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SINGLE-BUNCH KICKER PULSER*

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The single-bunch kicker magnet is powered by a capacitor discharge pulser. The ferrite-core magnet is used to kick out one of twelve proton bunches circulating in the AGS (Alternating Gradient Synchrotron) into the experimental area. The magnet current pulse has a half-sinusoid shape, with a peak current of 2800 A. The pulse current rises and falls to zero, with minumum undershoot, in 410 nsec to minimize effects on adjacent bunches. The magnet inductance is 1.0 μHy.

The pulser is mounted on the kicker magnet in the AGS ring, and is exposed to ionizing radiation. The HVDC power supply, controls, monitoring, and auxiliary circuits are housed approximately 300 feet away external to the ring.

A two-gap thyratron is used to discharge the energy storage capacitor. Two hydrogen diodes are series connected to function as an inverse diode.

Introduction

A single bunch extraction (SBE) capability was added to the AGS in 1983. In the SBE mode of operation, one of the twelve proton bunches circulating in the AGS ring is extracted into the east experimental area, while the remaining eleven bunches are extracted into the north experimental area. Figure 1 is a schematic representation of the AGS extraction system.

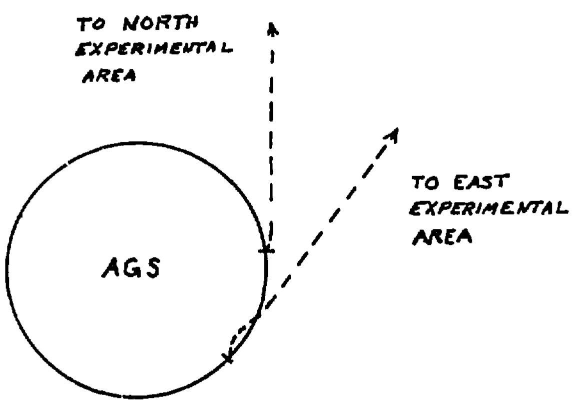

Fig. 1

The SBE fast kicker magnet is a single turn ferrite core "C" magnet located in the E5 straight section of the AGS. The magnet is 1 meter long and has a field strength of 1.25 kG at 3000 A. Clean extraction; i.e. no effect on bunches on either side of the bunch to be extracted; requires the kicker magnet field to rise and fall within the 410 ns space shown in Fig. 2.

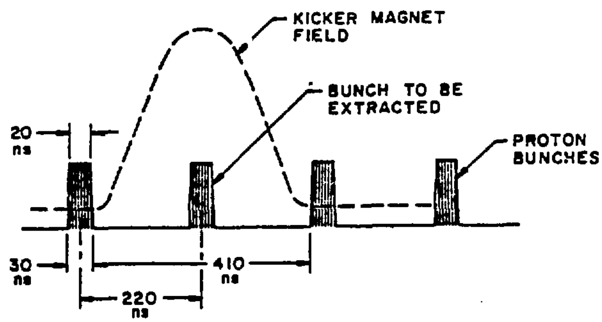

Fig. 2

The half sinusoid current pulse in the kicker magnet is generated by the resonant discharge of an energy storage capacitor. The pulser has the following electrical parameters:

a. 2800 A peak pulse current.
b. 400 ns wide (< 5% width).
c. 180 ns rise time.
d. 5 ns leading edge jitter.
e. 5% pulse undershoot.
f. 0.3 to 1 pps repetition.
g. 1 μH magnet inductance rate (load).

The pulser is mounted on the kicker magnet in the AGS ring. Pulse controls, triggering, and monitoring are located 300 feet away external to the ring in an equipment building.

Design

The pulse current is generated by discharging an energy storage capacitor into the kicker magnet coil using a thyratron switch. The energy storage capacitor resonates with the high Q magnet inductance at a 800 ns period to generate a 400 ns half-sinusoid pulse. The energy storage capacitor and the magnet inductance form an underdamped series resonance circuit (thyratron plate impedance and magnet coil resistance are negligible) as shown in Fig. 3. Assuming a total circuit inductance of 1.5 μH (1.0 μH magnet plus 0.5 μH stray), the maximum value of energy storage capacitance is calculated by:

$$C = \frac{t^2}{(2\pi)^2 L} = 1.08 \times 10^{-8} = 0.011\ \mu F$$

The capacitor charging voltage, based on a 0.01 μF storage capacitor and a 95% energy transfer is calculated by:

* Work performed under the auspices of the U.S. Department of Energy.

$$0.95\ CV^2 = LI^2$$

$$V = 37.7\ kV$$

An inverse circuit, refer to Fig. 4, is used to spoil the circuit Q when the capacitor voltage reverses, and reduces the inverse voltage across the switch tube. The inverse circuit is connected as shown to prevent inverse current from flowing through the magnet coil. The optimum value of inverse resistance is determined by:

$$R = (L/C)^{1/2} = 12.2\Omega$$

The switch tube will return to the blocking state for the negative portion of the oscillation, producing a half-sinusoid current pulse in the magnet.

