

A FAST INJECTION KICKER MAGNET FOR THE TEVATRON

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Abstract

A new proton injection kicker system is required for the Tevatron in the Run II era. The new system was designed to supply 1.25 kG-m into a magnetic aperture of 48 mm vertical x 71 mm horizontal x 5 m long with a 396 ns bunch spacing. The system was designed to be upgraded to 132 ns bunch spacing with additional pulse supplies. The design of the magnet incorporated some novel features in order to meet these requirements. These include adjustable bus spacing to set the inductance and balanced positive and negative high voltage buses. This system has been installed in the Tevatron.

1 INTRODUCTION

The Tevatron for Run II requires 36 proton x 36 pbar bunch stores with a 376 ns rise time and a 2.6 us fall time. The pbar injection kicker was successfully upgraded in 1995, but the proton injection kicker was only satisfactory for injection with an 770 ns rise time. To allow for even higher luminosity, it was decided to build the proton injection kicker with the capability of 132 ns bunch spacing (112 ns rise time). This was done by installing five magnets in the beam line; fewer could have been used to meet to initial rise time requirements. These shorter magnets are now powered as two systems, with two in series and three in series. When the shorter bunch spacing is needed, additional power supplies will be added and all the magnets will be individual powered. The power supplies and system are discussed in a companion paper

2 MAGNET DESIGN

The magnet design posed several mechanical and electrical issues. There is not much room in the Tevatron beam line and therefore the magnets had to be relatively small. There are obstructions 10" above and below the Tevatron beam line center. Design impedances of 16.7 Ohms and 12.5 Ohms and balanced and unbalanced drivers were simulated using Spice. The impedance chosen for the best system performance was 12.5 Ohms with a balanced positive and negative pulsers driving 20 kV into matched loads.

First, to optimise the performance, a new ceramic vacuum chamber was designed. The minimum clear aperture for the Tevatron in colliding mode was determined by the machine physicists. Eleven new rounded rectangular ceramic tube were then manufactured and the best six selected for use. Some elements on the final magnet design were determined by the as delivered beam tube, but design work continued.

The second design issues were the capacitors used to accomplish the impedance and segmentation. The value required, 160 pF per cell per side, could have been accomplished in two ways. Two capacitors of 160 pF and at least 40 kV could be used in parallel or four capacitors

of 80 pF and at least 20 kV could be used two in series and two of those in parallel. Either option would require some capacitor development, in either a higher voltage or lower capacitance. The second option was preferred because there seemed less risk in a ceramic formulation that reduced capacitance than one that increased voltage gradient. A parallel plate capacitor was also considered, however the size was not small, the design would be hard to execute and the cost would be relatively expensive compared to commercial ceramic capacitors.

Because of the variability in the nominal capacitor value, the inductance per unit length in the magnet also had to have some adjustment range. This was accomplished by adjusting both bus bars to tight tolerances, ± 0.01 inches. This feature also allowed for the compensation of stray capacitances which would otherwise change the impedance of the magnet. The adjustment range was very useful during the tuning of the magnet impedance. Finally, a small parasitic inductance for the capacitors was also required. This meant the ferrite needed to have a copper foil along the sides and have cross coupling between adjacent ferrites [1], [2].

2.1 Magnet Capacitors

The relative tolerance on high voltage ceramic capacitors is an industry standard of $\pm 10\%$. For the pbar injection kicker [1], attempts were made to build a long lifetime parallel plate capacitor. When those attempts failed, several batches of capacitors were purchased from the manufacturer. These were then measured and sorted in sets of 4 to make the required total capacitance. It was noted at that time that while from batch to batch the capacitance could vary significantly, within a single batch the tolerances were very tight ($\pm 1\%$). For this project, the sorting method could not be effectively used for two reasons. First, the capacitance per section is so small that it was less than the standard values. Second, the capacitors in this magnet are used in series between the high voltage buses; there is no common connection. The lack of a common connection is purposeful. Because this is a balanced driven system, when one of the thyratrons pre-fires it drives a common mode and differential mode voltage on the high voltage buses. This results in $\sim 75\%$ of the open circuit voltage occurring on one bus and $\sim 25\%$ on the other. The result is the same voltage in either nominal or fault conditions when there is not a capacitor connection to common. With the connection a 50% over voltage would occur in the fault case. This also means the capacitance of each side has to be closely matched to avoid exciting the common mode of the magnet and introducing reflections and coupling between the modes.

