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Increased Particle Confinement with the Use of External dc Bias Field in the CTX Spheromak

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Abstract

Spheromaks are formed in a mesh flux conserver in the presence of an external dc bias field. The spheromaks remain stable to tilt instabilities with ratios of bias-to-spheromak flux of up to $47 \pm 7\%$. Normally applied bias flux puts the spheromak separatrix inside the metal mesh and improves the particle confinement.

Spheromaks are toroidal magnetic confinement configurations of a compact nature (no material linking the torus). They have been made stable to gross magnetohydrodynamic instablities [1,2] by the presence of close fitting flux conservers[3] or passive stabilizers.[4] The use of mesh flux conservers provides stability, reduces wall area, and improves plasma parameters by producing cleaner plasmas[5]. Induced currents in the poloidal-flux-conserving toroidal hoops create some private flux which causes spheromak flux to pass outside the mesh. Resistive loss in the mesh continues to increase the fraction of this open linked flux[6].

An external dc bias field creates flux that is trapped inside the flux conserver. The result of positive or normal bias is to push the separatrix of the forming spheromak inside the metal mesh, and to close the field lines near the geometric axis within the flux conserver (thus eliminating the open linked flux.) The particle confinement times in these flux conservers are important because they have limited energy confinement in CTX spheromaks[6]. Previous spheromak experiments with bias field in solid flux conservers [3,7] were done on cold plasmas with lifetimes less than the particle confinement time. No improvement in confinement in these solid flux conserver experiments was reported. We now see increased plasma density and reduced hydrogen radiation under conditions of sufficient bias flux to eliminate the open linked flux. Reversing the direction of the bias flux (producing negative bias) and increasing the open linked flux degrades these indicators of particle confinement. Once formed, the spheromaks are found to be stable for positive bias-to-spheromak flux ratios of up to $47 \pm 7\%$.

The external bias field is generated by a set of 10 coils in series, each 14 turns at a mean radius of 0.928 m. Their axial positions are shown in Figure 1. The bias field is not quite symmetric about the midplane, and weakly mirrored with a field curvature index $n_i = -\frac{R}{B_z}\frac{\partial B_z}{\partial R} \simeq 0.19$ at 0.45 m radius (the location of the spheromak major radius.) The flux inside the 0.67 m radius of the flux conserver midplane is calculated to be 0.25×10^{-6} Wb per Ampere of current. This value has been measured by a Hall probe in agreement to within 10% of the calculated value. The current in the coil set is monitored on each discharge to determine the bias flux.

The spheromak poloidal flux can be calculated from measurements of currents in the toroidal hoops of the mesh flux conserver. A computer code that solves the Grad-Shafronov equilibrium equations has been used to calculate the induced currents in the hoops, both with and without bias field, and with different equilibrium current-density profiles[8]. The spheromak poloidal flux can be determined to within 15% error (5% measurement, 5% theory, 10% profile determination). The magnitude of the bias flux will often be quoted by its percentage ratio to the spheromak poloidal flux. Figure 1 shows calculated equilibrium flux surfaces with +15% bias flux.

During the formation of the CTX spheromak the poloidal flux is built up from zero. For the discharges studied in these bias field experiments the source sustains and increases the flux for 0.6 ms at which time the

