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TITLE THE HIGH DENSITY Z-PINCH

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THE HIGH DENSITY Z-PINCH

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INTRODUCTION

During the past few years techniques have been developed for producing pinches in solid deuterium. The conditions which exist in these plasmas are quite different from those produced earlier. The pinch is formed from a fiber of solid deuterium rather than from a low density gas, and the current is driven by a low impedance, high voltage pulse generator. Because of the high initial density, it is not necessary to compress the pinch to reach thermonuclear conditions, and the confinement time required for energy production is much shorter than for a gas. This system was proposed by Hammel, Scudder, and Schlacter[1] in 1984, and the first experiments were reported by them in 1985[2]. The experimental results, which have been verified by experiments performed at higher current by Sethian, Robson, and DeSilva[3], were quite surprising and encouraging. The pinch appeared to be stable for a time much longer than the Alfven radial transit time. In this paper, however, I argue that the pinch is not strictly stable, but it does not appear to disassemble in a catastrophic fashion. It appears that there may be a distinction between stability and confinement in the high density pinch.

In the discussion below I will present the status of the high density Z-pinch experiments at laboratories around the world, and I will describe some of the calculational and experimental results. The literature on the Z-pinch is extensive and a bibliography has been compiled by A. E. Robson of the Naval Research Laboratory[4]. I will not review the Z-pinch in general, but, rather, I will confine my remarks to recent work on the high density pinch. There has also been recent work done on the reactor aspects of the high density Z pinch, but I will leave a discussion of this work to reference 5.

FACILITIES

Although the interest in the high density pinch is increasing rapidly, much of the work on the science and technology is now primarily done at three installations. They are: the Imperial College of the University of London in the United Kingdom, the Naval Research Laboratory in Washington, DC, USA, and the Los Alamos National Laboratory in Los Alamos, New Mexico, USA. An experiment has also been done at Dusseldorf in the Federal Republic of Germany, but the effort there is considerably smaller than at the other three laboratories. I will describe the facilities which are in operation or planned at these laboratories in this section, and I will discuss the results of theory and experiment in a later section.

The group at Imperial College has done experiments and theory on gas pinches for a number of years, and they have contributed strongly to the theory of the dense Z-pinch and to diagnostic development for the pinch[6]. They are currently planning an experiment which can be increased to 1 MA by adding standard modules.

The group at the Naval Research Laboratory has performed experiments at currents at currents up to 640 KA using the POSEIDON pulse generator. A diagram of the POSEIDON water line, pulse forming sections and fiber maker are shown in fig. 1. The generator applied a voltage of 400 to 600 KV to a solid deuterium column to produce a current rising nearly linearly in a time of 130 ns. The fibermaker[7] was a cryostat which produced fibers at 11 K. The fibers ranged in diameter from 80 to 200 μm. The POSEIDON generator has been disassembled to provide room for a new system which is designed to produced a current of 1 MA with a current rate of rise, dI/dt, the same as that of the POSEIDON machine. The new device will use a water dielectric capacitor charged by

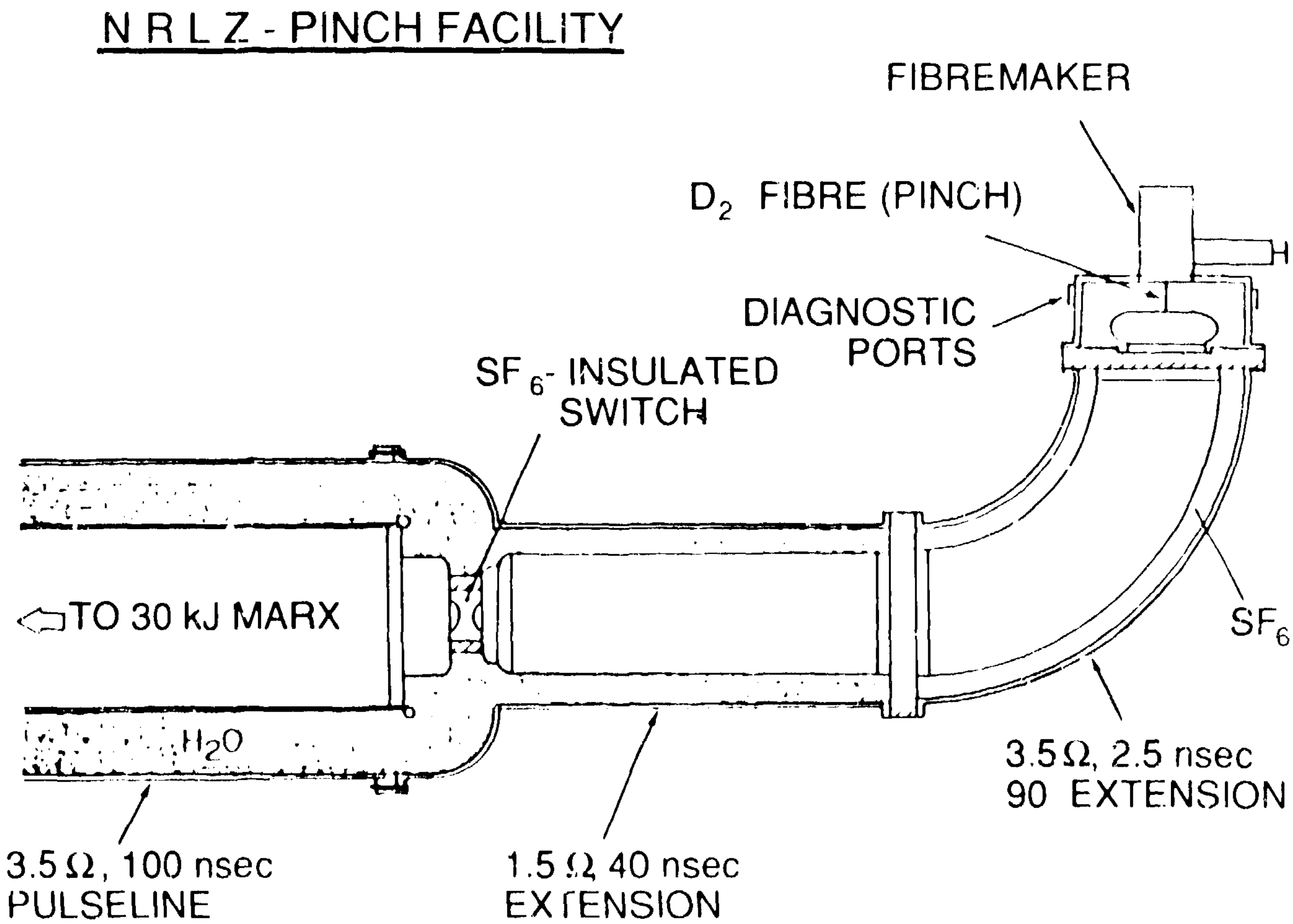

Figure 1 Diagram of the Poseidon pulse generator used in the NRL experiment.

a Marx bank rather than the water insulated transmission line used in earlier experiments It will be interesting to see whether the change in pulser characteristics will affect plasma behavior.

