*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-5.047 (2002)*

Route to high temperatures by current amplification in the Sustained Spheromak Physics Experiment (SSPX)

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1. Introduction

For the spheromak to be attractive as a reactor concept it would be necessary to sustain the configuration with a low recycling power, reflected in the current amplification factor: $A_I=I_{tor}/I_{gun}$, where I_{tor} is the toroidal current and I_{gun} is the gun current. It is understood that A_I needs to be around 60 for a reactor [1], although the highest obtained so far in the spheromak has been ~3 [2]. The spheromak is a simply connected toroidal confinement device related to the reversed field pinch in that the q-profile falls at the edge and the first wall is conducting, although the central solenoid is absent. In the spheromak, the paradigm for field generation (and hence current amplification) is the injection of helicity, $K=\int A.B dV = 2\Phi\psi$ where Φ and ψ are linked fluxes. Helicity is additive in the process of electrostatic injection by a coaxial gun [3]: $\dot{K}=2V_{gun}\psi_{gun}$, where V_{gun} is the voltage applied between two coaxial electrodes (giving the rate of toroidal flux injection) and ψ_{gun} is the poloidal vacuum flux connecting them. SSPX [4] is a 1m wide coaxial-gun-driven spheromak with W-coated copper electrodes (FIGURE 1) and a uniquely programmable vacuum field configuration. SSPX was built to assess if confinement can be reasonably preserved during injection, and to address the specific physics of the processes governing helicity injection.

2. Recent results

MHD fluctuations have been suppressed in SSPX by gently driving current at the edge of the spheromak, flattening the λ-profile ($\lambda=\mu_0 J/B$), and giving $\delta B/B$~1%, core T_e=120eV, $<\beta_e>$=4%, and core $\chi_e=30m^2/s$ [5]. SSPX has now been operated over a wide range of density and field, and databases show trends indicative of beta-limited discharges [6]. Specific instabilities have been observed that cap beta (m/n=2/4 [7], interchanges and possible Mercier modes). Given reasonable confinement and evidence for beta-limits, the push has been to raise the field of the spheromak by amplifying current. In recent experiments we have increased the gun-voltage by a factor of two by operating the gun continuously at the ejection threshold (I_{gun}=const. for ~3ms), giving the highest sustained helicity injection rate for SSPX and highest current amplification factor A_I=2.2 [8]. We have also exceeded, by a factor of two, the previous offset-linear scaling of edge field with injected current ($B_p(T)$~$0.6I_{gun}(MA)$ reported in [6]). The raised voltage is accompanied by large amplitude voltage spikes, which originate in the gun (revealed by fluctuation analysis).

3. Modelling

Our main tool for understanding current amplification is the 3D nonlinear resistive MHD code NIMROD. Simulations at high $S(=\tau_R/\tau_A=10{,}000)$ show a continued rise in the field for periods longer than those obtainable in the experiment, although not inconsistent with previous results at lower S in which a dissipation limit was found after t=L/R. Recently, we have installed a constant current model to simulate the experiment. When operating with a simple can geometry, we find that the voltage fluctuations are not present. If, however, the process results from the multiple expulsion of current filaments from the gun (as argued in [8]), it would be necessary to run NIMROD with the correct geometry. The formation of hot-spots on the electrode could generate inductive voltages [9] – electrode physics is not present in NIMROD.