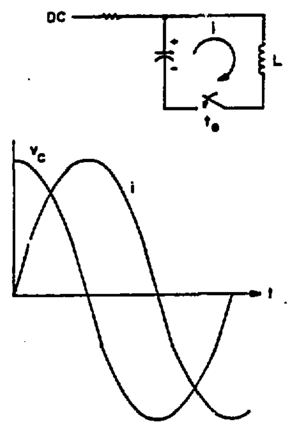

Fig. 3

Resonant Discharge

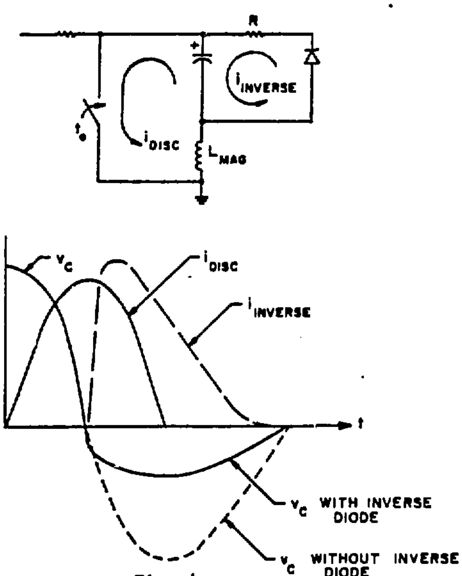

Fig. 4

Inverse Circuit Added

Figure 5 is a photo of the current pulse in the magnet during preliminary testing using a single gap tetrode thyratron. The undershoot is a result of the stray capacitance of the pulser discharging into the magnet. This undershoot can be controlled by adding a shunt resistor across the magnet to provide a resistive discharge path for the stray capacitance. This resistance value is a trade off between; undershoot, pulse fall time, and additional charging voltage. A value of 15 to 20 ohms will reduce the undershoot to 5% at the expense of 10% additional charging voltage.

Ground loops must be eliminated to provide noise free monitoring signals. All return leads must be isolated from ground particularly those that carry a pulse or trigger current. Due to the high frequencies present in the pulse and the low impedances of the pulser and load, large noise voltages can be coupled back to the control and monitoring equipment outside the AGS ring.

Fig. 5
Magnet current pulse; i=2800A peak, Horiz.=100 ns/div.

Radiation Effects

The type of construction used in the energy storage pulse capacitors was determined from experience on another AGS ring mounted kicker magnet pulser.[1] Standard mylar/oil pulse capacitors were selected in place of mica capacitors. The mica capacitors offer superior radiation characteristics but cost approximately 10 times a mylar/oil capacitor. In addition, the mica capacitors had a poor form factor for the AGS pulsers. A search of the literature revealed a NASA report that indicated an acceptable life expectancy for mylar/oil capacitors in a radiation environment can be achieved if the ambient temperature is kept under 50°C.[2]

An estimated 3×10^{17} proton will strike the magnet during operation, based on a 10 week run per operating year. At this level the capacitors should last 1 to 2 years before failing. The capacitor windings are in a metal cylinder sealed at one end, instead of a phenolic cylinder as the original H5 capacitors. A ceramic terminal is used as one terminal of the capacitor. This construction will result in a capacitor that will resist bursting. The capacitor wetting agent was changed from mineral oil to a silicon oil to reduce the fire hazard if a capacitor should rupture.

A test capacitor was built with a pressure gauge replacing the insulated terminal. The test capacitor was mounted on the H5 magnet in a position to receive more radiation than the PFN capacitors. (The AGS ring is divided into 12 "superperiods" designated A through L counterclockwise. Each "superperiod" has twenty bending magnets designated 1 through 20 counterclockwise. Equipment location in the AGS is designated by the superperiod letter and nearest bending magnet number.)

