IMPROVED OPERATION AND MODELING OF THE SSPX SPHEROMAK*

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Abstract

Progress in understanding both magnetic field generation and confinement is enabling the production of high magnetic field spheromaks with plasma core electron temperatures (T_e) >200eV in the Sustained Spheromak Physics Experiment (SSPX). The highest measured T_e occurs when the edge magnetic fluctuation amplitude is lowest. Improvements over previous results were produced with higher formation bank current, longer discharges, and better matching of edge current and bias flux to minimize magnetic fluctuations. New experiments show for the first time that the field energy of the spheromak can be increased in a step-wise manner using repetitive current pulses. These multi-pulse discharges produce the strongest magnetic fields yet in SSPX (0.7 T at the geometric axis), and an important scaling of magnetic field with current has been exceeded. 3D resistive MHD simulations with NIMROD for conditions similar to SSPX single and double pulse discharges with increasingly realistic representations of the gun geometry, magnetic bias coils, and current-drive pulse histories, and with Braginski temperature-dependent resistivity and anisotropic thermal conductivities are tracking the reconstructions of the magnetic configuration, and the temperature and magnetic fluctuation histories with increasing fidelity.

1. Introduction

The spheromak is a compact self-organized toroidal plasma configuration in which confining magnetic fields are produced by poloidal and toroidal currents flowing in the plasma [1]; there are no toroidal magnetic field coils linking the plasma. A spheromak can be formed and sustained by injecting magnetic helicity and energy from a magnetized coaxial plasma gun into a conducting shell, or flux conserver. Through magnetic fluctuations and associated reconnection the injected plasma then relaxes into an axisymmetric toroidal geometry. Because helicity is injected by current flowing along open magnetic field lines in the edge of the plasma, transport of this current into the plasma (the dynamo process) requires breaking of magnetic surfaces, which also allows energy transport.

The main issues in spheromak research are magnetic field amplification and energy confinement. The primary goal of the Sustained Spheromak Physics Experiment (SSPX) is to test whether a favorable energy confinement scaling can be obtained in a spheromak plasma sustained by coaxial helicity injection. This requires that we produce adequate magnetic field to obtain a high-temperature plasma. Thus, the physics of magnetic field generation is necessarily a major focus of the experimental program. We are also examining magnetic field amplification (ratio of final spheromak toroidal field to initial vacuum magnetic field), which is predicted to increase with temperature [2]. If a favorable balance between current drive efficiency and energy confinement can be shown, the spheromak has the potential to yield an attractive magnetic fusion concept [3]. In this paper we discuss our recent experimental and modeling results that have lead to an increased understanding of energy confinement and magnetic field generation in the spheromak. In Section 2 we review the operation of the SSPX, and in Section 3 we discuss energy confinement. Section 4 covers magnetic field

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buildup, and in Section 5 we present results of theoretical studies of spheromak instabilities. Finally, we discuss future work in Section 6.

2. Operations on SSPX

The SSPX device [4] produces 1.5 - 3.5 msec, 1m dia. spheromak plasmas with a plasma minor radius of ~0.23m. DC coaxial helicity injection is used to build and sustain the spheromak plasma within the flux conserver. The four phases of a discharge include breakdown, formation, sustainment, and decay. During spheromak formation, the poloidal field builds rapidly and is sustained by driving an instability of the open flux, a toroidal n=1 mode, which in turn provides fluctuations for a MHD dynamo to drive toroidal current. The n=1 mode provides the fluctuation power that couples current from the open flux into the spheromak. During sustainment excessive edge current and fluctuations degrade confinement. Optimal operation is obtained by flattening the profile of $\lambda=\mu_0 j/B$, consistent with reducing the drive for tearing and other MHD modes, and matching of edge current and bias flux to minimize $|\delta B/B|_{rms}$. With these optimizations, the highest measured T_e (~250 eV, peaked at the magnetic axis) and lowest core thermal diffusivity (χ_e ~ 10-20 m^2/s) have been obtained.

