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THE ELECTRICAL SYSTEM OF THE BEVATRON RAPID BEAM EJECTOR (BEAM KICKER)

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ABSTRACT

The operation cycle of a bubble chamber includes a brief period during which charged particles entering the chamber produce optimum tracks. Following the lead of Rahm at the Brookhaven Cosmotron, a group at the Berkeley Bevatron constructed a rapid beam ejector to produce brief pulses of particles. Energy stored in a capacitor bank is transferred to an air-core magnet surrounding the proton beam of the Bevatron. The protons are displaced from their normal orbit and strike a suitably located target; particles from this target can then emerge from the accelerator. A capacitor bank of 120µf stores 13,500 joules at 15,000 volts. Two ignitrons in parallel connect the capacitor to the magnet. The magnet current rises to the peak of 52,000 amperes in 55 microseconds; at peak current a resistor is connected in parallel to damp the current decay.

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INTRODUCTION

The Cosmotron and Bevatron (proton synchrotrons) do not eject protons directly; external beams are obtained from targets inside the accelerating chamber by scattering or from other interactions of the internal beam with these targets.[1]

The operation cycles of bubble chambers include relatively brief periods of optimum response to charged particles. The methods of scattering protons in use since before the development of bubble chambers result in pulses of relatively long duration - of the order of milliseconds.

In 1956 David Rahm at Brookhaven[2] directed the development of the Cosmotron rapid beam ejector in order to obtain pulses of particles of durations of the order of 3 μsec.

After initial successes of the Cosmotron installation, Glen Lambertson of the University of California Radiation Laboratory at Berkeley directed the development of the Bevatron rapid beam ejector whose electrical system is described in this report. Because it is customary at the Bevatron to think of targets as general purpose devices that are relatively independent of other equipment, that part of the system not including the targets has been referred to as a beam-kicker.

The essential element of the rapid beam-ejector system is the two-turn air-core magnet surrounding the normal position of the high-energy proton beam in one of the straight sections of the synchrotron.

The air-core magnet is energized by discharging a large capacitor bank through its windings. The resultant magnetic field causes the protons to shift from the normal orbit to a new orbit which is roughly eccentric to the normal orbit. A suitably located target can be hit by protons in the displaced orbit and can scatter particles during the upper part, or parts, of the magnet current pulse.

The following table (Table I) compares the Cosmostron rapid beam ejector system with the Bevatron system.

TABLE I

Comparison of the Bevatron and the Cosmotron rapid beam ejector systems

	Cosmotron	Bevatron
Magnet		
Total number of turns	2	2
Coil connections	Parallel	Series
Peak line current (amperes)	50,000	52,000
Length of each one-turn coil (inches; center to center)	65	96
Width of each coil (inches, center to center)	8	16.5
Vertical spacing of coils (inches, center to center)	7	13.5
Conductor diameter (inches)	0.625	2
Inductance (microhenries)	2 (system total)	7
Deflection strength $\int \bar{B} \times dl$ (gauss inches)	70,000	110,000
Deflection of orbit (inches)	4.5 (at 3 Bev)	6.5 (at 6 Bev)
Pulser		
Capacitance (microfarads)	8	120
Peak charging potential (volts)	25,000	15,000
Stored energy (joules)	2,500	13,500
Switch	Three-electrode spark gap	Two type-5555 ignitrons in parallel
Pulse shape	Oscillation, damped by circuit resistance	Unidirectional pulse; $\frac{1}{4}$ sine-wave rise, critically damped decay
Pulse rise-time (microseconds)	6	55
Transmission Line		
Form	Rigid, coaxial	Parallel RG-14/U coaxial
Inductance (microhenries)	small	1.1
Length (feet)	~6	130[a]

[a]Includes 65 ft in the fault inductor.

THE ELECTRICAL SYSTEM[3]

A simplified equivalent circuit is shown in Figure 1a. The impedance of the transmission line and load is predominantly inductive and is represented by L in the equivalent circuit. Energy stored in the capacitor C is transferred to the inductance L when S-1 is closed. At peak magnet current (zero voltage), S-2 is closed, connecting the critical damping resistance in parallel with the magnet and capacitors. Note that the currents in S-1, L, S-2, and R are unidirectional, and that virtually all of the original stored energy is transferred to the inductive load.

Figure 1b represents the idealized magnet current and voltage. The elements of the electrical system include

1. the pulser,
2. the load circuit,
3. the control and monitoring circuits, and
4. the radiofrequency compensation.

These elements are described in detail below and are shown in the block diagram of Fig. 2.

PULSER

The pulser is made up of two parallel sections which are energized from a common power supply. The important circuit elements of one section are represented in Fig. 3.

When V-1 is triggered, the capacitor discharges into the load. When the capacitor voltage reverses, V-3 conducts through the ignitor of V-2, firing V-2 and connecting the damping resistor in parallel with the capacitor and the magnet-coil load.

Power Supply

The power supply now in use is a general-purpose portable unit, which is controlled by an induction regulator and is connected three-phase full-wave delta-wye. (Fig. 4). The rectifiers are type-6894 mercury diodes. The supply is rated at 20 kv, 50 kw, but the induction regulator range is limited for this application to 15-kv maximum output voltage.

Capacitor Banks

Each of the two capacitor banks consists of an angle-iron frame enclosed within steel panels and hinged doors, and housing sixty capacitors. Each capacitor is rated at 1 μf, 25 kv. The capacitors are connected in parallel in twelve groups of 5 each, and each 5-μf group is connected to one RG-14/U cable through a high-voltage fuse.[4] The far ends of the twelve cables are connected in parallel in the adjacent ignitron cubicle.

Trigger Amplifiers

A "standard Bevatron trigger pulse" of plus 50-v amplitude and 10-μsec duration triggers a type-2050 thyratron, which discharges a capacitor through a transformer. The 200-v pulse output is connected to the grid of a 5C22 hydrogen thyratron. The 5C22 discharges an 0.15 μf capacitor at 5000 v through two (one-to-one ratio) high-voltage isolation transformers, applying positive pulses to the ignitors of the two type-5555 ignitrons which are designated V-1.

The 2050 and 5C22 amplifiers are in separate chassis. In the chassis with the 2050 amplifier is a univibrator that operates a relay each pulse. When the high-voltage chain is complete, closure of this relay operates a pulse-counting register.

Ignitron Assembly[5]

Switches S-1 and S-2 of the simplified equivalent circuit (Figure 1a) correspond to the type 5555 ignitrons represented in Fig. 3 as V-1 and V-2 respectively.

