# PERFORMANCE OF THE 10-kV, 100-kA PULSED-POWER MODULES FOR THE FRX-C MAGNETIC COMPRESSION EXPERIMENT*

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## Abstract

In this paper, we present detailed performance data collected from over a year's operation of the 25 and 50-kJoule pulsed-power capacitor-bank modules[1] developed for the Los Alamos magnetic fusion facility *FRX-C*.[2] These modules supply the 5-MA magnet current needed for the compressional heating of compact toroid plasmoids. To date, 54 modules have been built and successfully tested at their full design rating: 100-kA peak output current at 10-kV charge, $\tau_{1/4}$ = 60 $\mu$s (25-kJ module), or 110 $\mu$s (50-kJ module), crowbar $L/R \leq 1$ ms. Modules are compact, cost about $5,000 each, and though designed for 25 or 50 kJ, they can be easily modified for other pulsed-power applications. Energy is stored in 25-kJ capacitors. Start and crowbar switching is performed with a pair of water-cooled, size-D ignitrons. As an alternative to an ignitron, crowbar switching by solid-state rectifiers has been successfully demonstrated. Current is conducted between components and to the load by parallel-plate transmission lines and by a parallel array of commercially-available coaxial cable.

## Design

Module design has been thoroughly reviewed in Reference 1 and documented in a set of detailed engineering drawings soon to be available to the public through the National Technical Information Center. For completeness, important features are briefly reviewed here. Design objectives included: (1) efficient and reliable energy transfer with adequate inductive isolation and fault-current protection; (2) low-cost; (3) light weight; and (4) simple assembly, inspection, and maintenance. As illustrated in Fig. 1, modules are readily stacked atop one another.

The principal parameter that influenced the design of the *FRX-C* module is the output current. In particular, ignitron current is kept at or below the conservative operational value of 140 kA at 11 kV and 70-C charge transfer, established on the *NOVA* laser facility at Livermore.[3] Because of ringing through the start ignitron loop, the peak current in a crowbar tube can be 40% larger than the output current. Therefore, each module has been designed to supply and crowbar 100-kA output at a 10-kV charge.

Type *NL488A* ignitrons have been selected for the modules. The basic tube, designed by GE, is currently available either as the *NL488A* from National Electronics or as the *BK488A* from English Electric Valve. The 488A was chosen because of its busbar anode construction. Braided "pigtail" anodes found on other size-D tubes have occasionally failed during previous high-current applications. The cathode jacket is maintained between 10° and 15°C by a circulating, deionized water system. There is no active anode temperature control; however, as explained below, the start tube anodes are passively heated by a series resistor connected to the anode bus.

High-energy-density capacitors, 0.5 mF @ 10 kV (25-kJ), capable of 10,000 discharges at 100 kA and 20% reversal, are used in the modules. With connecting hardware, the equivalent series resistance (ESR) and inductance (ESL) of a capacitor are 11 m$\Omega$ and 0.10 $\mu$H, respectively.

Power flow is along parallel-plate strip lines made from aluminum busbars. The busbars are held together by clamps and spacers made from G-10 laminate, connected by stainless steel bolts. The busbars are spaced 1¼" apart and are insulated only by ambient air and the G-10 strips. Each ignitron is mounted and housed inside a welded-aluminum cage. The cathode bar is affixed rigidly to the cage bottom with annealed copper brackets. The cage top connects to the lower busbar through copper gaskets. The fragile glass-metal seal around the anode bar is isolated from mechanical shock through a pair of high-current, flexible braided connectors. Brass hex stock is used to extend the capacitor high-voltage terminal above the low-profile header. The hex stock and the low-voltage capacitor connections are connected to the busbars with copper sheet metal. The busbar-ignitron assembly and the capacitor are held in position by a space frame made from square aluminum tubing.

