225
8-4-82 (A)

①

I-4604

dr. 729

PPPL 1909

UC20a,b,f

PPPL 1909

MASTER

DISRUPTION MODEL

By

John G. Murray and George Bronner

JULY 1982

PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

DISRUPTION MODEL

John G. Murray and George Bronner
Princeton Plasma Physics Laboratory
Princeton, NJ 08544

PPPL--1909
DE82 018142

Abstract

Calculations of disruption time and energy dissipation have been obtained by simulating the plasma as an electrical conducting loop that varies in resistivity, current density, major radius. The calculations provide results which are in good agreement with experimental observations. It is believed that this approach allows engineering designs for disruptions to be completed in large tokamaks such as INTOR or FED.

This electrical engineering approach is primarily concerned with the phase of disruption where the plasma current decays, and the plasma circuit self-inductive energy is dissipated. The basic model maintains conservation of energy and allows the plasma major radius (R) to move to maintain an equilibrium condition. As the plasma current changes, the equilibrium position moves toward the wall or limiter. As the plasma moves into the wall, the outer circumferential layer is scraped off.

It is assumed that a hot plasma with a peaked current density in the center disrupts in a short period of time. The initial disruption, called the thermal quench time, results in the release of essentially all the thermal energy, and the current distribution becomes essentially uniform. This stage of the disruption is simulated in the engineering model by a change in resistivity of the plasma circuit. The resistivity of the plasma changes from that of a hot plasma (10 keV for FED) to one where the resistance is about the same as that obtained with only the ohmic heating system (approximately 100 eV). This change is assumed to occur in the so-called thermal quench time of a few 100 microseconds or less.

During the second stage of disruption, called the current quench time, the plasma self-inductive energy transfers to the passive and active circuits of the tokamak. The portion of the inductive energy that is transferred to the plasma is accomplished by increasing the current density in the plasma. As this is occurring the outer edge of the plasma is being scraped off by the wall, or limiter. This is modeled by assuming that the plasma confinement is poor. As quickly as the current density trys to increase, it heats up the plasma, and the energy is lost in the form of thermal energy. The plasma circuit resistivity, therefore, is held at a constant value in the model during the current quench time.

Important factors are noted from this model calculation:

1. The calculations show that an appreciable portion of the plasma self-inductive stored energy is transferred energy, particularly when the torus structure near the plasma has a short time constant.

2. The calculations provide data to limit disruption damage by specific design of system eddy current paths and equilibrium control fields. Parameters can be engineered to effect the current decay phase of a dissipation.

Description of Computer Model

The computer model used to make the calculations includes the poloidal coil circuits and the passive structure circuits. It includes the variations in plasma self-inductance and the mutual inductance between the plasma and the other circuits as the plasma major and minor radii change. To provide for various current density profiles and shapes of the plasma, the model subdivides the plasma into several loops with different resistivities. By making the center loops low resistivity, a higher current is simulated in the center of the plasma.

Since the purpose for this engineering approach is to provide data to specify hardware, the worst case disruption parameters were selected in the model. The procedure for calculating the thermal quench time used in the model is an over simplification and should not be taken seriously. However, the results indicate that elementary engineering calculations support the ability to have worst case thermal quench times as low as those used in the model calculations.

If the time for the internal current distribution to change is fast, an elementary electrical circuit analysis would indicate that there is a change in the plasma current and a change in the torus structure internal skin current. Initially the plasma current will increase, and the structure skin current will flow in a negative direction. The time for this transition to uniform resistivity has been estimated by two methods described below:

Method (1).

$$\tau A \approx \frac{L_A}{R_A}$$

where L_A = vessel wall and plasma coaxial inductance.

L_A = 0.140 ($\log_{10} r_2/r_1 + 0.015$) μ H/ft (for a circular plasma),

R_A = Average plasma resistance during change from the given initial temperature to the ohmic heating supported temperature, plus the toroidal skin resistance of the structure,

r_2 = Vessel radius, and

r_1 = plasma radius.

