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by

D. A. Freiwald
J. N. Downing

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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A SURVEY OF A 210-KJ DENSE PLASMA FOCUS
(DPF 6)

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ABSTRACT

An experimental survey has been done on a 212-kJ dense plasma focus machine (DPF-6) in order to obtain statistical data on its performance, including optimization thereof. Several shots were taken for each of various combinations of charging voltages and fill gas pressure, with a total of several hundred shots, for a fixed system geometry.

Reported here are voltage, current, focus x-ray pulse width, and x-ray and neutron measurements, from which intramachine scaling parameters are obtained.

This survey, probably more complete than any heretofore reported for a DPF facility, may also be useful for interfacility comparisons, and comparison of various plasma focus theories.

The effect of the presence of large copper probes near the focus plasma is briefly discussed in the Appendix.

I. INTRODUCTION

A review of dense plasma focus (DPF) work has been given by Mather.*

The purposes of this study were:

- 1) To determine the degree to which the performance of a moderately high energy DPF (212 kJ) is predictable.

- 2) To provide a statistical foundation for the operation of DPF-6 against which changes in electrode geometry and gas fill can be evaluated.

The results presented in this paper include "warm-up" and "conditioned (facility)" data as well as observations made after extended use (several hundred shots). The total results should indicate the maximum degree of non-reproducibility. It is important to note that radiation measurements for a given combination of fill gas pressure (P_0) and bank charging voltage (V_0) were reproducible when

*J. W. Mather, "Dense Plasma Focus", Methods of Experimental Physics, Vol. 9B, Academic Press, N. Y., 1971.

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Since the intent of this survey was to make defacto characterization study based on a reasonable set of statistics for a given facility with a fixed geometry and electronics, there has been no attempt to make extensive comparisons of the data with the various plasma focus theories. The empirical scaling relations obtained in this report do not necessarily imply scaling between different DPF devices. For a given voltage range the electrode-insulator geometry should be modified to give the best performance; hence, it would be unreasonable to expect the performance of DPF-6 to remain optimized over the entire voltage range of 30 kV - 50 kV.

The DPF-6 discharge chamber is schematically illustrated in Fig. 1 where relevant dimensions

The discharge tube is powered by a 50-kV, 168- μ F (~ 212 -kJ_{max}) capacitor bank. The bank consists of 12 modules, each containing four 20-kV, 14- μ F capacitors. A module circuit is schematically shown in Fig. 2, where C represents two capacitors

in parallel. The capacitors are charged to V_0 ~25 kV. The reversal switch is then triggered and half the modules discharge through a swinging LC Marx circuit* (~80- μ sec half-period) such that the total voltage across the module is ~50 kV. The two pairs of capacitors are then discharged in series via a field distortion switch* and 16 coax cables (192 total for all 12 modules) to the coaxial discharge tube header plates. This unique high-energy circuit has the advantage that circuit components are pulsed for ~80 microseconds to 50 kV, rather than for several seconds as would be the case for D.C. charging.

The load cables are terminated at the aluminum circular parallel plate header with 130 parallel

⁺Developed by J. Mather and P. Bottoms.

* J. P. Carpenter, A. H. Williams, K. D. Ware,
P. J. Bottoms, and J. W. Mather, IEEE Trans. Nucl.
Sci., NS-18 4 (1971).

strings of resistors, each string consisting of eight 20-ohm 2-watt carbon resistors, giving a header termination resistance of ~ 1.2 ohm.* This termination provides transition impedance matching between the cables and the load.

The bank and header inductance is 23.2 nH, giving a quarter-period of ~ 3.2 μ s.

The discharge tube is evacuated with a turbomolecular pump to $\sim 5 \times 10^{-6}$ Torr, then filled with deuterium gas. To remain "timed", as defined when peak current is reached at the end of rundown phase, we find that the mass density $n_0 \propto V_0^{2/3}$.† This timing constraint permits the maximum capacitor energy to be stored inductively in the coaxial discharge tube prior to the collapse of the plasma sheath to form the focus.