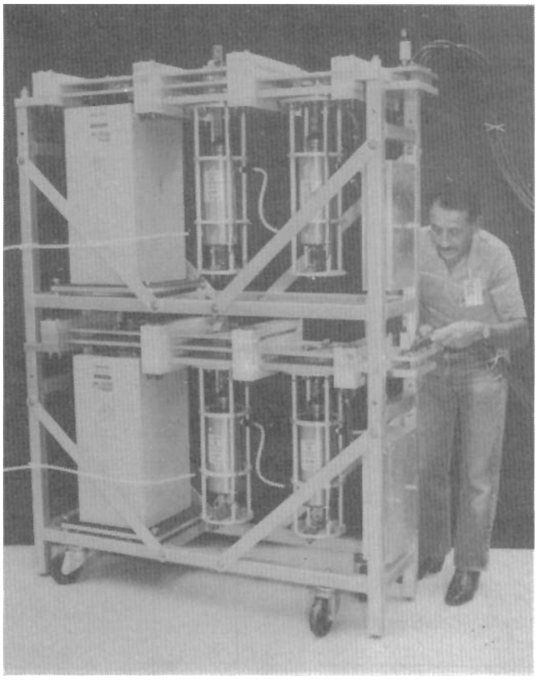

**Fig. 1. Photograph of two 25-kJ modules.**

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14. ABSTRACT
**In this paper, we present detailed performance data collected from over a year’s operation of the 25 and 50- kJoule pulsed-power capacitor -bank modules 1 developed for the Los Alamos magnetic fusion facility FRX-C.2 These modules supply the 5-MA magnet current needed for the compressional heating of compact toroid plasmoids. To date, 54 modules have been built and successfully tested at their full design rating: 100-kA peak output current at 10-kV charge, ’T,;. = 60 J-LS (25-kJ module), or 110 J-LS (50-kJ module), crowbar L/R :S 1 ms. Modules are compact, cost about $5,000 each, and though designed for 25 or 50 kJ, they can be easily modified for other pulsed-power applications. Energy is stored in 25-kJ capacitors. Start and crowbar switching is performed with a pair of water-cooled, size-D ignitrons. As an alternative to an ignitron, crowbar switching by solid-state rectifiers has been successfully demonstrated. Current is conducted between components and to the load by parallel-plate transmission lines and by a parallel array of commercially-available coaxial cable.**

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An important module component is a 7-mΩ damping resistor, installed in series with the start ignitron. The resistor helps protect equipment during standard operating and fault modes. It consists of two parallel inconel strips, 9" long × 1" wide × 0.031" thick, separated by a phenolic spacer. Nickel tabs (2" long × 1" wide), welded to the ends of each strip, insure good electrical connection for the 50-kA current. The resistor assemblies are connected with bolts directly to start ignitron anode and to the flexible braided connector. During a normal discharge, up to 15% of the capacitor energy is dissipated in the inconel resistor. A 10-kV discharge causes the inconel temperature to rise by 110°C (25-kJ module) or 190°C (50-kJ module). The resistors expand by 0.016" when heated 200°C above room temperature. The inconel is effectively cooled by convection of ambient room air during the ten minutes between shots. A small fraction of this heat is also conducted to the ignitron through the anode-resistor current joint. This heat, combined with the cathode cooling, "conditions" the tube. The temperature differential prevents mercury condensation near the anode, thereby maintaining the ignitron high-voltage standoff capability.

The 100-kA output current is transmitted from a module by twelve parallel coaxial cables. Belden *YK-198* cable (0.57" o.d., 50 kV, 27 nH/ft, 103 pF/ft, 2.1 mΩ/ft) has been selected. Cables are connected to busbars at one end of the module (see Fig. 1). The outer braids are connected by hoseclamps to copper couplings pressed into the middle bus. The inner conductors are swaged onto brass "banana-plug" connectors which are slotted and plugged into the lower bus.

The equivalent electrical circuit for a 25-kJ module is given in Fig. 2. The capacitor, busbars, and ignitrons contribute about equally to the 0.4-μH module inductance. The ignitron-cage assembly inductance is about four-times larger than the 40-nH value for the bare ignitron. Most of this increase results from the extended cathode and anode connections. The relatively large inductance of the busbar is a result of the 1¼" gap, and the 5' length. For low-impedance loads, the ignitron cage and busbar dimensions could be decreased, at the expense of increased insulation and assembly problems.