3. Energy confinement

The time history of a representative SSPX discharge with good confinement is shown in Fig. 1. The highest measured T_e (>200 eV) and lowest core thermal diffusivity (χ_e ~ 10-20m^2/s) occurs when the edge magnetic fluctuation amplitude ($|\delta B/B|_{rms}$~0.5%) is lowest. Spatial profiles during this time are shown in Fig. 2. Improvements in energy confinement and spheromak parameters were produced by 10% higher formation bank current (first current pulse in Fig. 2a), longer discharges (upgraded sustaining bank pulse-forming network), and better matching of edge current and bias flux to minimize $|\delta B/B|_{rms}$. It is also necessary to obtain low density and very clean conditions achieved by a rigorous program of good vacuum practices, baking, glow discharge cleaning, and titanium gettering of the flux conserver every third shot [5]. Saturation of the gettered surfaces is readily indicated by increased density and H_α radiation.

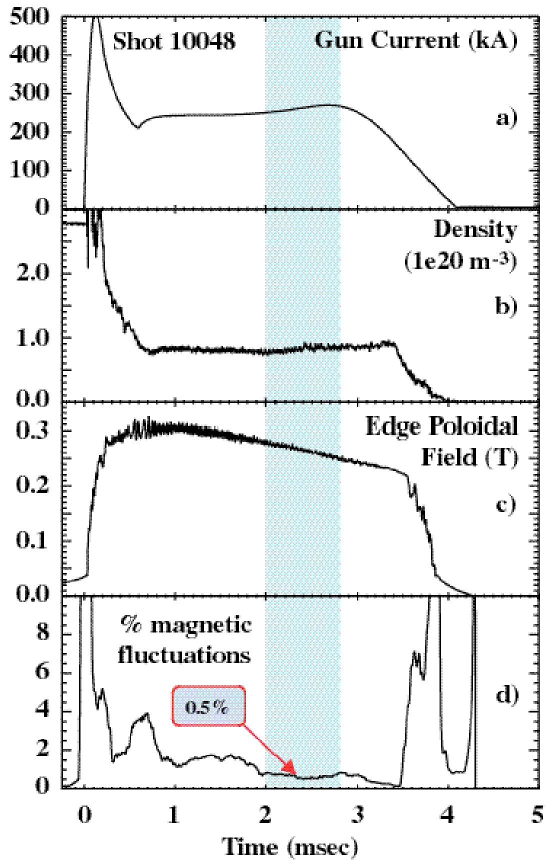

Fig. 1. Time evolution of high T_e shot.

Energy confinement time, τ_E, is calculated by balancing ohmic heating, P_{OH}, with heat content: $dE/dt = P_{OH} - E/\tau_E$ where $E = 1.5\int_{vol}(n_e kT_e + n_i kT_i)d^3r$. τ_E is determined when T_e peaks and dE/dt = 0; spectroscopic measurements show $T_i \approx T_e$ during this phase of the discharge. P_{OH} is calculated in decaying spheromaks by observing the decay of magnetic energy in the system. This cannot be done here because the system is being driven and the magnetic energy is decaying only slightly. The input energy calculated from the discharge voltage and current is difficult to quantify because of the electrode plasma sheath potential

