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LLNL Plasma Focus Project

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Lawrence
Livermore
Laboratory

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Results of the
LLL Plasma Focus Project

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I. Introduction

A Plasma Focus (P.F.) is essentially an electrical power compression apparatus which accepts electrical energy from a slow source (usually a capacitor bank with a few microsecond time constant) and stores it mostly in the form of magnetic energy which is subsequently delivered to a load over a period of a few tens of nanoseconds. Figure 1 is a diagram of the Livermore device which is a typical P.F. of "Matner" geometry. The current path is closed by a plasma sheet which is pushed down the coaxial "gun" by the magnetic pressure. As the current sheet moves the inductance of the gun increases simultaneously with the increase in current so that a substantial fraction of the initial stored energy is transferred to the gun in the form of magnetic energy ($1/2 LI^2$). In a well-matched gun the current sheet reaches the end of the cylindrical part of the anode at about the time of maximum current and subsequently collapses on the axis to form a Z-pinch. As the cylindrical collapse proceeds there is a rapid increase

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in inductance associated with the transfer of energy from the magnetic field to the plasma which increases in kinetic and thermal energy. There also seems to be an increase in the effective resistance of the current sheet though the mechanisms which cause this increase are not well understood. If the gas filling the apparatus is D_2 , neutrons are produced evidently by the interaction of deuterons accelerated in the focus region with other deuterons either in the focus region or a few centimeters away. If the initial density of the fill gas is low (typically between .5 and 2 Torr) very energetic ions and electrons are produced.⁽¹⁾ The most energetic ions (several MeV deuterons) move in a rather narrow beam along the axis away from the anode. The great majority of the ions are, however, of much lower energies (tens to hundreds of keV) and have a more nearly isotropic velocity distribution. These slower ions (probably confined by the magnetic field) are responsible for the bulk of the neutron production which is optimized at a somewhat higher fill density (Fig. 2) than is the fast ion production. Substantial production of fast ions is accompanied by the acceleration of energetic electrons (typically 700 keV in the LLNL Focus) as evidenced by the bremsstrahlung radiated when they impinge on the anode.

Many plasma focus projects have been in existence over the past two decades and some are still active both in the United States and abroad. There are sizable programs in France, Italy and Germany as well as in the Soviet Union, Japan and other places. The various projects have had many different goals including attempts to increase the neutron production, development of fast x-ray, UV, and neutron sources, basic plasma studies, development of energetic ion sources and pellet fusion studies.

The project at LLNL was aimed at investigating the plasma focus as a driver for the implosion of small pellets. A few DT-filled glass micro-balloons were exposed to the focus environment in exploratory experiments and their neutron production measured. X-ray and fast-ion diagnostics were employed also to study electron and ion-beam production as well as direct coupling of energy to simple targets. This report describes what conclusions can be drawn from the experimental results.

II. Detailed Description of P.F. Operation Prior to Pinch (Computer Simulation)

Although the final pinched configuration achieved by the plasma focus can not be completely described by simple magnetohydrodynamics, still, MHD calculations can be instructive. In studying the physical processes which are dominant in the focus, it is useful to determine how early in the development of the pinch the simple calculations diverge from experimental measurements and what alterations to the physics calculated by the code can improve the agreement. Experimental data pertaining to the pre-pinch dynamics are very sparse and particularly so in the Livermore project where concentration was on x-ray and neutron measurements rather than on the motion of the current sheet or the measurement of magnetic fields. For this reason we have relied on the experience of other laboratories, particularly that at Frascati, Italy, as well as our own. At Frascati, very careful magnetic probe measurements⁽²⁾ were made which indicate that a substantial fraction of the total current (over 20% at peak) leaked across the surface of the insulator and was not available to push the plasma toward the focus.