Method (2).

A computer model was employed to estimate the thermal quench time by solving the time response of a circuit which contains the vessel and a multicircuit plasma. By step changing the resistivity of the center of the plasma from a low value to a high value, the decay of the current transients can be determined.

The validity of the current decay calculations does not depend on the accuracy of these two methods of estimating the fastest thermal quench time. It is only necessary that the thermal decay time be approximately an order of magnitude faster than the current delay time.

Having obtained estimated values for the fastest thermal quench time the current quench parameters can be calculated. As the result of the change in resistivity the plasma current changes, and the equilibrium results in a change in the plasma major radius. If the equilibrium field or plasma current is not compensated properly to reestablish equilibrium in the center of the vessel, the plasma will be driven into the structure wall.

During the current decay period the model assumes that the outer perimeter or circumferential shell is removed (scraped off) as the plasma moves toward the wall. The accompanying loss of plasma stored self-inductive energy must be transferred to the external circuits or into the plasma itself. The transfer of inductive energy to the plasma thermal energy is accomplished by attempting to increase the plasma current and temperature. However, because of the disruption condition, we assume the plasma temperature cannot be raised above that obtained by the ohmic heating circuit. Thus this energy is conducted or radiated to the walls as quickly as it is absorbed by the plasma.

To obtain a self-consistent solution, a proportionality factor which related the transfer of inductive energy to thermal energy is obtained. To accomplish this, one can match a solution to the two known points: the first being the initial condition before the loss of equilibrium, and the second being when the center of the plasma moved to the wall. At this later point, all the plasma stored energy must be transferred to external circuits or structures. Thus, by varying a scrape-off area proportionality factor (AA), one can obtain a solution where the plasma stored inductive energy goes to zero when the plasma major radius moves a distance equivalent to the radius of the torus.

This procedure provides a self-consistent solution for currents, times, and energies; it also gives a value for the total energy loss to the wall by radiation and convection. It does not provide a breakdown of the percentage of the total energy which is radiated or conducted away. But, by knowing the total energy, temperature, and the time of transfer, the percentages of each can be calculated for a specific machine by determining the type and volume of wall or limiter in contact with the plasma and the heat absorption characteristics of those surfaces.

Refinements of Assumptions

The procedure outlined above is useful to the machine design engineer to determine the worst case disruption parameters such as maximum currents, forces, and heating of the structures. Disruptions have been characterized as major and minor, and there are all degrees of disruption. The calculations for the maximum values described above are the ones for which the structures must be designed. The number and frequency of the disruptions are also a necessary design factor in determining errosion and fatigue characteristics, but these are not addressed in this paper. (If the mode of operation can be maintained with sufficient margin of safety, or if disruption damage control can be provided, the fatigue may not be a dominant design factor.)

In any practical machine, the external power could be applied to improve the equilibrium position. This could be accomplished by varying the OH field or by changing the vertical field. (The application of these factors to the design can also result in determining the size of control fields to assist in the control of disruption damage.)

To provide refinements in the model outlined above, the validity should be further established or corrections should be applied:

(1) During the initial stage (thermal quench stage) the good confinement is lost, and the peaked current distribution is assumed to be uniform for the worst case condition. The distribution may not become completely uniform and the transition may not be linear.

(2) The time constant for initial stage τ_A would be lower if a conducting gas were produced on the outside of the original plasma surface (the scrape-off region). This could provide a better path for the coaxial return current to flow than in the skin of the torus structure. R_A would thus be reduced.

(3) The number and location of the plasma circuits used in Method (2) have an effect on the estimated time constant τ_A.

(4) During the current quench phase of the disruption, the outer periphery may not be uniformly removed in proportion to the movement of the plasma toward the wall.