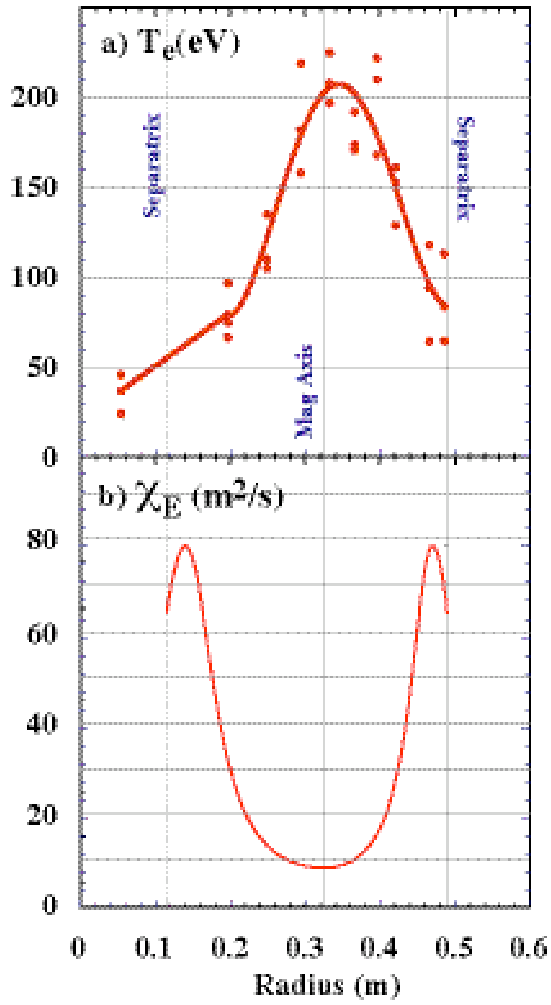

Fig. 2. Spatial profiles of a) T_e and b) thermal diffusivity.

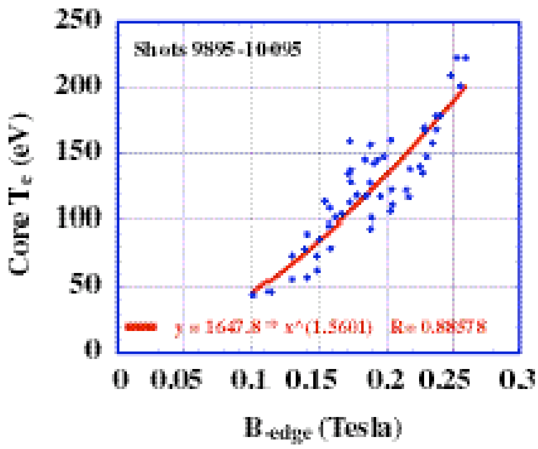

Fig. 3. Scaling of Te with B.

drops and because the transport of energy coupled into the spheromak plasma by the dynamo is difficult to determine [6]. For this paper we define $P_{OH} = \int_{vol} \eta_{sp} j^2 d^3r$, calculating $j(\vec{r})$ using CORSICA and making estimates of the plasma resistivity where η_{sp} is the classical Spitzer resistivity with an estimated Z_{eff}=2.3. The integrals are taken over the volume within the separatrix between the magnetic axis and edge plasma.

T_e has increased over previous results [7] from 120 eV to >200 eV with the peak value close to the CORSICA-inferred magnetic axis. χ_e in the core is reduced by a factor of four to < 10 m^2/sec. Ohmic heating in the core is about the same as previously but the dissipation near the separatrix is reduced which, when combined with the higher core T_e, doubles the energy confinement time (within the separatrix) to τ_E > 200 mS. A series of shots were analyzed to determine the scaling of T_e with B. These shots had low impurities and similar T_e profiles. Parameters scanned were formation gun flux and current producing shots with B_{edge} = 0.1 to 0.25 T. Results (Fig. 3) show a very clear correlation of $T_e \sim B^{1.5}$.

Experiments with D_2 fueling were conducted to explore possible further improvement in plasma performance. In tokamaks, operation with deuterium fueling offers improved energy confinement as compared to hydrogen [8]. In SSPX, D_2 fueled discharges show similar results to those with H_2 fueling with T_e>200eV. To obtain the same measured plasma parameters, more input energy was required for the D_2 fueled discharges and the measured edge poloidal magnetic field for deuterium discharges was less and decays more rapidly. The increased input energy and a more rapid magnetic field decay time correlates with an increase in plasma resistivity. Spectroscopic measurements showed a modest increase in titanium line emissions. The increased titanium emissions are attributed to an increase in the sputtering yield of titanium by deuterium ions. Electron temperatures of ~200eV with similar electron densities were observed, so we conclude that confinement is not dependent on mass in SSPX.

