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Plasma Heating in a High-Voltage Toroidal θ Pinch*

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Rapid heating of ions and electrons to keV temperatures in $\lesssim 1$ μsec has been observed at densities of 1×10^{14} cm^{-3}. This is to be compared with experiments in which energy losses along the magnetic field limit the electron temperature. The most striking difference is in the ratio of electron to ion temperature which is now $\lesssim 0.3$ as in comparable open-ended θ pinches.

One of the major problems in controlled-fusion research is the achievement of sufficiently high ion temperatures. Among the various plasma heating devices, θ pinches have relatively high efficiencies, especially those driven by fast, high-voltage pulses. However, in such experiments[1-5] electron energy transport along the lines of the solenoidal magnetic field is very fast[6,7] so that average electron temperatures have been relatively low. The question therefore arises whether the various ion heating mechanisms based on microinstabilities[8-10] remain sufficiently strong when the energy is confined, as required for fusion research.

In order to address this question, a high-power[11] ($\lesssim 10^{12}$ W), pulsed (≈ 1-μsec rise time), high-voltage ($\lesssim 600$ kV) toroidal θ pinch (20-cm minor radius, 50-cm major radius), "Thor," has been constructed (see Fig. 1). The initial experiments described here were performed with ~2 mTorr D_2 in an acrylic vacuum vessel. Breakdown and preheating are achieved by discharging capacitors (in parallel) through the toroidal field coils. Further preheating and toroidal current generation are accomplished by capacitor discharges through the primary of an (air core) transformer situated in the center of the machine. These ringing circuits have a period of 17 μsec. Another slower circuit with a 640-μsec period, fired first, generates a quasistatic toroidal bias field of 100 G, which is less than the preheating field.

Most of the measurements presented here were taken using $\frac{1}{4}$ of the peak design power, i.e., with a 280-kV charging voltage and a toroidal compression field rising to ~6 kG in 0.9 μsec. Figure 2(a) shows the corresponding current trace. The current is crowbarred (i.e., the capacitors are shunted) at ~1.2 μsec from its initiation and then falls with an L/R time constant of ~30 μsec.

Neutron emission is observed, by using lead-shielded fast-scintillator–photomultiplier combinations, before and near the current peak [see Fig. 2(b)]. The total neutron yield, measured

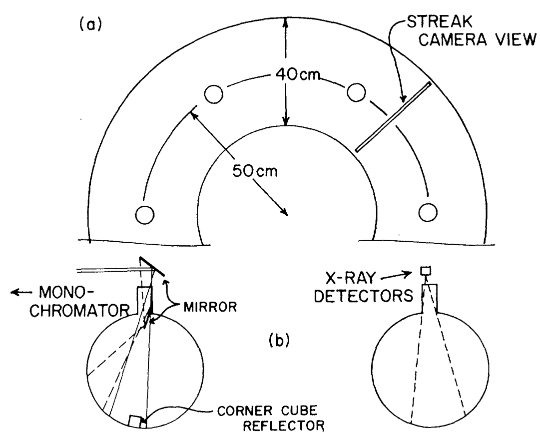

FIG. 1. (a) Top view and (b) cross-sectional side view of toroidal vacuum vessel. Various diagnostics are indicated.

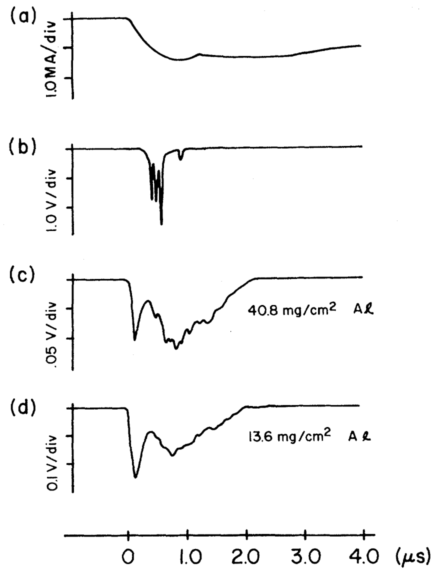

FIG. 2. Oscilloscope traces of (a) toroidal-field-coil current, (b) neutron-detector signal, and x-ray signals transmitted through (c) thick and (d) thin aluminum foils.