The H5 pulser was operated for the last FEB (fast extracted beam) run. There was no electrical degradation of the PFN capacitors after an estimated 1.5×10^{17} protons struck the H5 magnet during the 5 week run. The magnet read 20 R immediately after the run, and decayed to a 1 R level in two days. The pressure in the test capacitor at the end of the run was 2-1/2 psi, apparently due to gas released due to radiation induced chemical changes.[3]

Construction

Figures 6 and 7 are simplified schematic diagrams of the E5 pulser HV and LV sections respectively. Figure 8 is a photo of the E5 pulser mounted in the AGS ring. Figures 9 and 10 illustrate the pulser access.

A two gap tetrode thyratron is used as the main switch tube since the maximum charging voltage is 41 kV. A pair of hydrogen diodes are connected in series to act as the inverse diode.

The energy storage capacitor is a pair of 0.005 μF - 50 kV dc pulse capacitors in parallel. These capacitors are the mylar/oil type.

The switch tube is triggered by a 150 ns wide 2 kV pulse. The trigger source is a bootstrap thyratron circuit located outside the ring around 300 feet away from the pulser.

The primary grid and bias grid power supplies are located in the LV section of the pulser. All voltage controls, signal monitors and interlock circuits are transformer isolated for EMI reduction. All potential ground loops between the ring mounted equipment and the control/monitoring equipment house had to be eliminated. If ground loops are not eliminated the pulse noise is coupled into the control circuits of the pulser and other equipment in the house. This induced noise will result in erratic equipment operation.