Type 5555 ignitrons are manufactured primarily for power-rectifier and resistance-welding service and are rated by their manufacturers for those applications. However, they have been used successfully (at UCRL, Livermore and at other laboratories) in high-current, high-voltage, capacitor-discharge circuits. These high-current applications have usually permitted a life of as few as 10,000 pulses (for example). A "crystal-ball" interpolation was made between the rectifier-service rating and the pulse-application experience at Livermore, and the values of potential and current, which we hope will permit a life of one million pulses, are listed in Table II below. (One million pulses corresponds to about three months of continuous operation with the Bevatron.) Table II compares rectifier-service ratings with the beam-kicker application.

Ignitrons have a short life if the arc transfers from the mercury pool to the stainless steel wall (the wall is at cathode potential). To keep the magnetic forces that result from the high currents in this system from driving the arcs to the walls, the ignitron tubes are mounted coaxially in copper cylinders and the cylinders carry the return currents. The necessary openings in the cylinders are made symmetrical so that asymmetry of magnetic forces is minimized.

The ignitron cubicles are shown in Fig. 5; Fig. 6 is a view inside one of the two ignitron cubicles. The larger cylinder contains two type 5555 ignitrons, V-1 below V-2. The smaller cylinder contains the air-cooled damping resistor. The transmission line consisting of six parallel-type RG-14/U cables is visible at the lower right.

Because the average current is very low, the power dissipation in each ignitron is less than 20 watts. The damping resistor blowers (at lower left in Fig. 6) are the only cooling provided in the ignitron cubicle.

TABLE II

Comparison of type-5555 ignitron ratings with the beam-kicker application

	Rectifier service application (Manufacturer's ratings)	Beam-kicker Application V-1 position (Series switch)	Beam-kicker Application V-2 position (Damper switch)
Maximum peak forward anode potential (volts)	2,100	15,000	-
Maximum peak inverse anode potential (volts)	2,100	-	15,000
Maximum peak anode current (amperes)	1,200	26,000	23,000
Surge current for 0.15 sec (amperes)	9,000		
Anode current averaged over 165 μsec (amperes)		17,000	
Anode current averaged over 110 μsec (amperes)			17,000
Continuous average current (amperes)	150	0.5[a]	0.35[a]

[a] 10 pulses per minute

Damping Circuit

Peak magnet current is reached when the electrical energy that was initially stored in the capacitor banks has been transferred to the inductive load. The capacitor voltage passes through zero, and the magnitude of the negative voltage increases as energy is transferred back to the capacitor. When the reversed voltage magnitude reaches a few volts, the type-575A mercury diode, V-3, conducts current through the igniter of V-2. If the initial capacitor-bank voltage, V_o, was between 5 and 15 kv, V-2 will fire approximately 10 to 5 μsec after zero voltage. After V-2 fires, the voltage applied to V-3 and its series resistor is the tube voltage drop of V-2 (about 20 to 30 v), and the igniter-circuit current drops to a low value.

The damping resistor is connected in parallel with the inductive magnet load when V-2 fires. Each damping resistor has a resistance of 0.24 ohms, which is slightly less than the critical value.

The resistors are coaxial assemblies of nichrome ribbon supported inside copper tubes. The ribbons are bent into a sinuous shape which reduces the distance between the ends to one-half the extended length. The sinuous shape permits the ribbon to absorb the sudden pulse (6000 joules) and the corresponding thermal-expansion impact without excessive mechanical stress.

The inductance of the resistors is tolerable in this application—the time-constant is less than 10 μsec and does not significantly modify the idealized behavior of the pulser. The damping resistor assembly is at the left of the coaxial ignitron assembly in Fig. 6. The centrifugal blower (lower left) cools the ribbon.

LOAD CIRCUIT

Each pulser discharges into a bundle of six parallel RG 14/U cables. These bundles of cables from the separate pulsers are brought together at the fault inductor; they are connected in parallel (electrically) at the vacuum feed-through plate. At the feed-through a 4 ohm resistor (in series with a 0.25 μf, 20 kv capacitor) absorbs most of the high-frequency energy in the steep-front voltage wave that is transmitted through the twelve parallel 50-ohm cables. The vacuum feed-through assembly forms a single coaxial circuit through an epoxy-glass insulator which is mounted on a port in the inside wall of the south tangent tank of the Bevatron. Inside the tank a group of eight RG 14/U cables continues the circuit, forming a flexible link to the magnet assembly. A junction assembly terminates the flexible link and connects it in series with the magnet coils through two groups of eight cables.

Fault Inductor

The capacitors, ignitrons, and paralleled-cable transmission line constitute a very-low-impedance source of electrical power. The single-bushing capacitors rest on angle-iron members in the capacitor rack, which is connected through copper conduit to the tangent tank. The impedance between the tangent tank and the capacitor racks is low, but it would have to be much lower than the source impedance to prevent a line-to-ground fault at the tangent tank from developing a high potential difference between the ends of the conduit return.

The fault inductor (Fig. 5) is a multilayer coil of 12 RG-14/U cables in parallel.[6] It is actually a continuous link in the transmission line; its leads are connected at the ignitron cubicles and at the vacuum feed-through plate, respectively. The normal-load current returns in the cable shields and cancels all but the coaxial inductance of about 1 μh. However, if a fault occurs between the line or load and the tangent tank or the conduit beyond the fault inductor, the total multilayer inductance of about 40 μh is effective in limiting the fault current. Before the fault current can rise to a significant magnitude the normal current circuit will discharge the capacitors.

Vacuum Feed-Through[7]

Electrically, the vacuum feed-through is an insulated coaxial circuit through the inner wall of the south tangent tank. A laminated glass-epoxy-resin plate 1 in. thick supports the atmospheric pressure load over a 19-in. diam. port and insulates both sides of the transmission line circuit. Figure 7 is a photographic view of the feed-through looking into the large conduit termination box outside of the vacuum tank. The cable shields terminates in special threaded fittings which are secured in a brass plate. Twenty-four bare No.-10 copper wires connect the plate to a brass ring sealed on the epoxy plate by an O ring. Figure 8 is a view inside the tank showing the corresponding wires connected to a junction and then to the shields of the eight cables that make up the flexible link to the magnet. The end of this link is shown in Fig. 9. Number 10 wire was used for the shield connections so that the same spring plug connectors that terminate the RG-14/U No. 10 center conductors could be used.

The load circuit is insulated from ground to permit reversing the magnet polarity. The parts necessary to reverse polarity have been designed but not yet fabricated.