For best focus performance, the system is generally operated by "voltage oscillating", i.e., if a high-voltage shot is desired, say at 50 kV, the system is first fired at $V_0 \sim 35$ kV. This procedure seems to aid in system conditioning, giving higher average yields for higher voltage operation than without voltage oscillating.

The current, I , is measured with a rogowsky loop located in the ground return header and the voltage, V , is recorded with a resistance divider across the header plate. Typical I and V oscillograms are shown in Fig. 3, where time increases to the right. The current rises to peak value in a quarter-period, then drops sharply as the current sheath collapses to form the focus. The voltage across the header rises sharply at $t = 0$ to a value $V \approx V_0 \left(\frac{L_i + L_h}{L_e + L_i + L_h} \right)$ where L_e is the circuit inductance external to the header, L_i is the insulator inductance and L_h is the header inductance. The voltage then drops slowly as the current rises according to $V \sim LI + I\dot{L}$, until current sheath collapse time (focus) when the corresponding large $\dot{L}$ gives rise to a voltage spike or back-voltage.

Plasma diagnostics include a PIN silicon detector (see Fig. 1) to monitor x-ray production, a scintillator capped photomultiplier tube enclosed

DPF-6 Shot No. 22 1/23/73
50 kV, 17 Torr D_2

Fig. 3. Sample Oscillograms.

in lead and located 15 m from the focus plasma to record neutron production, two silver activation neutron counters for absolute neutron measurements, and two tantalum foil type E (60 μ V/ $^{\circ}$ C) thermocouples affixed to tantalum foils (TC-1: 0.08 mm Ta, and TC-2; 0.26 mm Ta) to form calorimeters for measurements of time integrated x-ray fluences. The calorimeter chambers were evacuated at all times.

Sample silicon detector, neutron and calorimetric signals are also given in Fig. 3. The silicon detector trace shows the prompt x-ray emission at time of focus. The dN/dt trace shows two time separated signals: the first signal corresponds to a γ pulse, and the second signal corresponds to the neutron pulse, with the time separation being due to the time of flight of the neutrons. The variation in the calorimeter signals which is due in part to the differences in foil thickness, will be discussed in more detail below.

* Subsequent to this survey the carbon resistor strings have been replaced with copper sulphate water resistors.

† K.D. Ware, R.A. Gerwin, J.W. Mather and A.H. Williams, Bull.Amer.Phys.Soc. 17, 1023(1972).

III. EXPERIMENTAL RESULTS

All x-ray, current and voltage results are given in units of centimeter deflection on the oscillograms. This technique enables rapid assemblage of data, and, because detector calibrations are linear, the deflections can be converted to absolute "real unit" values using stated calibration factors. All oscillograms were read with a Gerber scale, to an accuracy of .05 cm.

A. X-Ray Fluence ($\bar{\Phi}$) vs. Charge Voltage

At least 10 shots (generally more, with >20 for timed cases) were taken for each combination of fill gas density and capacitor bank charge voltage. Peak calorimetric readings (see Fig. 3) were determined by extrapolating the thermocouple heating signal to zero time.

X-ray yields $\bar{\Phi}$ for TC-1 and TC-2 are given in Figs. 4a and 4b, respectively, where the number inside each symbol indicates the number of overlapping data points.

The average $\bar{\Phi}$ values for each combination of voltage and pressure are shown in Figs. 5a and 5b, where the letter "T" adjacent to the symbol indicates a timed case. Standard deviations (large error bars) and standard deviations of the mean (small error bars) are also given for the timed cases. The timed case averages are connected by dashed lines. Also in Figs. 5a and 5b are solid curves for $\bar{\Phi} \sim V_0^2$.

