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Restrike Particle Beam Experiments on a Dense Plasma Focus

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Diagnostic tools (especially an electron magnetic spectrometer and a fast Faraday cup) have been used to measure the scaling of parameters of the particle beams generated in a plasma focus with the current flowing in the circuit just before the radial collapse of the pinch, I_{MB}. The results show that negative power law energy spectra of the electrons are observed where the exponent of that power law, x (x>0), scales as $I_{(MB)}^{(-1.15\pm0.2)}$ and thus the energy spectra get harder with increasing I_{MB}. The

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Abstract (Cont'd)

peak in the fast electron current scales as $I_{MB}^{2.9\pm0.5)}$ and reaches a value of 15 kA for I_{MB}~450 kA. Preliminary experiments show the fast electrons occur simultaneously (±5nsec) with a peak in I_{MB} which supports a model that current interruption is the accelerating mechanism for the particle beams. The results of other experiments testing this model and some of the implications for the application of the plasma focus as an opening switch are discussed.

a) Abstract

Diagnostic tools (especially an electron magnetic spectrometer and a fast Faraday cup) have been used to measure the scaling of parameters of the particle beams generated in a plasma focus with the current flowing in the circuit just before the radial collapse of the pinch, I_{MB}. The results show that negative power law energy spectra of the electrons are observed where the exponent of that power law, x (x>0), scales as $I_{MB}^{-1.15\pm0.2}$ and thus the energy spectra get harder with increasing I_{MB}. The peak in the fast electron current scales as $I_{MB}^{2.9\pm0.5}$ and reaches a value of 15kA for $I_{MB} \sim 450$ kA. Preliminary experiments show the fast electrons electrons occur simultaneously (± 5nsec) with a peak in $\mathring{I}_{MB}$ which supports a model that current interruption is the accelerating mechanism for the particle beams. The results of other experiments testing this model and some of the implications for the application of the plasma focus as an opening switch are discussed.

b) Research Objectives 1980-1981

On page 1 of the proposal[1] submitted for research support to cover this period, the research objectives were listed as follows:

1) Finish development of electron and ion beam diagnostics and perform voltage and pressure scaling experiments for bank voltages below 25 kV.
2) Development of DPF plasma diagnostics to measure $T_e(t)$, $n_e(t)$
3) Development of theoretical model for acceleration processes.
4) Develop ultraviolet (UV) and vacuum ultraviolet (VUV) detectors and appropriate targets for the particle beams.
5) Design, construct a high voltage DPF.

However, in response to perceived needs of the Air Force[2] the emphasis of the research was changed from the application of the dense plasma focus (DPF) as a particle accelerator to the application as a repetitive plasma opening switch.

In regard to this latter application the emphasis is on understanding the phenomena occurring in the focus plasma during current interruption rather than the direct utilization as a piece of opening switch hardware. Although some novel techniques utilizing the DPF have been proposed[3], the results[4] of attempts to use the DPF in a conventional manner as an opening switch (see Fig. 1) have been disappointing. The percentage of current interruption is small (20%; ~ 100kA) and occurs irratically. By operating the Illinois DPF in a more ideal mode, where the interruption is 250kA in 150 nsec (Fig. 2), it is hoped that the phenomena occurring in the plasma under these conditions will be more clearly understood and the results will provide support to the data base for the design of the 'ultimate' plasma repetitive opening switch, whether a conventional DPF, a modified DPF, or neither of these.

With this emphasis in mind the objectives of the research changed. That is the last two objectives listed on page one were eliminated for the time being. The UV diagnostics were to be used to study the interaction of the fast electron beam generated by the DPF with various metal targets which is not relevant to the opening switch study. Similarly, scaling up the device to higher power levels is not as important to the opening switch research as it is to the accelerator application of the DPF. As shown in the next part of the report, scaling experiments can reveal some of the physics, but this can be done at lower capacitor bank energies and so upgrading the device to operating voltages above 25 kV is not essential.

c) Status of the Research Effort

1) Introduction

During the past year considerable progress has been made in the area of the scaling of the electron (and presumably the ion) beam parameters with mainbank current a pinch time (which is at the time of current interruption as well). Since these beams are generated at the peak in $|\overset{\circ}{I}|$ ($\overset{\circ}{I}<0$) they are apparently related to the failure of the plasma focus circuit to completely open. Since the current of these beams is in a direction which closes the circuit and, since the $\overset{\circ}{I}$ of these currents is of the same order as that of the peak $|\overset{\circ}{I}|$ of the mainbank current, understanding and controlling them may be vital to the success of a plasma focus as an opening switch. The scaling experiments have relevance to the opening switch problem since by performing scaling experiments one can provide a test for theoretical models.

In the next sections the progress in beam diagnostics will be outlined, the results of the scaling experiments presented, and finally the results of some preliminary experiments to see if a current interruption model can explain the acceleration process will be presented along with a discussion of some of the implications for a plasma focus opening switch.

2) Summary of diagnostic development

In the past contract year the following diagnostic tools have been developed and used to perform measurements on the Illinois plasma focus:

1) An ion Faraday cup time-of-flight system
2) A high energy ion fluence technique with Solid State Nuclear Track Detectors (SSNTD)
3) An electron magnetic spectrometer
4) A fast rise-time electron beam Faraday cup.

The design details of these tools and some preliminary measurements were presented in last year's report[5]. The significance of each will be discussed in this section.

The ion Faraday cup time-of-flight system[6] has greatly reduced the energy attenuation of the ions traveling to the detector usually encountered in other plasma focus devices. This improvement allows us to measure ion energy spectra below 250 keV directly which was not done before[7] and our present[6] lower limit for the ions is ~25 keV. Since this range (25-250 keV) is that of most of the deuterons in the beam[6], and since most of the fusion reactions are generated by particles in this range[8], the results of this new diagnostic can be used to check the deuteron-acceleration mechanism. The results of this analysis will be discussed in section 4 of this report.

The SSNTD technique to measure high fluences of light ions[9] gives us a means to get a quantitative measurement of the total number of ions accelerated. Fast deuterons striking a converter layer of $Li_2B_4O_7$ interact to produce energetic (d,α) alpha particles which are recorded by a a SSTND placed on the opposite side of the layer. If the shape of the deuteron energy spectrum is known the track density can be used to estimate the incident beam fluence. The ion energy spectral shape determined by the ion Faraday cup and the observed track density can be used to conclude that 1.2 kJ of the energy deposited in the plasma (~3.5 kJ out of 12 kJ) goes into deuterons accelerated to 25 keV or more. Thus the energy efficiency for this process is about 10% and these fast particles might present a problem in fast plasma opening switch applications with regard to erosion from long term operation.

The electron magnetic spectrometer[10] which measures the energy spectra of electrons passing through the hollow anode (Figure 3) was used to make the first direct measurements of the electron energy spectrum of the fast electrons generated by a plasma focus. This diagnostic tool was used in two ways: to determine whether there is any similarity with the ion energy spectrum (see above); and to determine how the electron energy scales with magnetic energy. These measurements have been performed and will be discussed in section 3. Some of the details of the electron magnetic spectrometer are reported in reference 10.

The electron beam Faraday cup was developed to get a direct quantitative measurement of the primary current of the electron beam generated by the plasma focus. Since this current helps prevent the opening of the plasma focus circuit (the $\mathring{I}$ introduced by this current is of the same order as the mainbank current; Figures 2 and 4), the measurement is very relevant to the opening switch application. Rogowski coils have been used to estimate the magnitude of the electron beam current but because a return current is produced by potentials in the head of the beam in the plasma generated by the beam, interpretation of Rogowski coil signals is not easy. Figure 4 shows simultaneous wave forms of Rogowski coil and Faraday cup waveforms. The Faraday cup has a thin mylar window to suppress the plasma return current. Previously a Faraday cup such as the one used here was used by Molen[15] who measured 30kA of primary current for a peak mainbank current of about 650kA. However, the scaling measurements reported in section 3 are the first of their kind.

The design of the electron Faraday cup closely follows that of Pellinin[10] with some modifications which are presented[17] in Appendix B. The cup was designed to measure 100kA currents, has an experimentally determined bandwidth of 450MHz, and the 1/4 mil mylar plasma current filter normally used permits primary electrons with energies down to 27 keV to be collected by the cup.

Thus these diagnostics give the Illinois plasma focus group the opportunity to make energy spectral measurements and quantitative fluence measurements of both species and thus they are able to perform meaningful scaling experiments. The results of these experiments will be discussed in the next section.

3) Results of the Scaling Experiments with Mainbank Current Before Interruption

In a Mather type plasma focus the radial collapse of the current sheath is rapid (~150 nsec) as compared with the rundown period along the anode (~2μsec) and the quarter cycle time of the bank (~1.8μsec). Thus the mainbank current just before the collapse is representative of the magnetic energy available ($\sim 1/2\ LI^2$) at that instant to couple into the pinch phase and is obviously representative of the current to be interrupted. Hence all quantities are varied with respect to this current since at lower bank voltages the pinch occurs later and later after the current maximum and so the bank voltage (or peak current) is not a good measure of either the magnetic energy available (some has been restored in the capacitors) or the current to be interrupted. Thus the bank voltage was varied between 17.5kV and 25kV or a 30% variation in this quantity (from 25kV) whereas the mainbank current at pinch time (I_{MB}) varied between 280kA and 450kA or a 38% variation.

The nature of the energy spectrum and total primary electron current were observed over this range in I_{MB}. To avoid the complications of radial spoke formation and parasitic currents[18] which may vary from shot to shot only those data were selected which had a neutron yield within a factor of two of the best yield at that bank voltage. This occurs over 60% of the time at 25kV where the spark gaps and anode length are more optimal but occurs at lower and lower percentages as the bank voltage is reduced. It is assumed that the effects of parasitic current formation are minimal at high neutron yields (there is no neutron yield when radial spokes form[18]) and the peak yield scales as the $I_{MB}^{4.4\pm0.3}$ for the Illinois plasma focus, a dependence (Fig. 5) reported by several other investigators when the performance of their plasma focus devices is optimal.[19]

The electron magnetic spectrometer was operated in the configuration shown in Fig. 6. The perpendicular magnetic field was 192G, and six energy channels were used; spanning a mean energy range between 30 keV and 400 keV. For other details see reference 10.

In general power law energy spectra were observed for the electrons (Fig. 7) although bumps-on-the-tail of the energy distribution were sometimes observed at lower bank currents (Fig. 8). Since the bump formation process appears to be different from the power law formation process[20] and is intermittent, these bumps were ignored. The results are shown in Fig. 9 where the vertical error bars represent the root mean square error in the least squares fits of the energy spectra as a power law. The electron spectra appear to harden with increasing I_{MB} and this is a new result[21] (the possibility of which has been discussed earlier) which is possible with a direct measurement such as this. Thus these measurements are of great interest to the plasma focus community.