(5) Matching the two points as described above and assuming that the scrape-off energy proportionality factor (AA) is a constant may not be the proper assumption. In fact, (AA) may be nonlinear. This is likely to be true if a conducting gas develops in the scrape-off area similar to that noted in item 2 above.

(6) The temperature of the plasma during the current quench phase of the disruption was assumed to remain constant at the machine OH developed value. The actual temperature will vary, and the range of variation as well as the temperature distribution will have to be evaluated. A refinement in the design may be obtained by assuming that the currents and heat induced in the plasma is a skin effect.

Specific Results

In developing this engineering approach to obtaining disruption calculations, the PLT device was used as the initial device to study. The resultant calculations are shown in Figs. 1 and 2. The model included the insulating break in the structure and assumed that there was no current conduction across the break during the disruption.

It assumed an initial plasma of 1 keV which decayed to 100 eV in τ_A seconds. τ_A for PLT, was calculated to be 0.45 ms for a condition where the plasma was simulated by 5 circuits and there was 8 cm between the plasma and the vessel wall. The current disruption time as determined by the computer models for an equal to 1 millisecond was 2.1 ms without any changes in the OH power supplies. By pulsing the OH system up to full power when a major disruption starts, the OH power system was only able to increase the disruption time from 2.1 to 3.1 ms. Since the PLT Vertical Field Power Supply System power has a 6-phase control converter, it has a possible delay in current reduction of as much as 2.7 ms and, therefore, is not likely to be useful in controlling disruption equilibrium once a major disruption starts. It is also noted that the actual value of τ_A does not result in a noticeable change in the current decays calculations unless it becomes larger than 100 microseconds. Decreasing it from 1 ms to 100 microseconds changes the current decay disruption time by a factor of 30%. Decreasing it from 100 to 10 microseconds had essentially no effect on the current disruption time. The percent of inductive energy transferred to plasma thermal energy is 88%.

The model was then applied to the IXS-B configuration. The results are shown in Figures 3 and 4. For this case the plasma inductive stored energy is an order of magnitude lower than PLT. The computed current decay time is 1.8 milliseconds, but the percent of inductive energy transferred to thermal energy is 47%. This equivalent current decay time and reduction in percent of thermal energy from that calculated for PLT is the result of the longer vacuum vessel structure time constant.

The final calculations were made on the FED September 1981 baseline configuration. These results are shown in Figures 5 and 6. For FED the plasma stored inductive energy is 144 megajoules. The computed current decay time is 25 milliseconds. The percentage of self-inductive stored energy transformed to plasma thermal energy is only 2%. The data in Figure 5 shows that the τ_A greater than approximately 500 microseconds results in an increase in current decay time. The value of τ_A calculated by Method (1) produces a value of τ_A of 2200 microseconds. The faster time is the worst case condition and should be used as the design value. The large value of τ_A calculated by Method 1 is the result of the large scrape off region of 20 centimeters, which produces a large value for La. This configuration may result in a plasma being formed in the scrape off region which conducts current in the negative direction during thermal disruption.

The summary of the three sets of calculations are given in Table 1.

CONCLUSIONS

1. The thermal quench time estimate is not greatly affected by the wall impedance, and it is probably too fast to be affected by feedback control systems unless an anticipatory signal can be obtained. Providing cooling at the edge of the plasma may be a way to reduce the thermal quench energy damage, but it would have to be injected in times of approximately 100 microseconds.

2. Feedback controls for EF and OH controls can be engineered to reduce the energy dissipation during the current discharge phase of the disruption. If the plasma can be held in the center of the vacuum vessel, the plasma inductive energy will not be dissipated.

3. During the current quench stage of the disruption, a major portion of the plasma self-inductive stored energy can be transferred into the plasma as thermal energy and hence can be deposited on the walls or limiter. The percentage of thermal conduction or radiation can be reduced by providing a low time constant shell near the plasma.

4. Calculation of energy, currents, and voltages resulting from a disruption can be calculated and the engineering designs completed using the procedure described.