Magnet Assembly

Figure 10 is a photograph of the two-turn air core magnet. (The photograph was taken while the outside cover plate of the Bevatron's south tangent tank was off.) The magnet is constructed of 2-in.-diam copper tubing; it is 96 in. long, $16\frac{1}{2}$ in. wide, and the upper and lower coils are spaced $13\frac{1}{2}$ in. apart (center-to-center dimensions).[8] The two coils are connected in series at the junction assembly shown in Fig. 9. The computed magnitude of the field in the center of the aperture is 1170 gauss at 52,000 amp. The inductance is approximately 7 μh.

Epoxy-glass insulators support the magnet coils in the vacuum tank. The beam-kicker magnet and the (steel) internal beam deflecting magnet share the mechanism that permits the adjustment of their radial positions from outside the vacuum tank (See Fig. 11).

CONTROL AND MONITORING CIRCUITS

The electrical system of the rapid beam ejector includes a conventional interlock chain for personnel and equipment protection. The pulser and power supply can be controlled remotely from the Bevatron main control room.

Four panel meters in the main control room display power-supply voltage, power-supply current, and charging-line voltage of each capacitor bank. The capacitor charging-line-voltage signals come from compensated dividers of 1 to 1000 ratio.

A set of four cables transmit pulser output-current signals from each ignitron cubicle. The signals are the integrated voltages induced in electrostatically shielded air-core coils surrounding the leads from the series-ignitron cathodes. The coils have a mutual inductance of about 0.45 μh, and after integration in RC integrators of about 10 msec time constant, the signal amplitude is 45 mv per 1000 amp. A balanced circuit permits the signals from the two pulsers to be examined individually, and the sum and difference signals can be observed (on an oscilloscope) by connecting the lines in series aiding or series opposing.

The current signals are also used to compensate for the radio-frequency error described below.

RADIOFREQUENCY COMPENSATION

When the beam-kicker magnet is energized, the Bevatron proton orbit is displaced—roughly eccentric to its normal orbit, but distorted so that the perimeter of the perturbed path is shorter than normal. The maximum deflection (toward the south) is about 2.5 in. at the magnet in the south tangent tank and 6 in. in the north tangent tank.

If the accelerator radiofrequency is not varied to compensate for the shorter path, the phase error accumulates until the protons lose synchronism and are no longer accelerated. However, if the radiofrequency is temporarily increased so that it matches the perturbed-orbit frequency, the beam can be returned to its normal orbit with most of the original protons in phase with the accelerating voltage. The missing protons include those purposely striking the target and those lost because of imperfect compensation. The recovered protons can be used in additional experiments and will not appear as undesired background within the acceptance time of the experimental system using the kicker.

The phase error per turn is very nearly proportional to the deflection, which in turn is proportional to the magnet strength. The magnet strength is proportional to the current, which makes the current signal a convenient signal with which to modulate the radiofrequency.

The Bevatron master oscillator uses a Colpitts circuit with semi-fixed capacitors. The accelerator-cycle starting frequency is controlled by adjusting the capacitance, and the frequency-modulation during acceleration is achieved by varying the control current in saturable inductors. The frequency response of the saturable inductors is inadequate for the fast beam-kicker pulse, and it was expedient to install a voltage-responsive variable capacitor. The capacitor used is a paralleled group of silicon p-n junctions. Although the capacitance varies approximately as the square root of the applied voltage, it is possible to get satisfactorily linear response over the required range because the necessary frequency change is small (about 0.3%).

A voltage proportional to the magnet current is attained by connecting the current inductor integrators (Figure 3) in series. This signal (the peak amplitude is about 2 v) is fed into a variable-gain line driver. The low-impedance output modulates the p-n junctions about 1 v through a circuit that includes a 100 ohm, 100 kc audio transformer. The dc bias on the junctions is about 8 v and the 2.5-Mc peak voltage is about 3 v.

OPERATING EXPERIENCE

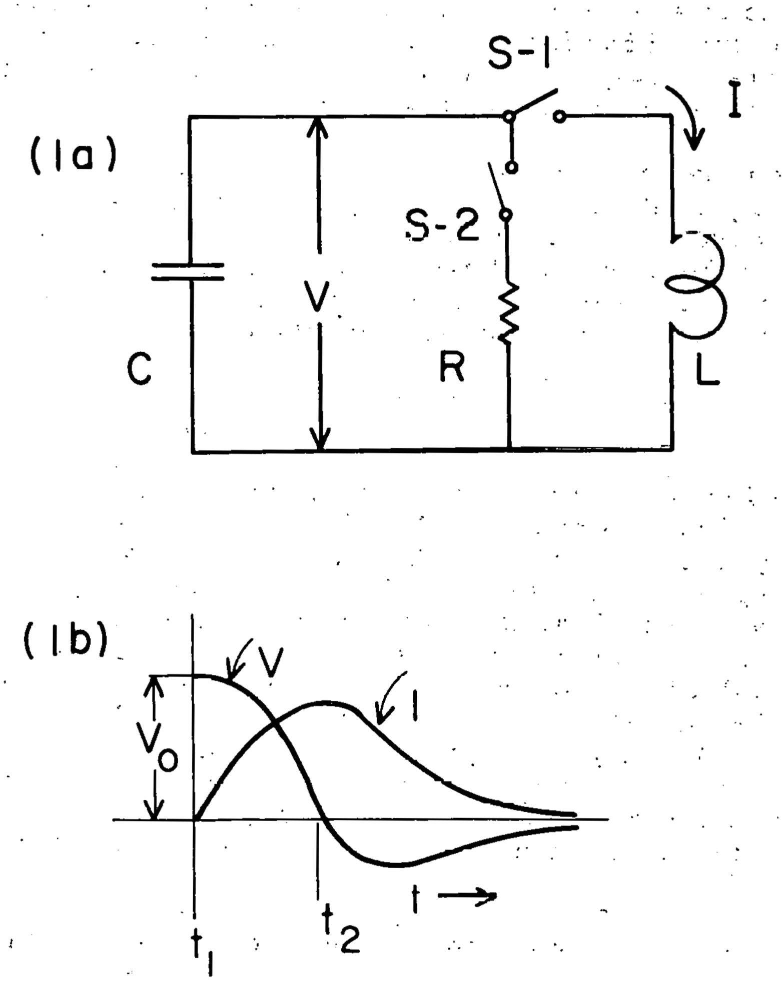
While this is being written the pulse-counter register stands at 202,000. The type-5555 ignitrons have conducted between 15,000 and 26,000 amp peak current per pulse. None of them have failed, and we hope for 1,000,000 or more pulses without failure.

When the beam-kicker is pulsed at 15 kv with no target and no radiofrequency compensation, none of the proton beam continues to accelerate. When radiofrequency compensation is used, as much as 90% of the proton beam survives the maximum beam-kicker pulse. In some experiments the lost protons appear as objectionable background, and it will probably become desirable to increase the survival percentage.