The fill pressure for the DPF for all the data reported here is 3 torr of deuterium. However, varying the pressure between 2 and 4 torr at a bank voltage of 25kV (I_{MB}~450kA) had no affect on the power law (-3.4 ± 0.4) although the signals were stronger at 2 torr and weaker at 4 torr.

The scaling of the peak in the primary current with I_{MB} was also measured. The electron magnetic spectrometer (Fig. 6) was replaced by the electron Faraday cup (Fig. 10) to measure the primary current of the electron beam. The filter had to be replaced after each shot and so a gate valve was inserted into the drift tube and opened after the plasma focus had been conditioned.

Typical data are shown in Figure 11 where the Rogowski coil signal (net current) is included for reference. When the filter is removed the Faraday cup signal closely follows the form of the Rogowski coil signal although reduced by about 15% presumably due to beam divergence. A possible reason[22] why the net current is so high could be due to the slow rise of the broad second peak which is the same magnitude as the fast rising first peak in the primary electron beam. The slow rise causes the induced electric fields to be too low to induce a significant return current whereas the fast rising first peak is absent in the Rogowski waveform presumably due to the stronger electric field induced by it. This illustrates the difficulty in interpreting Rogowski coil signals for electron beams which have been reported in the past[11-14].

The results of the scaling measurements for the fast rising are shown in Fig. 12. These measurements are the first of their kind although the scaling of the net current current with I_{MB} has been previously reported by this group with a similar power law[5,27]. The data point reported by Molen[15] is included for reference. These results have been compared with the results of classical electron runaway model[23-26]

(Fig. 13). The scaling of induced electric field, the Dreicer field, and the plasma parameters are based on the assumptions of adiabatic compression and the *Bennett pinch relation* (*Appendix A*). *As seen from Fig.* 13 the data (including Molen's point) most closely fit the curve where the ratio of the induced electric field, E, to the Dreicer field, E_D is 0.25 as is consistent with the assumptions in the classical runaway model. While the exact nature of the scaling of these parameters is not known this calculation indicates that such a dependence of the primary current on I_{MB} should not be unexpected. This also illustrates the use of scaling experiments to test theoretical models and the need for a wider range of I_{MB}. Thus the results of these scaling experiments are new and are relevant to the opening switch problem. That is they indicate stronger potentials are induced (scaling of the power law exponent) and larger fast electron currents are generated as one tries to interrupt larger currents by use of a plasma focus. The results of some preliminary experiments to determine the beam acceleration mechanism are discussed in the next section.

4) Preliminary Tests of the Model That Current Interruption is the Acceleration Mechanism

If current interruption were the cause of the fast particles in a plasma focus then it is likely that anytime one tries to use a rapidly opening plasma switch such acceleration will occur. There will always be charged particles around to be accelerated by the large induced fields. It is hard to avoid a Z pinch configuration occurring with a large current flowing through the plasma and the pinch will have a null in the azimuthal field on the axis allowing axial acceleration of the charged particles. Hence considering the situation it would be surprising if it didn't occur.

One hypothetical model for this process would be as follows:

1) During the radial collapse and pinch phase instabilities (microscopic or macroscopic) cause field penetration and hence an ion or plasma diode forms across this region of poor conductivity,

2) Voltages induced across the diode by the magnetic field decay accelerate particles across the diode with electrons and ions moving in opposite directions and each in the direction to maintain the field and hence the current in the circuit,

3) The accelerating voltage, V, is given by two terms:

$$V = -L\dot{I}_{MB} - \dot{L}I_{MB} \qquad (1)$$

where $\dot{L}>0$ during collapse ($v_r<0$) and $\dot{L}<0$ during expansion of the pinch.

4) The currents generated are sufficient to prevent the plasma switch from completely opening and a runaway current model should apply.

If such a mechanism were correct one could **begin** the attempt to improve the performance of the plasma focus as an opening switch. One way might be to induce the current interruption before the end of the radial collapse so the two terms on the right hand side of equation (1) tend to cancel and little voltage is generated to accelerate particles especially if the process is runaway (see Appendix A). Exactly how the interruption can be induced before the total collapse may not be obvious but at least the problem has been better defined.

Experimental tests of this model would include:

1) In a plasma diode the accelerated particles should have energy distributions that "mirror" each other.

2) The time at which the particles are accelerated should occur at a peak in $|\dot{I}|$ if current interruption is important.

3) The induced voltage estimated using equation (1) should be of the order of the maximum energy observed on the electron magnetic spectrometer.

4) In a plasma diode the acceleration process should have a runaway dependence with mainbank current. (Appendix A).

The fact that the energy spectra of the ions and electrons are mirror images of each other has been clearly demonstrated by the Illinois DPF group[10,27]. These were the first measurements of their kind although the existence of this phenomenon had been hypothesized[7]. The unique diagnostics[6,10,27] developed by the Illinois group have made the necessary direct measurements possible.

Figures 14 and 15 show that the fast electrons as evidenced by the 100 keV channel of the electron magnetic spectrometer and the hard X ray bremsstrahlung peak on our plastic scintillator-photomultiplier tube occur simultaneously[28] with a peak in $|\overset{\circ}{I}|$. The bremsstrahlung peak occurs at the second and slightly smaller $|\overset{\circ}{I}|$ peak (Fig. 15) and this may indicate a change in sign in $\overset{\circ}{L}$ in equation (1) as discussed above.

Figure 16 shows the magnitude of the terms not involving $\overset{\circ}{L}$ estimated[28] for I_{MB} = 450kA. To compare this with the maximum (E_M) energy of the particles accelerated, the maximum energy channel receiving signal is the 400 keV channel. Thus the 140 keV estimated in Fig. 16 is only about one third E_M. This could be due to two reasons:

1) The risetime of the Rogowski coil used is over 10 nsec[29] and the risetime of the signals in Fig. 14-16 is of this order.

2) The $\overset{\circ}{L}I$ term is very important (as possibly evidenced in Fig. 15).

A one turn Rogowski coil will replace the 20 turn coil used to obtain the data in Figures 14-16 to eliminate this ambiquity. If the outer velocity of the current sheath were on the order of that of the collapse, $-\overset{\circ}{L}I \sim 160$ kV so this term definitely could be important[30]. The complete resolution of this matter awaits the results of subsequent experiments.

Evidence supporting a runaway current model is shown in Fig. 13. While this analysis is quite preliminary, it does show a promising trend toward consistency between the model and experiment. More sophisticated computer models are being developed to test the scaling of Appendix A.

Although maybe not completely conclusive, the evidence supporting a current interruption model for particle acceleration is fairly strong involving the results of four independent experiments. Further experiments to test this promising model are planned.

5) Summary

The unique diagnostic tools, described in section 2, have been developed and used to perform scaling experiments and experiments to test a theoretical model for the acceleration process. There is considerable evidence for this model which if confirmed would significantly strengthen the data base for plasma opening switches and suggest new ways to attack this problem.

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Appendix A: Runaway Current Scaling with Mainbank Current

To predict the runaway current, I_R scaling with mainbank current at pinch time, I, one has to be able to predict how the plasma density, n, temperature, T, and the accelerating field, E, scale with this quantity since the runaway current density, the area of the pinch and runaway area are functions of them. Adiabatic compression and $\beta=1$ (Bennett pinch) are assumed so these relations are obtained:

$$n \propto V^{-1} \qquad (A.1)$$

$$TV^{\gamma-1} = \text{const.} \qquad (A.2)$$

$$NkT \propto I^2 \qquad (A.3)$$

where V and N are the volume of the pinch and the number of particles per unit length in the pinch respectively. γ is assumed to be 5/3, because during the radial compression phase, the gas should be ionized and dissociated, and since the collisional mean free path is very short at these densities, magnetic field effects on γ should not be important.

Sonic longitudinal (z direction) flow is assumed so:

$$\ell = C_s \Delta t \qquad (A.4)$$

where ℓ, C_s and Δt are the pinch length, the speed of sound and radial compression time respectively. Since the compression is magnetic:

$$\Delta t = \frac{r_o}{C_A} \qquad (A.5)$$

where r_o is the initial radius and C_A is the Alfvén speed. Also

$$C_s = \sqrt{\frac{\gamma kT}{m_+}} \qquad (A.6)$$

and

$$C_A = \frac{B}{\sqrt{4\pi\rho}} \propto \frac{I}{r\sqrt{\frac{M_o}{r^2\ell}}} \propto \frac{I\sqrt{\ell}}{\sqrt{n_o m_+}} \qquad (A.7)$$

where m_+, r, ρ, n_o, M_o and B are the ion mass, the pinch radius, the pinch mass density, the initial fill density, the initial fill mass and the pinch magnetic field respectively. Combination of (A.4) - (A.7) yields:

$$\ell \propto \frac{\left(T_e n_o\right)^{1/3}}{I^{2/3}} \qquad (A.8)$$

Using (A.3)

$$NkT \sim \frac{n_o kT}{\ell} \propto I^2 \qquad (A.9)$$

and (A.8) one obtains:

$$n_o T \propto I^2 \qquad (A.10)$$

(A.1), (A.2) and (A.10) then yield:

$$n \propto T^{\frac{1}{\gamma-1}} \propto I^{\frac{2}{\gamma-1}} \qquad (A.11)$$

or $n \propto I^3$, for $\gamma = 5/3$.

The induced electric field, E, scales as

$$E = \frac{L\dot{I}}{\ell} \sim \frac{\mu_o}{2\pi} \ell n\left(\frac{r_o}{r}\right) \frac{I}{\Delta t} \propto \frac{IC_A}{r_o} \qquad (A.12)$$

and ignoring logarithmic dependencies:

$$E \propto I^2 \qquad (A.13)$$

Again ignoring logarithmic dependencies

$$E_D \propto \frac{n}{T} \propto I \qquad (A.14)$$

or $$E_{D/E} \propto I^{-1} \qquad (A.15)$$

On the basis of this analysis and the uniform current density model (c.f. Section II), the runaway current, I_R, should scale as:

$$I_R = n\nu \frac{A_r}{A_p} \pi r_p^{\ 2} \gamma_R \propto \gamma_R \qquad (A.16)$$

where $\gamma_R \propto \left(\frac{E_D}{E}\right)^{3/8} \exp\left\{-\frac{E_D}{4E} - \left(2\frac{E_D}{E}\right)^{1/2}\right\} \qquad (A.17)$.

Appendix B: Electron Beam Faraday Cup-Design and High Frequency Response Calculations

The high current, fast rise time Faraday cup first designed by Pellinen[16] has been extensively used for measuring nanosecond electron beam currents. The original design made use of a carbon center electrode and a sealed stainless steel shunt. A modified design is described in this Appendix which uses an unsealed resistive shunt and a hybrid center electrode made of carbon and aluminum.

The modified Faraday cup design used for the experiments is shown schematically in Fig. 10. The distance between the hybrid center electrode and the shunt is exaggerated in the drawing and is actually .003". A .001" stainless steel 304 shunt is used because of the availability and conductivity of this material. Small rectangular tabs were cut in the stainless steel and folded onto the center electrode. Pressure contact is maintained with a brass ring and 16 tapped holes in the aluminum cylinder.