The experiments at Los Alamos have been done at currents up to 250 KA using the HDZP1 system which is similar to POSEIDON. A diagram of the end of the water line and the fiber maker are shown in fig 2 The line was rotated by 90 degrees so that gravity could be used to aid in the extrusion of the fiber The curved elbow of the water line limits the voltage that can be applied to the fiber, and machines currently under construction are vertical rather than curved The applied voltage was 600 KV The fibermaker produced fibers having diameters 20 to 60 μm Thus, although the current was lower than the POSEIDON current by a factor of two, the reduced line density produced a temperature higher than that of the NRL experiment. The HDZP1 system has been modified recently so that gradual increases in current to 500 KA can be obtained. The HDZP2 system is in operation, and a new system, ZEBRA, is under construction at a site removed from that of HDZP2 The ZEBRA system is designed to produce current up to 1.2 MA at a voltage of 1MV. The components of ZEBRA were tested at the Sandia National Laboratory high voltage test facility using fibers of polyethylene and dummy loads. The building has been prepared, and the water tanks have been installed First experiments should begin in six to ten months A diagram of ZEBRA is shown in fig 3.

At Dusseldorf an experiment was done in 1987 using the Speed 2 capacitor to drive a fiber produced by the NRL fiber maker, which was transported to Germany and adapted to the Speed 2 experimental chamber It was intended to produce a current higher than the

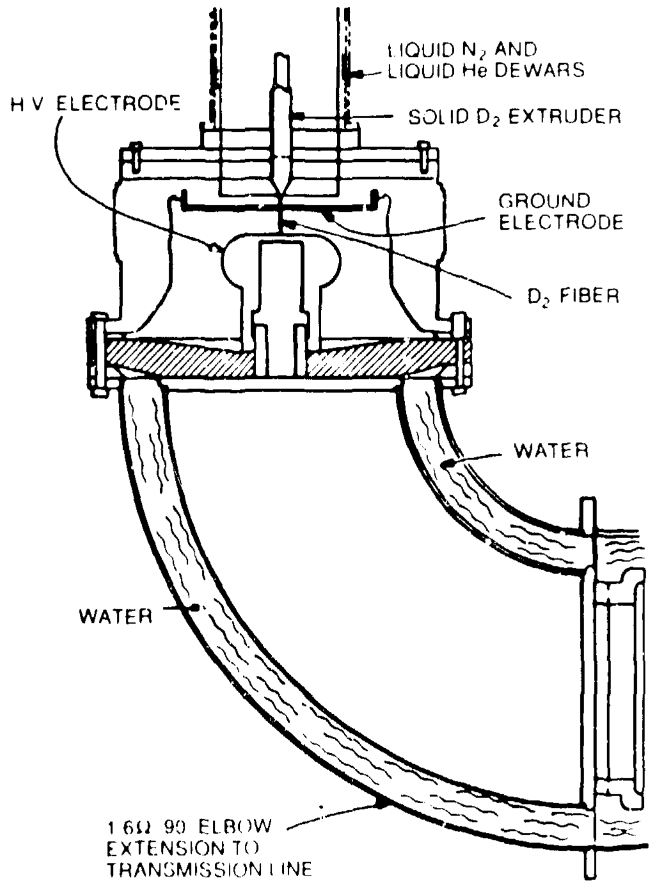

Figure 2. Diagram of the water line and fiber maker used in the Los Alamos HDZP1 experiment.

Pease–Braginskii current, which is required to produce radiative collapse. The experiments were inconclusive, and they were discontinued,

EXPERIMENTAL RESULTS

A typical current pulse used in the HDZP1 experiments is shown in fig. 4. Schlieren photographs were taken by Scudder using a mode locked laser as a pulsed backlighting source and a streak camera to record the images. The spacing between frames was 10 ns. Unfortunately, the photographs are not suitable for reproduction in these proceedings. The plasma expanded slowly for 40 to 50 ns, and then began to expand more rapidly. By 90 ns after the start of current, a pattern suggestive of a number of "m 0", or "sausage", instabilities was evident. Although the modulation of the pinch diameter was large by 90 ns, there was no disruption of the current, and the pinch remained linear. More recent shadowgraphs taken by Lovberg using a CCD camera and a laser backlighting source, which he developed, are shown in fig. 5. In these photographs, the beginning of m=0 behavior is evident at 50 ns in some shots and well developed by 90 ns. More will be said about these results in the discussion of calculations below. The experiments produced neutron yields which were, typically, 10^7 with a peak of 10^8 at a current of 250 KA.

The NRL experiments used a current pulse similar to that shown in fig. 6. The plasma diameter was measured as a function of time by orienting the slit of a streak camera perpendicular to the axis of the pinch and recording the visible light emitted by the plasma. The result of the measurement is shown in fig. 7. The plasma exhibits a slow expansion at a velocity of $1.0 \cdot 10^5$ cm/s until a time near the peak of the current. At peak current the expansion velocity increased to $4.0 \cdot 10^6$ cm/s. It has been speculated by the NRL group that an instability