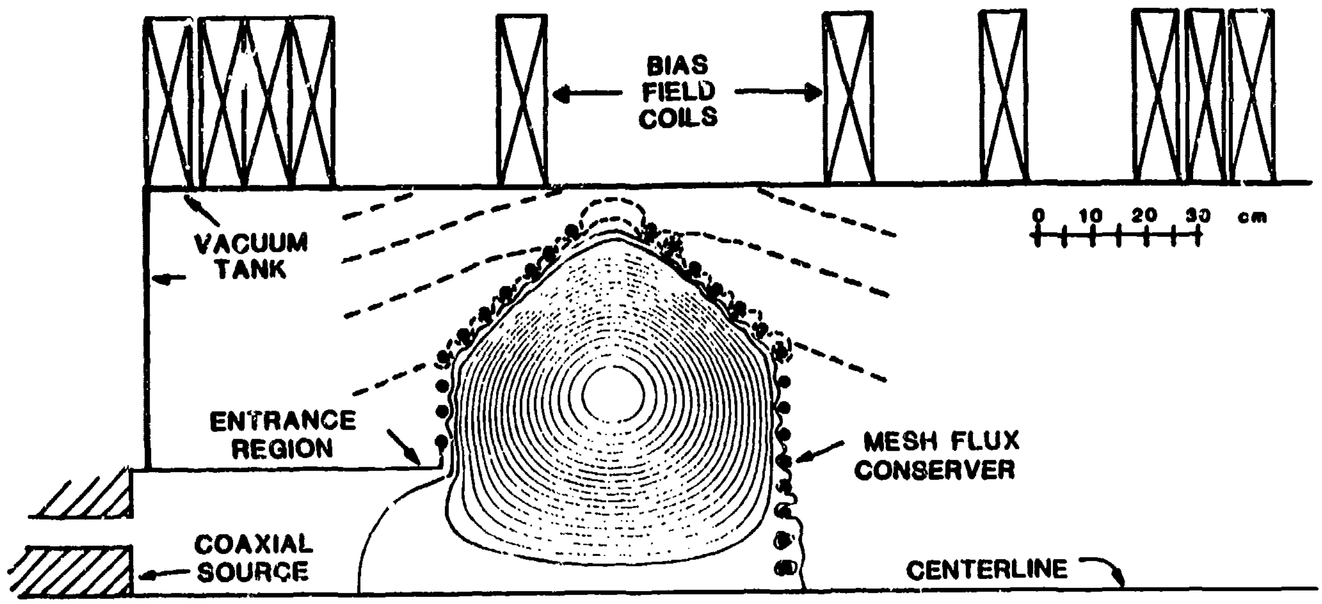

Figure 1: Diagram of CTX experiment with bias coils, and computed equilibrium in the presence of +15% bias flux.

source voltage is turned off and the spheromak magnetically disconnects from the source. From this initial peak flux the spheromak resistively decays, and the ratio of dc-bias-to-spheromak flux increases.

Too much bias flux causes the spheromak to become tilt unstable. The limit depends on the flux ratio, which determines how far the separatrix is from the stabilizing wall. The tilting limit on the applied bias flux appears in two ways: 1) the spheromak can flip initially during formation; and 2) spheromaks with normal bias flux can go unstable during the resistive decay.

The initial flipping causes an operational limit on the amount of applied bias flux. The limit has been seen before, and depends on the shape of the flux conserver.[3] The spheromak flux must be built up from zero during formation in the presence of the dc bias flux. Initially the spheromak is tilt unstable as the flux ratio (bias-to-spheromak) reduces from infinity. Whether the spheromak flips depends on the time spent in the unstable regime relative to the growth time of the tilt instability. Even with no bias flux the spheromaks initially flip 10% of the time. At 0-15% flux ratio (determined at peak spheromak flux), 10 out of 84 shots flipped, not very different from the no bias flux result. Above 15%, 4 out of 7 flipped initially, making reproducible experiments difficult. Two discharges out of 47 actually flipped initially in the presence of negative bias, resulting in spheromaks with initial positive flux ratios of 3 and 5%.

Discharges successfully formed with high initial positive flux ratios are observed to go unstable and flip during their resistive decay. This effect was seen on the Beta-II experiment[7]. In these CTX experiments the flux ratio at time of tilting is $47 \pm 7\%$. This limit is close to the 54% limit predicted by theoretical calculations of Dalhed[9]. The differences in flux conserver geometry and a mesh wall instead of solid may explain any small discrepancy in the limits. The flip rotates the magnetic axis through 180°, resulting in a stable spheromak albeit with closed flux pushed outward in major radius as in negative bias operation. The plasma is observed to flip within 50-60μs. Magnetic signals deviate from the normal time decay with an exponential time constant of 10-20μs. This growth rate agrees within a factor of 2 with the rigid-toroidal-loop model of Munson *et al.*[10]

Without bias field, the global particle confinement time τ_p in the 0.67 m mesh flux conserver is 0.2-0.6 ms. The magnetic energy decay time τ_W is usually longer than τ_p with values of 0.4-0.6 ms. While values of τ_p less than τ_W allow pump-out[5] of the impurities and 100 eV values of the temperature, the resulting values of β are lower and there is no improvement in the energy confinement time. Values of τ_p larger than τ_W require the impurity radiation to be burned through and would then result in improved energy confinement dependent on the particle confinement[6]. Burn-through of low-Z impurities in general requires the current-density-to-plasma-density j/n to be sustained at over 2×10^{-14}A m[6]. Such conditions have not yet been achieved in CTX.