4. Magnetic field generation and buildup

Progress has been made in understanding the mechanisms that generate fields by helicity injection. Two new operating modes are observed to increase the magnetic field: (A) Operation with constant current and spontaneous gun voltage fluctuations. In this case, the gun is operated continuously at the threshold for ejection of plasma from the gun: stored magnetic energy of the spheromak increases gradually with $\delta B/B$ ~2% and large voltage fluctuations ($\delta V \sim 1$kV), giving a 50% increase in current amplification, I_{tor}/I_{gun}.[9] (B) Operation with controlled current pulses. In this case, spheromak magnetic energy increases in a stepwise fashion by pulsing the gun, giving the highest magnetic fields observed for SSPX (~0.7T along the geometric axis) [10]. In each case, the processes that transport the helicity into the spheromak are inductive and exhibit a scaling of field with current that exceeds those previously obtained. Newly found scalings suggest how to achieve higher temperatures with a series of pulses [11].

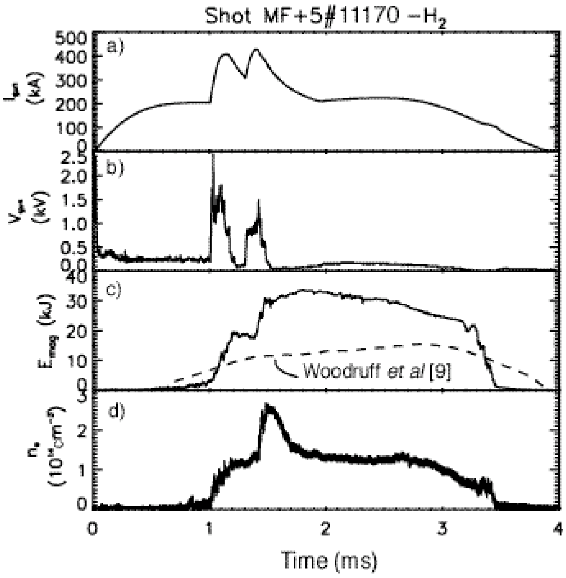

Fig. 4. Double pulsed build-up (solid) with previous continuous buildup (dashed).

In this new operating mode, two 450kA current pulses are produced as shown in Fig. 4a by firing each half of the formation bank separately some time after the pulse-forming network has fired. Also shown in Fig. 4 are: b) resulting gun voltage (peaked twice at 1-1.5kV); c) total magnetic field energy as inferred by a magnetic field coil at the mid-plane calibrated with CORSICA; and, d) plasma line-averaged density measured on a chord through the magnetic axis. Close timing of the two pulses gives an increase of the stored magnetic energy from 18 to 32kJ, after which time, the spheromak decays. By this means, the highest magnetic fields yet observed in SSPX are produced (0.35T at the wall and 0.7T at the geometric axis) and the ratio of the edge field to the injected current is higher by 25% than the usually observed scaling of $B_{edge}(T)=0.65I_{gun}$ (MA) (shown in Fig. 5). Maximum toroidal currents to date are observed at ~600kA. CORSICA infers that the increase of the magnetic energy is attributable to an increase of the total current enclosed by the separatrix, i.e. pulsing increases the fraction of current flowing from 210kA to 350kA, an increase of ~70%. The dashed line on Fig. 4c shows the attained magnetic energy for a previously reported operating mode [9]. During the second pulse, the density is temporarily increased by a factor of two, however it falls rapidly to a level that is

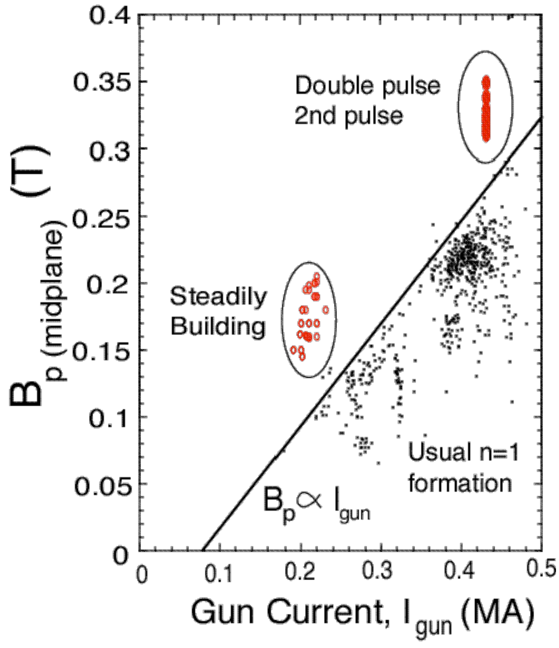

Fig. 5. Edge field scaling with I_{gun} for fast formation plasmas (dots), and for the steady build-up cases (circles).