ACKNOWLEDGMENTS

The Bevatron rapid beam ejector system includes the invaluable contributions of many workers: Glen R. Lambertson, Clarence A. Harris, Edward C. Hartwig, and Ivan C. Lutz contributed specifications, guidance, and helpful suggestions. David R. Branum, Leonard J. Morence, and Hubert W. Van Ness of UCRL-Livermore generously shared their experienced knowledge of pulsed capacitor systems. Robert C. Acker kept the initial tests going while the writer was away for two weeks. Electrical Coordinator Percy H. Cutler did the detailed electrical design of the system and directed its assembly. Mechanical Engineer Jack T. Gunn directed the mechanical design and construction of the magnet, the vacuum feed-through, and the fault inductor. No less important is the work of the draftsmen, technicians, electricans, mechanics, machinists, and all who contributed their special skills.

This work was performed under the auspices of the U.S. Atomic Energy Commission.



MU-15685

Fig. 1. (a.) Simplified equivalent circuit. S-1 closes at t_1; S-2 closes at t_2. (b.) Simplified pulse forms. For $0 < t < t_2$, I is equal to $V_0 \sqrt{C/L} \sin t/\sqrt{LC}$ and V is equal to $V_0 \cos t/\sqrt{LC}$. For $t_2 < t < \infty$, I is equal to $V_0 \sqrt{C/L}\ [1 + t - t_2/2RC]\ e^{-t-t_2/2RC}$ and V is equal to $-V_0\ t - t_2/2RC\ e^{-t-t_2/2RC}$ $(2RC = \sqrt{LC})$.

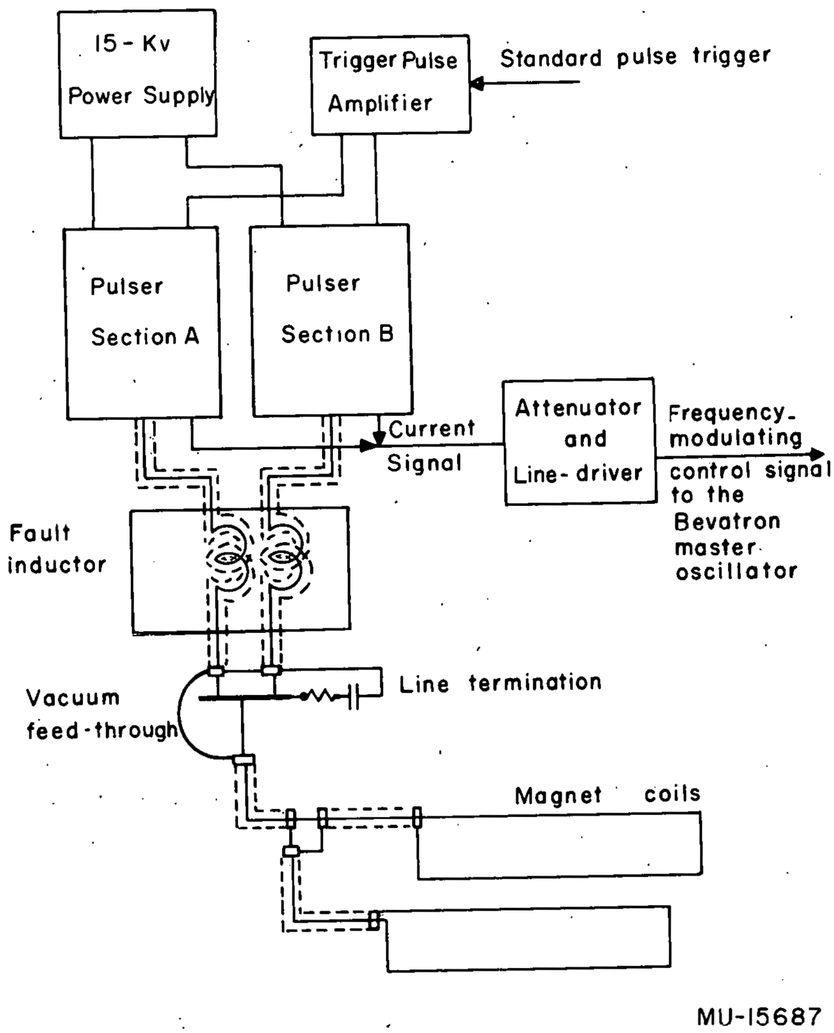


Fig. 2. Diagram of the electrical system of the Bevatron rapid beam ejector.

