LA-UR-81-3037

CONF-811040--36

MASTER

TITLE: ENGINEERING DESIGN OF THE FRX-C EXPERIMENT

AUTHOR(S): R. W. Kewish, Jr., R. R. Bartsch, R. E. Siemon

SUBMITTED TO: 9th Symposium for Engineering Problems
of Fusion Research
Chicago, Illinois
October 26-29, 1981

University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer

Form No. 836 R3
St. No. 2629
12/78

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

ENGINEERING DESIGN OF THE FRX-C EXPERIMENT*

R. W. Kewish, Jr., R. R. Bartsch, R. E. Siemon
Los Alamos National Laboratory
University of California
Los Alamos, NM 87545

Summary

Research on Compact Toroid (CT) configurations has been greatly accelerated in the last few years because of their potential for providing a practical and economical fusion system. Los Alamos research is being concentrated on two types of configurations: 1) magnetized-gun-produced Spheromaks (configurations that contain a mixture of toroidal and poloidal fields), and 2) field-reversed configurations (FRCs) that contain purely poloidal magnetic field. This paper describes the design of FRX-C, a field-reversed theta pinch used to form FRCs.

Results from previous FRX-A and FRX-B experiments demonstrated the formation and stable confinement of FRCs for many Alfvén transit times. The lifetime appeared to be limited by the poor confinement resulting from the relatively small size of the earlier experiments. Thus FRX-C is a system twice as large (eight times the volume) designed to test the scaling of confinement and stability with size over a significant range of plasma temperature and density.[1]

System Description

To provide the required E_θ, the theta-pinch coil of FRX-C has two feeds. Voltage is applied at ± 45° from the vertical with "gull wing" shaped collector plates, as shown in Fig. 1. The coil is 45 cm i.d. and 200 cm in length, giving an inductance of 100 nH. The overall dimensions of the collector plate assembly are 5.5 meters by 2.0 meters. The discharge tube is [illegible] cm o.d. and 3.6 meters long.

For the initial operation, the main bank, Fig. 2, consists of 140 capacitors, each having 2.8 μf and rated at 60 kV. At the anticipated maximum operating voltage of 55 kV, the main bank energy is 600 kJ. Each capacitor is switched using a Scyllac-type, four element cascade spark switch with a ferrite loaded "piggy back" crowbar switch.[2] Risetime of the main bank current is ~ 5 μsec and the crowbar decay time is ~ 300 μs.

The reverse bias field, necessary for FRC production, is powered by a 10 kV, 510 kJ capacitor bank. Initial operation has been with 60% of the bank, and results in a risetime of 116 μsec. The full bias bank is capable of generating a reverse bias of 5.0 kG maximum.

For initial operation, plasma production has been initiated by a 75 kV, 31 kJ theta-pinch preionization (PI) capacitor bank that has a ringing frequency of 200 kHz. This PI bank is capable of an amplitude sufficient to bring the field of the bias bank back to zero at the peak of the first cycle when the bias field is ≤ 2.5 kG. A few tens of kilowatts at 36 MHz is applied to antennas near the ends of the discharge tube to generate an r.f. discharge prior to initiation of the theta-pinch PI waveform.

Circuit Description

The circuit for FRX-C was designed using Scyllac technology[3] for the fast banks. Components used in construction were from Scyllac and ZT-40 experiments.

