Processes that govern the gun voltage in SSPX

S. Woodruff, B. W. Stallard, C. T. Holcomb, C. Cothran*, and the SSPX Team
Lawrence Livermore National Laboratory, L-637, 7000 East Ave, Livermore, CA94550
**Swarthmore College, 500 College Avenue, Swarthmore, PA 19081*

Abstract. The physical processes that govern the gun-voltage and give rise to field generation by helicity injection are surveyed in the Sustained Spheromak Physics experiment (SSPX) using internal magnetic field probes and particular attention to the gun-voltage. SSPX is a gun-driven spheromak, similar in many respects to CTX, although differing substantially by virtue of a programmable vacuum field configuration. Device parameters are: diameter=1m, I_{tor}~400kA, T_e~120eV, t_{pulse}~3ms. SSPX is now in its third year of operation and has demonstrated reasonable confinement (core χ_e~30m^2/s), and evidence for a beta limit ($<\beta_e>_{vol}$~4%), suggesting that the route to high temperature is to increase the spheromak field-strength (or current amplification, $A_I=I_{tor}/I_{inj}$). Some progress has been made to increase A_I in SSPX (A_I=2.2), although the highest A_I observed in a spheromak of 3 has yet to be beaten. We briefly review helicity injection as the paradigm for spheromak field generation. SSPX results show that the processes that give efficient injection of helicity are inductive, and that these processes rapidly terminate when the current path ceases to change. The inductive processes are subsequently replaced by ones that resistively dissipate the injected helicity. This result means that efficient helicity injection can be achieved by harnessing the inductive processes, possibly by pulsing the gun. A pulsed build-up scenario is presented which gives A_I>3 and emphasizes the need to maintain reasonable confinement while the field of the spheromak is being built.

I Introduction

In order for the spheromak to serve as a vehicle for fusion, current amplification needs to be demonstrated (or at least understood). Typically, for a reactor, it is expected that A_I needs to be around 60 [1] – that is: the ratio of the toroidal current to the current injected at the electrodes needs to exceed a large number in order for the recirculating power to be low enough to make a reactor economically viable. SSPX [2] has been built to address *field generation* and *confinement* – two necessary components of a successful concept. Our first objective has been to demonstrate reasonable confinement (obtained core χ_e ~30m^2/s [3]). By taking a large set of data, we have been able to determine trends that may indicate a beta limit [4], which implies that high field spheromaks will give high temperatures. Recently we have been able to increase the impedance of the gun, giving a factor of two increase in the sustained helicity injection rate and a raised current amplification [5].

Helicity remains the paradigm for spheromak physics. Helicity is a measure of the linkage of the magnetic flux, is additive, and is conserved in instances where magnetic energy is not (e.g. in reconnections). The helicity injection rate of the gun-driven spheromak is usually expressed in terms of the gun voltage and the flux linking two coaxial electrodes: $\dot{K} = 2V_{gun}\psi_{gun}$, and the spheromak helicity evolution is expressed as:

$$K(t) = \exp\left(\int_0^t \frac{-dt}{\tau_K}\right)\int_0^t 2V_{gun}(t)\psi_{gun}(t)\exp\left(\int_0^{t'} \frac{dt''}{\tau_K}\right)dt' \qquad (1)$$

The main issues concerning helicity injection for the spheromak are to determine what processes govern V_{gun}, and finding a process to exploit that gives efficient formation or sustainment of the spheromak (with minimum effect on the confinement). Here we consider one process in detail (the expansion of a current sheet) that gives very high voltages, and characterize it with a probe mounted in the injector (see FIGURE 1) and by comparison with other less efficient processes.

The SSPX is a Marshall-gun-driven spheromak, 1m in diameter with a gun that is of equal radius to the flux conserver, with 9 independently programmable field coils that generate the vacuum field (see FIGURE 1). The plasma is well diagnosed [6], although here we consider only the magnetic- and gun-circuit-diagnostics. We have achieved clean conditions with the burn-through of most impurities (OVI is notable exception): when running clean, radiated power is <10% of total input power.

The paper is structured as follows. Section II contains the results and analysis; section III is the conclusion; and section IV outlines our plans.