The Livermore experiments included no electrical measurements other than total current and voltage, so there is no direct information on the leak current. Our computer simulation, however, indicates that in the Livermore P.F. a similar fraction (about 15% of the current at peak) has to be diverted from the plasma in order that the timing of the pinch be consistent with the value of the total current. Paradoxically, we have not been so successful in calculating the timing of the Frascati experiments with the observed leak currents.⁽³⁾

The current trace and timing are not exactly the same on each shot. Figure 3 shows an example of current traces for two successive Livermore shots with identical gas fills (2 Torr of H_2). It can be seen that the second of the two had a slightly lower peak current and an earlier pinch. We can understand this behavior if we assume that the physical condition of the insulator on the second shot was such that the leakage was less than it was on the first shot. The smaller leak current produces a smaller total current but a larger current through the plasma since the plasma path and the leak path are in parallel. (Figure 4 is a schematic drawing of the circuit). Consequently, a larger magnetic pressure and an earlier pinch is consistent with a lower total current. Also plotted on Figure 3 are values of the plasma current, leak current and total current as calculated with the VOA code⁽⁴⁾ operating in the MHD mode. VOA is a two dimensional Eulerian hydrodynamic code which considers heat transport, magnetic diffusion, and forces due to currents and electromagnetic fields. The code has been used with the circuit parameters listed in Figure 4 in an attempt to match the current trace for shot #5063 for which there exists also a streak-camera record of the collapsing pinch. In these calculations the

leak current is determined by Ohm's law up to an arbitrary limit taken here to be .25 Ma. Figure 5 (a-d) shows the contours of density and rB as calculated by VOA at successive times starting with the lift-off of the current sheet from the surface of the insulator and continuing through the axial run-down. Figure 6 (a-d) shows details of the calculated density and rB profiles during the final .2 μs while the radial collapse takes place. In Figure 7 we compare the late-time current and radius measurements with the VOA calculations. The experimental radius is taken from the streak camera record which gives the time when visible light is first seen at a given radius and presumably represents shock arrival. The timing of the streak camera is correlated with the $\dot{i}$ trace which is taken from an oscilloscope record triggered at the same time as the camera. The shape of the anode tip used on this shot was as shown in Figure 1, a flat-ended cylinder 1.25 cm in radius. The streak camera record indicates a radius which decreases rather smoothly from 3.8 cm to 1.8 cm then falls suddenly to the radius of the cylindrical tip where it pauses for .05 μs before plunging to the axis. The $\dot{i}$ curve has similar characteristics. The current first begins to drop at about 2.4 μs . $\dot{i}$ reaches -1.2×10^{12} amp/sec at the time when the radius reaches 1.25 cm. $\dot{i}$ is nearly constant while the radius pauses and then drops suddenly when the radius collapses to the axis.

In order to compare the calculated radii with the experimental values we have passed a plane perpendicular to the axis through the point of smallest current sheet radius at each time. (The plane is drawn in Fig. 6-b as an example.) The open circles in Figure 7 are drawn at the radii in those planes where rB reaches half its maximum value. That is, half the

current flows above the open circles and the other half below. The line connecting the circles is parallel to the experimental radius displaced about $.03 \mu s$. The calculated $\dot{i}$ curve is correlated with this calculated radius qualitatively as the experimental $\dot{i}$ is correlated with the experimental radius. The trend in $\dot{i}$ is reversed while the radius pauses at 1.25 cm. $\dot{i}$ then drops suddenly as the radius collapses.

The hash marks drawn above and below the circles in Figure 7 represent, respectively, the calculated positions of the outer boundary of the current carrying plasma and of the shock. There is reason to believe that the thickness of this region of shocked plasma is too great in the calculation due to coarseness of zoning and perhaps also due to the fact that the calculation did not include cooling by radiation from impurities. We surmise, therefore, that the shock radius, recorded by the streak camera is very nearly the radius of the current sheet as well. If we adjust the relative timing by shifting the time scale $.03 \mu s$ the calculated radius will nearly fall on top of the measured radius and the calculated negative $\dot{i}$ peak will be almost simultaneous with the measured one.

A measurement of the actual plasma current would have permitted a more detailed study of the correlation of current drop with shock radius and an inference concerning the plasma resistance. Since we have measurements on $\dot{i}$ of the total current and no direct knowledge of the leak current the potential drop across the pinched plasma is not determined. In Section IV of this paper it will be inferred from x-ray measurements that electrons are accelerated to energies of about seven hundred kilovolts in the pinch region. The existence of such a potential lasting for the lifetime of the observed x-ray pulse (~ 20 ns) would result in a drop in the plasma

current which is considerably greater than the drop in the total current shown in Fig. 7. The VOA calculation achieved a reasonable value for the total current drop by arbitrarily limiting the leak current to .25 Ma and allowing the plasma current to be reduced by the I_L voltage produced by the pinch with no plasma resistance other than collision-dominated classical value which is negligible. The resulting voltage drop across the pinch is inadequate to explain the electron accelerations observed. An alternate model would be to allow the leak current to continue rising according to Ohm's law as the voltage rises and to introduce an anomolous resistance of about 1Ω in the pinch. The same drop in total current would be achieved but the plasma current would drop faster and would be compensated by a sharp rise in leak current.

