Material End Plugging of Straight θ Pinches[(a)]

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The interaction of a θ-pinch plasma with cold-material end plugs is investigated with a numerical hydrodynamic and heat flow model. A very appreciable improvement in energy confinement is obtained for the 5-m system considered compared to the same system without plugs. The improvement is due to the elimination of convective energy loss, a reduction of thermal conductive loss when $Z > 1$ end plugs are used, and some recompression of the plasma by ablated plug material.

Although the linear θ pinch has a fundamental advantage over a toroidal θ pinch in terms of plasma stability, there has been little interest in it in recent years as a potential fusion reactor. The principal reason is well known: In an open-ended θ pinch the particle and energy confinement is determined by free streaming out the open ends. The confinement time τ then scales as L/v, where L is the half-length of the pinch and v is the ion thermal velocity.[1] To obtain the necessary confinement time, lengths of the order of 1–10 km are required.[2] A number of schemes for reducing end loss have been considered, in particular, material end plugs.[3,4] This paper reports detailed numerical calculations of the behavior of a hot plasma confined by material end plugs.[5] Attention is concentrated on short systems (length $L \sim 5$ m), in order to make comparisons with end-plug experiments now underway at Los Alamos.[6,7] Preliminary results from these experiments are not yet sufficiently detailed to permit quantitative comparison with theory, but to date are in qualitative agreement with the conclusions of this Letter. The theoretical results indicate significant improvement in energy confinement relative to open-ended systems. Similar calculations for reactor-length plasmas, which will be published elsewhere, also indicate significantly increased energy containment.

The numerical model is a quasi-one-dimensional Lagrangian hydrodynamics and thermal-conduction code, CHAMISA. It treats plasma and heat flow along the axis, and approximates the radial dynamics by a one-zone sharp-boundary hydrodynamic model rather than simple radial-pressure balance. Radial inertia does, for instance, significantly modify flow in magnetic mirrors and near end plugs. All plasma parameters in a given zone are presumed constant in radius out to the boundary. There is no radial heat flow in the model. The radial sharp-boundary model will be discussed in detail elsewhere. Electron and ion thermal conduction and thermal cross relaxation are included.[8] A fully ionized perfect-gas equation of state is used for all materials. Ionization energy is a small correction since we restrict our attention to relatively low-Z (Z is the atomic number) end-plug materials, for which the average ionization energy per free electron is much smaller than the mean electron energies at the temperatures considered. Solid materials are initially at normal solid density and at essentially zero temperature. The use of hydrodynamics and classical transport coefficients is justified by confirming that particle mean free paths are generally shorter than axial gradient lengths. This assumption comes closest to not being satisfied for the ions in the hot, low-density deuterium plasma, but would be well justified for the treatment of reactor-length θ pinches. Radiation losses are considered separately; it is shown that radiation losses in the ablated end-plug material will restrict the choice of plug materials.

The model has been tested by comparing calculations of the end loss from the linear Scyllac ($n_i = 2\times10^{16}$ cm^{-3}, $T_i = 2.7$ keV, $T_e = 600$ eV, external $B_z = 60$ kG, $\beta = 0.74$) to experimental measurements.[9] β is the ratio of the plasma pressure to the pressure of the external magnetic field. These comparisons, both with and without mirrors, were quite good (agreement of loss rates within 20%) and will be published elsewhere.

