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TITLE THE PHYSICS OF THE HIGH DENSITY Z-PINCH

AUTHOR(S) A. H. Glasser, J. E. Hammel, H. R. Lewis, I. R. Lindemuth, G. H. McCall, R. A. Nebel, D. W. Scudder, J. S. Schlachter, R. H. Lovberg, P. Rosenau, and P. T. Sheehey

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A. H. Glasser, J. E. Hammel, H. R. Lewis, I. R. Lindemuth
G. H. McCall, R. A. Nebel, D. W. Scudder, and J. S. Schlachter
Los Alamos National Laboratory
Los Alamos, New Mexico, United States of America

R. H. Lovberg
University of California at San Diego
La Jolla, California, United States of America

P. Rosenau
Technion, Israel Institute of Technology
Haifa, Israel

P. F. Sheehey *
University of California at Los Angeles
Los Angeles, California, United States of America

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THE PHYSICS OF THE HIGH-DENSITY Z-PINCH

A.H. GLASSER, J.E. HAMMEL, H.R. LEWIS, I.R. LINDEMUTH, G.H. MCCALL, R.A. NEBEL, D.W. SCUDDER, J.S. SHLACHTER
Los Alamos National Laboratory
Los Alamos, New Mexico, United States of America

R.H. LOVBERG
University of California at San Diego
La Jolla, California, United States of America

P. ROSENAU
Technion, Israel Institute of Technology
Haifa, Israel

P.T. SHEEHEY*
University of California at Los Angeles
Los Angeles, California, United States of America

Abstract

THE PHYSICS OF THE HIGH-DENSITY Z-PINCH

The fiber-initiated High-Density Z-Pinch (HDZP) is a novel concept in which fusion plasma could be produced by applying 2 MV along a thin filament of frozen deuterium, 20 - 30 μm in diameter, 5 - 10 cm long. The megamp-range currents that result would ohmically heat the fiber to fusion temperatures in 100 ns while maintaining nearly constant radius. The plasma pressure would be held stably by the self-magnetic field for many radial sound transit times during the current-rise phase while, in the case of D-T, a significant fraction of the fiber undergoes thermonuclear fusion. This paper presents results of Los Alamos HDZP studies. Existing and new experiments are described. A succession of theoretical studies, including 1D self-similar and numerical studies of the hot plasma phase, 1D and 2D numerical studies of the cold startup phase, and 3D numerical studies of stability in the hot regime, are then presented.

1. EXPERIMENTS

In existing Los Alamos experiments, [1] currents rising to 250 kA in 150 ns have been passed through linear z-pinch columns formed from fibers of solid deuterium 20 – 40 μm in diameter and 5 cm long. [2] The columns

* Performed under U.S. DOE Magnetic Fusion Energy Technology Fellowship, administered by Oak Ridge Associated Universities.

[1] SCUDDER, D.W., Experiments on high density Z pinches formed from solid deuterium fibers, Bull. Am. Phys. Soc. **30** 9 (1985) 1408.

[2] GRILLY, E.R., HAMMEL, J.E., RODRIGUEZ, D.J., SCUDDER, D.W., SHLACHTER, J.S., Production of solid D_2 threads for dense Z pinch plasmas, Rev. Sci. Instrum. **56** 10 (1985) 1885.