Note in Figs. 5a and 5b that for a given fill pressure P_0 , $\bar{\Phi}$ increases rapidly up to the timed condition, but that beyond that point $\bar{\Phi}$ increases less rapidly until finally the DPF will not operate properly above some voltage V_0 . Beyond the timed condition for a given P_0 the focus occurs early, i.e., before the current reaches its maximum amplitude. In any event $\bar{\Phi}$ is overall highest for the 50-kV, 17-Torr (timed) case in this system.

It is important to note that machine operation for a given combination of P_0 and V_0 was reproducible when taken weeks apart. The average of a number of shots for the given set of conditions generally fell within the standard deviation of the mean calculated for the total number of discharges at that condition. Thus, with a sufficient sampling the average performance of this device is "predictable".

Fig. 4a. TC-1 Data: X-ray Fluence $\bar{\Phi}_1$ vs Charge Voltage V_0 .

Fig. 4b. TC-2 Data: Fluence ϕ_2 vs Charge Voltage V_0 .

Fig. 5a. TC-1 Data: X-ray Fluence ϕ_1 Averages vs Charge Voltage V_0 .

Fig. 5b. TC-2 Data: Fluence ϕ_2 Averages vs Charge Voltage V_0 .

Spot checks were also made to compare the magnitude of the back voltage generated during the rapid collapse at time of focus (see Fig. 3) to the ratio obtained from TC-1 (ϕ_1) and TC-2 (ϕ_2). Results indicate that the larger the voltage spike the smaller the flux ratio, suggesting a somewhat harder x-ray source for large back voltages.

The .051-mm Be window plus .013-mm Be heat shield used for each calorimeter would absorb 90% of all x radiation below ~ 1.6 keV. TC-1 would absorb 95% of x radiation at 30 keV, and TC-2 would absorb 88% of x radiation at 55 keV.

If the x-radiation spectrum was sufficiently soft that the radiation is totally absorbed by TC-1, the calorimeter signals should read inversely proportional to the tantalum foil mass ratios (3.47:1). During this survey we found that for the same operating conditions: 1) the signal ratios varied on different discharges from $\sim 1:1$ to $3:1$, and 2) that the average ratio ϕ_1/ϕ_2 was ~ 2.34 . In view of the focus dynamics and the presence of the tungsten rod in the center electrode (see Fig. 1), one would suspect that the x-ray spectrum is a composite of bremsstrahlung and thick target radiation. Note that these data are not for a B_z stabilized focus. The B_z stabilization will soften the spectrum and reduce ϕ .

B. X-Ray Fluence Histograms

Histograms, showing x-ray fluence versus the number of times that a given yield was achieved from some sampling N, were made for large number of shots for both TC-1 and TC-2. Histograms for timed cases are shown in Fig. 6 for ϕ_1 .

Histograms show that the scatter in the ϕ data increases with charging voltage V_0 . The TC-1 scatter, see Figs. 4a and 5a, is generally larger than that for TC-2, and the non-timed cases scatter was generally larger than that for timed cases for equivalent charge voltages.

Consider the 50-kV results in Fig. 6. The histogram shows that 6 times out of 27 ($\sim 22\%$) one can achieve a $\phi > 2$ (cm), with the average ϕ being ~ 1.5 (cm). Note also that DPF-6 can easily be fired 50 times per day (up to 100). Thus even though the ϕ scatter is relatively large, one's chances of achieving even the highest ϕ (> 2.5 times ϕ average) more than once per day are good.

Fig. 6. X-ray Fluence Histograms: Fluence ϕ vs Number of Times a Given Fluence was Obtained.

This should be useful information for those planning irradiation experiments.

