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TITLE IMPROVED PLASMA CONFINEMENT AND EVIDENCE FOR A PRESSURE-DRIVEN INSTABILITY FROM REDUCED MAGNETIC FIELD ERRORS IN THE CTX SPHEROMAK

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Improved Plasma Confinement and Evidence for a Pressure-Driven Instability from Reduced Magnetic Field Errors in the CTX Spheromak*

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The 0.67 m radius mesh flux conserver (MFC) in CTX was replaced by a solid flux conserver (SFC), resulting in greatly reduced field errors. Decreased spheromak open flux led to vastly improved decaying discharges, including increased global energy confinement times τ_E (from 20 to 180 μs) and corresponding magnetic energy decay times τ_{B^2} (from 0.7 to 2 ms). Improved confinement allowed the observation of a pressure-driven instability which ejects plasma from the spheromak interior to the wall [Wysocki, F., et al., Phys. Rev. Lett. 61 (1989) 2457].

In the CTX 0.67 m radius mesh flux conserver (MFC), $\approx$ 1/4 of the spheromak poloidal flux forms the "edge", with open flux intersecting the FC wall[1]. Fig. 1 shows one half of a cross section of the MFC, along with the poloidal flux contours for a typical decaying CTX spheromak. $l_{eff} \approx 3$ m represents the effective length between the points where the (poloidal) open field lines intersect the wall[1]. The effective poloidal electric field $E_{eff} = \eta j$ at the edge is also illustrated. To replenish mainly the rapid plasma losses on open field lines, spheromak refueling is achieved with a static H_2 filling pressure surrounding the MFC, typically 1 - 8 mT. Because of low edge T_e, the neutrals penetrate deep into the spheromak, allowing refueling from the electrical breakdown of the neutrals by the spheromak edge currents. $E_{eff} l_{eff}$ agrees with the Paschen voltage[2] for breakdown of neutral H_2 at the given neutral pressure[1].

Maintaining spheromak edge currents causes a high loss rate of spheromak helicity (magnetic-flux linkage). Without external voltages, the helicity decay rate is given by[3]

$$\frac{dK}{dt} = -2\int E \cdot B \, dvol = -2\int \eta j \cdot B \, dvol \qquad (1)$$

where $E + (v \times B) = \eta j$ has been used. The high neutral density in the edge increases η much above the Spitzer resistivity. Throughout the plasma, ηj is negligible compared to E_{eff} at the edge, so that $dK/dt \approx -2E_{eff}\int_{edge} B\, dvol$. The result is spheromak magnetic energy decay times τ_{B^2} which are uncorrelated with the electron temperature, but which are correlated with the edge neutral pressure[1]. This model is also consistent with the results in the HBTX1B reversed field pinch discharges with limiters[3].

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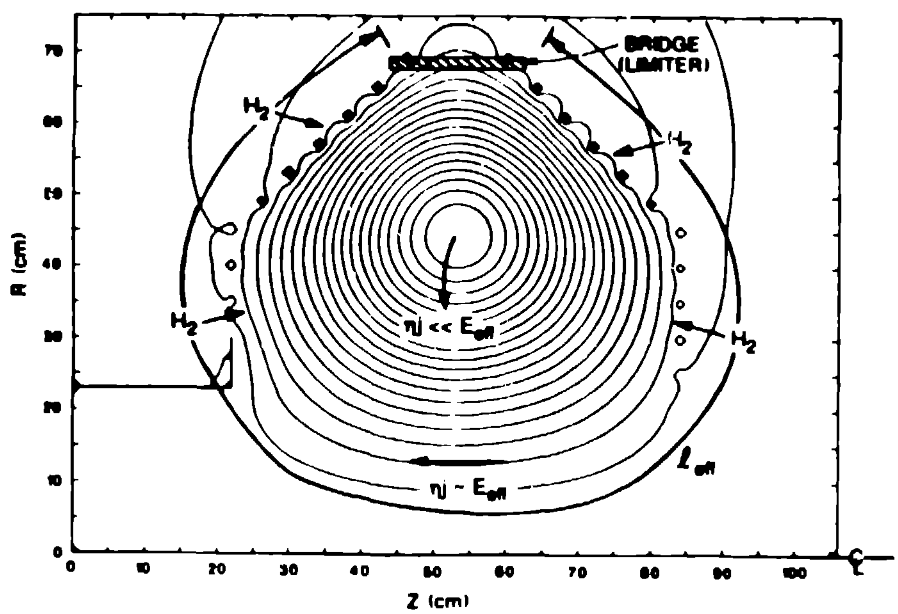

Figure 1: One half of the MFC cross section is shown. Typical normalized spheromak poloidal flux contours (5% increments) during decay are included. The poloidal magnetic field wraps around the magnetic axis in the counter-clockwise direction, while the toroidal field goes into the page.

