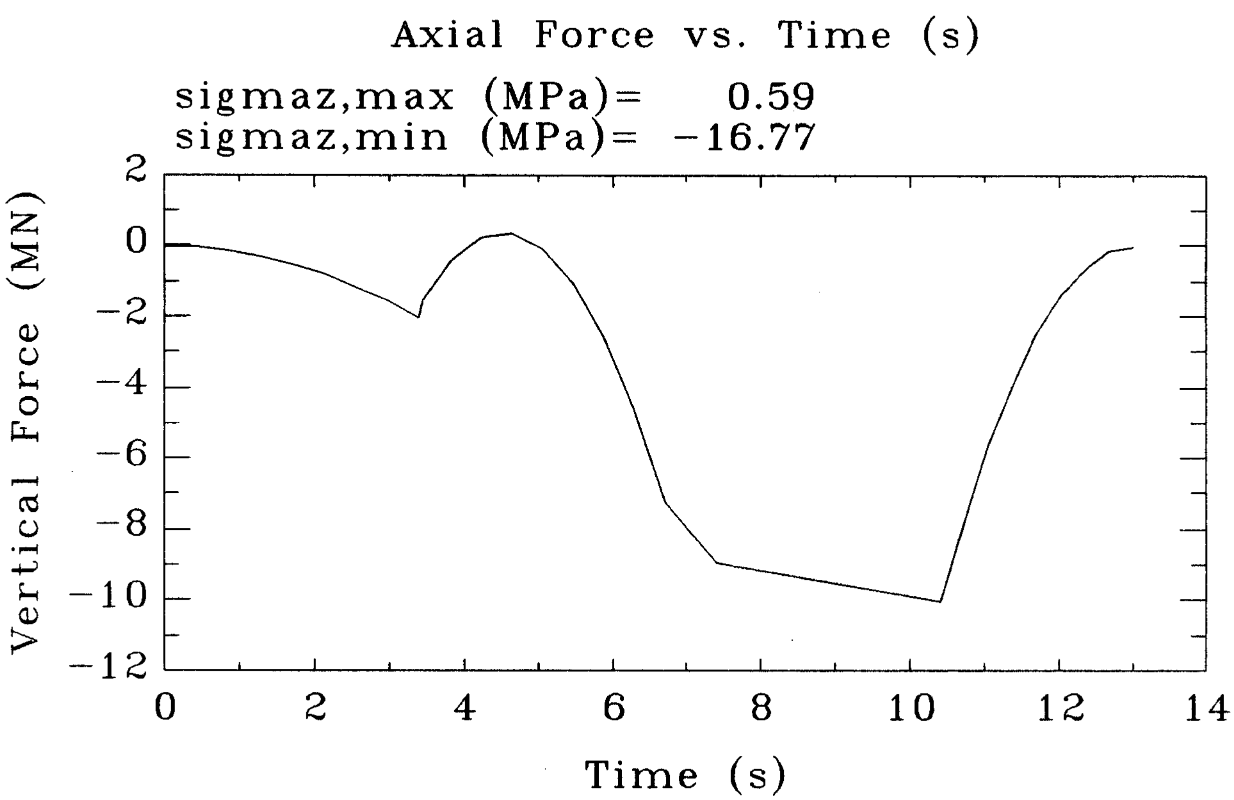

OH1,U
Current (kA) vs.Time (s)
R_c = 0.38
Z_c = 0.18
I,max = 29.30
I,min =-35.00
Conductor Current (kA)
30
20
10
0
-10
-20
-30
-40
0 2 4 6 8 10 14
Time (s)

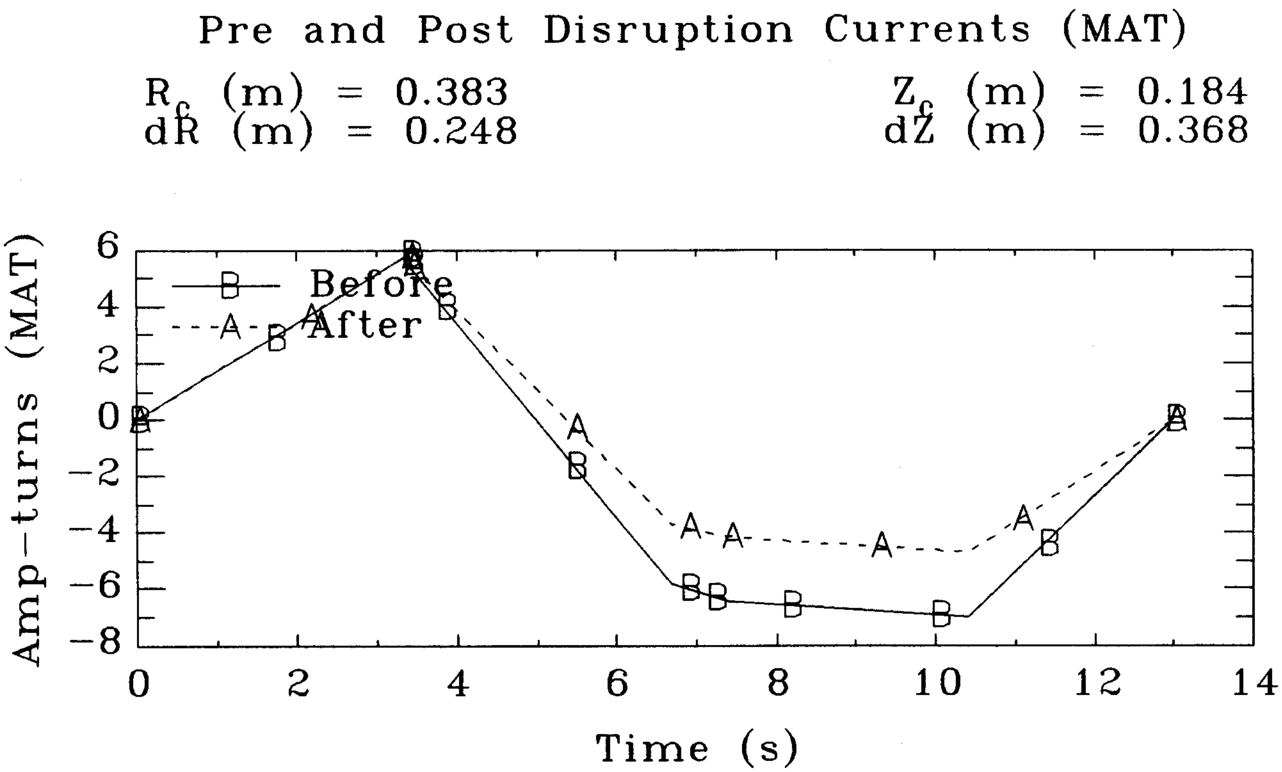

Voltage (V) vs. Time (s)
nturns = 200.0
Vt,max =6.06E-01
Vt,min =-2.78598
Terminal Voltage (kV)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
0 2 4 6 8 10 14
Time (s)


Flux Linkage (Wb) vs. Time
VS,max =7.04729
VS,min =-5.59458
Flux linkage (Wb)
8
6
4
2
0
-2
-4
-6
0 2 4 6 8 10 14
Time (s)

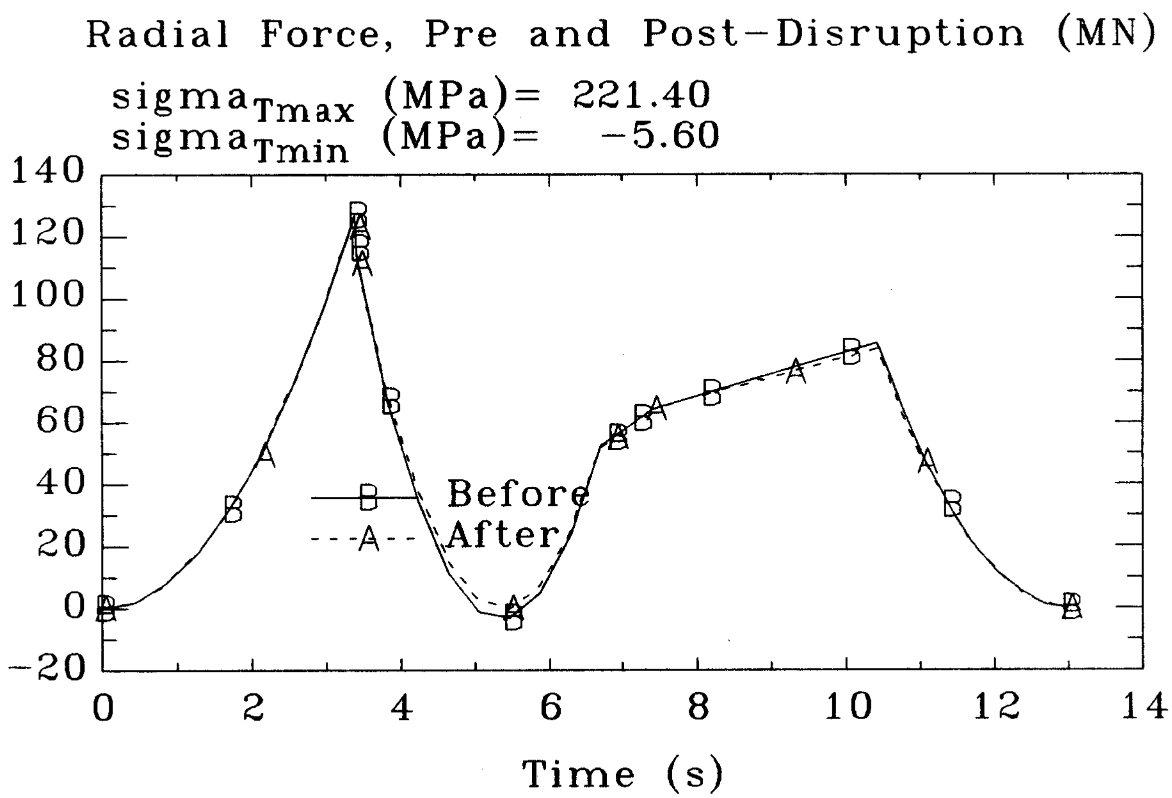

Temperature (K) vs. Tim
J2t, norm =6.57195
Espec (J/cc) =1057.77
T,max (K) =292.358
Temperature (K)
300
250
200
150
100
50
0 2 4 6 8 10 14
Time (s)


Radial Force vs. Time (s)
R_c (m) = 0.383
dR (m) = 0.248
Z_c (m) = 0.184
dZ (m) = 0.368
$sigma_T$,max (MPa)= 221.40
$sigma_T$,min (MPa)= -5.60
Radial Force (MN)
Tot
Self
Mut
Time (s)
140
120
100
80
60
40
20
0
-20
0
2
4
6
8
10
12
14


Axial Force vs. Time (s)
sigmaz,max (MPa)= 0.59
sigmaz,min (MPa)= -16.77
Vertical Force (MN)
Time (s)
2
0
-2
-4
-6
-8
-10
-12
0
2
4
6
8
10
12
14



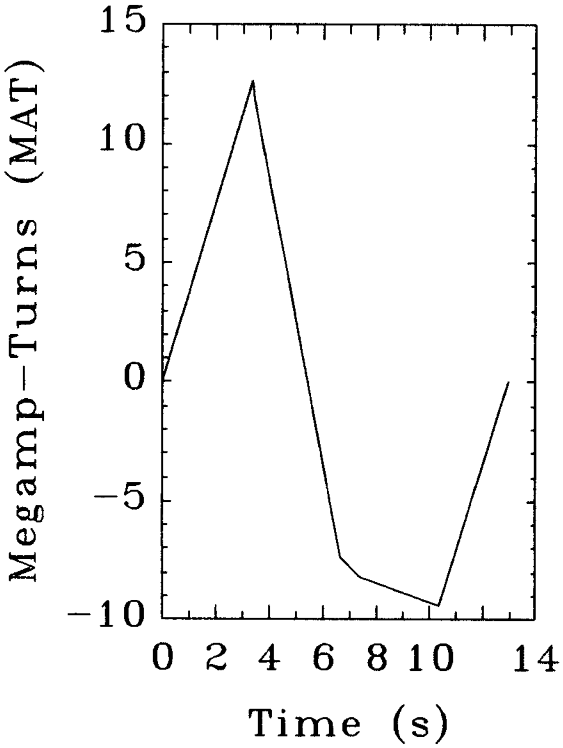
Pre and Post Disruption Currents (MAT)
R_c (m) = 0.383
dR (m) = 0.248
Z_c (m) = 0.184
dZ (m) = 0.368
Before
After
Amp-turns (MAT)
Time (s)



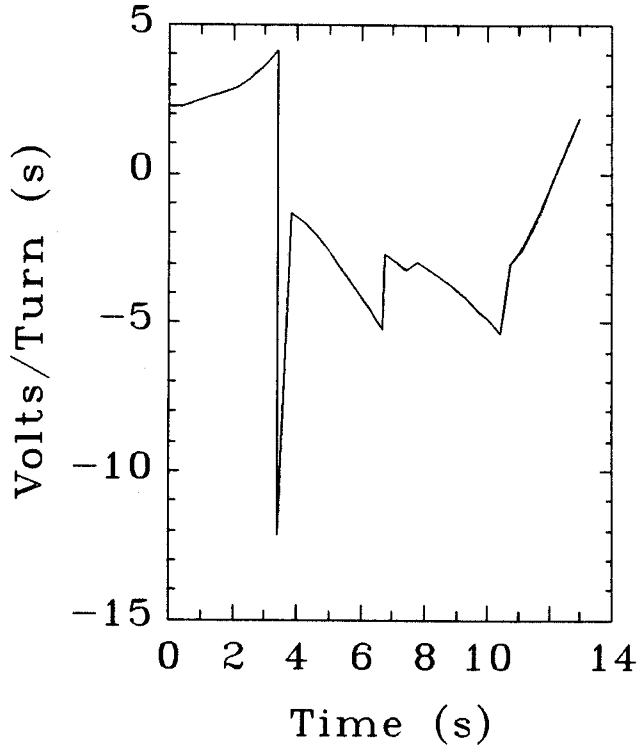
Radial Force, Pre and Post-Disruption (MN)
$sigma_{Tmax}$ (MPa)= 221.40
$sigma_{Tmin}$ (MPa)= -5.60
Before
After
Time (s)

OH2,U

R_c (m) = 0.38
Z_c (m) = 0.68
MA-Turns vs. Time (s)