Calculations of this type have been performed using a very simple code employing a hand-held programmable calculator. The code⁽³⁾ does no MHD calculation but determines gun, leak and total currents by means of electrical circuit equations and characterizes the moving current sheet as a variable inductance. Figure 8 shows the total current and voltage drop across the pinch for two such calculations one of which (to be compared with the VOA calculation shown in Figure 7) limits the leak current to .25 Ma and employs no pinch resistance. The other calculation allows the leak current to rise to .45 Ma but introduces 1Ω of resistance to the pinch when its radius is less than 1 cm. The resulting voltage drop is similar to what would be required to produce the accelerated electrons and makes it evident that the introduction of a model for anomolous resistance into the MHD calculators would be a reasonable next step in the computer modeling.

III. Plasma Focus Experiments with DT-Filled Microballoons

In early experiments at LLNL, glass microballoons filled with DT were placed on the axis of the plasma focus machine at the position where the pinch is believed to occur. In these experiments the gas initially filling the apparatus was H_2 so that any neutron production was assumed to be due to gas in the balloon. In some of these initial experiments,⁽⁵⁾ there were indications that neutrons had been produced, but later experiments of this type with more complete neutron diagnostics failed to confirm the production of neutrons. In these experiments the microballoons were exposed directly to the plasma focus environment; they were supported in the pinch region by attachment to a fine glass fiber with no protection from possible precursors which might destroy the balloon before it could be affected by the main pinch.

Since the experiments were performed with the plasma focus operating in the low-density mode in which electron and ion beam production is a dominant channel for dissipation of magnetic energy, it was speculated that the neutron production, erratic as it was, might have resulted from the interaction of a very concentrated electron beam with the glass balloon. Both because the balloon in the "direct exposure" position was unprotected from precursors and because the glass fiber mounting was known usually to quench the production of intense electron beams it was decided to try alternate experiments in which the microballoon was mounted inside a small (2 mm diameter) cavity in the apex of a conical copper tip attached to the center of the anode. (Fig. 9) Usually, the cavity was covered with a thin foil transparent to energetic electrons and the balloon was positioned 2-5 mm behind the foil. Thus, the balloon was exposed to the electron beam but

protected from precursors and there was no mounting fiber to prevent the production of the beam. In all, there were twenty such experiments of which eight produced neutrons. The number of neutrons produced in the various shots ranged from 2×10^6 to 6×10^7 . Any production less than about 1×10^6 would not have been identified due to the level of the background in the Ag activation detectors. O_2 activation detectors (threshold ~ 10 MeV) which had been installed to determine whether the neutrons were sufficiently energetic to have been made in D-T reactions, did not respond to any of the signals seen in the Ag detectors. The background level in the O_2 detectors was such that neutron production less than a few $\times 10^6$ * could not be seen but it is evident that, at least in the four shots for which the number of neutrons was $> 10^7$ most were produced by reactions other than D-T.

Subsequent to this series of experiments it was found that occasionally neutrons were produced in the H_2 -filled Plasma Focus even in the absence of a DT microballoon. The neutrons were never energetic enough to be detected in the O_2 detector. Neutron production was found to occur in only about 5% of the shots whereas with DT microballoons in the anode tip, neutrons were produced in 40% of the shots attempted. In both the experiments with microballoons and those without, it was found that neutrons were produced only in those shots for which there was substantial formation of energetic beams of electrons as evidenced by the production of hard bremsstrahlung although there were many shots with intense electron beams and no neutrons.

*The exact number depends on the level of the background during any particular shot.