are observed to remain free of instabilities for 60 - 80 ns, approximately 200 Alfvén times, while undergoing slow expansion ($v_r \approx 4 \times 10^5$ cm/s), whereas ideal MHD predicts the growth of unstable modes in about one Alfvén time. Temperatures of 150-300 eV at densities of $\approx 2 \times 10^{21}$ cm^{-3} have been observed. Diagnostics include X-ray pinhole photography, filtered X-ray diode temperature measurement, neutron yield and time history, and schlieren photography. [3] A new diagnostic based on a laser microscope has been developed to search for the low-plasma-density corona that might surround the fiber. A new experiment under construction at Los Alamos will utilize a 200 kJ Marx bank that will extend the current in these pinches to 1.2 MA with 100-ns risetime and could utilize D-T. This current, passing through a 30 μm diameter fiber, is expected to produce a temperature of 10 keV, allowing the study of plasmas under fusion conditions. The current will be close to the Pease limit of 1.4 MA, for which steady-state balance between Ohmic heating and bremsstrahlung radiation is predicted. Such a discharge could produce $> 10^{17}$ D-T fusions, which, if repetitively pulsed, promises an intense neutron source of $10^{18} - 10^{19}$ n/s for materials testing. The yield can exceed the input energy, thus also giving promise of a high-Q source of fusion energy. [4] A diagram of the new experiment is shown in Fig. 1. Initial data will be taken during the winter of 1988-9.

2. SELF-SIMILAR TIME ASYMPTOTICS

Between about 25 eV, where the fiber enters the plasma phase, and a few keV, beyond which the mean free path exceeds the scale lengths, the pinch is well described by Braginskii's dissipative fluid equations. A 1D model, with radial variation, has been studied analytically and numerically. A subset of these equations, incorporating finite electrical and thermal resistivity in the limit of strong magnetic field, but neglecting inertia, viscosity, and radiation, admits a class of self-similar solutions. Analytical solutions for the time evolution as well as numerical solutions for the spatial profiles have been obtained. [5] [6] Numerical solutions

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[3] HAMMEL, J.E., SCUDDER, D.W., GLASSER, A.H., LINDMAN, E., NEBEL, R.A., The Los Alamos solid-deuterium-fiber Z-pinch, experiment and theory, Los Alamos Report LA-UR-87-2102, Proc. Plasma Focus and Z-Pinch Workshop, Toledo, Spain, 1987.

[4] HAGENSON, R., HAMMEL, J., KRAKOWSKI, R., MILLER, R., NEBEL, R., SCUDDER, D., WERLEY, K., The high-density Z-pinch (HDZP) as a fusion neutron source, Los Alamos Report LA-UR-87-3463, Proc. IEEE 12th Symposium on Fusion Engineering, Monterey, CA, October 12-16, 1987, IEEE Catalog #87CH2507-2 (1987) Vol. 2, p. 835.

[5] ROSENAU, P., NEBEL, R.A., LEWIS, H.R., Analysis of plasma transport with application to Z-pinch fibers, Los Alamos Report LA-UR-87-3319, submitted for publication in Phys. Fluids.

[6] GLASSER, A.H., A moving finite element model of the high density Z-pinch, Los Alamos Report LA-UR-88-746, submitted for publication in J. Comp. Phys.

of the full set of equations are found to relax to self-similar behavior at late times. This is shown by two numerical tests. [7] One is that, when the current is programmed as $I(t) = I_0(1+t/t_0)^\alpha$, the quantity $f/(df/dt)$ becomes linear in t for all dependent variables $f(t)$. The other is that the normalized spatial profile of each physical quantity approaches its own universal shape (the self-similar profile), and this asymptotic profile depends only on the value of α, as illustrated in Fig. 2. [5] These tests also show that the approach to self-similar behavior is qualitatively more robust than the analytical derivations suggest. First, inertia and viscosity become unimportant in the time asymptotic limit. [6] Second, although radiation formally breaks the invariance, its main impact is on the time dependence of the plasma radius and other scale factors, leaving the profiles nearly unchanged. [5] Third, inclusion of the full expressions for the transport coefficients makes only a small change to the results obtained in the strong field limit. [5,6]