In decaying CTX spheromaks with high edge resistivity from electron-neutral collisions, the edge currents decay until the resulting peaked current profile becomes unstable. The instabilities which grow up cause relaxation toward the minimum-energy state, which implies a current drive at the edge (which will be called relaxation current drive). It is observed that the poloidal edge $E_{eff} \approx \eta j$ driven by relaxation is up to ten times greater than the electric field produced by toroidal flux decay.

Relaxation current drive is the reason why the edge plasma must be refueled. With negligible edge electron density n_e, relaxation would try unsuccessfully to drive currents in the edge. The resulting large E_{eff} would quickly dissipate the spheromak helicity (Eq. 1). CTX results agree with this model. Without the filling pressure, only the plasma from the helicity source feeds the spheromak. After the source is turned off, the edge n_e decays within a particle confinement time τ_p. After n_e has decreased enough, the spheromak decays extremely rapidly[4,5].

It has been proposed that strong relaxation activity would result in direct ion heating[1]. Fig. 2 shows selected time traces for discharge 15805, one of the nearly identical 47 discharges previously studied[1]. The maximum reproducible Thomson scattering T_e ever achieved in the MFC is $\approx$ 100 eV. The top trace shows the spheromak toroidal current. The middle trace shows the line brightness of the impurity line used, OV at 2781 Å. The bottom trace is the Doppler broadening temperature T_D. Since the calculated ion equilibration time is much shorter than τ_p and similar to the plasma energy confinement time τ_E, T_D should reflect the bulk ion temperature T_i. These high T_D indicate an anomalous ion heating mechanism, as expected from strong relaxation activity. Anomalously high T_i have also been observed in reversed field pinches[6,7]. The oscillations in T_D (Fig. 2) are correlated with the n = 1 (sustainment) and n = 2,3 (decay) saturated, rotating, current driven kink modes[8]. T_D oscillations are most probably due to the mode exposing the spatial profile of T_i, which we cannot resolve with our single-chord instrument. Accounting for $T_D \gg T_e$, the previously presented[1] energy confinement times $\tau_E \equiv 3/2\langle\beta\rangle_{vol}\tau_{B^2}$ in the MFC should be corrected up to the 50 – 100 μs range, and $\langle\beta\rangle_{vol}$ up to $\approx$ 5%. Still, large charge exchange losses and enhanced transport from excessive relaxation activity (caused by high edge resistivity) almost surely degrade confinement significantly.

A 0.60 m radius solid flux conserver (SFC) has been designed to decrease the relative fraction of open spheromak magnetic flux much below the value in the MFC. The observed result is a much longer τ_p, so the filling pressure has been eliminated. Ti gettering of the SFC walls has produced non-radiation dominated discharges with low edge neutral density. In the SFC, as in the MFC, the spheromak equilibrium is deduced from magnetic field measurements at the FC surface, coupled with a Grad-Shafranov MHD equilibrium solver[8]. The n_e and T_e are diagnosed by an absolutely calibrated multi-point Thomson scattering system. T_e and n_e are combined with the MHD equilibrium calculations to determine the electron β_e and pressure p_e. The result is an accurate calculation of τ_E.

τ_{B^2} in the SFC scales proportionally with T_e at the magnetic axis. With reproducible $T_e \approx 150$ eV, maximum τ_{B^2} is 2 ms. In the SFC the OV T_D is similar to T_e, and maximum global $\tau_E = 180$ μs (using $T_i = T_e$). Fig. 3 shows the increase in τ_E for similar discharges over time as the decaying spheromak plasma heats up. In this figure, only τ_E values measured before the pressure-driven instability (discussed below) are included. These SFC results suggest reduced open magnetic flux resulting in less relaxation activity, which reduces direct ion heating and increases plasma confinement, as also reported for HBTX1B[7].

In the SFC, a pressure-driven instability ejects the spheromak plasma in a distinct event[9]. As the maximum electron pressure gradient ∇p_e increases, $\langle\beta\rangle_{vol}$ remains at $\approx$ 3–6% (using $T_i = T_e$). At a threshold ∇p_e, p_e moves towards the outer flux surfaces within 10–20 μs, indicating a flux interchange. No concurrent signature on the magnetic probes at the wall is observed, as normally occurs with current-driven instabilities.