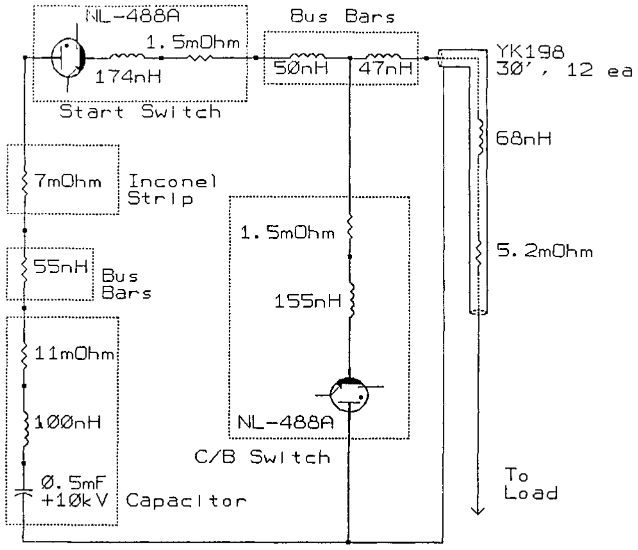

**Fig. 2. Simplified circuit diagram for the 25-kJ module.**

The 50-kJ module is a "stretch" version of the 25-kJ module. Two 0.5-mF capacitors are used. The frame and busbars are elongated to accommodate the extra capacitor. The remaining components are identical to those used in the 25-kJ module.

## Performance

Prototype modules were built and subjected to extensive testing. Experiments were performed in the *Scyllac* test-bay at Los Alamos. Three 25-kJ modules were discharged up to 2000 times at their full rating: 10-kV charge voltage, 100-kA output current. Similarly, a prototype 50-kJ module was also discharged 150 times at its full rating. Currents through each ignitron and through a test load were measured with passively-integrated Rogowski coils. The trigger current pulse to each ignitor was monitored with a self-integrating current transformer. Capacitor voltages were measured during a discharge with a resistor voltage divider.

The 25-kJ module was successfully hi-potted to over 25 kV dc. Voltage breakdown was first observed at 28 kV. Usually, the arc tracked along a G-10 clamp terminating at a busbar corner. [This problem was eliminated with a single layer of 0.031"-thick, 6"-wide polyethylene wrapped around the busbars at the locations of the clamps. Voltages up to 40-kV were successfully withstood.]

The first 1500 discharges were with a single 25-kJ module fired into a 3-μH test load. The output current was similar to that expected on *FRX-C*: $I_{max} \approx$ 10 kA per kilovolt charge, $\tau_{1/4} \approx 60 \mu s$. Only six of the twelve output cables were connected to the module, so that each cable and connector could be tested at currents up to 17 kA, two times the design value.

Data from a typical 10-kV discharge are shown in Fig. 3. The measured 20% capacitor voltage reversal and 55% current reversal were in good agreement with circuit simulations.[1] In accordance with manufacturers' recommendations, the crowbar ignitron was not triggered until there appeared a forward voltage across the tube, *i.e.,* not until a modest capacitor voltage reversal (0.1 kV). The 55-μs crowbar current risetime was primarily a result of finite inductance. The inconel resistor was removed for a limited number of discharges and larger reversals in the capacitor voltage (28%) and series ignitron current (74%) were measured. At the time of maximum current reversal, the crowbar ignitron current dropped almost to zero. These low crowbar currents were undesirable because the tube resistance increased and the arc sometimes extinguished. The characteristic L/R decay time of the output current was somewhat faster than the case with the inconel, presumably due to the increased start loop current and crowbar ignitron resistance.

The necessity for proper ignitron conditioning became immediately obvious during prototype testing. The first 50 discharges were without ignitron cooling. Because of mercury condensation near or on the anode electrode, both the start and the crowbar tube prefired frequently, even at voltages as low as 5 kV. A 10-kV crowbar prefire fault occurred twice during testing. Maximum fault currents through the start and crowbar tubes were 180 and -140 kA, respectively. Fortunately, both ignitrons survived the crowbar prefire fault with no sudden drop in ignitor-cathode resistance.

