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Design and Construction Details of the FRX-C/T Device: A Compact Toroid Plasma Translation Experiment

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DESIGN AND CONSTRUCTION DETAILS OF THE FRX-C/T DEVICE: A COMPACT TOROID PLASMA TRANSLATION EXPERIMENT

by

D. J. Rej

ABSTRACT

The engineering design and construction details for the compact toroid plasma translation experiment FRX-C/T are reviewed. A translation region consisting of a 0.4-m-i.d., up to 6-m-long metallic vacuum chamber has been added onto one end of the field-reversed theta-pinch device FRX-C. A 2.5-MW, dc-powered, water-cooled solenoid magnet produces an axial magnetic field of up to 10 kG in this region. A complete directory of all related engineering drawings is also included.

I. INTRODUCTION

During 1983, the field-reversed configuration (FRC), magnetic fusion experiment FRX-C¹ was modified to enable the study of axial translation of hot, compact toroid plasmas. (The FRX-C device is operated by CTR Division at Los Alamos National Laboratory and is located in Building SM-105, Room 189.) In the new experiment, renamed FRX-C/T, plasmas are launched out of a slightly conical theta-pinch coil into a translation region consisting of a metallic vacuum chamber and a dc magnetic guide field.² A schematic diagram depicting the initial configuration of this new apparatus is shown in Fig. 1. A photograph of the experiment appears in Fig. 2.

This report documents the design and construction details of the FRX-C/T experimental hardware. The theta pinch and its associated high-voltage technology have been described elsewhere;^{1,3,4} therefore, only the modifications associated with the translation experiment are reported. This report is divided into two major parts, corresponding to the dc magnetic field and the vacuum hardware systems. A listing of all related engineering drawings appears in the Appendix.*

*Drawings available from D. J. Rej, Group CTR-3, Los Alamos National Laboratory.

II. dc MAGNET SYSTEM

The translation region can be up to 6 m long and consists of an axial guide magnetic field, $B_z \leq 10$ kG. This field is generated by a set of water-cooled pancake coils energized by a 2.5-MW dc power supply.

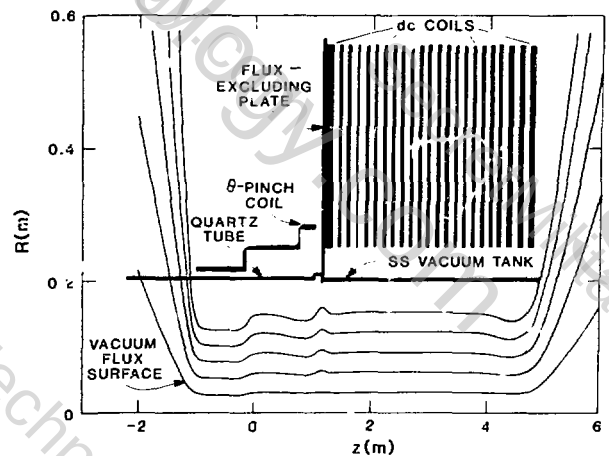


Fig. 1. Schematic diagram depicting the initial configuration of the FRX-C/T device.

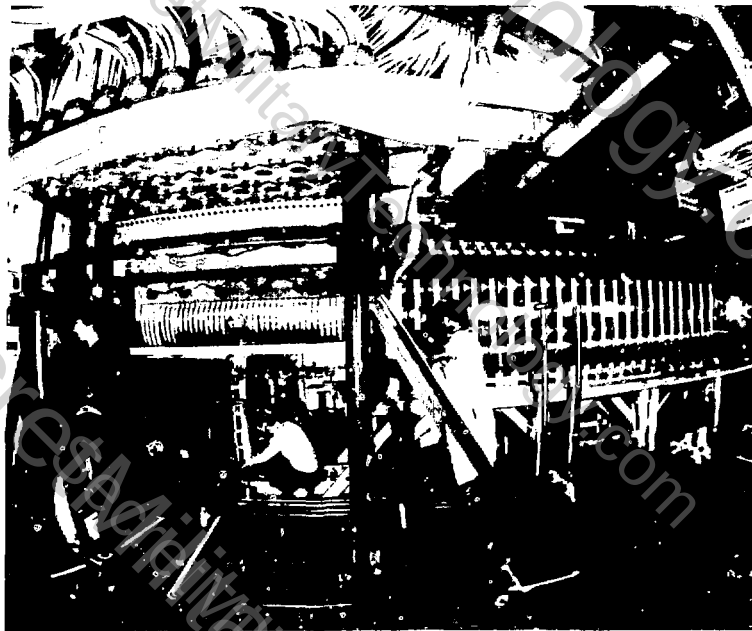


Fig. 2. Wide-angle "fish-eye" photograph of the FRX-C/T experiment.

A. Magnet Coils

The guide field is produced by a set of up to 42 "pancake" magnets. Each pancake (see Fig. 3) consists of two separate 16-turn coils. The dimensions of a pancake are 20-in. i.d., 43-in. o.d., 1.625 in. wide. These magnets were built about 1963 by Pacific Electric Motor, Oakland, California, and were used in Q-machine experiments operated by the CTR-I Group between 1969 and 1981.⁵ There are no known original drawings of these coils; however, a drawing has recently been made (Los Alamos Dwg. No. 33Y180762) from an existing pancake for the purpose of procuring new coils, and it does include the following minor deviations from the existing coil sets: (1) more nearly standard pipe fittings for cooling hose connections, (2) fiber glass reinforcement, (3) Kapton insulation, and (4) fiber glass straps.

These magnets are water-cooled. The deionized cooling water passes through a 0.375-in.-diam hole that passes through the 0.625-in. x 0.625-in.-square cross-section copper conductor that forms the coil. The electrical resistance of each 16-turn coil is approximately 3.6 m Ω . The two coils are wound intertwined. The windings are wrapped with a cloth insulation and the pancake is impregnated in an epoxy. No documentation of the high-voltage insulation properties for these coils could be found; moreover, no experimental high-voltage tests have been performed, in view of the high

replacement cost (about \$10,000) of a pancake should one be destroyed. Instead, the design philosophy has been to adequately shield these magnets to prevent induction of any high voltage (see Sec. II.D).

Of the magnets used in the experiment, there are two different sets of pancakes. The coil parameters are essentially the same for both sets; however, for the same voltage polarity across the coil terminals, the direction of the current through the windings (or the polarity of the B-field) in one set is opposite that of the other. (The obvious physical difference between these two sets is the shape of the top of the epoxy casting. One set has a pointed top while the other has a flat, chamfered top.)

