Development of a High Quality Kicker Magnet System

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Abstract

As part of the Fermilab Tevatron upgrade, a 6.25Ω ferrite loaded traveling wave kicker magnet has been designed. The critical parameters are the field rise time and flatness during and after the pulse. A picture frame pole piece configuration was chosen which requires two pulses of equal amplitude but opposite polarity. Low inductance, high voltage capacitors placed between each of the pole pieces provide the shunt reactance necessary to achieve the 6.25Ω impedance. Cross coupling adjacent cells is used to improve the transient response of the magnet. The compensated termination resistors are built into the magnet to minimize reflections. Two spark gap pulsers provide the two 4800A fast rise time current pulses necessary to drive this magnet. The field in this 2.4 m long magnet rises to 1055G in less than 400ns. This paper describes the design choices involved with this system and preliminary test results.

Introduction

Presently, there are 6 proton and 6 antiproton bunches used for collider operation in the Fermilab Tevatron. As the number of particles in these bunches increases, experimenter's detectors begin to saturate. To alleviate this situation, protons and antiprotons will be redistributed in 36 bunches instead of 6. In order to carry this out, the rise and fall times of the Tevatron antiproton injection kicker which deflects the antiprotons into their equilibrium orbit must be reduced to accommodate the increased number of bunches circulating in the machine.

To function in its new capacity, the kicker magnet system must meet the requirements in Table I:

Table I
System Design Parameters

∫Bdl	0.508 T m
Space available	5.8 m
Horizontal aperture	50.8 mm
Vertical aperture	40.6 mm
Good field (±0. 1%) width	35 mm
Field rise/fall times	395 ns
Flattop	1260 ns
Flattop stability	±1%
Post flattop stability	±1% of full field

For a magnet to meet these criteria, its inductance per unit length as seen by the source must be minimized. For a given aperture, this can be done by using a picture frame magnet powered by two pulses of opposite polarity. Two magnets are required, each with a magnetic length of 2.41 m. The relevant parameters for the magnet are in Table II:

Table II
Magnet Design Parameters

Magnetic length	2.41 m
Gap height	5.72 cm
Gap width	6.50 cm
Peak field	1055 G
Peak current	4800 A
Characteristic impedance	6.25 Ω
Field propagation time	275 ns
Number of cells	68
Inductance per half cell	25.3 nH
Capacitance per half cell	645 pF

Magnet Design

Of the 5.8 m available in the tunnel for this magnet system, only 4.82 m remain for the production of field. Assuming negligible reluctance drop in the ferrite, the peak current can be determined from gap dimensions. We will consider the picture frame magnet design as two "C" magnets sharing a common gap as shown in Figure 1. The inductance per half cell is determined by the aperture volume of each "C" magnet.

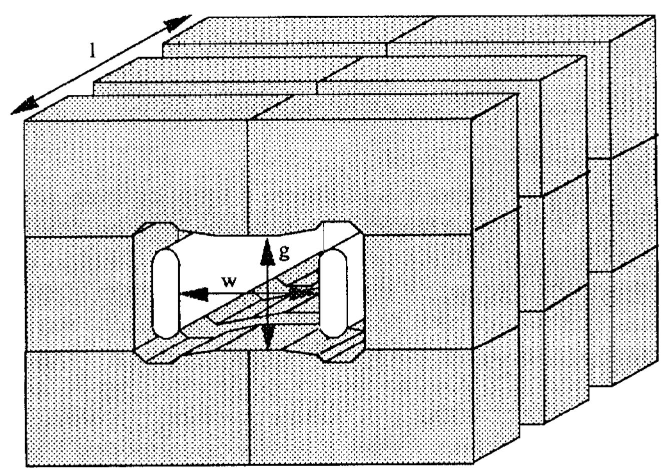

Figure 1 "Picture Frame" magnet showing ferrite and bus bars

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For the sake of reliability, the pulse forming line cables are operated around 60 kV, therefore, the magnet impedance must be such that the design current can be achieved. This impedance is also required to be a submultiple of 50Ω. A magnet impedance of 6.25Ω meets these two requirements. A shunt capacitor is required to compensate the inductance of each ferrite pole piece to achieve this impedance in a traveling wave magnet according to $Z_0 = \sqrt{L_c/C_c}$.

The function of the ferrite is to efficiently guide stored magnetic energy into the gap. In order to do this, the magnetization must increase to the required value as rapidly as possible for a given drive level and source impedance. To select the ferrite which best meets this criteria, samples of a standard size were obtained from four manufacturers. These samples were subject to pulsed tests where the B and H fields were measured at high drive levels, ~6 kV, into a 50Ω load. The selection of the ferrite was based on these criteria:

1. high saturation magnetization
2. low remnant induction
3. fast time to a given induction level

Three of the samples; CMD5005 by Ceramic Magnetics, Inc. ; 8C11 by Phillips Components; and PE12C by TDK performed similarly in the testing having roughly the same magnetic flux density rise time. The CMD5005 has a slightly higher saturation flux density than the other two samples. The operation of the test system was verified by replacing the ferrite with a dielectric sample of the same dimensions.