We purchased 100 capacitors with a nominal values of 80 pF and 30 kV from three manufacturers [3],[4],[5] to

determine if they would meet the lifetime requirements. Each manufacturer was within the allowed $\pm 10\%$ nominal value. Tolerances over each build were less than $\pm 0.75\%$. These capacitors were placed in a prototype magnet and pulsed at 25 kV for 10^6 pulses, longer than the lifetime of the system. All succeeded and we then purchased 1000 capacitors from the vendor with the most timely delivery. These final capacitors were then measured at 1V and 1 kHz and sorted into 1 pF bins. The average value was used to set the nominal spacing for the bus bars. The capacitors were installed in the magnet using capacitors from the same 1 pF bin in series and using a set of capacitors from another 1 pF bin in parallel with those.

A special end value of capacitance is also used. The value was empirically determined to be about twice the standard cell capacitance. While the exact value of the end capacitor for optimum performance is not known, measurements and simulations of the magnet clearly showed an improvement in the 1%-99% field rise time when the end capacitor is 150-200% on the main value.

2.2 Magnet Inductance Design

The setting tolerance on the inductance is $\pm 1\%$, however a tuning range of approximately 5% is also required because of the range in average capacitance. As a result of our prototype testing we knew the approximate values of the stray capacitance and therefore the required inductance of our design.

Given this inductance, a cross section of the magnet was modelled using Opera-2D [6]. An AC simulation at 1 MHz was done of half the magnet and the stored energy was calculated both in the gap and in the rest of the magnet. The same model was then done with the relative permeability of the ferrite set to 1. The energy stored in the magnet, except the region of the air gap, was then calculated for this air filled magnet. The total inductance per cell was then calculated by multiplying the stored energy of the gap by the cell length (ferrite length plus gap between adjacent ferrite) and adding the stored energy of the rest of the magnet when modelled as ferrite time the length of the ferrite plus the stored energy of the rest of the magnet when modelled as air times the length of the gap between ferrites. These numbers were compared with measurements and found to be accurate to $\sim 2\%$, which is about the same accuracy as the simulation.

The simulations also showed that our initial ferrite pole piece design required modification. Since essentially all the flux in the gap (the length of a cell) returns through the ferrite, the flux density in the ferrite is higher than the simulation by the inverse of the packing factor, 0.83 for this design.

2.3 Other Design Issues

One of the hardest problems related to fast kicker systems is measuring the performance. While the final measurement is done with the beam, it is imprudent to rely on this as the system has then been installed and is

difficult to change. One of the early modifications we made to the magnet was suggested by John Dinkel (retired Fermilab). We put in a capacitive pickup directly around the input high voltage lead. This pickup is quite fast and accurate. We used this pickup to measure the magnet input and output voltage and from those calculate the integrated field. Without these pickups, the compact nature of the magnet made any high voltage measurements impossible.

The final magnet cross section is shown in Figure 1. This view shows only half of the magnet. The full magnet is symmetrical about the beam line center.