The initial dc coil configuration (Fig. 1) consists of 28 pancakes spanning a 4-m length. A 17-cm gap separates the high-voltage, pulsed theta-pinch coil and the dc coil set. Three pancakes are placed next to one another at the theta-pinch end. Next to these coils are 19 single pancakes evenly spaced 15.2 cm apart. At the downstream end, a dc mirror B-field is generated by three pairs of pancakes. A central B_z-field of 2.6 G/A of coil current is produced. Typical vacuum flux surfaces and axial B-field profile generated by the present configuration of coils have been calculated and are plotted in Figs. 1 and 4, respectively.

The dc magnetic field axial profiles are measured using a Hall probe (F. W. Bell, Model No. 811AB controller and No. ZOB-8-3208 three-axis probe). A motor-driven, cantilevered arm has been built (Los Alamos

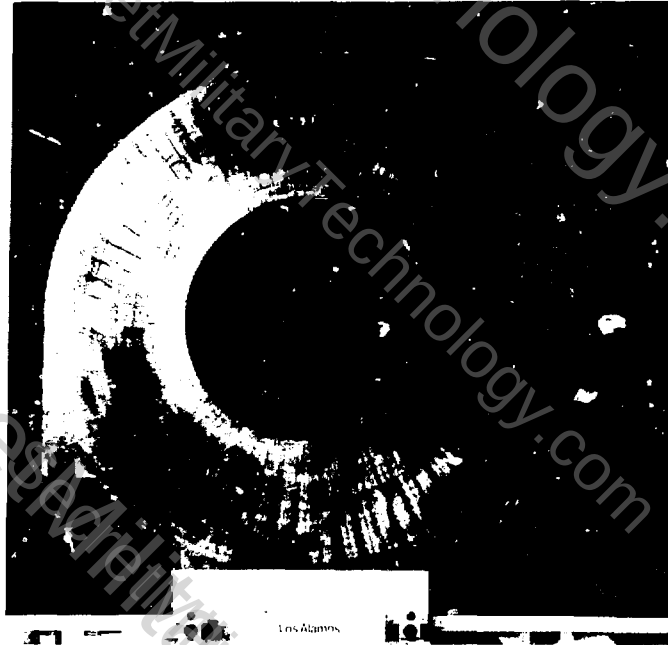


Fig. 3. Photograph of one of the pancake magnet coils used to generate the translation region guide field.

Dwg. Nos. 33Y180823 and 33Y180852) to hold the Hall probe and automatically traverse the entire translation region length in approximately 1 min. The probe output is recorded using a LeCroy 8210 digitizer and is stored in the FRX-C/T Prime 400 computer. A sample measured dc B_z -field profile is displayed in Fig. 5. The rise and falltimes of the dc coil power supply are each approximately 1 min (see Sec. II.B). During normal operation, the dc magnets are energized simulta-

neously with the charging of the high-voltage, theta-pinch coil capacitor banks. Following the plasma discharge (which lasts less than 1 ms), the dc power is ramped down to a minimum power level of about 3 kW.

Vacuum field perturbations caused by ferromagnetic materials (e.g., bearing shafts, conduits, steel I-beams, deck plates, stainless steel welds) surrounding the dc coils have been measured and they were found to be a few gauss. Plotted in Fig. 6 are axial B_z profiles with the

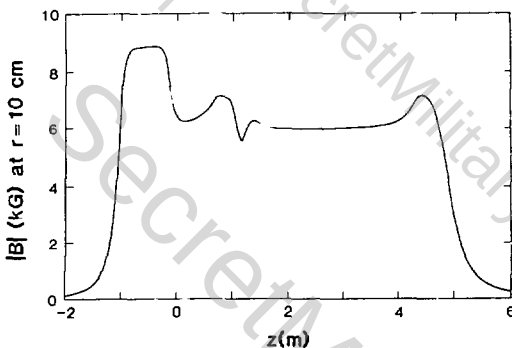


Fig. 4. Magnitude of the vacuum magnetic field at radius $r = 10$ cm calculated as a function of axial position. The pulsed theta-pinch coil is centered at position $z = 0$. The dc coils are located between axial positions $z = 1.2$ and 4.8 m (see also Fig. 1).

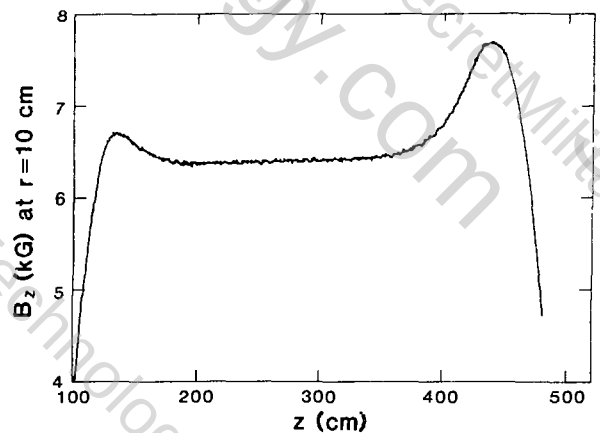


Fig. 5. Axial profile of the dc B_z -field at radius 10 cm. These measurements were made with a Hall probe.