The mechanism for production of neutrons in the H_2 -filled Focus remains unknown. If the rather sparse production statistics are relied upon it could be argued that, since the introduction of DT-filled micro-balloons greatly enhances the probability of neutron production, the neutrons must be produced, in those cases, by accelerated deuterons or tritons though evidently not by D-T reactions.

IV. Diagnostics of Electron Beams Produced by the Plasma Focus (X-Rays)

Study of the accelerated electrons and their interactions with the anode tip has required x-ray diagnostics over a very broad spectral range. At least some of the radiation is probably as hard as a few MeV because it was found to be necessary to shield the neutron time-of-flight detectors with as much as 10 cm of Pb to bring the x-ray background down to an acceptable level. It appears, however, that typical electron energies are 600-700 keV and detectors designed to measure the bremsstrahlung from such electrons have been used to infer the beam intensity. These high energy x-ray (HEX) detectors are fluorsors coupled to photo diodes. They were shielded inside a lead "dog house" viewing the anode tip through appropriate filters. In the set-up used for all the data quoted here, there were three detectors filtered respectively by 1.57 mm Al, .79 mm Cu and 1.02 mm Pb which were sensitive to x-rays roughly above 18 keV, 80 keV and 250 keV respectively. These detectors viewed the anode from an angle of about 22° off the axis. (Figure 10)

The middle range of x-ray energies (.9-20 keV) was covered by silicon PIN diode detectors and also a pinhole camera. Both these detection

systems viewed the anode from an angle of about 70° off axis (Fig. 16). The softest x-rays were detected by a set of Al cathode x-ray diodes (XRD) viewing the anode from 22° off axis (Fig. 10). These detectors were insensitive below about 50 eV because of absorption by the hydrogen fill gas in the Plasma Focus tank. The greatest sensitivity of the XRD detectors was in the region of 100 eV (Figure 11) falling by a factor of 20 at about 600 eV. Thus, the spectral region 600-900 eV was poorly covered by both the XRD and the PIN systems, and consequently that part of the spectrum is uncertain.

Six shots were selected for detailed analysis of x-ray output. These shots were all on previously unused conical anode tips (Fig. 12); two of Ta with 1 mm diameter flats, two of Cu with 1 mm diameter flats, and two more of Cu with 3 mm diameter flats.

Figure 13 shows the sensitivities of the three filtered HEX detectors to bremsstrahlung spectra produced by electrons of various energies. These curves were used to interpret the time-integrated signals from the detectors in terms of bremsstrahlung from mono-energetic electrons. Table 1 displays the results of the analysis. It is assumed here that the bremsstrahlung intensity per steradian is:

$$\frac{dI}{dh\nu} = \frac{1}{4\pi} E_b Z^2 K (1 - h\nu/\epsilon_e) \quad h\nu < \epsilon_e$$

$$\int_0^{\epsilon_e} \frac{dI}{dh\nu} dh\nu = \frac{1}{4\pi} E_b Z^2 K \epsilon_e$$

where E_D is the total energy in the electron beam*, ϵ_e is the electron energy in keV and Z is the atomic number of the anode material. The constant K is taken from Evans (6) as 7×10^{-7} , a value appropriate for electron energies of several hundred kilovolts. The excellent agreement (in this spectral range) of the values of time and energy-integrated bremsstrahlung intensity as inferred separately from the three channels supports the assumption of monoenergetic electrons. It is known however, that there are some electrons much more energetic and there may be another population of much lower-energy electrons which will be mentioned later.

The beam energies listed in Table 1 have been calculated from the signal in the copper-filtered channel. There seems to be rather good shot-to-shot uniformity in the characteristics of the electron beam. The averages and rms variations of the values given in Table 1 are:

$$\epsilon_e = 690 \pm 62 \text{ keV}$$

$$\epsilon_D = 972 \pm 140 \text{ Joules}$$

A typical value of the beam current (taking 20 ns as the duration) is 70 kA which is about 10% of the total current at the time of the pinch.

An important question which the LLNL Plasma Focus project has tried to answer concerns the compactness of the electron beam as it impinges on the anode tip. The cross sectional area of the beam at peak power together with the current and the energy of the electrons would determine the local heating rate on the surface of the tip provided that the electron range is known. The pinhole camera channels which are sensitive to x-rays softer

* We speak here of an electron beam only in the sense that the electrons move generally toward the anode. The compactness of the beam is not measured by these detectors.

