A New Fast Rise Time Kicker System For Antiproton Injection Into The Tevatron

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There are six proton and six antiproton bunches used at the present time for Tevatron Collider operation. As the luminosity is increased for a fixed number of bunches, the number of interactions per bunch crossing increases. The quality of the physics data taken by the CDF and D0 detectors is enhanced by reducing the number of interactions per bunch crossing. To this end it is planned to collide 36 proton bunches with 36 anti-proton bunches. To do this, it is necessary to construct and install a new 150 GeV injection kicker system with a faster rise and fall time than the existing injection kickers. This paper will describe the design, construction and testing of the new kicker magnet along with the associated spark gap pulsers, pulse forming lines and trigger circuits. Difficulties and our solutions will also be presented.

I. INTRODUCTION

In order to place the injected 150 GeV antiprotons onto the closed orbit in the Tevatron, a kick of one milliradian at location D48 is required. This has been accomplished using two transmission line magnets coupled to each other in parallel and pulsed using a thyratron based pulser. The system impedance is 5 Ω and operates at 55 kV. The rise time for this system is 1.1 microseconds with a flattop of 500 nsec. The fall time is on the order of 1.6 microseconds and there is considerable ringing that affects circulating beam. For present operations this waveform is acceptable. However, for the upgrade to 36 proton bunches colliding with 36 antiproton bunches, it is planned that for each injection 4 antiproton bunches be injected thus requiring a total of 9 injection cycles.

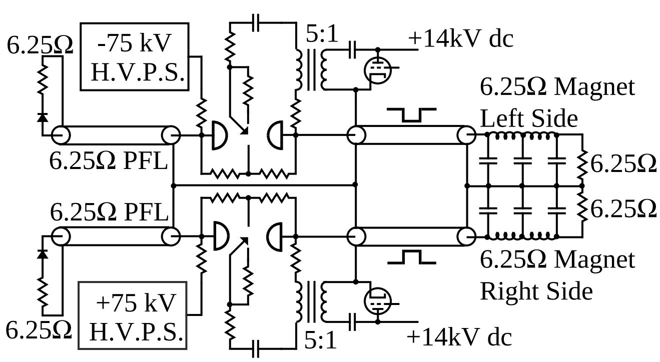

Figure 1. D48 Kicker Magnet System Schematic Diagram

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* Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

Since the bunch spacing will be 21 bunches (which translates into 396 nanoseconds center to center) this requires a flattop of at least 1.2 microseconds. 36x36 operation also puts constraints on the rise time and fall time. The existing kicker does not meet any of these requirements. In order to meet the fast rise time and flattop length requirements, we have made a transmission line magnet pulsed via pulsers that use spark gap switches and RG-220 pulsed forming lines (PFLs). The impedance of the system is 6.25 Ω. The overall system for one magnet is shown schematically in Fig 1. The overall system will be composed of 8 back terminations, 32 PFLs, 4 spark gap pulsers, 4 trigger units and 2 magnets. In addition there will be a controls system that will monitor all important operating parameters and disable the high voltage in case of a fault.

II. DESIGN PARAMETERS

The system design requirements and magnet design parameters are shown in Table 1 below:

∫Bdl	0.508 T-m
Space Available	230 inches
Horizontal Aperture	50.8 mm
Vertical Aperture	40.6 mm
Good Field (+/- .1%) width	35 mm
Field Rise Time	376 nsec
Flattop	1207 nsec
Field Fall Time	1053 nsec
Flattop Stability	±1%
Post Flattop Stability	±1% of full field
Magnetic Length	2.41 m
Gap Height	5.72 cm
Gap Width	6.50 cm
Peak Field	1053 Gauss
Characteristic Impedance	6.25 Ω
Measured Magnet Fill Time	344 nsec
Number of Cells	68
Inductance per Half Cell	25.3 nH
Capacitance per half cell	647 pF

Table 1

The aperture requirements are determined by the amount of separation of the two beams, their emittances and their momentum spread. The manufacturer of the ceramic beam tubes, Coors Ceramics, required the tube to be tapered, and imposed a lower limit on the straightness they thought they could achieve, thus constraining our minimum gap width. The requirements on the good field region account for alignment errors, injection errors, beam size and magnet straightness. The rise and fill times are such that the kickers are able to get to full field in the time between two bunches which, in the 36 on 36 scheme, implies a maximum time of 21 buckets or 376 nanoseconds. The flattop length is set by the requirement of injecting 4 antiproton bunches which implies a flattop time of 1.207 microseconds. These two requirements determine the minimum length of our PFLs to be 1.583 micro-seconds (which corresponds to 157.8 meters of RG220 cable with a polyethylene dielectric). The fall time is dictated by the requirement that the field in the kickers be less than 1% of full field when circulating protons arrive. The total time available for the pulse is 2.617 microseconds.