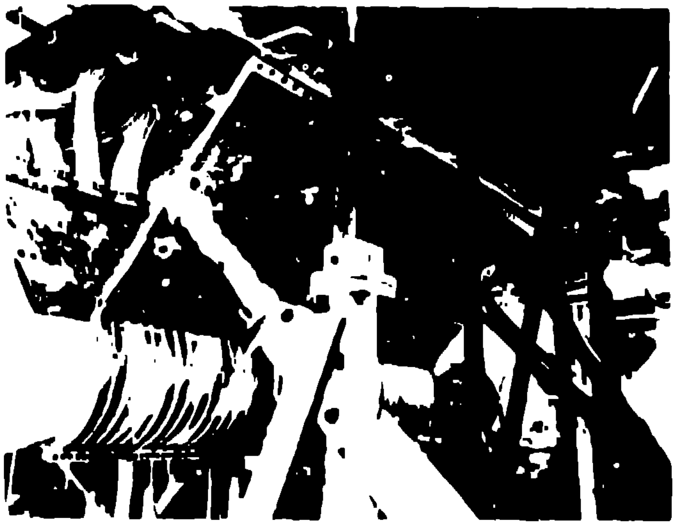

Figure 1
"Gull Wing" Collector Plate

Figure 2
Main Bank Capacitor Rack

---

*Work performed under the auspices of the U.S. Department of Energy.

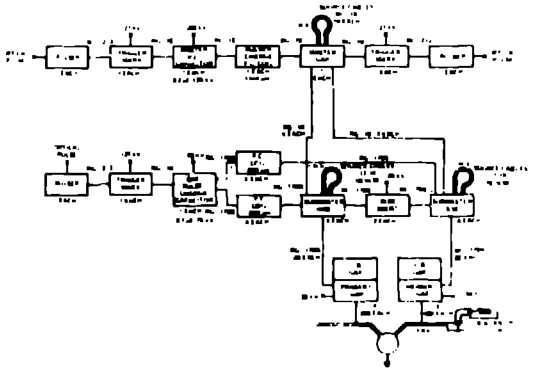

Figure 3
Schematic of Main Bank Trigger System

Figure 3 shows a block diagram of the main bank capacitor and trigger system.

Two types of cable cartridges were used to connect the cables from the capacitor bank to the collector plate. One type of cartridge connects half of the bank feeding voltage to the lower side of one gull wing, and the other type connects the other half of the bank feeding voltage to the upper side of the other gull wing. It is in this manner the capacitor bank voltage is doubled around the coil when the capacitors are discharged, and permits operation with the charge polarity on all of the main bank gaps which gives the widest window of operating conditions.

Advantages of such an arrangement are that all capacitors in the main bank can be charged to the same potential, and a common trigger system can be used with only one master gap. The disadvantage is that grounding becomes a problem. The grounding problem has been solved by isolating the capacitor racks from ground and allowing the racks to "float" to some potential between ground and bank voltage. Further, the coil ground has been defined by a ground strap geometrically halfway between the feed slots, at the bottom of the coil as shown in Fig. 3.

The trigger system for the main bank is patterned after Scyllac and consists of eight submaster (SM) gaps, each triggering 10 or 20 main bank start switches. The energy source for each submaster consists of ten source cables used as capacitors (.022 µf for each SM). By pulse charging the source cables through large inductors (800 µH) from a .7 µf pulse charge capacitor, the source cables will charge to 1.6 times the voltage on the .7 µf capacitor. Voltage on the source cables reaches about 100 kV. Because L and C of the SM circuit are small, the trigger pulse for triggering the main bank spark gaps rises very rapidly (10 kV/ns) with excellent simultaneity.

A single master gap with a similar pulse charge circuit is used to trigger the SM gaps. With this circuit, the pulse voltage is 1.8 times the voltage on its pulse charge capacitor (more near the theoretical limit of 2.0). The pulse voltage on the master gap during operation is 130 kV.

Risetime for pulse charging both the master and SM gaps is on the order of 7 µs. The "timing window" for correctly firing the master is long enough, ~ 2 µs, so that timing does not present a problem.

Triggering of the ferrite-loaded crowbar gaps requires considerably more energy than triggering of the main bank gaps. Figure 4 shows the crowbar trigger capacitor bank, which consists of 16 capacitors, each rated at .7 µf and 75 kV. Since crowbarring of the main bank is critical to the health of the machine, a redundant trigger system is used. Failure to crowbar the main bank can be potentially serious since the result may be: decreased life of main bank capacitors, damage to insulation, or worse, a shattered discharge tube. The crowbar (C/B) master gaps are dc charged by separate power supplies and each has its own trigger system. As shown, each CB master triggers half the crowbar gaps on each side of the collector plate. In the event of one C/B master failing, the only consequence is a poorly crowbarred waveform of the m: bank.