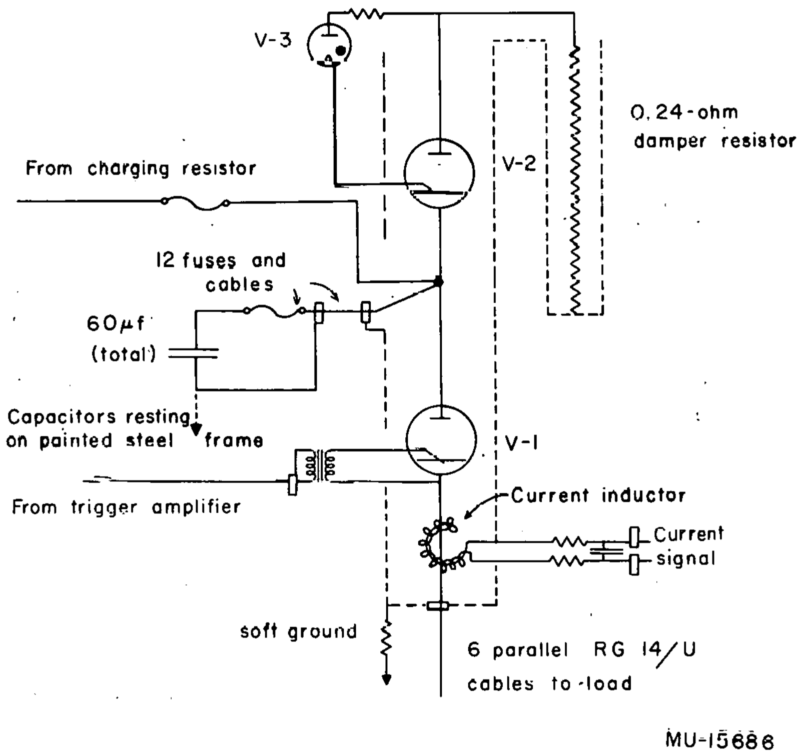
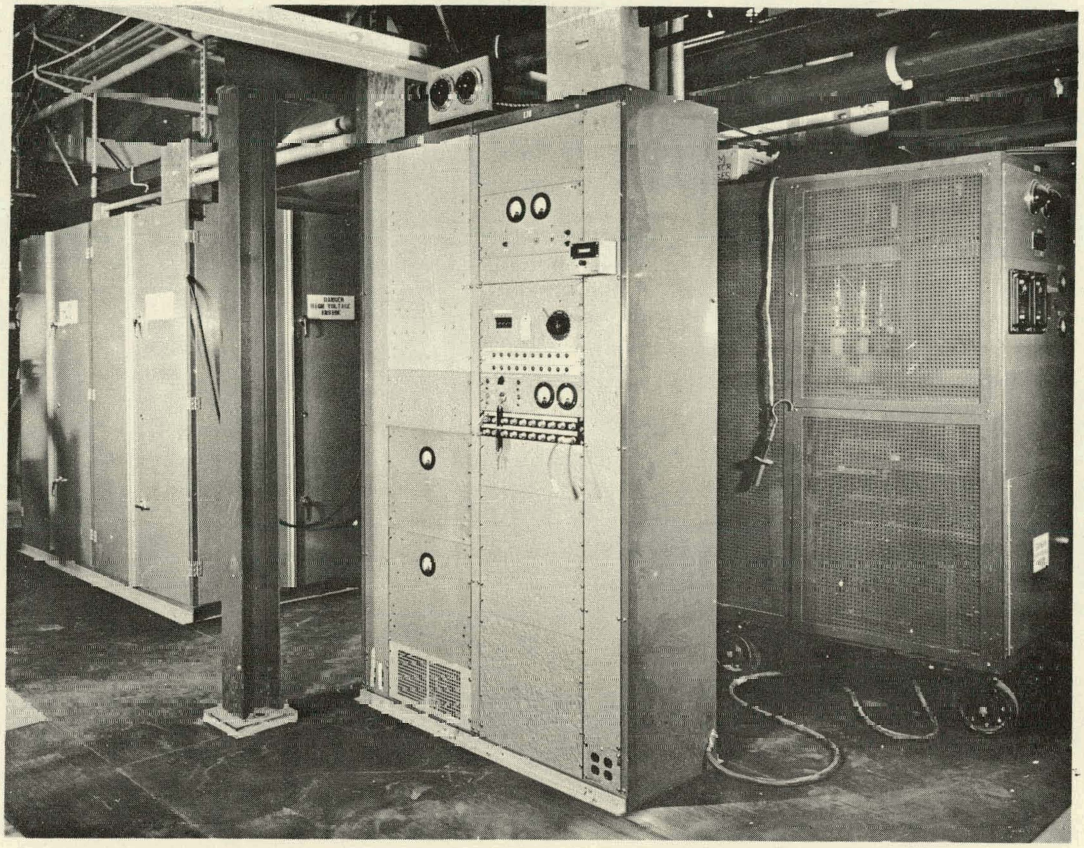
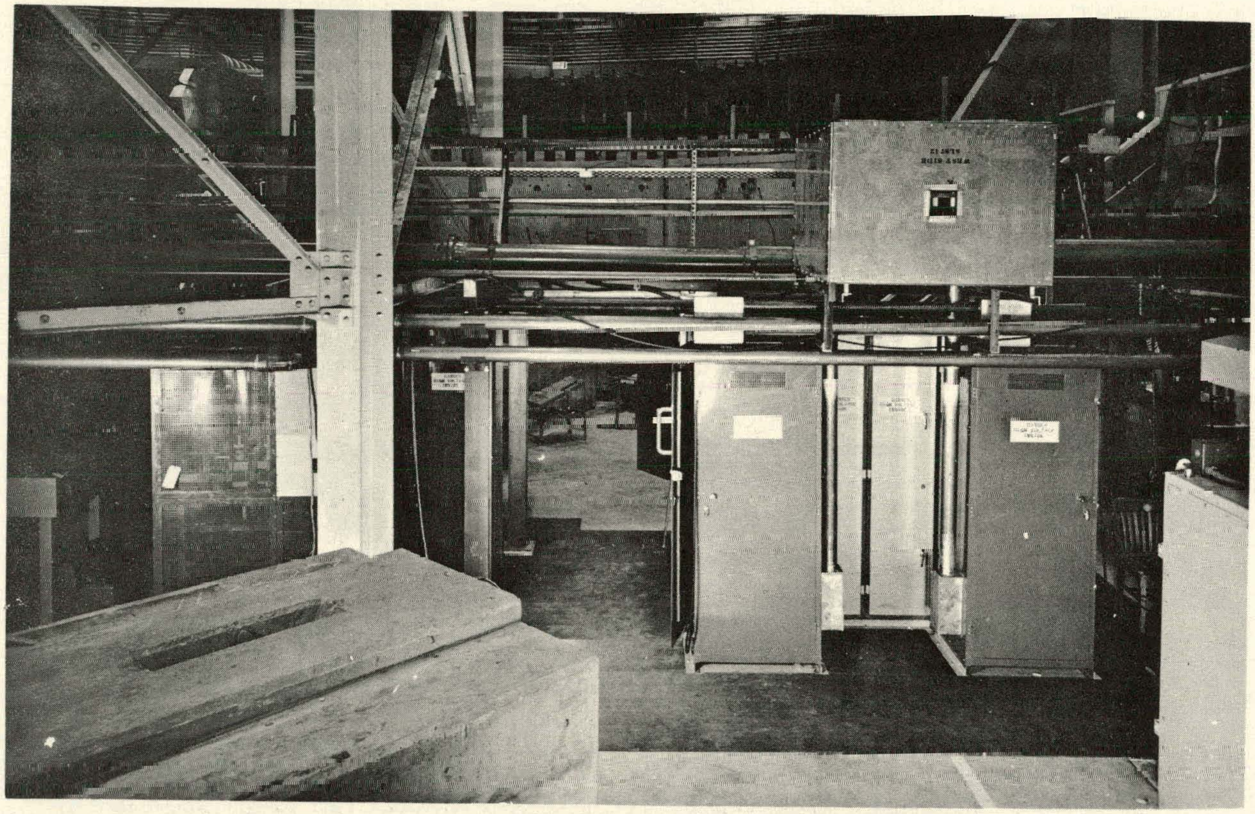


Fig. 3. A diagram of one of the two pulsers in the magnet power supply.