3. 1D NONLINEAR FLUID SIMULATIONS

Two codes have been used to solve the 1D Braginskii equations more completely. [5,6] The first, a transport code, assuming pressure balance and neglecting inertia and viscosity, uses a Lagrangian grid. The second, incorporating inertia and viscosity as well as transport, uses an adaptive grid scheme called Moving Finite Elements. Both also treat bremsstrahlung radiation. Both solve for the motion of plasma within a moving boundary with a radius of order the initial fiber radius. Both show a strong tendency to relax to self-similar profiles closely resembling those obtained analytically. The final profiles are independent of details of the initial conditions, even when initialized far from pressure balance so that large-amplitude oscillations occur. In the presence of inertial effects, relaxation to pressure balance and self-similarity is caused primarily by ion viscosity, which scales as $T^{5/2}$. Simulations of the new Los Alamos experiment show relaxation to self-similar profiles relatively early in time, as illustrated in Fig. 3, [6] while for the earlier experiments such behavior is seen only quite late or not at all. These codes adequately reproduce conditions observed in the existing Los Alamos experiment and predict substantial D-T burn under conditions of the experiment now in preparation.

4. COLD STARTUP

These codes cannot address two important classes of questions. One concerns cold startup. Braginskii's equations are valid only at sufficiently high temperatures and cannot treat the behavior of the initial transition from the solid phase. It is especially interesting to understand how current begins to flow through the fiber. Two codes address these issues by using the Los Alamos SESAME atomic data base to determine the pressure,

[7] ROSENAU, P., HYMAN, J.M., Analysis of nonlinear mass and energy diffusion, Phys. Rev. A **32** (1985) 2370.

specific internal energy, and electrical resistivity of solid, cryogenic deuterium. One is a 1D code which also treats the effects of degeneracy and line and continuum radiation on heat transport. [8] The other incorporates 2D effects and is capable of treating some stability issues. [9] Both show that the current initially flows through a large-radius corona of low density material ablated from the solid fiber. Both indicate that the fiber in the earlier experiment does not fully ablate until late in the discharge, as shown in Fig. 4. [9] The density then falls rapidly because the early experiment does not have enough current to maintain the pressure. After the fiber is completely vaporized, the profiles approach the self-similar ones discussed above.

5. STABILITY

The other class of questions concerns stability. Ideal MHD theory predicts that the HDZP should be unstable to $m = 0$ sausage modes and $m = 1$ kink modes. Implosion pinch experiments are plagued by such instabilities. The HDZP has been observed to remain free of sausage modes for many Alfvén times, and free of kink modes throughout the discharge. Two efforts are underway to understand this anomalous stability. Both are based on the complete fluid equations of Braginskii, including the full magnetized viscosity tensor and all other transport coefficients. One treatment is based on a 3D nonlinear pseudospectral code. The other, an eigenvalue treatment which reduces the equations to a high-order set of complex coupled ordinary differential equations, is essentially linear but capable of greater numerical speed and accuracy. Preliminary results with the pseudospectral code, run in the linear regime, have shown that both viscosity and resistivity have a stabilizing influence on sausage modes, the former at high temperatures and the latter at low temperatures.

[8] MCCALL, G.H., The high density Z-pinch, Proc. 3rd Latin American Workshop on Plasma Physics, Santiago, Chile, July 18-29, 1988.

[9] LINDEMUTH, I.R., NEBEL, R.A., Fiber ablation in the solid deuterium Z-pinch, Los Alamos Report LA UR 88 2037, submitted for publication in Phys. Rev. Letters.

