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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[(a)]Work performed under the auspices of the U. S. Energy Research and Development Administration.

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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.

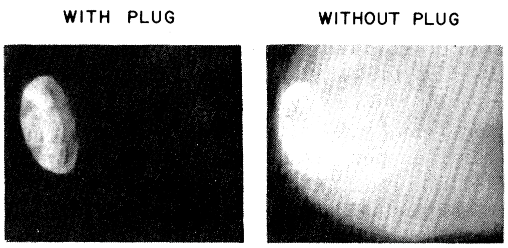

FIG. 1. Time-integrated (open shutter) Polaroid photographs of end vessel, taken with and without plugs. The camera views the coil ends. Aperture setting is the same for each exposure.

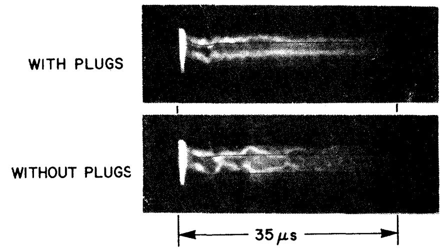

FIG. 2. Stereoscopic streak photographs with and without plugs. The upper image in each photograph corresponds to a top view of the plasma and the lower image corresponds to a side view of the plasma.

The phenomenology of the plasma flow in the regions exterior to the θ-pinch coil ends was studied photographically and with total-magnetic-flux loops. Figure 1 shows two time-integrated photographs of a 20-cm-diam, 50-cm-long end vessel located at the end of the 8.8-cm-i.d. discharge tube, taken with and without plugs inserted. No plasma light is observed in the end vessel with the plugs inserted, indicating that the flow of plasma out of the ends of the discharge tube is eliminated. Time-resolved photographs of the end vessel confirm this result. Additional evidence of the absence of plasma in the end vessel was provided by total-magnetic-flux loops that encircle the end vessel and are arrayed along its length. The data obtained from these loops on primary bank discharges with no initial D_2 fill were identical to the data obtained from plasma discharges with plugs inserted. Conversely, plasma discharges taken with the plugs retracted yielded data that showed clear evidence of plasma flow.[8]

Stereo streak-camera photographs (viewing from the top and side simultaneously) taken at the coil midplane with and without the plugs inserted are shown in Fig. 2. In the streak photograph obtained without plugs, the plasma-column wobble instability[1,9] sets in about 5 μs after initiation of the primary magnetic field. This time corresponds to roughly 1 Alfvén-wave transit time from the coil end. The instability saturates at an amplitude of approximately 2 plasma diameters and then begins to damp. The streak photograph obtained with the plugs inserted shows the instability saturating at about 1 plasma diameter and damping out more rapidly, suggesting a stabilizing effect on the plasma wobble by line tying[1] at the plugs. The plasma light intensity in the streak photograph obtained with the plugs inserted persists 20–30% longer than that in the photograph obtained without plugs.

By combining the results of measurements of plasma diamagnetism and estimates of the plasma e-folding radius, a, obtained by fitting plasma luminosity with a Gaussian radial density profile, the plasma β on axis, β_A, can be determined[10] [$\beta_A \equiv 2\mu_0 n_A k_B (T+T_e)_A / B_z^2$, where μ_0 is the permeability of free space, k_B is Boltzmann's constant, n_A is the density on axis, $(T_i+T_e)_A$ is the total temperature on axis, and B_z is the magnetic field outside of the plasma]. The plasma energy per unit plasma length on axis, E_l, is then

$$E_l = (\beta_A B_z^2 / 2\mu_0)\pi a^2. \qquad (1)$$

Figure 3 presents the results of the above analysis for discharge with and without plugs at the

