LSX, THE WORLD'S LARGEST FRC PLASMA PHYSICS EXPERIMENT

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INTRODUCTION

The summer of 1990 marked the completion (on time and under budget) of a $14M very large reversed-field theta pinch experiment, called LSX (Large s Experiment), at STI Optronics. LSX is currently generating field reversed configurations (FRCs) with dimensions such that the physics has reactor relevance. The FRCs are formed using slow, programmed formation techniques which rely upon ohmic heating and axial compression heating rather than the more standard theta pinch method of radial shock heating [1,2]. Figure 1 demonstrates the FRC plasma geometry.

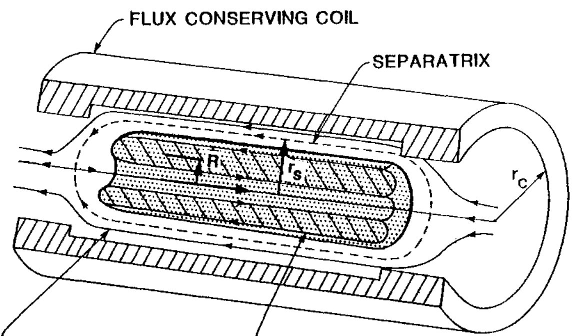

Figure 1. FRC Geometry

The principal component of LSX is a 90-cm diameter, 4.5-m long single-turn coil which can be divided into several individually energized sections. Some of the basic engineering features are reverse bias and forward field capacitor banks, programmed formation end coils and power supplies, multipole wall protection and stabilization fields, preionization sources, and the necessary ancillary systems. The following sections will provide an overview of FRC physics, discuss the LSX design philosophy and operating modes, describe the capacitor banks, energy storage modules and ancillary systems, discuss the fault prevention techniques, and report on the machine performance for the first year of operation.

PHYSICS REVIEW

An FRC is a compact toroid plasma, confined solely by poloidal magnetic fields, which has very attractive fusion reactor attributes. The principal goal of LSX is to study the stability and transport of FRCs in a more reactor relevant regime, characterized by the parameter s, the number of internal ion gyroradii. FRCs have been produced in previous devices with maximum s values of about 2 [3,4], while LSX is designed to produce s=8 plasmas. About s=30 is thought to be required for a fusion reactor.

An FRC is formed in several discrete steps: 1) deuterium gas is preionized in the presence of an initial reverse bias field; 2) the magnetic field of the main coil is reversed, creating an anti-parallel field line structure and radially compressing the plasma; 3) programmed formation techniques are used to connect the anti-parallel field lines at the ends, thus confining the plasma between the trapped initial reverse bias flux and the primary magnetic field; and 4) the plasma is compressed radially and contracted axially to form a high beta compact toroid plasma.

DESIGN PHILOSOPHY

Reliability and flexibility were the key design requirements. Changes in magnetic field timing, amplitude and profile can be made through simple control input parameter adjustments. A modular energy storage system, versatile charging, firing and control systems, pulse shaping techniques, and variable end magnet configurations are employed to enhance the system flexibility. The modular design also divides the energy into manageable segments and allows the module size to be scaled to the specifications of commercially available switches. Other advantages of a modular system include the ability to continue the experiment if a module fails; to replace modules easily, and to perform maintenance on an ongoing, rotating basis. A total coil voltage of 50 kV was needed to provide a 25 μsec magnetic field risetime, and a plus/minus 25 kV bipolar charging scheme was selected in order to permit simple air insulation.

LSX OPERATING MODES

A schematic of the axial confinement system, which consists of the main magnet, two sets of bubble/trigger magnets, and quasi-steady end plugs, is shown on Figure 2. A design drawing is shown on Figure 3, and the characteristic wave forms are shown in Figure 4. The formation process is controlled by the plug magnets in conjunction with the six bubble/trigger magnets, which are independent and can be connected in a variety of ways. The machine is designed to operate in two fundamental modes, "slingshot" and "bubble". Operation to date has been in slingshot mode which is illustrated in Figure 5. The fundamental modes can be reconfigured into numerous submodes. Table 1 summarizes the LSX capacitor banks, and Figure 6 shows an electrical schematic for the full 4.5 m long theta coil.