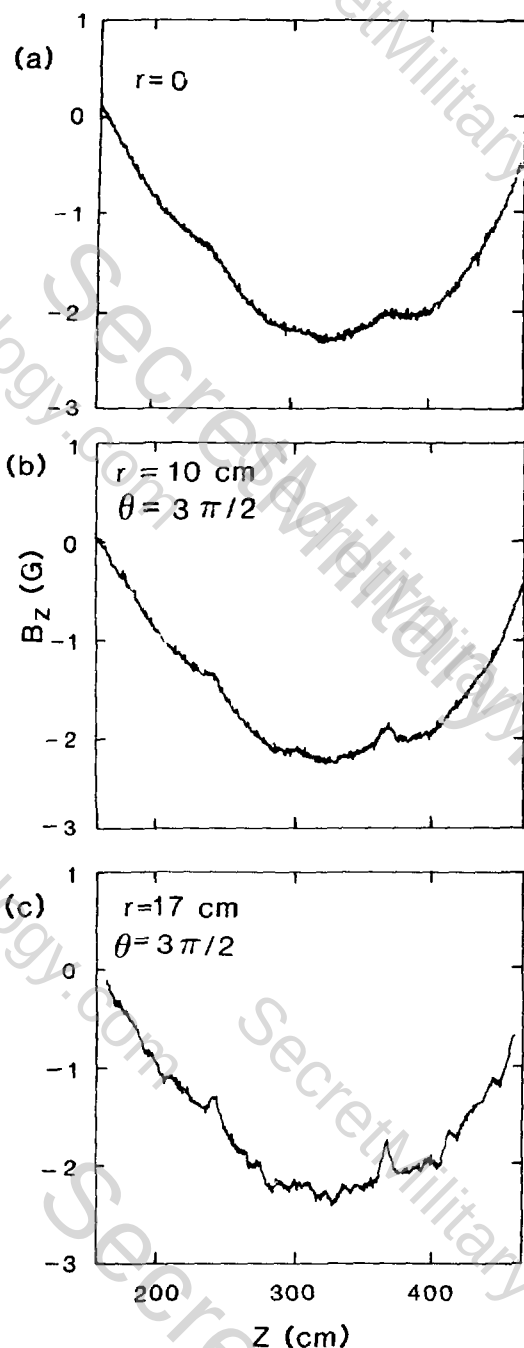


Fig. 6. Typical stray B_z -fields created by the magnetized objects surrounding the experiment. Axial profiles of B_z were measured at radii (a) 0, (b) 10, and (c) 17 cm. These Hall probe measurements were made after the magnets were energized to near full power.

dc power turned off for radii of (a) 0, (b) 10, and (c) 17 cm. These measurements were made after the coils have been energized to produce a 7.5-kG field. The B_r and B_θ components are of the same magnitude as (but always less than) B_z . The primary source of these stray fields appears to be the galvanized steel diagnostic conduits that pass directly over the translation region and are routed to the CTX experiment. The 0.5-G fine structure in the axial $B_z(z)$ profile at 17-cm radius results from magnetized stainless steel welds in the vacuum chamber that became ferromagnetic from the welding process (see Sec. III.A).

B. dc Power System

The magnet coils are energized using a 12-phase, 2.5-MW dc power supply manufactured in 1960 by the ITE Circuit Breaker Co., Philadelphia, Pennsylvania. This apparatus has been used in the CTR-1 Q-machine experiments.^{5,6} A detailed description of this power supply and its associated control, cooling, and safety systems is available from Rita Gribble, Los Alamos Group CTR-3. The supply output can be varied from 72 kA at 35 V to 9 kA at 280 V. The latter combination is used in FRX-C/T experiments to minimize resistive losses in the busbar feeds (see below). The rise and falltimes of the dc output are limited to approximately 1 min by the power supply inductor voltage regulator.

The power supply is located outside the south wall of Building SM-105, Room 180. The output penetrates this wall and is connected to the FRX-C/T magnet coils by a pair of busbars (Los Alamos Dwg. No. 33Y180800) approximately 100 ft long that runs between Rooms 180 and 189. In Room 180, a busbar interface exists where the dc power can be diverted from the FRX-C/T device to the EMET project operated by the CTR-4 Group. The busbars are made of either 1.625-in. $\times$ 10-in. cross-section, type 6101 aluminum or 1.75-in. $\times$ 10-in. cross-section, type 6061 aluminum. The busbar sections range up to 12 ft in length and are joined together by welds or by 0.375-in.-thick copper plates bolted to the aluminum bars. A conducting grease (Catalog No. 21059, manufactured by Thomas and Betts Co., Raritan, New Jersey) is used at these junctions to minimize the electrical resistance. The total electrical resistance of the busbars is approximately 0.2 m Ω . At full power, the corresponding resistive loss in the busbars is 16 kW. A high-power, "free-wheeling" diode (Westinghouse Model No. RA200648, 600-V reverse voltage, 4.8-kA dc forward current) is installed in reverse polarity across the busbars in Room 180 and conducts the total load

current in case of a sudden power loss. The decay time of the current in this situation is limited by the L/R (load inductance/load resistance) time and is about 0.3 s.

The load consists of two or three parallel legs, each leg consisting of up to 15 pancake magnets (i.e., 30 coils) connected in series. The current in each leg may be adjusted to within $\pm 5\%$ using a water-cooled, 0-10-m Ω variable shunt resistor (Los Alamos Dwg. No. 33Y180801) that is connected in series with each leg. Each connection between the busbars and the load is made using five parallel 4/0 welding cables. In addition to their existing insulation, these cables are wrapped with 0.375 in. of polyethylene (Bishop biseal tape No. 3) and are shielded using a grounded braid.

Series electrical connections between coils within a single pancake are made using 0.25-in.-thick, annealed copper plates approximately 4 in. high and 1.5 in. wide. Connections between adjacent pancakes are typically made using 0.25-in. x 4.5-in. x 5.5-in. copper plates.

The total busbar current is measured indirectly using a magnetic Hall probe (Micro Switch Model No. 91SS12-2) mounted between the busbars. The bus voltage is also measured with a high-resistance voltage divider. Voltage and current isolation of these monitors is obtained using battery-operated fiberoptic transceivers (Los Alamos Dwg. No. 45Y123941).

The potential electrical hazards involving the entire dc power system are reviewed in the Standard Operating Procedure submitted by CTR-3 to Los Alamos HSE

Division in August 1983.* For safety purposes, the busbars are entirely enclosed by an electrically grounded metallic cladding. The busbars are supported by phenolic blocks, and a gap of at least 2 in. separates the bars from the cladding. Most of the cladding consists of perforated steel or aluminum sheets. In the experimental area, 0.5-in.-thick aluminum plates are used to better shield the busbars against induced voltages.

C. Cooling Systems

The two independent water-cooling systems in FRX-C/T are used for the 2.5-MW dc power supply and for the magnets. A description of the power supply cooling system is available from Rita Gribble, Los Alamos Group CTR-3.

Because of the nominal 1-min risetime for the dc power, a dc magnet cooling system is necessary. A schematic diagram of the FRX-C/T magnet cooling system appears in Fig. 7. Some of this equipment has been used previously in the CTR-1 Q-machine experiments. Water is forced through this closed loop at head pressure of up to 300 psi and flow rate of 350 gal./min using a pump powered by a 100-HP motor. This pump and its electrical systems are located in SM-163.

*Unpublished (available from D. J. Rej, Group CTR-3, Los Alamos National Laboratory).