4. Injector probe measurements

An 18 coil (6 x Bz, Br, Bt) probe mounted in a BN sheath was constructed to investigate the processes governing helicity injection. The probe was mounted in the mouth of the gun, designed to the span the gap. At this location, the probe measures all the components of field necessary to determine the injection flux (giving the injection rate), and the gun lambda (to give the ejection thresholds). We found additionally, that by constraining our 2D equilibria in the CORSICA code during formation, we were able to significantly affect the internal lambda profile (FIGURE 2), giving lower fitting errors, a more hollow lambda profile and lowering the safety factor throughout the volume. Such a result indicates the need to constrain equilibria with these field measurements in the future if, for instance, accurate stability analysis is to be performed. We measure the injector flux by spline-fitting the axial field data in the channel, and integrating outwards to the wall (R_2) from the zero-crossing (R_1): $\Psi_{inj} = 2\pi\int_{R_1}^{R_2} rB_z(r)dr$. We find that at most half of the total programmed flux is swept into the confinement region (FIGURE 3c), that it varies with time, and that the fraction depends on the vacuum field configuration that is used. This is in contrast with previous spheromak experiments, in which the injected flux was assumed constant. Such low flux 'capture' explains why we have over-estimated the spheromak helicity when we project using the full gun-flux. FIGURE 3 shows an example of a helicity balance in which the spheromak helicity is measured using an edge poloidal field coil at the midplane (FIGURE 1), calibrated with CORSICA. This is compared with the projected helicity evolution by integrating the product of voltage and flux with dissipation (eq. 3 ref [3]). We find that irrespective of the flux configuration, there is good agreement between the projected and measured helicity during formation. However, marked differences in the flux time-histories, and also in λ_{gun} are produced by change of vacuum field configuration. FIGURE 3e shows one example of gun-lambda for a configuration in which the vacuum fields are radial across the gap ('standard flux' - see FIGURE 1). After a short drive period, the B_z fields fall to zero in the gap, indicating a disconnection. This is to be contrasted with 'modified flux' – in which some fraction of the injector flux penetrates the bottom of the inner electrode: gun flux continues to be finite throughout the shot, λ_{gun} remains low, and voltage reverses, indicating that the spheromak does not disconnect from the source. Finally, when the n=1 mode is onset, the field in the gun becomes asymmetric (FIGURE 4) and the symmetric definition of the injector flux fails (and 2D equilibrium reconstructions become meaningful only in a time-averaged sense). The injected helicity can be expressed as a surface integral (eq. 16 in [10]). The surface area of the asymmetric injection could be lower than a symmetric one and explain the fall in the helicity injection rate during onset of the n=1 mode (V_{gun} can be attributed to sheaths /resistive-losses on open lines [6]), although we have yet to measure this.

5. Summary

Databases indicate a trend of beta-limited discharges, suggesting an obvious route to high temperature by current amplification (raising B). We have investigated current amplification within the context of helicity injection and found operating modes where the gun voltage is doubled, giving highest $\dot{K}$ for a sustained spheromak, and highest A_I in our experiment. We have used 3D modelling and a probe mounted in the injector to further characterize the processes governing helicity injection. We plan more diagnostics to investigate helicity injection and will modify bank and gun to increase helicity injection rate.

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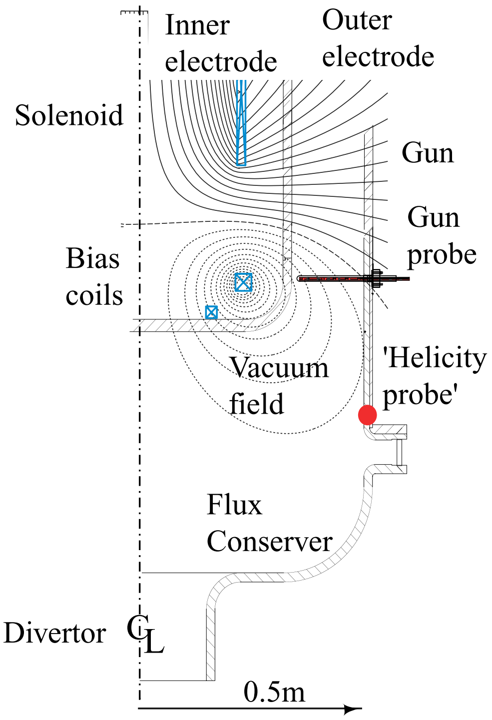

Figure 1. SSPX with probe locations and the ‘modified flux’ vacuum field configuration.