The ignitron prefire problem was eliminated by tube conditioning. The cathode temperature was maintained between 10° and 15°C with chilled, deionized water circulated through the channel provided inside the tube jacket. After the cathode cooling system was installed, the prefire fault was never observed on up to 2000 discharges at full rating on every module.

A trigger system failure resulted in the ringing, "no-crowbar" fault mode on at least two occasions at 10-kV charge. The measured reversals in voltage and current were 60% and 70%, respectively. All components survived the fault. From these ringing discharges, the capacitor ESR was estimated to be 11 mΩ. This was the largest resistance in the module circuit.

Three 25-kJ modules were discharged successfully in parallel into a common 0.7-μH test load. There were approximately 120 discharges at 10-kV charge and another 300 at 8 kV. A peak load current of over 300-kA was measured. Inductive isolation promoted current sharing to within ±25% in the three crowbar ignitrons.

The *NL488A* ignitrons performed satisfactorily during the prototype experiments. The ignitor-cathode resistances decreased with the number of shots at an acceptable rate. From the resistance data plotted in Fig. 4, one anticipates a tube lifetime of at least 10,000 discharges at the design rating. X-ray photographs[1] revealed no further deterioration of ignitron components, such as anode erosion or bending.

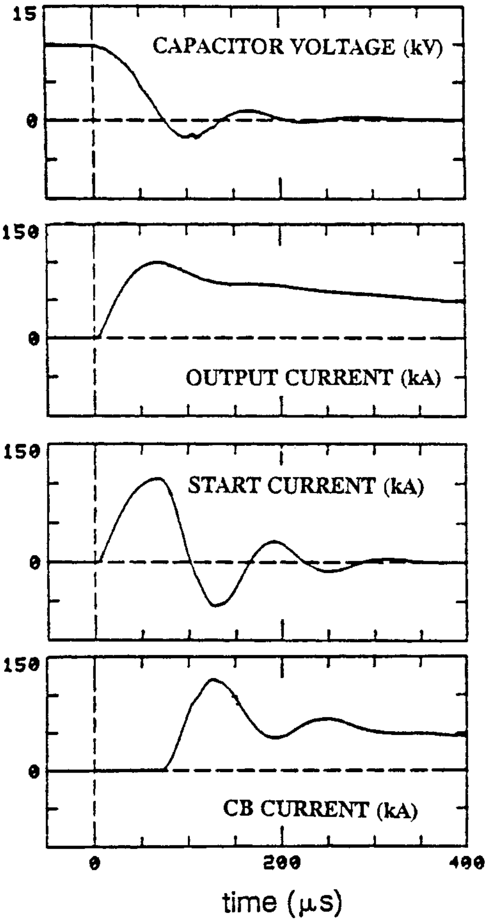

**Fig. 3. Experimental data from a 25-kJ module.**

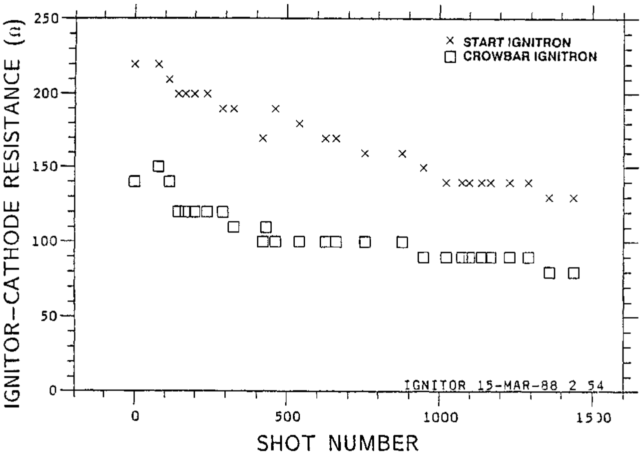

**Fig. 4. Variation of ignitor-cathode resistances with the number of 10-kV, 100-kA discharges on a 25-kJ module.**

Eighteen *YK-198* cable-connector assemblies were tested during the prototype experiments. Each assembly was routinely operated at 17-kA, two-times the design value. The cable performed satisfactorily throughout the tests. Provided they were carefully prepared and installed, connectors did not deteriorate. There was evidence of arcing at the banana plug connections when the plug diameters were undersized. Erosion was observed in the aluminum module busbar. When the plug diameter was sufficiently large to ensure a tight fit, there was no evidence of arcing, even for 1000 discharges at 33-kA per connector.