The hybrid center electrode is composed of an aluminum cylinder (2 1/8" in diameter, 5/8" long) and a carbon face (1/8" thick). Carbon is used for the collector because of its low backscattering coefficient, which is about 10%. Aluminum is used for the bulk of the center conductor in order to reduce its internal inductance. The entire center electrode in the original Faraday cup design is made of carbon. However, the internal inductance of the carbon electrode in reference 16 is 3.7×10^{-11} H at 100 MHz; the inductance due to the geometry of the cup is 3.0×10^{-11} H. The inductance of the Faraday cup has to be kept as small as possible to minimize the voltage across the Mylar dielectric at the cup input. A large voltage can lead to flashover or Mylar breakdown which would produce erroneous output waveforms.

The high frequency response of the Faraday cup has been measured with a Hewlett-Packard 8505A network analyzer, used in conjunction with an HP 8503A S parameter test set and an HP 8501A storage normalizer; results are shown in Table B.1. Also shown in Table B.1 is the calculated[17] frequency response. The error in the calculated values is due mainly to the uncertainty in the output inductance L_0; this value is estimated to be within 20% of 12 nH. It can be seen that the calculated values agree with the experimental values, to within experimental error ($\pm$ 1.0 dB), for frequencies up to 700 MHz.

The output voltage of the Faraday cup was calibracted with a nanosecond pulser[17]; the shunt resistance was determined to be $3.66\text{x}10^{-3}\Omega$.

V(MHz)	$\frac{V_{OUT}/I_{IN}}{R_{DC}}$ (calc.)	$\frac{V_{OUT}/I_{IN}}{R_{20.4MHz}}$ (meas.)
20.4	1.0 (0 dB)	1.0 (0 dB)
100	0.99 (-.12 dB)	0.97 (-.3 dB)
200	0.95 (-.47 dB)	0.89 (-1.0 dB)
300	0.89 (-1.0 dB)	0.81 (-1.8 dB)
400	0.82 (-1.7 dB)	0.75 (-2.5 dB)
500	0.75 (-2.5 dB)	0.68 (-3.4 dB)
600	0.68 (-3.4 dB)	0.69 (-3.2 dB)
700	0.61 (-4.3 dB)	0.64 (-3.9 dB)
800	0.55 (-5.3 dB)	0.68 (-3.4 dB)

Table B.1. Comparison of the measured frequency response of the Faraday cup with the predicted response[17]. The error in the measured values is 1.0 dB.

The following is a summary of the Faraday cup characteristics:

$L(\text{Total}) \simeq 1.1\times10^{-11}$ H

$C(\text{Total}) \simeq 1.1\times10^{-9}$ F

$R_{DC}(\text{Shunt}) = 3.66\times10^{-3}\ \Omega$

- 3.0 dB Bandwidth ≃ 450 MHz

Thickness of the Mylar insulation = .003"

0-90% diffusion time into the shunt ≃ .34 nanoseconds

Figure Captions

Fig. 1. Inductive energy supply circuit. The energy is stored in the inductance L_1 with switch S_1 closed. Ideally the energy would be transferred to load L_2 by simultaneously opening S_1 and closing S_2.

Fig. 2. Waveform of the mainbank current of the Illinois plasma focus as observed with a Rogowski coil.

Fig. 3. The plasma focus (Mather type) consists of two coaxial electrodes immersed in 1-10 torr of gas. A capacitor bank is discharged into the device which forms a plasma current sheath across the insulator. This current sheath is rapidly pushed (~ 2 μsec) to the top of the electrodes and forms a pinched (plasma focus) plasma over the center of the inner electrode. Disruption of the plasma current (Fig. 2) generates the intense particle beams shown.

Fig. 4. Electron beam current measurement of electron current flowing down through the center electrode (c.f. Fig. 3) of the Illinois plasma focus with 12.5 kJ of bank energy and 3 torr of deuterium. The top trace is the signal on a high current Faraday cup behind a 25 μm Mylar foil and 70 cm away from the plasma pinch. The bottom trace is the simultaneously recorded net or plasma current as observed using a Rogowski coil surrounding the beam line 35 cm away from the pinch. The beam diameter at 70 cm is estimated to be 3 cm from the damage pattern on the Mylar foil.

Fig. 5. Plot of peak neutron yield versus plasma focus current at pinch time, I_{MB}. Filling pressure was 3 torr deuterium; bank voltage range was 16-24kV.

Fig. 6. A schematic view of the electron magnetic spectrometer.

Fig. 7. Typical time integrated electron energy spectrum observed with the electron magnetic spectrometer (c.f. Fig. 6) for I_{MB} = 450kA. The filling pressure was 3 torr deuterium; the bank voltage was 25kV ($1/2\ CV^2$ = 12.5kJ).

Fig. 8. Typical time integrated electron energy spectrum observed with the electron magnetic spectrometer (c.f. Fig. 6) for I_{MB} = 300kA. The filling pressure was 3 torr deuterium; the bank voltage was 17.5kV ($1/2\ CV^2$ = 6.1kJ).

Fig. 9. Observed scaling of the power law exponent, x ($dN/dE \propto E^{-x}$), with I_{MB}. The filling pressure was 3 torr deuterium; the verticle error bars represent the least square error in the power law slopes for the various observations.

Fig. 10. A schematic view of the high current fast Faraday cup which was used to measure the primary electron current along with a signal taken during a DPF shot. Areas behind the filter are evacuated to about 0.04 torr to increase the voltage standoff.

Fig. 11. Simultaneous waveforms of the fast electron primary current as measured on the fast Faraday cup (top), the net electron current signal as measured on a Rogowski coil mounted on the electron drift tube (middle; c.f. Fig. 6) and the current flowing in the DPF as measured by a Rogowski coil mounted on the anode (bottom; c.f. Fig. 6). The rectangular pulses at 100 nsec on the top two traces are time markers and the electron currents are simultaneous with the end of the dip in the plasma focus current (±50 nsec). The filling pressure was 3 torr deuterium; the bank voltage was 25kV.

Fig. 12. Observed scaling of the peak primary current (first peak in top trace of Fig. 11) with I_{MB}. The filling pressure was 3 torr deuterium.

Fig. 13. Data from scaling measurements the relation of the primary current, I_R, (top trace, Fig. 11) to mainbank current a pinch time, I, (where the mainbank current, Fig. 2, starts to drop sharply). The mainbank current has been normalized to 450 kA, I_0, and superposed are the predictions of equations A.16) and A.17). A data set reported by Molen[15] for a higher mainbank current and a 125 μm Kapton cover on the Faraday cup at 3 torr D_2 is the point labeled by 'M'. The parameters are the ratio of the Dreicer electric field to induced electric field at a mainbank current of 450 kA.

Fig. 14. Simultaneous waveforms of the a) 100 keV (±20 keV) channel of the electron magnetic spectrometer and b) the $\overset{\circ}{I}$ waveform of the mainbank current. The filling pressure was 3 torr deuterium; the bank voltage was 25 kV.

Fig. 15. Simultaneous waveforms of the a) scintillator photomultiplier tube and b) the $\overset{\circ}{I}$ waveform of the mainbank current. The long narrow peak in a) has been identified as the hard X ray bremsstrahlung produced by the fast electrons in the beam and the broader second peak as the neutrons produced by the device. Waveform a) is delayed 40 ± 4 nsec with respect to b) due to the inherent delay of the photomultiplier tube, the differences in cable length and time-of-flight. The filling pressure was 3 torr deuterium; the bank voltage was 25 kV.

Fig. 16. Typical waveforms of a) the voltage across the capacitor bank (q/C) and b) $\overset{\circ}{I}$ of the mainbank current (not simultaneous). These waveforms can be used to calculate two of the three terms of the possible accelerating voltage across the plasma diode (excluding the $L\overset{\circ}{I}$ term). The circuit inductance at pinch time is estimated to be 72 nH on the basis of time integrated pinhole camera pictures so the total of q/C and $L\overset{\circ}{I}$ is 140 kV. (The base line in a) is one division below the top.)