Sequence of operation for main bank operation is as follows. Trigger Marx units, pulse units, master and SM capacitors, and main bank capacitors are charged to their respective dc voltages. Two seconds after charging of the capacitor banks is complete, optical signals initiate an H.V. pulse to begin pulse charging of the SM and master gaps. Seven microseconds later, at peak pulse charge, an optical signal starts a pulser unit to trigger the master gap. Within a few tens of nanoseconds, the primary gaps begin to carry current. About 5 µsec later, at peak main bank current, the crowbar gaps close and isolate the load coil from the main bank. Current in the load then decays with its characteristic L/R decay time.

Except for triggering, the theta-pinch PI bank is identical to the crowbar bank: 16 capacitors are used rated at .7 µf and 75 kV for a total bank energy of 31 kJ. Schematics for both the theta-pinch PI and bias banks are also shown in Fig. 5. The theta-pinch PI bank is less likely to experience the severe EMI that the main bank and trigger system impose on the crowbar bank. It is also less critical if it does not discharge. Therefore only a single PI master gap is used to trigger the bank. Thus far the PI bank is indeed more reliable than the crowbar bank.

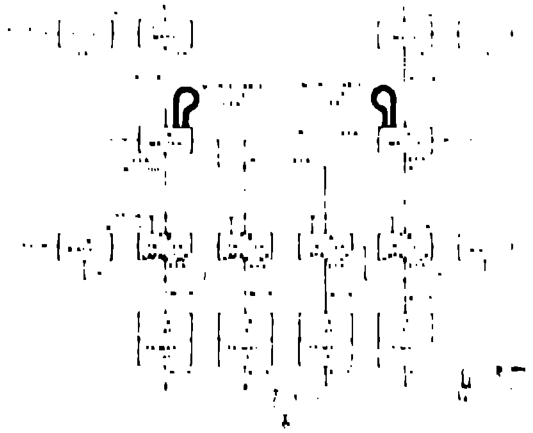

Figure 4
Schematic of Crowbar Trigger System

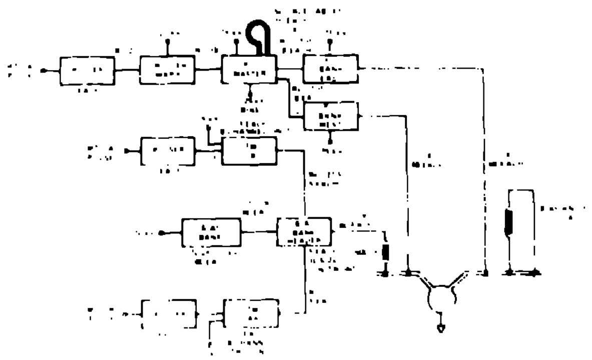

Figure 5
Theta pinch PI and Bias Schematic

Computer Control and Diagnostic System

In FRX-C, as in other recent Los Alamos experiments, e.g., Scylla IV-P, and ZT-40, operation is completely computer-controlled. The operator rarely does more than modify software to operate different capacitor banks after initial set up is complete. By monitoring important features of the experiment on a computer terminal, Fig. 6, the experienced operator is able to effect proper operation of the machine.

A block diagram of the computer control system is shown in Fig. 7. Since the computer control system was designed, a Prime 300 computer has been completely dedicated to machine operation. A Prime 400 computer is shared with the magnetized gun experiment for bank diagnostics and data reduction.