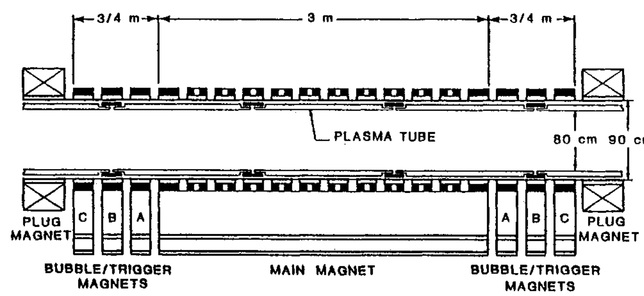

Figure 2. Axial Magnets & Plasma Tube Sections

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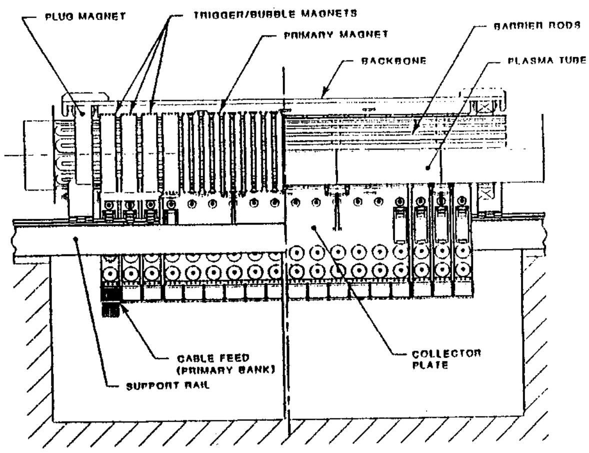

