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KICKERS AND POWER SUPPLIES FOR THE FERMILAB TEVATRON I ANTIPROTON SOURCE*

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KICKERS AND POWER SUPPLIES FOR THE FERMILAB TEVATRON I ANTIPROTON SOURCE

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Abstract

The Fermilab Antiproton Source Accumulator and Debuncher rings require 5 kickers in total. These range in design from conventional ferrite delay line type magnets, with ceramic beam tubes to mechanically complex shuttered kickers situated entirely in the Accumulator Ring's 10^{-10} torr vacuum. Power supplies are thyratron switched pulse forming networks that produce microsecond width pulses of several kiloamps with less than 30 nanoseconds rise and fall times. Kicker and power supply design requirements for field strength, vacuum, rise and fall time, timing and magnetic shielding of the stacked beam in the accumulator by the eddy current shutter will be discussed.

Overview

The Fermilab Antiproton Source consists basically of a target to produce antiprotons, a lens to focus them, various beam transport lines and two concentric 8 GeV rings, the Debuncher and Accumulator. Since the bunch structure of the antiprotons produced at the target is identical to one "Booster batch", and the Debuncher is the same circumference as the Booster, strict requirements were put on Debuncher kicker rise and fall times. The radio frequency (rf) harmonic number in the Debuncher is 90. Only 80 bunches of antiprotons will be produced during a given fill, leaving one ninth of the revolution period available for injection kicker fall time. After injection, a gap preserving rf signal is turned on leaving a 200 nsec gap in the beam for extraction kicker rise time. Both kickers are paired with pulsed septum magnets which convert the angular kick of the kickers into a larger horizontal displacement.

Because the Accumulator is only about 100 nsec shorter in circumference than the Debuncher, the Accumulator injection kicker must have a fall time of less than this. After antiproton accumulation, rf cavities are turned on which effectively compress the beam into a small fraction of the Accumulator circumference. Hence, the Accumulator extraction kicker has very loose rise time requirements. It was decided to make the injection and extraction kickers identical to facilitate backward injection of protons into the Accumulator for study purposes.[1]

All the kickers for the Debuncher and Accumulator consist of three separate modules each capable of being individually pulsed. This was done to limit the propagation delay, to below 200 and 100 nanoseconds for the Debuncher and Accumulator respectively, while still providing the necessary field integral to give the required "kick".

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Debuncher Injection and Extraction Kickers

The Debuncher injection and extraction kickers are standard, single-turn transmission line pulsed magnets similar in design to kickers built previously at Fermilab and elsewhere.[2,3] One non-standard feature for a Fermilab kicker is the 200 nanosecond rise and fall times. Typical Main Ring or Tevatron kickers have 20 microsecond pulse widths with microsecond rise and fall times. Computer simulation using the circuit analysis program SPICE, led us to believe that this well-proven design could be made to have the rise times we needed. Initial testing of a magnet proved this to be incorrect. Lead inductance off the capacitors and coupling between the cells of the magnet tended to degrade the rise time. Reducing the capacitor lead inductance and intercell coupling by allowing small air gaps between the ferrites proved to be a simple solution.

The beam tube for these kickers is an elliptical alumina ceramic tube with metallized joints to the end flanges and a semiconductive coating on the inside to bleed away accumulated charge.[4,5]

Table I Basic Parameters of the Antiproton Source Kickers

	Deb. Inj.	Deb. Ext.	Acc. Inj&Extr
Kick required (milliradians)	6.1	4.6	4.0
B - dℓ kilogauss-meter	1.81	1.34	1.19
Rise time max(ns) nanoseconds	-	190	1000
Fall time max(ns) nanoseconds	205	-	75
Nominal impedance (ohm)	10	12.5	25
Magnet voltage (kilovolts)	25	30	35
Ferrite type	Ceramic Magnetics CMD5005		Ferroxcube 4C-6
Capacitor type	"Doorknob"		Parallel plate
Beam tube	ceramic with semiconductive coating		none
Shutter	none		5 mm aluminum
Vacuum (torr)	10^{-8}		10^{-10}