Figure 1 shows a typical set of density and temperature profiles near a material end plug at one

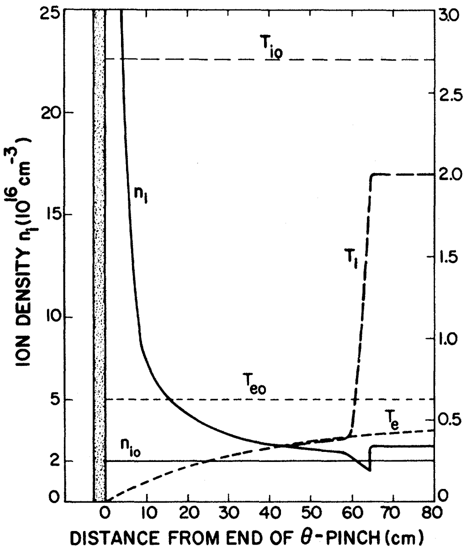

FIG. 1. Density (n_i) and temperature (T_e,T_i) profiles near a carbon end plug after 10 μs. Carbon ions extend from $z=0$ to $z=65$ cm. The plasma parameters are essentially constant within the deuterium plasma, which lies between $z=65$ and $z=250$ cm (θ-pinch midplane). The cold, unablated plug is represented by the shaded vertical bar at $z=0$. T_{e0}, T_{i0}, and n_{i0} are the initial deuterium plasma parameters.

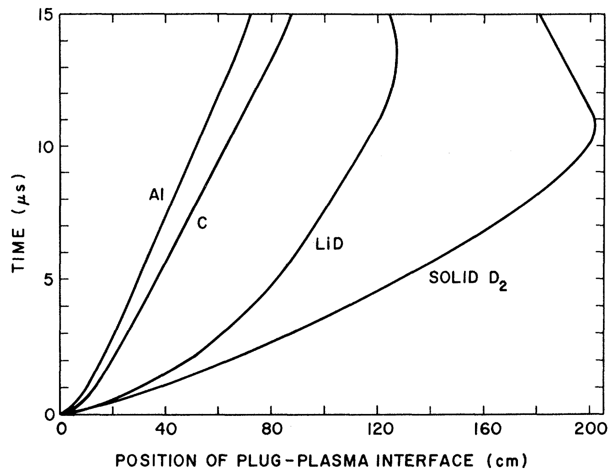

FIG. 2. Trajectories of the interface between the deuterium plasma and the ablated plug material for frozen deuterium, LiD, C, and Al end plugs.

end of a linear θ pinch. T_{e0}, T_{i0}, and n_{i0} are initial values of the electron and ion temperatures and the ion density in the deuterium plasma. The initial position of the solid-density carbon ($Z=6$) plug is indicated by the shaded vertical bar. At the time shown (10 μs), carbon ablated from the plug by heat flow from the deuterium plasma has moved 65 cm toward the center of the pinch. The discontinuity in n_i at the interface is a consequence of continuity of temperature and pressure, and the different n_e/n_i ratios in fully ionized carbon and deuterium. In short θ pinches, such as this one, competition between electron-ion cross relaxation and electron thermal conduction to the ends keeps T_e well below T_i in the deuterium plasma,[1] while in the plug the larger cross-relaxation rate due to higher Z ($\tau_{ei} \propto Z^{-2}$) and lower temperatures cause T_e and T_i to become essentially equal. Plugs with $Z>1$ virtually eliminate ion thermal conduction into the plug because $K_i \propto Z^{-4}$ (K_i is the ion conductivity) and therefore give very flat T_i profiles in the deuterium as seen here (see also Fig. 4).

Recompression of the deuterium plasma by the expanding plug material plays a significant role in the plasma energy balance. The heat transferred to the plug causes rapid ablation, which drives a compression wave back into the plasma. In the case of the solid D_2 end plug, the velocity of the ablated material initially exceeds the sound speed in the cooled plasma, changing the pressure wave into a mild shock. Figure 2 shows the plug-material–deuterium interface as a function of time for different materials. Both compression and shock heating reintroduce a significant part of the deuterium-plasma internal energy which is first lost into the plugs by thermal conduction. It is important to appreciate that these compressions and shocks can only form if axial compression can increase the density and, therefore, pressure of the plasma. This requires that the confining magnetic field be "stiff" to radial expansion of the plasma column: This occurs either if β is significantly less than unity or if the effective coil radius is close enough to the plasma radius that expansion of the plasma significantly increases the external magnetic pressure.