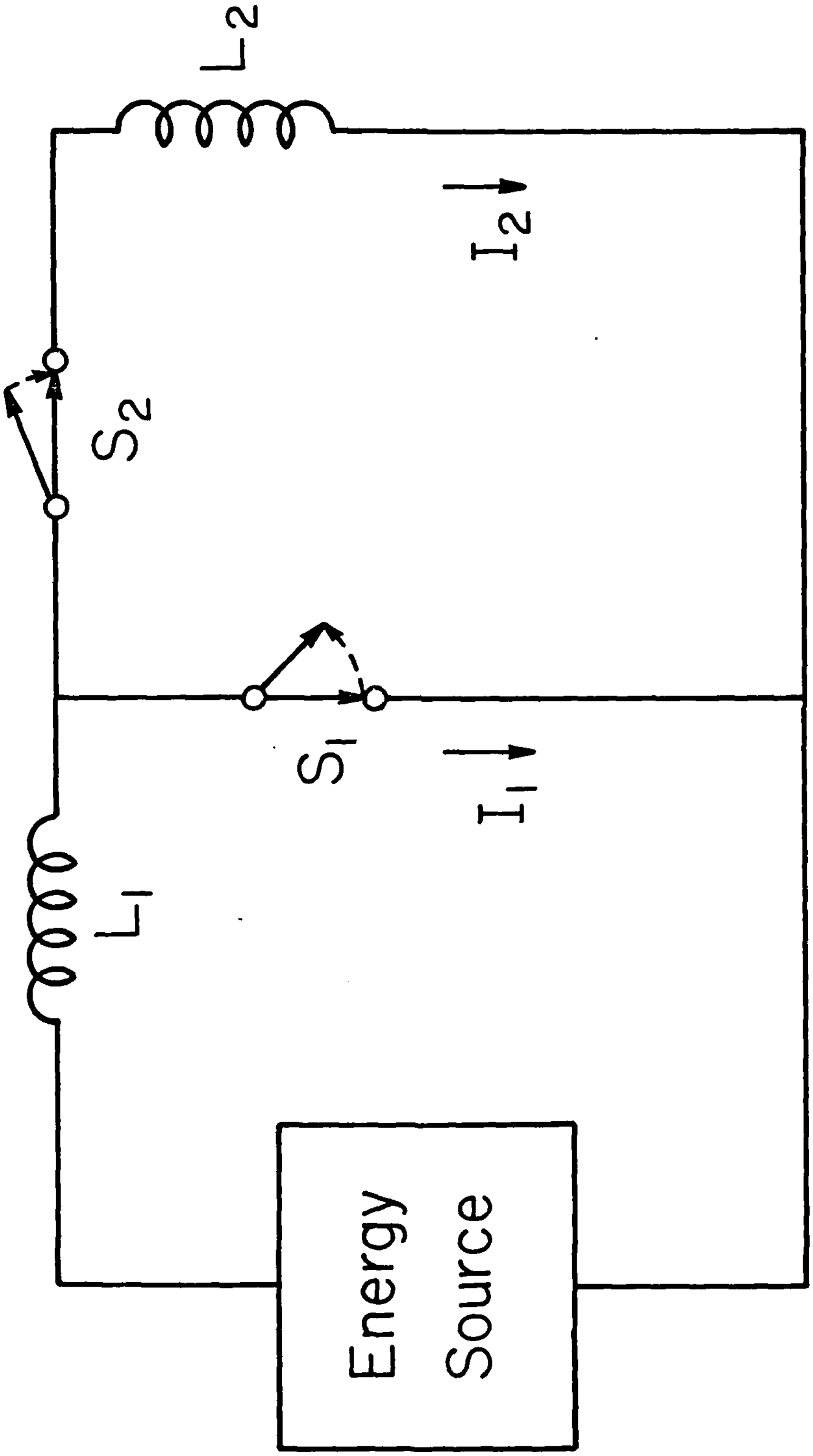

Fig. 1

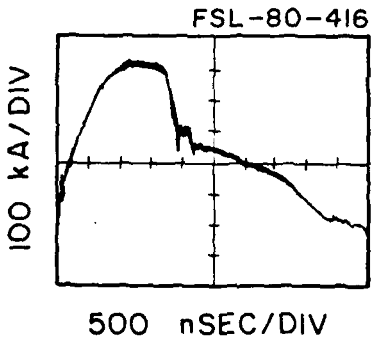

Fig. 2

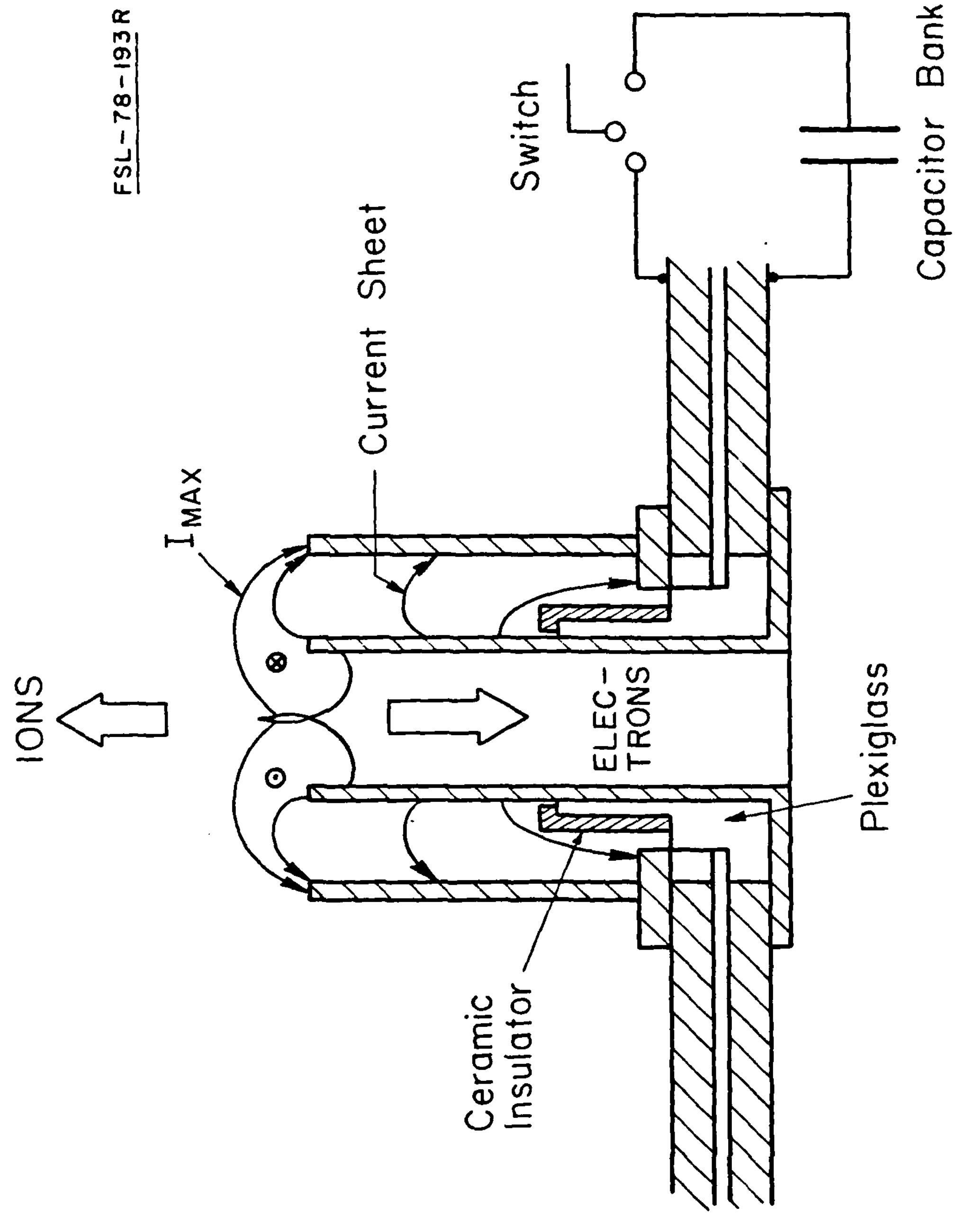
FSL-78-193R
IONS
I_{MAX}
Current Sheet
Switch
Capacitor Bank
ELEC-
TRONS
Plexiglass
Ceramic
Insulator

Fig. 3

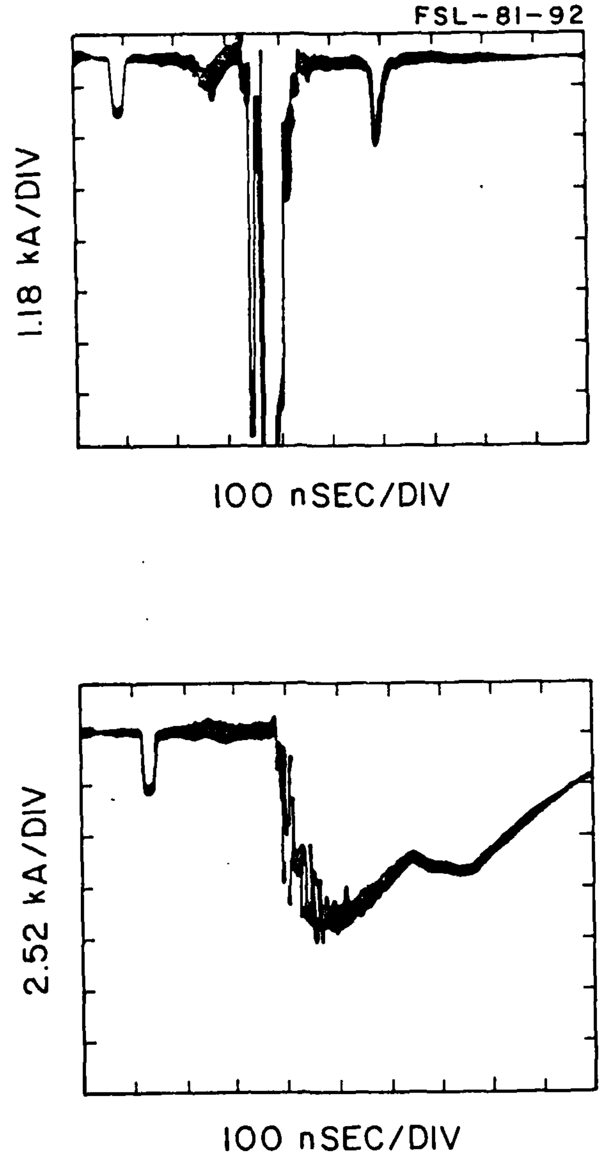

Fig. 4

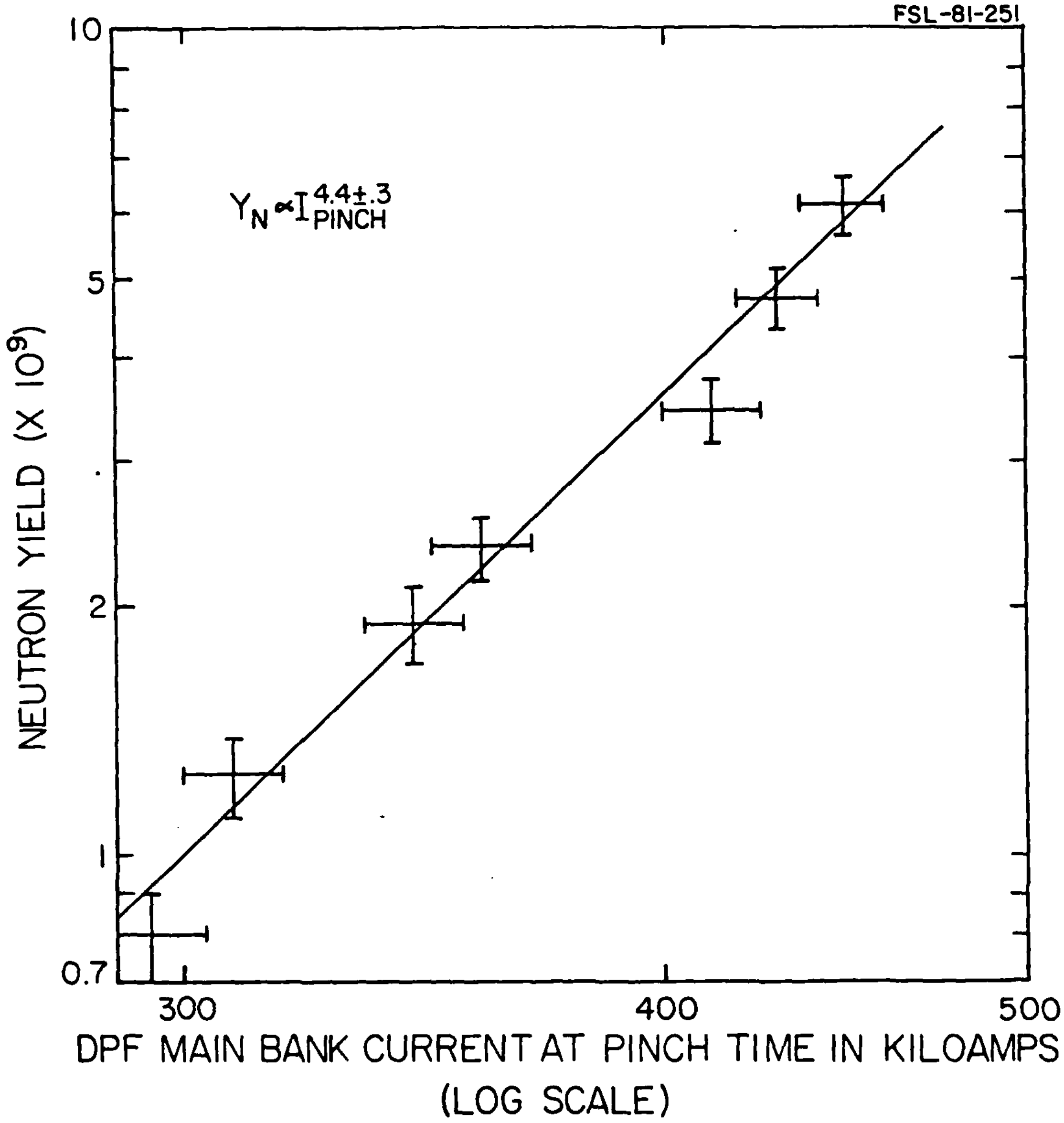
FSL-81-251
$Y_N \propto I_{PINCH}^{4.4\pm.3}$
10
5
2
1
0.7
NEUTRON YIELD (X 10^9)
300
400
500
DPF MAIN BANK CURRENT AT PINCH TIME IN KILOAMPS
(LOG SCALE)

