Energy- and Particle-Confinement Properties of an End-Plugged, Linear, Theta Pinch

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(Received 16 April 1979)

Experiments show that axial confinement of plasma in a straight theta-pinch solenoid is improved by placing solid lithium deuteride plugs at the ends. The energy confinement is increased nearly threefold in agreement with theoretical estimates which assume classical electron thermal conduction and no convective losses. The confinement of deuterium ions is explained by classical Coulomb collisions in the ablated lithium deuteride plasma.

Plasma energy loss from linear magnetic fusion devices in which the field lines are not closed is dominated by the convective loss of energy associated with particle flow along the open field lines. In the absence of flow, axial thermal conduction becomes dominant. Motivated by early suggestions,[1] experiments directed at reducing the particle flow in a linear theta pinch[2,3] and laser-heated solenoids[4,5] by using material end plugs have recently been performed. The theta-pinch experiments with quartz plugs[2] yielded encouraging results of enhanced column stability and no serious contamination. However, the decay time for the energy line density improved by only ~25%. This improvement was not in quantitative agreement with either a Langrangian fluid-code computation[6] which neglected radiative-energy losses, or with the predictions of a zero-dimensional code,[3,7] in which the particle flow rate was set equal to zero, *ad hoc*.

In this Letter we present results obtained with relatively low-Z lithium deuteride plugs using the same theta pinch on which the earlier quartz (SiO_2) experiments were done. Measurements of particle inventory and total plasma-energy confinement show that the net particle flow to the ends of the device is greatly reduced, resulting in an increase in energy confinement by a factor of about 3. This enhancement is in quantitative agreement with the zero-dimensional code predictions and with fluid numerical computations, in which radiative losses were self-consistently included.[8] The confinement properties observed with low-Z plugs can be understood qualitatively with a physical model in which central ions collide with cold ions from the ablated plug plasma and are reflected with little loss in energy.

The theta pinch used in this experiment was the Scylla IV-P device.[2,3] It is a 5-m-long, 11-cm-diam linear theta pinch with a peak magnetic field of 48 kG. The field rise-time is 3.1 μs, at which time the capacitor bank is crowbarred and the field subsequently decays with an L/R time of 110 μs. The following diagnostics were used for determining the plasma parameters in both the open-ended and end-plugged geometries. The magnetic flux excluded by the plasma, $\Delta\varphi$, was obtained from compensated diamagnetic loops located at seven axial positions. A coupled-cavity interferometer (3.39 μm), located 133 cm from the end of the coil, measured $\int ndl$, where n is the electron density and dl an element along a diameter of the discharge tube. The plasma radius and position were determined from a side-viewing luminosity apparatus and other optical position detectors.[9] Measured neutron emission[10] and the interferometric density measurements were combined to infer the ion temperature, T_i. The electron temperature, T_e, was measured near the coil midplane using 90° Thomson scattering. Nominal values of the plasma parameters at the peak of the magnetic field for the open-ended configuration are $T_e \simeq 550$ eV, $T_i \simeq 2.7$ keV, and $n \simeq 1.5\times 10^{16}$ cm^{-3}. The LiD end plugs were 5 cm in diameter by 3.8 cm thick, the same dimensions as the SiO_2 plugs used in the earlier experiments. The front face of the LiD plugs was located 10 cm inside the coil ends. As in the earlier experiments, a 10-mTorr fill of deuterium was used.

For β small compared to unity (β is the ratio of plasma pressure to the pressure of the confining magnetic field) the flux excluded by the plasma is related to the perpendicular plasma energy per unit length, E_l, as follows[11]:

$$E_l \equiv \int nk(T_e + T_i)dA \simeq B_z \Delta\varphi/\mu_0, \qquad (1)$$

where n is the particle density (electron and ion density assumed equal), dA is an element of plasma cross-sectional area, B_z is the magnetic field outside the plasma, μ_0 is the permeability of free space, and k is Boltzmann's constant. For a Gaussian radial pressure profile the approximation is good to within 10% for a β on axis of 0.7. Figure 1 is a plot of $E_l(t)$ measured at the coil midplane for open-ended and LiD end-plugged