TABLE 1

Shot Number	Tip Material	Flat Diameter (mm)	ϵ_e Assumed Electron Energy (keV)	$\epsilon_e \int_0^{\epsilon_e} \frac{dI}{d\nu} d\nu$	E_D Beam Energy (Kilo Joules)		
				Total Energy of X-Rays (Joules/Steradian)	Channel		
				Al	Cu	Pb	
4973	Cu	3	760	1.44	1.43	1.44	1.16
5027	Cu	3	650	1.16	1.15	1.19	1.10
4939	Cu	1	610	.76	.77	.77	.79
4969	Cu	1	685	.89	.89	.90	.80
4944	Ta	1	780*	3.25**	3.01	--	.95
4965	Ta	1	645	2.88**	2.68	2.68	1.03

* This electron energy is uncertain because data is missing in the Pb channel.

** The Al channel sees characteristic Ta K-radiation as well as bremsstrahlung.

than 1.6 keV show intense emission from a small spot on the end of the conical anode tip (Fig. 14). The spot diameter is typically .25 mm. On shots using a conical tip with a 3 mm diameter flat the spot, though on the flat, may be slightly off center but when a 1 mm diameter flat or a pointed tip is used the spot is still on the end of the tip having been steered close to the axis. We would like to know what fraction of the energetic electrons impinge on the tip within the small spot seen by the pinhole camera but it is not an easy question to answer. No images are available of the source of the very hard bremsstrahlung or of the very soft x-rays ($h\nu \leq 900$ eV) but the pinhole camera channels sensitive to x-rays between 2 keV and 20 keV, specifically including the characteristic Copper K or Tantalum L radiation, show a source a few millimeters in extent covering the surface of the anode tip. Independent spectroscopic data indicates that line radiation dominates this part of the x-ray spectrum. The small spot which is very intense in the softer (< 1.6 keV) x-ray images is seen also in the harder (> 2 keV) images but is only part of the emitting region and represents only about 5% of the energy seen by the PIN detectors in that part of the spectrum. There are two possible explanations. Either the energetic (700 keV) electron beam strikes the anode over a broad region producing Cu K and Ta L radiation as well as the hard bremsstrahlung but is not responsible for the strong heating of the small spot, or the energetic electron beam is sufficiently narrow to produce the small spot but the CuK or TaL radiation is produced by a separate population of lower energy electrons.

The data shown in Fig. 15 gives some support to the second alternative. Here four scope traces from shot #4973 are juxtaposed to demonstrate

the relative durations of the x-ray pulses in various parts of the spectrum and the time of their occurrence relative to the current dip. The time scale (in nanoseconds) begins near the current maximum. The upper curve is $\dot{i}$ which has a slight bump at 110 ns and reaches its peak at 156 ns. The width of the $\dot{i}$ peak is about 30 ns FWHM. The lower curves are scope traces from three x-ray detectors sensitive to different parts of the spectrum. The HEX trace is from the detector with the copper filter and thus represents the hard bremsstrahlung of energy greater than about 80 keV. The breadth of this hard x-ray pulse is similar to that of the $\dot{i}$ peak and considerably more narrow than the peak in the characteristic copper K-radiation represented by the PIN detector. It seems plausible then that the latter is produced by a separate population of accelerated electrons whose energies are much lower than 700 keV and whose temporal distribution is broader than those of the very energetic electrons. The third x-ray trace in Fig. 15 is from a XRD detector with a thin parylene filter which was sensitive to radiation from about 70 eV to the carbon edge at about 280 eV. This trace has a very narrow spike protruding from a lower peak whose width is similar to that of the very hard bremsstrahlung. There is also a precursor which begins a little before the $\dot{i}$ bump at 110 ns. The $\dot{i}$ bump was seen more strongly in the case of the flat cylindrical tip discussed in Section II where it is associated with the arrival of the current sheet at the radius of the cylinder. In the case of a conical tip the bump probably occurs when the current sheet arrives at the shoulder of the tip (radius 1.25 cm). The associated plasma stagnation and heating could be the cause of the precursor in the soft x-ray emission.