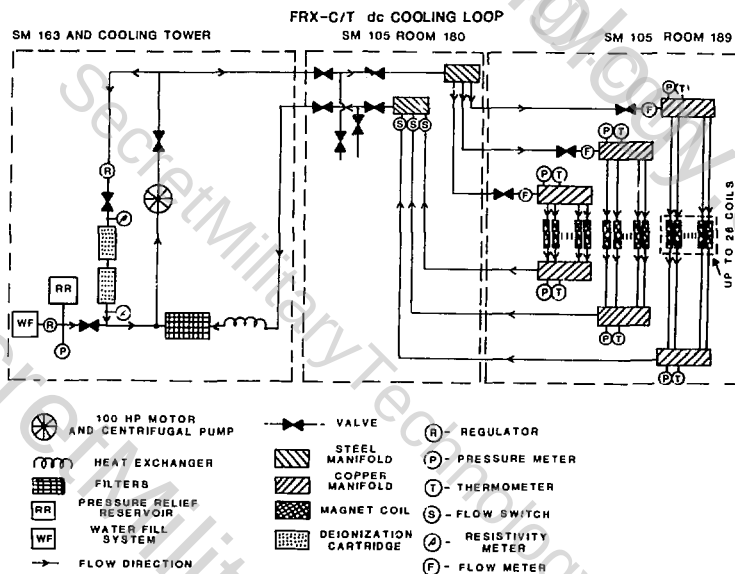


Fig. 7. Schematic diagram of the FRX-C/T dc magnet cooling system.

The water is pumped underground through 4-in.-i.d. schedule 80 steel pipe into SM-105 Room 180. The most economical method of bringing this water to the magnets in Room 189 uses three parallel hydraulic hoses (Aeroquip Model No. 2580-32: 1.81-in. i.d., 2.22-in. o.d., 350-psi working pressure, 1400-psi burst pressure, 13.25-in. minimum bending radius). The hose lengths range between 100 and 125 ft. The combined pressure drop across the three supply and three return hoses is about 31 psi for 330 gal./min. These hoses are connected at one end through steel manifolds to the supply and return 4-in. pipes in Room 180 and at the other end to copper manifolds in Room 189 (Los Alamos Dwg. No. 33Y180805).

The flow through each supply copper manifold can be adjusted using a valve located at the inlet. The flow rate in each is monitored using a Venturi-type flow meter (RCM Industries, Orinda, California, Model No. 2-71-R-200-H). Pressure gauges and thermometers are also mounted on each copper manifold. The remaining twenty-eight 0.5-in. NPT fittings in each copper manifold are connected to the magnet coils using nominally 5-ft-long hydraulic hoses (Weatherhead Model No. H10110: 0.625-in. i.d., 0.906-in. o.d., 250-psi working pressure, 1000-psi burst pressure, nonconducting). "Quick disconnect" fittings (Snap Tite Inc., Model No. BVHN 8-8-F and No. BVHC 8-8-F) are used to connect the hoses to the manifold. (The entire hose assembly is sketched in Los Alamos Dwg. No. 33Y180803.) All fittings are made from brass with the exception of the steel bearings inside the quick disconnect fittings.

The dc magnet coils are all cooled in parallel. Figure 8 plots the calculated pressure drop ΔP as a function of water flow rate through each approximately 130-ft-long coil conductor. Typical operating values are $\Delta P = 128$ psi at 4.3 gal./min per coil. At steady-state conditions with a 2.7-kA coil current, the return water temperature is about 14°C warmer than the supply water temperature. The observed time-dependent return water temperature for a 2.7-kA coil current applied for about 3 min is plotted in Fig. 9.

The magnet coils are also protected against overheating by the following methods: (1) The 100-HP pump is interlocked such that when turned off, the FRX-C/T Prime 300 control computer system issues an abort to the power supply. This abort decreases the power level to the safe minimum value. (2) Similar aborts are actuated by flow switches (Harwil Corp., Santa Monica, California, Model No. Q-5/3/H/-A) mounted on the inlets of the return manifold in Room 180 (see Fig. 7). (3) A thermistor system* has been built to monitor individual coil temperatures. (4) The temperature of each coil is also monitored by two precision thermostats

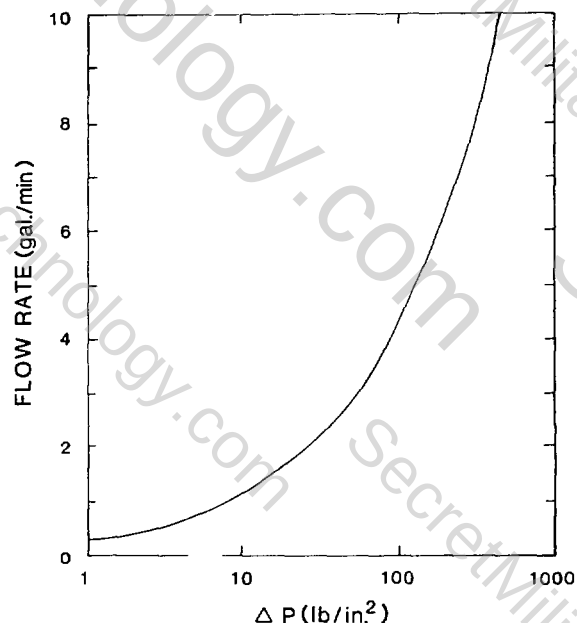


Fig. 8. Water flow rate through a single magnet coil calculated as a function of the pressure drop across the coil.

(Klixon Model No. C4344144). When a coil temperature T_c exceeds 66°C, a warning message is immediately sent by the computer to the machine operator. When T_c exceeds 79°C, an abort signal is sent to the power supply.

In SM-163, the cooling water also passes through deionization cartridges placed in a parallel loop directly across the pump. The water resistivity ρ_w is monitored at the cartridge inlet and outlet. Typical ρ_w values are 0.80 and >18 M Ω ·cm at the inlet and outlet, respectively.

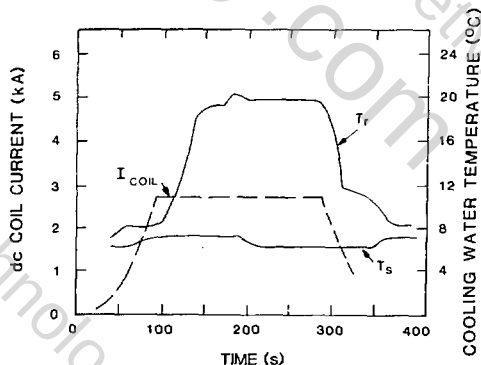


Fig. 9. Water temperature rise of the supply and return magnet cooling lines, T_s and T_r , measured as a function of time. A peak dc current of 2.7 kA was applied for approximately 3.3 min to each coil.

