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Ohmic Heating to 100-eV and Helicity Injection in CTX

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Introduction

In the year since the last CT symposium, two major CTX results have been achieved. Electron temperatures over 100 eV have been obtained[1] and the magnetic fields of the spheromaks have been sustained by helicity injection from the coaxial magnetized plasma source.[2] The behavior and magnitude of the fields in the spheromak can be predicted from just the source voltage and flux by assuming a constant rate of helicity loss by resistive decay.

Electron Temperature Measurements

Ohmic heating by plasma currents in CTX spheromaks has produced electron temperatures in excess of 100 eV as measured by Thomson scattering near the magnetic axis of the toroid.[1] These high temperatures at plasma densities of $\sim 5 \times 10^{13} cm^{-3}$ correspond to mean free paths for collisions greater than the size of the plasma and are consistent with low-Z impurity radiation losses no longer being dominant. The increased temperature, however, has not produced a significant increase in the ~ 1.0 ms total lifetime of the spheromaks.[3]

The spheromaks are generated in, and confined by, a copper-mesh type flux conserver with an oblate shape 80 cm in diameter, similar to the previous solid wall copper flux conserver. The mesh is fabricated from 12-mm-diameter oxygen-free copper rods with toroidal hoops spaced 5 cm apart welded to 24 poloidal rods, as shown in Fig. 1. Image currents in the mesh provide fields which stably confine the spheromak. With the more open design, the impurity radiation, as measured by VUV spectroscopy, is observed to drop more rapidly than with the solid-wall conserver.[4,5] To produce the 100 eV results, the vacuum tank is filled with 30 mTorr of H_2 before the discharge is initiated. The spheromaks are formed during the first 0.15 msec (about 100 Alfvén times) using a coaxial magnetized plasma source operated in the "slow mode" (the input power is supplied to the source for ~ 0.06 ms using a 3×10^{-3}F, 10-kV capacitor bank).[2] During the next 0.2 ms, the plasma is ohmically heated in the magnetically decaying spheromak from ~ 25 eV to over 100 eV. The spheromak temperature decreases after that as the fields decay further so that the $\langle\beta\rangle_{vol}$ remains approximately constant.[3] The magnetic fields are measured by a magnetic probe inserted along the geometric axis 5 cm into the flux conserver, and more recently by Rogowski loops placed on the flux conserver bars.

Temperature and density profiles over a full flux conserver radius are obtained using multipoint Thomson scattering. The density profiles are normalized to the density obtained from a line-averaged measurement using a laser interferometer.[1] The results for three similar discharges at different times are shown in Fig. 2. This demonstrates the heating of the spheromak in time and the peaking of the temperature and density near the magnetic axis at the later times. Figure 3 shows the average of the "core" temperature as a function of time for all the data from a series of discharges under similar conditions (4-13 shots per data point). The core temperature for a shot is defined as the average of temperatures measured from r = 21 to 35 cm, which is approximately the region containing the innermost 25% of the poloidal flux. Thus the core temperature is lower than the peak temperature. The peak in the core temperature occurs at the time that the electron density (initially $\sim 2 \times 10^{14} cm^{-3}$) has dropped to the plateau ($\sim 5 \times 10^{13} cm^{-3}$) value. The data have been obtained in two somewhat different flux conserver configurations. At first, to minimize interference with diagnostics, there were only twelve poloidal straps across the mid-plane gap of the flux conserver. Then, to eliminate frequent sudden plasma disruptions or tipping, the number of straps was increased to 25. This change better stabilized the spheromaks and delayed the time of the peak in the core temperature by ~ 0.1 msec (which in both cases occurred at the time of onset of the density plateau), and extended the total spheromak lifetime by the same amount.

Helicity Injection into the CTX Spheromak

The magnetic fields in CTX spheromaks are produced by the injection of helicity from the magnetized coaxial source. The equilibrium of the spheromak is a minimum energy state with the constraint that helicity is conserved on time scales short compared to the magnetic energy lifetime.[6] Turner et al.[7] first showed that the helicity content of the spheromak was related to the amount of helicity injected from the source on fast, Alfvén time scales. We have extended the analysis to longer times by also considering the helicity loss due to ohmic decay. The rate at which helicity is created is twice the source voltage, V(t), (the rate of toroidal flux creation) times the magnitude of the source poloidal flux, Φ_p. The poloidal flux remains approximately constant during the CTX discharge. This flow of helicity into the flux conserver initially supplies and later replenishes the total spheromak helicity which is at the same time decaying as a result of the plasma resistivity. A helicity balance equation can then be used to describe the predicted evolution of the spheromak magnetic fields:

$$\frac{dK(t)}{dt} = - \frac{K(t)}{\tau_{B^2}} + 2V(t)\Phi_p ,$$

where $K(t) \approx 0.17 R^4 B_0^2(t)$ is the helicity content of the spheromak calculated assuming Bessel-function field profiles in a cylinder with radius, R, equal to length, L, and where $B_0(t)$ is the peak magnetic field at the center on the geometric axis. Since K(t) is proportional to $B_0^2(t)$, the magnetic energy decay time, τ_{B^2}, is also the resistive decay time for the helicity. The value of $B_0(t)$ then can be calculated by integrating the voltage-flux product of the source and using a τ_{B^2} value consistent with known plasma parameters,

$$B_o(t) = \left[e^{-t/\tau_{B^2}} \int_0^t \frac{2V(t')\Phi_p(t')}{0.17R^4} e^{t'/\tau_{B^2}} dt' \right]^{1/2}$$

Figure 4 shows the agreement of actual peak poloidal magnetic fields, measured at the center of the spheromak at the end of the injection phase in the "slow" mode (~ 180 μsec after start of discharge), with the corresponding predicted field values. The predictions are calculated using the actual source voltage and flux, and assuming $\tau_{B^2} = 200$ μs, and helicity injection efficiency of 100%. In addition, the actual behavior in time of the resulting spheromak field values can be predicted by the above equation to within 20% over a wide range of source operation.