slightly higher than, but consistent with, most SSPX operations. The plasma density can be lowered: after around 100 shots, and by marginally increasing the programmed vacuum field, it is lower by a factor of two compared with the original shots indicating that the large increase of density during the second pulse can be attributed to poor surface conditioning, and the introduction of a dense edge plasma.

The complete ensemble of SSPX discharges show that the edge poloidal magnetic field (and thus the toroidal current) scale linearly with the injected current. These data appear in Fig. 5, where we plot the peak midplane edge poloidal field vs. the peak injector current. There is a clear upper bound to the magnetic field data corresponding to $B_{pol}(T)=0.6I_{gun}(MA)$, which is exceeded for these two new operating modes.

If the bank could be programmed to deliver a train of similar pulses, the injected helicity is expected to be much higher. Using the helicity balance equation, $dK/dt = 2\psi_g V_g - K/\tau_K$, the limiting helicity content can be found. Helicity input from each pulse is $\Delta K_g = \int_t^{t+\delta t} 2\psi_g V_g dt$, where δt is the pulse width of each pulse in the pulse train, and assuming constant τ_K, the limiting helicity is given by, $K_\infty = \Delta K_g\{1-\exp(-T/\tau_K)\}^{-1}$ where 1/T is pulse frequency. This relation balances the input rate from each pulse with the helicity decay between pulses $K_\infty\{1-\exp(-T/\tau_K)\}$. In this case (with T=300μs and τ_K=1000μs), one would expect $K_\infty=3.8\Delta K_g$, providing of course that the spheromak dissipation time does not grow with time, in which case the upper limit may be significantly higher [2]. Future bank modifications will be made to explore both the addition of several more pulses and the effects of a longer sustained pulse

5. Theoretical studies of spheromak instabilities and field line quality

Reconnection activity in spheromaks is commonly associated with unstable *n*=1 helical perturbations of the central part of the discharge [12, 13]. We have considered the use of either a full length or half-length conducting insert down the center of the spheromak as means to control the stability of the *n*=1 mode, accounting for line-tying at the end electrodes [14]. The insert makes the central current-carrying column look like a hard-core pinch and can increase the threshold for the kinking. The critical total current *I* in terms of the Kruskal-Shafranov current $I_{KS}=pa^2cB_z/L$ for a full length insert is presented in Fig. 6 as a function of *D*, the ratio of the current in the bulk of the column to the total current (sum of the bulk and skin currents): $D\equiv I_{bulk}/I$, $I=(I_{skin}+I_{bulk})$, for various ratios of the insert radius *b* to the plasma radius *a* (where *L* is the length of the plasma column, B_z is an axial magnetic field, and *c* is speed of light). One notes that the insert has to be quite thick, *b*~0.7*a*, to have a significant effect on the kink stability of the central column for a quasi-uniform current distribution (*D*=1). Instead, if an insert with *b*=*a* radius occupies approximately half of the anode-cathode gap *L*, our results indicate that this would lead to an increase of the critical plasma current by roughly a factor of 2 compared to the case of no insert. Nonlinear simulations with an insert are underway and will be reported elsewhere.

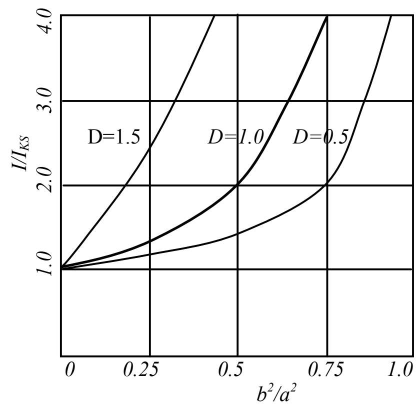

Fig. 6 The critical current normalized to the Kruskal-Shafranov current for various current distributions. Configurations lying below the curves are stable.