The authors wish to thank B.A. Carreras, Y.K.M. Peng, J.A. Schmidt, W. Stodiek, and J. Wesley for their assistance in giving descriptions and data on plasma disruptions.

This work was supported by U.S. Department of Energy Contract DE-AC02-76-CHO-3073.

Table 1

			Units	PLT	ISX-B	FED (81 baseline)
Maximum plasma temperature assumed			keV	1	1	10
τ_{A1}	=	La/RA	μs	-	200	2200
τ_{A2}		computer number	μs	450	500	1000
τ_{A3}		(accuracy limit)	μs	500	500	500
τ_c		(current decay time)	ms	1.8	1.8	25
E_p		plasma initial energy ($1/2\ LI^2$)	MJ	.35	0.033	144
P_h	=	percentage thermal	%	88	47	2

τ_{A1} is the value of τ_A estimated from the coaxial inductance divided by R.

τ_{A2} is the computer model estimate.

τ_{A3} is the value above which there would exist a change in the values for the current quench data.

T_c is the current quench time. That is the time required for the plasma to move the radius of the torus and hence go to zero current.

E_p is the initial self-inductive stored energy in the plasma. It is the energy that must be transferred to external structures in the current decay phase of disruption.

P_h is the percentage of E_p which is dissipated in the structure by way of thermal energy conducted or radiated from the plasma.