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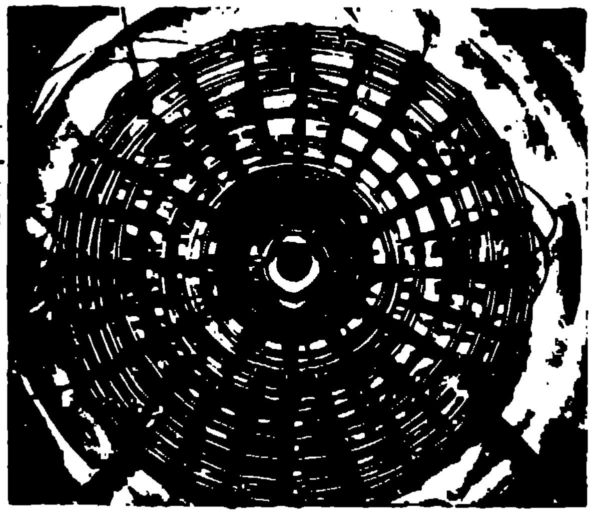

Fig. 1. The 80-cm-diameter copper-mesh flux conserver installed in the CTX vacuum tank.

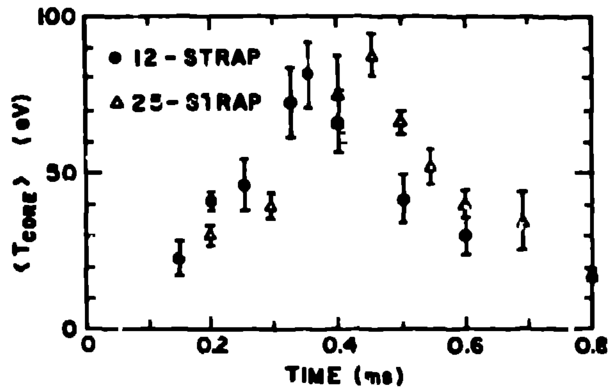

Fig. 3. Core temperatures of CTX spheromaks vs. time. The bars at each point give the rms deviation of the temperature measurements from the average, divided by the square root of the number of measurements for that point.

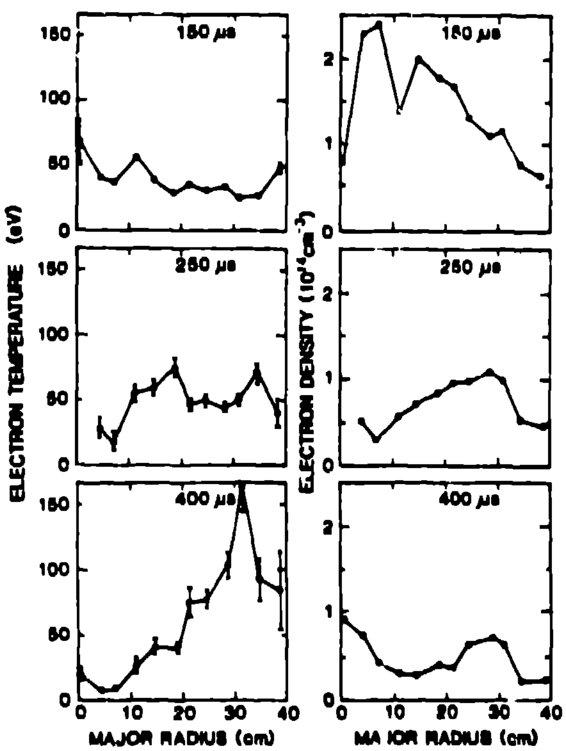

Fig. 2. Electron temperature and density for three CTX shots measured at different times from the start of the discharge.

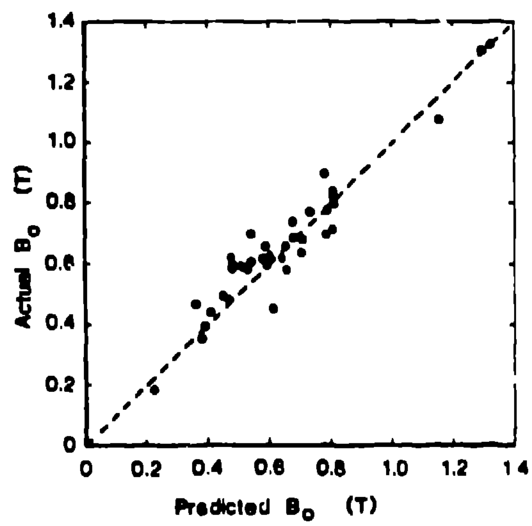

Fig. 4. Actual measured peak poloidal magnetic field on the axis at the center of the CTX flux conserver compared to that predicted from helicity injection and resistive decay.