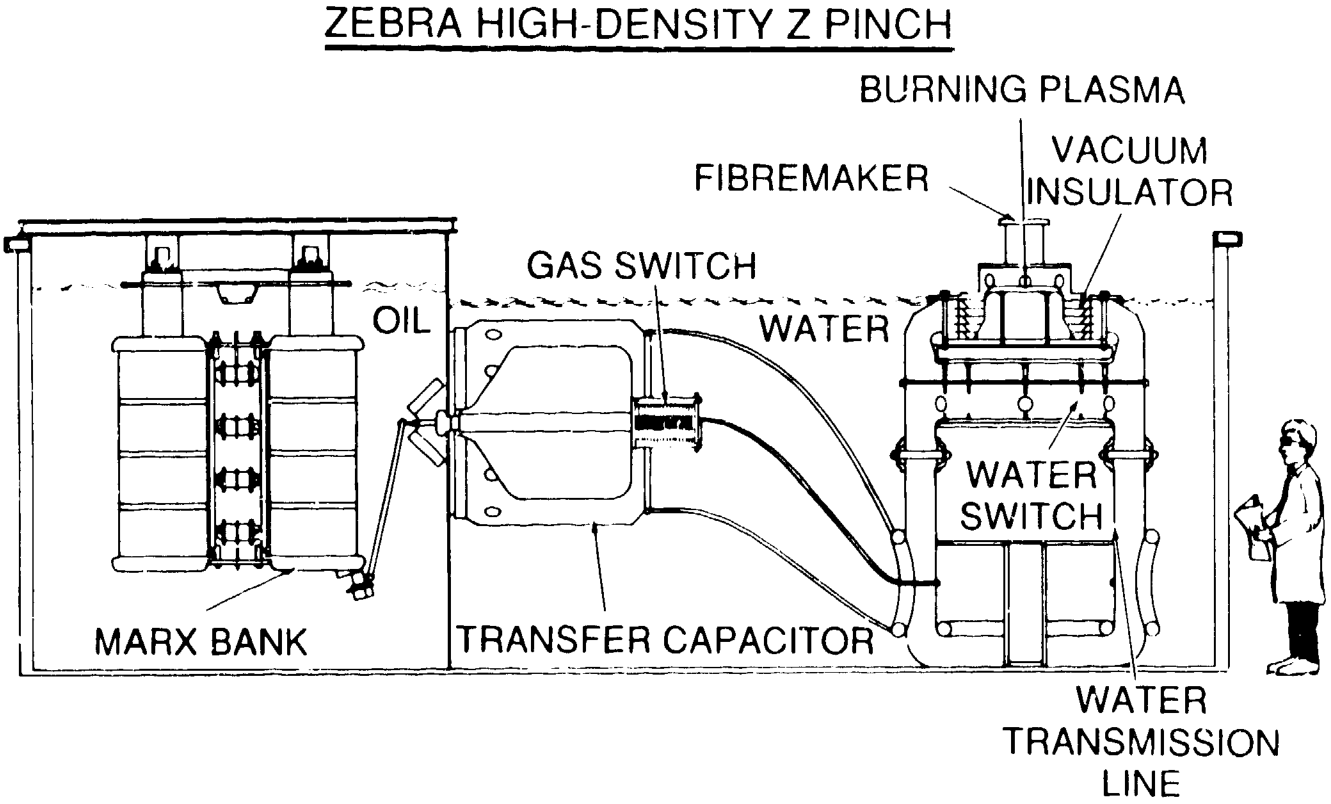

Figure 3. Diagram of the ZEBRA device under construction at Los Alamos.

occurs when dI/dt=0, but at present, no convincing heoretical argument has been made to explain the behavior.

The neutron yield as a function of current is shown in fig. 8. Yields up to 3×10^9 neutrons were observed. The dependence of yield on current was quoted as I^{10}, and, indeed, a slope this large does fit the data, but because of the variability of yield at a given current the accuracy of the fit is not high. The yield at 250 KA was lower than that of the HDZP1 experiments. Comments related to this difference and an explanation of the physical effects which produce the neutrons will be given below.

NUMERICAL CALCULATIONS

Calculation of pinch behavior has been done with MHD computer codes. These calculations assume stability, and, as was shown above, such an assumption is not completely accurate. These calculations have, however, been successful in demonstrating some features of the high density Z pinch. Calculations of stability are underway at several laboratories, and the results are interesting, but there is, as yet, no consensus on the growth of instability, or lack of it, in these plasmas. Therefore, I will present MHD calculations done by this author, and I will take responsibility for the results.

The computer code used for the MHD calculations shown here is the RAVEN code[8] written by Tom Oliphant at Los Alamos. The code has an implicit hydrodynamics algorithm which is quite useful in problems of this type where the plasma remains near equilibrium for long periods of time. If the code timestep were limited by the Courant condition, the calculations would require much more computer time. The radiation treatment in RAVEN is one temperature diffusion using either Rosseland mean or Planck averaged opacities. The diffusion treatment is not accurate for optically thin plasma, and a bremsstrahlung loss treatment is being installed. The transport coefficients treat both degenerate and non-degenerate plasma. The degenerate treatment is that of Lee and More corrected for electron-electron collisions for low Z plasma[9], and the non-degenerate case is treated using the Fokker-Planck quantities calculated by

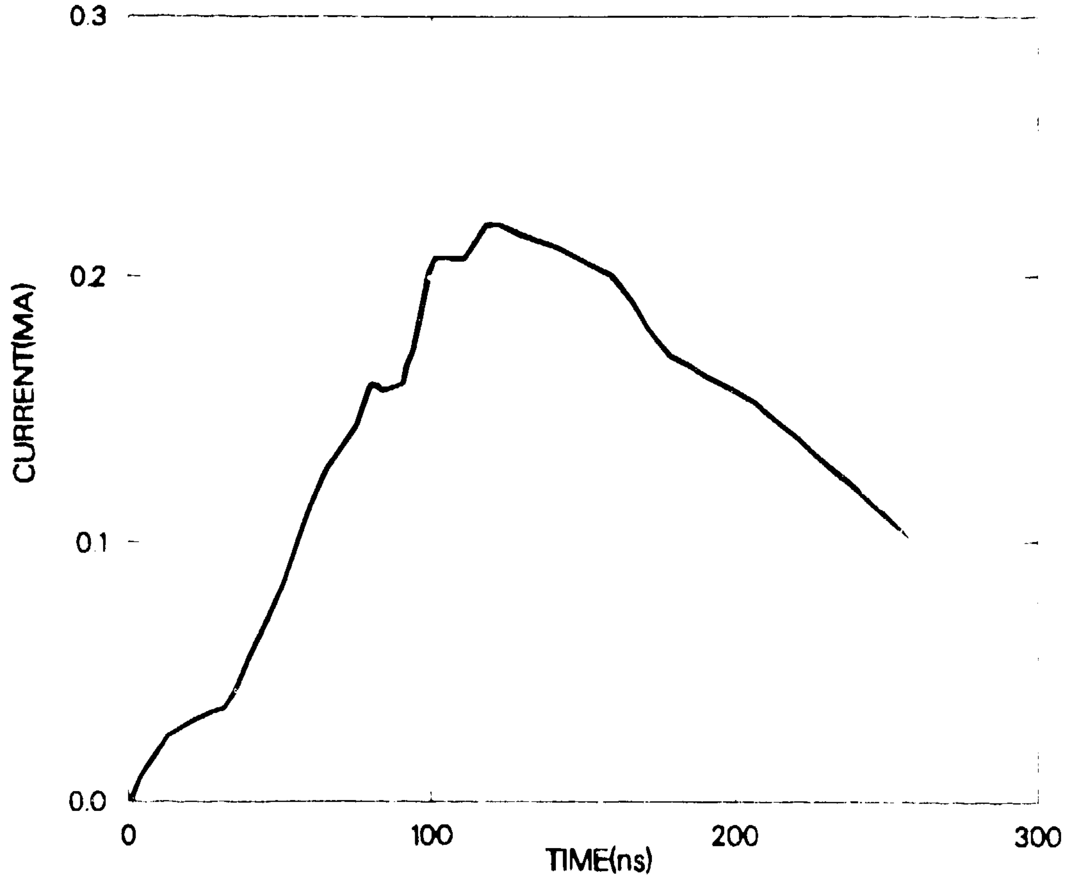

Figure 4. Current as a function of time applied to a solid deuterium fiber in the Los Alamos HDZP1 experiment.

Epperlein and Haines[10]. The effect of the magnetic field on the transport was included. These coefficients do not, in general, agree with the Spitzer or Braginskii coefficients.