II Results and analysis

In order for the current sheet to be expelled from the gun, the magnetic pressure resulting from the injected current must exceed the pressure from the programmed vacuum field, resulting in an ejection threshold expressed usually in terms of the injected current: $I_{gun} > I_{crit}$ for ejection. When I_{gun} falls below I_{crit}, the injection of helicity ceases [7]. For $I_{gun} \sim I_{crit}$, the helicity in a current sheet can be rewritten in terms of the inductance of the sheet, L, and the electrode separation distance, Δ [8]:

$$\dot{K} = \mu_0 I_g^2 . \Delta L / \tau$$

where τ is the time taken for the sheet to disconnect from the gun. Helicity injection in this instance means the injection of inductive energy. The inductance of the current sheet is essentially that of a coaxial gun [9]:

$$L = \frac{\mu_0}{2\pi} l_{gun} \log\left(\frac{r_2}{r_1}\right)$$

where r_2 and r_1 are the outer and inner electrode radii respectively, and l_{gun} is the length of the gun, and for SSPX, L~50nH. By combing these two expressions (for L and K) we observe that there is a geometrical relationship for the magnetic helicity introduced with each current sheet (more below). Furthermore it can be shown that the injection of each current sheet is efficient, proving that the injection time is short compared with the resistive dissipation time of the sheet [8].

We observe the highest gun-voltages for symmetric ejection of the initial current sheet. FIGURE 2 shows the voltages obtained by: 1) operating with $I_{gun}=I_{crit}$ transiently ($V_{gun}\sim$7kV – consistent with the full gun inductance); 2) operating with $I_{gun}=I_{crit}$ continuously ($V_{gun}\sim$1kV) and 3) operating with $I_{gun}>I_{crit}$ continuously ($V_{gun}<$300V). These processes are associated either with inductive or resistive processes, and characterized by the current path. A changing current path (as depicted in FIGURE 3a) is associated with the higher voltages [5], whilst a static current path (FIGURE 3b) results in a voltage that can be attributed exclusively to a resistive element and sheath drops [4]. In order to obtain high helicity injection rates it is necessary to exploit a process that gives a high gun voltage, namely the expulsion of a current sheet from the gun.

A circuit model for the pulsed injection uses switches controlled by the injector current. FIGURE 4 shows a two-section circuit for injection of a current sheet: the left side is the bank, and right side is the spheromak. At t=0, S_1 is 'up', S_2 is open and the bank energy is deposited into the spheromak as inductive energy. When the ejection threshold is reached, then S_1 switches 'down' to a short path in the gun, and the gun voltage becomes near-zero, while the switch S_2 closes as the spheromak disconnects from the gun and decays resistively. It may be possible to produce multiple pulses in this manner providing that the current path is controllable.

The gun probe shows evidence for reconnection as the injected current falls to $I_{gun}=I_{crit}$. The injected flux is measured in the gun by assumption of axisymmetry and integration of the axial field from a zero crossing (near the center of the channel, R_0) to the wall, R_1: $\psi_{gun} = 2\pi\int_{R_0}^{R_1} rB_z dr$ - determined as a function of time, shown in FIGURE 5. (To our knowledge this is the first direct time-dependent measurement of the injected flux for a gun-driven spheromak). For the shots surveyed, the injector flux appears to be only half (10mWb) of the total programmed solenoid flux (20mWb) – and consistent with all of the flux below the puff valves. As I_{gun} falls to I_{crit}, the axial field in the channel falls at a rate perhaps consistent with resistive diffusion through the gun plasma, ultimately falling to zero. The existence of a disconnected spheromak downstream from the probe indicates that field lines must have reconnected close to the probe. Analysis of a wide range of shots reveals that the assumption of axisymmetry does not hold in all cases, making the determination of the helicity injection rate ($2V_{gun}\psi_{gun}$) problematic. The current path is observed to change also during the reconnection: toroidal field in the channel falls to zero as the current path changes from flowing into flux-conserver to flowing in the gun above the location of the probe. As the field reconnects in the gun, the gun-voltage falls to ~zero, consistent with the S_1 switching to the down position in FIGURE 4 – the threshold appears to operate as a high current switch.

Assuming that it is possible to repeatedly meet the threshold by modulating the current (or field in the gun), then one might expect to be able to produce a series of current sheets that eject and merge with the spheromak in the can. (This idea is borrowed from [10] and references). Projecting the evolution of the spheromak helicity shows the possibility of obtaining high A_I for pulsed injection. FIGURE 6 is the helicity evolution as per equation 1 for a series of current sheets with parameters that have been measured in the experiment – V_{gun}~7kV (modeled as an exponential function), ψ_{gun}~10mWb and τ_K~1ms. By inspection, the current amplification reaches saturation after ~$2\tau_K$, making it clear that irrespective of the magnitude of V_{gun}, the dissipation time must grow with time (in order to reach high A_I). An argument that this should occur is that the spheromak may rapidly heat to a beta limit, in which case it can be shown that $\tau_K \propto K^{1.5}$, although data to substantiate this is lacking. Still, it may be possible to exceed previous current amplifications by examining other limiting factors.

