Scale Model of a Solid-State Driver for the Beam Sweep Magnet

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This report describes a 1/4-scale model of a driver for the sweep magnet based on compression of a slow pulse waveform by saturating inductors. Measurements and SPICE simulation of its performance are presented. Scaling up the circuit to performance required of a full-scale supply (about 6 kA, 6 kV, 625 kHz) appears to be relatively straightforward, in principle.

Antiprotons are collected from the interaction of a 120-GeV proton beam with a solid nickel target. The efficiency of collecting antiprotons from the target rises as the size of the proton beam spot on the target is reduced. However at the same time the peak energy deposition on target rises. Under Main Injector conditions (5 x 10^{12} protons in a 1.6-μs pulse), the spot size will have to be increased to at least 0.25 mm to keep peak energy deposition near current levels. To bring the density of energy deposition with a 0.1-mm spot size down to currently-existing levels, a system to sweep the beam spot on the target has been proposed[1]. Two pairs of sweep magnets are envisioned - one pair to trace a circle on the target with the 120-GeV proton beam, the other pair downstream of the target to redirect out the sweep motion of the antiprotons formed at the target. The upstream and downstream pairs must be matched to properly return the beam parallel to axis of the AP2 beamline. The sweep magnets must be provided with approximately 6 kA in a 1.6-μs period sine wave by a power supply located on the floor of the AP0 service building. In the case of the downstream magnet pair, the current will be supplied through cables over a distance of approximately 10 m into the target vault, and by 2.5 m of strip line through steel shield modules to the magnets at the bottom of the target vault. The inductance of the cable, in series with the sweep magnets, places severe demands on a power supply that directly supplies the desired current to the magnet. Two approaches that reduce the requirements on the power supply have been considered. In both cases a capacitor is placed at the top of the target vault, connected in parallel resonance by a strip line to the inductance of the sweep magnet, and the resonant circuit is tuned to 625 kHz.

1. The tuned circuit may be driven by another tuned circuit, switched with a high-speed hydrogen thryatron. This circuit has been described previously [1]. The energy is supplied through at least 16 parallel RG-220 cables in 2-3 current reversals, with an initial voltage requirement of well over 30 kV at the energy-storage capacitor. EEV

hydrogen thryatrons exist that can switch the necessary current (3-4 kA) on the required time scale.

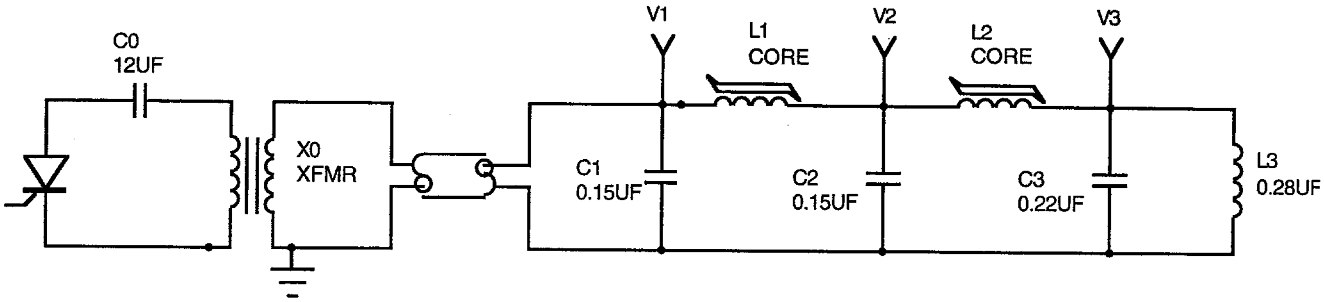


Fig. 1. Schematic of the circuit.