Fig. 9 shows a calculation of the NRL experiment using the current pulse of fig. 6. There is a curve for each cell in the problem, and the pair of graphs on the left are for the case where radiation diffusion was turned on and the Rosseland opacities were used. The calculation becomes inaccurate at temperatures above, approximately, 15 eV and the decrease of the radius at late time in the upper left plot indicates the inapplicability of the calculation. The radiation loss calculated is far higher than the actual loss. The important point in this calculation is that the innermost cell of the fiber heats rapidly at 90 ns. The pair of curves at the right were produced by a calculation where the radiation diffusion was turned off, although the ion and electron thermal conduction were allowed. It can be seen that the center of the fiber was still unheated at 150 ns. It is clear that radiation transport could be an important effect at early time in these plasmas. The assumption of the applicability of one–temperature diffusion must be examined carefully, but the interpretation of the experiment may depend on whether the fiber is completely ionized, and the radiation transport can be important in the ionization.

The rapid expansion of the outer cells at early time is not physical. One to five low density cells at an initial temperature of 0.2 to 1 eV were placed at the periphery of the plasma to provide an initial conduction path for the current. The conditions in these cells did not affect the behavior of the bulk of the plasma, but the rapid expansion, which is not confirmed by experiment, indicates that the chosen model for the initial of the fiber is not accurate. The expansion velocity of the edge of the high density region is $1.2 \cdot 10^5$ cm/s in good agreement with experiment as shown in fig. 7.

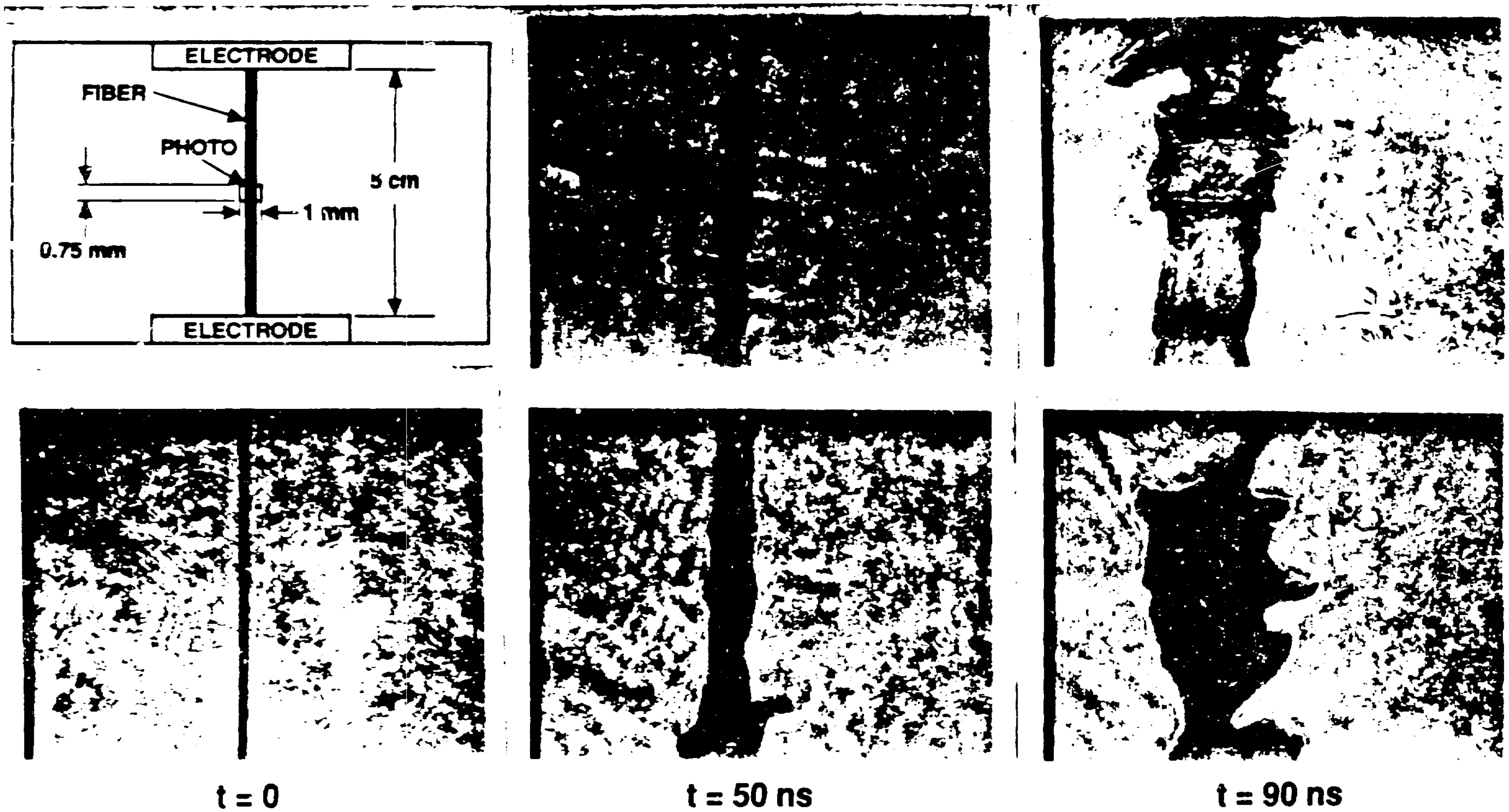

Figure 5. Microscope photographs of the pinch produced in the HDZP1 experiment at Los Alamos. Photographs are single frames taken on four shots by R. Lovberg.