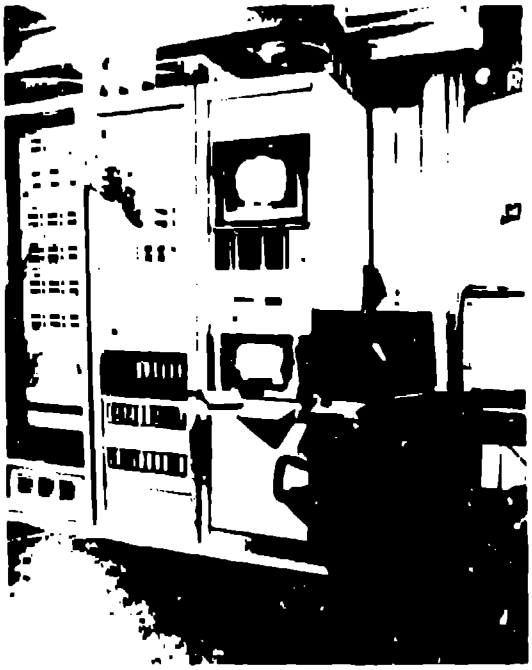

Figure 6
Control Console

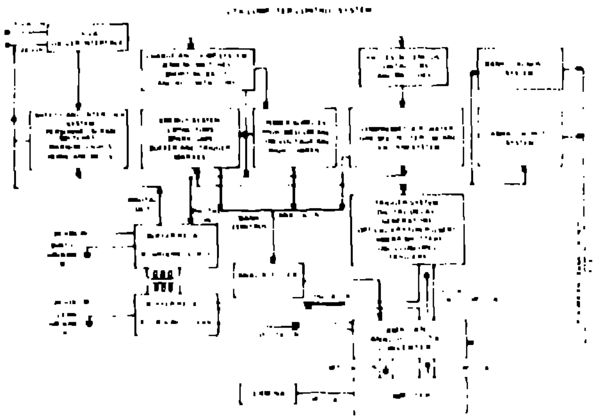

Figure 7
Block Diagram of Computer Control System

With recent advances in fiber optic technology, the computer can be housed in an EMI-shielded room and be coupled to the outside only by fiber optics. To protect CAMAC, A/D converters, and other delicate electronic equipment, output signals go to the high-voltage experimental area only after being buffered by a 24 V to 24 V relay system, filtered, or both, or transmitted optically. Input signals from the experiment are either filtered or buffered. Careful consideration was given to grounding the machine to avoid transients. The ground plane is tied to utilities ground at one point only and has "arms" which radiate from that one point to deal with the problem of ground loops.

To insure that the banks have operated properly from shot-to-shot and to aid in trouble shooting when failures occur, a system of diagnostics is used for the capacitor bank system. Slow signals, i.e., all charging voltages and vacuum and safety interlocks, are monitored by the computer. Anytime one of these signals falls outside predetermined limits, the computer will follow an abort sequence and shut the system down, safely discharging all high-voltage systems. Most of the signals from charging capacitor banks are monitored during the charge cycle by the operator who can manually initiate an abort sequence.

Fast signals, i.e., discharging of capacitor banks into their respective loads, are monitored by voltage and current probes. Figure 8 shows the discharging of pulse charged SM and master gaps, crowbar gaps, and the resulting signal from the B-field probe in the coil.

A significant new feature in bank diagnostics has been added to FRX-C, a gap monitor system. There has always been a requirement to know the performance of each main bank capacitor as its energy is switched to the load. Because of costs and technical difficulties, previous attempts at monitoring each gap in a large capacitor bank system have been less than successful. The gap monitor system consists of shielded Rogowski loops to detect current in one of the load cables from each main bank capacitor. An A/D convertor samples signals from each loop every 5 μs. When main bank shots are analyzed, the computer shows the performance of all of the gaps on one display. Although sampling steps only give gross indication of performance, one can, at a glance, determine the general quality of a shot and the specific performance of one capacitor.