Accumulator Injection and Extraction Kickers

The Accumulator injection and extraction kickers are similar in design to those used in CERN's AA Ring.[6] Since the Accumulator's function is to accumulate, a way of shielding the stored antiprotons from the kicker magnetic field during the injection of the next pulse is required. A mechanical shutter of conductive material serves this purpose. The lumped capacitance in this magnet is achieved by distributing parallel plate capacitors along the length of the magnet, the high voltage plate attached to the center conductor and ground plates on either side of the high voltage plate. To achieve the necessary capacitance with vacuum-gap capacitors (no dielectric except vacuum) would require the plates to be very large, very close together, or very densely packed. Instead, it was decided to place a dielectric between the plates to increase the capacitance without making the plates unmanageably large, or making the high voltage hold off problem intractable. Alumina ceramic was chosen for the dielectric plates as well as for all the insulating components of the magnet because of its excellent vacuum, mechanical, and electrical properties.

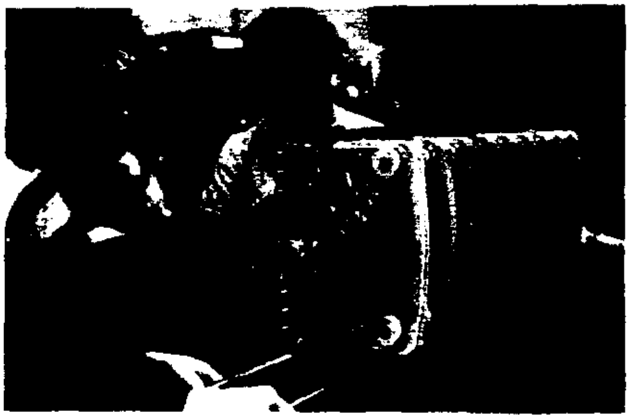

Fig. 1 Final assembly of one accumulator kicker module with capacitor plates shown. Injected beam goes through the gap that is just visble to the left of the cylindrical conductor in the center of the photograph.

Two problems encountered upon initial testing were our inability to accurately predict the capacitance of the complicated three dimensional structure, and the surface flash-over which occurred across the ceramics despite relatively large path lengths. The former problem has produced an impedance mismatch between the magnet and its power supply of about 40%, while the latter has been partially alleviated by additional insulation and the high temperature bake required to achieve the Accumulator's ultra high vacuum requirement. Further work in these problem areas is required.

The magnet was also modeled using SPICE, and two different static electric and magnetic field mapping programs, POISSON and ANSYS. The simulations were done to guarantee field uniformity requirements and to better understand the electric field patterns around the capacitors and their influence on high voltage breakdowns. To this date the magnetic field has not been mapped in the actual device because of the difficulty in getting the resultant signal out of the vacuum chamber and the problem of the large amount of capacitive coupling that would occur with any B-dot coil placed in the kicker gap.

Vacuum Requirements

The Accumulator's ultra high vacuum environment dictated the choice of materials for the kicker components. Conductors of vacuum-degassed 316L stainless steel, alumina ceramic insulation, and specially prepared and handled ferrites were used. All metal parts were electropolished to a 10 micro inch finish or better, with generous radii on all corners. The magnet and tank is baked under vacuum at 300°C in situ. To date, 3×10^{-9} torr has been achieved with only three of the five titanium sublimation pumps operational.[7,8]

Shutter

The shutter is a simple four-bar linkage driven by a DC stepping motor. The rotary motion of the motor is converted to a near-sinusoidal oscillation of the shutter blade by the relative lengths of the driving links. The shutter itself is a bar of aluminum ten feet long in the beam longitudinal direction and 5 mm thick in the beam transverse direction. It is supported by three titanium arms. The arms are made to "rock" by a pivoting mechanism rigidly attached to the tank and using teflon-lead bushings as bearings. The mechanical motion is transmitted into the vacuum by a stainless steel welded bellows. The shutter mechanism is designed to be balanced on the fixed pivots to minimize the power required to move it. The motor transmits its torque through a special low backlash gear box.