*Information available from Rita Gribble, Los Alamos Group CTR-3.

The return water from the magnet coils passes through a heat exchanger located in the cooling tower adjacent to SM-163. The tower is cooled by water circulated from a sump and is also air-cooled by a pair of two-speed 8-ft-diam fans. All of these components are operated either manually from switches located in SM-163 or automatically using a Johnson step controller which maintains a preset supply-water temperature.

The busbars are currently not water-cooled. Because of the busbar mass, the rate of temperature rise is quite low, even at full power. Current operation requires a duty cycle less than 5% (for full power operation). Ambient air cooling between shots is adequate. If, however, dc operation over intervals greater than about 1 h becomes desirable, some slight modifications will be necessary. The temperature rise in the type 6101 Al busbars, in the absence of any cladding, has been calculated. The ohmic power dissipated by the bars heats the aluminum while heat is lost by air convection and radiation to the room. The results from these calculations are plotted in Fig. 10 for a busbar current of 7.5 kA and radiative emissivities of 0.028 and 0.5. The former value corresponds to present conditions, whereas the latter value might be achieved if one were to paint the busbars black. The temperature rises from room temperature to 115°C and 75°C, respectively, requiring approximately 4 h to reach these steady-state values. Air convection cooling is ineffective for the busbars surrounded by the solid Al plate cladding. These busbars, however, contain two 0.5-in.-i.d. holes bored through

their entire lengths that can be used to pass cooling water.

The 4/0 welding cables that connect the coils to the busbars are not water-cooled and are designed only for low-duty cycle operation. For higher duty cycles, water-cooled flexible welding cable is available and should be used.

D. Electrical Shielding, Transient Suppression, and Insulation

The approximately 1000-turn, 0.3-kV dc magnet coils are located 17 cm from the single-turn, 100-kV theta-pinch coil. Careful shielding design has been necessary to minimize the voltage induced by the theta pinch across the dc coil windings and the busbar feeds. The design criterion has been to limit any induced voltage to less than 1 kV. A 0.75-in.-thick aluminum flux-excluding plate (Los Alamos Dwg. No. 33Y180799, Sheet 5) has been erected between the theta-pinch and dc coils (see Fig. 1). This plate diverts the theta-pinch magnetic flux, preventing this flux from linking the dc coils. The calculated vacuum flux surfaces generated in the absence of any flux-conserving boundaries at the dc coil locations are plotted (see Figs. 11a and 11b) for conditions without and with the flux-excluding plate and steel vacuum chambers, respectively. The plate can reduce this linking flux by nearly two orders of magnitude; however, this flux diversion is not enough because about 30 kV could still be induced across a single pancake. Moreover, the magnetic flux at axial locations greater than about 2 m beyond the plate remains essentially unaffected by the presence of the plate. These calculated flux values have been confirmed by measurements made before coil installation.

To reduce the induced dc coil voltage to an acceptable level, individual or groups of up to three pancakes have been clad on all exposed surfaces. The cladding consists of electrically grounded, 0.063-in.-thick, type 1100 aluminum. Electrical joints between cladding surfaces are made using tinned copper braid and aluminum rivets. An additional 0.005-in.-thick Mylar sheet is placed between the pancake and the aluminum. The magnetic field penetration time through the cladding is several ms, thereby reducing the induced coil voltages about another three orders of magnitude. This penetration is long enough to contain the oscillating magnetic field created by the 720-Hz ripple current (approximately 10^{-4} amp ac/amp dc) associated with the 12-phase rectification of the power supply. The ripple field causes the cladding to vibrate at this resonant frequency. The cladding vibrations are audible.

When one specifies that the magnetic flux at a particular boundary be zero, the voltage across the coil

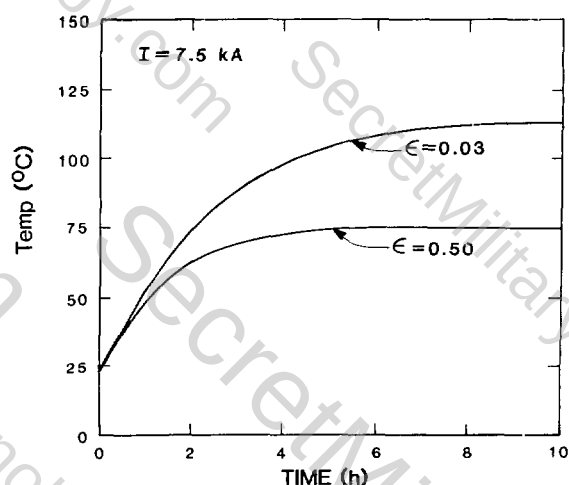


Fig. 10. Busbar temperature calculated as a function of time assuming a constant 7.5 kA current. The bars are heated by ohmic dissipation and they are cooled by air convection and by radiation. Calculations were performed for radiative emissivities ϵ of 0.03 and 0.50.

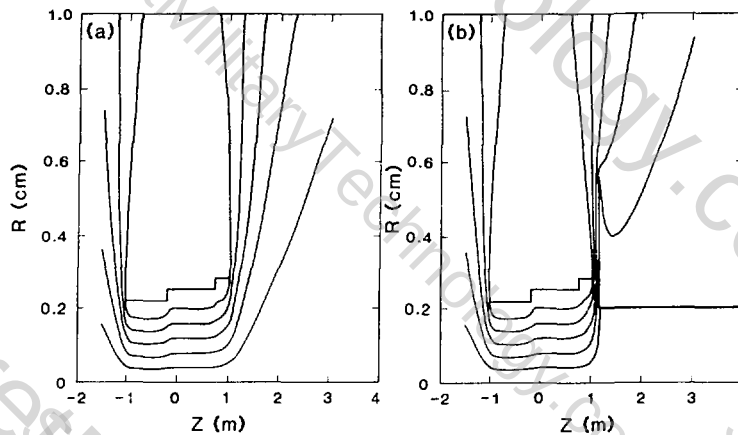


Fig. 11. Vacuum magnetic flux surfaces generated by the pulsed theta-pinch coil for cases (a) without and (b) with the presence of the flux-excluding plate and the translation vacuum tanks.

terminals is not necessarily zero because of the finite coil geometry. To ensure that this voltage is minimized, a pair of metal oxide varistors (General Electric Model No. V27ZA60 and No. V18ZA40) has been installed across the terminals of each magnet coil. These components resistively damp any transient voltages and keep the coil voltage significantly less than 30 V. Each varistor can absorb 20-40 J per pulse. The sum of low-voltage transients across all of the series coils could lead to an unacceptably large voltage across the power supply output. To suppress these transients, a 320-V, 300-J varistor (General Electric Model No. V320HE300) is placed across the busbars near the free-wheeling diode. Two 0.47- μ F, 600-V capacitors are also placed in parallel across the busbars near the same location.

