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Publication Date
1959-03-01

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Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

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Printed for the U.S. Atomic Energy Commission

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ABSTRACT

Following the lead of Rahm at the Brookhaven Cosmotron, a group at the Berkeley Bevatron constructed a rapid beam ejector to produce the brief pulses of particles required for optimum bubble chamber photographs. 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 Bevatron. A capacitor bank of 120 μf stores 13,500 joules at 15,000 volts. Two ignitrons in parallel connect the capacitor to the magnet. The magnet current rises to 52,000 amperes in 55 microseconds; at peak current a resistor is connected in parallel to damp the current decay.

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The Bevatron and Cosmotron, which are 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]

With the Bevatron or Cosmotron, the shortest duration beam normally obtainable was about 1 millisecond. This is rather long for use with a bubble chamber, since there is only a very brief period during which optimum tracks can be produced. In 1956 David Rahm at Brookhaven directed the development of the Cosmotron rapid beam ejector in order to obtain a pulsed beam of about 3 microseconds duration.[2] Following the lead of Rahm, Glen Lambertson of the University of California's Lawrence Radiation Laboratory directed the construction of a similar system for use with the Bevatron.

The key component in the rapid beam ejector system is the two-turn air-core magnet surrounding the normal position of the high-energy proton beam. This 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 the protons in the displaced orbit and can scatter particles during the upper part, or parts, of the magnet current pulse.

The Bevatron beam kicker differs from the Cosmotron system in several respects. The higher proton energy and larger size of the Bevatron led to a larger air core magnet with more magnetic field energy. At the Cosmotron the capacitor bank is switched to the magnet through a three-electrode spark gap, while the Bevatron system switches with ignitrons. The current pulse of the Cosmotron system is an oscillatory discharge damped by circuit losses. The Bevatron pulse is a single, unidirectional pulse which is produced by switching a damping resistor in parallel with the magnet when peak current is reached. Another unique feature of the Bevatron system is the compensation of the accelerating radiofrequency to keep it in synchronism with the perturbed orbital frequency.

A simplified equivalent circuit and pulse forms are shown in the first slide. 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.

In this simplified circuit the switches S-1 and S-2 correspond to type-5555 ignitrons. Ignitrons of this type 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 and other laboratories in high-current, high-voltage, capacitor-discharge circuits. The second slide compares the manufacturer's normal ratings to the actual usage involving the beam kicker. At the present time the pulse-counter register on the Bevatron beam kicker stands at ~720,000. During each pulse the ignitrons have conducted between 15,000 and 26,000 amp peak current. In spite of this heavy load, none of the ignitrons has failed, and we hope for a million or more pulses without failure.

The next slide shows the important circuit elements of one section of the pulser, which is made up of two parallel sections. Each of the two capacitor banks has sixty individual capacitors, each capacitor being rated at 1 μf, 25 kv. The capacitors are connected in parallel in twelve groups of five each, and each 5-μf group is connected to one RG-14/U cable through a high-voltage fuse.[3] The far end of the twelve cables are connected in parallel in the adjacent ignitron cubicle.

A "standard Bevatron trigger pulse" of 10-μsec duration triggers a type-2050 thyratron, which discharges a capacitor through a transformer. The pulse output is connected to the grid of a 5C22 hydrogen thyratron. The 5C22 discharges a 0.15-μf capacitor through two high-voltage isolation transformers, applying positive pulses to the igniters of the two type-5555 ignitrons, which are designated as V-1.

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, designated V-3, conducts current through the igniter of V-2. If the initial capacitor-bank voltage, v_0, 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 of V-2, and the igniter-circuit current drops to a low value.

A damping resistor is connected in parallel with the inductive magnet load when V-2 fires. Each damping resistor has a resistance slightly less than the critical value. These 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.

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. The fault inductor is a multilayer coil of twelve RG-14/U cables in parallel, and is actually a continuous link in the transmission line. 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 fault current can rise to a significant magnitude, the normal current circuit will have discharged the capacitors.

In the final slide we see a photograph of the two-turn air-core magnet. This photograph was taken while the outside cover plate of the Bevatron's south tangent tank was off. The magnet is constructed of 2-in.-diameter copper tubing. It is 96 in. long, 16-1/2 in. wide, and the upper and lower coils are spaced 13-1/2 in. apart. The two coils are connected in series. The computed magnitude of the field in the center of the aperture is 1170 gauss at 52,000 amperes. The inductance is approximately 7 μh.