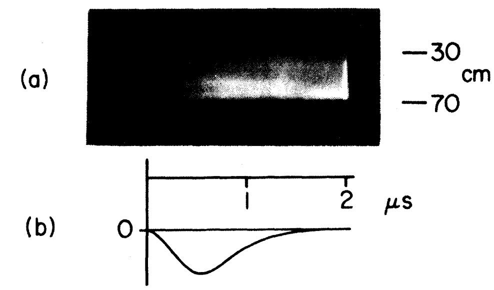

FIG. 3. Streak photograph of (a) plasma column, with inner and outer vacuum-vessel boundaries as marked, and (b) D_α line intensity.

with a silver-foil activation counter, is $\sim 2\times 10^6$. It corresponds near 0.5 μsec from initiation of the main discharge to $kT_i \approx 3.5$ keV in a fully Maxwellian plasma occupying 25% of the volume originally filled with deuterium at a density of $\sim 1 \times 10^{14}$ cm^{-3} (see below). This temperature is much larger than kinetic energies of ions that are elastically reflected by the imploding magnetic piston (~0.4 keV). The ion heating is therefore probably due to microinstabilities in the piston region, as observed in the University of Maryland small θ pinch.[5] More likely than not, this mechanism first leads to a two-dimensional Maxwellian at a temperature somewhat higher than 3.5 keV. The drop in neutron emission after 0.6 μsec may then be associated with a rapid transition to a three-dimensional Maxwellian, e.g., due to an ion cyclotron instability,[9] rather than with an ion-energy-loss process. Another possible reason for the drop in neutron emission is the sharing of ion energy with a larger number of ions as ionization becomes complete.

In order to estimate the electron temperature, two thin-foil-scintillator–photomultiplier detectors were placed on one of the six pump ports, so that their field of view ranged from about the center of the torus cross section to halfway to the outer wall [see Fig. 1(b)]. Figures 2(c) and 2(d) show signals from x rays transmitted through 40.8 and 13.6 mg/cm^2 of aluminum. Temperatures were determined from signal ratios[12] through these foils, and on other shots through 27.2 and 6.8 mg/cm^2 of aluminum and 46.0 and 11.5 mg/cm^2 of nickel. On the basis of these measurements we estimate the electron temperature at 0.5 μsec from the initiation of the main discharge to be 7.0 keV or higher for 75% of the shots taken. (The lowest temperature measured at 0.5 μsec is 3 keV.) The temperatures derived for the first intensity maximum (0.1 μsec) are not particularly high (1–4 keV), indicating that these x rays are less energetic than those emitted in the second intensity maximum. (The signal minimum near 0.3 μsec is possibly due to further rapid ionization of the fill gas producing a sudden influx of cold electrons into the discharge.)

From 0.5 to 1.5 μsec, the x-ray emission measurements indicate a further increase in the energy content of the electron distribution function. This suggests sustained heating, presumably due to microinstabilities. The decrease in x-ray signals after 0.8 μsec is readily explained by the outward motion of the plasma column and the observation geometry [see Fig. 1(b)].

The absolute intensities of x rays are consistent with calculations also allowing for bremsstrahlung on ~5% of (carbon) impurities. In contrast to observations[13] on the University of Maryland high-voltage θ pinch,[1] the measured intensities may actually be below expected values, although not by more than a factor of ~3 of the estimated uncertainty in this measurement. Future Thomson-scattering measurements of the electron distribution function may settle this question and provide spatial resolution.