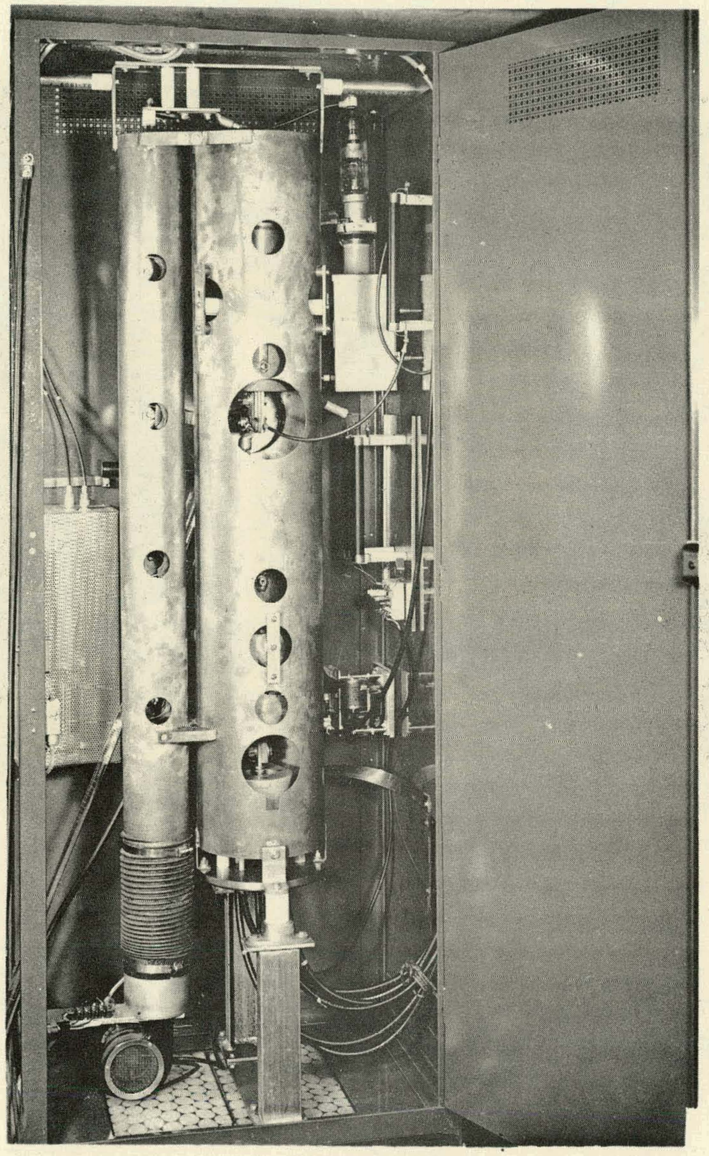
ZN-1974

Fig. 4. Beam-kicker installation. The control rack is in the foreground; the capacitor banks and the power supply are in the left and right background.



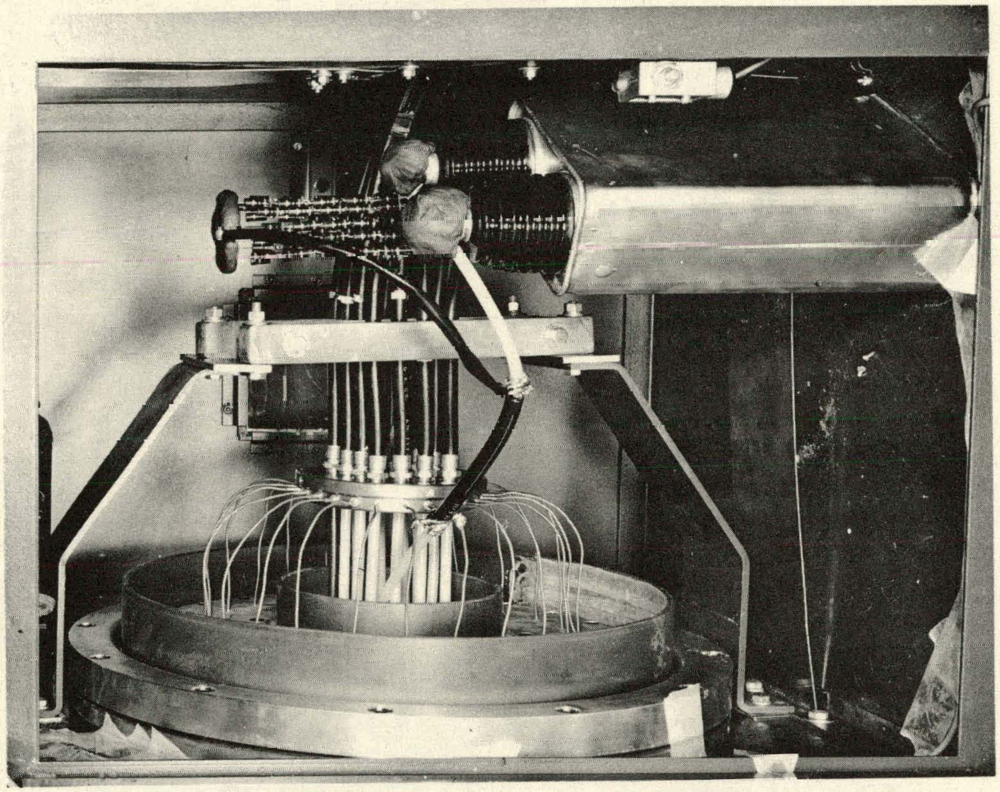
ZN-1975

Fig. 5. Beam kicker installation. The two ignitron cubicles are in front of the capacitor banks at the lower right. The fault inductor is above.