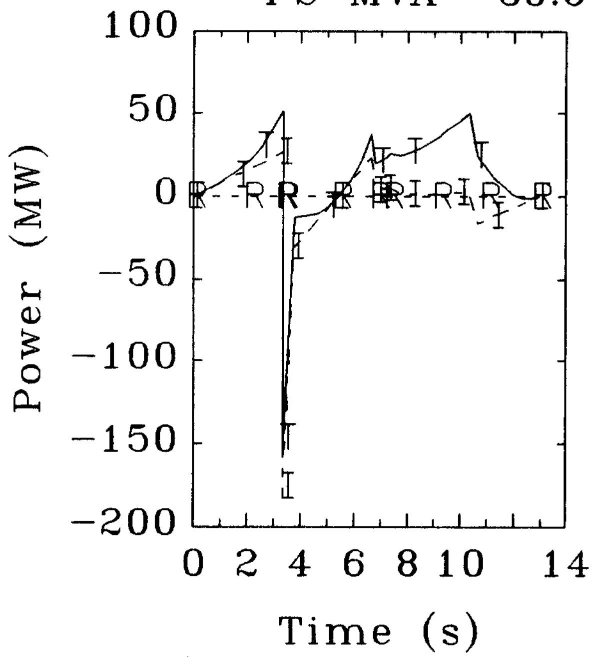


dR (m) = 0.248
dZ (m) = 0.632
Volts/Turn vs. Time (s)



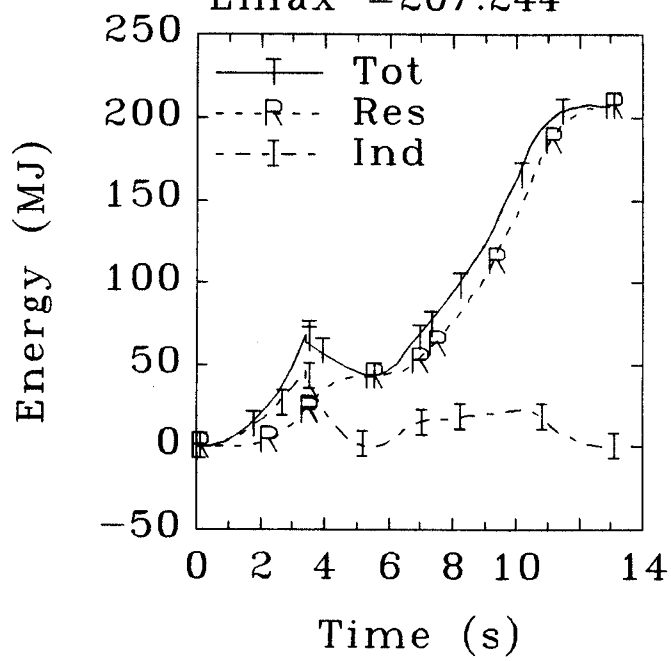
Power Flow (MW) vs. Time

Max power =52.5261
Min power =-181.474
\+ PS MVA =52.5261
\- PS MVA =50.979



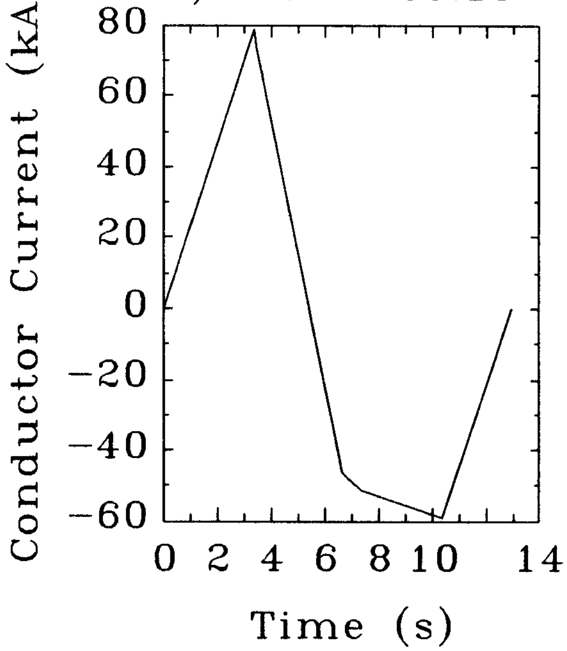
Energy (MJ) vs. Time

Emax =207.244

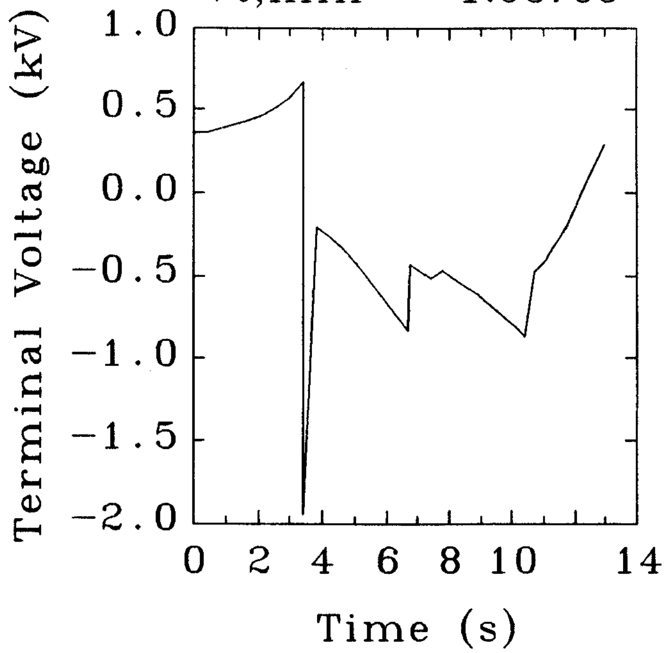


OH2,U

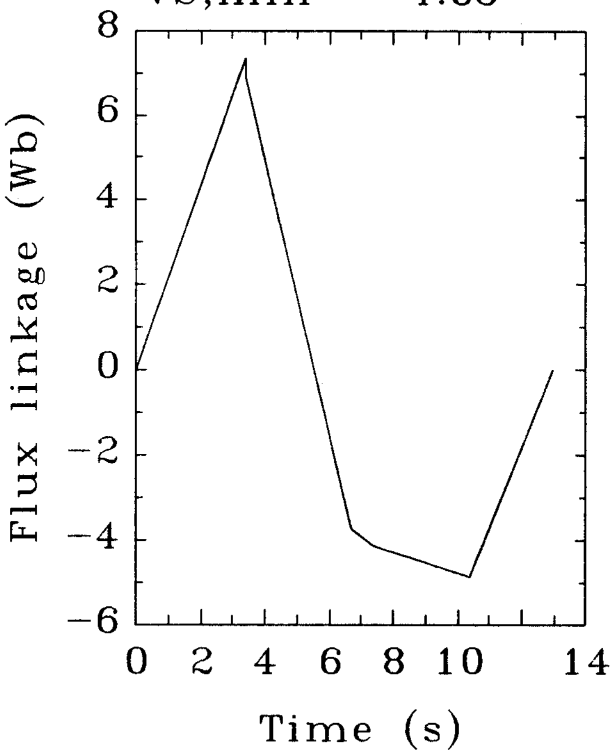
Current (kA) vs.Time (s)
R_c = 0.38
Z_c = 0.68
I,max = 78.75
I,min =-59.13



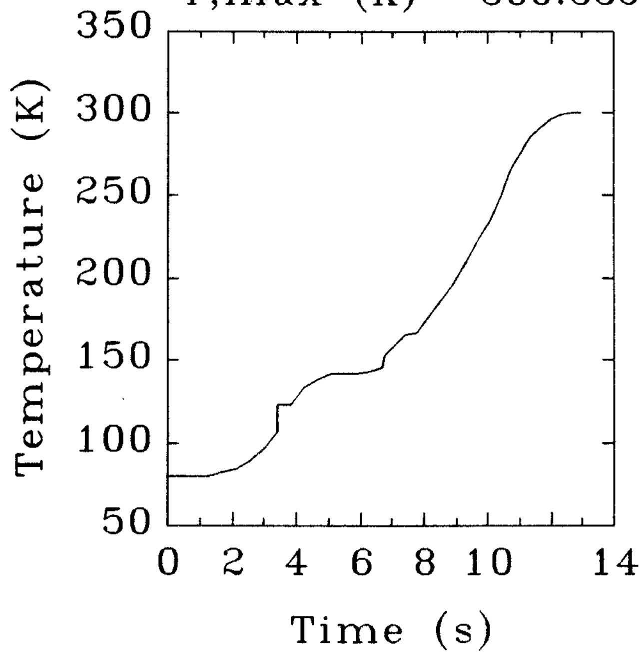
Voltage (V) vs. Time (s)
nturns = 160.0
Vt,max =6.67E-01
Vt,min =-1.93783

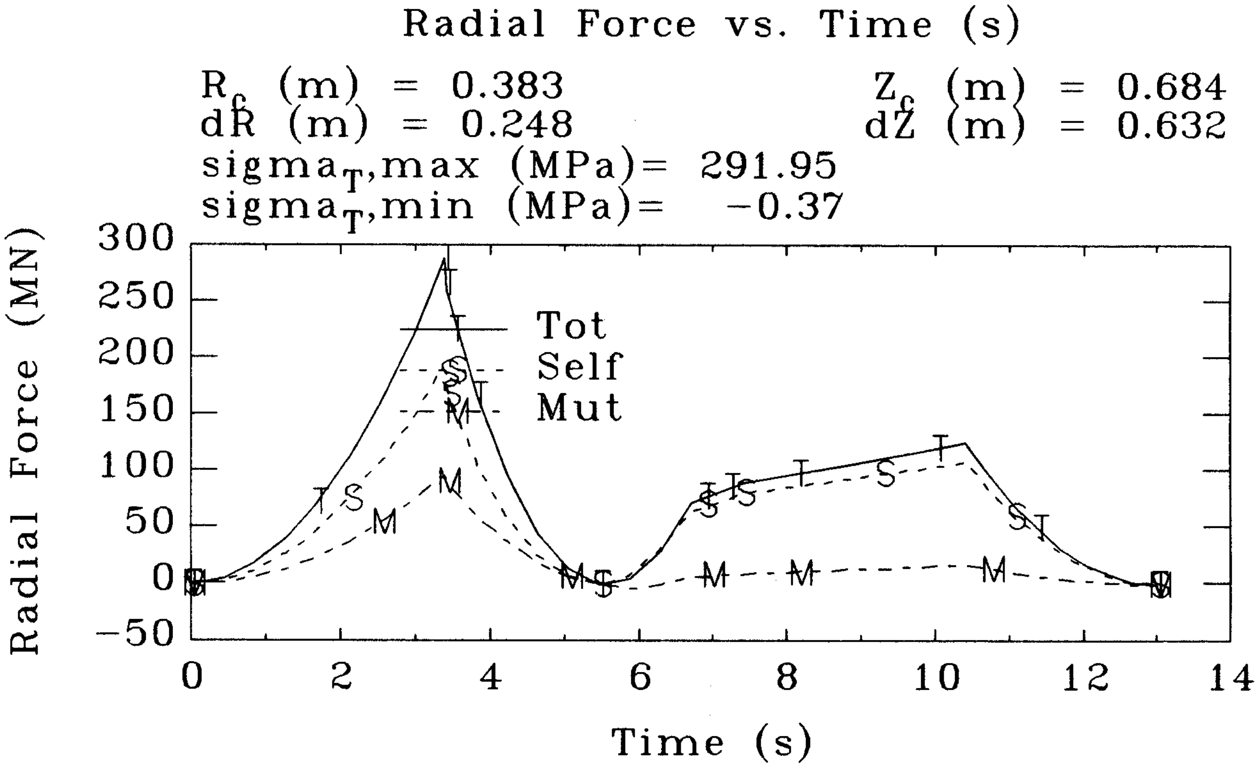


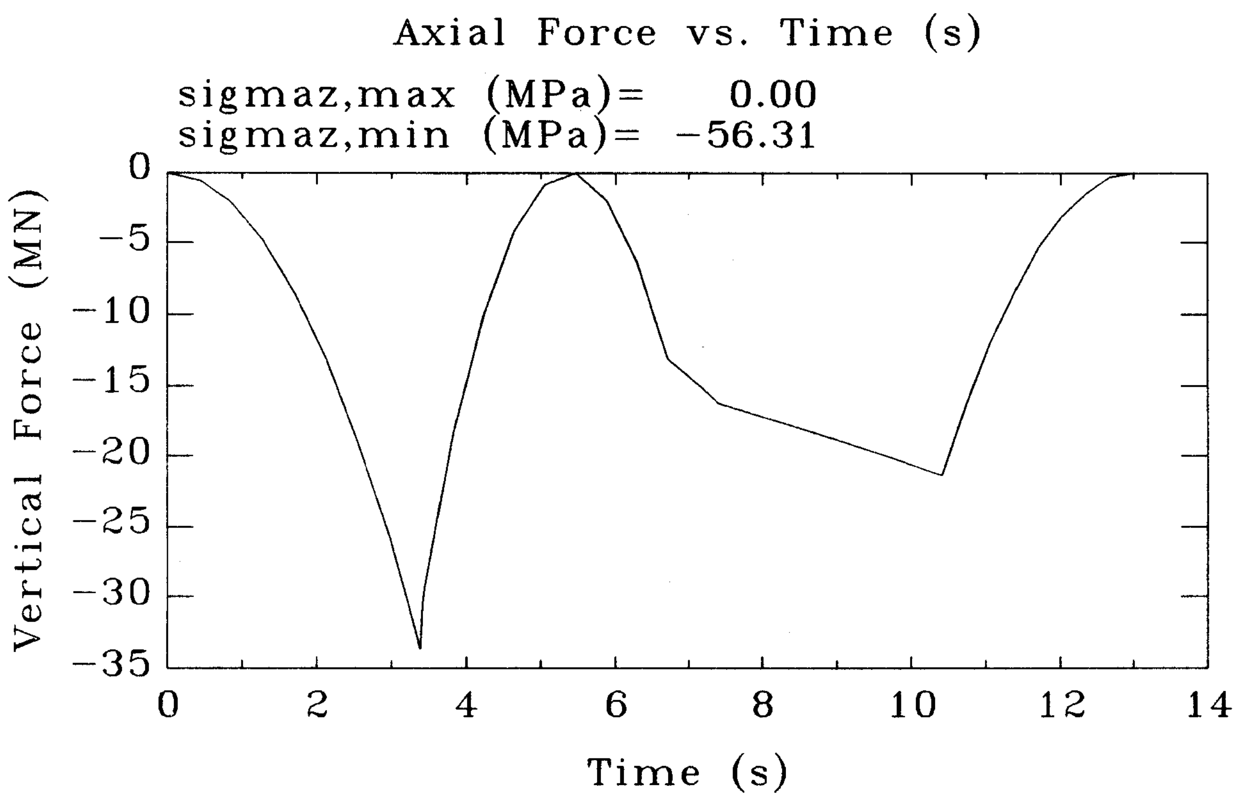
Flux Linkage (Wb) vs. Time
VS,max =7.34052
VS,min =-4.85