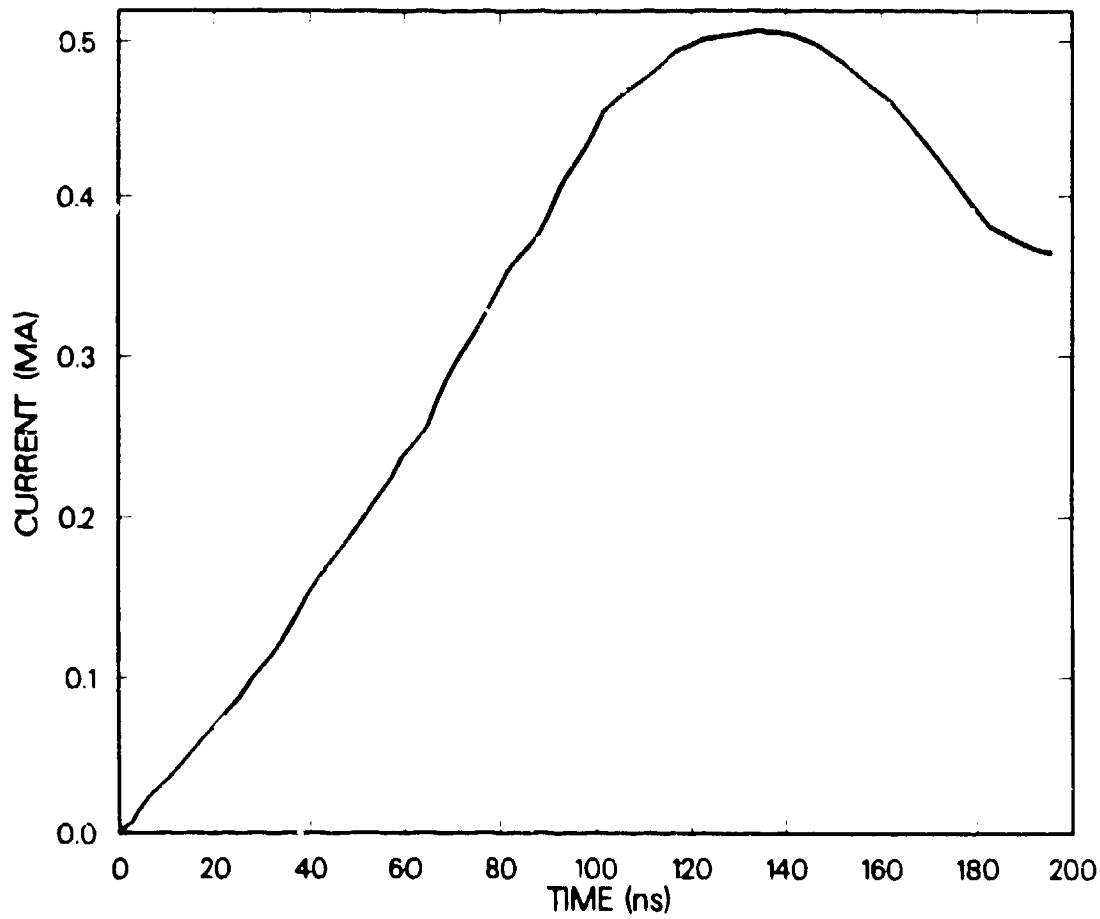

Figure 6. Current as a function of time applied to a solid deuterium fiber in the NRL experiment.

Fig. 10 shows the result of a calculation for an HDZP1 experiment using the current pulse of fig. 4 and a fiber 30 μm in diameter. The case where radiation was considered is at the left. The upper curve shows that the inner cell of the fiber heats at a time of 50 ns. The lower curve is a plot of the electron density as a function of radius at 50 ns. The experimental result from the Lovberg measurement is shown by an arrow. The calculation is consistent with the measured diameter and with the appearance of light transmitted through the center of the fiber. The curves on the right were calculated with radiation diffusion turned off. The fiber is seen to "burn through" after 50 ns, and the center is quite dense, consistent with a dark center. The final resolution awaits further analysis of hte experiment, but it appears that radiation transport cannot be neglected as a factor in plasma formation and heating. Because of the small fiber diameter in the HDZP1 experiments, the fiber is completely ionized by 70 ns whether or not the radiation transport is considered. The one–temperature treatment of the radiation transport can lead to substantial inaccuracy, and the results should be considered preliminary.

MODELING OF NEUTRON YIELD SCALING

Phenomenological modeling of the m=0 instability was done in an attempt to understand the behavior of the plasma, at least qualitatively. It was assumed that the instability growth was the result of pinching of a section of the plasma. Ions were assumed to flow out of the pinched region at their thermal velocity. The flow of mass is slow enough, however, that the pinch is expected to remain in Bennett equilibrium during the growth of hte instability. The reduced line density requires the plasma to heat to remain in equilibrium. The energy for this heating is supplied by PdV work which results from plasma

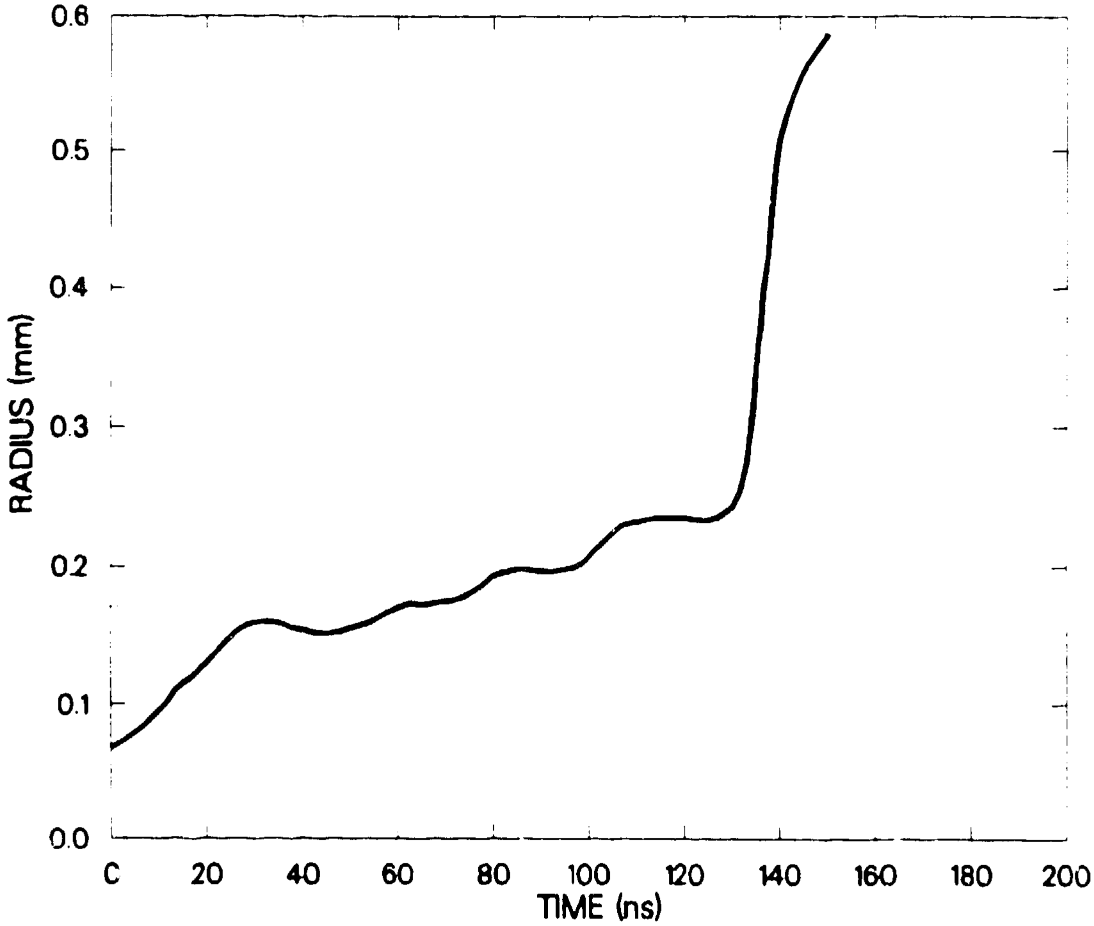

Figure 7. Radius as a function of time of a fiber of initial radius of 62.5 μm in the NRL experiment.

contraction. The power input from the current as I^2R losses was also included in numerical calculations, but it was found to be unimportant late in the development of the instability. If the ohmic heating is neglected, an analytic description of the collapse of the instability can be given.