One 50-kJ prototype module was discharged into a 6-μH test load on 150 discharges at 10 kV and 100 kA, and for 65 at 8 kV and 80 kA. Typical data are plotted in Fig. 5. The only major difference from the 25-kJ waveform is the longer pulse, $\tau_{1/4} \simeq 110$ μs, $L/R \simeq 1.5$ ms. The module performed satisfactorily during these tests except for a rapid deterioration of the crowbar ignitor. The ignitor-cathode resistance dropped monotonically with the number of shots from 240 Ω to 0. The L/R decay time was substantially longer than that on *FRX-C*; consequently, about 130 C of charge was transferred through the crowbar tube, a value well above the 70-C design limit. Less than 50 C is transferred during normal operation on *FRX-C*; consequently, tube deterioration has not been observed there. An interesting observation related to the prototype failure was the resuscitation of the crowbar ignitor by "trigger conditioning." Following a technique developed at PI,[4] the wetted ignitor was energized approximately 100 times by the 700-A, 4-μs trigger pulse. No voltage was applied between the anode and cathode. The ignitor resistance increased to approximately 10 Ω after 30 pulses, reaching 30 Ω after 100 pulses.

A substantial amount of prototype development was invested in the trigger system. Each ignitron was triggered by a unit consisting principally of a 0.5-μF, 5-kV (6-Joule) capacitor, a 1:1 isolation transformer, and a 5-Ω current-limiting resistor. The isolation transformer was made from several turns of detonator cable wrapped around a ferrite core. The maximum open-circuit voltage and short-circuit current were 6 kV and 700 A, respectively. For parallel module operation, all of the start trigger capacitors were discharged through a common master switch consisting of a size-A ignitron. The crowbar trigger capacitors were similarly connected. The modular design promoted equal

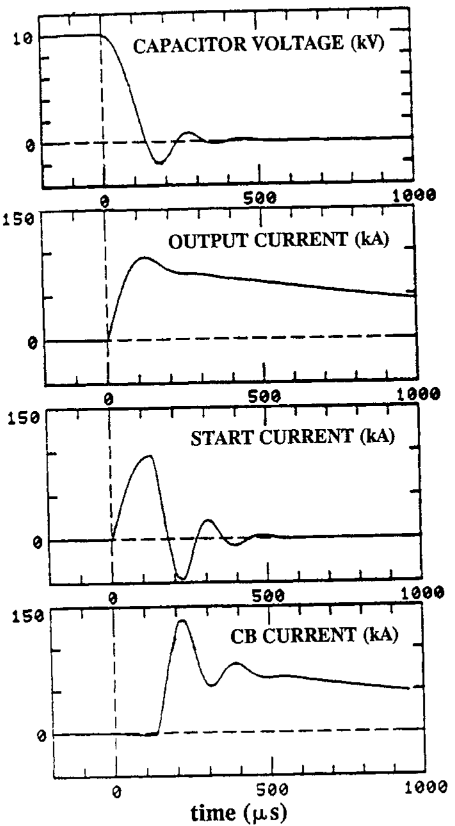

**Fig. 5. Experimental data from a 50-kJ module.**

distribution of ignitor current. A peak current of 650 A was observed with risetime and FWHM pulse-width of 1.8 and 4 µs, respectively. The trigger system operated satisfactorily during these tests,[1] always firing the ignitrons without significant jitter.

