BANK UPGRADE FOR SSPX AT LLNL[*]

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Abstract

A new 5kV, 1.5MJ modular capacitor bank has been designed for the Sustained Spheromak Physics Experiment (SSPX) at LLNL. The new bank consists of thirty 4mF capacitors that are independently controlled by light-triggered thyristors. By closing all switches simultaneously, the bank will provide a mega-ampere discharge. The new bank will also allow additional capabilities to SSPX, including higher peak gun current, longer current pulses, and multi-pulse plasma buildup. Experiment results for a single stage prototype will be presented.

I. INTRODUCTION

Currently SSPX has two capacitor banks used for plasma production. The formation bank is a 12 capacitor 10kV, 0.5MJ bank that produces a 0.5ms 600kA current spike to initially create the plasma in SSPX. The sustainment bank is a 30 capacitor, 5kV, 1.5MJ bank that produces a 3ms 250kA current pulse that sustains the plasma. Unfortunately, these two banks provide little variability in pulse shape.

The modular bank is designed to deliver a greater variety of pulse shapes to SSPX. It is much like the sustainment bank except that each capacitor has its own dedicated switch so that it is more like thirty mini-banks than a single large bank. Each switch in the bank can be individually triggered allowing each capacitor to begin its energy dump into the plasma at any point in time. All switches can be triggered together to deliver a single large current spike, or, switches can be triggered in sequence to deliver a longer lower current pulse. Multiple pulses can be created by triggering sections of the modular bank in intervals.

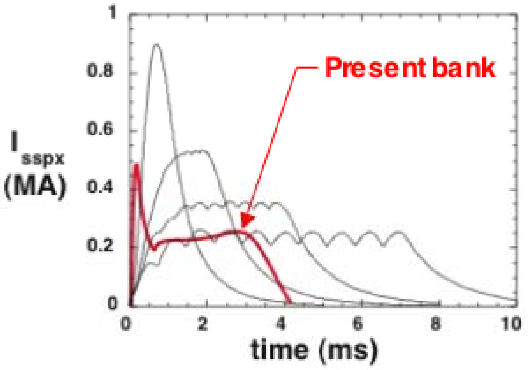

Figure 1. Typical current pulse delivered by the formation and sustainment banks overlaying waveform objectives for the modular bank.

II. AN INDIVIDUAL MODULE

Each module consists of a 4mF, 5kV, 50kJ capacitor, an optically triggered thyristor, a current limiting inductor, two series diodes, one anti-parallel diode, and low resistance cable to connect each module to SSPX.

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14. ABSTRACT

A new 5kV, 1.5MJ modular capacitor bank has been designed for the Sustained Spheromak Physics Experiment (SSPX) at LLNL. The new bank consists of thirty 4mF capacitors that are independently controlled by light-triggered thyristors. By closing all switches simultaneously, the bank will provide a mega-ampere discharge. The new bank will also allow additional capabilities to SSPX, including higher peak gun current, longer current pulses, and multi-pulse plasma buildup. Experiment results for a single stage prototype will be presented.

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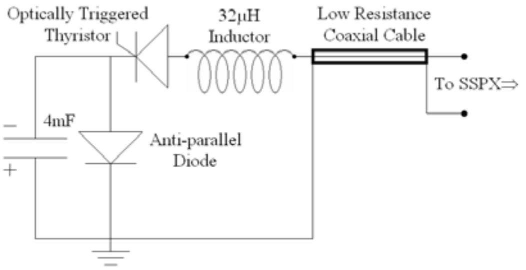

Figure 2. Functional schematic of a module—series diodes are not shown

Originally, it was planned to convert the existing sustainment bank into the modular bank, thus, the design process was centered on meeting specifications for the capacitors already in the sustainment bank. The capacitors cannot support current output greater than 50kA, therefore, the first step was to limit the current out of each module. Using a SPICE program and a series resistance-inductance plasma model, ~0.5μH and ~2mΩ, as determined from previous output waveforms, we found that 32μH will limit the current output to 50kA when the capacitors are charged to the 5kV limit.