Figure 3 shows the thermal energy as a function of time, normalized to unity at $t=0$, for solid LiD, C, and Al plugs, for no plug or mirror, and for a 150-kG mirror but no plug. Also shown is a (puffed) neon-gas plug initially at room temperature and at a fill density of 2.5×10^{20} atoms/cm^3. The energies in the plugged cases drop faster at first because conduction into the plug is initially a more effective loss mechanism than expansion out an unplugged end. However, the overall ad-

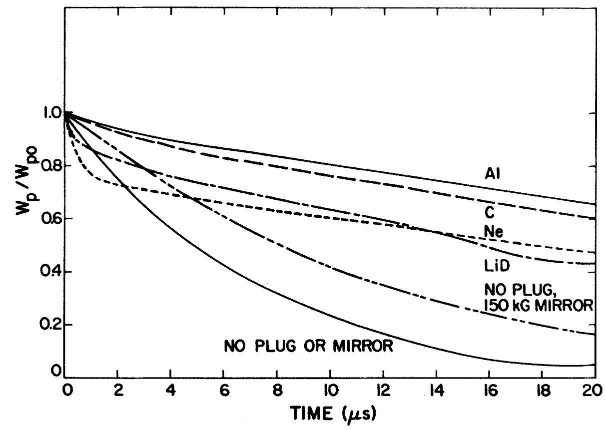

FIG. 3. The normalized deuterium-plasma energy versus time for open, mirrored, and plugged ends. Only the plasma remaining within the coils is counted in the open and mirrored cases.

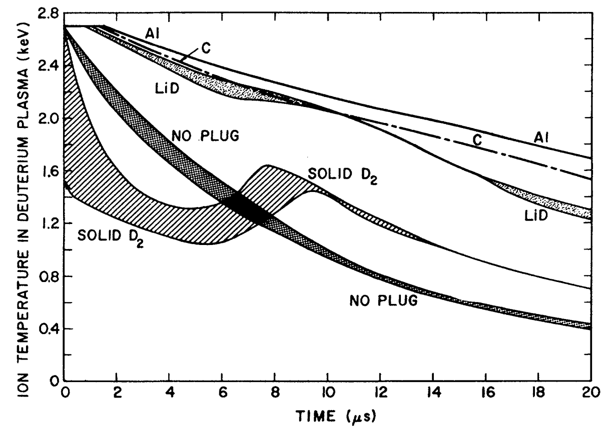

FIG. 4. The deuterium-plasma ion temperature versus time for open and plugged ends. The shaded areas illustrate the range of temperatures within the pinch; for C and Al, the temperature is flat to a few percent and so no range is shown. With no plug, only the plasma still within the coils is considered. With the solid D_2 end plug, only the temperatures in the original plasma are shown.

vantage of the plugs in reducing energy, as well as fuel-mass, loss is clear. In addition to eliminating mass loss, thermal-conduction losses from the deuterium plasma are reduced, because of the lower thermal conductivity in the ablated end-plug material. Furthermore, in the present calculations with solid end plugs, 15 to 20% of the energy lost by thermal conduction to the end plug was returned to the plasma through recompression by the ablated plug material. The initially lower-density gaseous neon plug was less effective in this respect: Less than 10% of the energy was returned through recompression.

The case of a solid D_2 end plug is omitted from Fig. 3 because the fractional energy remaining in "deuterium plasma" is unity, if the ablated plug material is included. The energy criterion thus rates a D_2 plug as optimal; this is misleading because, while the energy remains as internal energy of deuterium, it is degraded by being distributed over a larger quantity of material. Figure 4 indicates this degradation.