III. MAGNET DESIGN

The overall design is described in the design review [1]. The magnet itself is a ferrite loaded picture frame magnet. In order to achieve the necessary fill time, it is necessary to power the magnet with two pulses of opposite polarity. Each magnet consists of 68 cells (136 ferrite pieces and 138 capacitors), two 6.25 Ω resistive loads, four high voltage probes, and a 100" long ceramic beam tube with a high resistance paste coated on the inside for static charge bleed off. The magnet is filled with a liquid dielectric called Flourinert FC-77. In order to avoid problems associated with magnetic coupling between the two halves, a 0.005" copper Faraday shield extends down the length of the magnet on both top and bottom. Dollops of RTV were applied between the bus bars and the beam tube to hold the gap width, crucial to maintaining the correct inductance.

The ferrite material used is CMD5005. Its properties were tested and compared with other ferrite materials. The results of these tests are described elsewhere [2]. Since we have a tight tolerance on field uniformity across the gap, POISSON was used to optimize the shape of the pole tip. Calculations indicate the field in the midplane is uniform to within 0.05% over 1.4 inches. The ferrites are cross coupled to each other in order to minimize inductance for the displacement current in the shunt capacitors. Tests indicated that using a 10 Ω resistor in series with the cross coupling windings reduced ringing in the waveshape. Both horizontal and vertical alignment of the ferrites is important in order to maintain good field uniformity. Vertical alignment is maintained by use of precision machined holders. Horizontal alignment is accomplished by adjusting positioning lugs to set the ferrites on each side to the same distance from the bus bars. This can be done optically or mechanically.

Two different capacitor designs have been tested. The capacitors need to stand off 35 kV and carry a peak current of 650 Amps. In addition, they must fit in the space between adjacent ferrites which is 0.4 inches. The first design was a 6 layer PC board with a glass reinforced polyimide dielectric and was basically two capacitors in parallel. The thickness of the dielectric is 0.090 inches. The high voltage planes compose the inner layer while the ground planes are on the outer layers. Thus, besides being a capacitor, they also act as a Faraday shield between ferrites. Also, since the high voltage planes are shielded by the ground planes, stray capacitance is minimized. After building a prototype magnet with these capacitors we found that these capacitors started failing. The cause of the failures was due to poor bonding of the glass fibers to the polyimide material. This problem was solved by using a smaller glass weave in areas of high electric field stress. An operational quality magnet made with capacitors of the new design has had no faults in over 50,000 pulses. There is no noticeable voltage coefficient for these capacitors which means the design value of 640 pF is the value of the capacitance desired from the manufacturer. The major drawback of these capacitors is the high level of corona they exhibit; in many of these capacitors we observed corona at voltages as low as 7.5 kV. The nominal operating voltage will be 28 kV pulsed. Since there was a large range of capacitance values for the 138 capacitors, we arranged the capacitors such that the higher capacitance was at the input end of the magnet and the values decreased as smoothly as possible so as to match both ends of the magnet as well as possible.

The second design uses commercially available E.I.A. Class I ceramic doorknob capacitors. These capacitors are mounted on a copper plate which attaches to the bus bar. We have found that there is a 4% decrease in the capacitance under voltage. From pulsed high voltage tests we have found the optimum value for the capacitance to be 665 pF. The major advantage of these capacitors is that they are corona free up to 40 kV and it is for this reason that they are the capacitor of choice for the magnet. In either case, the capacitors have not varied in their value of capacitance either due to pulsing (>100,000 pulses) or due to the liquid dielectric.

The loads, which are an integral part of the magnet structure, are composed of eight 50 Ω resistors in parallel. Each resistor is placed in a cylindrical tube so as to maintain a low inductance design. The resistors are tubular and have corona rings on both ends which are connected to the resistor using a conductive epoxy. On-going tests are looking into late life failures of these resistors. These failures may be related to an electro-migration effect at the junction of the resistive material and the metal corona ring. The entire load is potted in RTV with a high dielectric constant. This potting keeps the Flourinert out of contact with the resistors which helps to keep the value of the resistance stable and also adds capacitance to help with matching the magnet to the load at high frequencies.

In order to monitor the performance of the system and to make accurate measurements of the field quality, voltage probes have been installed at both the input end and at the load box. In addition, there are current viewing resistors in the loads. By taking the difference between the input and output voltages, one gets a $\dot{B}$ signal. Integrating this gives the field. A hybrid transformer assembly mounted to the magnet combines input and output voltage signals to make a $\dot{B}$ signal which can be monitored in the Main Control Room.

IV. PULSERS

This system will require a total of four pulsers, two positive and two negative. We use triggered spark gaps instead of thyratrons as the series switching element due to their compact size, low cost and ability to transfer high currents at high voltages. One of the main disadvantages of spark gaps is the lower lifetime. This shouldn't be a problem since antiprotons are injected infrequently; we expect only about 20,000 pulses per year. The gap chosen is the Maxwell #40264 gap rated for operation from 25 kV to 100 kV. This standard unit is slightly modified in this system. We inserted 0.060" copper spacers under each electrode to reduce the gap spacing. This reduced the observed jitter at typical operating voltages. Since the rise time of the pulse is determined by the electrical properties of the pulser, a coaxial design is used as much as possible in the design of all components. Calculations indicate the pulser inductance is between 80 nH and 120 nH. This is consistent with the rise time at the output of the pulsers which has been measured at 38 ns (0-95%).