Figure 3. Major Magnet Components Profile View

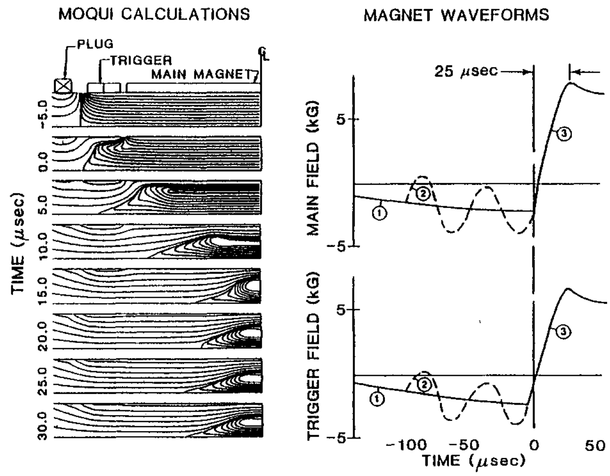

Figure 5. Slingshot Mode Formation on LSX

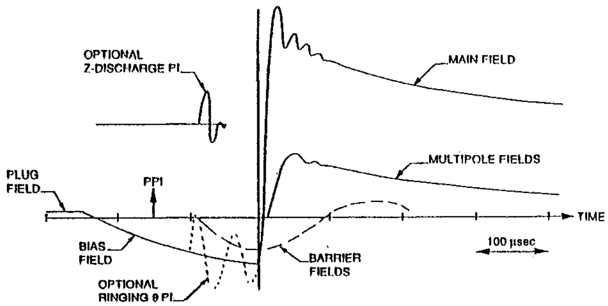

Figure 4. LSX Operation - Characteristic Waveforms

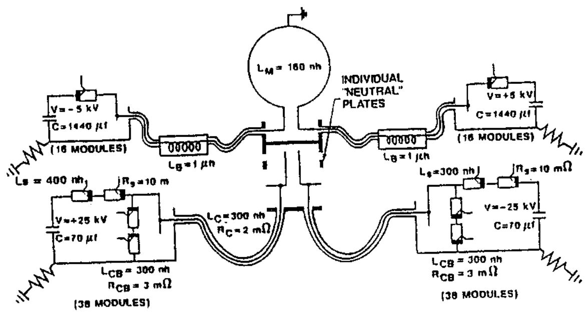

Figure 6. Electrical Schematic for Full 4-1/2 m Length Coil

Table 1. LSX Capacitor Banks

BANK NAME	MODULE TYPE	NO. OF MODULES	TOTAL ENERGY	I_o	$t_{1/4}$	$t_{L/R}$
1. Primary (4.5-m total magnet)	±25 kV 43 kJ	(38)	1.63 MJ	4.2 MA	25 ms	0.7 ms*
Ringing		(7)		1.4 MA	14 μs	0.2 ms
2. Bias (4.5-m total magnet)	±5 kV 36 kJ	(16)	0.58 MJ	0.7 MA	250 μs	2.5 ms
3. Multipole (4 pairs in parallel)	±25 kV 43 kJ	(4)	0.17 MJ	0.4 MA	30 μs	1.0 ms*
4. Barriers (6 quads in parallel)	12.5 kV 16 kJ	(3)	0.05 MJ	0.2 MA	55 μs	1.0 ms
5. z-Discharge	25 kV 21 kJ	(2)	0.04 MJ	0.2 MA	28 μs	0.4 ms
6. Plugs (plugs independent, all pancakes in series)	10 kV	(2)	0.40 MJ	2 kA	33 msec	

* Crowbarred

PRIMARY BANK

The primary bank stores a total of 1.6 MJ and delivers 4.2 MA to the primary magnets, generating a peak magnetic field swing of ~ 9 kG. The bank is divided into (38) 44-kJ energy storage modules, 2 of which are equipped with Type "A" PFNs to provide a hesitation in the magnetic field waveform of the end magnets (bubble mode). The quarter-cycle time to the > 100 kA current peak is ~ 25 µs, and the modules are crowbarred with an L/R decay time of ~ 650 µs. The modules consist of positive and negative sections, which are charged to + / - 25 kV respectively, and are discharged in series to generate 50 kV across the magnets. An artist's rendition of a module section is shown in Figure 7.

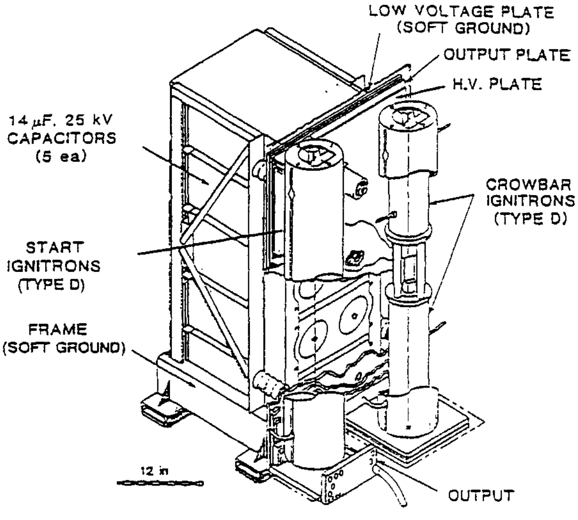

Figure 7. Plus Section of ± 25 kV Module

Each module section contains (5) 14-µF, 4.4-kJ energy storage capacitors. The capacitors are connected to the low and high voltage plates of a low inductance triplate stripline, which sandwiches an output plate (Figure 7). Two 25 kV Type D ignitrons are connected in series to hold off the 25 kV module charge voltage (12.5 kV ea.), and to serve as the module section crowbar switches. Type D's minimize the crowbar resistance and easily handle the large coulomb transfer during the long L/R decay time. The energy from the + / - sections is transported to the magnet via 10 parallel coaxial cables. A custom cable design minimizes the crowbar circuit resistance and increases the voltage holdoff from the braid to the ground. Round trip cable resistance is ~ 0.3 mΩ per foot and the nominal O.D. is ~ 0.8". The peak current per cable is ~ 10 kA. Commercially available high current contacts are used to terminate the cables. The cable braids from the + / - sections are connected together at a plate common to only that module, and insulated from the remaining modules, where possible, to prevent prefire communication. RC cable snubbing networks are installed at the input to each section cable bundle to reduce voltage spikes due to switching transients.

Single stage, Type "A" PFN networks are installed in series with the start switches in both the positive and negative section on one of the modules. The PFN modules generate a trapezoidal pulse with a risetime of ~ 15 µs, and are used to provide a step on the output current when operating in bubble mode. It was intended to build four more of these modules at a later date. This step is a critical part of one method of programmed formation. The resulting delay in the application of forward field under the bubble magnets slows down the axial contraction and reduces dynamic destabilizing effects on the plasma during formation. The PFN modules can be converted to conventional energy storage modules by replacing the PFN inductor with a shorting bar that bypasses the PFN capacitors.