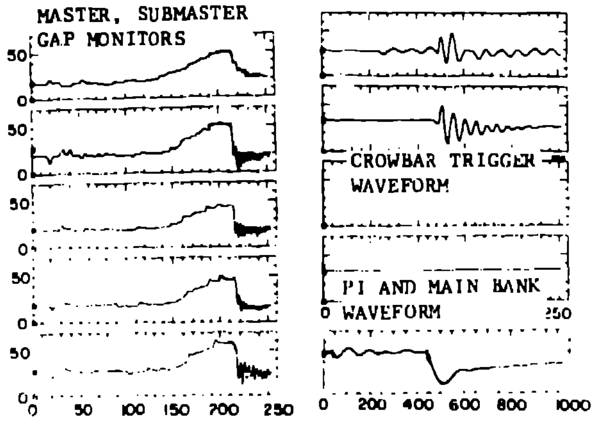

Figure 8
Master, Submaster, and Crowbar Trigger
Monitor Pulses and Main Bank Waveform

From early results, it appears that such a system has been developed for FRX-C. With this system, bank operation and maintenance will be improved.

A number of plasma physics diagnostics are also included. It is beyond the scope of this paper to discuss them but it is sufficient to say that signals from these diagnostics are fed to A/D converters then to a Prime 400 computer for data reduction on a shot-by-shot basis. With this capability, the parameters of operation can be changed according to current results and, thus, machine (and physics) operation can be optimized.

Future Operation

In the near term, a Z-pinch PI system capable of initiating a discharge up to the 5 kG limits of the bias system will be installed. This system will provide a 10 μsec half-period, 100 kA current pulse into the Z-current drive structure (estimated inductance 1.0 μH). The electronics of this system have been assembled and tested. Limited design work and power supply installation have been performed to allow for the inclusion, if indicated by experimental results, of multipole barrier fields and driven mirrors.

FRX-C is one of two experimental machines in the CTX facility at Los Alamos. A unique feature of the CTX facility is the 1.5 m diameter vacuum vessel enclosed by 10 kG dc magnetic field coils to be shared by both experiments, as shown in Fig. 9. In about two years, after initial FRC studies, plans include translation of the FRC compact toroids generated in the theta-pinch coil through a transition field to the large trapping and containment vessel (CTX tank).[4] With this facility, confinement and heating studies on CT-type plasmas can be done in a static magnetic field.

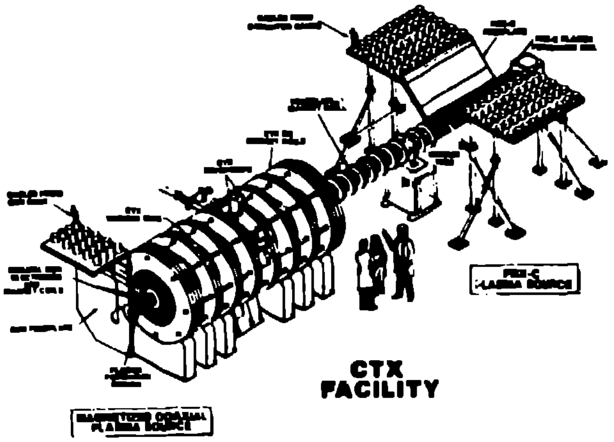

Figure 9
Machine Layout in CTX Facility

References

1. R. E. Siemon and R. K. Bartsch, "Scaling Laws for FRC Formation and Prediction of FRX-C Parameters," Proceedings of the Third Symposium on the Physics and Technology of Compact Toroids, Los Alamos 1980, Los Alamos National Laboratory Report LA-8700-C, (1981), p. 172.

2. R. F. Gribble, "A Ferrite Loaded Piggy-Back Crowbar Gap," Proceedings of Symposium on Engineering Problems of Fusion Research, Los Alamos, 1969 (LA-4250, 1969).

3. C. F. Hammer and R. F. Gribble, "Scyllac Spark Gap and Trigger System Development," Proceedings of Symposium on Engineering Problems of Fusion Research, Los Alamos 1969 (LA-4250, 1969).

4. H. Dreicer, "Proposal for FRX-C and Multiple Cell Compact Torus Experiments," Los Alamos Scientific Laboratory report LA-8045-P (October 1979).