The spheromak plasma density must be maintained against the particle loss in order to achieve long resistive decay times. A static hydrogen filling pressure provides a neutral source of particles to prevent sudden termination of the discharge when the density goes towards zero[11]. The spheromak density late in time is regulated by the filling pressure, while the density early in time is more dependent on the formation current.

Application of bias flux in the normal direction results in increased density and reduced hydrogen radiation. Reversing the bias has the opposite effect on both diagnostics. These changes to particle confinement diagnostics occur while the neutral hydrogen filling pressure is kept constant. Figure 2 illustrates three discharges under identical conditions except for the dc bias flux. The density is an average using all 8 chords of a CO_2 interferometer. The change in the density affects the resistive decay of the flux. Figure 3 shows how the amount of applied bias changes the density and L_α radiation at 1.0 and 1.5 ms into the discharge.

Normal bias can provide improved confinement of the density. By operating at lower filling pressure than with no bias an optimum density can be found that allows for our longest-lived spheromak discharges (over 2.0 ms after source turn-off.) Reversed bias significantly reduces the early time density and improves the j/n, for a short time, up to 2×10^{-14}A m. Such discharges initially have long resistive decay times, but they suddenly terminate when the particle density goes towards zero (see Figure 2(a).)

Accurate determination of the global particle confinement time requires information about the relation of the hydrogen radiation to the ionisation rate[12].

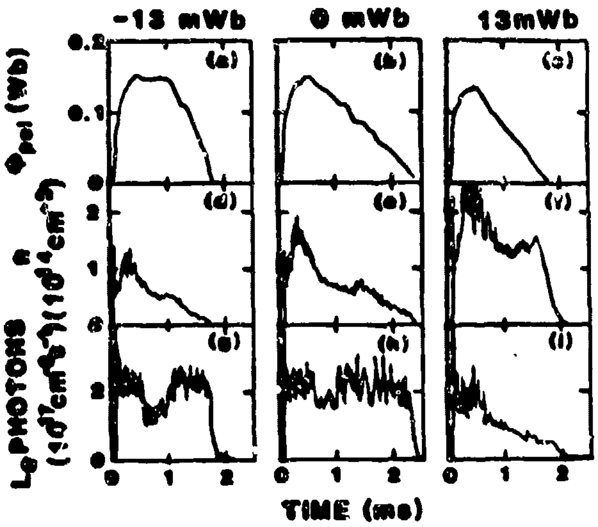

Figure 2: Spheromak poloidal flux, electron density, and L_α radiation for three discharges at −13, 0, and +13 mWb bias flux at 4 mT filling pressure.

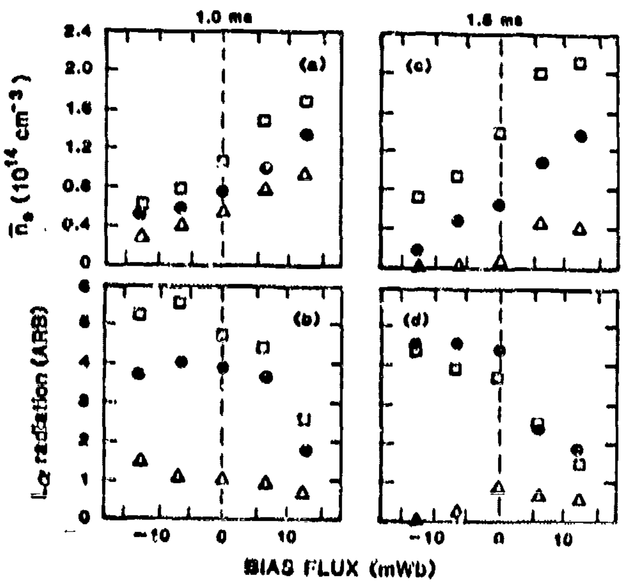

Figure 3: Density and hydrogen radiation versus bias flux at 1.0 and 1.5 ms for discharges at different fill pressures. Triangles are 1 mT, circles are 4 mT, and squares are 8 mT data. Shot-to-shot errors are about the size of the symbols.

The number of ionizations per photon depends sensitively on density above a few times $10^{13} cm^{-3}$ and on temperature below 25 eV. Profiles of the emission may vary under different conditions. Since the number of ionizations per photon increases with density, it is possible that a rise in density and a drop in L_α radiation could occur with no change in global particle confinement time τ_p. A strong edge temperature increase with applied positive bias flux could help explain the drop in hydrogen radiation for a constant τ_p.