BIAS BANK

The bias bank stores a total of ~ 0.6 MJ and delivers ~ 0.7 MA of current through isolation inductors to the primary magnets, generating a peak reverse field of ~ 2 kG. The bias bank is divided into (16) + / - 5 kV, 36 kJ energy storage modules. The bipolar scheme is maintained in order to achieve voltage symmetry across the magnets. The quarter cycle time to the 45 kA current peak is ~ 250 µs. A single Type D ignitron serves as the module section start switch. Four parallel 360 µF, 4.5 kJ capacitors are used per section. The busswork is similar to that of the primary bank modules, and 12 parallel RG217 coaxial cables transport the bias energy to the primary magnets. The cables feed into the magnet plates via bolt through connections. The bias bank is not crowbarred, but is allowed to ring forward, which causes it to act as a power crowbar, reducing the main field decay rate for about 500 µsec.

PREIONIZATION SOURCES

Uniform preionization has been shown to be critical for obtaining reliable FRC formation. LSX employs two primary mechanisms to preionize the plasma. The first is an axial electrical discharge thru the gas (z-discharge). The second is a ringing theta field superimposed on the bias field (see Figures 4 and 5). Microwave excitation is used as an additional assist.

Seven of the (38) 44-kJ modules can be fired into the primary magnets early, to produce the azimuthal "ringing theta pinch". The modules drive a total current of 1.4 MA with a full cycle time of ~ 56 µs. The modules are identical to the other primary bank modules except that double the number of output cables are used to keep the per cable current to 10 kA. The modules ring for two full cycles prior to firing the remaining (31) primary bank modules.

MULTIPOLE BANKS

Twenty-four evenly spaced "barrier" rods are mounted axially to the outer wall of the plasma tube. These barriers are used to produce a "picket fence" magnetic field which both assists preionization and protects the plasma tube wall during axial field reversal. The rods are 550 cm long straps of 60-mil, 2.5"-wide copper, which are operated in current pairs, with one rod carrying the current down and its neighbor carrying it back.

The inductance of each parallel pair of barrier rods is about 4 µH. The rods can be operated in either of two configurations. The first consists of 6 parallel sets of 2 pairs of rods in series, for a total magnet inductance of 1.3 µH. The second has all 12 pairs operating in parallel, for a total magnet inductance of 0.3 µH.

Preionization is most effective when the barrier rod current crosses zero at the same time as the ringing theta current. It is also important that the barrier field be near its peak during main field reversal, which is about 90 µs later. The unipolar bank is comprised of (3) 16 kJ energy storage modules. Each module has (5) 40-µF, 12.5 kV storage capacitors, and is switched by one Type D ignitron. Each module drives an equal share of the magnet configuration via 12 parallel RG217 cables. The barrier bank magnets are illustrated in Figure 3.

Multipole fields are needed to stabilize the FRC against a rotating n=2 instability. Currents are pulsed through four rods shortly after FRC formation. A quadrupole capacitor bank stores a total of 175 kJ and delivers up to 100 kA to each rod run in series/parallel. The quadrupole bank is divided into four modules which are identical to the primary bank energy storage modules. The initial LSX experiment utilizes straight axial quadrupole rods, however, hardware provisions will accommodate eight rods with a helical twist.

PLUG BANK

Two plug banks store 225 kJ each and produce a 33 msec quasi-dc confinement field in each end plug magnet. Each 10.6 kV unipolar bank contains ten 400 μF, 22.5 kJ capacitors. The capacitors have series resistors to provide protection in the event of a short circuit in the system or in another capacitor. A Type D ignitron serves as the start switch and two parallel Type D ignitrons crowbar the energy at peak current. A 5 Ω resistance added to the crowbar leg provides rapid current damping.

ANCILLARY SYSTEMS

The ancillary systems include: 1) grounding and shielding, 2) data acquisition, 3) control, 4) charge/dump, 5) ignitron triggering, 6) ignitron thermal control, 7) safety, and 8) vacuum.

The grounding and shielding system is designed around a single point experiment ground that interconnects the banks and ancillary systems in a "tree" arrangement, thus avoiding ground loops. Fiber optic and pneumatic links are used where feasible.

Plasma diagnostics are obtained primarily with magnetic probes and are transmitted to the screen room via RG223 coax cables. Bank output current monitoring via an output cable braid CVR drives a light emitting diode and the optical signal is reconverted back to electrical at the screen room, thereby providing sufficient precision to determine module health, firing time, and proper crowbar action.