The time signature of the very soft radiation, if the precursor is excluded, could be consistent with a model which depends on the very energetic electrons to impinge on the small spot heating it and causing it to emit thermal radiation. There are, however, difficulties with that interpretation which will be discussed below.

Figures 16-21 show the time-integrated spectra of the radiation (exclusive of the precursor) seen by all the x-ray detectors in the six analyzed shots. The soft part of the spectrum as shown is consistent within about 15% with the signals from five XRD detectors*, one of them bare and the others filtered by thin foils of Parylene, Al, Fe and Mg, respectively. The spectral sensitivities of these detectors are shown in Fig. 11. They are all rather insensitive for $h\nu > 600$ eV so are not useful in determining the intensity in that part of the spectrum. The very low level of radiation indicated between 700 eV and the line labeled Cu L at about 980 eV is inferred from one of the pinhole camera channels which has a thin Ni filter. This channel could have responded to radiation below the Ni L edge at about 860 eV but in fact recorded no appreciable image in any of the shots. The radiation indicated as being Copper L is the radiation which makes the small, bright image in the pinhole camera and which is also detected by a lightly filtered PIN diode. It is assumed to be line radiation because it appears to be a maximum in the spectrum.

*This does not mean that the inferred spectrum is accurate to 15% since the number of detector channels is insufficient to allow a unique interpretation in the absence of spectrographic data.

The total energy in that part of the spectrum below 700 eV (in shot 4973 for example) is about 44 Joules/ 4π steradians. If we assume that this radiation as well as the Cu L is emitted from a nearly spherical "blob" .25 mm in diameter (or a little larger) and that the duration of the pulse is roughly 20 ns as indicated by the XRD traces then the effective black body temperature would be $T_{eff} = 57$ eV where $\sigma T_{eff}^4 4\pi r^2 \Delta t = E$. The "blob" would have to be at least as hot as T_{eff} . Although the time signature of the x-ray pulses suggest that the very energetic electrons might have heated the small spot, it is not possible for such a beam of 760 keV electrons to heat the copper to that temperature if the classical stopping power applies. Furthermore, the spectrum (e.g., in Fig. 15) does not appear to be Planckian so the temperature would be higher than 57 eV. In Fig. 16 a smooth emission curve has been drawn to compare with the measurements which are displayed in a histogram. The smooth curve represents the spontaneous emission calculated on the basis of absorption coefficients for a sphere of copper (diameter = .44 mm, density .002 gm/cm³, temperature 65 eV) which was intended as a model of the soft x-ray emitting region. The absorption coefficients were calculated using the computer code described in Ref. 7. Such a sphere is optically thin except at photon energies of about 65 and 140 eV. In the curve shown in Fig. 16 there has been no correction for self-absorption except to limit the emission to be less than the Planckian curve labeled "Black Sphere". The line emission labeled Cu L stands well above the $T = 65$ eV Planckian and would have to be attributed to the presence of non thermal electrons. In this model the position of the L line (980 eV) is shifted by about 50 eV above the zero temperature position. The prominent feature at about 65 eV

(a $3p-3d$ transition) also stands well above the Planckian. The not surprising conclusion is that the electron velocity distribution is not Maxwellian. Though the general location of the spectral features seen in Shot 4973 are consistent with the calculations, in some of the other shots the spectral features from about 200 to 400 eV are not apparent (Figs. 16-21). Nevertheless, none of the measured spectra resemble a Planckian at anything like the effective black-body temperature or the 65 eV value taken for the above model.

The thickness of the copper sphere in this model (density $\times$ diameter) is only $.08 \text{ mg/cm}^2$ whereas the range of a 760 keV electron is about 280 mg/cm^2 and it would deposit only about .021% of its energy in $.08 \text{ mg/cm}^2$. Thus, if the 1160 Joule beam of 760 keV electrons seen in Shot #4973 were to impinge on such a sphere only about .24 Joules could be expected to be deposited whereas nearly two hundred times that energy is radiated as x-rays below 700 eV. If we were to assume a much larger mass for the emitting region then we would have to expect the spectrum to be more nearly Planckian. We conclude either that the very energetic electrons do not heat the emitting region or that the stopping power is quite anomolous.