FIGURE CAPTIONS

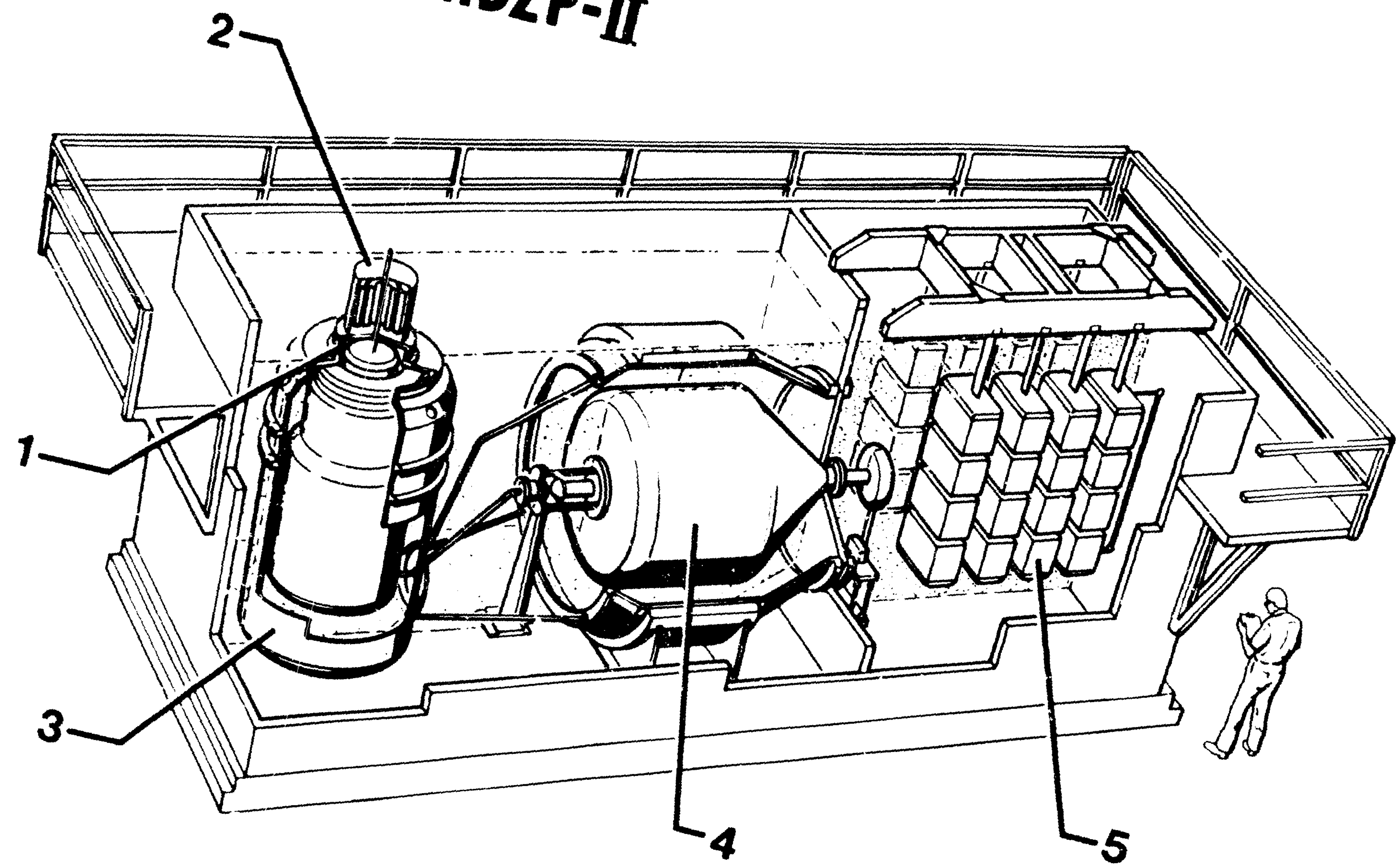
1. 1.2 MA Los Alamos High Density Z-Pinch Experiment, showing the following parts: 1. load chamber; 2. fiber maker; 3. vertical transmission line; 4. intermediate energy store; 5. Marx bank.