We are considering 4 possible limits to field build-up – these are dissipation, geometry, dynamic pressure balance and merger-time. These are discussed only cursively here:

- The *dissipation limit* results when the losses match the input: $2V_{gun}\psi_{gun} = K/\tau_K$, with a fixed dissipation time, K becomes fixed. One optimistic model points to a continued increase in the dissipation time – ensuring that a dissipation limit is never reached [11]. There is some tentative evidence from the experiment that the dissipation time increases with time, perhaps in a manner consistent with a beta limit [5].
- The *geometrical limit* is an extension of the dissipation limit - this is shown in our initial derivations above for the helicity of the current sheet: the injection rate depends explicitly on the log of the ratio of radii of the inner and outer electrodes. Presumably, by increasing this ratio (e.g. by widening the separation), higher helicity injection rates would be possible. This result runs somewhat counter to the current understanding that the voltage generally depends on $1/r_1$ [12], although this may be valid for continuous operation with steady flow.
- The limit given by a *dynamic pressure balance* has been examined by the CT fueling community to a greater degree – their concern was that the accelerated CT would penetrate the object into which it was being accelerated ([13] and references). Here ρv^2 can be significantly smaller than the magnetic pressure at the ejection threshold, in which case, the ejection threshold may become modified by the presence of the spheromak, impeding further ejecta.
- The merger-time limit results from the need for the injected plasma to merge with the spheromak before it has resistively decayed. One could anticipate that a hot spheromak

would exclude the field of an injected sheet, and thus would dissipate before having the possibility of merging.

Conclusion

The physical processes that govern the gun-voltage and give rise to field generation by helicity injection are surveyed in SSPX using internal magnetic field probes and particular attention to the gun-voltage. Results show that the processes that give efficient injection of helicity are inductive, and that these processes rapidly terminate when the current path ceases to change. The inductive processes are subsequently replaced by ones that resistively dissipate the injected helicity. A pulsed build-up scenario is presented which gives $A_I>3$ and emphasizes the need to maintain reasonable confinement while the field of the spheromak is being built. Various possible limits to the helicity build-up of the spheromak are outlined.

Further work

Initially, we plan to obtain data for 2 pulses by splitting the formation bank (LRC circuit) into two halves and firing independently with a delay. This will allow us to assess whether in principle it is possible to produce two current sheets and confirm that the helicity introduced by their injection is additive. We are also simulating pulsed operation with the 3D resistive MHD code NIMROD, although as yet we have not produced simulations of the current sheet as discussed in this paper. SSPX will operate for another 3 years to further investigate field generation and confinement. Our objectives are to demonstrate temperatures of a few hundred eV in a manner that is sustained. We plan to make several modifications to the machine (2^{nd} gun, extra diagnostics) and to the bank (modularized).

Acknowledgements

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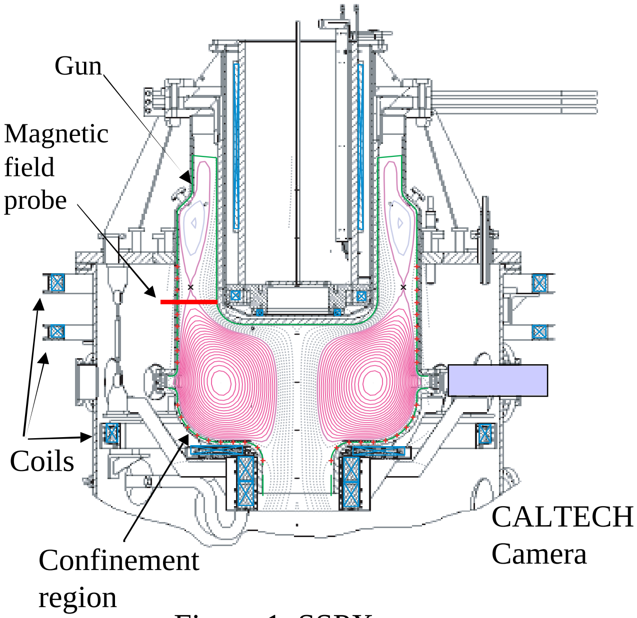