Fig. 5

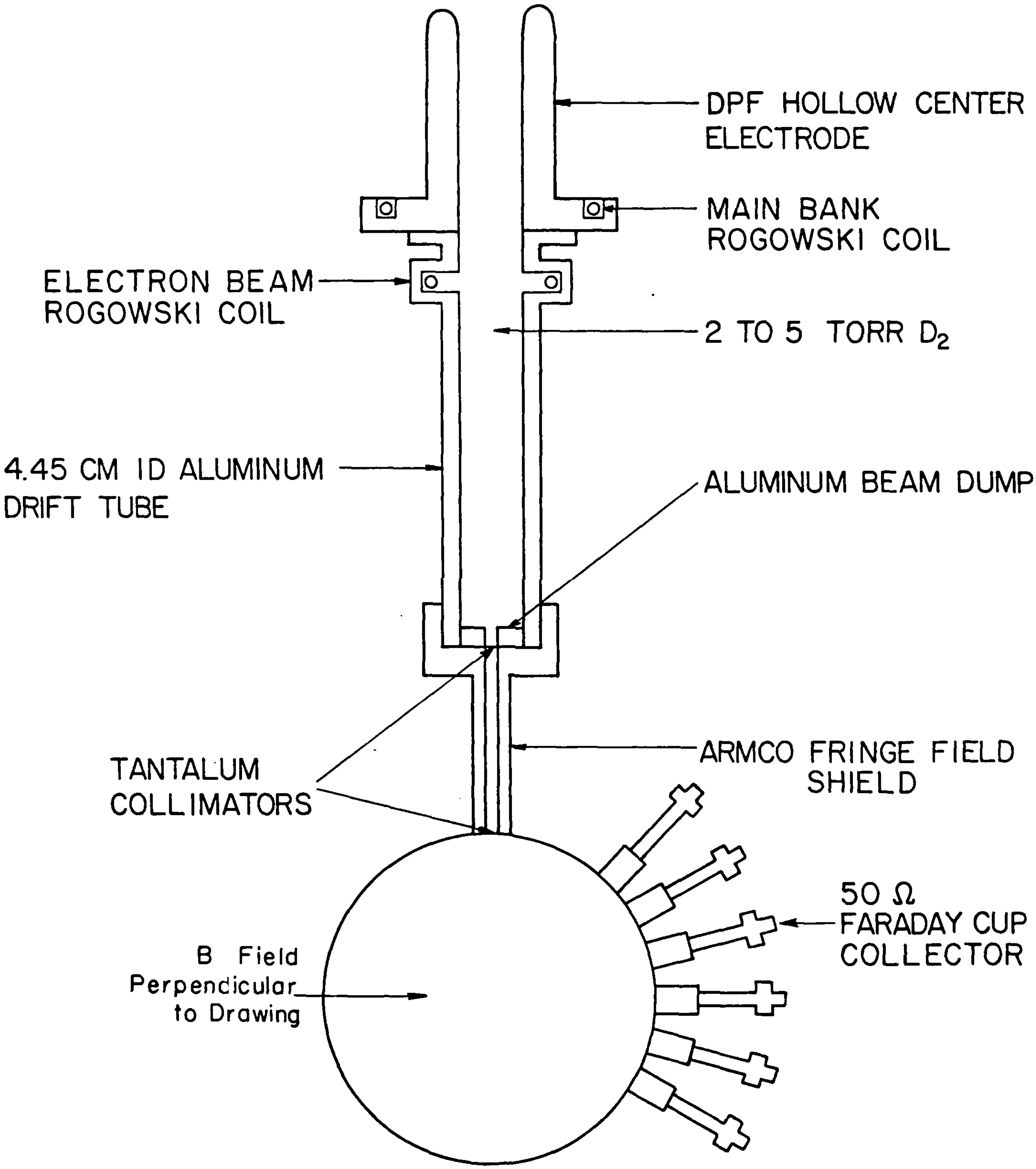
DPF HOLLOW CENTER ELECTRODE
MAIN BANK ROGOWSKI COIL
ELECTRON BEAM ROGOWSKI COIL
2 TO 5 TORR D_2
4.45 CM ID ALUMINUM DRIFT TUBE
ALUMINUM BEAM DUMP
ARMCO FRINGE FIELD SHIELD
TANTALUM COLLIMATORS
50 Ω FARADAY CUP COLLECTOR
B Field Perpendicular to Drawing

Fig. 6

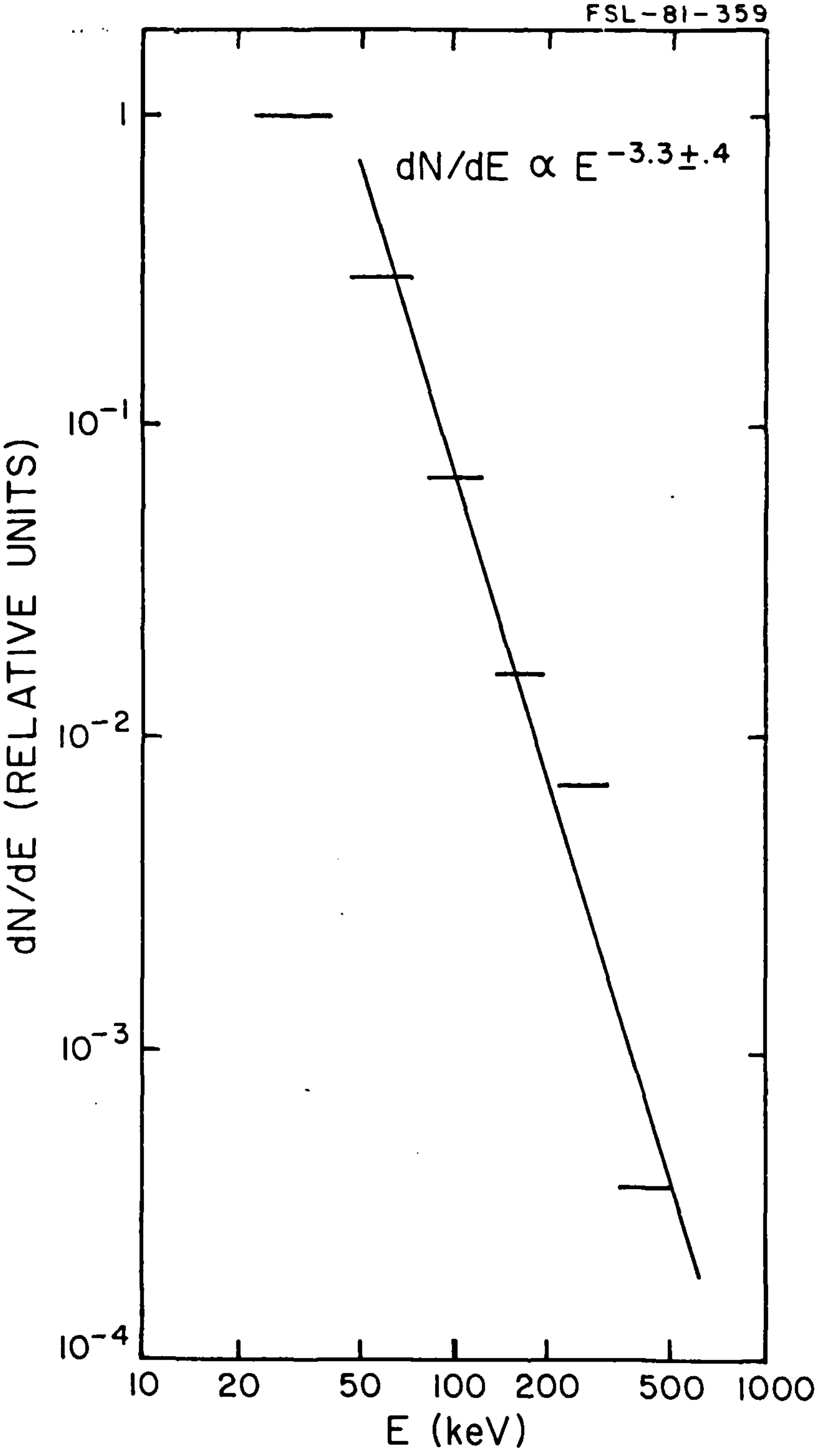
FSL-81-359
dN/dE α $E^{-3.3\pm.4}$
dN/dE (RELATIVE UNITS)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
50
100
200
500
1000
E (keV)