Insulation to prevent electrical breakdown is necessary in the 15-cm gap that separates the theta-pinch coil from the grounded flux-excluding plate. Three nested, high-density polyethylene "hats" (Los Alamos Dwg. No. 33Y180797) are placed with their 36-in.-diam brims in the gap and their 10-in.-long crowns (with ends cut off) inserted between the theta-pinch coil and the quartz discharge tube. The minimum thickness of each hat is 0.25 in. They have been fabricated using a relatively inexpensive (\$35/hat) thermovacuum forming process by A & W Plastics, Denver, Colorado, which will retain the molds and store them until March 1988. Inserted around and in between the hat brims are 25 sheets of 72-in. x 72-in., 0.010-in.-thick Mylar.

E. Structural Supports

Each dc magnet weighs approximately 500 lb. The coils are installed onto FRX-C/T using crane hoists (Los Alamos Dwg. 33Y180794). The pancake base fits inside a custom-designed carriage (Los Alamos Dwg. No. 33Y180775) that rides on bearings along the vacuum tank support stand (see Sec. III.E).

An axial compression force of up to 40 tons can be applied to the magnets by the 10-kG B-fields. The pancakes are reinforced against collapse by seven 5-in.-diam aluminum and brass spacers placed in every pancake gap (Los Alamos Dwg. No. 33Y180806). Four of these spacers are adjustable, whereas the other three are custom fit around the 2-in.-diam stainless steel support shafts that span the length of the coil set.

III. VACUUM HARDWARE

The construction of FRX-C/T has required major alterations and additions to the vacuum hardware. A 40-cm bore, up to 6.3-m-long stainless steel vacuum chamber has been added. The existing quartz discharge tube has been modified and the vacuum pumps moved. The theta-pinch coil ground plane has also been changed.

A. Stainless Steel Vacuum Tanks

The translation region vacuum vessel consists of up to five 4-ft-long modules, each consisting of a 16-in.-o.d., 0.188-in.-wall, type 304 stainless steel pipe (see Fig. 12 and Los Alamos Dwg. No. 33Y180772). There are 28 diagnostic ports in each module (twelve 6-in.-diam and sixteen 2.75-in.-diam stainless steel conflat flanges) welded around holes drilled through the tank walls at 6-in. axial intervals and at every 90° azimuthal position. Because of radial space limitations created by the 20-in.-i.d. dc magnet coils, the 6-in. conflat flanges are recessed about 0.625 in. inside the tank. Welded onto each module end are 18-in.-o.d. stainless steel flanges. Vacuum seals between modules are made using 16.510-in.-o.d., 16.100-in.-i.d. aluminum O-rings (Model No. HN200, manufactured by Helicoflex Co., Boonton, New Jersey).

Before installation the modules are vacuum prepared by the following procedure: (1) vapor degreasing in trichloroethylene, (2) electropolishing, (3) ultrasonic cleaning and rinsing with detergent (Alconox) and distilled water, (4) conflat-flange cover installation, and (5) leak checking. Los Alamos Group MST-6 (electrochemistry section) performed the first two steps and Group CTR-3 performed the remainder. An rf glow discharge cleaning system has been considered. The

base pressure of the stainless steel-quartz chambers (see below) is about 4×10^{-8} torr, a value about equal to that in FRX-C, which contained only half of the current volume.

Diagnostic and end flanges were welded before any vacuum preparation. As a result, impurities from the coated surface of the steel pipe became partially impregnated into the welds. This dirt could be only partially removed by electropolishing. To effectively clean these welds, the modules were precleaned by glass-bead blasting before the five-step procedure above, but this problem could have been prevented if the dirty pipe had been degreased and electropolished before being welded.

The welds of the vacuum tanks were made using type 308 stainless steel rod. Type 300 series stainless steels are known to undergo phase transitions to ferromagnetic materials as a result of welding. This added permeability can be reduced by annealing the steel in a vacuum furnace. Although this procedure was considered, it has not been followed because of the small (about 0.5-G) magnetic field errors caused by these welds (see Sec. II.B and Fig. 6). Metallurgists recommend using type 2169 stainless steel for more austenitic welds.

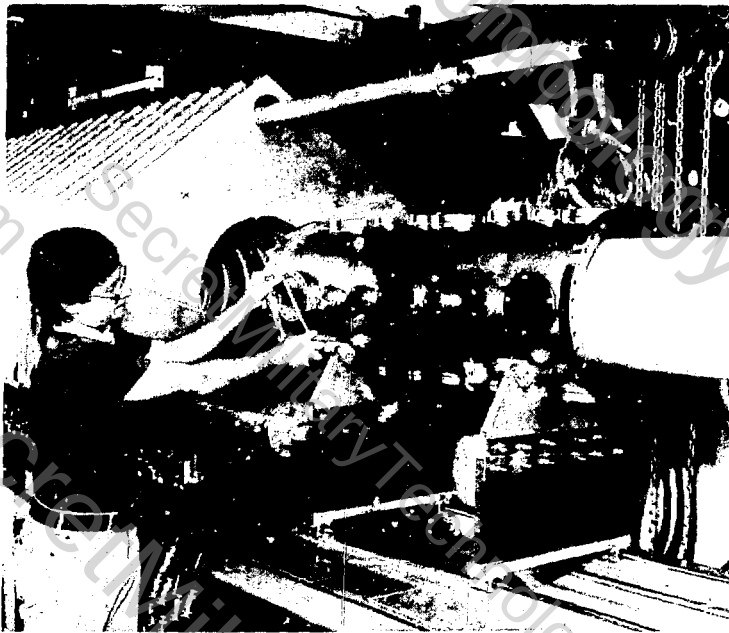


Fig. 12. Photograph of a single 4-ft-long translation region vacuum tank module. In this photo, the cantilevered Hall probe holder penetrates one end of the module. The cladded dc magnet coils appear in the background.