C. X-Ray Pulse Widths (τ_x)

Time resolved signals for soft x rays were monitored with a PIN silicon detector (see Fig. 1). The full width half-maximum ($\text{FWHM} = \tau_x$) of the first x-ray pulse of signals from a number of shots was measured. At 50 kV, 17 Torr, the average τ_x is ~ 40 nsec. The data, and averages shown by the solid symbols are shown in Fig. 7, and indicate that on the average $\tau_x \sim V_0^{-1}$, in agreement with theory.*

D. Current Characteristics vs Charge Voltage

Peak current I_{pk} vs charge voltage V_0 for timed and untimed cases is shown in Fig. 8a, where again the number inside each symbol indicates the number of overlapping data points, and symbols not specifically denoted in terms of pressure have the same meaning as those in Figs. 4a and 5a.

Averages of these results are shown in Fig. 8b, where: 1) the light lines connect data taken for the same fill pressure, 2) the dashed line connects timed cases, and 3) calculated curves are shown by the dark lines for $I_{pk} \sim V_0$ and $I_{pk} \sim V_0^{3/4}$ referenced to $I = 1.85$ cm and $I = 1.7$ cm, respectively.

* Theory by R. A. Gerwin, CTR-6, LASL (private communication).

Fig. 7. Soft X-Ray Pulse Width ($\tau_x = \text{FWHM}$) vs Charge Voltage V_o .

Fig. 8b. Peak Current Averages vs Charge Voltage V_o .

Fig. 8a. Peak Discharge Current I_{pk} vs Charge Voltage V_o .

The I_{pk} averages of the timed cases ("T") show $I_{pk} \sim V_o$. Data for I_{pk} for a given pressure show $I_{pk} \sim V_o^{3/4}$. These are both in agreement with theory* and previous experimental results† for the DPF machine rundown phase.

Figure 9 shows timed case data and averages for the ratio of current drop ΔI at focus time to peak current I_{pk} versus charge voltage. Results indicate that $(\Delta I/I_{pk}) \sim V_o^{-1/2}$, not in agreement with theory for the DPF pinch phase. The existing theory and experimental results** suggest that $(\Delta I/I_{pk})$ should be roughly constant. (See discussion section).

In comparing Fig. 9 to Fig. 6 it is of interest to note that although the scatter in ϕ increases with V_o , the scatter in $(\Delta I/I_{pk})$ decreases. This is somewhat explained by viewing Fig. 10, which is a plot of current drop ΔI vs $I_{pin} = (I_{pk} - \Delta I)$ for several timed-case shots.

*K.D. Ware (P-7) and R.A. Gerwin (CTR-6), LASL (to be published).

†K.D. Ware (P-7) LASL

**K.D. Ware (P-7) LASL, (Private communication).

Fig. 9. Current Dip ΔI Divided by Peak Current I_{pk} vs Charge Voltage V_0 .

Fig. 10. Current Dip ΔI vs Pinch Current I_{pin} .

The symbols here have the same meaning for pressure as those of Figs. 4 and 5. For a fixed pressure and voltage, ΔI should decrease inversely proportional to I_{pin} . This is generally the case, except for 50 kV, 17 Torr where more scatter is seen, corresponding to more scatter in ϕ at 50 kV. This is illustrated more clearly in Fig. 11, which is a plot of I_{pin} vs V_0 for timed cases. These results suggest that for a given V_0 , ϕ is more closely related to I_{pin} than to ΔI or $\Delta I/I_{pk}$. Pinch current versus average calorimetric readings is shown in Fig. 12 for timed and untimed cases.

E. Voltage Characteristics vs Charge Voltage

The sketch in Fig. 13 conceptualizes a typical voltage trace. If no focus occurs, then the voltage spike is not present. This is what we refer to as a "flat" discharge. In several focus shots we have

Fig. 11. Pinch Current I_{pin} vs Charge Voltage V_0 .

Fig. 12. Average X-Ray Fluences ϕ vs Pinch Current I_{pin} .

Fig. 13. Equivalent Flat Discharge Voltage V_{FLT} vs Charge Voltage V_0 .

plotted the equivalent "flat" voltage (V_{flt}) versus charge voltage (V_0) for timed cases. Data averages are shown by the solid symbols, and results indicate that $V_{flt} \propto V_0$ as expected.