2. The alternative proposed here is pulse compression by saturating inductors. A simple two-stage inductive pulse-compression circuit is shown in Figure 1. The SCR switches the energy-storage capacitor C0 into a step-up pulse transformer X0 and charges the intermediate capacitor C1 in the vault at the top of the steel shield module. The primary circuit and transformer are on the floor of AP0; charging occurs through a transmission line (cable) on a 10-μs time scale. The large initial inductance of the magnetic switch L1 allows the relatively slow supplying of energy to C1. The inductor is designed to saturate (turn on) when sufficient energy is available to drive the sweep magnet. The process is repeated in the second stage C2 and L2. When the inductor L2 saturates it rapidly discharges C2 into the resonating capacitor C3 at the top of the module, which in turn rings into the sweep magnet L3. The advantages of this technique are that it allows the use of a simple solid-state SCR-driven power supply, a simple cabling arrangement, and significantly lower operating voltages. It is necessary to install three capacitors and two ferrite magnetic switches (L1 and L2) on top of the module, below the concrete neutron cover. Lifetime of these components may be limited by the integrated radiation dose encountered at this location. Assuming 100 Rads/hr, the threshold for radiation effects to plastic capacitors (about 10^7 Rads) will be reached in 10 years of continuous operation. We may choose to use ceramic capacitors or provide local shielding if radiation is a concern.

A scale model of the circuit of Figure 1 was built in the laboratory. Component values are as shown. The capacitor C0 and the SCR are rated at 600 V. Voltage step-up is accomplished with a transformer wound on three tape-wound cores (Magnetic Metals 62P-33005) with an 8:1 turns ratio (135:15). A short piece of cable connects the secondary to the capacitor C1. The switch L1 consists of 9 turns on 18 cores of 3C85 material (Phillips 144T500). The switch L2 consists of a single pass through a number of Ceramic Magnetics ferrite cores with 6-cm ID, 12-cm OD (14 of CMD5005, height=19 mm, 3 each of CMD10 and MN67, height=25.4 mm); total length = 34.2 cm. A reset pulse was passed through all the cores before pulsing the circuit. The reset pulse magnetizes the cores to ensure the maximum available flux swing in the ferrite material. Waveforms are show in Figure 2 for an air-core load inductor L3, and in Figure 3 for an inductor in a stack of tape-wound cores. The voltage V1 on capacitor

C1 rises to 4300 V in about 10 μs; it discharges to C2 in about 2 μs; and C2 in turn discharges into the output L3, C3 in about 400 ns. The oscillation V3 is strongly damped for the tape-wound core inductor, showing the lossy behavior such as expected in the laminated-iron-core sweep magnet. The current in the tape-wound-core inductor L3 (calculated from the derivative of the voltage) peaks at about ±1500 A, or 1/4 of the current required by the sweep magnet.

Results of a SPICE model of the existing air-core circuit are shown in Figure 4. The model neglects the portion of the circuit to the left of the capacitor C1 - the capacitor is assumed to be initially charged to a constant voltage V1=4.8 kV. The first core begins conducting at about 5 μs in the model, charging the second core to 4.3 kV, and the second core transfers the energy to the output oscillator about 2 μs later. It was necessary to add parasitic inductance and resisitance, as shown, at the two model magnetic switches to approximate the measured waveforms. The resistor R3 models the resistive losses in the air-core inductor.

A version of the circuit scaled up to deliver the required 6 kA to a full-scale sweep magnet is shown in Figure 5.

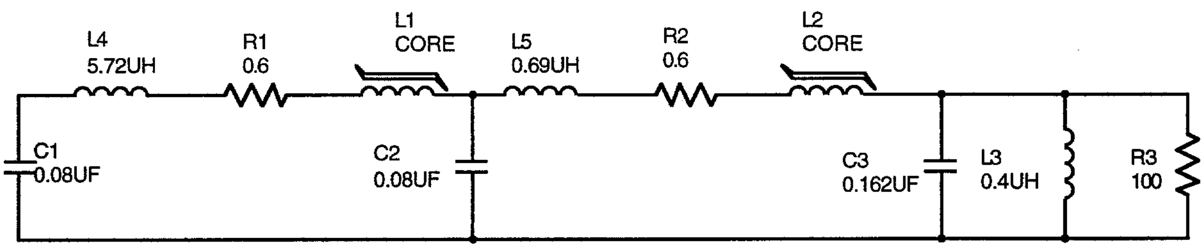


Fig 5. SPICE circuit model of the full-scale circuit.