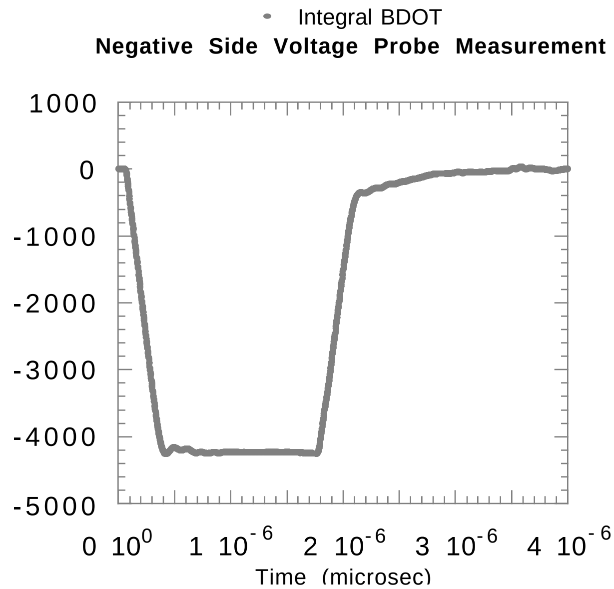
The spark gap is a three electrode, irradiation pin type unit. The center "midplane" electrode, biased at one-half the operating voltage, is triggered by a thyratron pulser. This pulser is transformer coupled to the gap to reduce the trigger current seen in the magnet. The transformer itself is high-voltage hook-up wire wound on a large CMD5005 core. Three primary turns and 15 secondary turns step up the voltage from the output of the thyratron by a factor of 5. The transformer secondary is coupled to the spark gap by means of a capacitor and two chains of resistors. The capacitor serves to block the charging voltage to maintain the bias of the midplane. The resistors were selected experimentally to minimize jitter and noise injected into the magnet from the trigger system. The trigger signal seen by the spark gap is on the order of 50 kV, with a risetime less than 50 ns. It has been observed that the irradiation pin must be set very precisely in controlled conditions. The factory setting proved unreliable for operation in this system. Improper setting often resulted in high measured jitter, and eventually complete failure of the breakdown process.

The spark gaps operate with compressed air as a dielectric. This air is furnished by a custom, oilless air compressor system which meets Maxwell's air requirements. Water and contaminants are removed with a system of refrigerators, dryers, and filters. Each spark gap is operated at an optimal pressure to balance the occurrence of pre-fires and fail-to-fires, while minimizing observed jitter. This pressure is determined mathematically after measuring the self-breakdown voltage of the spark gaps at various pressures, and fine-tuned by observation. After break-in, a system of four spark gap pulsers operating at 55 kV PFL voltage typically has about one fault every 10,000 pulses. Jitter is typically between 10 and 20 ns for each pulser. The firing of the spark gaps is coordinated by a 4 channel digital delay generator which compensates for system delays. Spark gap lifetimes in this system have been observed to exceed 200,000 shots at a charge transfer rate of approximately 0.007 Coulombs per shot.

The spark gap is mounted in a cylindrical aluminum housing which has been tin plated for corrosion resistance. Sulfur Hexafluoride is used as a dielectric, pressurized to 12 psia for operation up to 66 kV. Commercially available connectors[3] are used to simplify RG-220 cable installation. The design of the housing allows for simple replacement of key components including the spark gap. Glassman 75 kV, 50 mA supplies charge the PFLs through 3 MΩ resistors mounted in each pulser.

V. RESULTS

Results from the voltage probe measurements are shown below.



All requirements have been meet with the possible exception of the fall time. These measurements indicate that the field is at 1.5% of full field by the time protons arrive. It should be pointed out, however, that many components involved in the measurement have voltage coefficients as well as skin effects which make this measurement extremely difficult. Ultimately, it will take beam tests to determine if all requirements have been meet. Some research has been done using a spark gap to clip the tail of the pulse caused by the high frequency response of the PFLs. The results are inconclusive, and such a tail biter will not be incorporated into the system initially.

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VII. REFERENCES

[1] J. Dinkel, et al., "D48 Design Review" ,unpublished.

[2] C. Jensen, J. Dinkel, "Comparison of Ferrite Materials for Pulse Applications," IEEE Transactions On Magnetics, Vol. 31, No. 1, January 1995.

[3] A. Donaldson , et al., "High Voltage Pulse Cable and Connector Experience in the Kicker Systems at SLAC," IEEE Particle Accelerator Conference , Vol 5, pp3159-3161 , May 1991.