B. Quartz Discharge Tube

The theta-pinch vacuum chamber consists of a 297-cm-long, 41.7-cm-o.d., 0.45-cm-wall, fused silica tube (see Fig. 13 and Los Alamos Dwg. No. 33Y180523). A tube previously procured for FRX-C was cut to the above length by Los Alamos MEC-5 Shop No. 48 (SM-287, Room 101) using a diamond saw. A new tube of proper dimensions has also been procured from Herreus-Amersil, Sayerville, New Jersey. Two 0.75-in.-diam puff valve ports have been drilled at nearly opposite sides in the quartz tube at the center position of the theta-pinch coil, using an ultrasonic drilling machine with a diamond-tipped hole-cutting bit, by a ceramics shop (Los Alamos Shop 47) located near the MST-6 facilities. As in the FRX-C experiment, vacuum seals between the quartz and stainless steel supports on both ends are made with a 16.375-in.-i.d., 0.413-in.-thick Viton O-ring. The quartz tube-stainless steel translation region interface (Los Alamos Dwg. No. 33Y180799) is supported by the aluminum flux-excluding plate (Sec. II.D).

C. Vacuum Stand and Pumps

For FRX-C/T, the FRX-C vacuum stand (see Fig. 14 and Los Alamos Dwg. No. 33Y180567) has been modified and moved to the opposite (south) end of the quartz discharge tube. The stand is electrically connected to the ground plane, which spans the entire length of the device and follows the diagnostic conduits in a trench at the south end of the experiment. Both end supports for the quartz tube are grounded. The vacuum stand is supported against the 1-ton atmospheric axial force by an electrically isolated steel structure (Los Alamos Dwg. No. 33Y180816) that connects to enforced pillars supporting the theta-pinch collector plates. Without these reinforcements, an unacceptably large axial deflection of the vacuum stand and the quartz discharge tube occurs when the chambers are evacuated (see Sec. III.E). (The phenolic rods formerly used in FRX-C to counteract this force could no longer be used because they would have interfered with the electrical insulation placed on the north end of the quartz tube.)

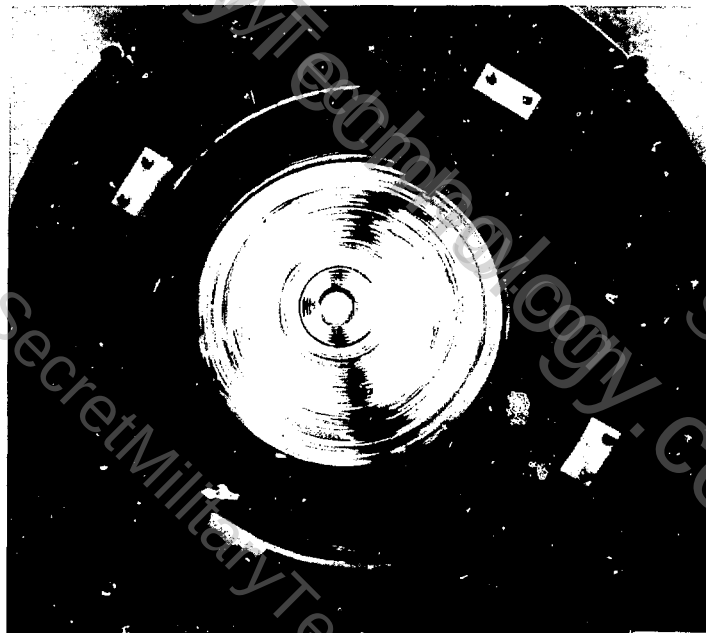


Fig. 13. Photograph of the 40-cm-bore vacuum chamber. The 3-m-long quartz discharge tube (foreground) is located inside the theta-pinch coil. The stainless steel translation region modules appear in the background.



Fig. 14. Photograph of the vacuum stand and the upstream (south) end support structure.

The vacuum pumps, control system, and gauges are the same used in FRX-C. The pumps and gauges have been moved with the vacuum stand, which required rerouting all of the electrical and pneumatic lines that connect the control racks and the computer inputs and outputs to the vacuum stand. A head for a residual gas analyzer (UTHE Technology International, Model No. 100C) has also been added to the vacuum stand.

D. Gas Fill Systems

Two modes of deuterium gas filling before plasma discharge are possible. The same "static" fill system used in FRX-C has been connected, in which gas from a several-torr, 54-cm³ plenum is transferred to the main vacuum chamber before starting the 90-s charge sequence. Using this static fill system, FRCs can be formed and translated through the 5- to 20-mtorr pressure D₂ neutral gas background. Translation through these neutrals can result in an unacceptably large plasma

energy loss due to charge exchange, excitation, dissociation, and ionization.⁷ To minimize these losses, a puff gas-injection system has been installed. Deuterium is puffed into the quartz tube 1-3 ms before the plasma discharge. This gas is localized in the source and the pressure is significantly reduced in the downstream translation region.

Puff valves developed for the CTX experiment at Los Alamos are used (Los Alamos Dwg. No. 33Y180511). These valves have been modified to include a larger plenum volume of 0.71 or 1.45 cm³. Two modes of puff gas injection are possible. Gas may be injected side-on from two valves (0.71-cm³ plenums) mounted on opposite sides at the theta-pinch coil center. The valves are physically supported by a structure connected to the theta-pinch coil (Los Alamos Dwg. No. 33Y180770) and are mounted to the discharge tube by a 1-in.-diam stainless steel welded bellows and attached to a 1-in.-o.d., 0.063-in.-wall, 6-in.-long, quartz tubulation that is epoxied to the discharge tube using Torr-Seal (see Fig. 15). This sealant is applied only to the outer surface of

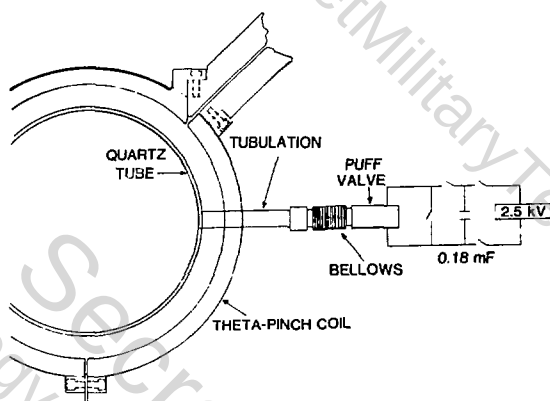


Fig. 15. Schematic diagram of the puff valve system.

the quartz discharge tube to prevent any contact between the plasma and the epoxy. The other mode of puffing uses end-on injection from a valve with a 1.45-cm³ plenum mounted on axis at the south end (i.e., on the vacuum stand) of the device.