Voltage and current waveforms are shown in Fig. 6. The output currents are larger than required. Peak charging voltage is 24 kV. If the circuit is supplied through a 10:1 step-up pulse transformer, voltage requirement on the SCR driver will be in the range of 2400 V. The model again neglects the portion of the circuit to the left of C1. No serious attempt has yet been made to complete the model in detail, or optimize performance of the full-scale circuit. The cores are 6-cm ID, 16-cm OD ferrite CMD10, which has high saturation and remnant fields, and have roughly 3 times the volt-seconds of the core of the existing circuit. The core L2, for example has a length of about 44 cm. It should be possible to build the circuit for less than $20K worth of ferrite, i.e. less than the cost of an EEV thyratron.

Finally, I thank Bob Vargo for his assistance in assembling some of the components of this circuit.

[1] F. M. Bieniosek, A Beam Sweeping System for the Fermilab Antiproton Source, Fermilab-TM-1857 (1993).

Fig. 2. Performance of circuit with air-core inductor.

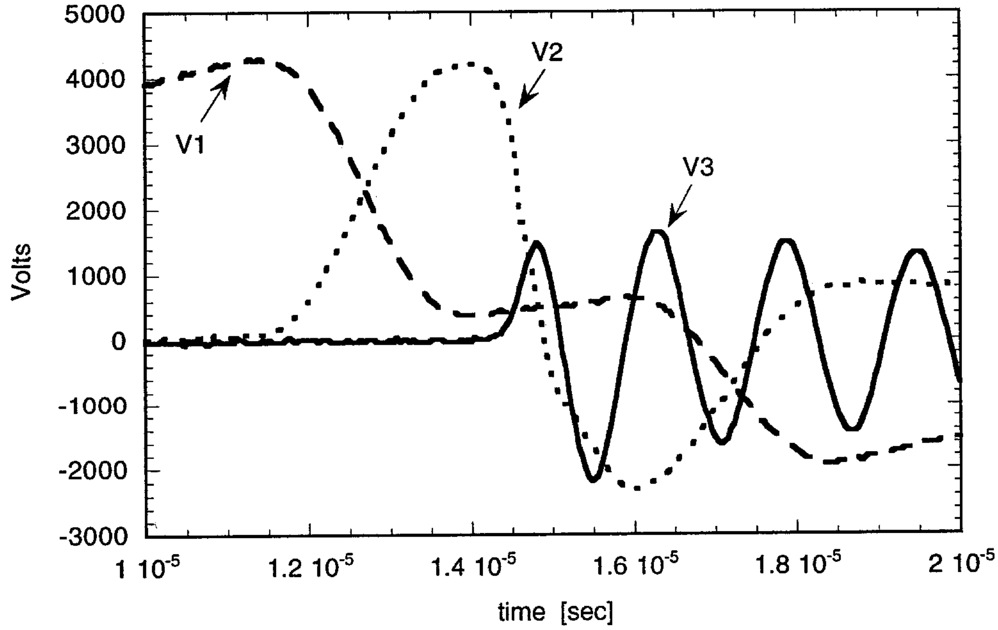


Fig 3. Performance of circuit with tape-wound-core inductor.