Ignitor current reversal did not appear to be detrimental to ignitrons during a discharge. A small fraction (≤ 0.3%) of the main tube current was often induced in the ignitor circuit. The reversed ignitor current magnitude was comparable to that of the trigger pulse but the pulsewidth was ten-times longer. This current was eliminated by a high-voltage diode placed in series with the isolation transformer secondary. The diode, however, proved unnecessary during prototype testing. This conclusion is supported by the Fig. 4 data in which the first 880 shots were with the diode, the remainder without. There was no discernible difference in the decay of ignitor resistance with or without the diode.

Exploratory tests were conducted with high-power, solid-state rectifiers used in place of the crowbar ignitron. There are obvious advantages of the solid-state crowbar, *e.g.*, elimination of an external trigger, and a faster turn-on. Two high-voltage diodes (International Rectifier type *R77R50A*, 4" diam., rated at 5-kV, 35-kA, for a non-repetitive 8.3-ms pulse) were mounted in series inside a modified ignitron cage (see Fig. 6). As illustrated by the representative 10-kV data in Figs. 7 and 8, both diodes successfully conducted peak currents of up to 140 kA, turning on quicker than an ignitron. Furthermore, diodes proved to be useful at ultra-low voltage discharges, well-below 1 kV, conditions where an effective crowbar could not be obtained with ignitrons.

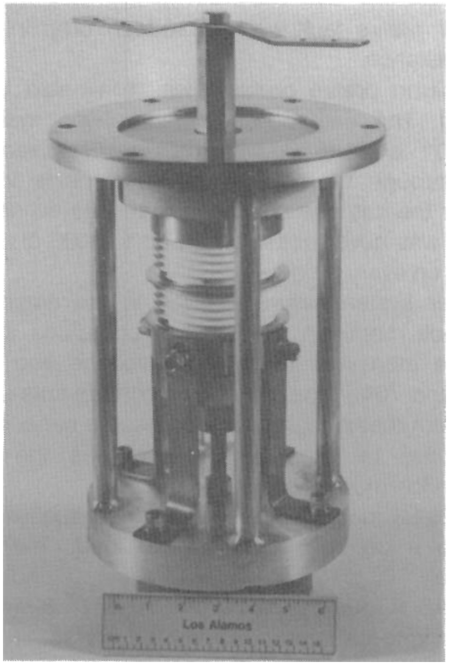

**Fig. 6. Solid-state rectifier crowbar assembly.**

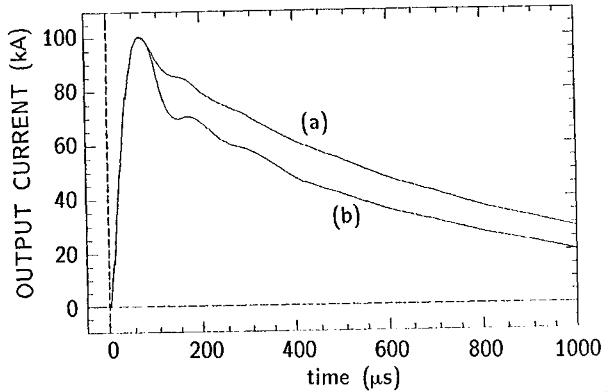

**Fig. 7. Waveforms obtained from the 25-kJ module discharged at 10-kV with the (a) diode and (b) ignitron crowbar.**

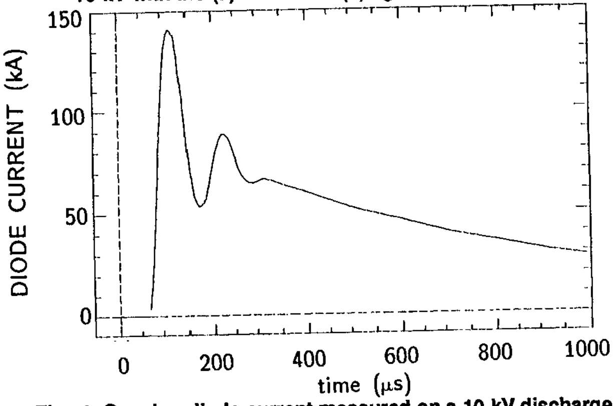

**Fig. 8 Crowbar diode current measured on a 10-kV discharge.**

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