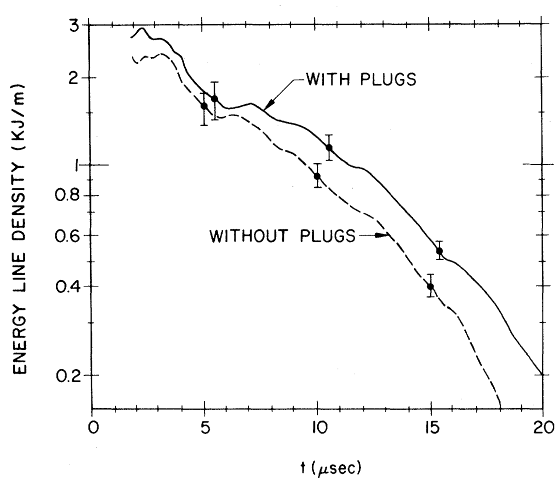

FIG. 3. Plasma energy per unit length as a function of time at the coil midplane. $t=0$ is the initiation of the primary magnetic field. Data are averaged over fifteen discharges.

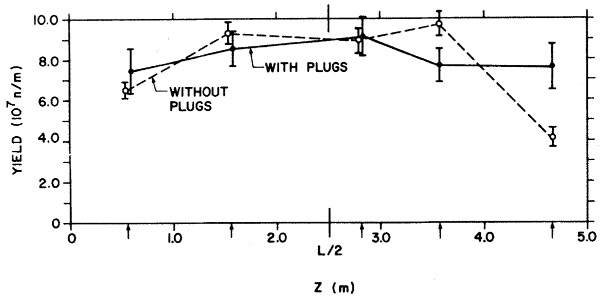

FIG. 4. Total neutron yield along the axis of the coil determined from silver-foil activation counters. Arrows indicate positions of detectors (L is the coil length). Data are averaged over 23 discharges.

coil midplane. As can be seen from the figure, the energy line density maintains a high value for a longer time when the plugs are inserted. The decay rate (average slope of the curve) is 20–30% less when the plugs are in.

Figure 4 presents a comparison of total neutron yield as a function of axial position with and without plugs inserted. In general, the presence of the plugs has little effect on the yield; however, there is some observed increase in yield at the ends of the coil. Neutrons produced in the beam-target interaction of plasma deuterons impinging on deuterium molecules adsorbed on the plug may be a possible explanation for the increase in yield near the ends. However, a crude estimate of beam-target neutron yield gives $\lesssim 10^7$ neutrons per shot, which is insufficient to account for the observed yield increase.

The plugs showed very little visible damage after 29 plasma discharges, the surface being slightly glazed with small pit marks barely visible to the naked eye. Under the assumption that all the plasma energy is deposited on the surface of the plugs during the plasma lifetime, significant ablation (~0.5 mm per discharge) of the plug material is expected,[11] although not observed. Energy-loss mechanisms, such as ionization and heating of ablated plug material, radiation, cross-field diffusion, or charge exchange, could reduce the energy deposition at the plug surface.

Although these results are qualitative, some preliminary observations can be made. In the presence of the plugs (1) the flow of plasma out of the device ends is stopped; (2) plasma stability is improved; (3) the total time-integrated neutron yield is improved; and (4) the decay rate of the plasma energy line density at the coil midplane is decreased some 20–30%. In conclusion, the insertion of the plugs has apparently not degraded the plasma, and has improved the energy confinement in this device.

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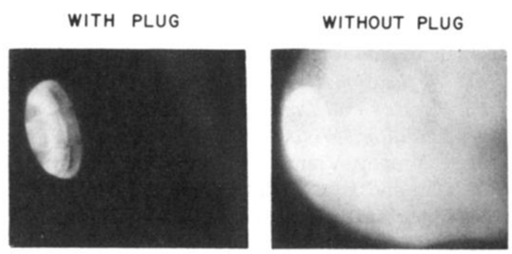

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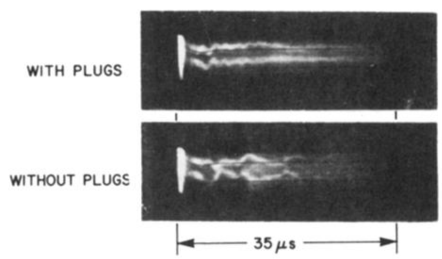

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