The total height of the focus voltage spike V_S is shown versus charge voltage in the upperhalf of Fig. 14 for several timed case shots. The solid line shown is a curve through the averages at each V_0 , indicating that V_S is nearly proportional to V_0 . Similarly, $(V_S - V_{flt})$ is plotted in the lower half of Fig. 14 and also shows that $(V_S - V_{flt}) \propto V_0$.

Fig. 14. Voltage Spike V_S and Voltage Spike Minus Equivalent Flat Discharge Voltage, $V_S - V_{flt}$ vs Charge Voltage.

F. $V_S \cdot I_{pin}$ vs X-Rays

The product $V_S \cdot I_{pin}$ should be related to the instantaneous power being delivered to the pinch at the time of focus. Results for $V_S \cdot I_{pin}$ versus ϕ for TC-1 and TC-2 are shown in Figs. 15-16 for several shots. Averages are shown by the solid symbols for timed cases, and the solid lines, drawn by inspection, represent approximate scaling of $V_S \cdot I_{pin}$ vs ϕ for the averages.

Fig. 15. Voltage Spike Times Pinch Current, $V_s \cdot I_{pin}$ vs ϕ_1 .

Fig. 16. Voltage Spike Times Pinch Current, $V_s \cdot I_{pin}$ vs ϕ_2 .

Comparing Figs. 15 and 16 one notes that ϕ increases faster with $V_s \cdot I_{pin}$ than ϕ_2 . This should be related to the mass ratio of the Ta calorimeters. If the TC-1 data solid line is shifted by the mass ratio (10.4/3), the large dashed line results in Figs. 15 and 16. The small dashed line on Fig. 15 represents the solid line of Fig. 16. The disparity between the two dashed lines of Fig. 15 again suggests that at least TC-1 is not absorbing on the average all the x-radiation incident, i.e., hard components may be passing through.

The ratio ϕ_1/ϕ_2 versus $V_s \cdot I_{pin}$ is plotted in Fig. 17 for several timed case shots. The overall average of ϕ_1/ϕ_2 is ~ 2.34 , though the solid symbols showing averages indicate that ϕ_1/ϕ_2 increases slightly with $V_s \cdot I_{pin}$. This dependence suggests that the source spectrum may be getting somewhat softer with increased $V_s \cdot I_{pin}$.

Fig. 17. Voltage Spike Times Pinch Current, $V_s \cdot I_{pin}$ vs Fluence Ratio ϕ_1/ϕ_2 .

It is also of interest to see how $V_s \cdot I_{pin}$ depends upon V_o . Different "scales" are shown vertically towards the right of Figs. 15 and 16. End point matching indicates that $V_s \cdot I_{pin} \sim V_o^{2.125}$, or approximately V^2 .

G. Neutron Yield

For much of the time during the acquisition of the data for this report we had problems with our silver counters. However, there were some series of shots for which reliable results were obtained, with 28.7 counts on the scaler equaling 10^{11} neutrons.

Fig. 18. Neutron Yield Y_n vs Charge Voltage V_o for $P_o = 17$ Torr D_2 .

Figure 18 shows neutron yield Y_n versus charge voltage V_o for $P_o = 17$ Torr D_2 , where each circle represents one shot. The vertical scale runs from 1 to 100 counts. The line on the graph is for $Y_n \sim V_o^5$. In general, experimental data averages obey this trend. According to R. A. Gerwin, this is evidence that the plasma is thermonuclear, since beam target or other models would not possibly fit the results.

Figure 19 shows neutron measurements for timed cases. The vertical scale runs from 10 to 100 counts. For the best data the neutron yield rises as V_o^4 , though the overall average rises as $V_o^3 - V_o^{3.8}$ when the 50-kV results are ignored.