One additional point should be mentioned. The line emission, assumed to be Copper L at 980 eV, is present whether a copper or a tantalum anode tip is used. Although the exact position of the line is not determined it is known to be below the 1.6 keV K edge in the aluminum filter on the PIN detector and pinhole camera. The strongest Ta M line is above that edge so we conclude that the copper which is producing L lines to form the small bright spot has been swept in from a larger radius on the anode and is not

evolved from the tip. If this is true then it follows that some of the pinched current could also be flowing at a very small radius and that it could be carried in part by a population of accelerated electrons of moderate energies which produce the Cu L line radiation and which might also provide the energy to produce the very soft x-rays.

In this model, which we believe to be the most plausible, the hard x-radiation has a narrower time signature than that of the Cu K radiation (Fig. 15) because the voltage pulse is high enough to produce sufficiently energetic electrons only near its peak. The very soft radiation would also be most intense near the voltage peak because the heating rate would be highest at that time and the emission rate would be very sensitive to temperature. The voltage pulse would be caused primarily by high resistance in the pinch, possibly the result of plasma instabilities. The acceleration of the energetic electrons would take place just outside the pinch where the plasma density is low. A very narrow beam would not be expected. There would be plenty of energy dissipation to account for the emission of the Cu L and the very soft radiation from the small central region near the anode. A voltage drop of 700 KV with a plasma current of about 600 Ka requires an effective resistance and/or $\dot{L}$ of about 1.2 Ω . Such a large $\dot{L}$ could not, however, be sustained for the 20 ns duration of the voltage pulse if the length of the pinch is anything like that indicated in Fig. (6-c). The inductance of the pinch would be

$$L = 2 \times 10^{-9} \ell \ln r_1/r$$

where ℓ and r are the length and radius of the pinch and r_1 is some outer radius. If we take ℓ to be about 1.5 cm then

$$\dot{I} = -3 \times 10^{-9} \text{ f/r} = \frac{3 \times 10^{-9}}{\tau}$$

where $\tau \equiv r/\dot{I}$ is the collapse time of such a pinch. Thus, $\dot{I}$ could be as large as $1.2 \text{ } \Omega$ for only about 2.5 ns. Evidently, then, a resistance of about $1.2 \text{ } \Omega$ is somehow achieved in the pinched plasma for a time of 20 ns. The energy dissipated is $IV \Delta t = 6 \times 10^5 \text{ amp} \times 7 \times 10^5 \text{ volts} \times 20 \times 10^{-9} \text{ sec} \approx 8 \times 10^3 \text{ Joules}$. A portion of the total current is carried by the energetic electron and ion beams which take about $2 \times 10^3 \text{ Joules}$ and the remaining $6 \times 10^3 \text{ Joules}$ is available to heat and otherwise excite the plasma.

V. Experiments with Solid Objects at the Pinch Location

One of the mechanisms whereby the Plasma Focus might be useful for driving small D-T pellets is by direct coupling of stored magnetic energy into a pellet-containing structure placed at or near the pinch location. The required driving energy might then be delivered to the pellet by electron conduction.

A number of very simple experiments have been performed to explore the effect of placing objects (targets) of low mass ($\sim 10^{-4} \text{ gm}$) at the pinch position. In general it is found that such an object inhibits the formation of energetic electron and ion beams and that at least some of the energy is absorbed by the target resulting in the emission of x-rays of a

few keV and softer. If the target is compact, such as an aluminum ribbon or a glass fiber, the x-rays of one to a few keV are emitted from very small spots on its surface (Fig. 22a) but if it is a more diffuse object, such as a tuft of glass wool, the x-rays are emitted more uniformly from the region where the energy coupling takes place (Fig. 22b). Preliminary spectroscopic measurements in the $h\nu > 1$ keV range indicate that, in the case of glass fibers in the focus region, the emission is mostly Si lines. It is very likely that lines are dominant in the one to few keV range also for the other objects which have been tried such as aluminum and Saran though no spectroscopic measurements have been made.