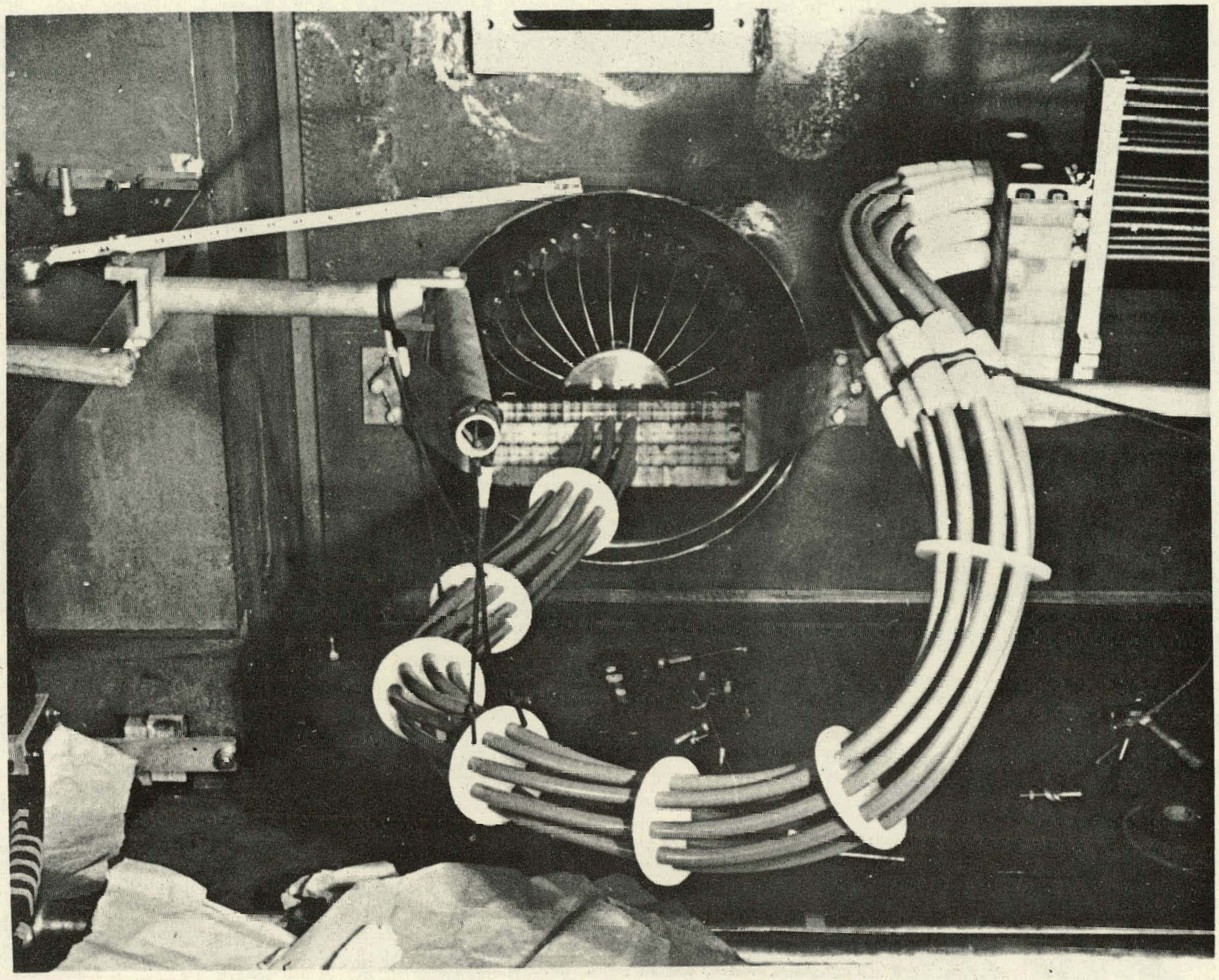
ZN-1977

Fig. 6. The inside of an ignitron cubicle.



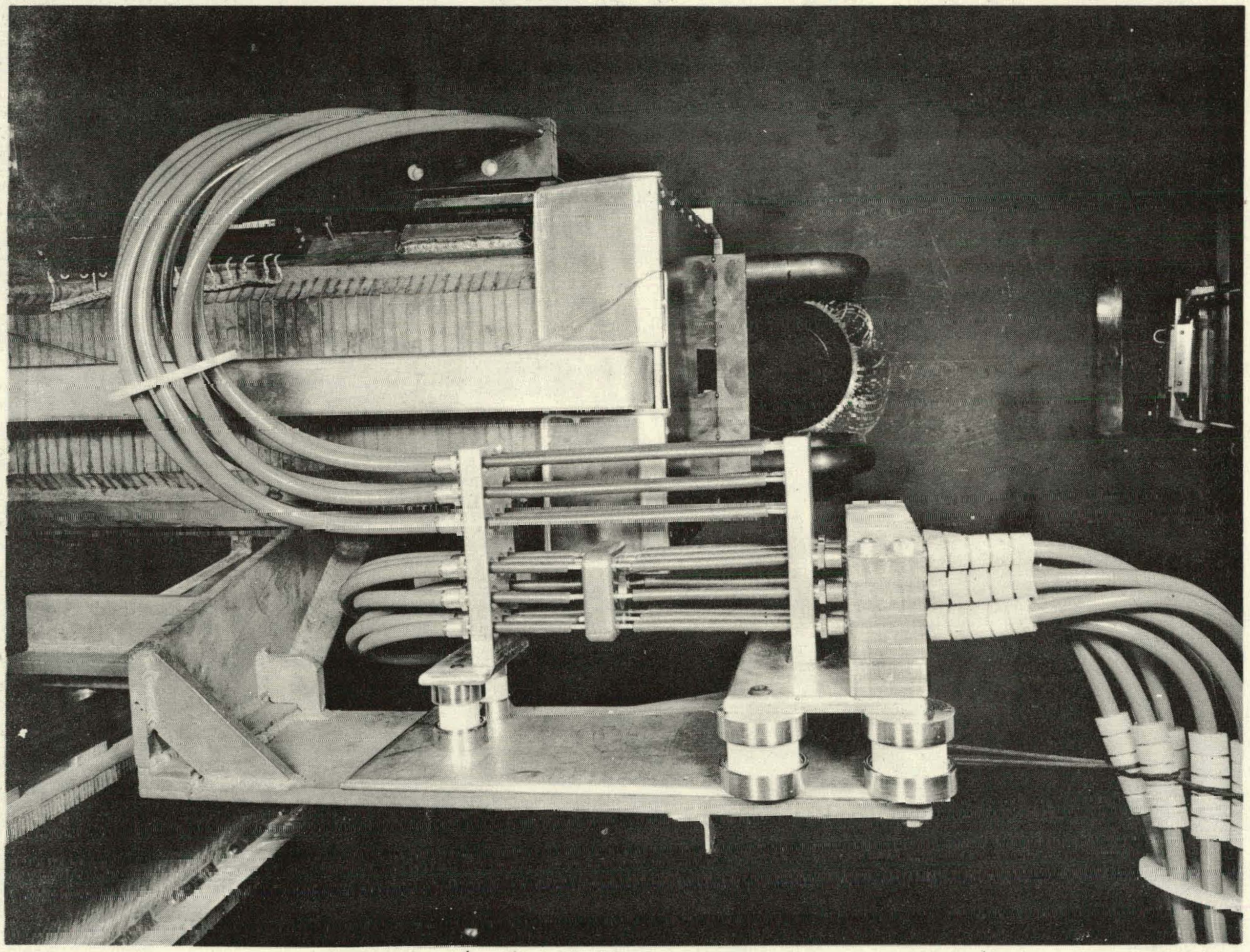
ZN-1976

Fig. 7. View, inside the junction box at the vacuum feed-through showing the transmission-line termination.