It is assumed that as the unstable region pinches, the length of the pinched region is equal to its radius, a. The 90 ns photograph of fig. 5 is consistent with this assumption, although one could use 2a for the length. The difference for the purpose of this calculation is unimportant. The total plasma energy in the pinched region is given by,

$$E = \frac{3}{2}(n_e + n_i)\,V = 3\,N\,a\,kT \qquad (1)$$

where, n_e, and, n_i, are the electron and ion densities, respectively, N, is the ion line density, T, is the temperature, V, is the volume of the unstable region and, k, is Boltzmann's constant. It can be seen that the total number of ions in the pinched region is Na. The rate of change of energy is given by the sum of the power loss as the result of mass flow out of the unstable region and the PdV work done on the collapsing plasma by the magnetic field. Therefore,

$$\frac{dE}{dt} = -P\,\frac{dV}{dt} + 3\,kT\,\frac{d}{dt}(Na) \qquad (2)$$

where, P, is the plasma pressure. If it is assumed that mass flows out of the pinched region at the thermal velocity of the ions, the particle loss term can be written as,

$$\frac{d}{dt}(Na) = -n_i v_{th} \pi a^2 = -N\,(kT/m_i)^{1/2} \qquad (3)$$

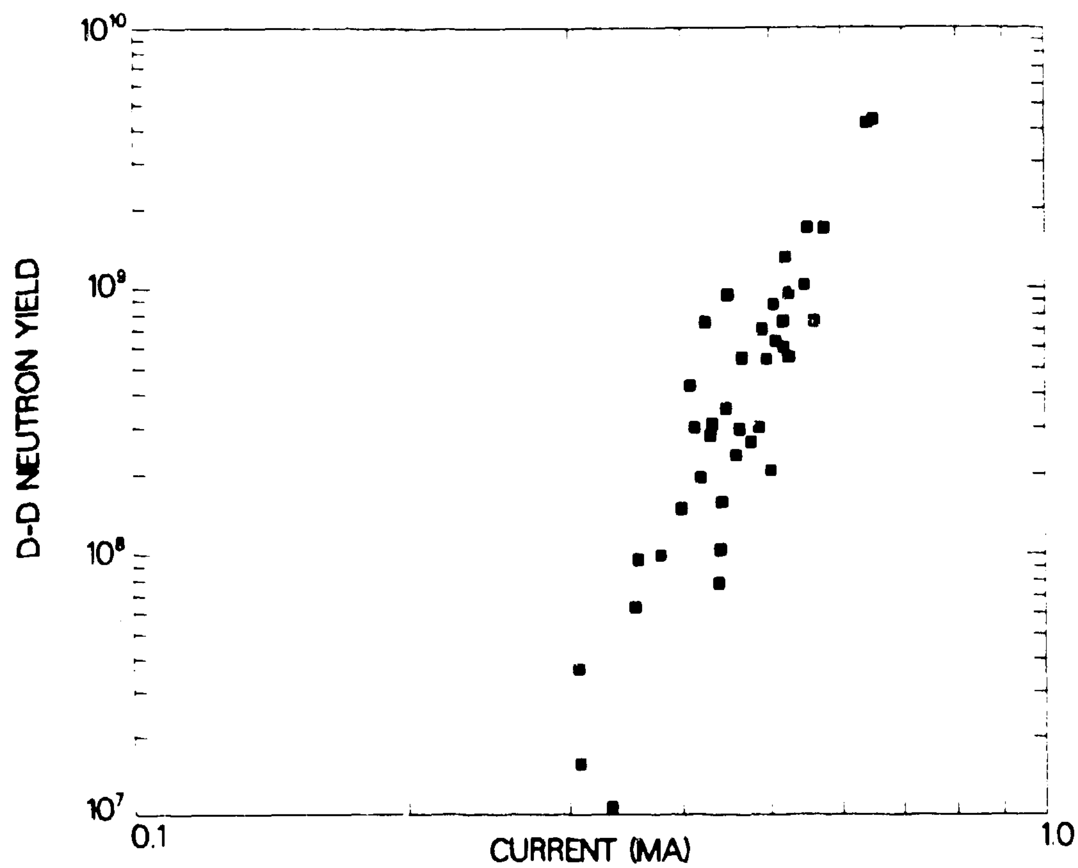

Figure 8. Neutron yield as a function of current for a fiber of initial radius of 40 μm in the NRL experiment.

where, v_{th}, is the ion thermal velocity and, m_i, is the ion mass.

The Bennett relation is given by,

$$N = \frac{\mu I^2}{16 \pi kT} \tag{4}$$

where, I, is the current , which is assumed constant.

It is seen that three equations in three unknowns result. The equations can be solved to give the time dependence of the dynamical variables, kT, N, and, a. If the initial values are kT_0, N_0, and a_0, respectively, the solutions are,

$$kT = kT_0 / (1 - \tau)^{2/3}$$

$$N = N_0 (1 - \tau)^{2/3} \tag{5}$$

$$a = a_0 (1 - \tau)^{2/3}$$

where,

$$\tau = t / t_0$$

and

$$t_0 = \frac{4}{3} a_0 (m_i / kT_0)^{1/2} \tag{6}$$

Note that t_0 is, approximately, the time for an ion to move an initial radius at the initial thermal velocity. Although a characteristic time this short raises some doubts about the assumption of equilibrium, the radius decreases with time, and the thermal velocity increases with time. Therefore, the equilibrium assumption becomes more valid at later time.