Each module required one of these inductors, so several geometries were explored during the design. The first was a toroid. The fact that a toroidal inductor contains its magnetic field better than a solenoid appealed to the project since thirty of these inductors were going to be placed in the same room. However, the toroid was abandoned because it occupies greater volume than a solenoid and is more difficult to fabricate. Also, there was a degree of uncertainty as to whether or not the short distance between the input and output terminals of the toroid would cause a shorting hazard. As a result, it was determined that a solenoid was the better choice—it's easier to fabricate, the volume it occupies tends to be less than a toroid, and the input and output terminals are on opposite sides, thus, shorting between terminals is not likely. Fringe fields were initially a concern—stray field could create mutual inductance with its neighbors. However, the fringe fields are negligible at one diameter distance from the edge of the coil because $B \sim R^{-3}$. If the coils are placed as such, then mutual inductance is not a problem.

A diode is placed anti-parallel to the capacitor to prevent back charging after triggering a module. This is important primarily because the capacitor is electrolytic—reversing its charge greatly shortens its lifespan. Additionally, the diode allows the electrons that would recharge the capacitor to continue circulating through the load, thus increasing the energy transfer. The present sustainment bank does not utilize this diode and succeeds in an energy transfer to the load of only 34% while the capacitors are recharged with 29% of their initial energy; the rest is dissipated in the transmission lines.

Because the plasma load is low resistance, it was necessary to find low resistance cable to facilitate energy transfer to the plasma. Therefore, cable with a large center conductor was chosen. This succeeds in transferring as much energy to the load as possible. Of course, more energy is transferred when all modules are fired in parallel than if they are fired in series—an estimated 85% energy transfer is expected when all thirty modules are fired simultaneously.

Not shown in the schematic are two series 5kV diodes that are placed between the inductor and the thyristor. Their purpose is to keep the formation bank from discharging into the modular bank in the event that only the formation bank is charged. If only the formation bank is charged, then 10kV is across the load (the Spheromak) until a plasma forms. If the capacitors of the modular bank are not charged then there is a 10kV potential difference that will attempt to charge them. Thus, the series diodes are present to hold off the 10kV at the Spheromak until the plasma forms. Each diode has a 2μF, 5kv capacitor, in series with a 2Ω resistor snubber circuit across it to distribute the voltage across the diodes evenly and to protect against high frequency transients since the diodes are easily damaged by large dI/dt.

The final major component in our system is an optically triggered thyristor. The existing capacitor banks use Ignitron switches because they can handle large currents—the models in present use can handle up to 700kA. This worked well since they were designed for a single mass charge dump—only two parallel ignitrons are required for each bank. Ignitrons are large tubes filled with liquid mercury. A trigger pulse initiates a mercury plasma, which creates a conducting bridge between the anode and cathode. For ignitrons to work effectively the anode requires heating to keep liquid mercury from condensing on insulating surfaces, which could make a permanent connection between the cathode and anode of the switch. Additionally, the cathode requires cooling to condense the mercury after use, thus opening the switch for the next shot. Heating the anode with lamps and cooling the cathode with pressurized water is not a problem when only four ignitrons are in use, but the modular bank is to use 30 switches. Thirty ignitrons appeared implausible, so solid state devices were examined. Thyristors are much smaller than ignitrons; they require no cooling or heating and do not pose a mercury safety hazard. The fact that these thyristors are optically triggered reduces the risk that they will misfire if the cathode is pulled negative by another module or by stray EMF. The thyristor is also protected from fast transients by a snubber circuit just like the series diodes.

III. PULSING CAPABILITY

As stated previously, the purpose of creating a modular bank was to allow for pulse shape variability in the waveforms supplied to SSPX.

The first waveform objective was a single high current spike, which is obtained by firing all 30 modules simultaneously. The output from the bank is estimated to be near a mega-ampere.

The second objective was a low current sustained pulse much like the output of the present sustainment bank. This is achieved by firing modules at equal intervals over some time period. The peak output current decreases as the firing time period increases.

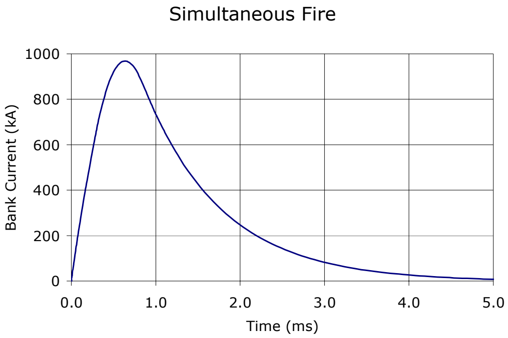

Figure 3. Simulation results showing a single current spike created by firing 30 modules simultaneously.