Fig. 7

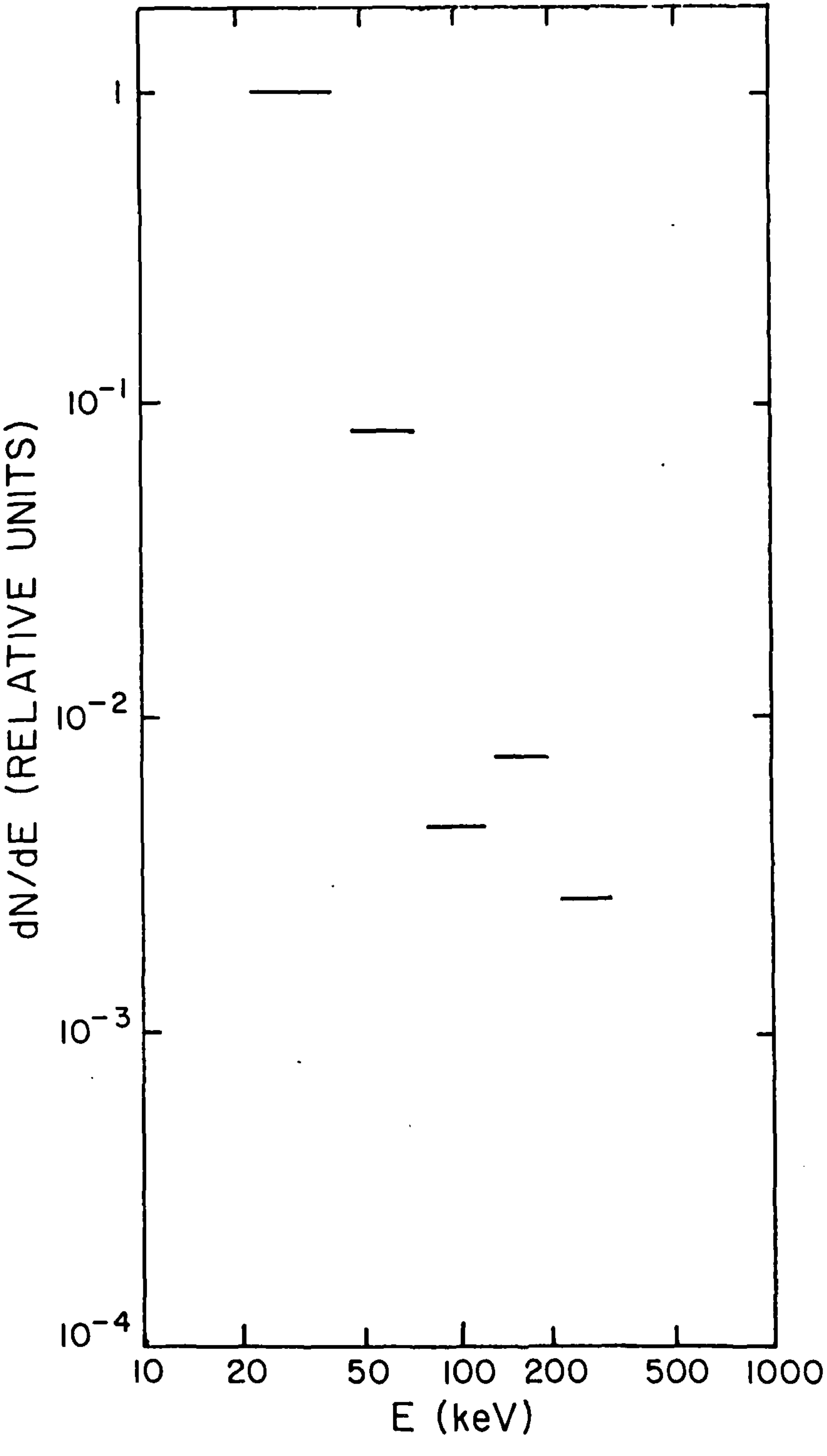
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
dN/dE (RELATIVE UNITS)
10
20
50
100
200
500
1000
E (keV)

Fig. 8

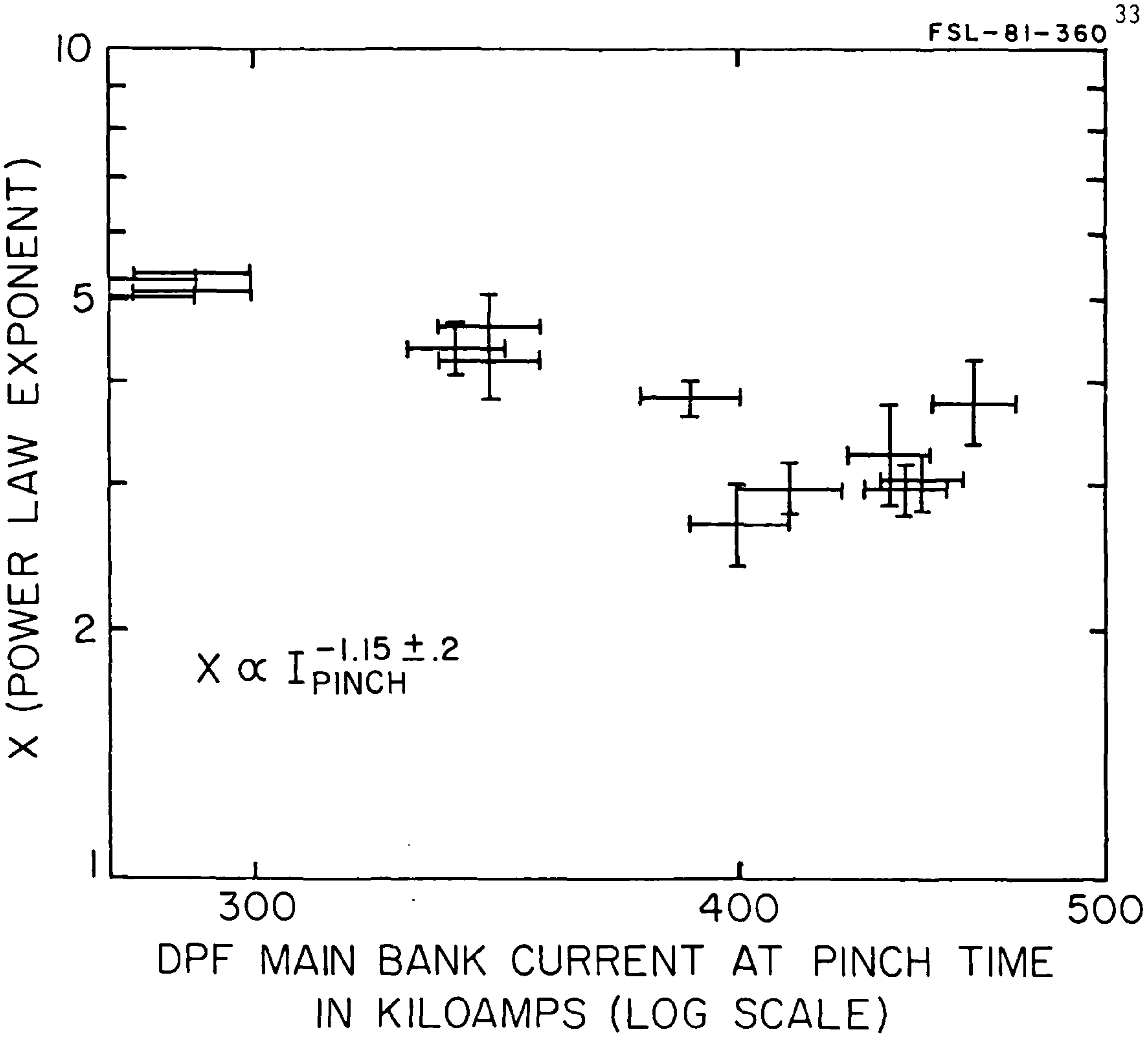
FSL-81-360
10
5
2
1
X (POWER LAW EXPONENT)
X ∝ I_PINCH^{-1.15 ± .2}
300
400
500
DPF MAIN BANK CURRENT AT PINCH TIME
IN KILOAMPS (LOG SCALE)

Fig. 9

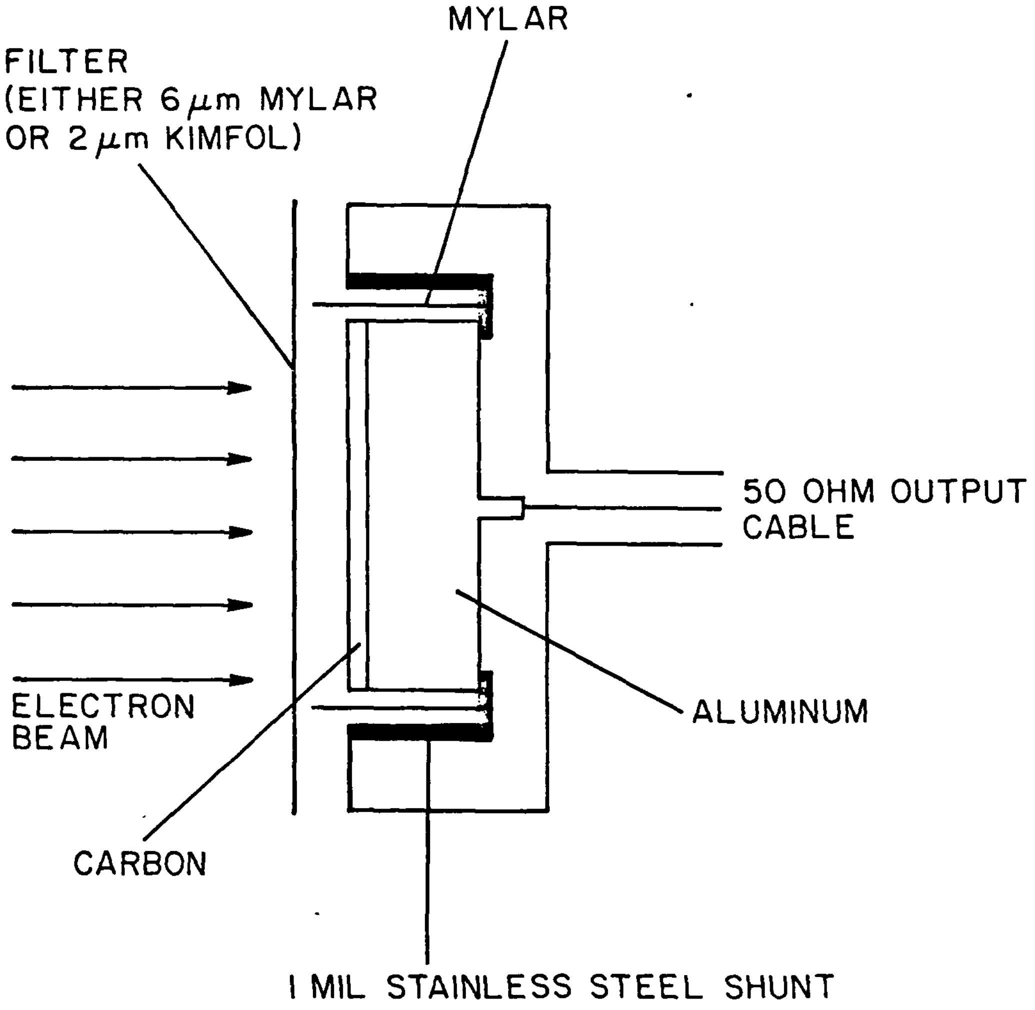
MYLAR
FILTER
(EITHER 6μm MYLAR
OR 2μm KIMFOL)
50 OHM OUTPUT
CABLE
ELECTRON
BEAM
ALUMINUM
CARBON
1 MIL STAINLESS STEEL SHUNT