Figure Captions

Fig. 1 PLT Disruption
Plasma Current vs time

Fig. 2 PLT Disruption
Plasma Position vs time

Fig. 3 ISX-B Disruption
Plasma Current vs time

Fig. 4 ISX-B Disruption
Plasma Position vs time

Fig. 5 FED Disruption
Plasma Current vs time

Fig. 6 FED Disruption
Plasma position vs time

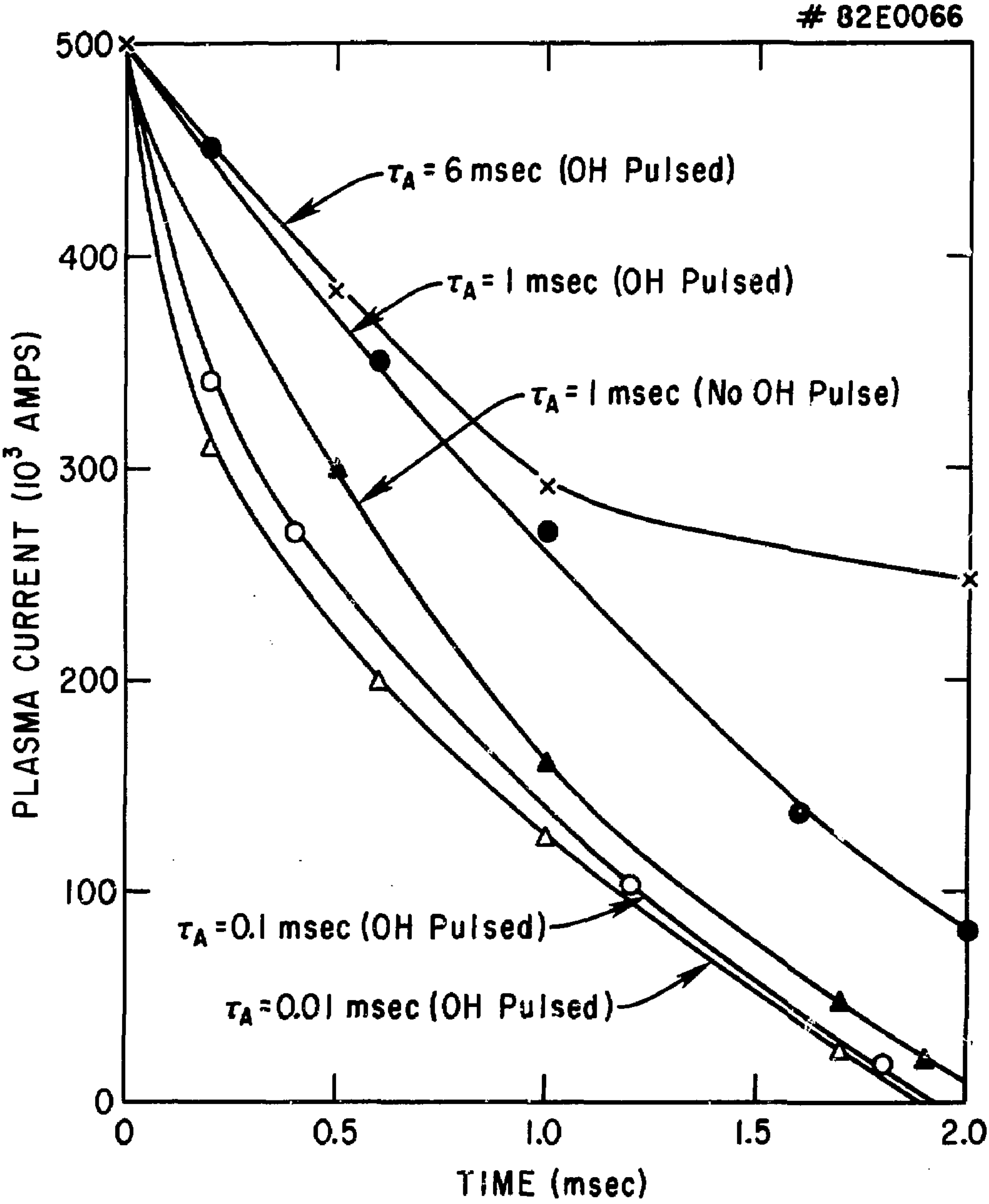

82E0066
500
400
300
200
100
0
PLASMA CURRENT (10^3 AMPS)
0
0.5
1.0
1.5
2.0
TIME (msec)
τ_A = 6 msec (OH Pulsed)
τ_A = 1 msec (OH Pulsed)
τ_A = 1 msec (No OH Pulse)
τ_A = 0.1 msec (OH Pulsed)
τ_A = 0.01 msec (OH Pulsed)