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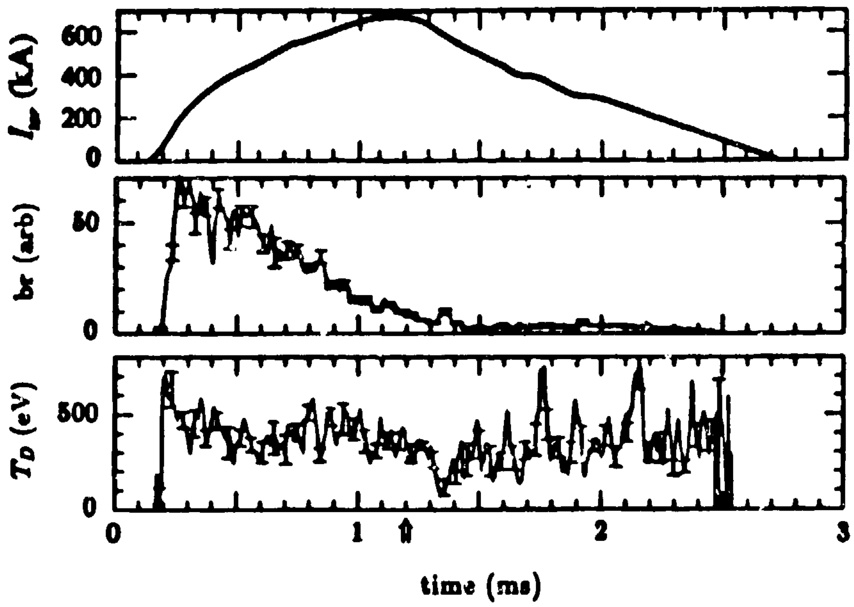

Figure 2: Traces versus time for typical MFC discharge 15805. The top figure shows the spheromak toroidal current, increased by helicity injection until 1.2 ms, when the source is turned off (arrow in the bottom figure). The middle figure shows the "brightness" br, defined as the area under the gaussian fit. The bottom figure shows the Doppler temperature T_D. Error bars at regular intervals illustrate the uncertainty resulting from the fit.

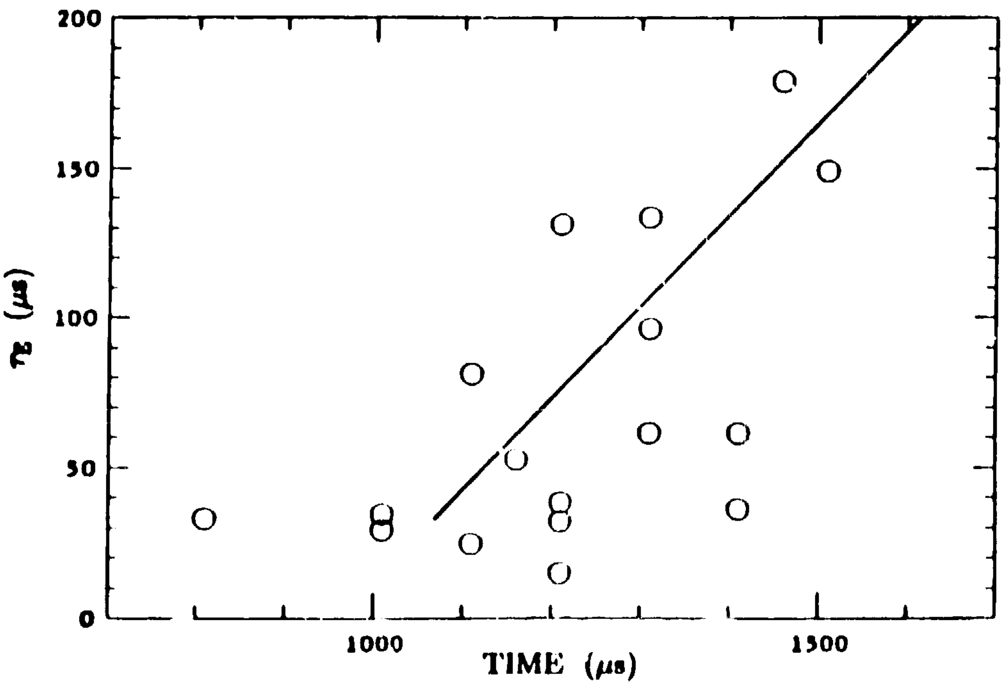

Figure 3: τ_E from similar spheromak discharges in the solid flux conserver are plotted versus time The helicity source is turned off at 700 μs