The effects of magnetic field fluctuations on the quality of confinement in SSPX have been studied using model magnetic field perturbations **δB** added to the spheromak equilibrium field as derived from edge magnetic probe data using CORSICA. The intrinsic fluctuation-induced, non-axisymmetric part of the magnetic field in SSPX is found from the edge magnetic fluctuations measurements to be a few percent [7]. The perturbation fields used for these calculations are constructed using a helical current filament to simulate a kinking perturbation of the central column. Poincaré puncture plots show for a variety of non-axisymmetric perturbations that a perturbation strength $\delta B/B$ > 3-5 % leads to dramatic degradation of confinement due to formation of magnetic islands and stochastic field regions in the outer part of the plasma. Calculation of heat transport by a Monte-Carlo procedure in the perturbed magnetic field demonstrates that heat transport induced by perturbations at the ~5% level can dominate over the Bohm loss rate (Fig. 7).

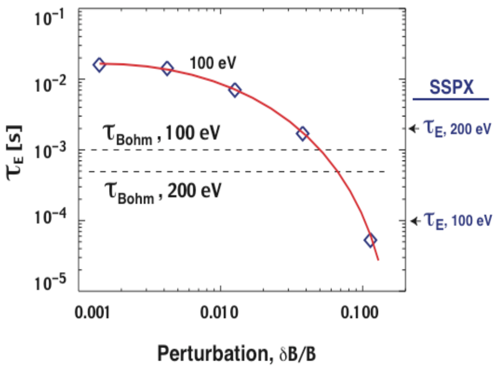

Fig. 7. Predicted energy confinement time vs. magnetic perturbation amplitude from Monte-Carlo calculation.

We are using the nonlinear, resistive MHD code NIMROD to simulate formation and sustainment of spheromak plasmas with increasing realism [15,16,17]. Simulation updates including more accurate gun geometry, bias magnetic fields, and time history of the current-drive produce better tracking of the temperature and magnetic fluctuation history in SSPX. In this instance NIMROD uses single-fluid, resistive MHD equations with a large density diffusivity in the continuity equations to maintain a smooth, nearly constant density inside the plasma and classical Braginski, temperature-dependent resistivity and anisotropic thermal conductivities. In the examples considered here the perpendicular thermal conductivity was a defined constant ($\chi_\perp$=15-21 m^2/s). An isotropic numerical viscosity equal to 2000 m^2/s was used in the momentum equation to provide nonlinear stability. Figure 8 shows temperature time histories from a NIMROD simulation that compare favorably to SSPX Thomson scattering data.

Figure 9 shows electron temperature contours, which align with the magnetic topology including the effects of islands. The plasma has continued to heat at the expense of magnetic energy during a partially-driven resistive decay as the system becomes more axisymmetric and energy confinement improves. From edge-probe data in the *lam06* simulation we note that during the strong drive period t < 0.4 ms the n=1 mode is very active with $\delta B_z / B_z \sim 7\%$, and the spheromak begins to form after 0.4 ms. There are n=1 and 2 modes present for 0.4 ms < t < 1.3 ms, which gradually subside during a quiescent period, 1.3 < t < 4 ms, where $\delta B_z/B_z$ < 1 %; and the plasma heats in excess of 120 eV for the peak electron temperature. The n=2 mode re-emerges and grows to large amplitudes for t > 4 ms, as the spheromak starts to collapse. All of these features are similar to observations in SSPX shots with similar current-drive time histories.

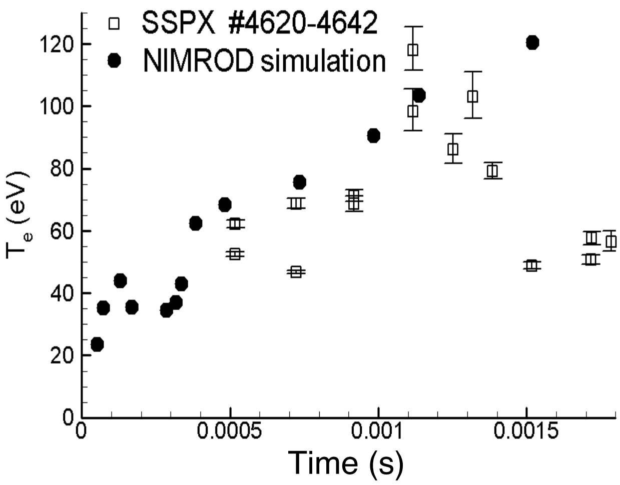

Fig. 8. Peak electron temperature time histories in NIMROD simulations and SSPX Thomson Scattering measurements.