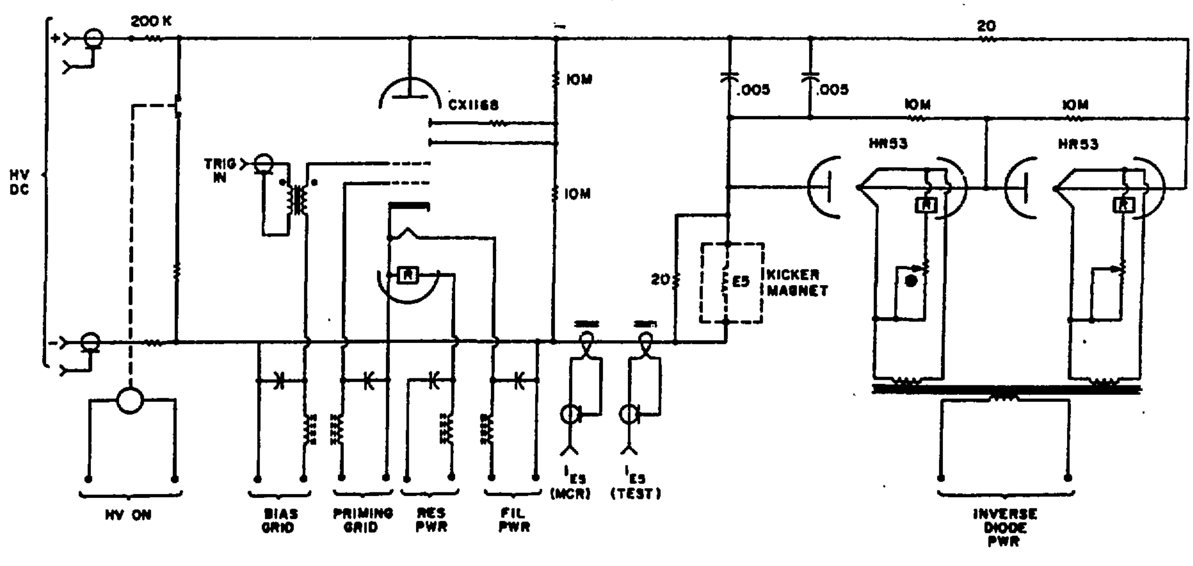

Fig. 6
Simplified Schematic Diagram - HV Section

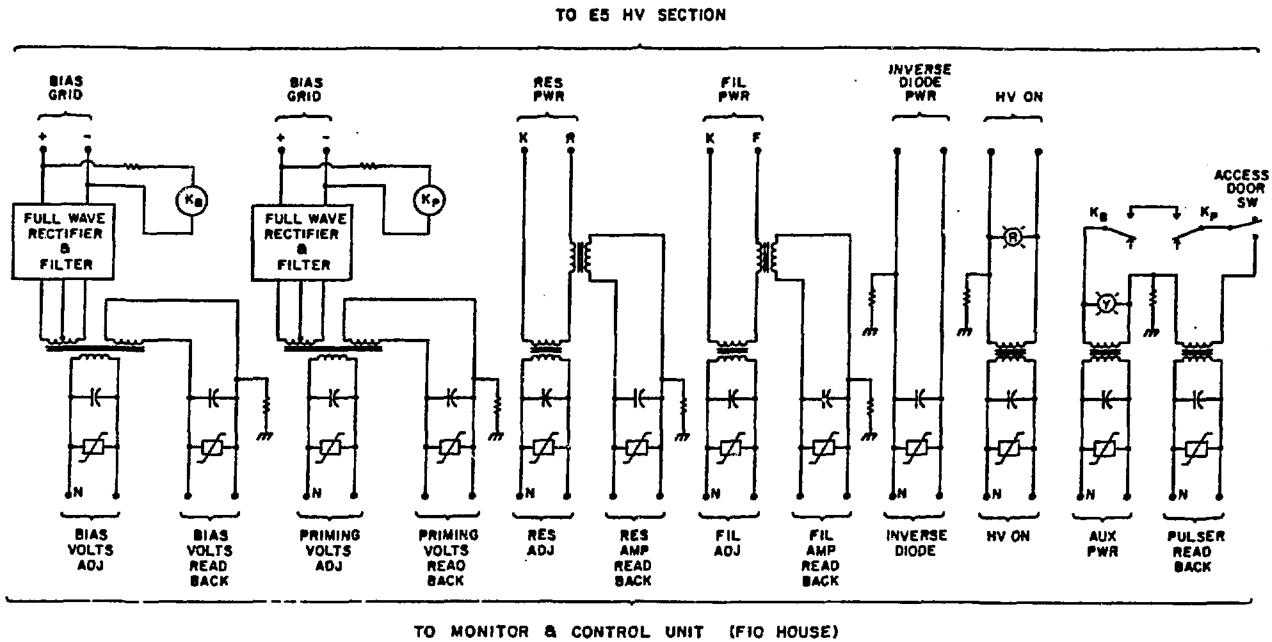

Fig. 7
Simplified Schematic Diagram - LV Section

Fig. 8. E5 Pulser Mounted on the Kicker Magnet in the AGS Ring.

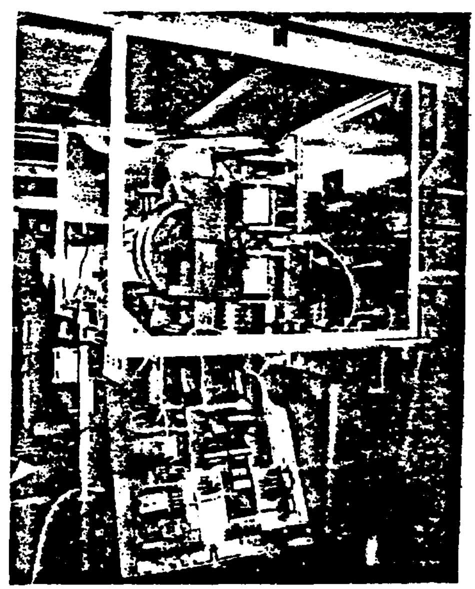

Fig. 9. E5 Pulser Illustrating Access to HV and LV Sections.

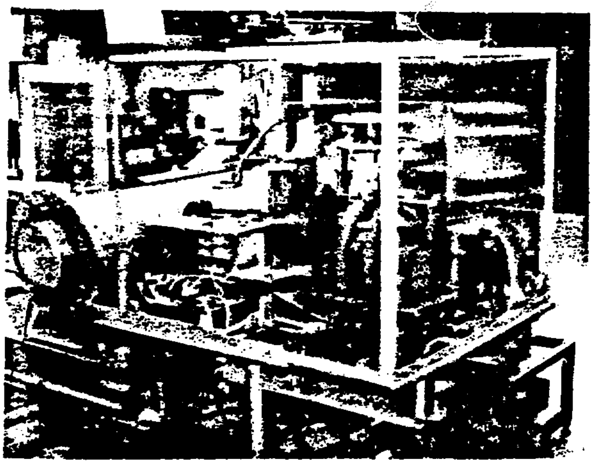

Fig. 10. E5 Pulser Access to Main Switch Tube.

Performance

During the January 1983 FEB run, SBE was successfully performed at the AGS. Figure 11 is a photo of a 2800 A current pulse in the kicker magnet. Figure 12 is a photo of the FEB beam current monitor illustrating the sixth bunch missing without affecting the bunches on either side.