Figure 1. SSPX

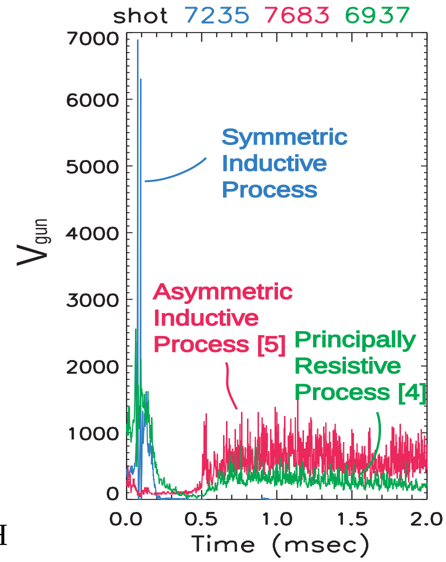


Figure 2. Gun voltages for different operating modes in SSPX

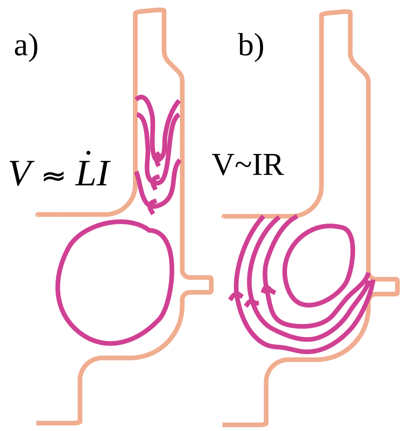
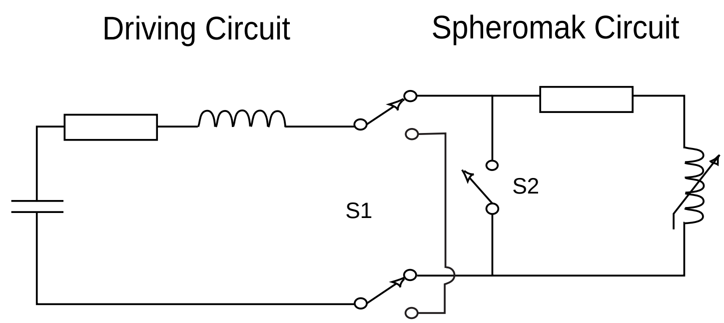


Figure 3. Current paths: a) time-varying, b) static



S1 switches to next branch when I_gun < I_crit
S2 is open at t=0,closes when I_gun < I_crit

Figure 4. Circuit for injection of a single current sheet.

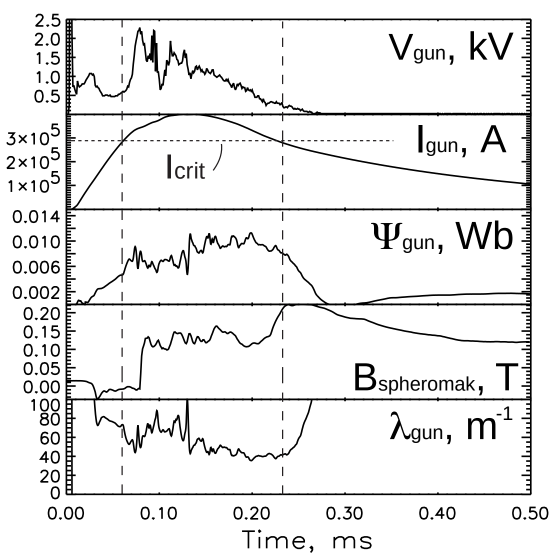


Figure 5. Measured V, I, ψ, B and λ

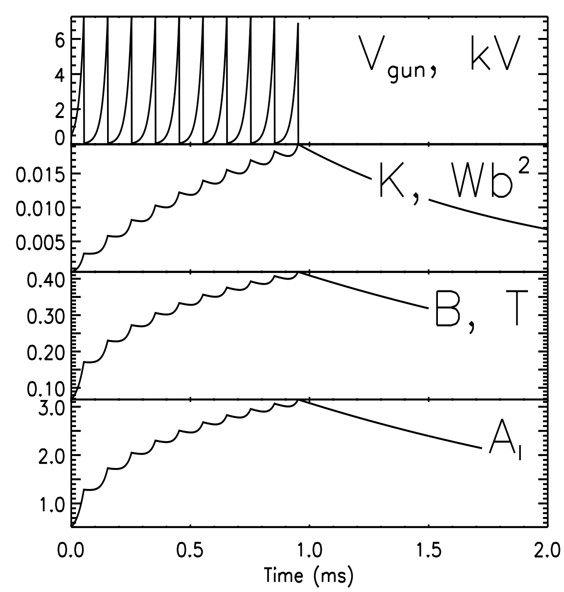


Figure 6. Projected helicity evolution for a multi-pulse scenario using experimentally measured parameters (V_{gun}, ψ_{gun}, τ_K)