The time histories of the maximum and minimum values of the ion temperature in the deuterium plasma are shown in Fig. 4. In the case with no plugs, only the plasma still within the coils is considered; in the case with solid D_2 end plugs, only the original deuterium plasma is considered. Minimum T_i almost always occur at the fuel/plug interface (see Fig. 1). While the maximum tends to occur at the pinch midplane, heating by compression waves driven along the axis by plug expansion can cause it to occur at intermediate positions, most notably in the case with D_2 end plugs. The flatness of the temperature profiles noted in the discussion of Fig. 1 makes the maximum and minimum values of T_i almost indistinguishable for $Z \geq 6$; therefore, only one curve is shown. The strong plasma recompression discussed with reference to Fig. 2 causes the temperature rise seen at 8 μs with a solid D_2 plug. The same phenomenon is seen to a lesser extent with LiD.

The increases in n_i and the effects of the increases in T_i which are predicted above to result from the introduction of solid-material end plugs should be clearly observable in experiments with end plugs of an appropriate material.

Figure 3 gives the impression that energy confinement continues to improve with increasing Z. This is not so because when radiation losses, which are omitted from these calculations, are included, the losses from higher-Z plugs are significant. At lower Z, typically $Z \lesssim 6$ for conditions treated here, estimates show that the bremsstrahlung, recombination, and line radiation rates are not dominant and that the ablated region of $Z > 1$ plug material serves primarily as a thermal insulator, as well as to reintroduce energy by recompression. However, at higher Z the radiation losses from the plug material can exceed heat flow into the cold material and cause the ablated material to be more important as a sink than as an insulator. There is, therefore, an optimum Z for maximizing heat retention. This optimum Z

varies with conditions and increases with increasing fuel temperature.

Work is in progress to repeat the present calculations with a complete material description, including ionization and radiation losses by all of the above-mentioned processes.

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Solid-End-Plug Experiment on a θ Pinch[(a)]

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Results from the first end-stoppering experiment on a high-energy ($T_i \sim 1.5$ keV, $n \sim 10^{16}$ cm^{-3}) θ pinch are reported. The experiment was done with quartz end plugs. The results show that the insertion of the plugs improves plasma stability, reduces particle end loss out of the device, and improves the energy confinement.

Linear θ pinches are devices in which plasmas of thermonuclear fusion interest ($n \simeq 10^{16}-10^{17}$ cm^{-3}, $T_i \simeq 1-4$ keV) can readily be produced.[1-4] However, the loss of both energy and particles from the ends presents a fundamental limitation in reactor applications for θ pinches, as well as for all open-ended devices. Solid end plugs have been suggested[5] as a means of inhibiting the particle loss from such devices. In addition, recent numerical calculations[6] indicate that solid end plugs may also increase the plasma energy confinement time primarily because of the reduced thermal conductivity of the resulting high-Z (ionic charge) plasma produced in the plug region. In this Letter, we present results of a solid-end-plug experiment performed on the Scylla IV-P θ pinch at the Los Alamos Scientific Laboratory.

Scylla IV-P is a 5-m-long, 11-cm-diam-bore linear θ pinch with a maximum capacitive energy storage of 2 MJ, of which 1.1 MJ were used in the present experiment. The magnetic field attains a peak value of 50 kG in ~ 3.4 μs, at which time the field is crowbarred and decays with an L/R time of ~ 110 μs. Under these conditions, the 10-mTorr D_2 initial fill yields a plasma (unplugged) with the following peak values of the characteristic parameters: $T_i \simeq 1.5-2.0$ keV, determined from scintillator and silver-foil neutron-activation diagnostics; $T_e \simeq 400-600$ eV, calculated from Morse's[7] expression for the balance between thermal conduction to the ends and electron-ion energy transfer; and $n \simeq 1.6\times 10^{16}$ cm^{-3}, with an e-folding radius of ~ 1 cm, obtained from end-on holographic interferometry.

Quartz end plugs were used in this experiment. The plugs were cylindrically shaped, 5 cm in diameter by 3.8 cm thick. Each plug was mounted on a quartz rod, and the entire assembly could be retracted out of or advanced into the quartz discharge tube. For the results presented here, the front face of the plugs was inserted $\simeq 5$ cm inside the coil ends.