Fig. 1

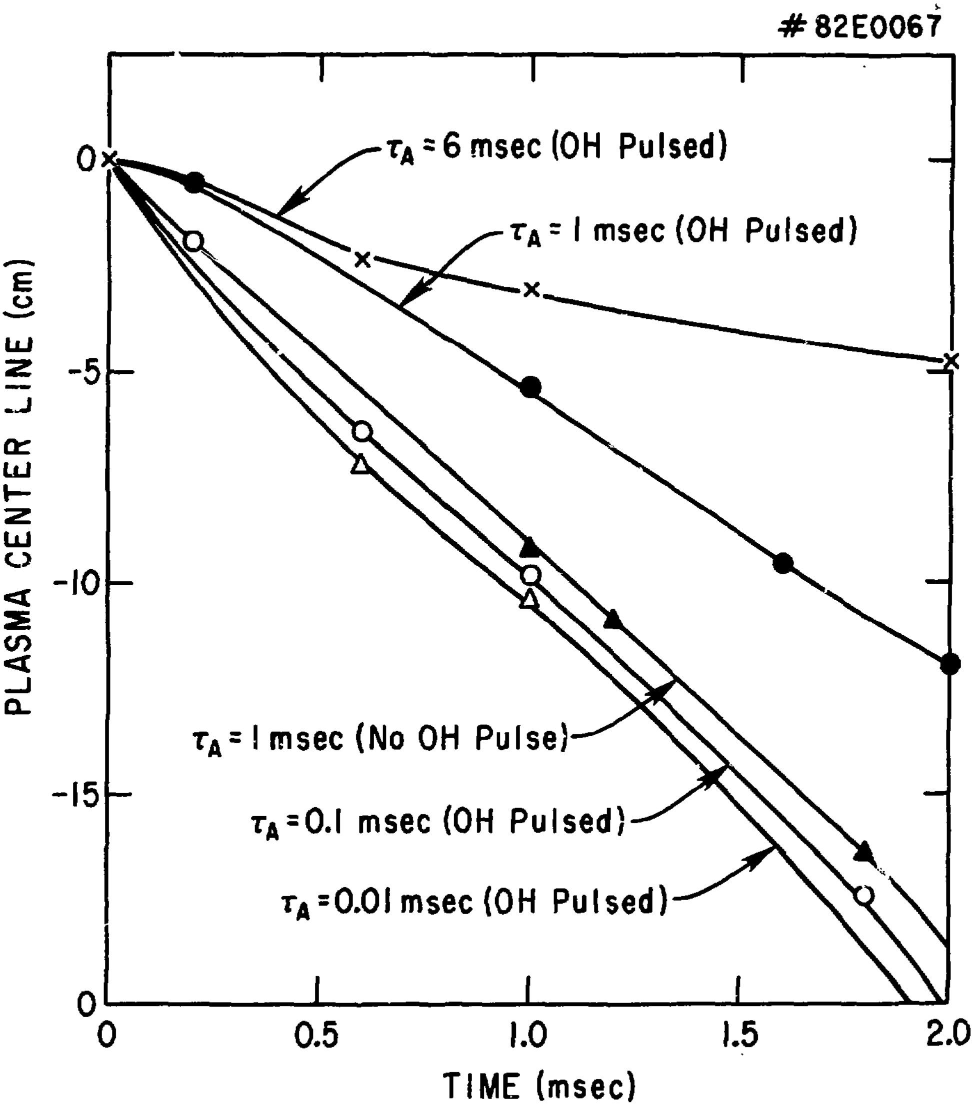
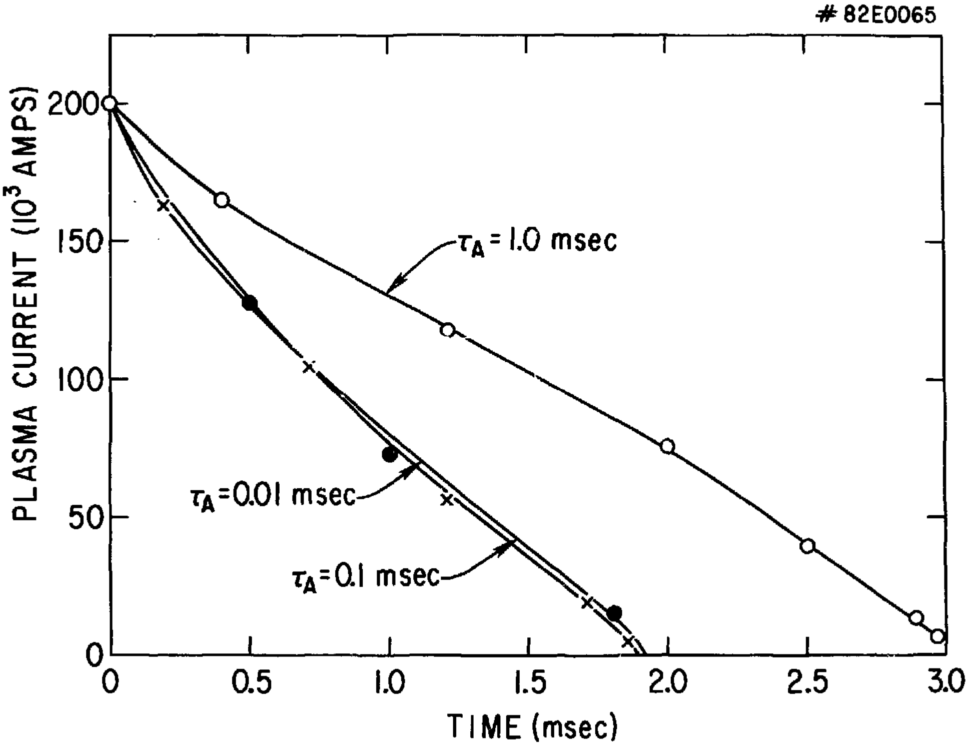
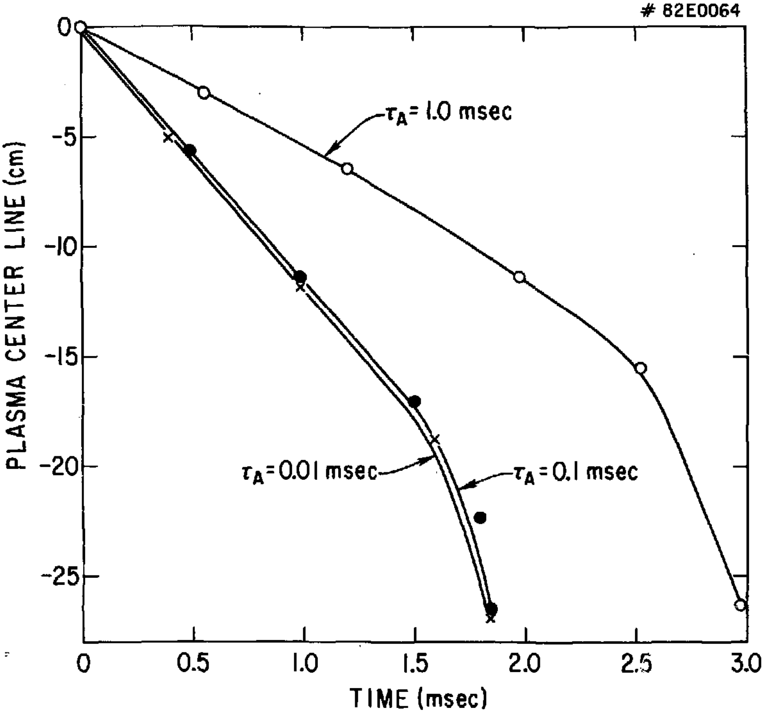