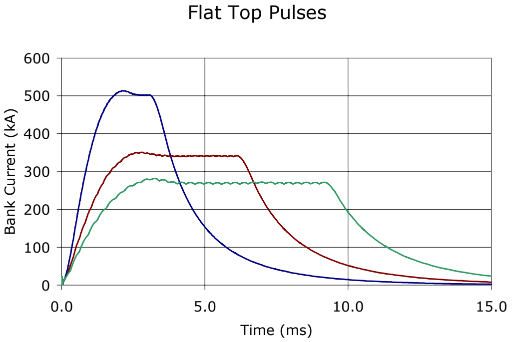

Figure 4. Simulation results showing flat top pulses produced by firing all 30 modules at equal intervals over 3, 6, and 9ms.

A multi-spike pulse is the third waveform objective. This can be achieved by firing groups of modules at equal intervals over a time period. For instance, 15 modules at t_0, and 15 at $t_0 + t_i$ would produce a two spike pulse.

The modular bank provides a degree of flexibility in pulse shape that the formation and sustainment banks cannot. This variability will allow for new and different plasma experiments with SSPX and will aid in furthering our understanding of Spheromak plasma physics.

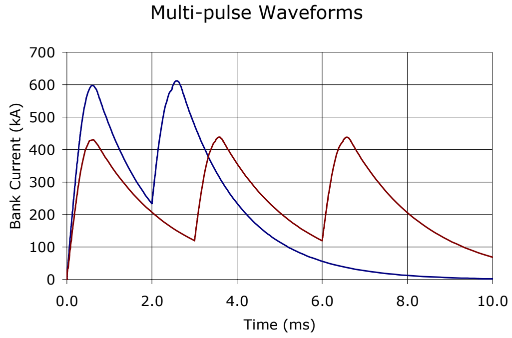

Figure 5. Simulation results showing multi-pulse waveforms. Using 15 modules per spike and firing them 2 ms apart produced two spikes. Using 10 modules per spike and firing them 3ms apart produced three spikes.

IV. MODULE PROTOTYPE EXPERIMENTAL DATA

The plasma load is dynamic—there are fluctuations in the resistance and inductance of the plasma. Therefore, it was decided that building a prototype would ensure that normal operation would not overburden the components in the module. The prototype was then connected to SSPX and used in multiple scenarios—fired alone, fired with the formation bank, fired with both banks, etcetera. The data looks much as expected and all components withstood repeated use. With the successful demonstration of the prototype, a 30 module bank is in development.

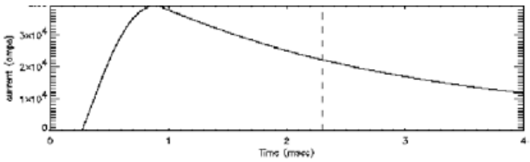

Figure 6. Prototype output when charged to 5kV and fired alone.

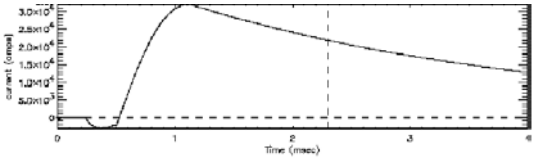

Figure 7. Prototype output when fired on top of the Formation Bank. Prototype is charged to 4 kV; Formation Bank is charged to 6.8 kV.

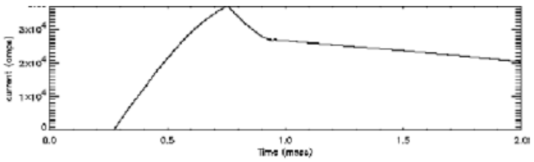

Figure 8. Prototype output when fired on top of the Formation Bank.

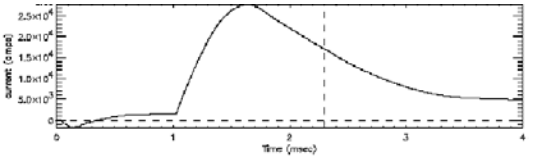

Figure 9. Prototype output when fired on top of the Formation and Sustainment Banks. Prototype and Sustainment Bank charged to 3.8kV; Formation Bank charged to 6.8kV.

V. SUMMARY

Using thyristors with high peak forward current ratings, it was possible to design a modular capacitor bank with a switch for each capacitor. This allows for a greater degree of variability in the pulse shapes supplied to SSPX. The prototype module was constructed and tested to ensure that all components were operating within their ratings. With its success, 29 more modules will be built to complete the modular bank. Using it in conjunction with the present formation and sustainment banks will allow for further exploration of plasma physics using SSPX.