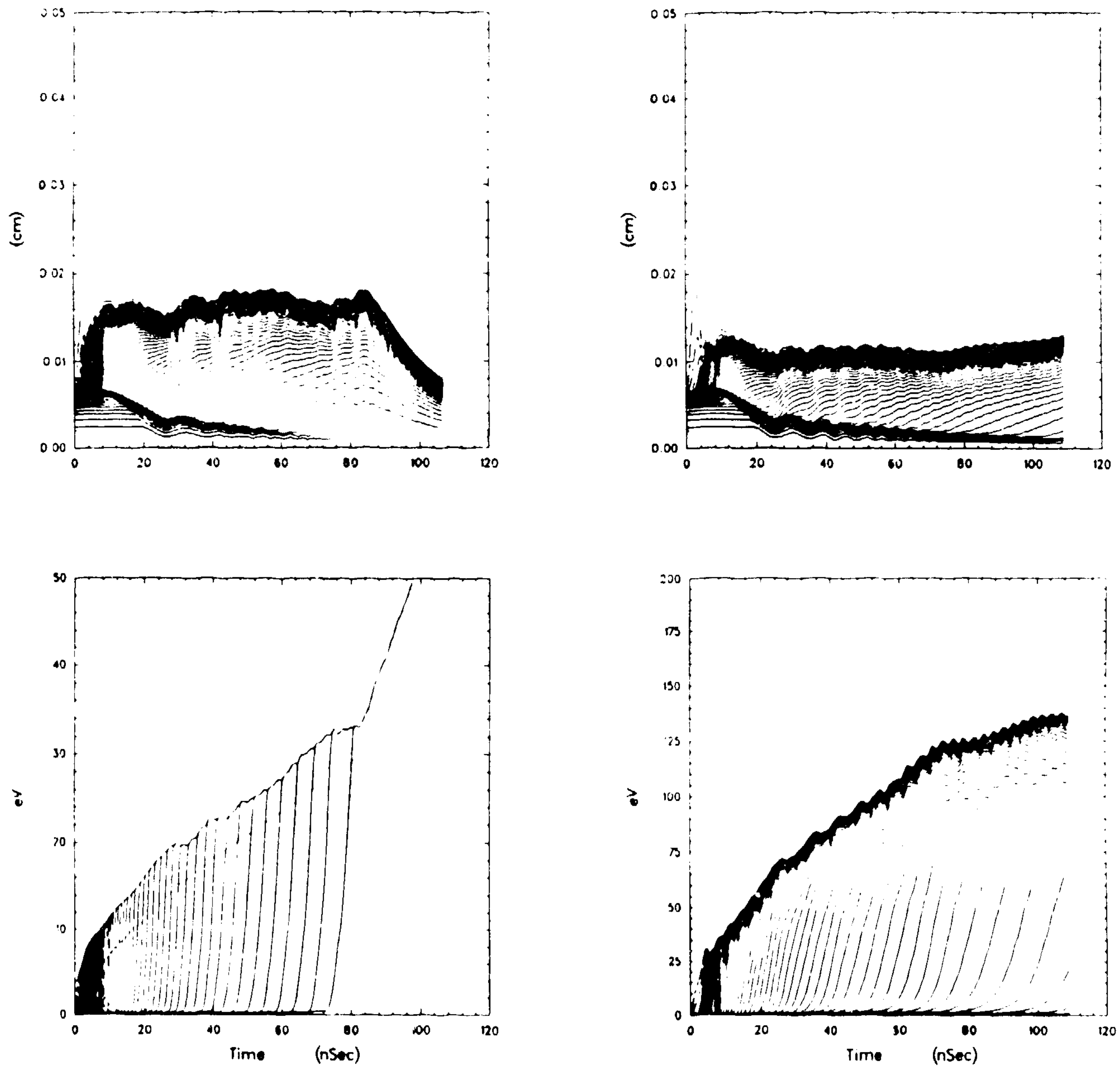

Figure 9. Calculation of the NRL experiment using the RAVEN code. Figures at left include radiation diffusion, those at right neglect radiation transport. Initial fiber radius was 62.5 Ñm. The current pulse of fig. 6 was used as input to the calculation

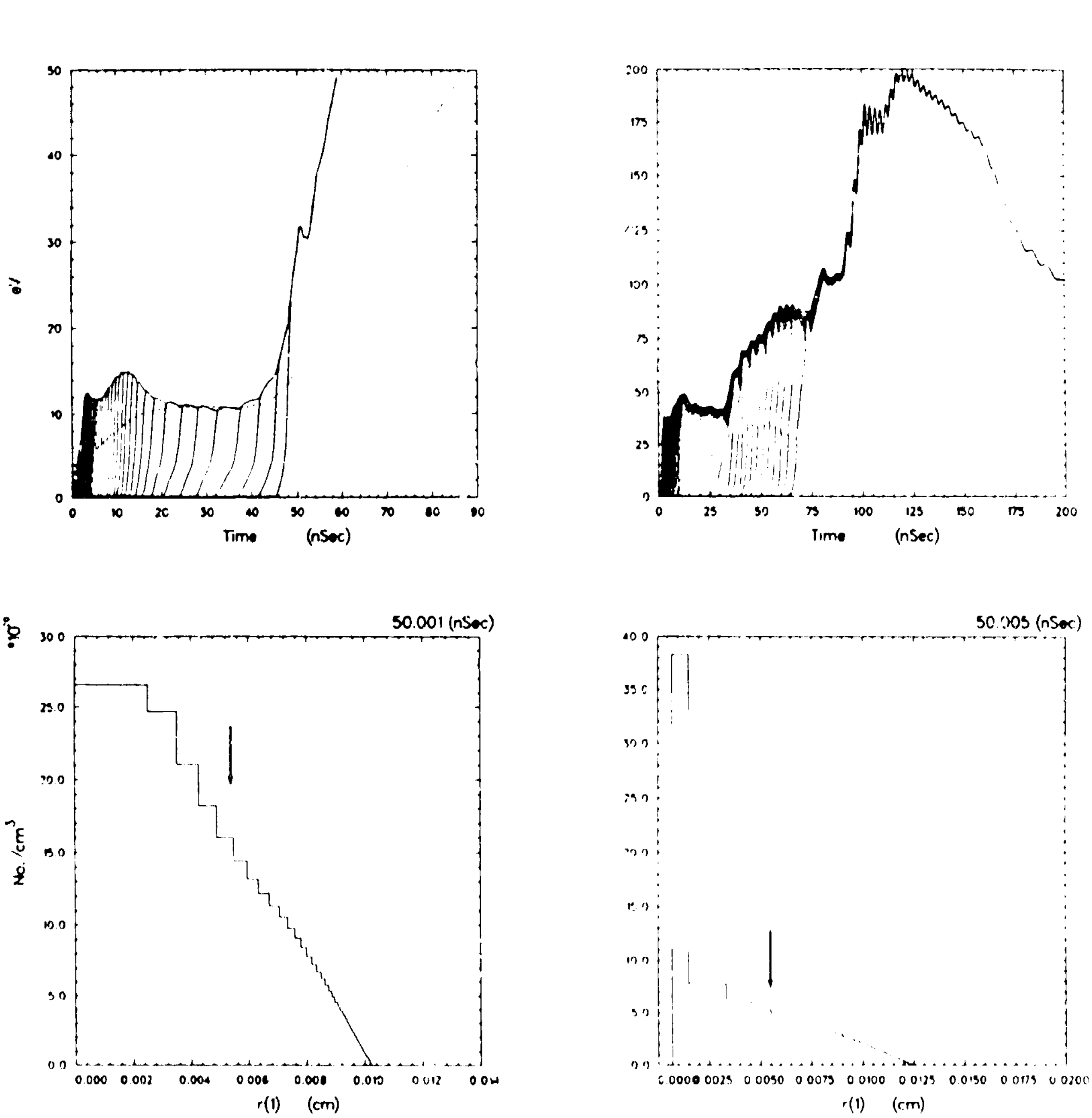

Figure 10. Calculation of the Los Alamos HDZP1 experiment using the RAVEN code. The figures at left include radiation transport, those at right neglect radiation transport. Initial fiber radius was 15 μm. The current pulse of fig. 4 was used as input to the calculation.

Next, the neutron yield can be calculated by assuming that the neutrons are produced in the thermal plasma of the instability. The yield rate can be written as,

$$\frac{dY}{dt} = \frac{1}{2} n^2 \overline{\sigma v} V = \frac{1}{2} \frac{N^2}{\pi a^2} \overline{\sigma v} \qquad (7)$$

It is well known that the D–D $\overline{\sigma v}$ can be approximated by an analytic fit[11],

$$\overline{\sigma v} \cong A \quad T^{-2/3} \quad \exp(\; -C \quad T^{-1/3}) \quad cm^3/s \qquad (8)$$

where, A, and, C, are constants. If T is the temperature in keV, $A=2.33\times10^{-14}$ and $C=18.76$.