#82E0067
τ_A = 6 msec (OH Pulsed)
τ_A = 1 msec (OH Pulsed)
τ_A = 1 msec (No OH Pulse)
τ_A = 0.1 msec (OH Pulsed)
τ_A = 0.01 msec (OH Pulsed)
PLASMA CENTER LINE (cm)
0
-5
-10
-15
0
0
0.5
1.0
1.5
2.0
TIME (msec)

Fig. 2



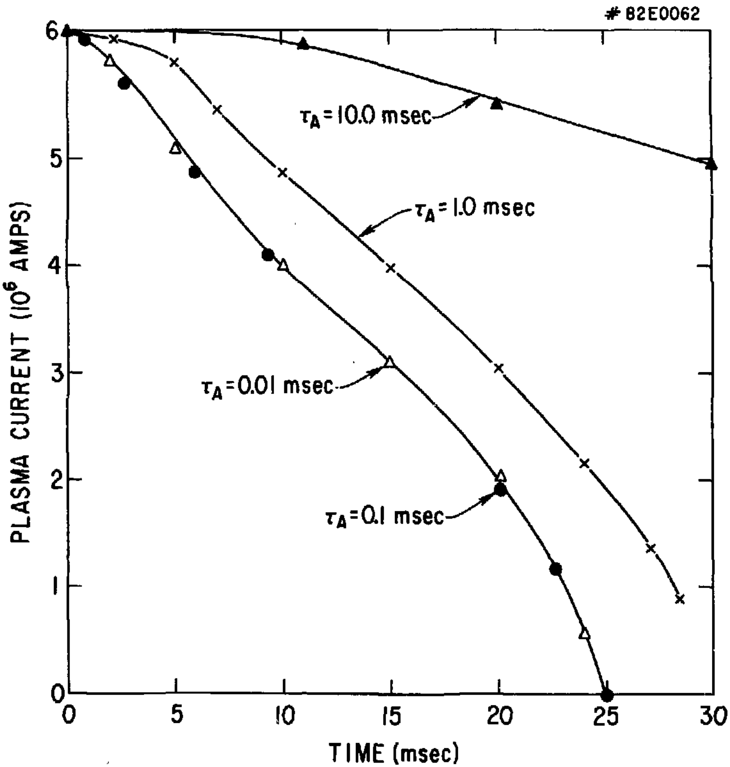
82E0065
PLASMA CURRENT (10^3 AMPS)
200
150
100
50
0
0
0.5
1.0
1.5
2.0
2.5
3.0
TIME (msec)
τA = 1.0 msec
τA = 0.01 msec
τA = 0.1 msec