However, the observed magnitude of the rise in density and decrease in hydrogen radiation seen on CTX with applied bias flux can only be explained by an increase in the particle confinement time. A rough estimate of the actual confinement time can be made using the following assumptions: 1) the temperature remains constant; 2) there are no profile changes in the L_α radiation that would change the emission volume; and 3) $\tau_p \sim 300\mu s$ in no bias field, 4 mT filling pressure operation. (This assumption is used to calibrate the L_α emission because during these experiments the absolute calibrations of the vacuum ultraviolet spectrometers monitoring the radiation were not accurately known. The value of $300\mu s$ is chosen as a fit to density and impurity pump-out behavior.) Using these assumptions the particle confinement time can almost double at +15% initial bias flux, and more than triple as the flux ratio exceeds +25% (Figure 4(a)). Reversing the bias can more than halve the confinement time at −10% flux. Temperature changes alone cannot explain the observed density increase and L_α decrease. A factor of 5 change in the number of ionizations per photon due to changing the temperature of the ionization region would be required to maintain a constant τ_p with positive bias flux. An additional factor of 7 would be required to explain the negative bias flux results. The edge temperature would have to go from less than 1 eV with reverse bias to a few eV with no bias to greater than 20 eV for normal bias. While the impurity radiation is lower with reversed bias because of the lower density, the radiation normalized to density does not decrease in time at a significantly different rate.

A scan was performed with similar bias flux at reduced initial spheromak fluxes. Figure 4 shows how the effects of the bias flux on the particle confinement time occur earlier as the initial spheromak poloidal flux is reduced and the time of +15% flux ratio occurs earlier. The decrease in τ_p late in time is associated

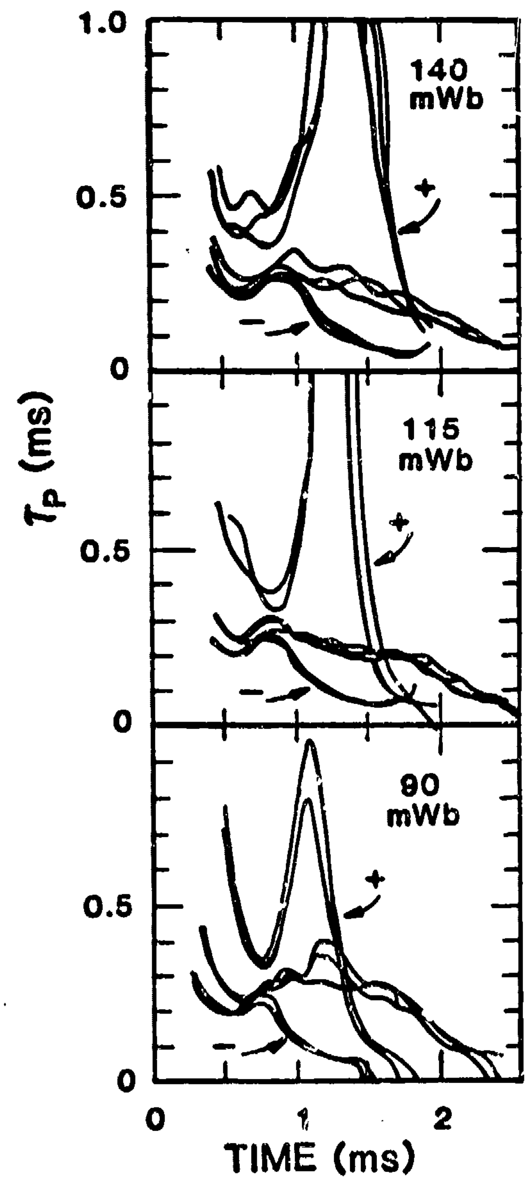

Figure 4: Estimated particle confinement time for discharges with +13, 0, and −13 mWb bias flux at different initial spheromak fluxes. Estimated τ_p's greater than 1 ms have been cutoff for these discharges with decay lifetimes of only ~ 1.5ms.

with the termination of the spheromak discharge.

The value of the flux ratio where the maximum effect on the particle confinement is observed is close to the value that just closes the open linked flux. At these flux ratios of 10-20% the spheromak is still observed to be very stable to the tilt instability in the presence of a nearby stabilizing flux conserver wall. The use of bias flux with stabilizing flux conservers holds great promise for improving the operation and confinement properties of spheromaks.

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