Temperature (K) vs. Tim
J^2t, norm =8.36783
Espec (J/cc) =1370.28
T,max (K) =300.559



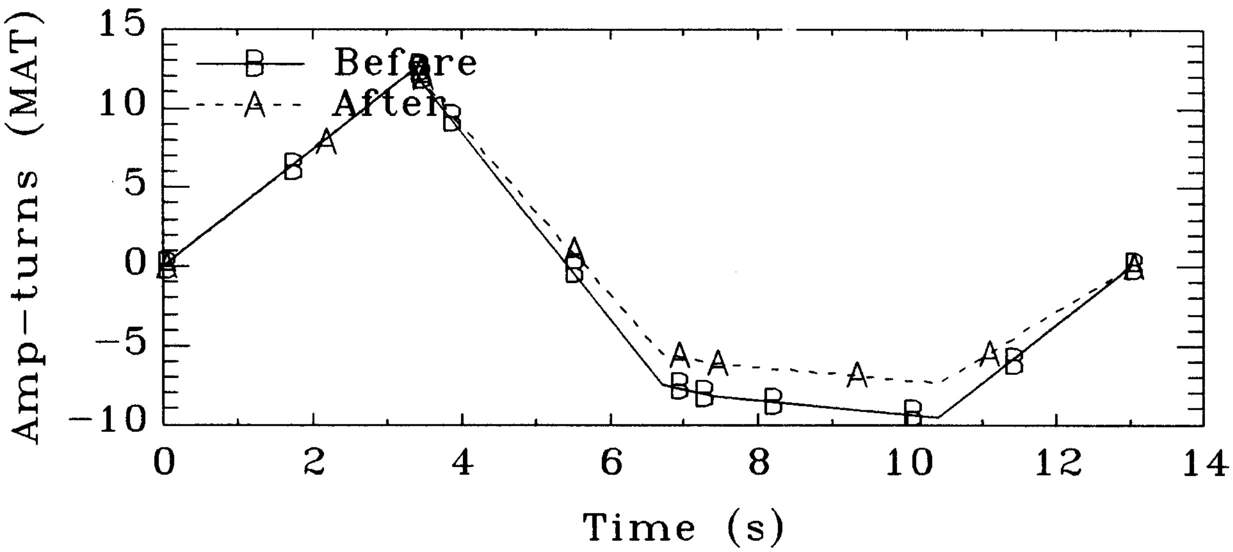

Radial Force vs. Time (s)
R_c (m) = 0.383
Z_c (m) = 0.684
dR (m) = 0.248
dZ (m) = 0.632
sigma_T,max (MPa)= 291.95
sigma_T,min (MPa)= -0.37
Tot
Self
Mut
Radial Force (MN)
Time (s)


Axial Force vs. Time (s)
sigmaz,max (MPa)= 0.00
sigmaz,min (MPa)= -56.31
Vertical Force (MN)
Time (s)

Pre and Post Disruption Currents (MAT)

R_c (m) = 0.383 Z_c (m) = 0.684

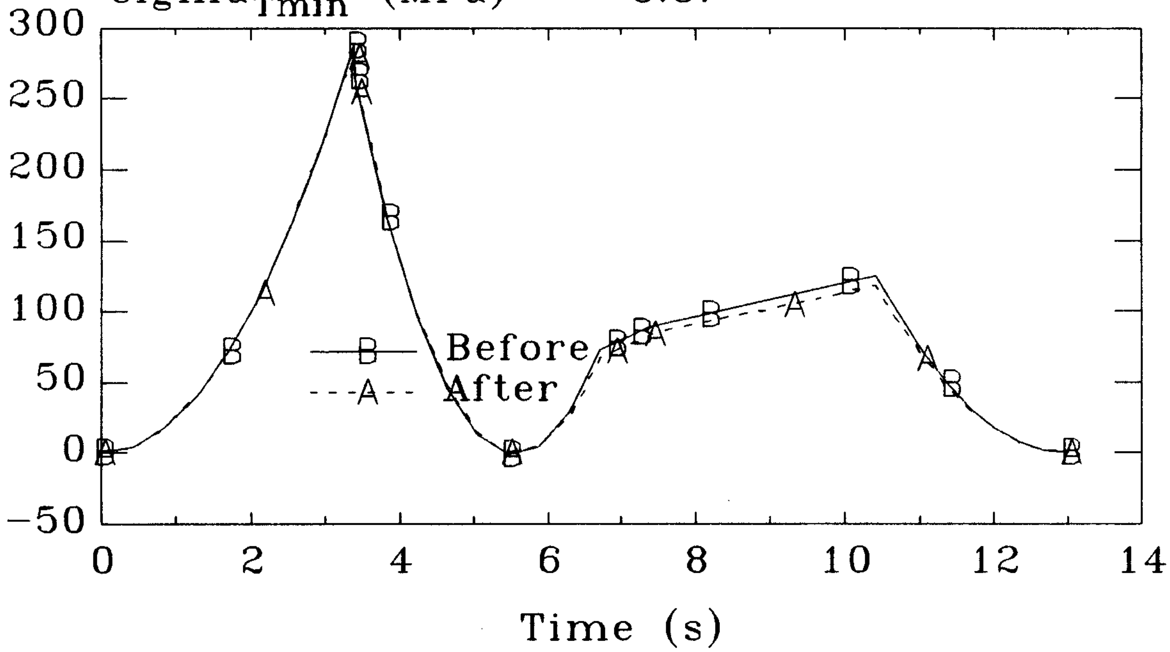
dR (m) = 0.248 dZ (m) = 0.632

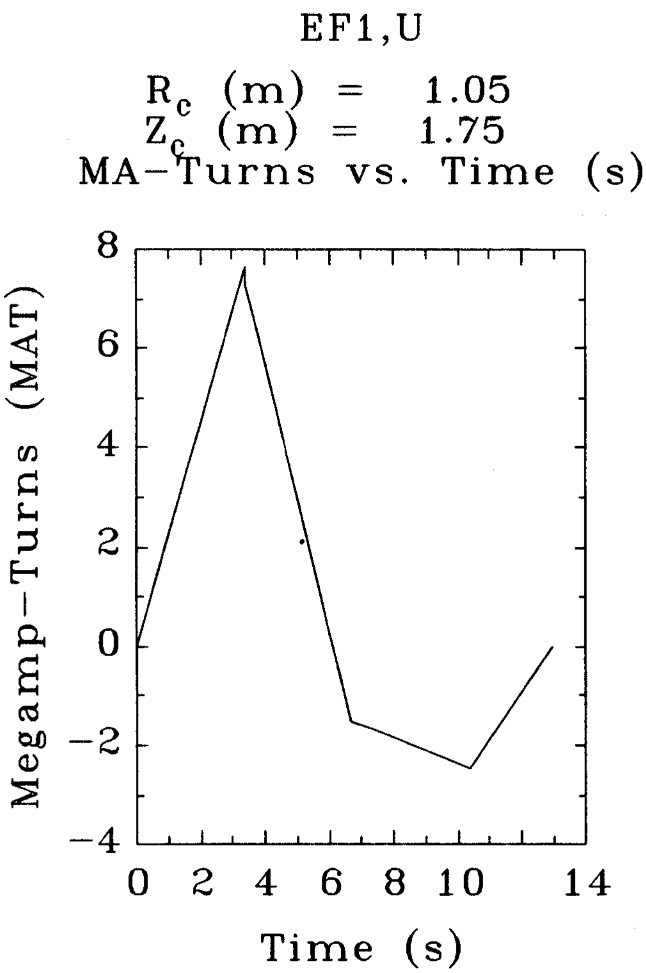


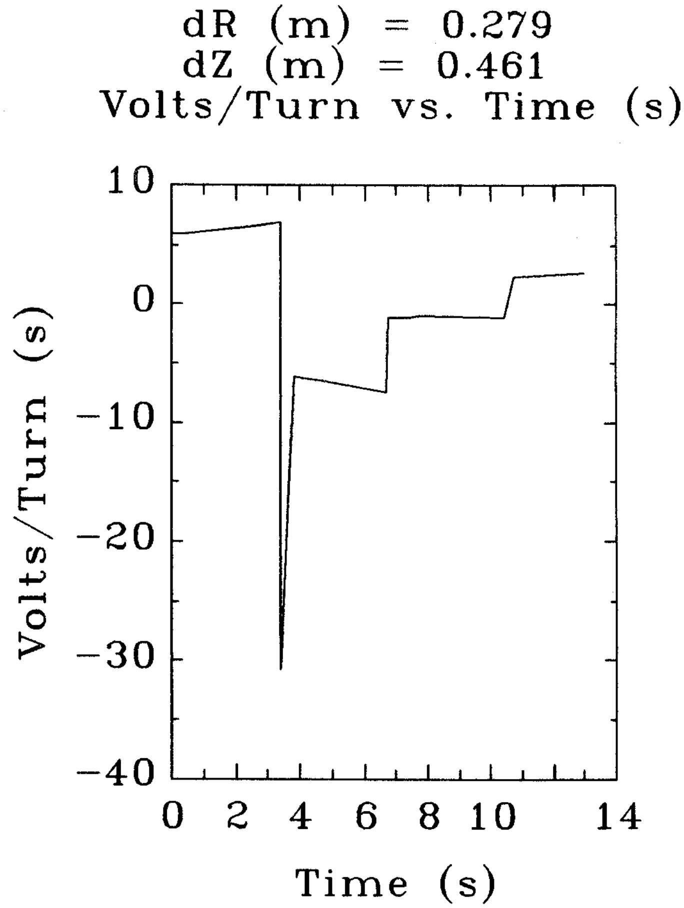
Radial Force, Pre and Post-Disruption (MN)