When the beam-kicker magnet is energized, the Bevatron proton orbit is displaced in such a way that the new path is shorter than normal. If the Bevatron accelerating radiofrequency is not increased 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.

The phase error per turn is very nearly proportional to the deflection, which in turn is proportional to the magnet strength. Because the magnet strength is proportional to the current, a current signal is suitable for modulating the radiofrequency.

The Bevatron master oscillator uses a Colpitts circuit with semifixed 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 obtained by integrating the output of a mutual inductor. The voltage modulates the p-n junction bias about 1 v through a circuit that includes a 100-ohm, 100-kc audio transformer.

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.

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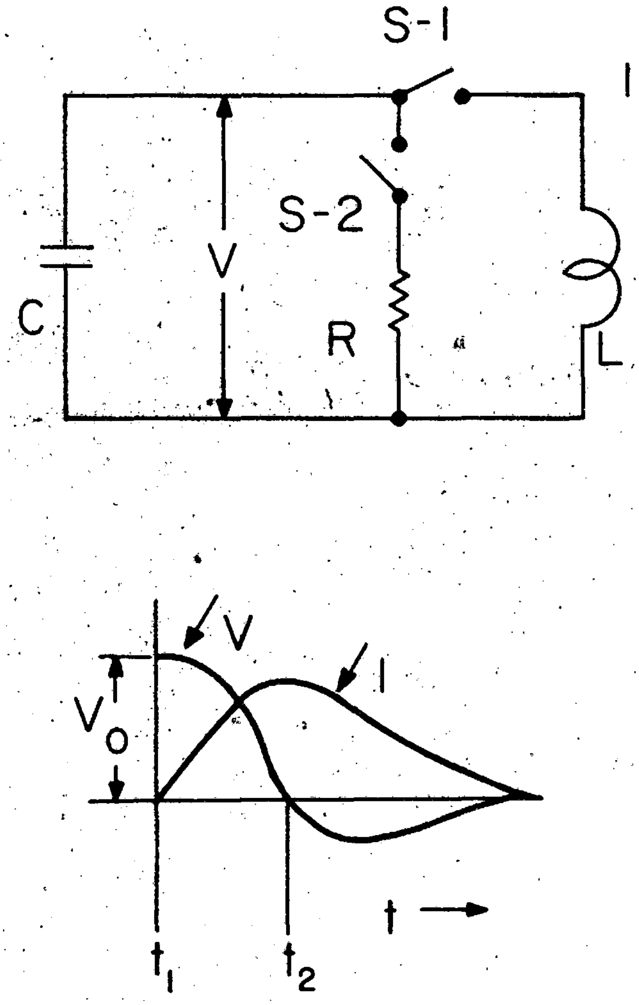
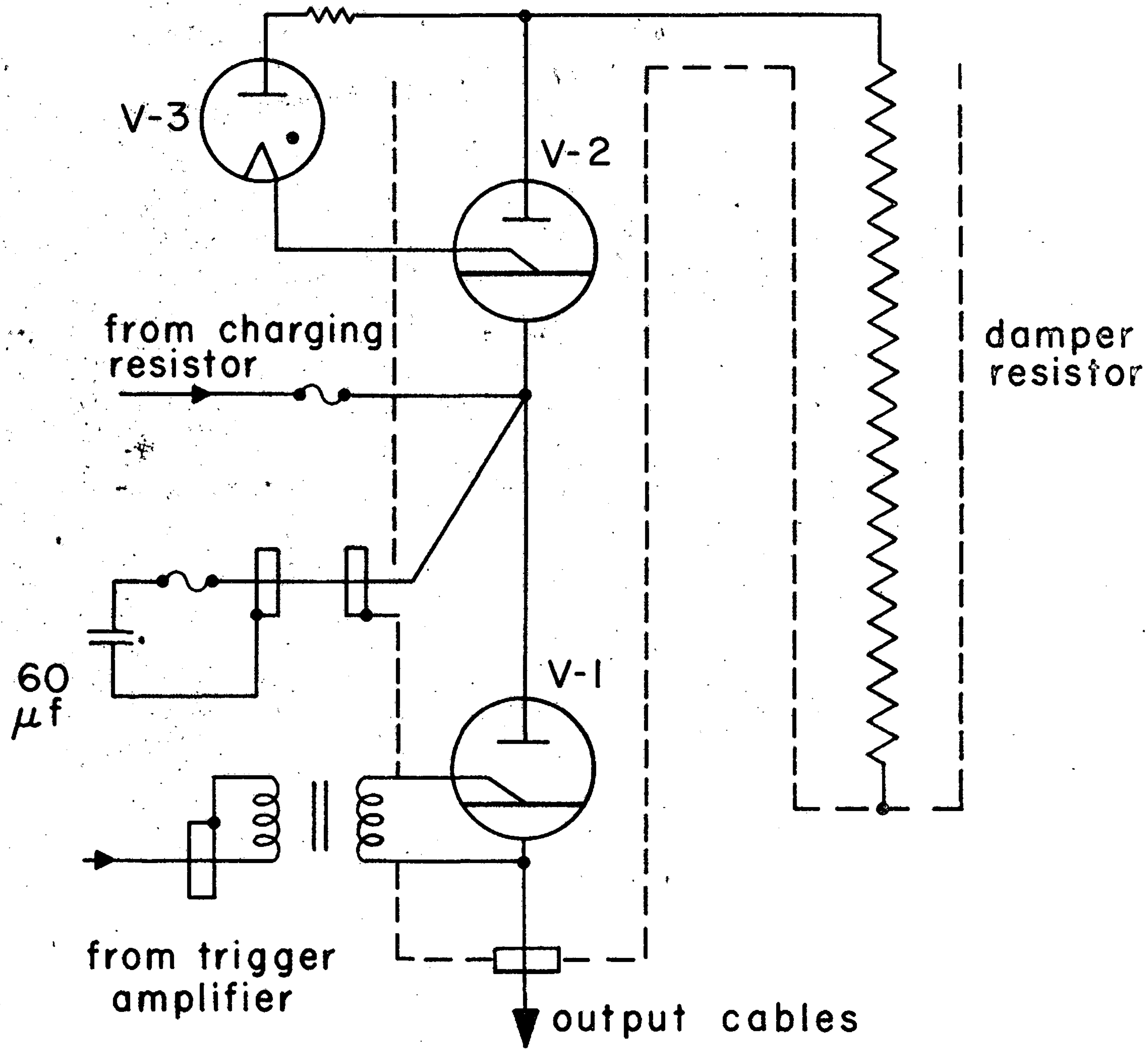