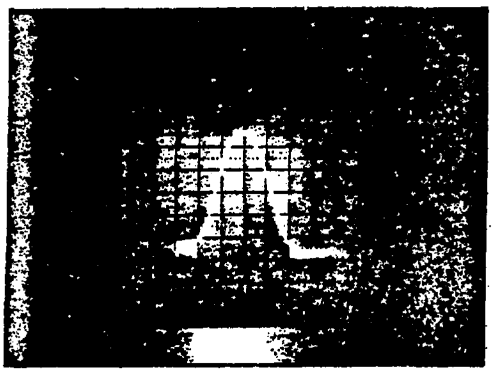

Fig. 11. Magnet current pulse, 2800A pk. horiz. 100 ns/div.

Fig. 12. Beam current monitor, sixth bunch missing

Figure 13 illustrates the anode conduction delay of the inverse diode referenced to the magnet current pulse. This photo shows an approximate 50 ns delay in the start of inverse current after the capacitor voltage reverses (peak of current pulse). This anode current delay of the inverse diode is a compromise between minimum delay and dc leakage. The delay is adjusted by optimizing in inverse diode filaments and reservoir voltage.

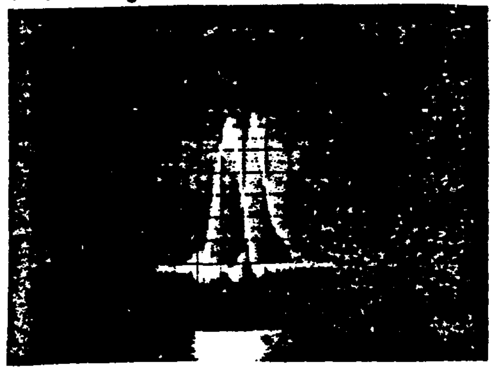

Fig. 13. Magnet current vs inverse diode current 200ns/div.

Figure 14 illustrates the voltage across the switch tube. Figure 15 is the switch tube voltage with the current pulse for reference. Excessive inverse voltage across the switch tube can cause "ring through"; i.e. the negative half of the sinusoidal oscillation resulting in undesirable current flow in the magnet. For an optimized inverse circuit resistance, i.e. critical damping of the inverse voltage, the inverse voltage is approximately 1/2 the charging voltage. As this inverse voltage approaches the tube limit, the turn off characteristics will have to be optimized. The bias grid voltage and reservoir voltage are adjusted for the shortest recovery time. The two gap thyratron recovery time was only slightly better that the single gap thyratron used during the prototype stage.

Leading edge jitter, measured from low level trigger pulse input to current pulse output is 5 ns or less. Although the trigger pulse amplitude is large to ensure clear jitter free triggering of the switch, care must be excercised to ensure it is not too wide at the base. If the grid of the thyratron is not negative at the end of the main current pulse there will be erratic turn-off problems.

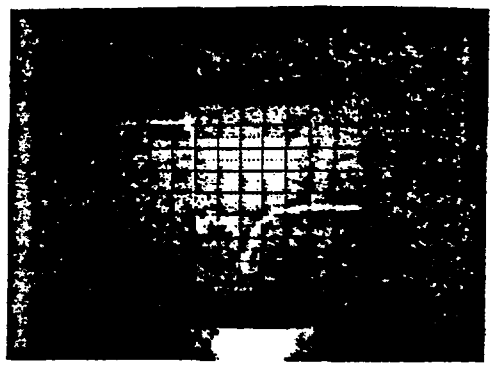

Fig. 14. Voltage across the switch tube; 200 ns/div.

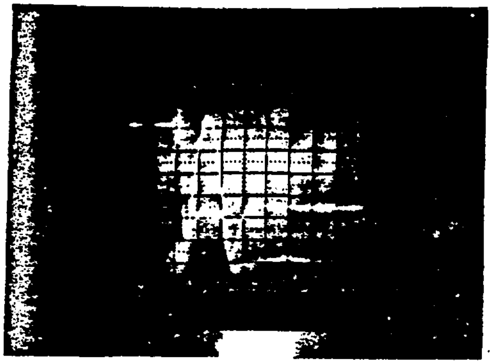

Fig. 15. Voltage across the switch tube vs magnet current, 200 ns/div.

References

1. "H5 Fast Kicker Magnet Pulser" by Frey, Ghoshroy and Cottingham, 1982, Proceedings of the Fifteen Power Modulator Symposium, pp 299-302.

2. "Radiation Effects Design Handbook, Section 3", by Hands and Hamman, 1971, NASA report CR-1787,

3. "Gamma Radiation Effects on Liquid Dielectrics" by Callinan, 1955, Electrical Engineering, pp 510-515.