It should also be noted that magnetic properties for ferrites can vary by as much as ± 20 % from batch to batch for the same material so that differences much less than this have little relevance.

The amount of energy required to drive the ferrite can be approximated by multiplying B(t) and H(t) to get the energy density. The larger the volume of ferrite, the more total energy is required to reach the desired induction level. The peak power required to reach this level will be determined by the source impedance. For the sample cores approximately 5 mJ were required to reach an induction level of 1400 Gauss in ~25 nsec. The volume of ferrite in the magnetic circuit of a half cell is 5 times greater than the test core, therefore we can conclude that ~25mJ would be required for the ferrite in a half cell or 3.3J for the whole magnet. This is about 0. 2% of the total stored energy.

The program POISSON was used to generate a pole tip profile which would meet the required field flatness over the desired horizontal aperture. The field at the mid plane of the gap is flat to within ± 0.05%. For a 3.8 mm offset from the mid plane, the field is flat to within ± 0.1%.

In previous designs, it was found that 2.5 cm wide ferrite pole pieces could be spaced up to 1 cm apart to accept the shunt capacitor without significant effect on the field at the mid plane. This spacing does, however, increase the flux in the ferrite by 40%.

A 29-cell low voltage test magnet has been built to measure the inductance and impedance characteristics of the final design. A copper Faraday shield 0.062 in. thick was placed vertically down the centerline of the test magnet to enable us to perform realistic measurements on a C- shaped half-cell magnet. Average inductance measurements at 1 MHz of a half cell are 25.8 ±0.3 nH. Repositioning the ferrite from adjacent to distant cells also permits us to measure the mutual coupling between cells directly. In both cases it was found to be 7.0 nH. Although the measured cell inductance calls for a shunt capacitance of 660 pF, the best pulse response was found with 640 ±5 pF of shunt capacitance per half cell and the flattest frequency response was found with 650 ±5 pF.

The displacement current through the shunt capacitor must pass between the backlegs of two adjacent ferrite pole pieces. This increases the inductance in series with the capacitor. To minimize this effect, these two backlegs can be cross-coupled to effectively cancel this flux. This effect was measured to be 12.9 nH less than with the two ferrites separated. Cross-coupling, from an equivalent circuit viewpoint, puts a negative inductance in series with the capacitor. The peak current in a typical cross coupling winding was measured and scales to 240A peak. Resistances of 10 Ω were introduced in these circuits to provide damping of the ringing of the displacement current.

The capacitor located at the input side of the first cell has a value of 320 pF and has a series resistor equal to Z_0 to terminate frequency components of the input pulse which are above the magnet cutoff frequency.

The shunt capacitors used in this magnet are a parallel plate design. They are required to operate at voltages of 35 kV peak and maintain a stable capacitance over their operating lifetime. Physically, each must fit within the 1 cm space between adjacent ferrite pole pieces. Such a design offers the lowest practical inductance. These capacitors are essentially six layer printed circuit boards which use a glass reinforced polyimide dielectric. Each conducting surface is made from double sided C-stage material which is 0.012" thick with 2oz. of copper cladding. Between these 3 conducting surfaces, which are externally connected as two capacitors in parallel, are layers of B and C stage material which form the working dielectric. The thickness of this dielectric is 0.090" which stresses it to 25% of its rated breakdown voltage of 1600v/mil. Twelve of these capacitors were pulsed to full voltage for 5×10^6 shots with minor degradation of the corona extinction level.

Another unique feature of this magnet system is the fact that the load resistors are an integral part of the magnet structure. This has the advantage of eliminating reflections from the cables and their associated connectors normally used with external resistors. With external resistors, it becomes necessary to match the magnet, the cables, and the load. Since the impedance of the cables is fixed, both the load and the magnet must be trimmed to match the cables.

Ideally, the load is matched to the impedance of the magnet for frequencies within its pass band of 40 MHz. The best results were obtained with 8 parallel 50 Ω resistors each of which is placed in a cylindrical tube to minimize inductance. A ninth resistor will be run in parallel to allow precise matching and trimming if necessary. The load resistors are Carborundum 'rod' type resistors with no-arc corona terminals. Pulses in this system are actually applied about eighteen times a day, spaced several minutes apart, resulting in a negligible average power dissipation in the load resistors.

A current viewing resistor (CVR) is used to monitor the current in the termination. The CVRs selected offer a 1 nsec rise time and a 3 J rating at 0.005 Ω.