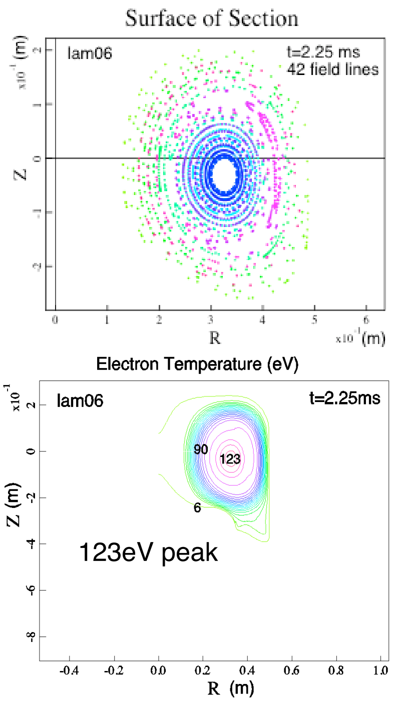

Figure 9. Poincaré puncture plots for magnetic field lines and corresponding electron temperature contours at 2.25ms in NIMROD simulation of SSPX.

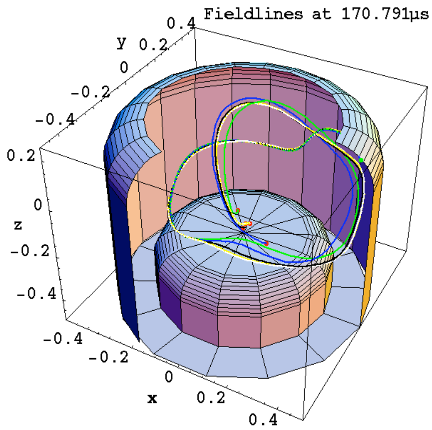

Fig. 10. A knotted bundle of fieldlines resulting from reconnection

We have also simulated double-pulse operation of SSPX with NIMROD. In one example the two current-drive pulses were 300 kA square pulses of duration 0.68 ms separated by 0.3 ms. The magnetic energy was not completely restored in the second pulse, but the electron temperature slightly increased to 60eV. This is much less than the peak electron temperature achieved with current-drive pulses consisting of a peaked formation pulse that transitions into a nearly flat-topped sustainment pulse as in Figs. 10 and 9, and in Ref. 17, and is similar to the experimental results in Ref. 8 contrasted with the results in Ref. 7. NIMROD is proving useful in evaluating alternative pulsed-current-drive operating scenarios in SSPX.

The formation of a spheromak in both experiment and NIMROD occurs when magnetic reconnection converts toroidal flux into poloidal flux. As magnetic field lines remain open during this formation, we call the resulting configuration a mean-field spheromak. Flux conversion occurs when the amplitude of the symmetry breaking, magnetic modes (especially n=1) reach large amplitude. In both experiment and simulation the process can occur either via a continuous "burbling" of the modes or as a sudden event lasting about 50 μs. Comparison of these events in SSPX and NIMROD shows many similarities, including a pulsed increase in the gun voltage. Reconnection is demonstrated by the change in azimuthally averaged magnetic topology with closed contours of azimuthally-averaged poloidal flux forming to generate a mean-field spheromak, and by individual field lines which connect cathode and anode becoming knotted along their trajectory (Fig. 10). The reconnection occurs near current sheets with negative $\lambda = \mu_0 J_{||}/B$, which are particularly strong near the x-point of the mean-field spheromak. Generation of these reversed-current sheets demonstrates the role of localized inductive electric fields including helicity redistribution throughout the volume. They are accompanied by cross-field currents to satisfy $\nabla \cdot \mathbf{J} = 0$. Order-of-magnitude variations in λ throughout the volume significantly increase the dissipation of both magnetic energy and helicity, with the latter loss resulting as the positive and negative regions of λ do not perfectly balance.