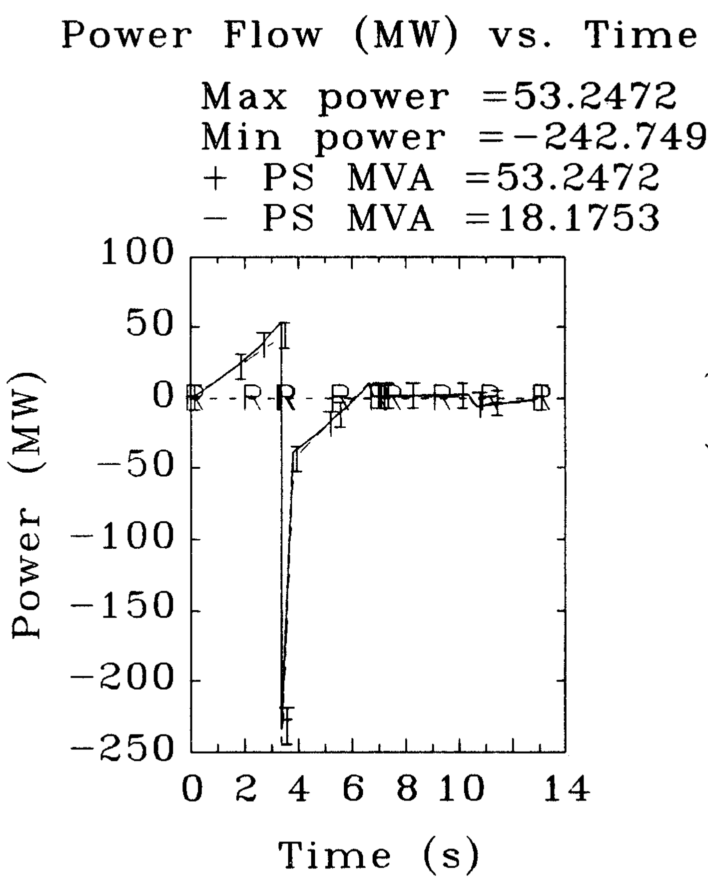
$sigma_{Tmax}$ (MPa)= 291.95

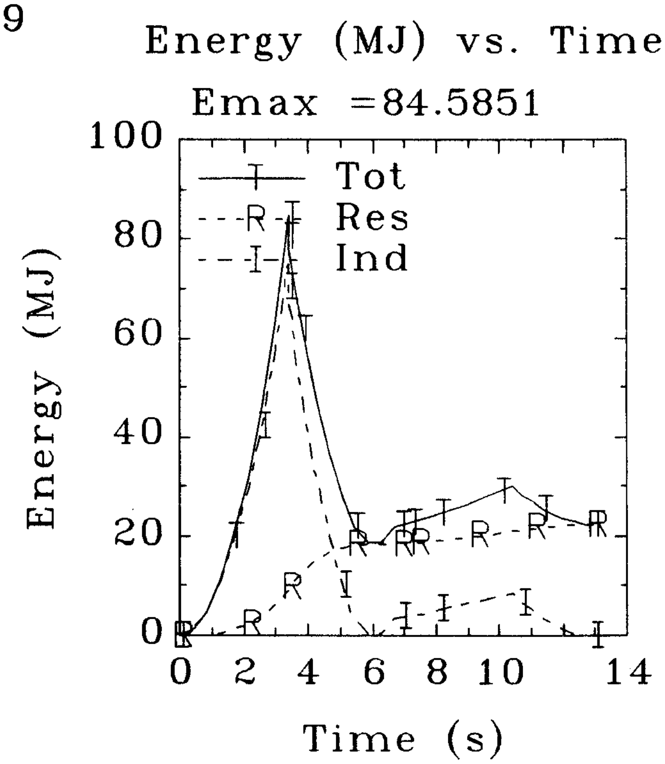
$sigma_{Tmin}$ (MPa)= -0.37

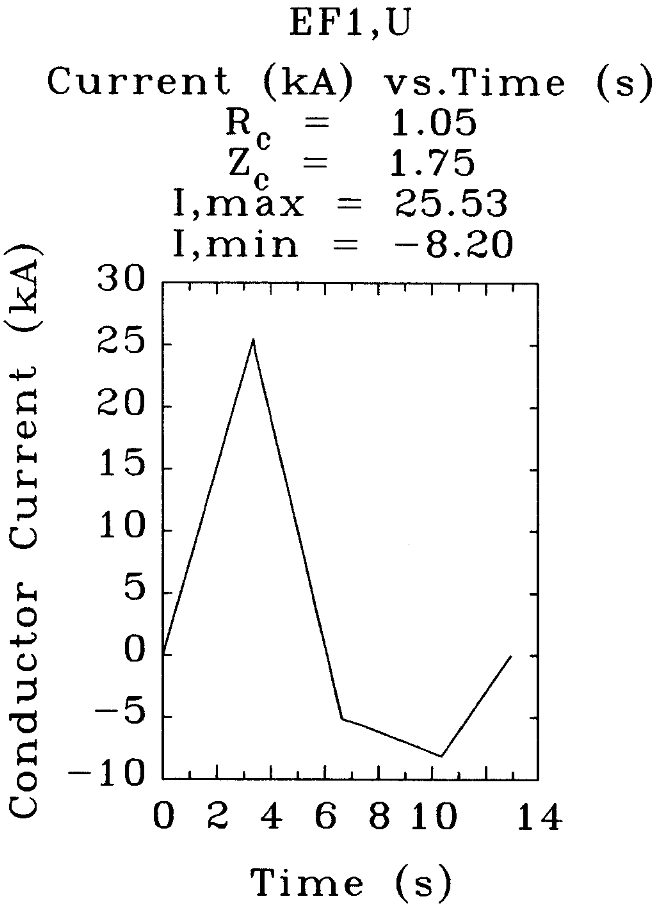


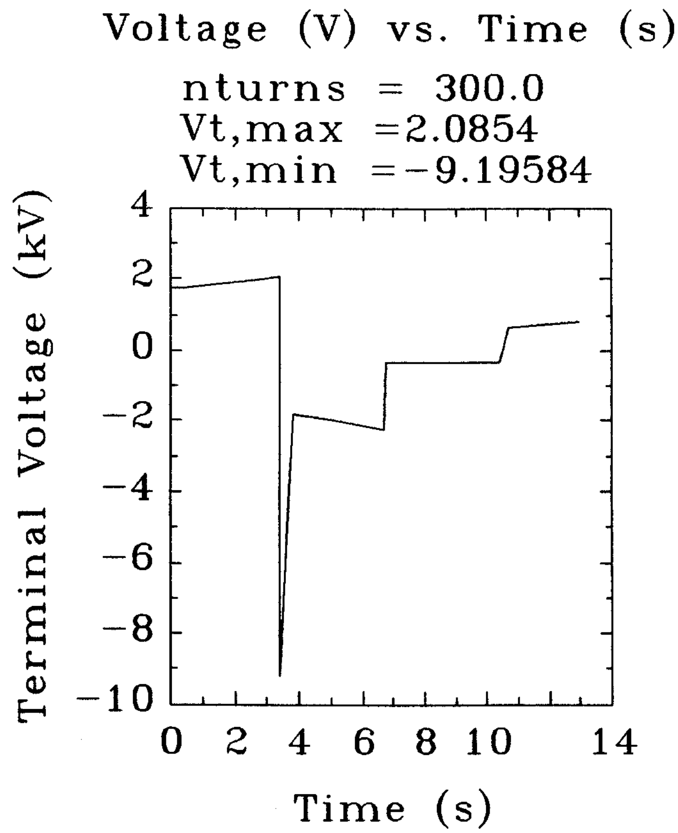

EF1,U
R_c (m) = 1.05
Z_c (m) = 1.75
MA-Turns vs. Time (s)
Megamp-Turns (MAT)
8
6
4
2
0
−2
−4
0 2 4 6 8 10 14
Time (s)

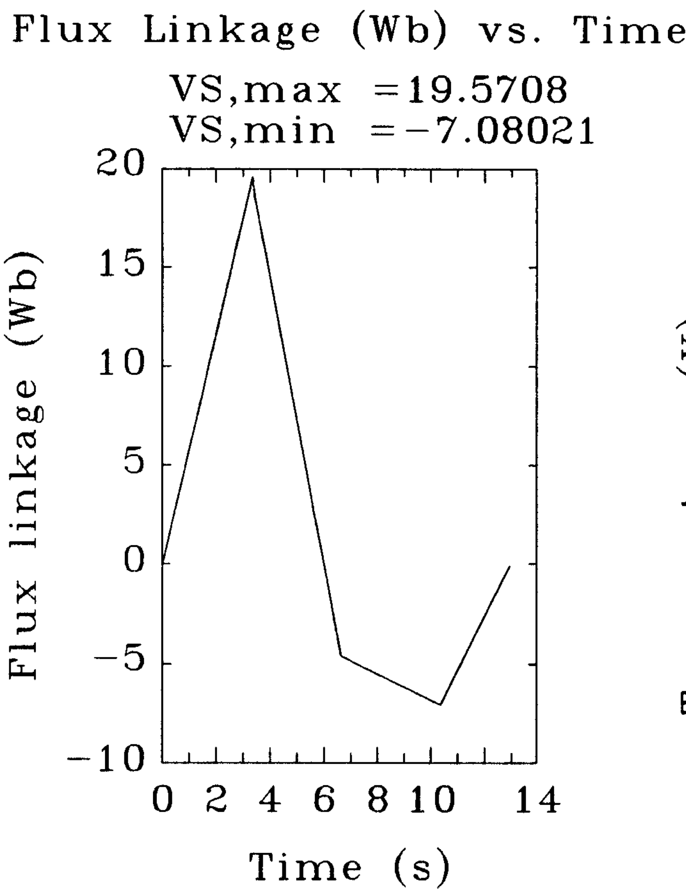

dR (m) = 0.279
dZ (m) = 0.461
Volts/Turn vs. Time (s)
Volts/Turn (s)
10
0
−10
−20
−30
−40
0 2 4 6 8 10 14
Time (s)

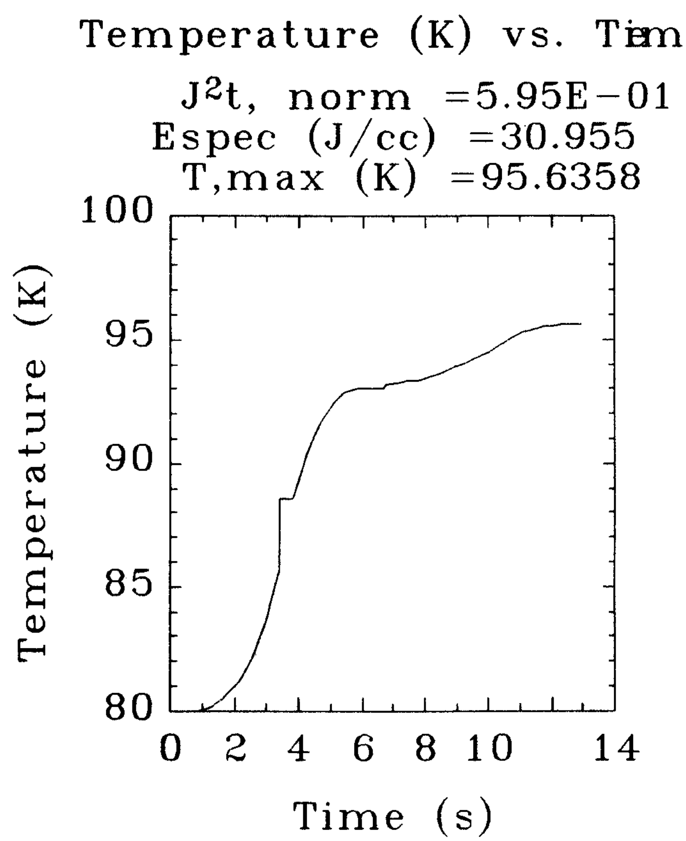

Power Flow (MW) vs. Time
Max power =53.2472
Min power =−242.749
+ PS MVA =53.2472
− PS MVA =18.1753
Power (MW)
100
50
0
−50
−100
−150
−200
−250
0 2 4 6 8 10 14
Time (s)

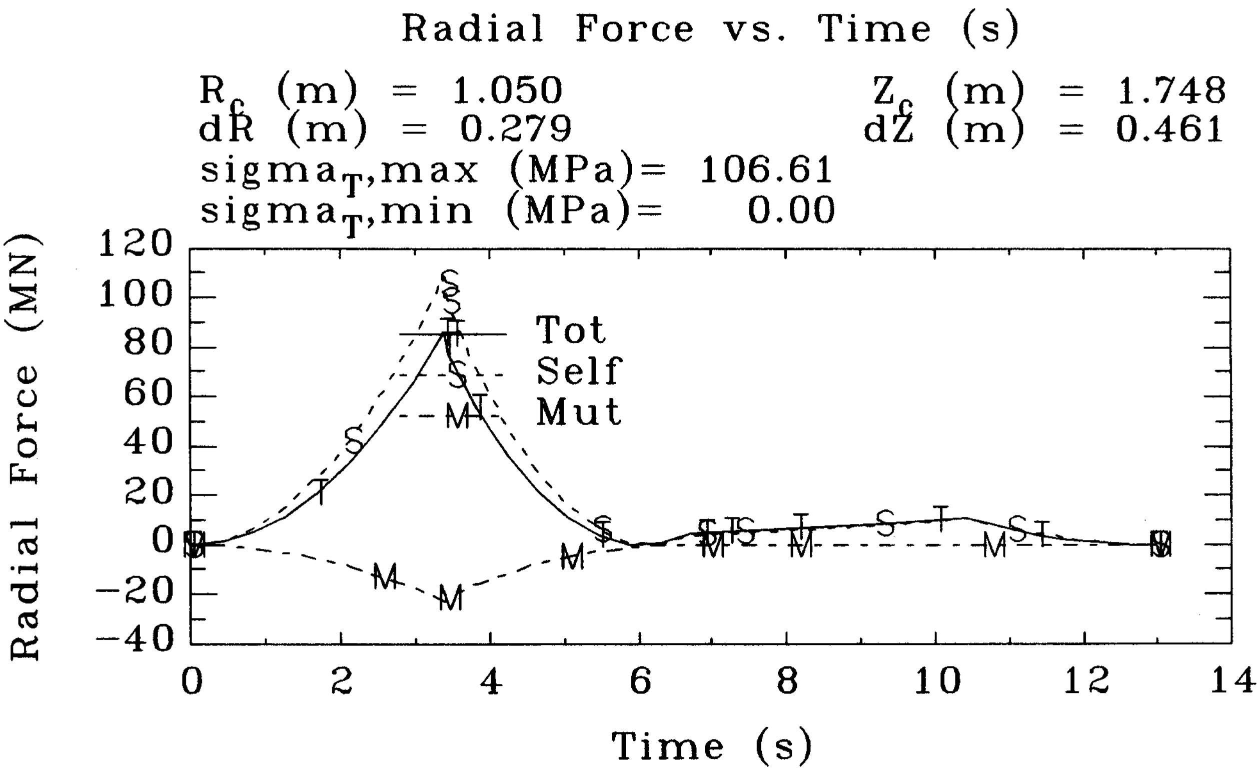

Energy (MJ) vs. Time
Emax =84.5851
Tot
Res
Ind
Energy (MJ)
100
80
60
40
20
0
0 2 4 6 8 10 14
Time (s)

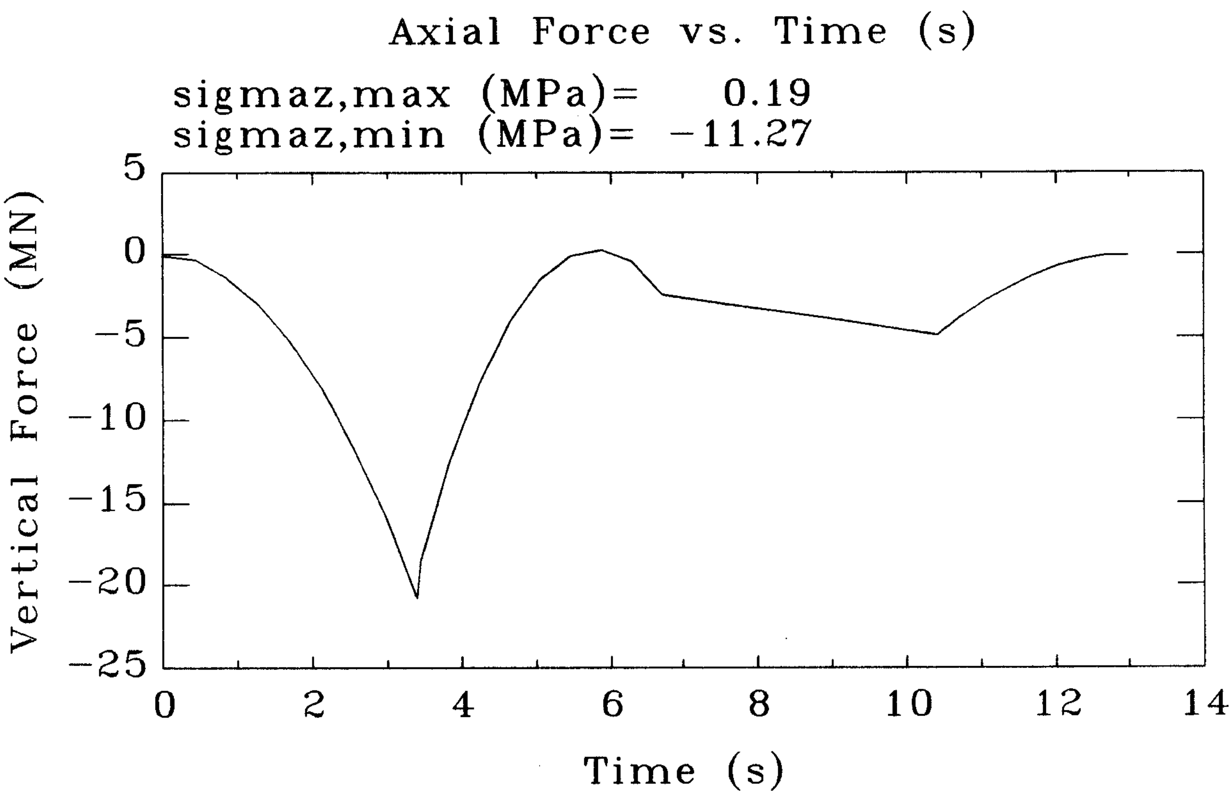

EF1,U
Current (kA) vs.Time (s)
R_c = 1.05
Z_c = 1.75
I,max = 25.53
I,min = -8.20
Conductor Current (kA)
30
25
20
15
10
5
0
-5
-10
0 2 4 6 8 10 14
Time (s)