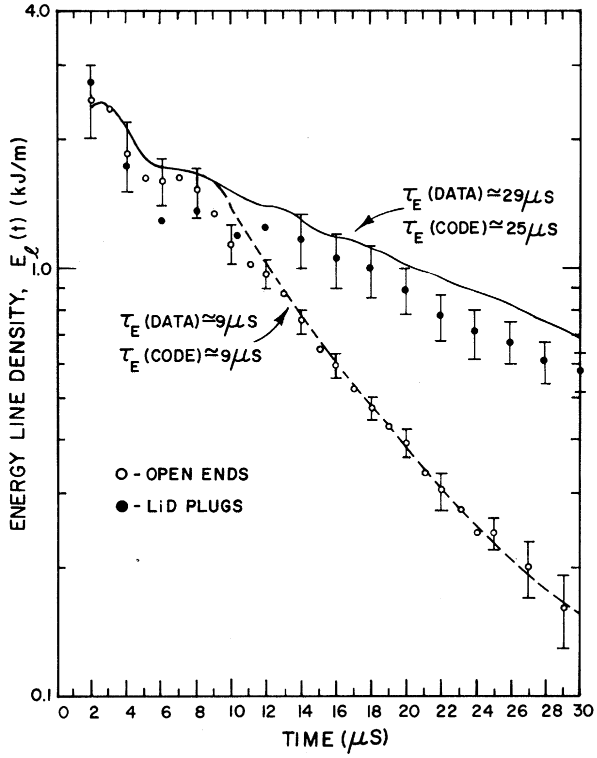

FIG. 1. Perpendicular energy line density, E_l, as a function of time measured at the coil midplane for open-ended and LiD end-plugged geometries. Also shown are predictions of the zero-dimensional code for open ends (dashed line) and for no particle flow (solid line).

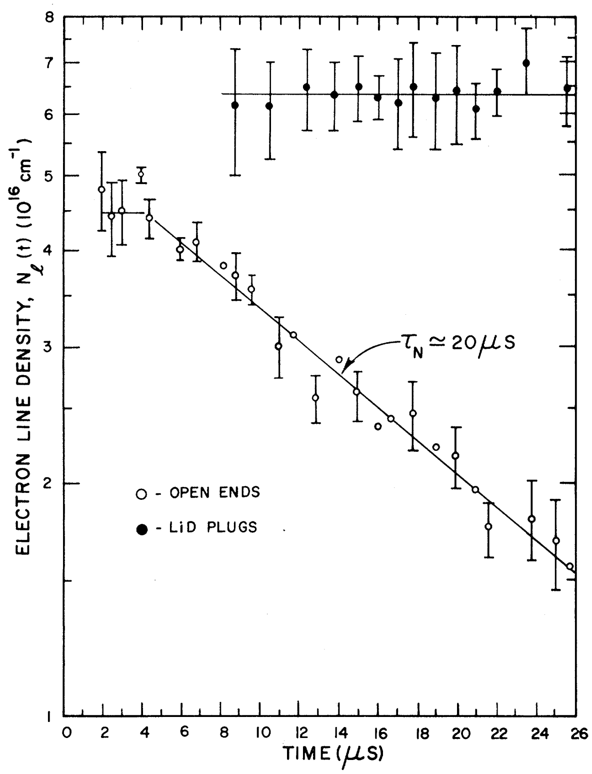

FIG. 2. Electron line density, N_l, as a function of time, measured 133 cm from the coil end for open-ended and LiD end-plugged geometries.

geometries. Also plotted are the predictions of the zero-dimensional code.[3,7] For the end-plugged case, the particle-loss rate in the code was set to zero. Agreement between theory and experiment is quite good, with a measured improvement in the energy confinement time, $\tau_E \equiv 1/E_l)(dE_l/dt)]^{-1}$,[3] of a factor of ~ 3. This result indicates that LiD plugs greatly reduced the net particle flow from the middle to the ends, compared to the high-Z SiO_2 plugs, which only showed a 25% improvement in τ_E.[2] The remaining loss processes are axial thermal conduction and adiabatic decompression due to the decay of the confining field. The observed behavior of $E_l(t)$ is also in quantitative agreement with predictions of a Lagrangian fluid numerical calculation in which plasma flow and radiation from the ablated plug plasma are treated self-consistently.[8]

The time behavior of the particle inventory, inferred from the measurement of $E_l(t)$, was verified by direct measurement of $N_l(t)$, the electron line density (number of electrons per unit length of plasma), both with and without plugs. This was accomplished by combining $\int n dl$, measured with the side-viewing interferometer, with the plasma radius obtained from the luminosity apparatus, using the assumption of a Gaussian radial density profile (substantiated by luminosity measurements). Figure 2 is a plot of the results for open-ended and LiD end-plugged configurations. The open-ended data were fitted with a model of a constant value, $\langle N_l \rangle$, for a time τ_c, followed by an exponential decay with a characteristic time constant, τ_N. The line drawn through the end-plugged data is an average of all the data for $t \geq 8$ μs. Data were not obtained for $t < 8$ μs because the plasma column drifted out of the field of view of the interferometer. It is clear that in the LiD plugged case $dN_l(t)/dt \simeq 0$. Similar data for SiO_2 plugs show only a slight improvement in τ_N, roughly consistent with the observed marginal improvement in τ_E. The increase (over the 10 mTorr equivalent) in electron inventory for the LiD plugged configuration can be explained by a combination of a small ($\lesssim$ 10%) increase in the ion inventory from plug ablation during preionization and axial compression.[6] Side-on streak-camera photography, axially resolved observation of plasma continuum and line emission, and fluid numerical calculations[8] all indicate that, during the time of observation, plug plasma ablated during the main discharge moves < 1 m into the column. The ablated plasma provides some axial compression, but does not otherwise influence the measurements near the coil midplane.