6. Future work

The primary goal of the SSPX is to test whether favorable energy confinement scaling can be obtained in a spheromak plasma sustained by coaxial helicity injection. This requires that we produce adequate magnetic field to obtain high-temperature plasmas. Experiments now underway will more fully examine the correlation between high temperatures and low magnetic fluctuations and we are working on designing a new, small diameter coaxial injector to test several theories of magnetic field generation. A previous modification to the power system extended the pulse length a factor of four (from ~1 ms to 4 ms) and the peak magnetic field strength more than doubled, to 0.3 T. Presently, we are constructing a modular capacitor bank to increase flexibility in programming the shape of the current pulse and, or extend the pulse length, which will double the energy coupled to the spheromak by minimizing coupling losses due to impedance mismatch. We are continuing NIMROD simulations addressing different current-drive pulsing strategies, the influence of a conducting insert, and the physics of magnetic reconnection in spheromak formation.

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References

[1] T. R. Jarboe, Plasma Phys. and Control. Fusion 36 945 (1994).
[2] T. K. Fowler Fusion Tech. 29 206 (1996).
[3] E. B. Hooper, *et al.*, Fusion Tech. 29 191 (1996).
[4] E. B. Hooper, L.D. Pearlstein, and R.H. Bulmer, Nuclear Fusion 39 863 (1999).
[5] R.D. Wood *et al.,* Journal of Nuclear Materials 290-293, 513 (2001).
[6] B.W. Stallard, E.B. Hooper, S. Woodruff, *et al*., Phys. Plasmas, 10, 2912 (2004).
[7] H. S. McLean, S. Woodruff, E.B. Hooper, *et al*., Phys. Rev. Lett. 88 125004 (2002).
[8] M. Bessenrodt-Weberpals *et al*., Nucl. Fusion 33, 1205 (1993).
[9] S. Woodruff, D. N. Hill, B. W. Stallard, *et al.*, Phys. Rev. Lett. 90 095001 (2003).
[10] S. Woodruff, H.S. McLean, E.B. Hooper, *et al.*, *Increasing the magnetic helicity content of a plasma by pulsing a magnetized source*, UCRL-JRNL-202013, accepted for publication Phys. Rev. Lett. October 2004.
[11] S. Woodruff, *et al.*, *Controlled and spontaneous magnetic field generation in a gun-driven spheromak*, UCRL-JRNL-207051, submitted to Physics of Plasmas, October 2004.
[12] D.N. Hill, R.H. Bulmer, B.I. Cohen et al. "Spheromak Formation Studies in SSPX", in *Proceedings of the 18th IAEA Fusion Energy Conference* (Sorrento, 2000), IAEA-CSP-8/C, ISSN 1562-4153, (CD-ROM, International Atomic Energy Agency, Vienna, 2001) paper ICP/09.
[13] K.J. Gibson, P.K. Browning, S.J. Gee, S. Woodruff, D.M. Willett. Plasma Phys. Contr. Fus., 42, 1331 (2000).
[14] D.D. Ryutov, R.H. Cohen, L.D. Pearlstein. Phys. Plasmas, 11, 4740 (2004).
[15] R.H. Cohen, H.L. Berk, B.I. Cohen et al., Nucl. Fusion 43,1120 (2003).
[16] C.R. Sovinec, J.M. Finn, and D. Del-Castillo-Negrete, Phys. Plasmas 8, 475 (2001); C. R. Sovinec, T. A. Gianakon, E. D. Held, S. E. Kruger, D. D. Schnack, and the NIMROD Team, Phys. Plasmas 10, 1727(2003).
[17] C.R. Sovinec, B.I. Cohen, G.A. Cone, E.B. Hooper and H.S. McLean, "Numerical Investigation of transients in the SSPX Spheromak," submitted to Phys. Rev. Lett. (October, 2004).