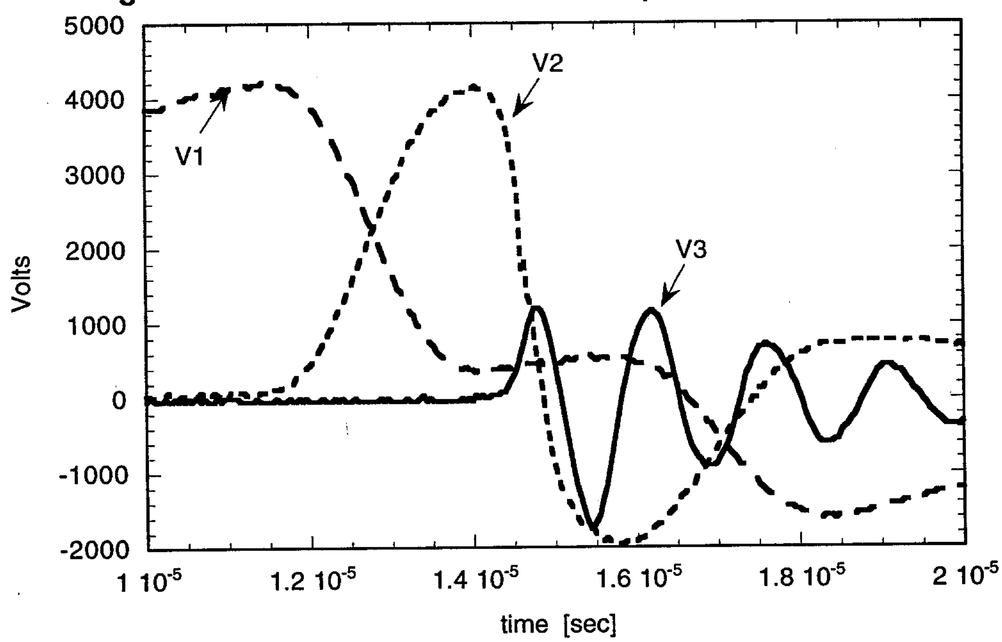
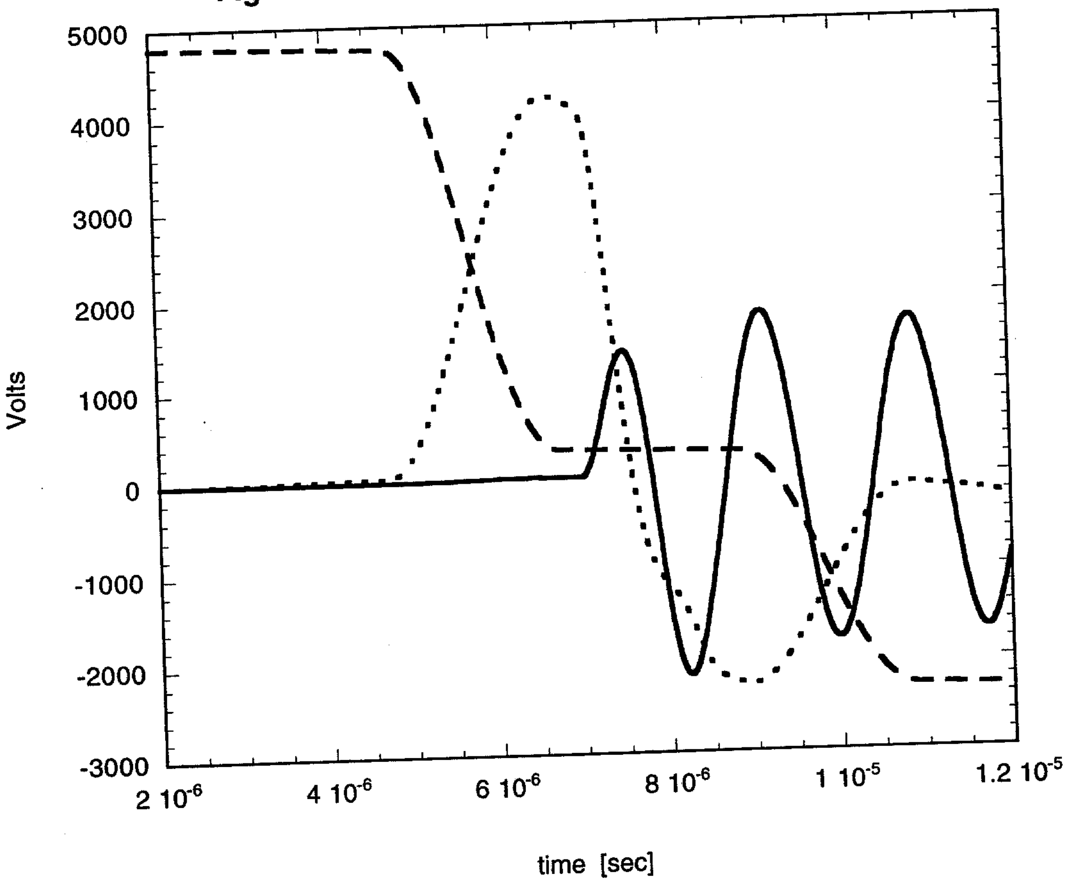


Fig. 4. SPICE model of the scale-model circuit.