VI. SUMMARY

A statistical base for the performance of DPF-6, particularly with respect to x rays has been established by acquiring data from a large number of shots for $P_o \sim 8-17$ Torr D_2 and $V_o = 30-50$ kV. Note again that: 1) the focus was not

Fig. 19. Neutron Yield Y_n vs Charge Voltage V_o for Timed Cases.

B_z stabilized; 2) a tungsten rod was used in the center electrode; and 3) data presented included that for all system conditions.

Time-resolved neutron measurements, $\frac{dN}{dt}$, were also taken. The results are not presented since neutron velocity spreads, which we need in order to unfold the pulse widths, τ_n , have not yet been measured for this facility. The neutron pulse width not only includes a finite production time but a velocity spread of the reacting deuterons. A large time of flight, corresponding to a detector distance, ~100 m would be necessary to obtain 2% accuracy in neutron velocity.

Using data averages, empirical scaling laws were found with regard to how the performance of the machine scales with charging voltage (bank energy). In most instances the results agree with scaling laws developed by R.A. Gerwin and K.D. Ware. In some cases, such as $(\Delta I/I_{pk})$ vs V_0 , the results do not agree with theory or previous experiments. However, the theory for the pinch phase does not explicitly account for a hemispherical center electrode or the presence of a tungsten rod protruding from the center electrode as used in the present experiment. These items were used in this survey since previous experience showed they gave enhanced x-ray production (ϕ 's) over flat ended electrodes with no tungsten rod.

The empirical scaling laws determined here should not be construed to reflect interfacility radiation yield scaling. There are at least 8 variables, namely V_0 , P_0 , L_e (external inductance), L_{ce} (center electrode length), Δ (electrode spacing or coax gap width), L_j (coax or barrel inductance), L_i (insulator length), C (bank capacitance), and R_{ce} (center electrode radius) that influence a DPF's performance in addition to the center electrode tip geometry, and use of tungsten rods.* All parameters must be considered when making inter-facility comparisons or when operating at different voltages on a given facility.

For this survey where L_e , L_{ce} , Δ , L_j , L_i , C and R_{ce} were fixed, the important parameter was V_0 for a given V_0 ; for best yields it was found that the facility should run "timed", giving $P_0 \sim V_0^2$.

The increasing spread in x-ray fluence data with charge voltage, the deviation of the radiation output from the empirical scaling law of V_0^4 , and the result

* R. A. Gerwin (CTR-6), LASL (Private Communication).

that $\Delta I/I_{pk} \neq \text{constant}$, suggests that the electrode and insulator geometry used in this survey may not have been optimum for the higher voltages.

The data of this experimental survey should be useful as a benchmark for future experiments on DPF-6, for gross interfacility comparisons and for comparison of various DPF theories to data.

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APPENDIX

Figure 1 shows a large copper "45°" probe inserted through a vacuum gimbal and "air lock" into the focus discharge chamber. Radiation sensors may be located within the probe. The gimbal allows for fine tuning of the probe angle, and the evacuable "air lock" between the gimbal and slide valve allows for probe insertion or removal without spoiling the vacuum in the discharge chamber.

In addition to the results of the survey reported in the main text above, we conducted several tests with 45° probe tips inserted to various distances along the probe axis from the focus axis.

The effect of the probe presence on ϕ_1 (TC-1) is shown in Fig. 20 for timed cases. For lower charging voltages the probe had little effect on ϕ until it was very close, < 1.2 cm, from the focus axis. For higher charge voltages the probe's presence appeared to enhance ϕ over ϕ_{np} (averages obtained from the above survey with no probe present), at least into $r \sim 1.2$ cm. In all cases the scatter in ϕ was reduced compared to ϕ_{np} data, suggesting that the probe may have helped somewhat to stabilize the focus.

The effect of the probe presence on time-integrated neutron yield Y_2 is shown in Fig. 21. In general, as the probe was moved closer than $r \sim 2.7$ cm, the average neutron yield decreased.