Voltage (V) vs. Time (s)
nturns = 300.0
Vt,max =2.0854
Vt,min =-9.19584
Terminal Voltage (kV)
4
2
0
-2
-4
-6
-8
-10
0 2 4 6 8 10 14
Time (s)


Flux Linkage (Wb) vs. Time
VS,max =19.5708
VS,min =-7.08021
Flux linkage (Wb)
20
15
10
5
0
-5
-10
0 2 4 6 8 10 14
Time (s)

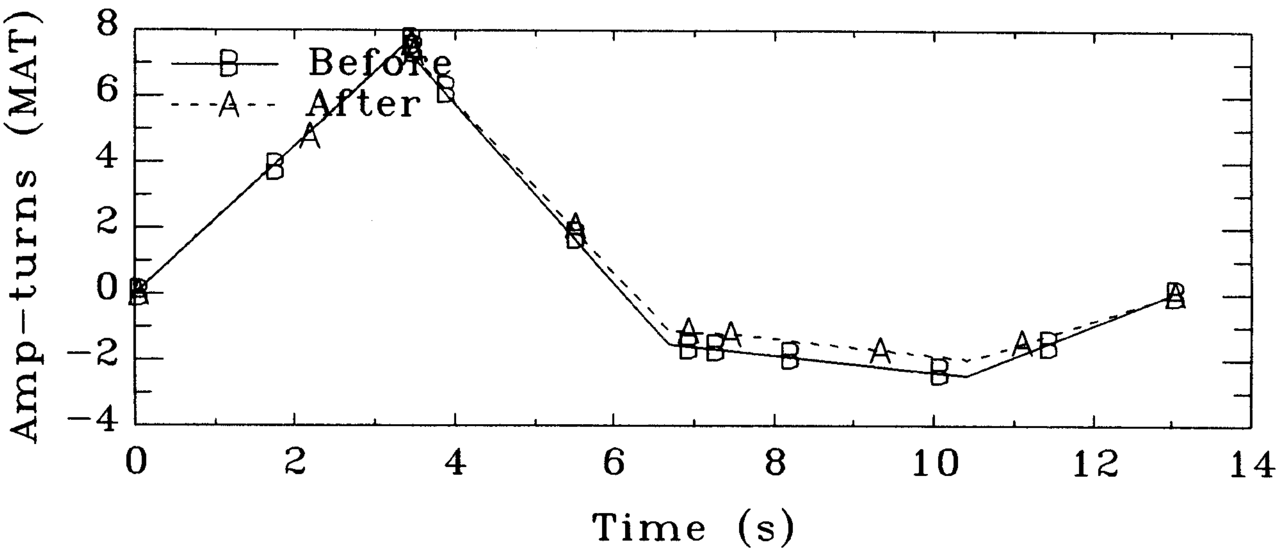

Temperature (K) vs. Tim
J^2t, norm =5.95E-01
Espec (J/cc) =30.955
T,max (K) =95.6358
Temperature (K)
100
95
90
85
80
0 2 4 6 8 10 14
Time (s)


Radial Force vs. Time (s)
R_c (m) = 1.050
Z_c (m) = 1.748
dR (m) = 0.279
dZ (m) = 0.461
sigma_T,max (MPa)= 106.61
sigma_T,min (MPa)= 0.00
Tot
Self
Mut
Radial Force (MN)
Time (s)
120
100
80
60
40
20
0
−20
−40
0
2
4
6
8
10
12
14


Axial Force vs. Time (s)
sigmaz,max (MPa)= 0.19
sigmaz,min (MPa)= −11.27
Vertical Force (MN)
Time (s)
5
0
−5
−10
−15
−20
−25
0
2
4
6
8
10
12
14

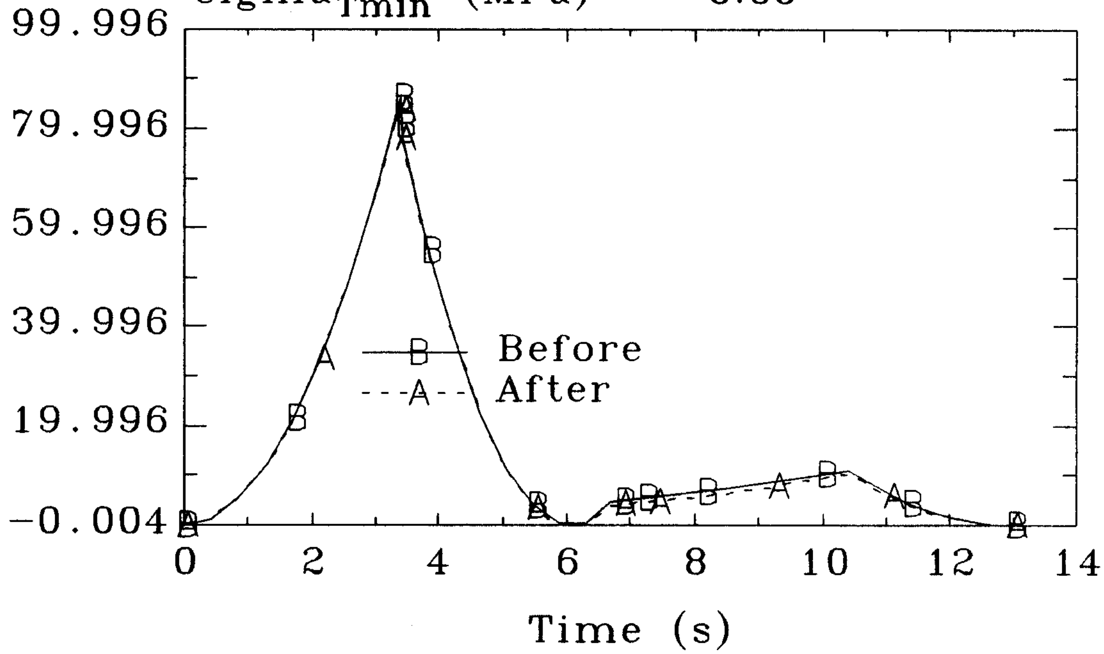
Pre and Post Disruption Currents (MAT)

R_c (m) = 1.050 Z_c (m) = 1.748
dR (m) = 0.279 dZ (m) = 0.461



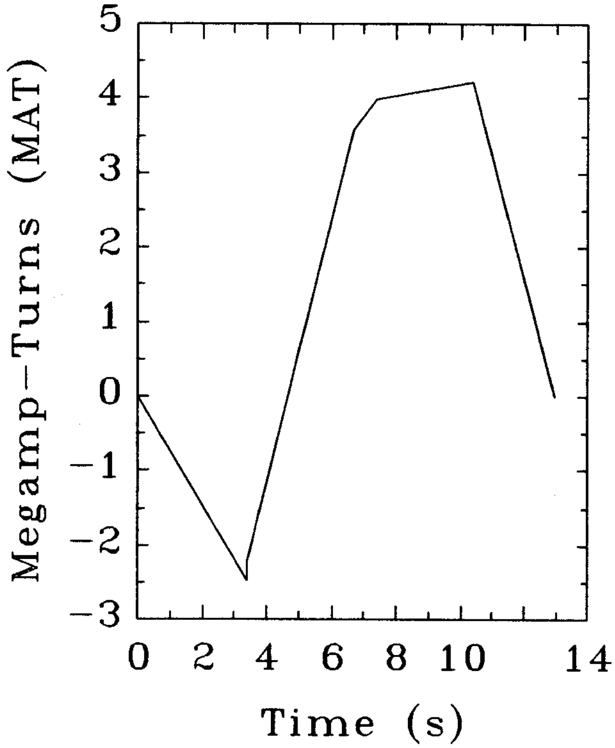
Radial Force, Pre and Post-Disruption (MN)

$sigma_{Tmax}$ (MPa)= 106.61
$sigma_{Tmin}$ (MPa)= 0.00

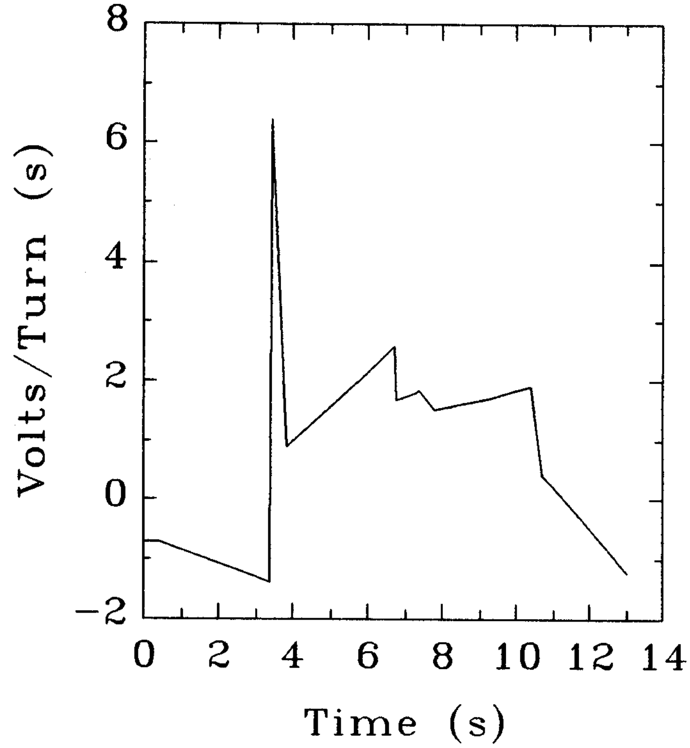


EF2,U

R_c (m) = 2.05
Z_c (m) = 1.68
MA−Turns vs. Time (s)

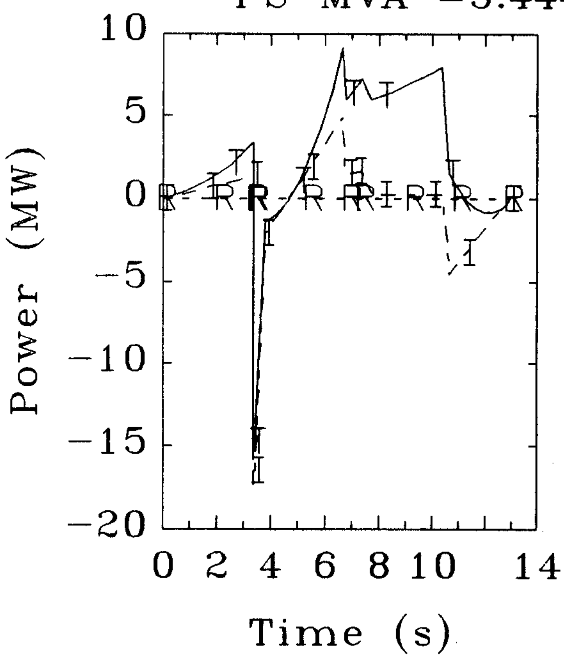


dR (m) = 0.326
dZ (m) = 0.326
Volts/Turn vs. Time (s)



