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Spheromak Buildup in SSPX using a Modular Capacitor Bank *

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Introduction

The Sustained Spheromak Physics Experiment (SSPX) [1] was designed to address both magnetic field generation and confinement. The SSPX produces 1.5 - 3.5msec, spheromak plasmas with a 0.33m major radius and a minor radius of ~0.23m. DC coaxial helicity injection is used to build and sustain the spheromak plasma within the flux conserver. 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 $|\delta B/B|_{rms}$ [2]. With these optimizations, spheromak plasmas with central T_e >350eV and β_e ~5% with toroidal fields of 0.6T [3] have been obtained. 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 [4].

The original SSPX power system consists of two lumped-circuit capacitor banks with fixed circuit parameters. This power system is used to produce an initial fast formation current pulse (10kV, 0.5MJ formation bank), followed by a lower current, 3.5ms flattop sustainment pulse (5kV, 1.5MJ sustainment bank). Experimental results indicate that a variety of injected current pulses, such as a longer sustainment flattop [5], higher and longer fast formation [6], and multiple current pulses [7], might further our understanding of magnetic field generation. Although the formation bank can be split into two independent banks capable of producing other injected current waveforms, the variety of current waveforms produced by this power system is limited. Thus, to extend the operating range of the SSPX, a new pulsed-power system has been designed and partially constructed. In this paper, we discuss the design of the programmable bank and present first results from using the bank to increase the magnetic field in SSPX.

Experimental Setup

The modular bank [8] consists of 30 independently triggered modules; 15 modules are currently available for experiments. Each module consists of a 4mF, 5kV, 50kJ capacitor, an optically triggered thyristor, a current limiting inductor, protection diodes, and low resistance cables to connect each module to the SSPX injector. Because the high-energy storage capacitors cannot support current output >50kA, a current limiting inductor is installed between the capacitor and the plasma load. The inductance of each module can be varied to

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provide slow and fast-rise time current pulses. Two independently controlled high voltage charging supplies can be used to charge individual modules or groups of modules to different voltages. Each module is fired independently using a solid-state optically triggered thyristor.

The modular bank was designed to provide a variety of injector current waveforms. The SSPX pulsed power circuit was modeled using a SPICE program and some of the predicted current waveforms are shown in Figure 1; the standard formation followed by sustainment waveform is also plotted for comparison (Fig. 1d). The first waveform objective is a single high current pulse, which is obtained by firing all 30 modules simultaneously. The output from the 30 modules is estimated to be near a mega-ampere. The second objective is an extended formation pulse. This is achieved by firing a portion of the modules. The third objective is a low current sustained pulse much like the output of the present sustainment bank. This is achieved by firing modules at equal intervals. The peak output current decreases as the time between firing intervals increases. Another waveform objective (not shown) includes a train of fast rise time pulses on top of a low current sustainment pulse. This is achieved by firing groups of modules at equally spaced time intervals. The modular bank provides a high degree of flexibility in injected current pulse shape that can be used with or without the initial formation and, or, sustainment banks.

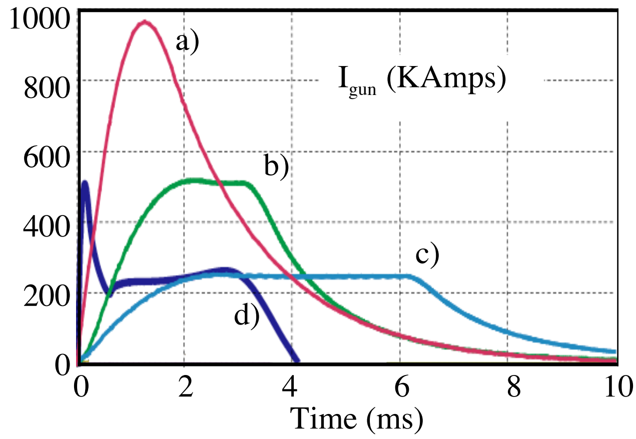

Figure 1. *Predicted current waveforms from the new modular bank; a) ~1 mega-ampere current pulse, b) extended formation current pulse, c) long current pulse and d) standard formation with sustainment pulse for comparison. Multiple current pulse not shown.*

Experimental Results

Shown in Figure 2 is a time history of a discharge with a single high current formation pulse (solid lines); a standard formation followed by sustaiment discharge is plotted (dashed lines) for comparison. For this discharge, the formation bank and modular bank (15 modules) are configured to provide a 500μs, 540kA current pulse (Fig 2a.). As seen in Figure 2c, the edge poloidal field builds to 0.45T, the highest value ever measured on SSPX. For the spheromak to be a viable fusion concept using helicity injection as a means to generate the magnetic fields, a high current amplification (ratio of toroidal plasma current to gun current) is needed [9]. Because the toroidal current is not measured directly, but computed from MHD equilibrium reconstruction, we use the ratio of the measured edge poloidal field to the measured injected current (edge B_p/I_{gun}) to provide an indication of the current amplification. The long pulse formation discharges also have the highest B_p/I_{gun}=0.85T/MA.