The control system is based on a programmable logic control (PLC) system. Two programmable logic processing units connect to three remote I/O ports via a serial fiber optic highway. The remote ports are connected to their relevant ground branch only. The I/O ports interconnect to the various ancillary systems mostly via 24 V dc twisted pair hard wire signals. However, fiber optic links are used for bank voltage metering and a pneumatic system actuates the charge/dump relay switches.

Eighteen power supplies ranging from 5 to 15 kW are used to charge the eight different module types, thereby achieving optimum flexibility for the various module/magnet configurations. Nominal bank charging times are ~ 45 s, but staggered charging has been employed to complete the charge on all the banks simultaneously. The charge is distributed from a single power supply to several parallel modules. Diodes and resistors are placed in the charge lines to prevent energy from adjacent modules from dumping into a fault, and module select/dump switches are installed in each of the parallel module charge legs. This enables any set of modules to be charged. Module sections will be independently dumped through four series/parallel ceramic resistors. Module voltage metering is achieved via fiber optic links to analog inputs on the PLC.

Thirty-eight trigger units, each with between 4 and 16 outputs, fire the start and crowbar ignitrons for the 8 module types, thereby achieving optimum timing flexibility for the various module/magnet configurations. The most difficult jitter specification is to fire up to 25 primary bank modules with a 500 ns spread. This specification is met easily with a 10 kV trigger pulse. The design utilizes a trigatron spark gap as the master switch, and individual capacitors driving a strong trigger pulse to each tube regardless of the status of its neighbors.

A hot propylene glycol system continuously maintains two zone (60° C anode and 30° C cathode) temperature control on the tubes in order to enhance the firing simultaneity and minimize the probability of prefires. Safety features include access control and fire systems, and manual shorting sticks. Access control devices include search and scram buttons, annunciators and rotating beacons. The vacuum and gas fill systems consist of cryo, turbo, and roughing pumps, and gas mix & puff fill hardware. These devices are controlled and monitored by one of the PLCs.

FAULT PREVENTION AND CONSEQUENCES

Fault protection against prefires is complicated because several banks that fire at different times are connected to the same magnets, and parallel modules within the same banks communicate prefires to the remaining modules. We have minimized the problem in several ways: 1) Two ignitrons are used in series to reduce the voltage holdoff per switch to 12.5 kV; therefore, they can take a large transient without self breaking. 2) Where possible, the bipolar module low voltage sides are isolated and allowed to float to high voltage during a section (1/2 module) prefire. Since the magnet is grounded, a section prefire will drive the low voltage side high, thereby doubling the voltage across all the opposite polarity module sections that are connected to the same magnet and share a common connection at the cable braids (see Figure 6). By individually isolating the module cable braid connections, a section prefire will impress large voltages (25 kV per ignitron) across only its mating module section. 3) The circuit inductance in each individual module (and cables) is intentionally left large with respect to the magnet inductance. In case of a prefire, most of the module voltage is dropped across its own components, without being impressed on neighboring modules. Also, the peak prefire currents are limited to nondestructive values.

MACHINE PERFORMANCE

LSX has performed very well to date, and there have been no surprises. The machine is fired at a rate of 4-5 shots per hour, and has a total of 2500 shots. Typical charge voltages are 22kV, 4-5kV, 8kV, and 8kV on the primary, bias, barrier and plug banks respectively. Zero damage prefires occur at a rate of approximately 1%, and failures that require repairs occur at a rate of approximately 0.1-0.3%. Six capacitors have failed; infant mortality can account for the two primary, and one bias bank failures. Three of fifteen barrier bank capacitors have failed indicating a somewhat serious problem, especially since the barrier banks have never been charged to full voltage. Electrical breakdown of the ignitron cooling port insulators are currently the most dominant failure. Other components are not typically damaged, and a few hours repair time is all that is required to return the system to service. During the shakedown we also experienced frequent power supply failures, some noise on the diagnostic signals, and a few blown input resistors on the PLC. A few minor repairs and modifications have eliminated the problems. Crowbar losses of approximately 5% more than anticipated was the most interesting subtlety.

CONCLUSIONS

The complex LSX system meets the performance specifications, and works reliably over a very wide operating range. Excellent results have been achieved with the formation of stable FRCs and the outlook is very promising. Optimization is a long and arduous process and the results will be presented in another forum.

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