Transient neutral gas distributions are measured using a CK5702 tetrode, fast-ionization gauge.⁸ Typical measured $p(z,t)$ axial D₂ pressure profiles from side-on injection are plotted in Fig. 16.

The solenoid coil of each puff valve is driven by an ignitron-switched, 180- μ F capacitor charged to 1.4 kV. The high-voltage and ground connections of this circuit

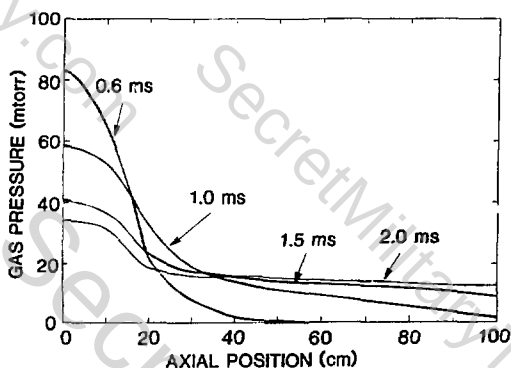


Fig. 16. Axial D₂ gas distributions measured on axis for side-on gas injection.

are removed before the discharge to prevent any current loops being created by the plasma. Microswitches positively sense this disconnection during the final 10 s of the charge sequence; otherwise an abort is issued by the computer, preventing the discharge.

E. Support Structures

The translation region vacuum tanks and dc magnet coils rest upon a support table (see Fig. 17 and Los Alamos Dwg. No. 33Y180775), which is made from type 6061 aluminum plates, I-beams, and channel. This table is electrically isolated from the floor by phenolic plates and is grounded at the south end by the theta-pinch ground plane. There are four separate tables ranging in length from 4 to 16 ft. The second table from the theta-pinch (south) end rests on a pair of 1-in.-diam rails and this entire unit can be translated up to 5-ft in the direction transverse to the machine axis.

Mounted along the entire length of these tables are two 0.625-in.-diam bearing shafts, spaced 18 in. apart, along which the vacuum tank and dc coil supports ride. The vacuum tank supports (see Fig. 12 and Los Alamos Dwg. No. 33Y180775) consist of a type 6061 aluminum base that houses the bearings. Attached to this base is a phenolic support that provides electrical isolation and connects to the 4-ft-long stainless tank modules with aluminum clamps. Some of the tank supports have been modified. The aluminum bases have been directly connected to the dc coil supports.

In the original design, the vacuum chambers were to be supported against the 1-ton atmospheric axial compressional force by the vacuum stand on the south end without the additional reinforcements and by the aluminum flux-excluding plate on the north end. This configuration was tried, but when the chambers were evacuated, the aluminum plate and the vacuum stand deflected sufficiently to cause an unacceptably large axial deflection (>0.125 in.) of the quartz discharge tube. Vacuum stand supports (Sec. III.C) have been added and an additional 0.75-in.-thick aluminum plate has been placed at the north end (see Fig. 18). This plate is reinforced with aluminum channel and connects the vacuum chambers to the support tables and the upper deck through the crane hoist I-beams. Electrical ground loops are avoided using phenolic breaks. When the vacuum chambers are evacuated, a 0.010-in. axial deflection of the discharge tube occurs.

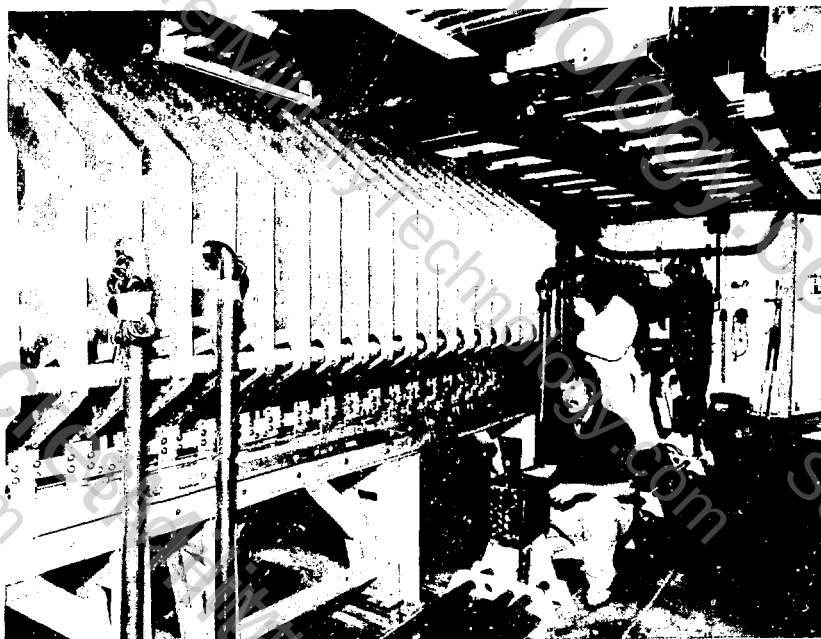


Fig. 17. Photograph of the support tables and dc magnet coils.



Fig. 18. Photograph of the downstream (north) end support structure.

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APPENDIX

RELATED ENGINEERING DRAWINGS FOR FRX-C/T DEVICE*

Part:	Los Alamos Drawing Number
Puff Valve System	33Y180511
Quartz Discharge Tube	33Y180523
Vacuum Pump Stand	33Y180567
Theta-pinch Coils	33Y180759
dc Pancake Coil	33Y180762
Experimental Room Layout	33Y180767
Puff Valve Supports	33Y180770
4-ft-long SS Vacuum Tanks	33Y180772
Translation Region Support Structure	33Y180775
Crane Hoists	33Y180794
Polyethylene Insulating Hats	33Y180797
Quartz-Stainless Interface	33Y180799
2.5 MW dc Busbars	33Y180800
0-10 m Ω Shunt Resistors	33Y180801
Magnet Cooling Hose Assembly	33Y180803
Cooling Manifolds	33Y180805
dc Magnet Support/Spacers	33Y180806
South End Support Structure	33Y180816
Hall Probe Holder No. 1	33Y180823
Hall Probe Holder No. 2	33Y180852
Fiberoptic Transceivers	45Y123941/6

*Drawings available from D. J. Rej, Group CTR-3, Los Alamos National Laboratory.