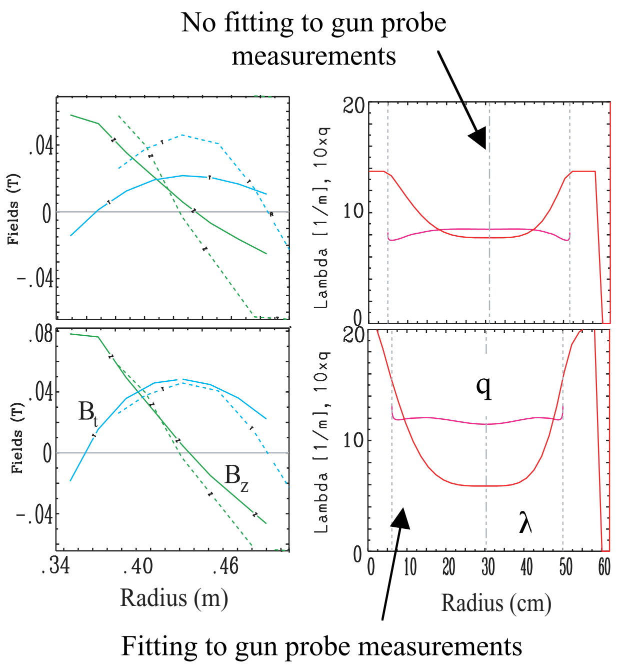

Figure 2. CORSICA fitting to gun probe measurements markedly changes internal profiles during formation (shot S#8114)

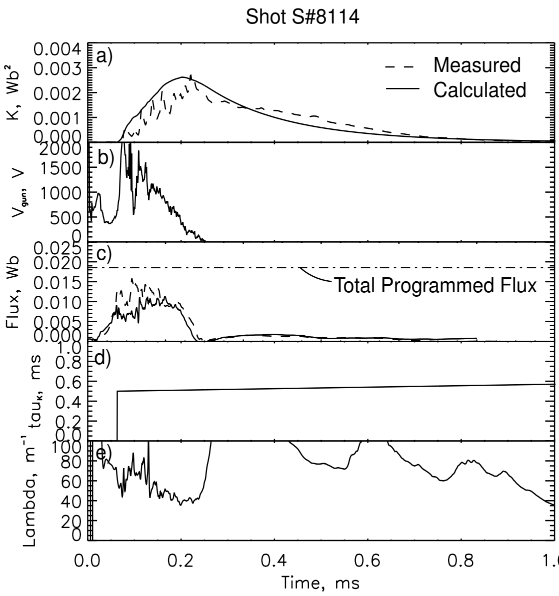

Figure 3. a) Measured and projected helicity; b) gun voltage; c) injector flux (total programmed flux: dot-dash, inferred flux: dash, measured flux: solid); d) dissipation time; and e) injector lambda ($=\mu_0 I/\psi_{gun}$).

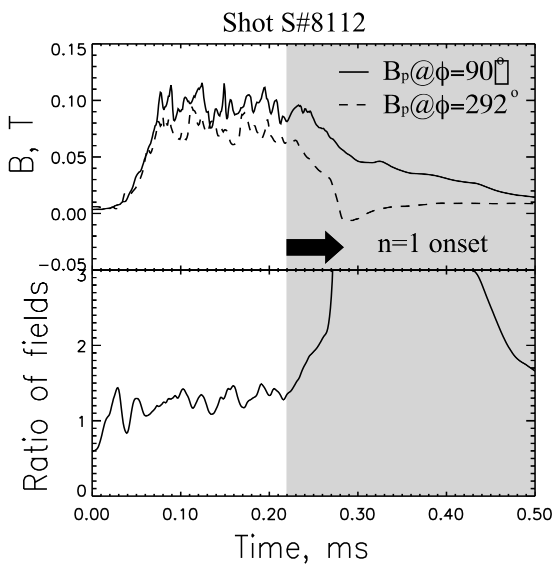

Figure 4. Onset of asymmetry shown in edge poloidal field in the gun at two toroidal locations. Fields become asymmetric at the onset of the n=1 mode (determined from mode-analysis of a toroidal magnetic-probe array).

* Work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.