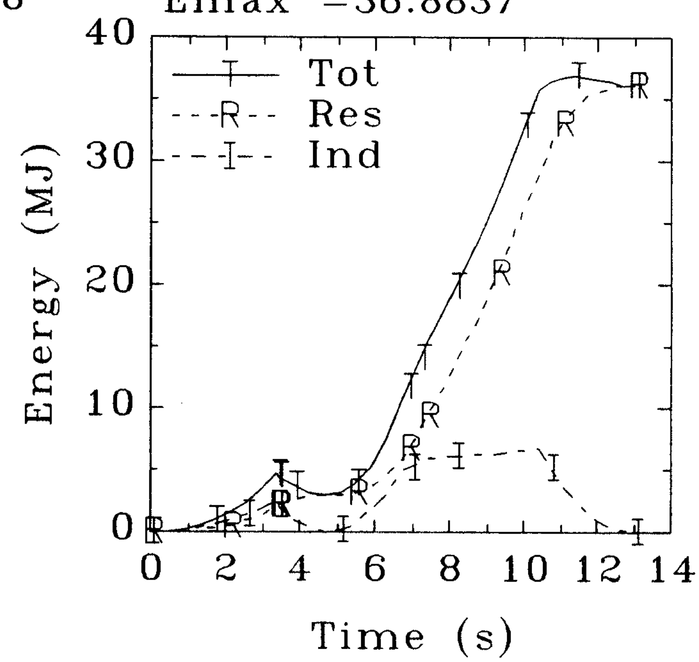
Power Flow (MW) vs. Time

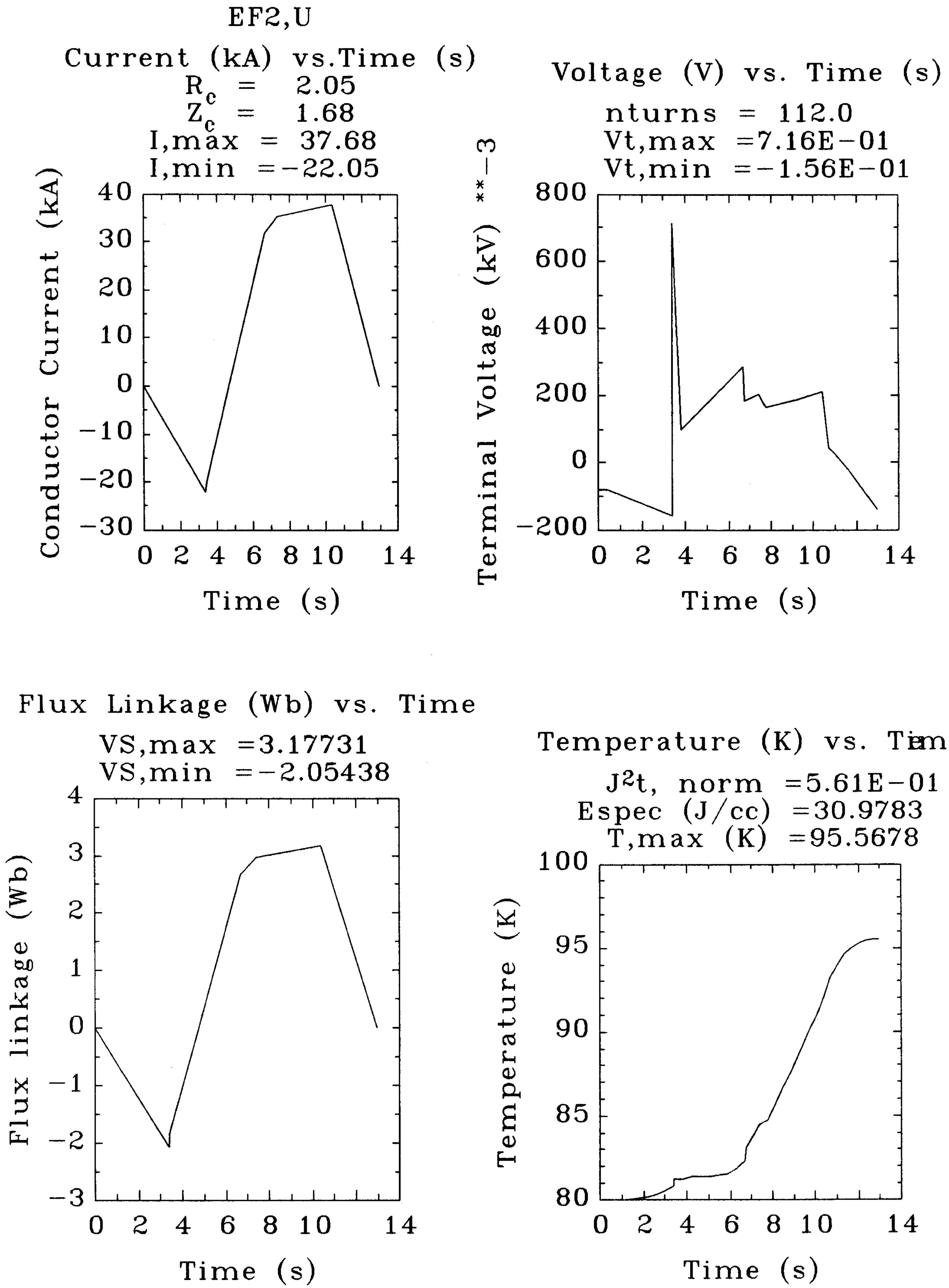
Max power =9.22343
Min power =−17.3578
+ PS MVA =10.8854
− PS MVA =3.44408