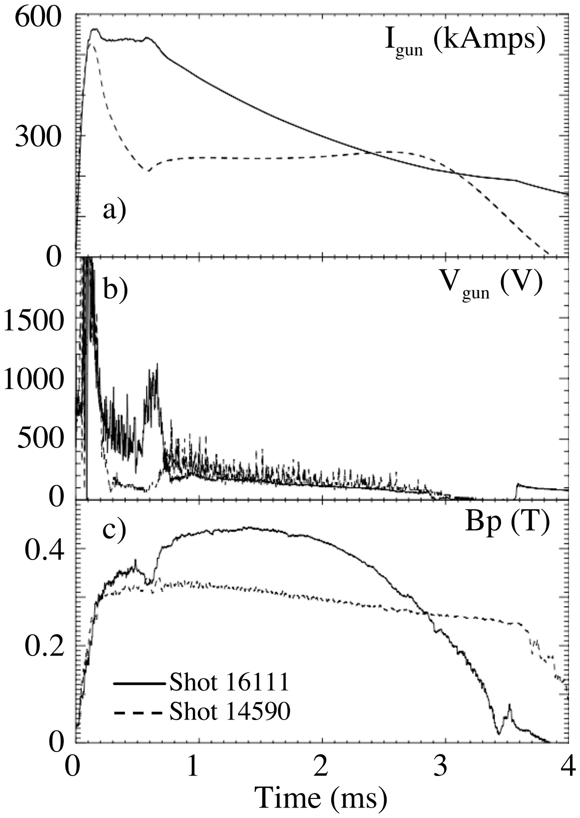

***Figure 2**. Time history of a long formation pulse discharge (solid) with standard fast formation followed by sustainment current pulse (dashed); a) injected current, b) gun voltage, and c) highest edge poloidal field measured on SSPX.*

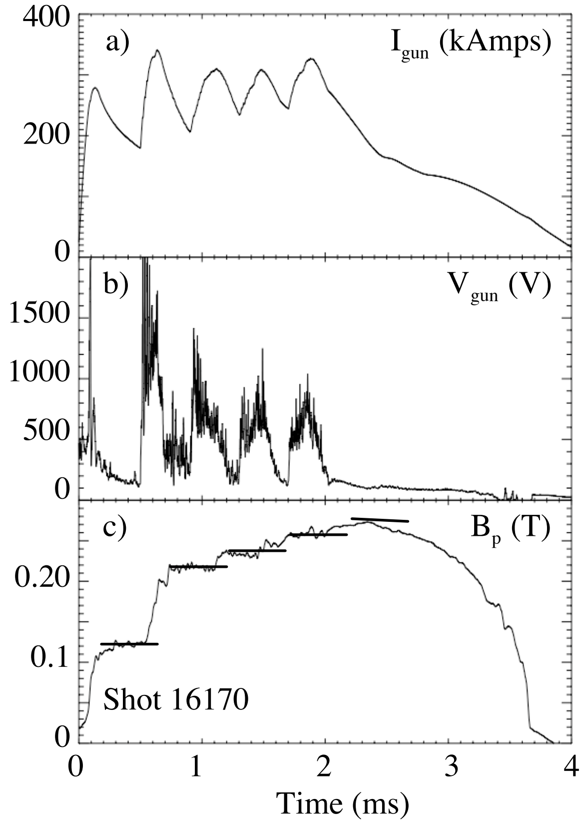

***Figure 3**. Time history of a multiple current pulse discharge; a) injected current with 5 pulses, b) gun voltage, and c) edge poloidal field showing stepwise increase in field. Note: I_{gun} and B_p y-axis scale different than in Fig. 2.*

We can also generate field efficiently using multiple current pulses, as shown in Figure 3. The injected current, Fig. 3a, shows a train of five ~200kA pulses on top of a 100kA flattop current pulse. From helicity balance $dK/dt= -K/\tau + 2V_{gun}\varphi_{gun}$, (where τ is the dissipation time) the rate of helicity injection is given by $2V_{gun}\varphi_{gun}$, where V_{gun} is the voltage applied between the two coaxial electrodes and φ_{gun} is the poloidal vacuum flux connecting them. As seen in Fig 3b, the injector gun voltage is similar for the last three current pulses indicating similar rates of helicity injection for each pulse. Each pulse of helicity injection provides a build up of magnetic field as measured at the edge of the plasma at the mid-plane, see Fig 3c. After the first two pulses the rate of magnetic field buildup is constant, that is, a stepwise increase in field is observed and the ratio of measured edge B_p to injected current is B_p/I_{gun}=0.8T/MA which is very close to that obtained with the single high-current pulse.

Other configurations have also been explored. Programming the fast formation with sustainment and modular banks together, longer pulse discharges (>6ms) have been achieved. The modular bank has also been used to simulate the sustainment bank current waveform shape but at higher injected current: ~300kA injected compared to 230kA. This configuration produced higher magnetic fields ($B_p \propto I_{gun}$), which in turn should lead to higher temperature spheromaks ($T_e \propto B_p^2$) [3]; T_e measurements were not available for these discharges.

Summary and future work

Experiments using the modular capacitor bank have produced discharges (long formation) with the highest edge poloidal fields measured on SSPX and discharges (multi-pulse) that continue to build magnetic field in a stepwise manner. The ratio of B_p/I_{gun} for these two modes (~0.8T/MA) exceeds the value of B_p/I_{gun}=0.65T/MA obtained with a standard discharge (fast formation followed by sustainment discharge as in Fig. 2). The higher ratio with the new waveforms may reflect longer total formation pulse duration than previous discharges, as suggested by NIMROD [6] simulations. Table 1 summarizes field buildup (the amount of magnetic field for a given injected current) results for four different injected current waveforms. In the near future, another 15 modules of the modular bank will be ready for operations. Future experiments will include adding more pulses to the multi-pulse waveform, longer formation pulse, long pulse sustainment and mega-ampere injected current discharges.

Configuration	**I_{gun} (MA)**	**B_p (T)**	**B_p/I_{gun} (T/MA)**	**Shot number**
Fast formation	0.53	0.34	0.65	14590
Slow building [5]	0.22	0.19	0.83	7683
Long formation	0.54	0.45	0.85	16111
Multi-pulse	0.33	0.27	0.80	16170

Table 1. *Summary of edge poloidal field buildup for different injected current pulse shapes.*

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