In the subkilovolt part of the spectrum the emission as seen by the XRD detectors, is somewhat greater in intensity when low mass objects are present at the focus than was observed in the bare conical tip experiments and the duration is longer. In Fig 23, we compare the scope traces from the unfiltered XRD channel for a bare tip shot (#4973) and a shot with a bundle of glass fibers at the focal position (#4696). The integrated signal is about three times as large in the latter case and the sharp spike is missing. Evidently the energy couples more gradually when a solid object is provided but there does not seem to be a dramatic increase in the amount of energy in very soft radiation. It is difficult to tell from these preliminary experiments just how much energy was coupled because the solid objects at the focus were greater than the ideal mass and consequently didn't get hot enough to be efficient radiators. The objects were also of irregular shape and were not uniformly heated, thus, the energy radiated is not a good measure of the energy absorbed. In order to improve these experiments it would be necessary to employ objects of controlled configuration with masses the order of 10^{-5} gm and also to make spectroscopic measurements of the subkilovolt x-rays.

VI Summary

The principal aims of the LLNL Plasma Focus project during 1978-79 were to verify and study the apparent production of neutrons in earlier experiments using DT-filled microballoons, to characterize the electron and ion-beams produced in the focus, and to measure and if possible enhance the rapid coupling of magnetic energy into prepared solid targets placed in the *focus region*.

The neutron production in DT-filled microballoons proved to be erratic and not related to thermonuclear burn. The neutrons produced were not from DT-reactions but probably resulted from reactions of accelerated deuterons and tritons with heavy nuclei from anode material.

Measurements of the ion-beam production are described elsewhere.⁽¹⁾ The production of energetic electrons was fairly reproducible in the LLNL focus. A typical burst consisted of roughly 1 KJ of 700 keV electrons with a duration of 20 ns. Although the width of the beam was not directly measured we believe it to be most likely that it was a few mm in width and not concentrated on the very small (~ .25 mm) spot which appeared very bright in CuL emission.

Soft x-ray measurements of the emissions from solid objects placed in the focus region showed no very dramatic increase over similar measurements made in experiments without targets. The experiments were, however, poorly controlled as regards the mass and configurations of the targets and probably do not represent the best that could be done to convert magnetic energy to thermal energy in the P.F.

References

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7. B. Rozsnyai, Phys. Rev. A5 1137 (1972).

Figure Captions

1. Diagram of the LLNL Plasma Focus Device.
2. Best Achieved Neutron Production for Various Initial Pressures of Deuterium Compared with Energetic (> 330 keV) Deuteron Production for LLNL P.F.
3. VOA calculation of Currents Compared with Measured Values for Two LLNL PF Shots.
4. Circuit Parameters Used in VOA Calculation.
- 5(a-d). Contours of Density and r_B Calculated by VOA; LLNL PF $0 < t < 2.3 \mu s$.
- 6(a-d). Contours of Density and r_B Calculated by VOA, LLNL PF $2.35 \mu s < t < 2.54 \mu s$.
7. Current, Current Rate of Change and Pinch Radius, VOA Calculation Compared with LLNL PF Shot #5063.
8. Simple Model Calculations of Current and Pinch Voltage With and Without Resistance.
9. Diagram of DT-filled Balloon Mounting Inside Conical Tip.
10. Diagram of the Configuration of X-ray Diagnostic Systems for LLNL PF.
11. Response Functions of XRD Detectors with Various Filters.
12. Diagram of Conical Anode Tip for X-Ray Measurements.
13. Response Functions of HEX Channels to Bremsstrahlung Photons.
14. Isodensitometer Plot of an X-Ray Pin Hole Image of the Hot Spot on the Anode Tip with overlay of density trace through the brightest point. The diagram shows the view seen by the camera.
15. Various X-Ray Pulse Shapes Compared with I.
- 16-21. Time-Integrated X-Ray Spectra for Six Selected PF Shots.
22. Pin Hole X-Ray Images of (a) An Aluminum Ribbon and (b) A Tuft of Glass Wool.
23. XRD Signals From PF Shots With and Without a Solid Target.

Figure 1

Figure 2

Figure 5

Circuit for VOA calculation

C_b	Bank capacitance	355 μF @ 27 kV
L_b	Bank inductance	20.3 nH
R_b	Bank resistance	5 m Ω
R_t	Leak resistance	120 m Ω
L_i	Inductance of the current path around the insulator	4.7 nH

Figure 4

Figures 5a and 5b

Figures 5c and 5d

Figures 6a and 6b

Figures 6c and 6d

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 21

Figure 22

Figure 23