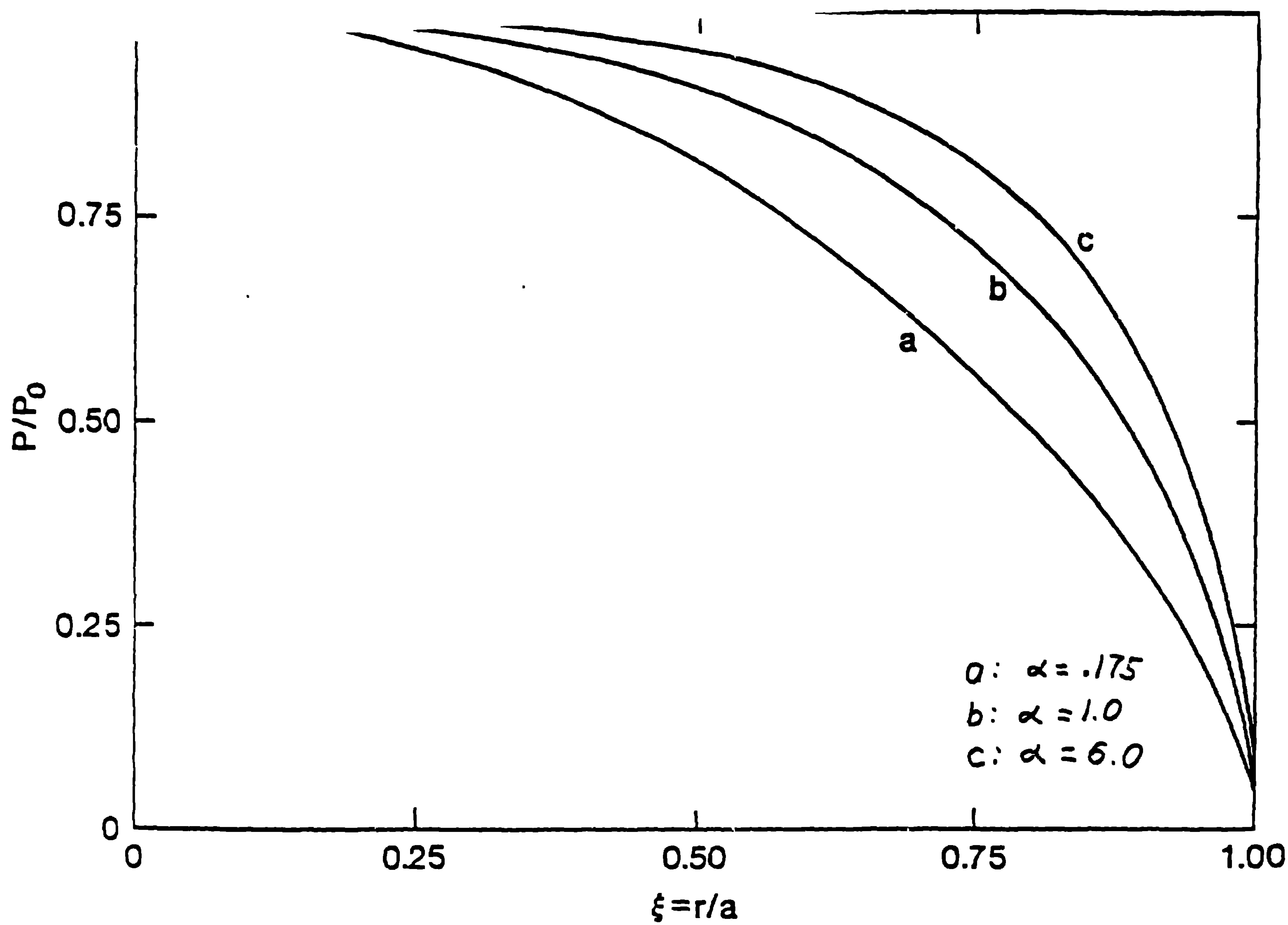
2. Scaled asymptotic pressure profiles P/P_0 vs. scaled radius ξ, showing dependence on α.