Figure 3(a) is a streak photograph taken from above through a radial slot [see Fig. 1(a)]. The luminous plasma column occupies even initially only the outer two-thirds of the torus cross section but later on detaches from the outer wall. The inner boundary of the luminous column is moving outward along the major radius at $\sim 10^7$ cm/sec; i.e., the implosion is rather one-sided in the equatorial plane. (In future experiments this will be corrected by biasing the initial density distribution toward the inner torus wall.) The hollow structure of the luminosity is probably due to line emission accompanying the ionization of neutral deuterium remaining after preheating.

Figure 3(b) shows the D_α line intensity, observed from above but looking slightly outward as indicated in Fig. 1(b). The D_α time dependence is typical of a rapidly ionizing plasma, and the decay time may be related to the effective ionization coefficient (including two-step ionization[14]), i.e., $\tau \approx (S_D N)^{-1}$. With $\tau \approx 0.37$ μsec and Born-approximation cross sections for $n=2$ excitation and direct ionization, this gives $N \approx 0.8 \times 10^{14}$ cm^{-3} about 0.5 μsec from the start of the main discharge. A density about 20% larger follows if the D_α line is observed by using a second mirror to view more towards the outside [Fig. 1(b)]. A corresponding interpretation of carbon line signals (C II, C III, and C IV) would lead to higher density values ($\sim 5 \times 10^{14}$ cm^{-3}), probably because of an influx of impurities. Densities $\lesssim 10^{14}$ cm^{-3}, on the other hand, are consistent with helium-neon laser interferometer data taken through another pump port and using a corner cube reflector [see Fig. 1(b)]. Combining this density estimate with the plasma column size inferred from Fig. 3(a), one concludes that only ~25% of the deuterium in the original fill gas is heated. From the carbon line intensities, relative to intensities from our small θ pinch,[5] the total concentration of carbon ions is $\lesssim 10\%$ near 0.5 μsec. (This situation should improve when the acrylic torus is replaced by a fused-silica discharge vessel.)

A set of three movable probe coils was used to map the toroidal magnetic field along a diameter in the equatorial plane. The results, summarized in Fig. 4, confirm the implosion velocity of $\sim 10^7$ cm/sec inferred from the streak pictures and show a 5–10-cm-wide magnetic piston, corresponding to $(1-2)c/\omega_{pi}$ at $N \approx 0.5 \times 10^{14}$ cm^{-3}. A low-field, i.e., high-β plasma region persists in the outer half of the torus for $\gtrsim 1$ μsec, and there is approximate balance between magnetic pressure on the plasma column and particle pressure inside it for $N \lesssim 10^{14}$ cm^{-3} and $k(T_e + T_i) \approx 10$ keV. However, the toroidal shift is large and only arrested at the wall. Here copious amounts of carbon are released, judging from the failure of the C III line intensities to decay when one views the outer-wall region with the other mirror [see Fig. 1(b)]. This plasma-wall interaction is probably responsible for the observed termination of the x-ray emission at ~ 2 μsec, although it is inhibited by the toroidal magnetic field. This is suggested by a much stronger carbon line emission for $t \gtrsim 0.6$ μsec when no crowbar is applied.

Nevertheless, it appears that during the implosion neither plasma-wall interaction nor radiation cooling is critical. This explains why the elec-