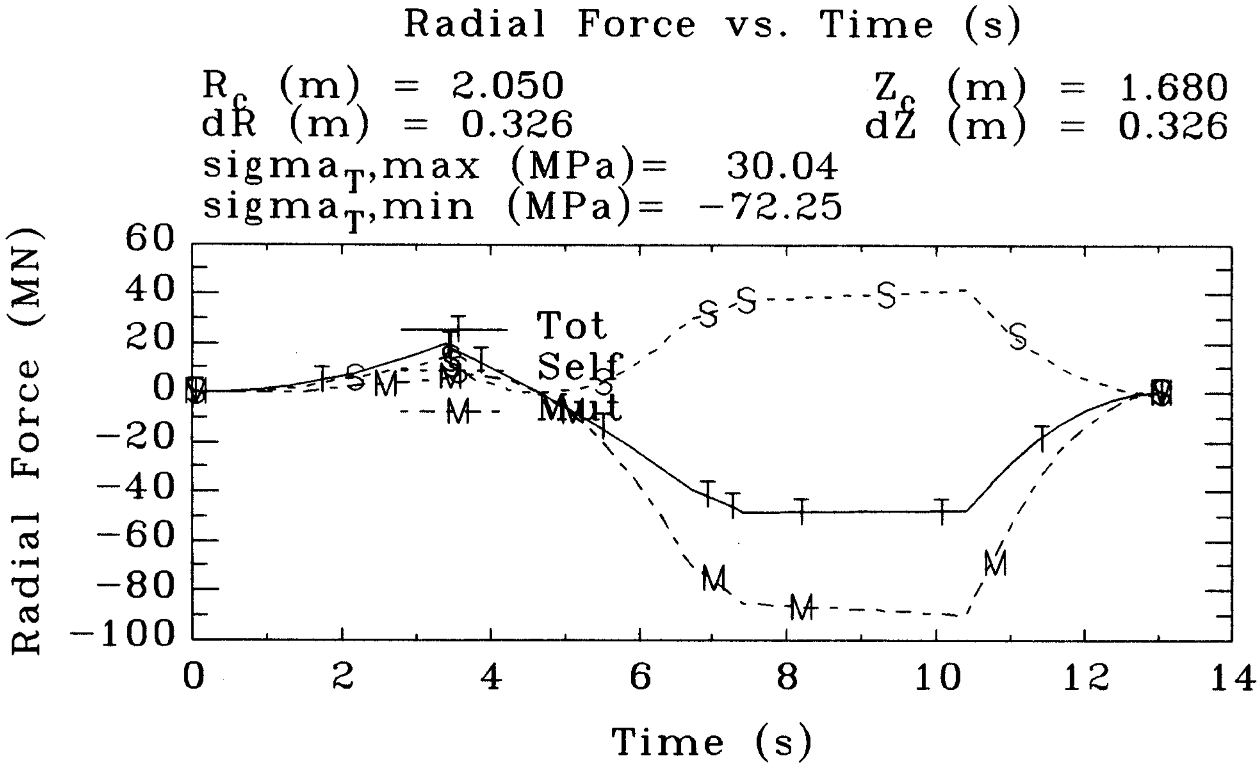


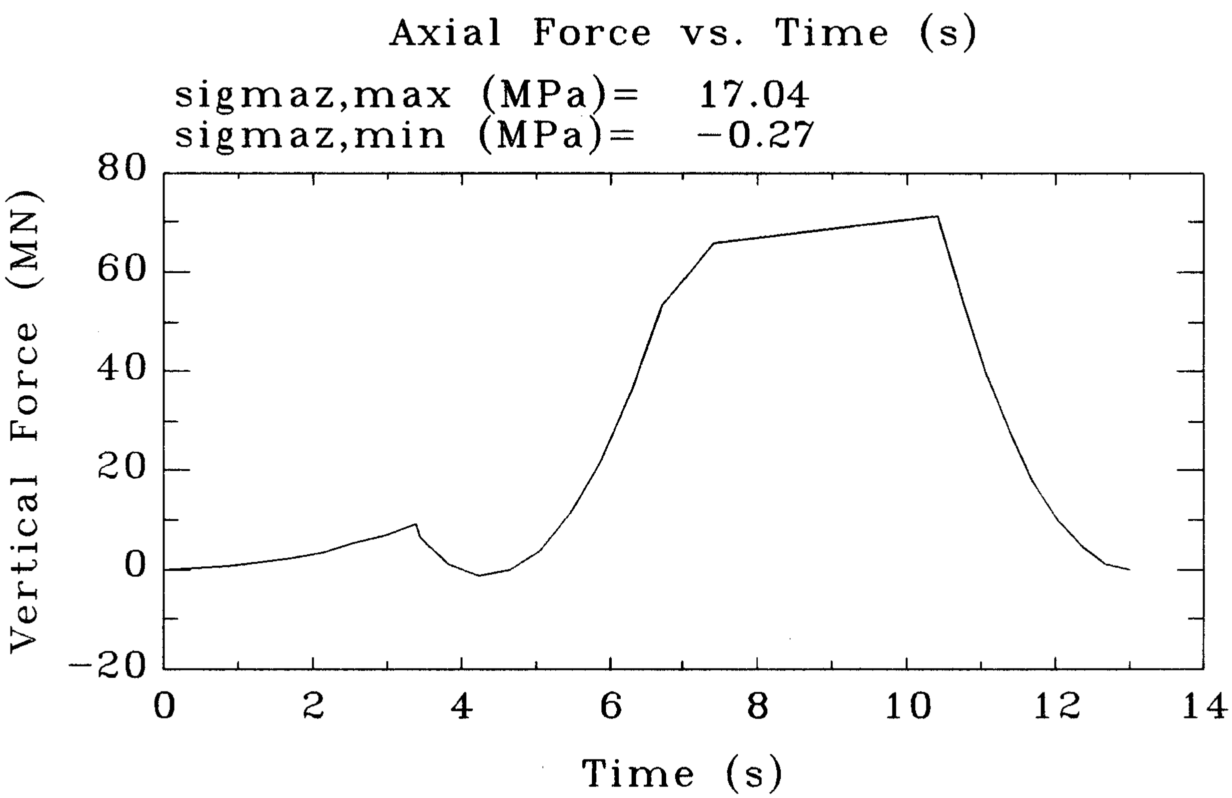
Energy (MJ) vs. Time

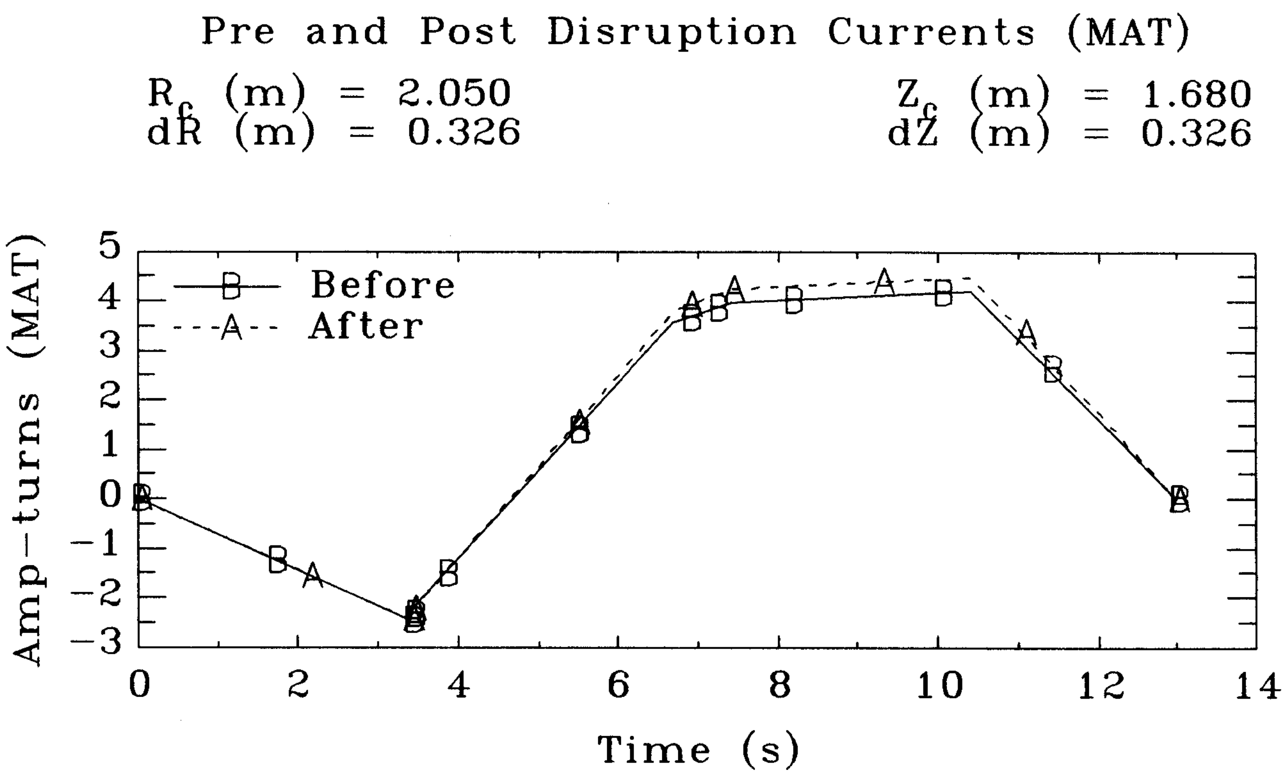
Emax =36.8837

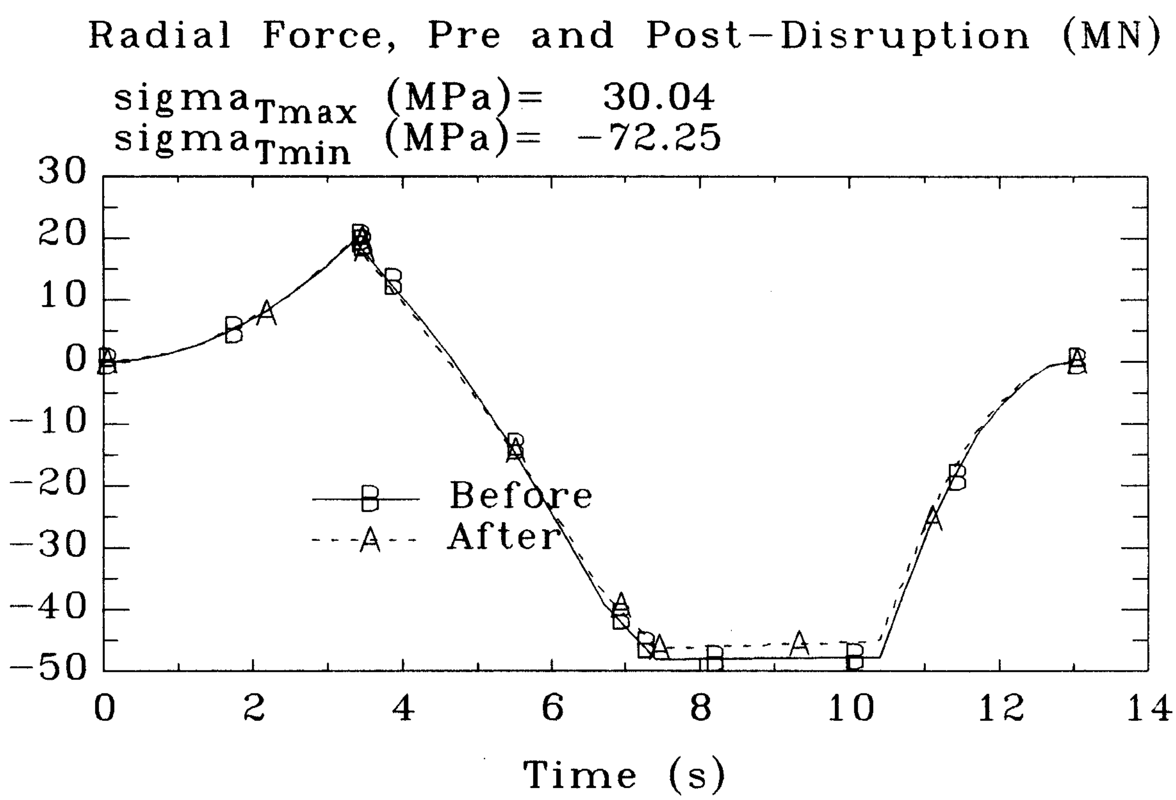


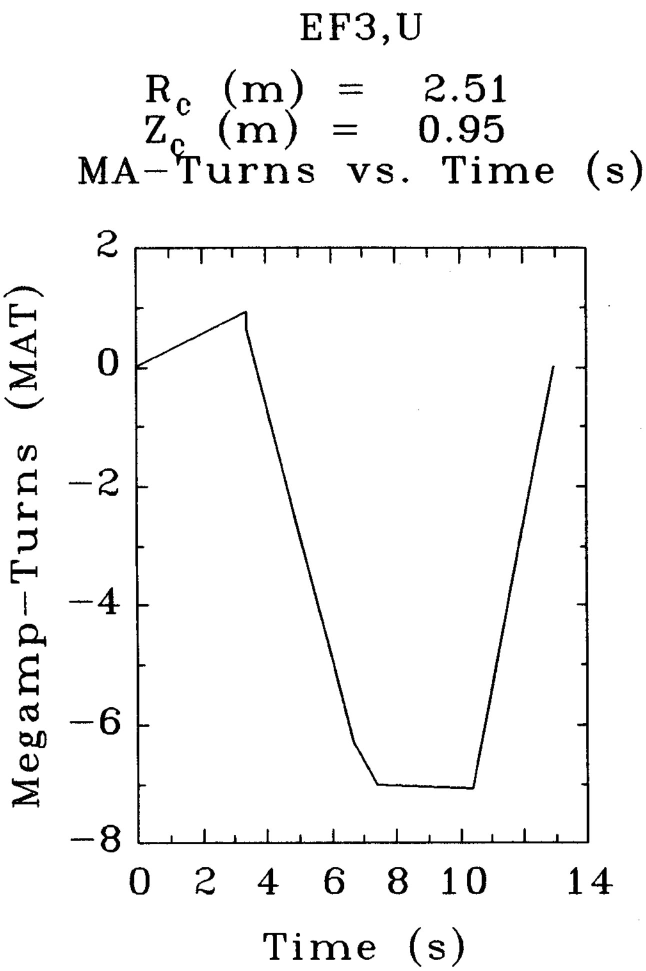

EF2,U
Current (kA) vs.Time (s)
R_c = 2.05
Z_c = 1.68
I,max = 37.68
I,min =-22.05
Conductor Current (kA)
Time (s)
Voltage (V) vs. Time (s)
nturns = 112.0
Vt,max =7.16E-01
Vt,min =-1.56E-01
Terminal Voltage (kV) **-3
Time (s)
Flux Linkage (Wb) vs. Time
VS,max =3.17731
VS,min =-2.05438
Flux linkage (Wb)
Time (s)
Temperature (K) vs. Tim
J^2t, norm =5.61E-01
Espec (J/cc) =30.9783
T,max (K) =95.5678
Temperature (K)
Time (s)

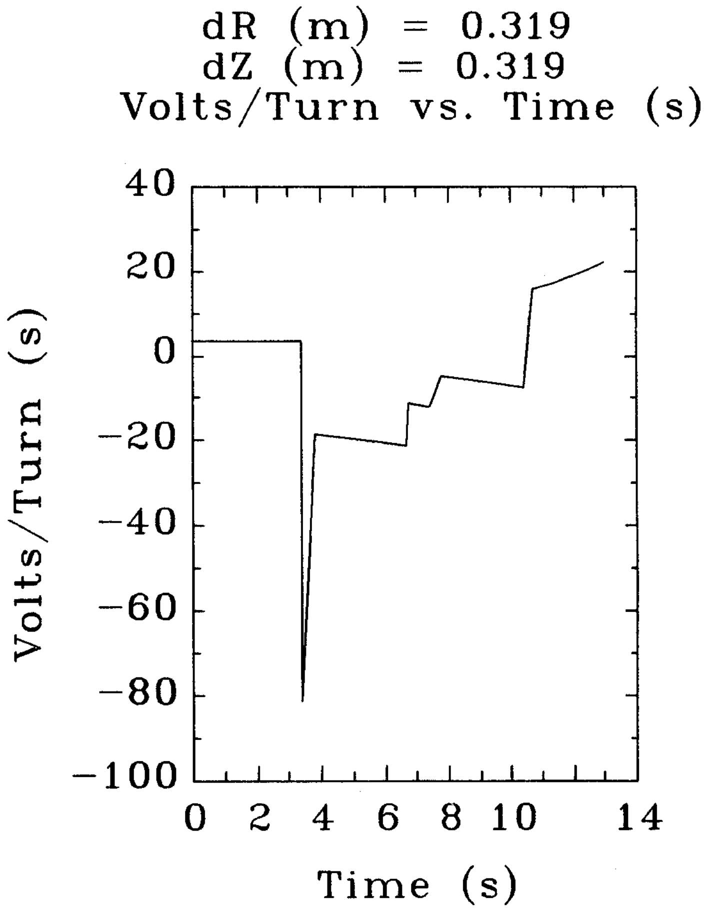

Radial Force vs. Time (s)
R_c (m) = 2.050
Z_c (m) = 1.680
dR (m) = 0.326
dZ (m) = 0.326
$sigma_T$,max (MPa)= 30.04
$sigma_T$,min (MPa)= -72.25
Tot
Self
Mut
Radial Force (MN)
Time (s)

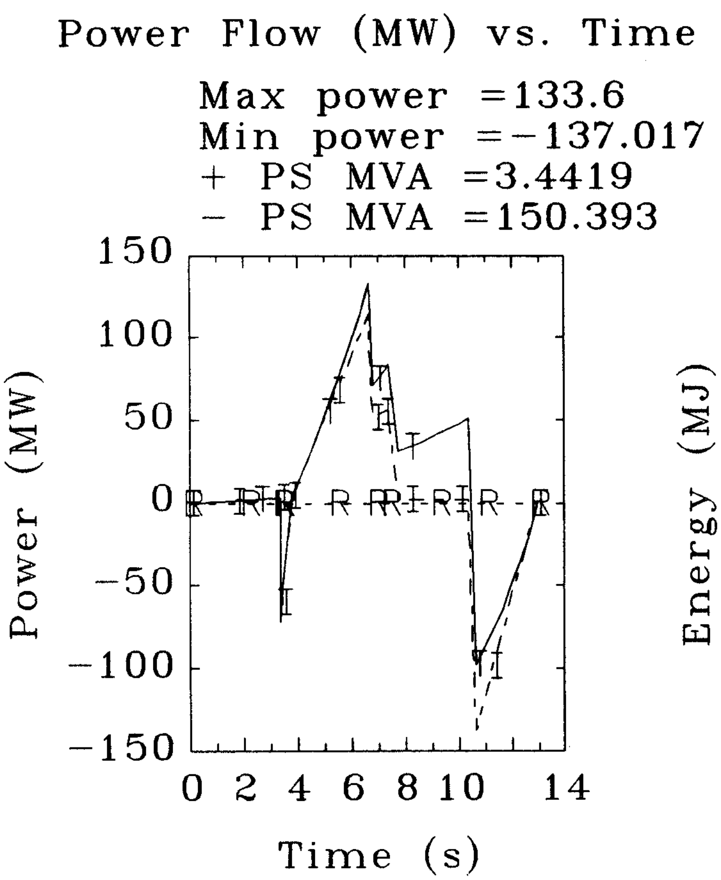

Axial Force vs. Time (s)
sigmaz,max (MPa)= 17.04
sigmaz,min (MPa)= -0.27
Vertical Force (MN)
Time (s)

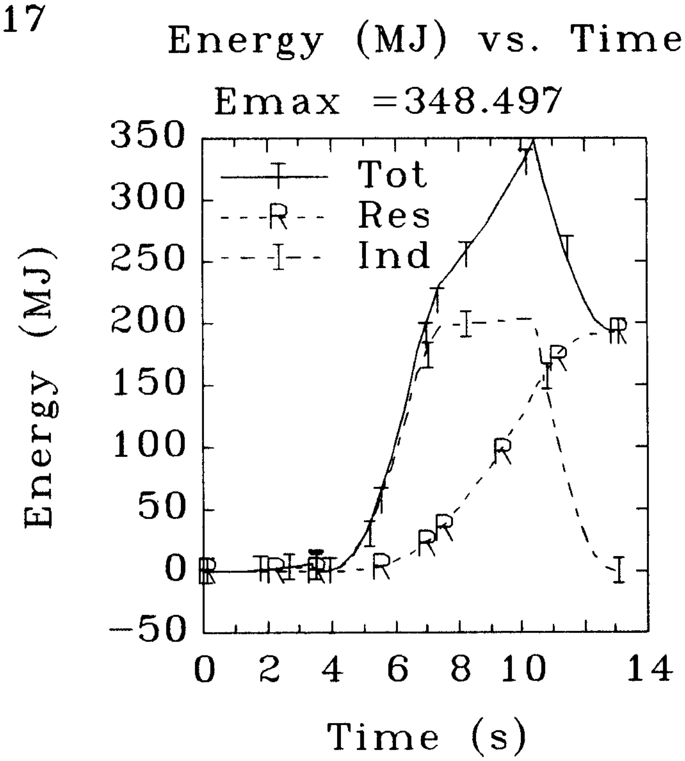

Pre and Post Disruption Currents (MAT)
R_c (m) = 2.050
dR (m) = 0.326
Z_c (m) = 1.680
dZ (m) = 0.326
Amp-turns (MAT)
Before
After
Time (s)


Radial Force, Pre and Post-Disruption (MN)
$sigma_{Tmax}$ (MPa)= 30.04
$sigma_{Tmin}$ (MPa)= -72.25
Before
After
Time (s)

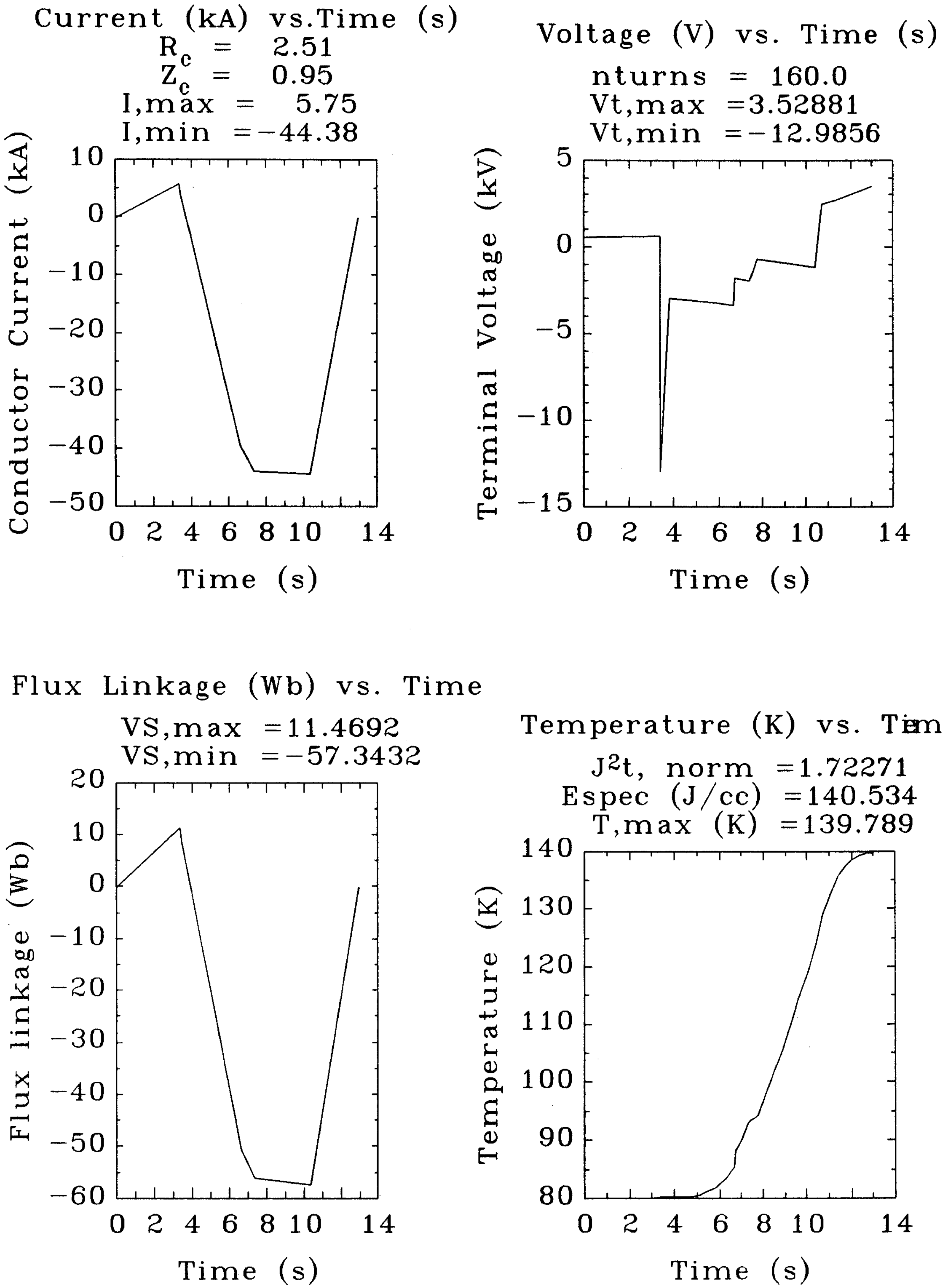

EF3,U
R_c (m) = 2.51
Z_c (m) = 0.95
MA-Turns vs. Time (s)
Megamp-Turns (MAT)
Time (s)