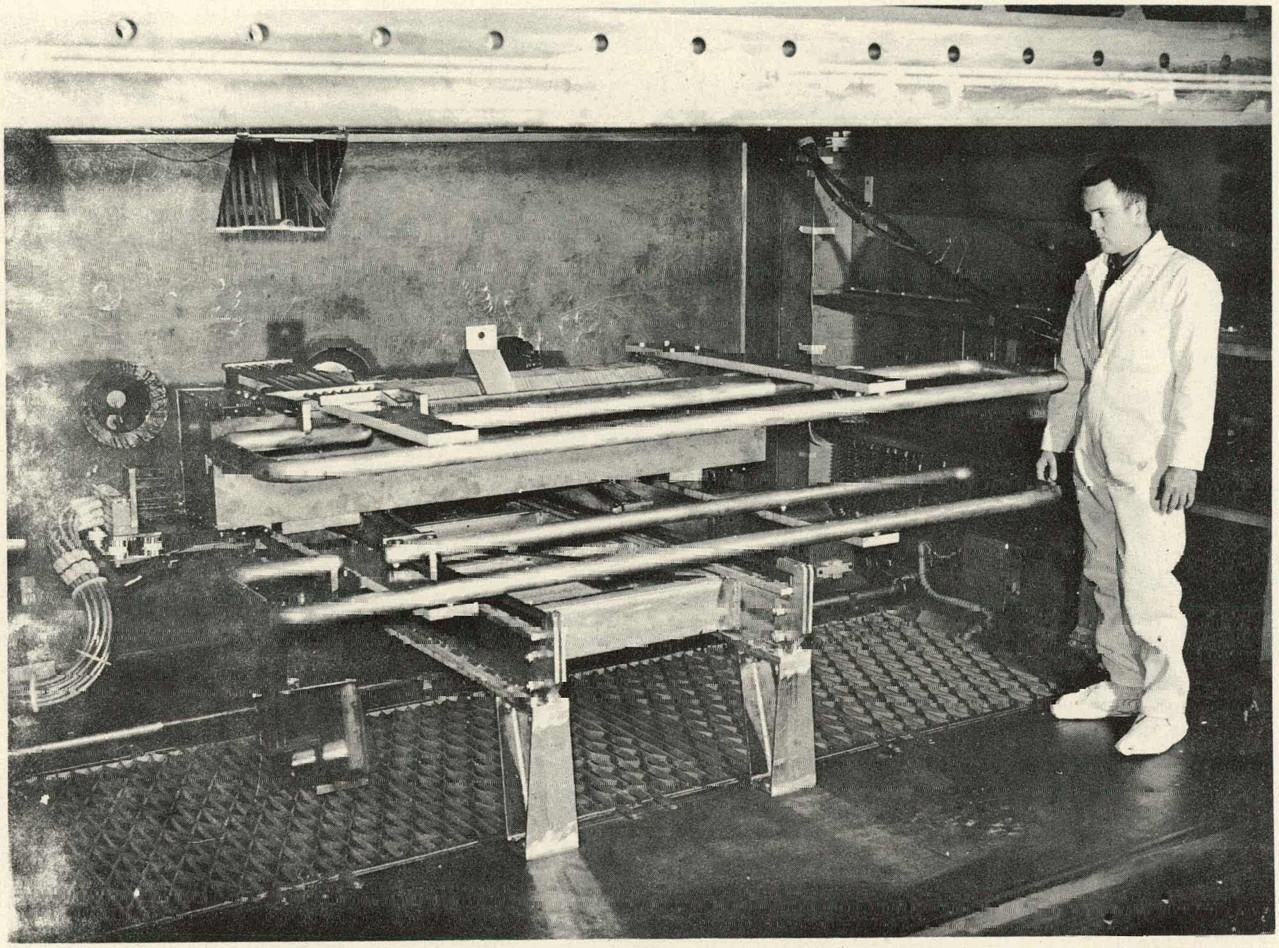
ZN-1972

Fig. 8. View of the vacuum side of the feed-through showing the flexible link to the magnet.



ZN-1973

Fig. 9. The junction assembly that terminates the flexible transmission line and connects the two magnet coils in series.



ZN-1978

Fig. 10. The beam-kicker magnet viewed from outside the open south tangent tank.

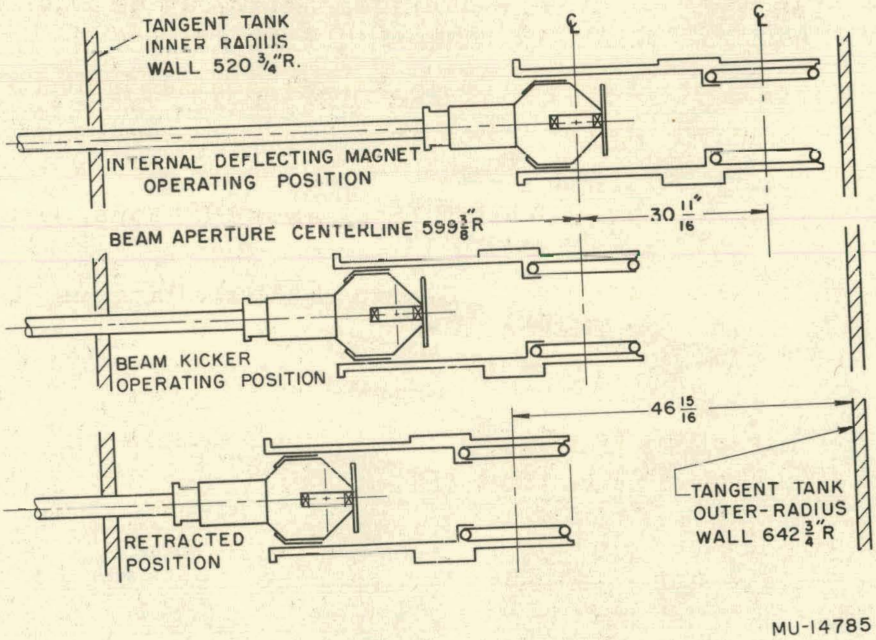


Fig. 11. Schematic diagram showing how the internal deflecting magnet and the rapid beam-ejector magnet share the same positioning apparatus.

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5. UCRL Drawing No. 6V9084, Beam-Kicker Coaxial Ignitron Assembly.

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7. UCRL Drawing No. 8L6445, Bevatron, Miscellaneous, General, Beam-Kicker Feed-Through Assembly.

8. UCRL Drawing No. 8L6215C, Bevatron, Miscellaneous, General, Beam-Kicker Assembly (Magnet Assembly).

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