A physical mechanism by which ions from the central plasma column are reflected, or turned around, in the ablated plug-plasma region without losing much of their energy can be outlined as follows.[12] These hot ions will undergo a 90° deflection most efficiently by virtue of collisions with cold, plug-plasma ions on a time scale $\tau_D^{ii'}$. In addition they will lose energy, at least initially, to colder, but faster, plug-plasma electrons on a time scale $\tau_E^{ie'}$. The ratio of these time scales can be expressed (in the limits cited above) as[13]

$$R = \frac{\tau_D^{ii'}}{\tau_E^{ie'}} = \frac{1.3\times10^{-2}}{Z_{\rm eff}'}\left(\frac{E}{kT_e'}\right)^{3/2}, \qquad (2)$$

where E is the energy of the exiting ions, $Z_{\rm eff}$ is the effective nuclear charge, and the primes denote ablated plug-plasma conditions. In order that the ions be turned back into the central plasma column without losing a significant portion of their energy, $R<1$. Thus for a given E, Eq. (2) suggests that $Z_{\rm eff}'$ and T_e' both must be large. However, for a nominal value of electron temperature during the early stages of the compression phase of 100 eV, simple time-dependent corona calculations indicate that lithium becomes fully ionized in $\lesssim 1$ μs; whereas, at the same electron temperature, higher-Z silicon or oxygen from SiO_2 plugs would not become fully ionized on a relevant time scale, and would consequently provide a significant energy-loss mechanism through line radiation. Thus with LiD plugs, line radiation is eliminated relatively early, allowing the plug-plasma electrons to be heated to the point where $R<1$. How elastic the reflection will be depends on the actual value for R. From Eq. (2), for $E=2.7$ keV and $Z_{\rm eff}'=3$, the minimum electron temperature needed for reflection is $\simeq$70 eV. The mean free path for reflection of a 2.7-keV ion, at a density of 10^{17} cm^{-3} (estimated from side-viewing holographic interferometry in the plug region) is about 6 cm, which is less than the axial extent of the ablated plasma.

For the present experiment, ions with energies $\gtrsim 10$ keV are not expected to be confined, since their interaction mean free paths are long compared to the ablated plasma region. These high-energy ions reside in the tail of the ion energy distribution and are responsible for the neutron-emission rate. Plotted in Fig. 3 are the measured neutron-emission rates for open-ended and LiD-plugged geometries. The two cases are indistinguishable, supporting the premise that the relatively small number of high-energy ions which produce neutrons are not confined for the LiD-plugged geometry. Also shown in Fig. 3 are calculations of the neutron-emission rates from the zero-dimensional code for open ends and for no particle loss, assuming, in both cases, that the ion energy distribution is an isotropic Maxwellian at all times. This simple model is inadequate to describe all features of the neutron emission, but it does indicate that an observable change in neutron-emission rate would occur if all ions were confined, independent of their energy. Ion temperatures, inferred from these measured rates and side-viewing interferometry, show only small differences between open and LiD-plugged ends.

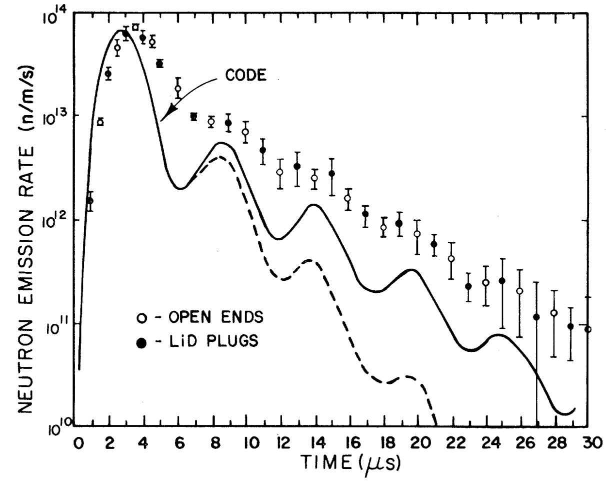

FIG. 3. Neutron emission rate, as a function of time, measured near the coil midplane. Data are plotted for open ends and LiD plugs. Also shown are predictions of the zero-dimensional code for open ends (dashed line) and for no particle flow (solid line).