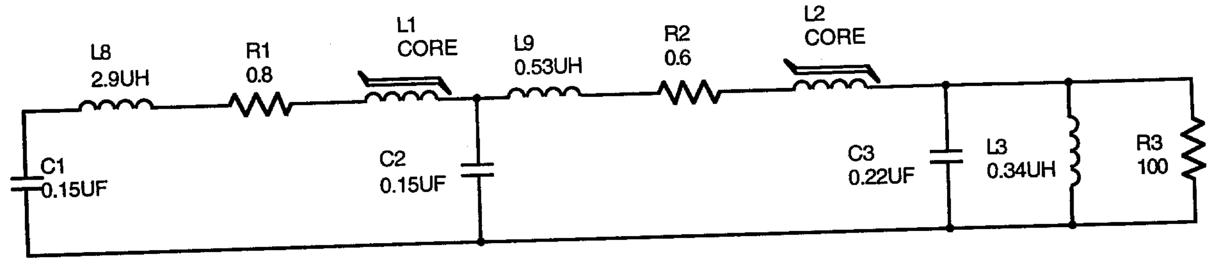
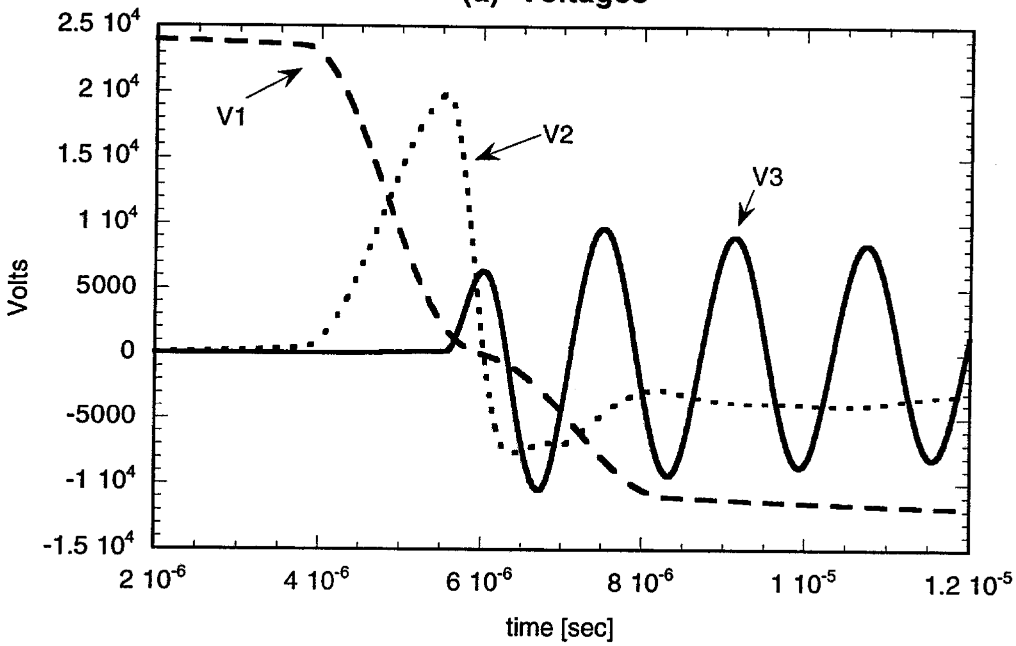


Fig 6. SPICE model of the full-scale circuit.

(a) Voltages



(b) Output current.