3. Plasma temperature T vs. radius r at time intervals of 2 ns for 100 ns, showing approach to self-similarity.

4. Temporal history of mass density: (a) on axis; (b) at $r = 25\ \mu m$; (c) at $r = 50\ \mu m$.

HDZP-II





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b
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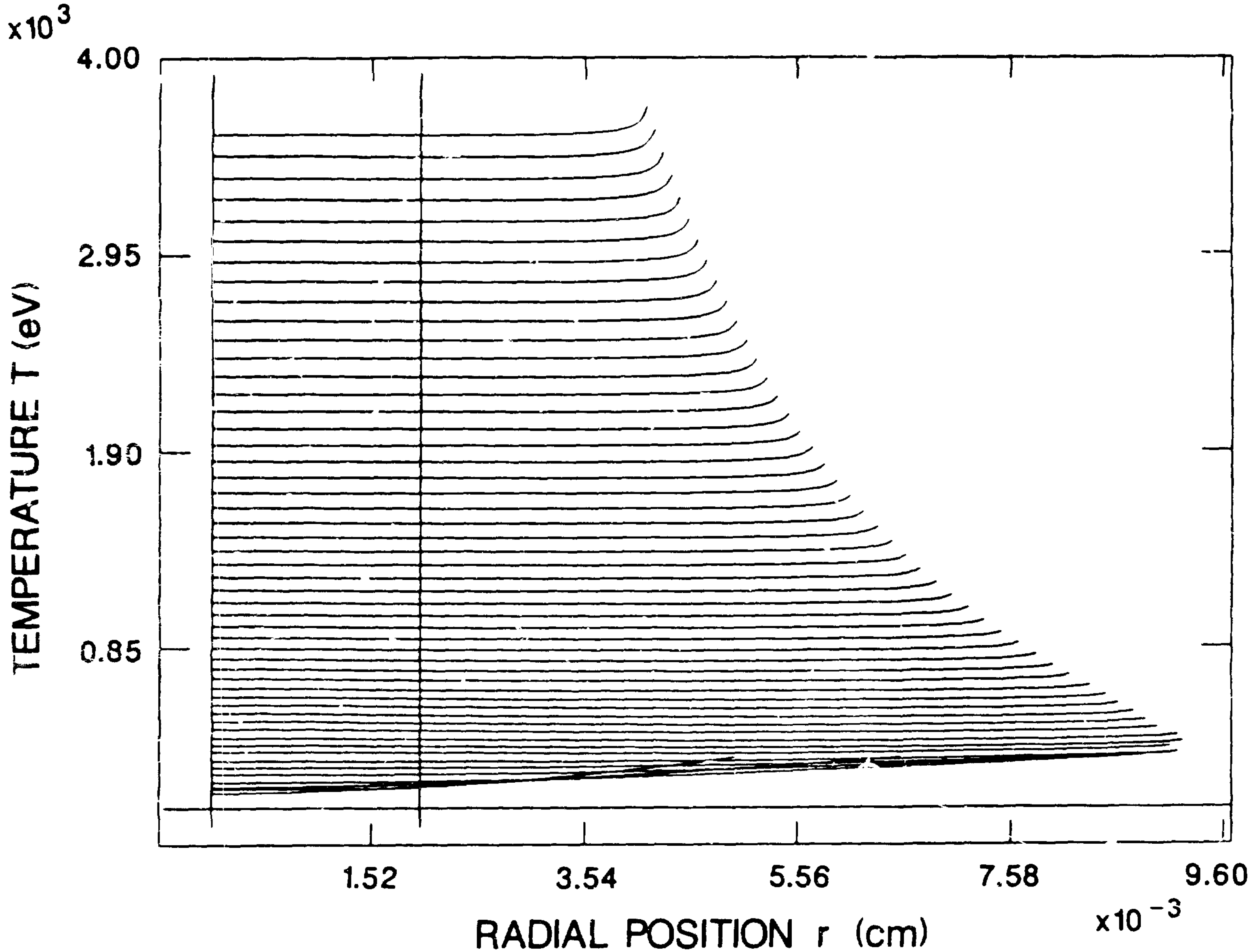
b: α = 1.0
c: α = 6.0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x10^-3
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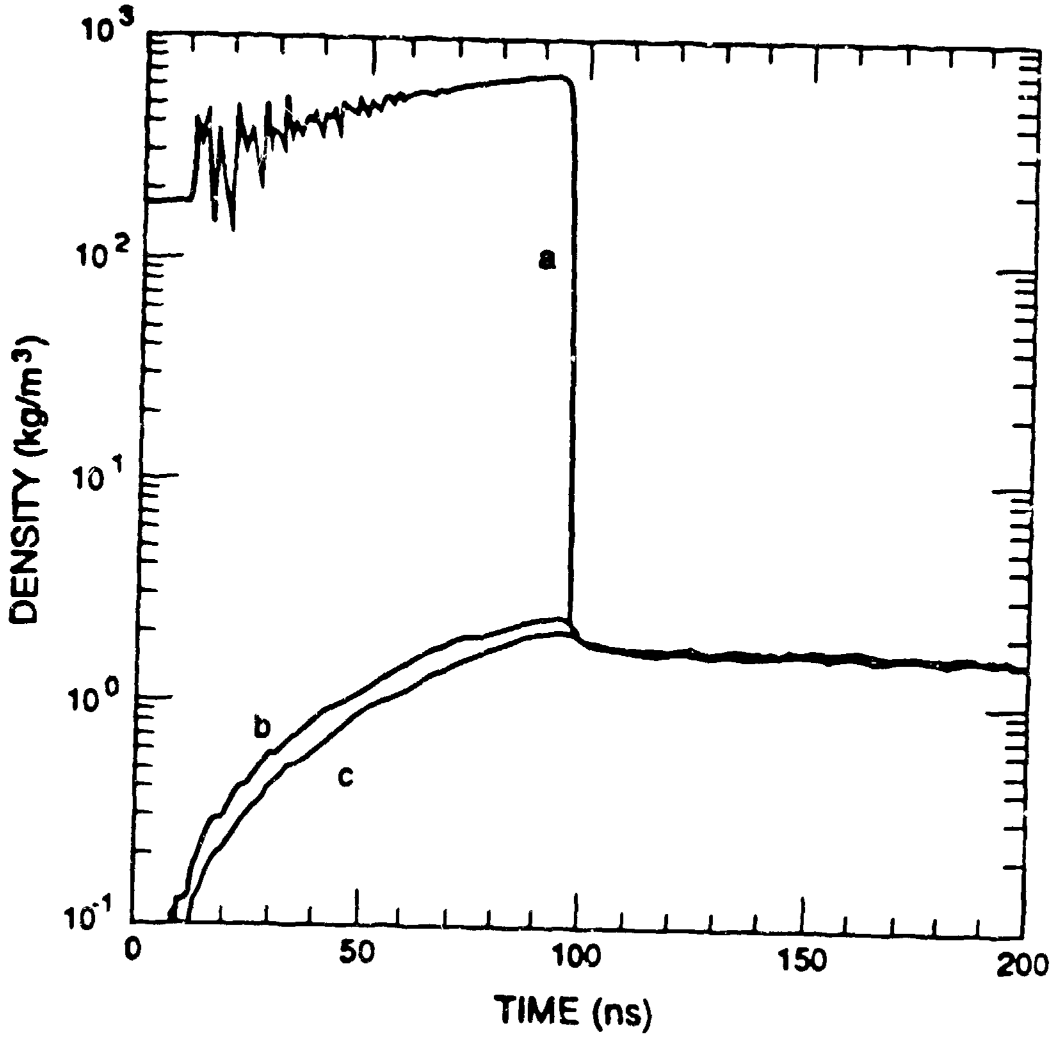
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10¹
10⁰
10⁻¹
a
b
c
0
50
100
150
200
TIME (ns)