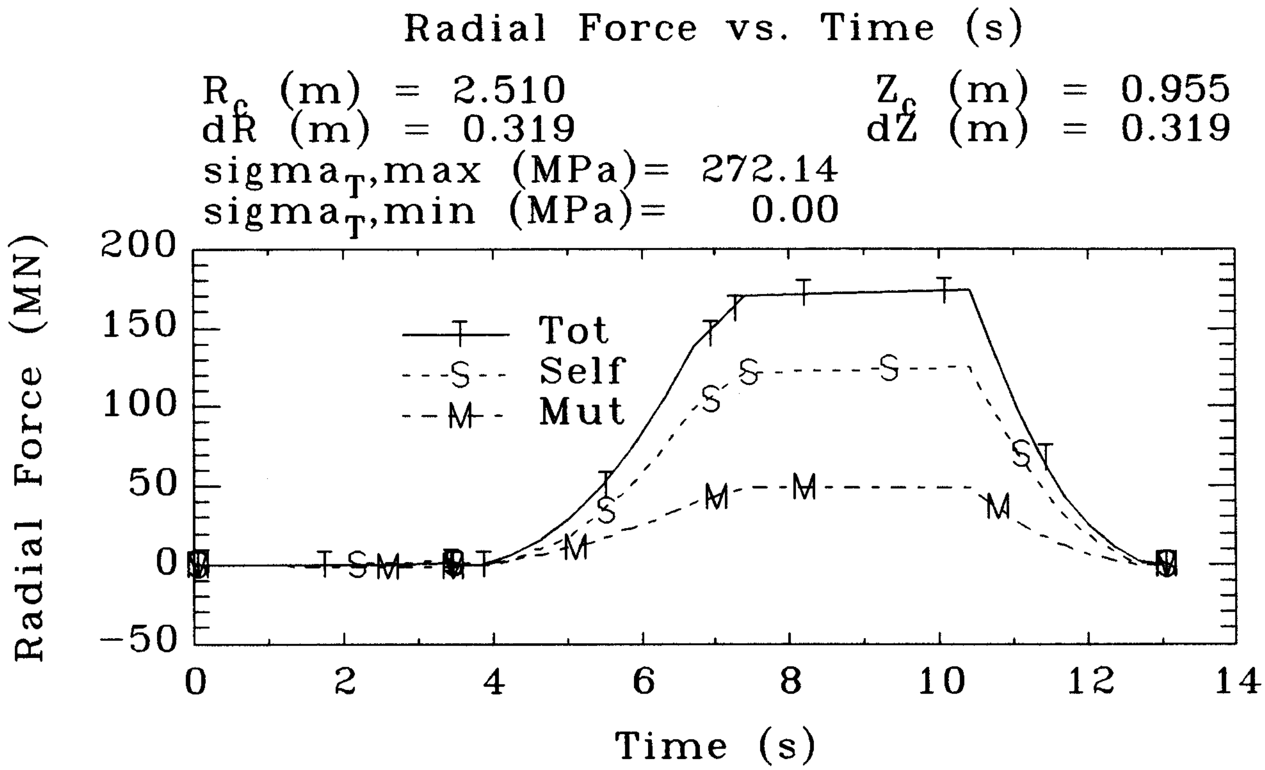

dR (m) = 0.319
dZ (m) = 0.319
Volts/Turn vs. Time (s)
Volts/Turn (s)
Time (s)

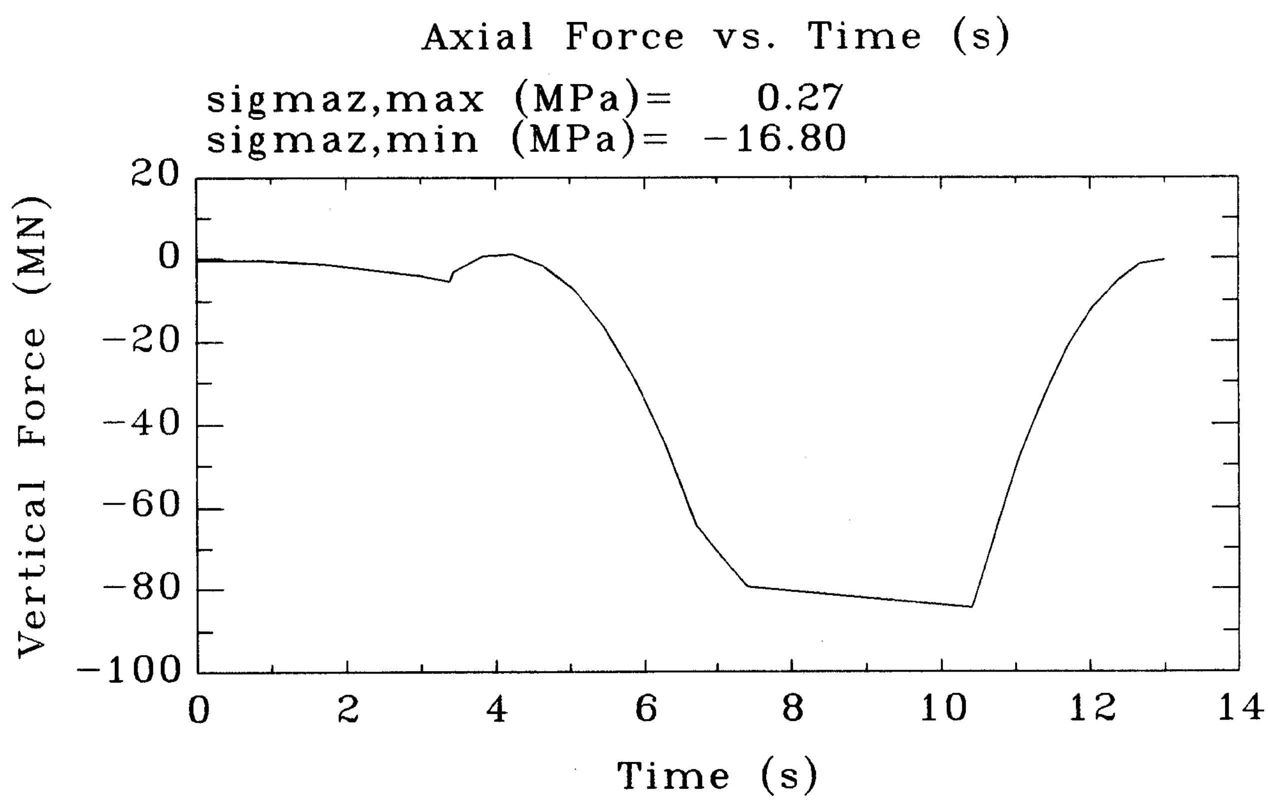

Power Flow (MW) vs. Time
Max power =133.6
Min power =-137.017
+ PS MVA =3.4419
- PS MVA =150.393
Power (MW)
Time (s)

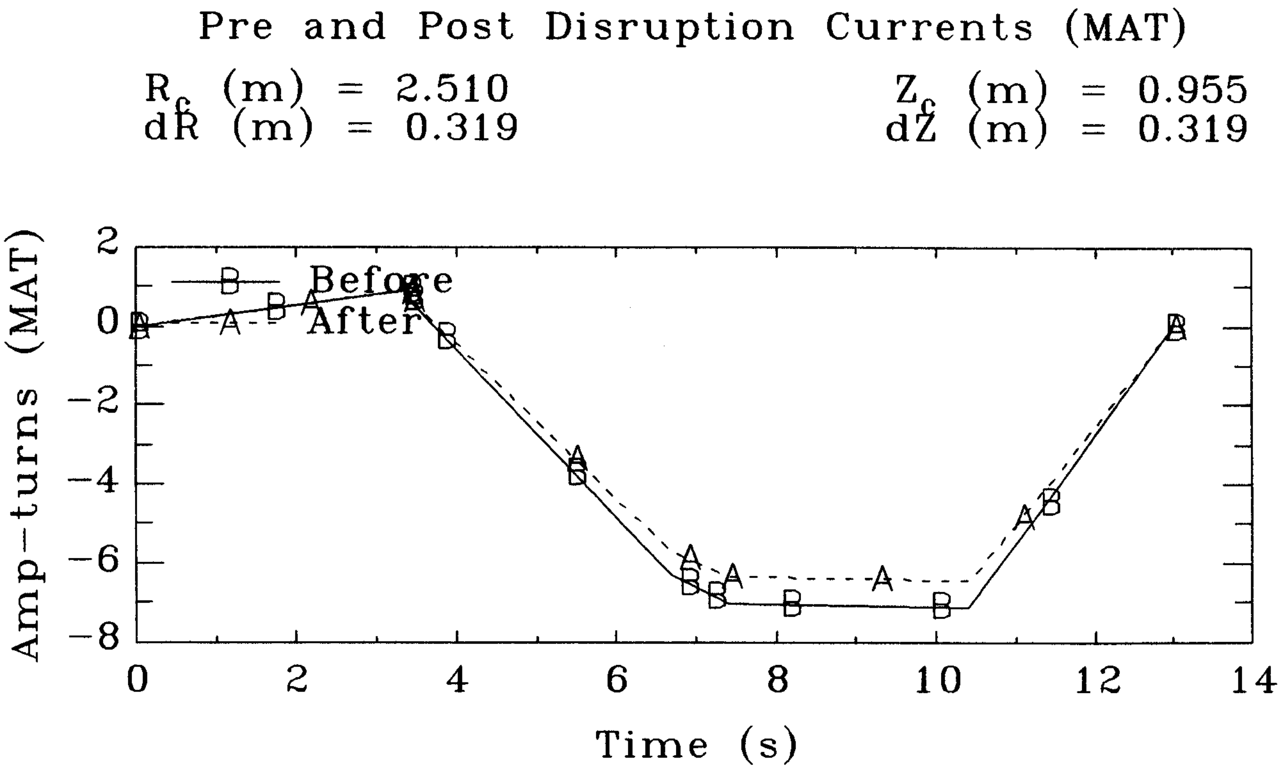

Energy (MJ) vs. Time
Emax =348.497
Tot
Res
Ind
Energy (MJ)
Time (s)

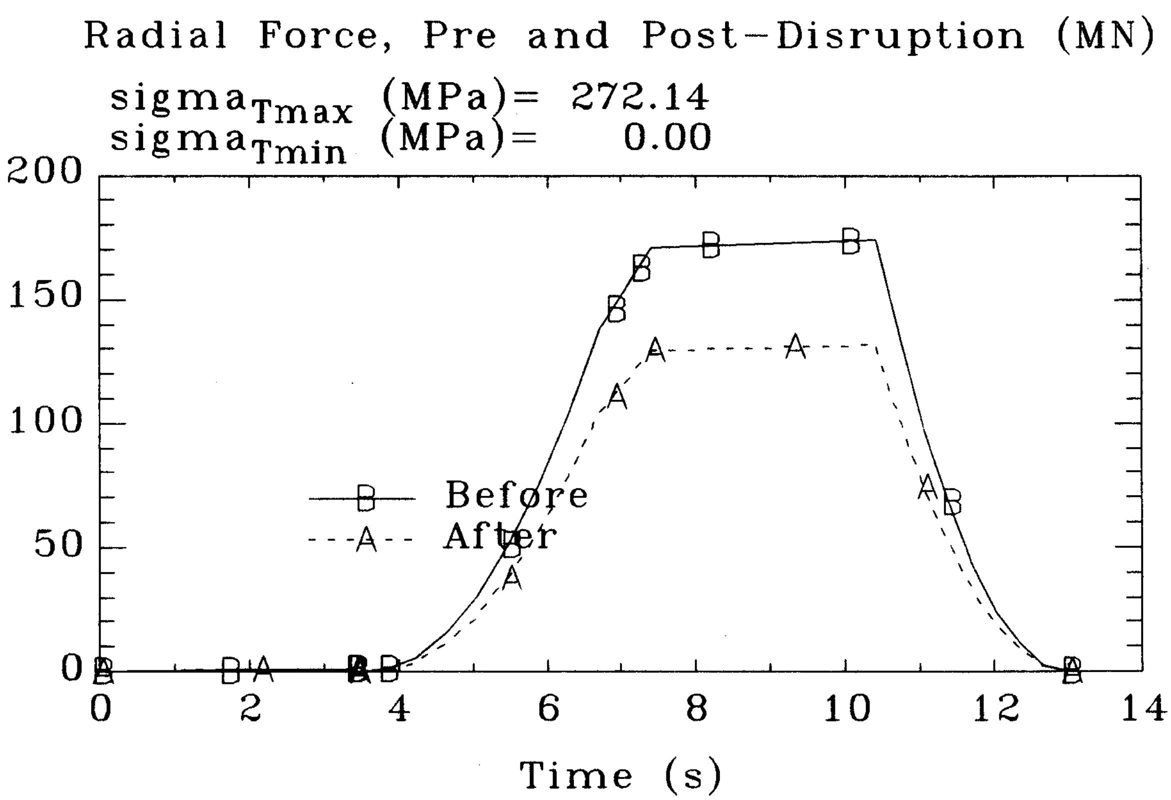
EF3,U


Current (kA) vs.Time (s)
R_c = 2.51
Z_c = 0.95
I,max = 5.75
I,min = −44.38
Conductor Current (kA)
10
0
−10
−20
−30
−40
−50
0 2 4 6 8 10 14
Time (s)
Voltage (V) vs. Time (s)
nturns = 160.0
Vt,max =3.52881
Vt,min =−12.9856
Terminal Voltage (kV)
5
0
−5
−10
−15
0 2 4 6 8 10 14
Time (s)
Flux Linkage (Wb) vs. Time
VS,max =11.4692
VS,min =−57.3432
Flux linkage (Wb)
20
10
0
−10
−20
−30
−40
−50
−60
0 2 4 6 8 10 14
Time (s)
Temperature (K) vs. Time
J^2t, norm =1.72271
Espec (J/cc) =140.534
T,max (K) =139.789
Temperature (K)
140
130
120
110
100
90
80
0 2 4 6 8 10 14
Time (s)


Radial Force vs. Time (s)
R_c (m) = 2.510
Z_c (m) = 0.955
dR (m) = 0.319
dZ (m) = 0.319
sigma_T,max (MPa)= 272.14
sigma_T,min (MPa)= 0.00
Radial Force (MN)
Time (s)
Tot
Self
Mut
200
150
100
50
0
−50
0
2
4
6
8
10
12
14


Axial Force vs. Time (s)
sigmaz,max (MPa)= 0.27
sigmaz,min (MPa)= −16.80
Vertical Force (MN)
Time (s)
20
0
−20
−40
−60
−80
−100
0
2
4
6
8
10
12
14


Pre and Post Disruption Currents (MAT)
R_c (m) = 2.510
dR (m) = 0.319
Z_c (m) = 0.955
dZ (m) = 0.319
Before
After
Amp-turns (MAT)
Time (s)


Radial Force, Pre and Post-Disruption (MN)
$sigma_{Tmax}$ (MPa)= 272.14
$sigma_{Tmin}$ (MPa)= 0.00
Before
After
Time (s)