Fig. 10

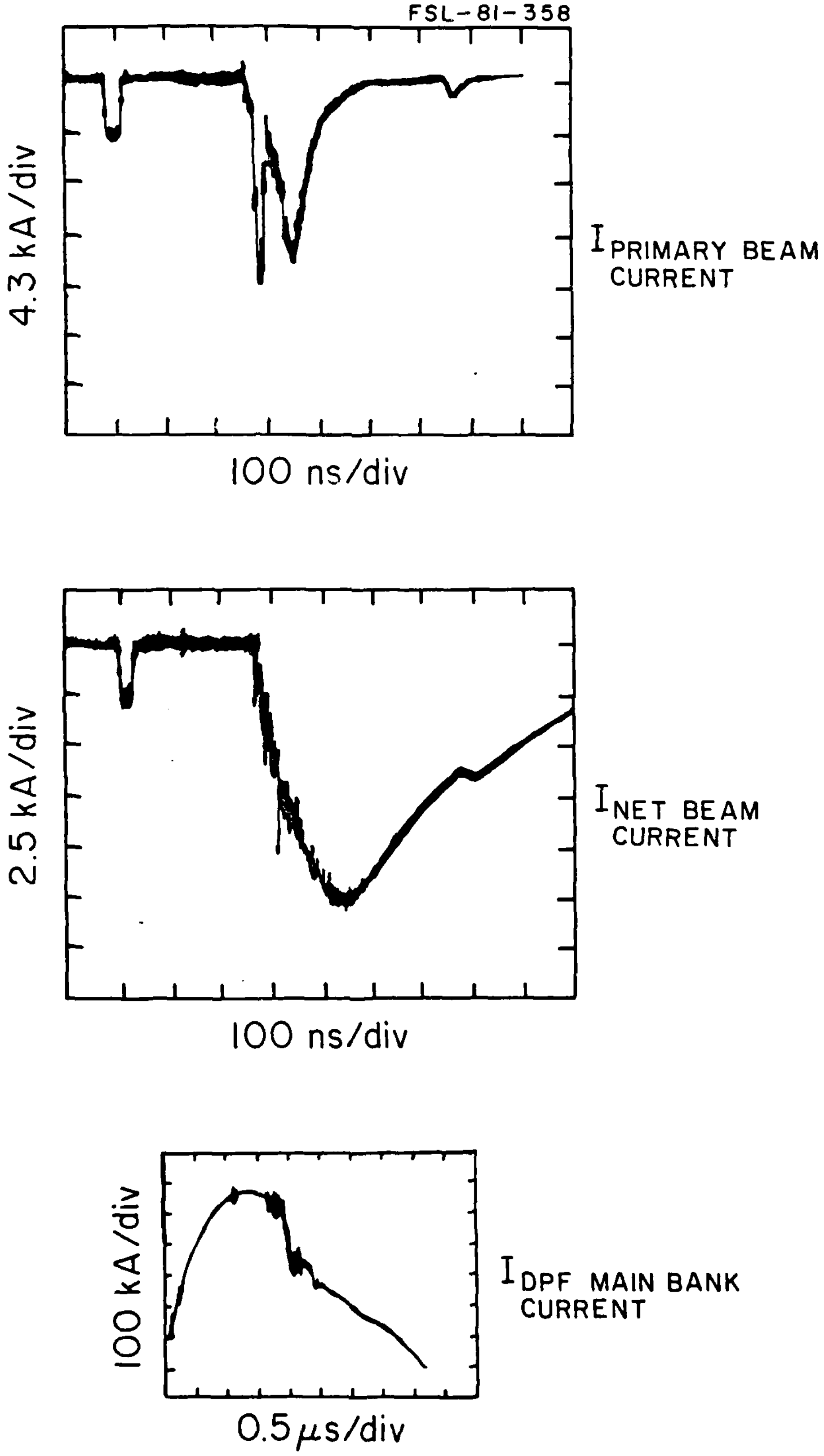
FSL-81-358
4.3 kA/div
100 ns/div
I PRIMARY BEAM CURRENT
2.5 kA/div
100 ns/div
I NET BEAM CURRENT
100 kA/div
0.5 μs/div
I DPF MAIN BANK CURRENT

Fig. 11

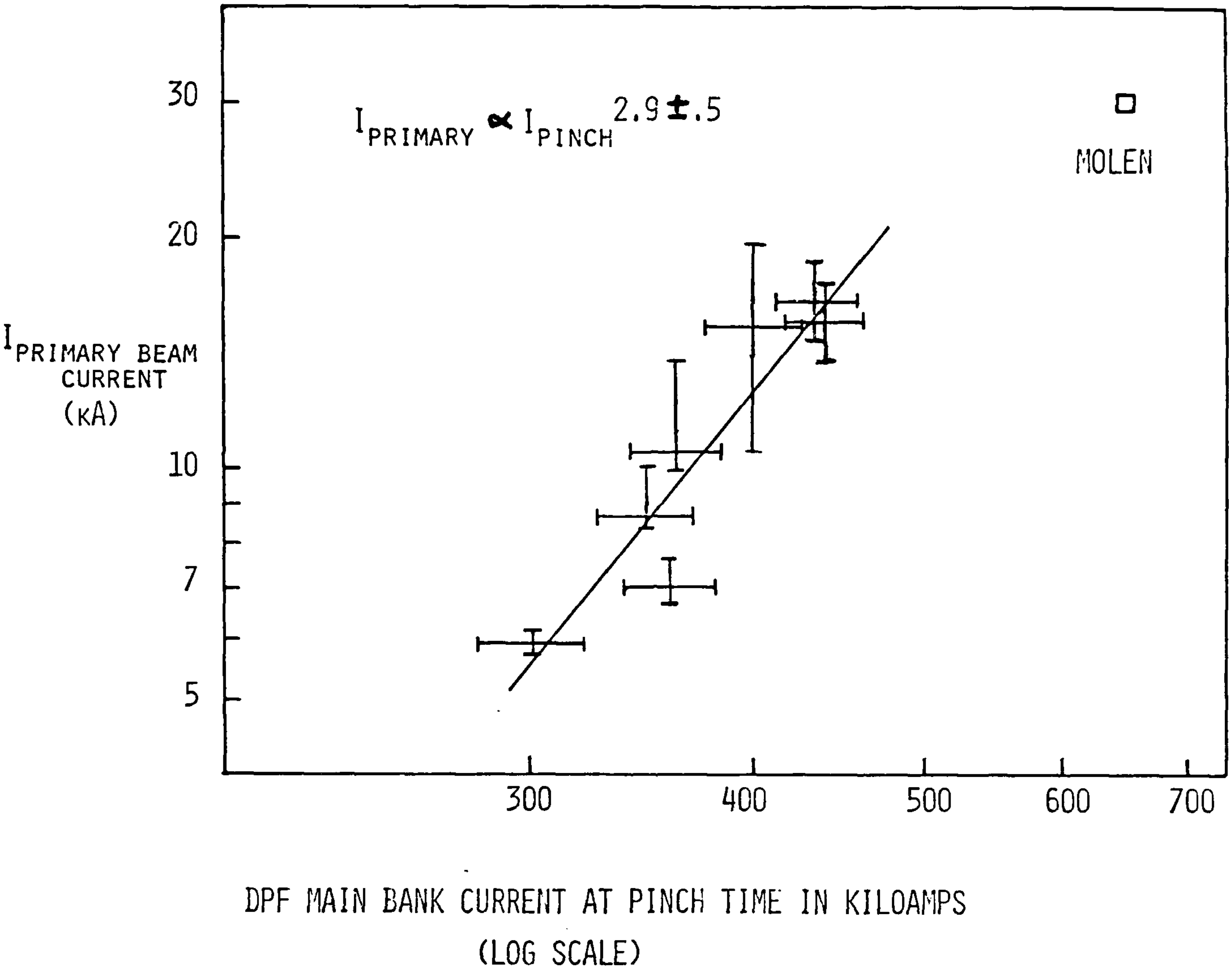
30
20
10
7
5
$I_{PRIMARY} \propto I_{PINCH}^{2.9 \pm .5}$
□
MOLEN
$I_{PRIMARY\ BEAM}$
CURRENT
(κA)
300
400
500
600
700
DPF MAIN BANK CURRENT AT PINCH TIME IN KILOAMPS
(LOG SCALE)