Beam-kicker equivalent circuit and pulse forms.

Type-5555 Ignitron

	mfgr. rec.	actual V-1 position	actual V-2 position
max. peak anode potential (V)			
forward	2,100	15,000	—
inverse	2,100	—	15,000
anode current (amp)			
max. peak	1,200	26,000	23,000
continuous avg.	150	0.5	0.35



High-current pulser

55018-1

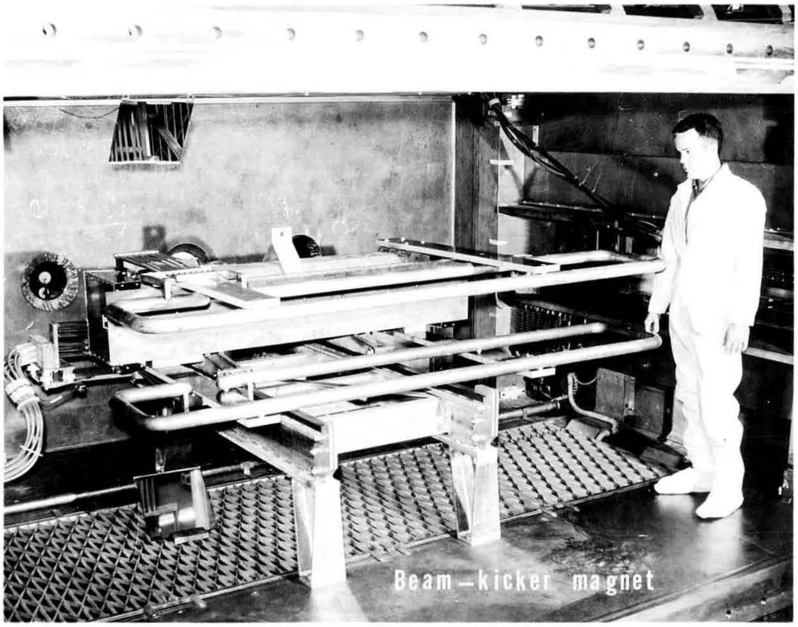


Fig. 4.