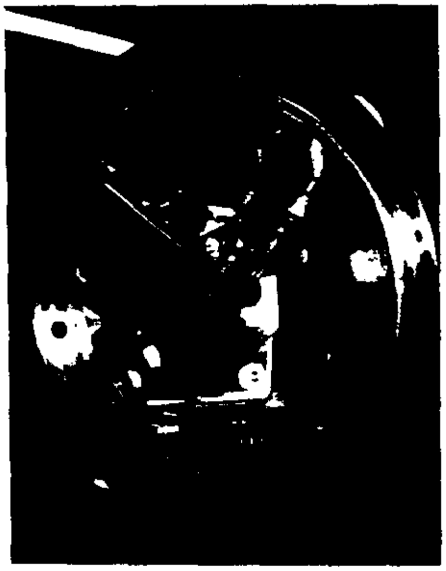

Fig. 2 Downstream end of the accumulator kicker inside its vacuum tank. Stacked beam passes through the elongated "C" shaped structure on the left which is separated from the injected beam by the shutter shown in its fully open position. At the upper right a HV feedthrough is visible.

The entire shutter mechanism and several of its components were modelled using the finite element program, ANSYS. Stress models were done to check the design for strength, modal analyses were done to ensure stiffness of the structure, and thermal analyses were done to determine the effect of the 300°C bake on the structure due to the differential thermal expansion of the materials comprising it.

All of the driving components of the shutter were life tested to determine the maximum obtainable fatigue life for the bellows. Hydroform bellows had a fatigue life of approximately one million cycles, stainless welded bellows have a minimum fatigue life of fifteen million cycles, and the bearings, gearbox and motor lasted for over one hundred million cycles.

High Voltage Pulse Power Supplies

The fall-time requirement for the Accumulator injection kicker determined almost completely the design of the high voltage pulsers for the antiproton source kickers. Circuit simulations showed that a 30 to 40 nsec fall time of the current to the magnet was necessary for a 75 nsec fall time of the magnetic field. A hydrogen thyratron switched delay line type modulator with a matched load design was chosen for its excellent current rise time, low jitter and high reliability.

To achieve the required 30 nsec fall time of the field, a low inductance coaxial housing for the switch tube was necessary. In addition, a delay line long enough to produce a 1.5 microsecond pulse would have non-zero dispersion and would produce a square pulse with a slight exponential "tail" that would degrade the fall time. A second thyratron, or "clip tube" is used to short this "tail" to ground by proper timing of its firing.

Table II Kicker Power Supply Parameters

DC Supply	80 kV, 40 mA programmable
Delay lines	RG220/U high voltage cable
Pulse width	1.5 μsec
Switch tubes	English Electric Valve Deuterium thyratron, 3 gap tetrode
Main tube	EEV CX 1171
Clip tube	EEV CX 1671-D
dI/dt max	8.3×10^{10} Amps/sec
Peak power	75 Megawatts
Avg. power (typical)	60 watts (at 1/2 Hz)
Total cable	30,000 feet

The English Electric Valve Co. supplied the deuterium thyratrons and was most helpful in the development of a special tube for the "clip" application, basically an 1171-D tube with an extra "screened-grid" to prevent spurious triggers due to inter-tube coupling. A hollow anode also prevents the destruction of the tube by reverse currents through it when shorting the "tail" current to ground.

Fig. 3 Prototype thyratron switch tube housing showing main and clip tubes, HV connections center and left, and isolation transformer (center bottom).

Extensive R&D work was done to develop fast trigger circuits with 30 nanoseconds rise time and less than 1 nanosecond of jitter and to reduce spontaneous triggers due to noise from the main tube. Forty kilovolt isolation pulse transformers with several tens of nanoseconds rise times were developed and careful impedance matching was done to insure good high frequency response without compromising the system's ability to hold off high voltage.

Operational Experience

Beam was first injected into the Debuncher on April 21, 1985. Initial running of the kickers has uncovered several problems. These problems all have to do with high voltage breakdown: in delay-line cables, D.C. supplies, and arcing in the magnets. The vendor is working on the D.C. supply problems, cable failures are thought to be infant mortality and should decrease with time and a slight redesign of the magnet insulation has apparently cured the arcing problem.

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