Pulser Design

A triggered spark gap was chosen for this design instead of a thyratron for a variety of reasons. Most importantly, spark gap systems are much smaller than thyratron systems. Next, spark gaps can transfer more energy at higher levels of voltage and current than thyratrons. Also, spark gaps are lighter and cheaper than thyratrons. There is also no filament or reservoir power, and thus no warm up time. Finally, spark gaps are more robust and can withstand larger inverse currents typical in tail-biter circuits. Disadvantages of spark gaps include low repetition rates, lower lifetime, necessity of a pressurized gas system, and finally the need for a high voltage trigger system.

The nominal PFL design voltage of 60 kV is also the voltage which must be held off by the spark gap. The Maxwell gap chosen for this application is rated for operation from 25 kV to 100 kV, at a maximum of 100 kA. The minimum length of the PFL cables is determined by the pulse length. The actual length will be somewhat longer than this minimum length to insure proper operation of the tail-biter spark gap.

An energy of 228 J stored in the PFL is also the energy transferred by the spark gap on each pulse. The charge stored by the cable determines the estimated lifetime of the spark gap. This is 400,000 shots of 7.6 mC for the Maxwell gap.

The rise time of the pulse is determined by the electrical properties of the pulser, specifically, the inductance related to the geometry of the tank. The pulser is constructed in a coaxial geometry to minimize the inductance while giving adequate clearance for high voltage constraints. Inductance as calculated from the physical geometry is 120 nH which agrees well with measurements. With a time constant of L/2Zo = 9.6 nsec, it takes approximately 50 nsec (5 time constants), to get to within 1% of the maximum value, neglecting any mismatches in the load.

The PFLs are charged through a series resistance which provides satisfactory isolation of the power supply during the pulse.

It is necessary to incorporate a high voltage pulse transformer to isolate the trigger generator from the main switch since it is in series with the PFL and the load. The trigger pulse transformer is a coaxial 3:1 step down design with the primary as the center conductor. The primary consists of 3 turns of 60kV silicon rubber insulated wire strung thru three single helical loops of refrigeration tubing connected in parallel to form the secondary. Current limiting resistors are placed on both sides of this transformer to maintain a high common mode impedance for the trigger circuit. We have been able to achieve a jitter of 7.4 nsec for 32 shots, and flattop ripple within 1% peak-to-peak.

High voltage requirements necessitate the use of a dielectric with adequate breakdown strength. In this system, the pulser is pressurized with sulfur hexafluoride to about 12 psig. At this pressure, sulfur hexafluoride has a breakdown strength greater than that of transformer mineral oil.

The exponential like 'tail' at the end of the pulse due to the $1/\sqrt{f}$ skin effect losses in the cables requires the use of a second 'tail biter' switch to short the output of the pulser to ground at the end of the pulse. This will reduce the fall time of the output pulse to the order of the rise time, about 50 nsec. Due of the inductance of the pulser, some energy is reflected into the PFL upon closure of the main switch. This energy can reflect back into the load one PFL length later. Fortunately, the recovery time of spark gaps is relatively long so reflections from any source will effectively be terminated by the tail biter and resistor/diode termination at the far end of the PFL.

The tail biter will also use a spark gap switch similar to that used for the main switch but with a capacitive divider network to provide the necessary mid plane biasing.

No discussion of a delay line pulser would be complete without addressing the dispersion effects caused by the skin effect losses in the PFL and interconnecting cables. The step response of a coaxial cable in which the skin-effect losses produce an attenuation whose magnitude in dB varies as the square-root of frequency have been approximated by:

$$(1)\ E_o = E_i\left[1 - erf\left(\frac{1.018x10^{-8} \times A \times l}{\sqrt{t}}\right)\right]$$

where A is the cable attenuation in dB/100 ft. at 1000 MHz, l is the cable length in ft., t is the time in sec., and erf is the error function. The step response of a coaxial cable used as a PFL can then be derived to be:

$$(2)\ E_o = E_{PFL}\left[1 - erf\left(1.018x10^{-8} \times V_p \times A\sqrt{t}\right)\right] \quad 0 \le t \le T_{PFL}$$

We can, therefore, combine these to approximate the transient performance of this system by the expression:

$$(3)\ E_o = E_{PFL}\left[1 - erf\left(1.018x10^{-8} \times V_p \times A\sqrt{t}\right)\right] \times \left[1 - erf\left(\frac{1.018x10^{-8} \times A \times l}{\sqrt{t}}\right)\right] \quad 0 \le t \le T_{PFL}$$

where l is the length of the cable between the magnet and the pulser. At the end of the pulse, the response is described by equation (3) with l equal to twice the physical length of the PFL plus the cable length between pulser and magnet.