Fig. 3



82E0064
PLASMA CENTER LINE (cm)
TIME (msec)
τ_A = 1.0 msec
τ_A = 0.01 msec
τ_A = 0.1 msec
0
-5
-10
-15
-20
-25
0
0.5
1.0
1.5
2.0
2.5
3.0

Fig. 4



82E0062
PLASMA CURRENT (10^6 AMPS)
TIME (msec)
τ_A = 10.0 msec
τ_A = 1.0 msec
τ_A = 0.01 msec
τ_A = 0.1 msec
0
1
2
3
4
5
6
0
5
10
15
20
25
30

Fig. 5

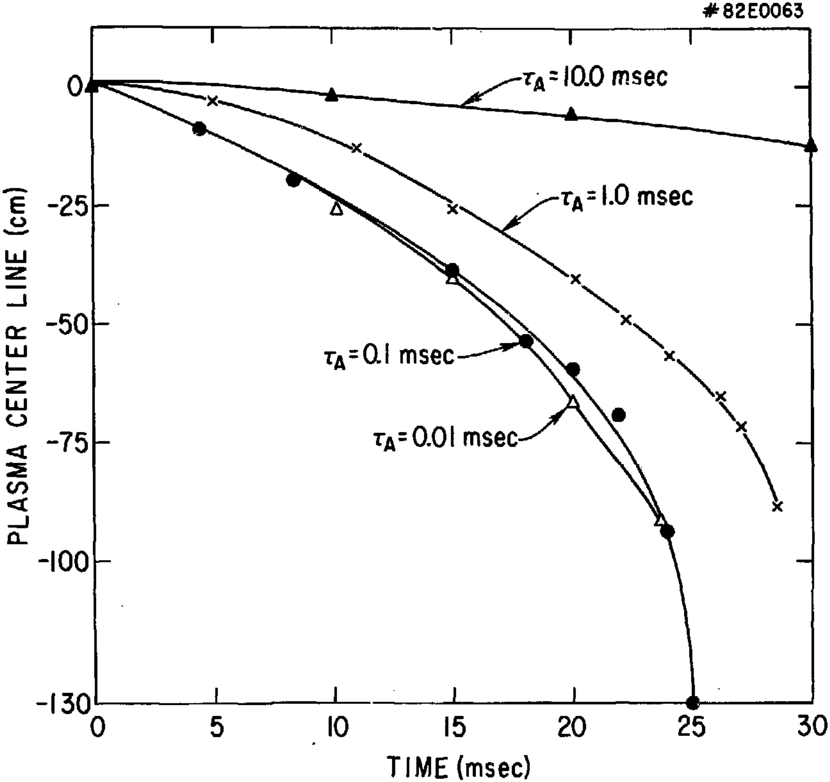

#82E0063
τ_A = 10.0 msec
τ_A = 1.0 msec
τ_A = 0.1 msec
τ_A = 0.01 msec
PLASMA CENTER LINE (cm)
0
-25
-50
-75
-100
-130
0
5
10
15
20
25
30
TIME (msec)

Fig. 6