A full time history of the electron temperature measured for open ends[3] was not obtained for the LiD-plugged case because of gradual discharge tube contamination caused by the plug. Measurements at the time of peak field show the same temperature, within experimental precision, in either case.

In conclusion, low-Z LiD end plugs have confined the ions associated with the bulk of the distribution, consequently improving the energy confinement of this thermonuclear plasma by a factor of ~3, compared to a ~25% improvement previously reported for high-Z SiO_2 end plug. The remaining loss processes are axial electron thermal conduction and adiabatic decompression due to the decay of the confining field. The observed improvement over the open-ended case is in quantitative agreement with theory. A model proposed for reflecting exiting ions is qualitatively consistent with the improved confinement observed with the low-Z plug material.

We wish to express our gratitude to Dr. K. B. Freese and Dr. R. Kristal for assistance with diagnostics, T. J. Zaugg for machine operation, and J. P. Montoya, J. S. Quintana, R. J. Sanchez, J. D. Smith, and V. P. Vigil for technical assistance. This work was performed under the auspices of the U. S. Department of Energy.

[1]J. M. Dawson, A. Hertzberg, R. E. Kidder, G. C. Vlases, H. G. Ahlstrom, and L. C. Steinhauer, in *Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971* (International Atomic Agency, Vienna, Austria, 1971), Vol. I, p. 673.

[2]R. J. Commisso, C. A. Ekdahl, K. B. Freese, K. F. McKenna, and W. E. Quinn, Phys. Rev. Lett. 39, 137 (1977).

[3]K. F. McKenna *et al.*, in *Proceedings of the Seventh International Conference on Plasma Physics and Controlled Fusion Research, Innsbruck, Austria, 1978* (International Atomic Energy Agency, Vienna, Austria, 1979), paper No. CN-37-U-5.

[4]T. K. Chu and L. C. Johnson, Bull. Am. Phys. Soc. 22, 1079 (1977).

[5]H. W. Hoida, T. N. Carlstrom, and G. C. Vlases, Bull. Am. Phys. Soc. 23, 776 (1978).

[6]R. C. Malone and R. L. Morse, Phys. Rev. Lett. 39, 134 (1977)

[7]E. K. Stover, E. H. Klevans, and T. M. York, Phys. Fluids 21, 2090 (1978).

[8]G. Sowers, P. McKenty, and R. Morse, Bull. Am. Phys. Soc. 23, 801 (1978).

[9]R. Gribble and G. Miller, Rev. Sci. Instrum. 48, 778 (1977).

[10]C. A. Ekdahl, to be published.

[11]F. Waelbroeck, C. Leloup, J. P. Poffe, P. Evrard, R. Der Agobian, and D. Vernon, Nucl. Fusion Suppl. Part 2, 675 (1962).

[12]R. C. Malone, to be published.

[13]L. Spitzer, Jr., *Physics of Fully Ionized Plasmas* (Interscience, New York, 1967), 2nd rev. ed., Chap. 5.

New Mechanism for Electromagnetic Emission near the Geometric Mean Plasma Frequency

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We report the experimental observation and theoretical description of a previously unrecognized mechanism for electromagnetic emission from plasmas near the geometric mean plasma frequency. Very clear emissions were observed from the electric-field–dominated NASA Lewis bumpy torus plasma at a frequency which is inconsistent with familiar mechanisms of plasma emission. A theory based on a Penning-discharge-like beam-plasma interaction predicts a frequency in excellent agreement with the observations.

The microwave radiation experiments described in this paper were conducted on the NASA Lewis bumpy torus plasma, a machine that operates in the steady state under the influence of a dc toroidal magnetic field and strong externally imposed dc electric fields along the minor radius of the plasma.[1,2] Gross confinement is provided by the bumpy torus magnetic field generated by twelve superconducting coils arranged in a toroidal array 1.5 m in major diameter. Radial electric fields heat the ions preferentially by $\vec{E}\times\vec{B}/B^2$ drift, and are a major factor in determining the plasma stability and confinement properties.[2,3] In these experiments the plasma was biased to high positive potentials with respect to the grounded coils by midplane electrode rings. Under these conditions, the plasma resembles twelve modified Penning discharges[4] in a toroidal array.

Previous studies of the rf emission spectrum from this plasma revealed broad peaks in the vi-