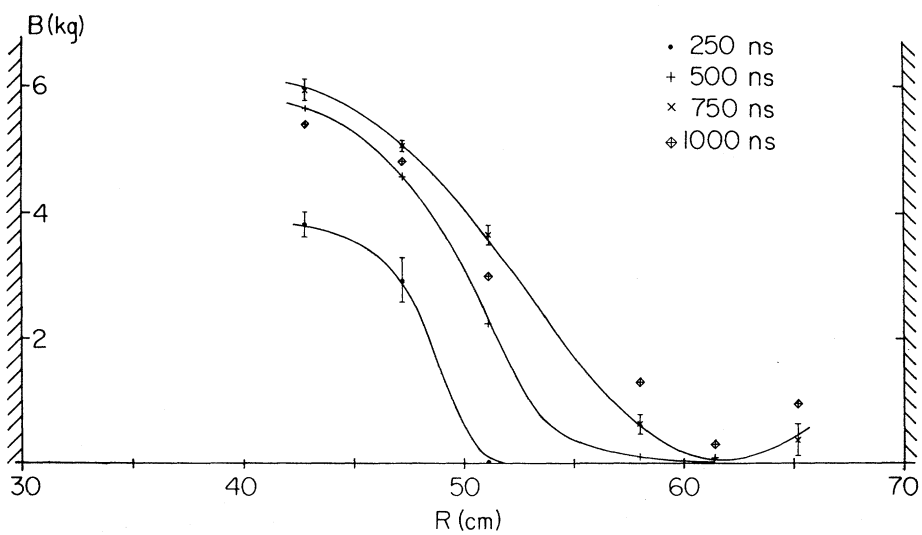

FIG. 4. Measured toroidal magnetic fields along a radius in the equatorial plane at various times from the initiation of the main discharge.

tron temperatures are higher than in otherwise similar θ pinches,[1-5] in which electron energy losses along the field lines are very important.[6,7] In contrast, the ion heating is about the same, and since both electron and ion heating must proceed by noncollisional processes, we can tentatively conclude that the microinstability heating processes[8-10] remain effective in going from $T_e/T_i \lesssim 0.3$ to $T_e/T_i \gtrsim 2$ and that the effective collision frequencies are rather high. For example, the observed electron heating rate corresponds to $\nu_{\text{eff}} \approx 3\omega_{pi}$, allowing for some adiabatic compression following the (anomalous) Ohmic heating.

Measurements of neutron yields at $\frac{1}{2}$ of the peak design power give $kT_i \approx 6$ keV, under the assumption that the densities increase by a factor of ~1.5. X-ray intensities through aluminum foils indicate no significant increase in the electron temperature, but x-ray intensities through nickel suggest populations of electrons in the 10–30-keV region well above those in a 7-keV thermal plasma. In both cases studied, ~5% of the stored electrical energy is therefore converted into plasma energy. It is also important to note that no macroscopic instabilities are evident, although ion transit times across the high-β plasma column are only ~0.3 μsec, to be compared with ~2 μsec of stable confinement.

We are grateful to Kenneth Diller and David Miller for their enthusiastic technical support in the construction and operation of the machine. We also wish to thank Dennis Markins and his associates from Maxwell Laboratories, Inc., for their patience and skills in bringing the low-inductance, high-voltage pulsers into operation.

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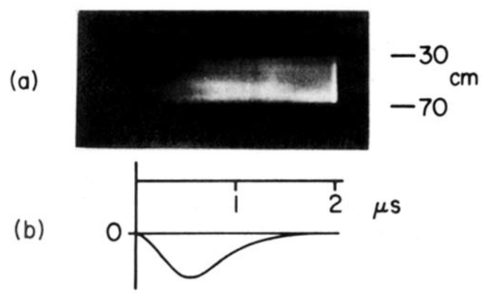

FIG. 3. Streak photograph of (a) plasma column, with inner and outer vacuum-vessel boundaries as marked, and (b) D_α line intensity.

MANIFEST LEFT-RIGHT SYMMETRY AND ITS EXPERIMENTAL CONSEQUENCES. M. A. B. Bég, R. V. Budny, R. Mohapatra, and A. Sirlin [Phys. Rev. Lett. 38, 1252 (1977)].

In Table I the upper bound for ρ should read 0.750 (instead of 1).

PLASMA HEATING IN A HIGH VOLTAGE TOROIDAL θ PINCH. Y. G. Chen, C. Chin-Fatt, Y. P. Chong, A. W. DeSilva, G. C. Goldenbaum, H. R. Griem, R. A. Hess, R. L. Merlino, and D. P. Murphy [Phys. Rev. Lett. 38, 1400 (1977)].

In the printed version, part of the last sentence of the Abstract was inadvertently omitted. This sentence should read as follows: The most striking difference is in the electron- to ion-temperature ratio which is now $\gtrsim 2$ rather than $\lesssim 0.3$ as in comparable open-ended θ pinches.