Substituting eq. (8) into eq. (7) and integrating over time, the yield is,

$$Y = constant \times N_0^2 (kT_0)^2 \int_0^{C/(kT)^{1/3}} x^{17/2} \, e^{-x} dx \qquad (9)$$

The upper limit of the integral is large for initial temperatures of interest here, and the integral can be written as an integral from 0 to infinity. The integral, therefore, is a gamma function $\Gamma(19/2)$ which is independent of the parameters of the problem. Using the Bennett relation of eq. (5), the yield is,

$$Y = constant \times I^4 \qquad (10)$$

The neutron yield is, therefore, independent of the line density, and depends only on the current to the fourth power. This scaling appears to explain the yield of the dense plasma focus. The I^4 scaling for the plasma focus was derived by Milanese and Pouzo[12], but their relation is not independent of the initial conditions of the plasma, because they used a constant length rather than a time–varying length. Their paper on neutron yield from the plasma focus[13] provides a good review of the dependence of yield on current and shows the independence of yield and fill pressure. The derivation given here also explains the 2–3 keV temperatures measured from the neutron spectrum of the focus, but that derivation will be given in a later publication. It can be seen that the equations describe a plasma which is heated by PdV work and in which particles flow out at a velocity which is proportional to the ion thermal velocity. Also, the length of the plasma is proportional to its diameter. These are the conditions which exist in a plasma focus, but the rate at which the mass flows out of the pinch region can be a small fraction of that calculated from the ion thermal speed because of the longitudinal confinement produced by the magnetic field. For the Z–pinch, however, the longitudinal confinement is small, and this mechanism should not be significant. The NRL experiment appears to confirm this conclusion.

The purpose here is to explain the yield of the dense Z–pinch which operates under conditions quite different from those of the focus. Therefore, I will now consider neutrons generated by ions accelerated by the inductive voltage generated across the instability as the plasma collapses. A similar mechanism was used by Anderson, et al in their 1958 paper[14], but they did not produce a unified model of the acceleration process, and it is not possible to calculate the current scaling from their work.

The voltage across the instability is given by,

$$V = L \frac{dI}{dt} + I \frac{dL}{dt} \qquad (11)$$

where, V, is the voltage and, L, is the time–dependent inductance across the instability. The current is assumed constant; therefore, $dI/dt = 0$. The inductance is,

$$L = \frac{\mu_0}{2\pi} a \log(r_w / a) \qquad (12)$$

where r_w is the radius of the chamber wall. Substituting eq.(12) into eq.(11) the result is,

$$V = I \frac{\mu_0}{2\pi} \frac{da}{dt} (\log(r_w / a) - 1) \qquad (13)$$

The wall radius is much larger than the plasma radius, and $\log(r_w / a) >> 1$. Over the range of interest the logarithm varies only 30 percent, and it will be assumed to be constant. Assuming that ions are accelerated to the voltage across the instability, the neutron production rate can be calculated. Again, the purpose here is to demonstrate the scaling of yield with current, and a more detailed exposition will be made in a later publication, but the general features of the model will be given below. Assuming that the accelerated ions stop in the high density plasma outside the instability in a way which is independent of plasma conditions and ion energy (an assumption which will be removed in the forthcoming publication) the rate at which particles strike the high density column is given by the product of flux and area and the yield rate is,

$$\frac{dY}{dt} = Bnv\pi a^2 = BN\sigma \left[\frac{2 \ V}{m} \right]^{1/2} \tag{14}$$

where, B, is a constant, n, is the time dependent density in the instability, N, is the time dependent line density, v, is the velocity, σ, is the neutron production cross section, V, is the voltage across the instability, m, is the ion mass, and, a, is the instability radius. Substituting the usual analytic expression for, σ, and substituting eq. (5), eq.(14) can be integrated to give an expression of the form,

$$Y = B' \frac{a_0}{N_0^{3/4}} I^9 \int_0^b x^5 e^{-x} dx \tag{15}$$

The upper limit is not, strictly, infinite, but for the present purposes it may be assumed so. The scaling of yield with current to the ninth power is in excellent agreement with the NRL measurement. The yield is not completely independent of the initial conditions as was the case in the expression of eq.(10). The dependence on plasma conditions explains, qualitatively, the fact that the Los Alamos experiment gave a higher yield at 250 KA than did the NRL experiment.

I believe that the discussion above shows conclusively that the neutrons measured in the high density Z-pinch experiments were produced by a m=0 instability.

RADIATIVE COLLAPSE

The new pulse generators under construction are intended to approach the current where the ohmic heating is smaller than the bremsstrahlung loss. When this condition is satisfied the plasma column must reduce its radius to provide PdV heating so that it can remain in equilibrium. The resulting increase in density increases the radiation loss, which is proportional to the square of the density, and the collapse rate increases. In the absence of instability, the radius can become vanishingly small. This author believes, however, that asymetries in the collapse will limit the collapse to a diameter no smaller than 10 or 20 percent of the initial radius, at best. The phenomenon is quite intriguing, however, and it is worth pursuing. A publication submitted by Haines[15] treats the dynamics of the collapse, and only the threshold will be calculated here. The power deposited in the plasma column by ohmic heating, assuming Spitzer resistivity, is,

$$P_{in} = I^2R = I^2 \frac{l}{\pi a^2} K \log \Lambda \ T^{-3/2} \tag{16}$$

where K is a constant, and l is the length of the column. The bremsstrahlung loss is,

$$P_b = B \ Z^2 \ n^2 \ T^{1/2} \ \pi \ a^2 \ l \tag{17}$$

If $P_{in} = P_b$, then eq.(17) can be equated to eq.(18) and the current required to satisfied the equality is,

$$I_{PB} = \frac{16 \ \pi}{\mu_0 \ C} \left[\frac{K \ \log \ \Lambda}{B \ Z} \right]^{1/2} \tag{18}$$

where, C, is a constant. The current, I_{PB}, is known as the Pease–Braginskii current[16,17] after the authors who, independently, calculated it in 1957 and 1958. For a hydrogen plasma, $I_{PB} \cong 1$ MA, and it is independent of the line density and other plasma conditins except through log Λ. It should be noted that the rate of collapse does depend on the line density, which the high density Z-pinch should be a useful vehicle for investigating the collapse phenomenon. It remains to be seen, however, if the collapse will be fast enough to be observed. At threshold current the time required for collapse is infinite, and the threshold current does depend slightly on the current distribution in the plasmma.

CONCLUSION

The dense Z pinch provides a rich variety of physical effects which are somewhat different from those usually encountered in magnetically confined plasma, and many of these phenomena are not yet understood. The next round of experiments will attempt to study the radiative collapse of the pinch when the radiative loss becomes larger than the ohmic input. The question of stability and that of confinement are yet to be answered.

definitively. It is clear from the measurements which have been made that the plasma is not completely stable, but the confinement of the pinch appears to occur for times much longer than calculated instability growth times.

The next few years promise to be exciting ones for this new field.

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