Fig. 12

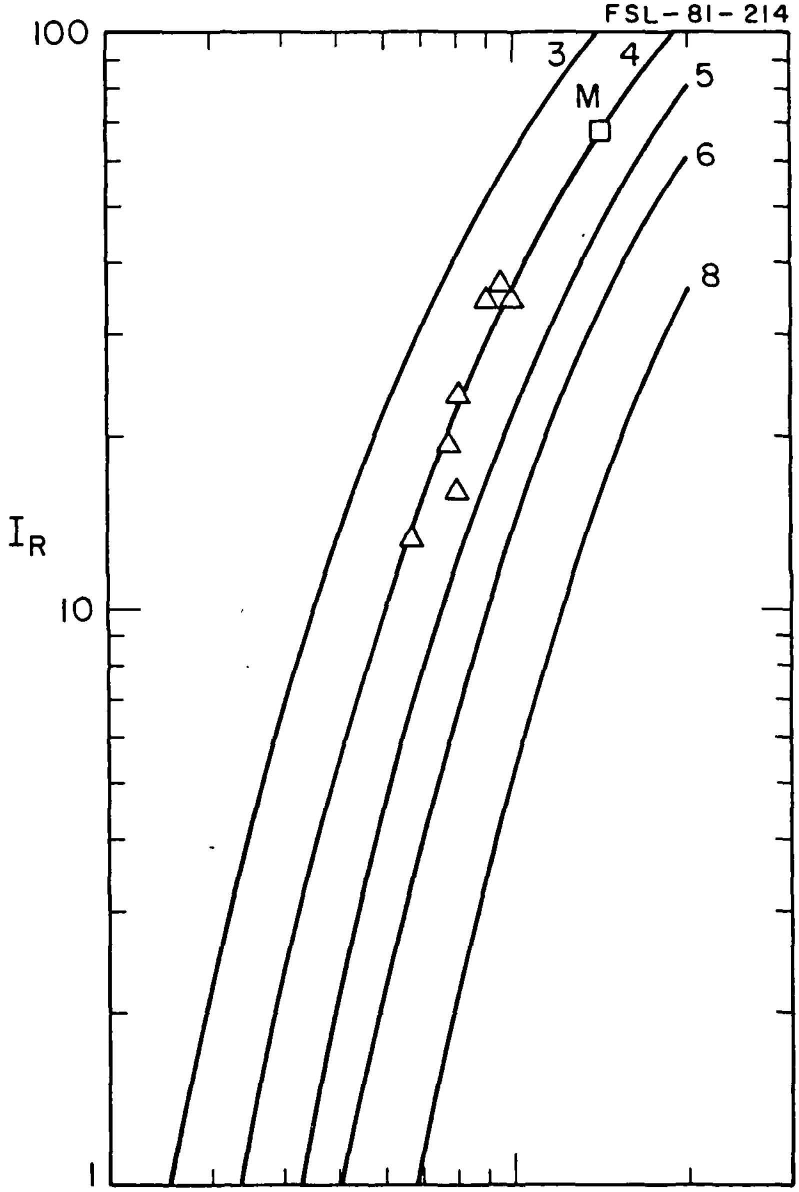

Fig. 13

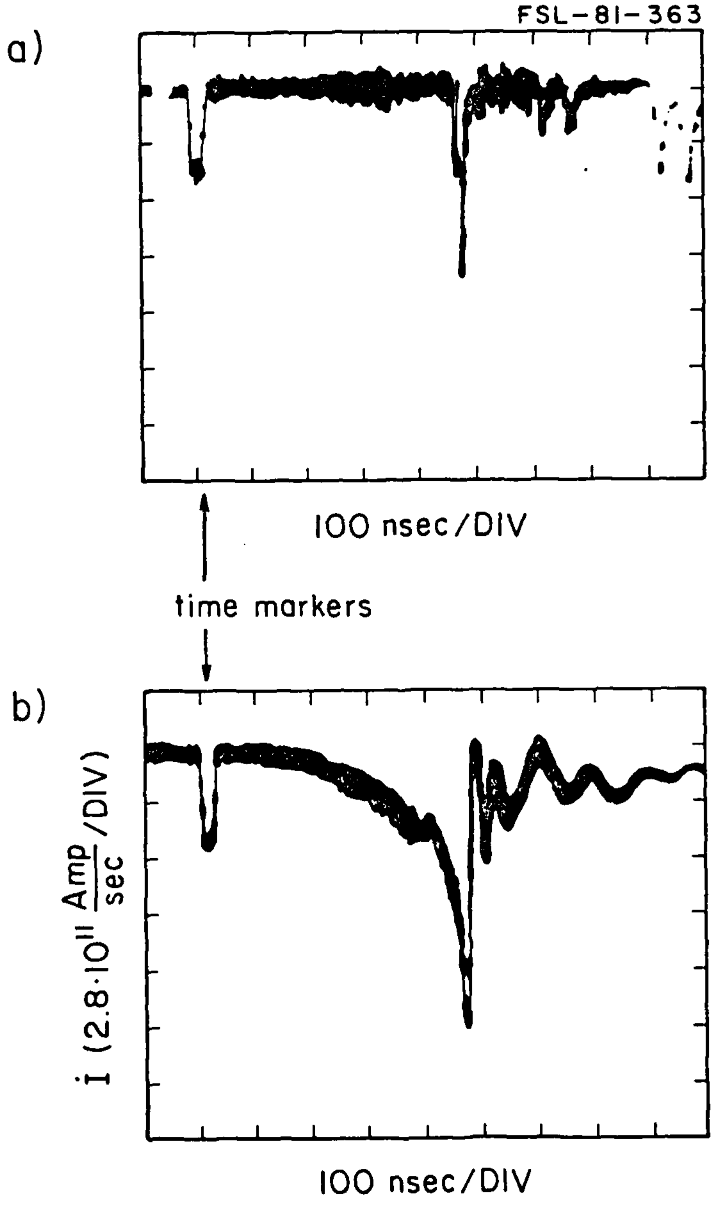
FSL-81-363
a)
100 nsec/DIV
time markers
b)
$\dot{i}$ (2.8·10^{11} $\frac{\text{Amp}}{\text{sec}}$/DIV)
100 nsec/DIV

Fig. 14

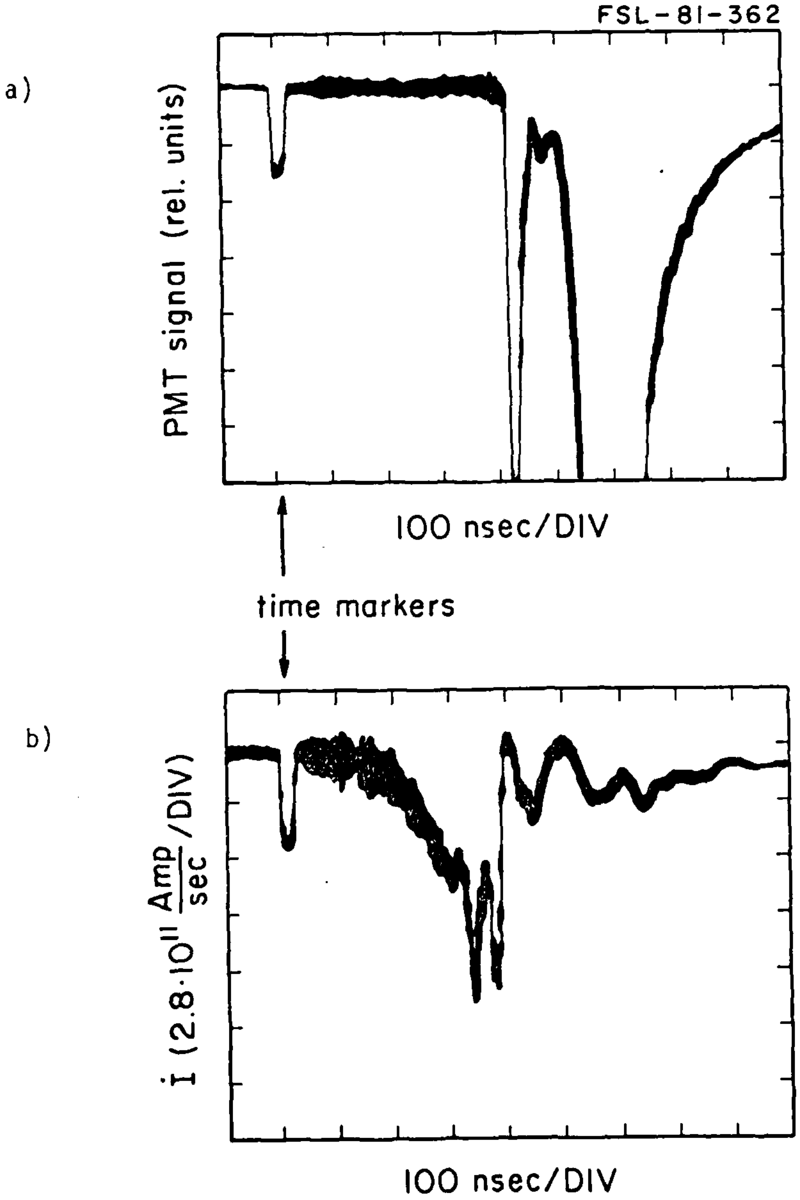
FSL-81-362
a)
PMT signal (rel. units)
100 nsec/DIV
time markers
b)
İ (2.8·10¹¹ Amp/sec /DIV)
100 nsec/DIV

Fig. 15

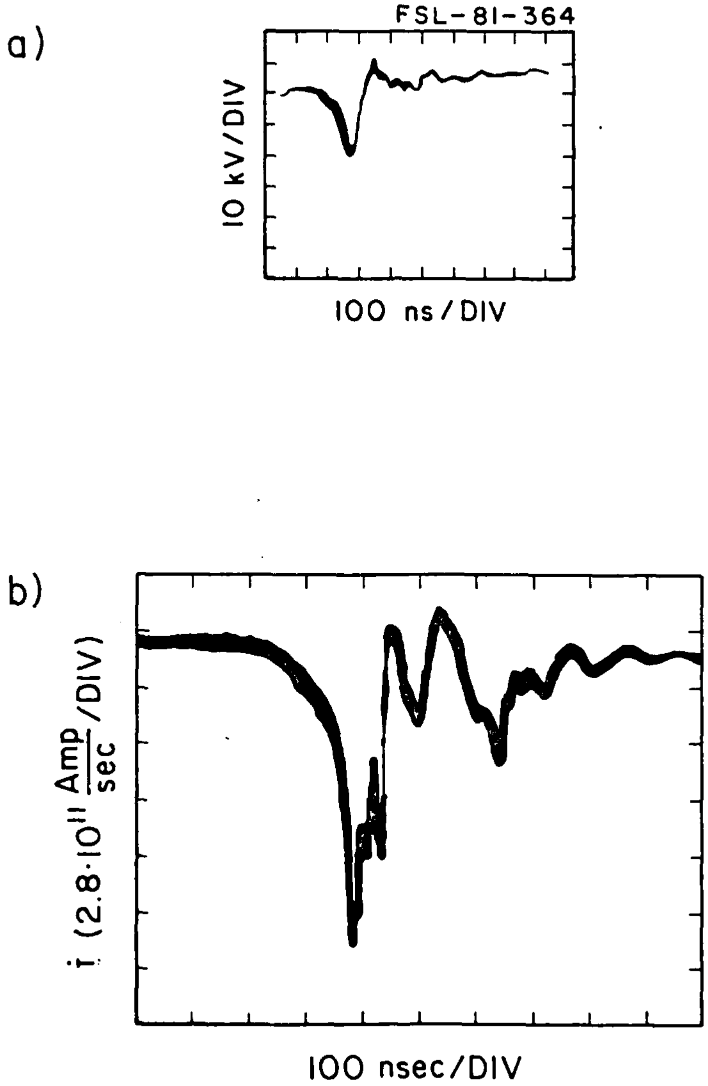
a)
FSL-81-364
10 kV/DIV
100 ns/DIV
b)
i̇ (2.8·10¹¹ Amp/sec /DIV)
100 nsec/DIV

Fig. 16

d) Cumulative Chronological List of Publications

G. Gerdin, W. Stygar, and F. Venneri, "Faraday Cup Analysis of Ion Beams Produced by a Dense Plasma Focus," J. Appl. Phys. 52, 3269 (May 1981).

G. Gerdin, J. Durham and R. Ilić, "Solid State Nuclear Track Detectors and High Fluences of Light Ions," to appear in Nuclear Tracks Sept. 1981.

W. Stygar and G. Gerdin, "High Frequency Rogowski Coil Response Characteristics," to appear in IEEE Trans. on Plasma Sci. in March 1982.

W. Stygar, G. Gerdin and F. Venneri, "Simultaneous Measurement of the Energy Spectra of Electrons and Ions Emitted by a Plasma Focus," submitted to Nucl. Fusion.

e) List of Professional Personnel Associated with the Research Effort

Personnel

Glenn Gerdin, Asst. Professor, Nuclear Engineering, Principal Investigator

William Stygar, graduate assistant supported by AFOSR

Francesco Venneri, graduate assistant supported by AFOSR (started Jan. 1980)

James Durham, graduate assistant supported by University of Illinois Research Board (started June 1980)

James Mandrekas, graduate assistant supported by seed money of Univ. of Illinois Nuclear Engineering Program

Advanced Degrees

Jan. 1980, William Stygar, Master of Science in Nuclear Engineering, University of Illinois at Urbana-Champaign, thesis title, "Design, Construction, and Operation of a Fast Rise Time, High Voltage Pulse Generator."

f) Interactions

Conference Papers

Fall 1980 Meeting of the Plasma Phys. Div. of the Amer. Phys. Soc.:

R. Ilić, G. Gerdin, J. Durham, R. Wehring, W. Stygar, T. Emoto, Bull. Amer. Phys. Soc. 25, 962 (1980).

W. Stygar, G. Gerdin, F. Venneri, Ibid 833.

Spring 1981 IEEE Conf. on Plasma Science at Santa Fe, NM:

W. Stygar, G. Gerdin, F. Venneri, J. Durham and J. Mandrekas, Conf. Record-Abstracts 1981 IEEE Int. Conf. on Plasma Sci., IEEE #81CH1640-2 NPS, 121 (1981).

Fall 1981 Meeting of the Plasma Phys. Div. of the Amer. Phys. Soc.:

G. Gerdin, W. Stygar, and F. Venneri, Bull. Amer. Phys. Soc. 26, 849 (1981).

Seminars

U. of I. Nuclear Engineering Program Seminar, Sept. 22, 1981.

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