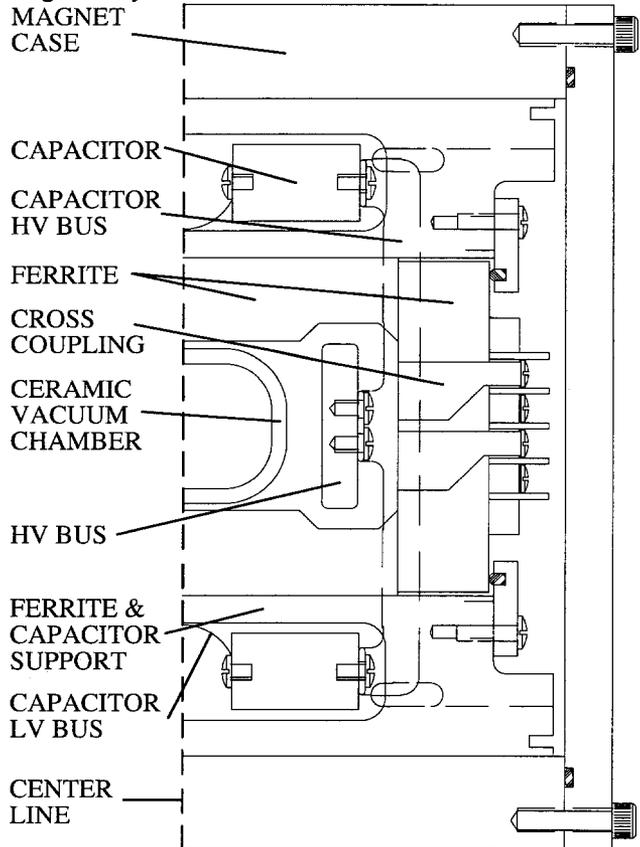


Figure 1.
Cross Section of Half of Magnet

3 MEASUREMENTS

After each magnet was assembled it went through a series of measurements. First the capacitance and inductance of the magnet were measured in a series of steps. These measurements were then fit to a model of the magnet and the inductance and capacitance per section of magnet were calculated. The capacitance was measured with air dielectric and a Fluorinert FC-40 as a dielectric ($\epsilon_r=1.9$) The distance between the high voltage bus bars was also measured. Given the fit to calculation of both the air and Fluorinert data, we then readjusted the spacing on the bus bar to get the required impedance ($\pm 1/2 \%$). It was important to do these measurements at the same temperature as the beam line enclosure as the capacitors have a significant temperature coefficient ($\sim -0.4\% / C$).

We adjusted the spacing to achieve an impedance of 12.45 Ohms as this gives a slight initial overshoot and results in a several ns reduction in the field rise time. Table I shows the measured parameters for all 5 installed magnets and Figure 2 shows the magnet equivalent circuit.

Our last measurements were the input and output voltage measurements. We used the capacitive dividers to measure the input and output voltage with a Lecroy LC584 oscilloscope. Then using a spreadsheet, we subtracting the input from the output voltage and numerically integrated over the pulse. This was done for a single magnet (for the 113 ns rise time requirement) and for the two and three magnet systems (for the 372 ns rise time). The two magnet and three magnet system have load resistors of 12.55 and 12.62 Ohms respectively and the difference in response can be seen.

We clearly have met our all the specifications and the system has been running in the Tevatron for since July of 2000. We anticipate installing the additional pulse supplies in a couple years when Run IIB of the Tevatron should start.

Table I. Measured Values of All Magnets

Magnet	C/section (CCELL)	C/section (CSTRAY)	L/section (LCELL)	Spacing
1	160.3 pF	14.5 pF	28.1 nH	2.905"
2	159.8 pF	14.3 pF	27.9 nH	2.909"
3	160.7 pF	13.8 pF	28.1 nH	2.908"
4	160.8 pF	13.9 pF	28.1 nH	2.931"
5	162.0 pF	12.0 pF	27.9 nH	2.904"

4 REFERENCES

- [1] J. Dinkel, et. al., "Development of a High Quality Kicker Magnet System", PAC 1993, Washington May 1993, pp1357-1359
- [2] G. Nassibian, "Traveling Wave Kicker Magnets with Sharp Rise and Less Overshoot", CERN
- [3] Murate Electronics Products, Smyrna GA 30080
- [4] High Energy Capacitor, Parkesburg PA 19365

[5] Ceramite, Grafton WI, 53024

[6] Opera-2D, Version 1.5, Vector Fields, Aurora IL 60505

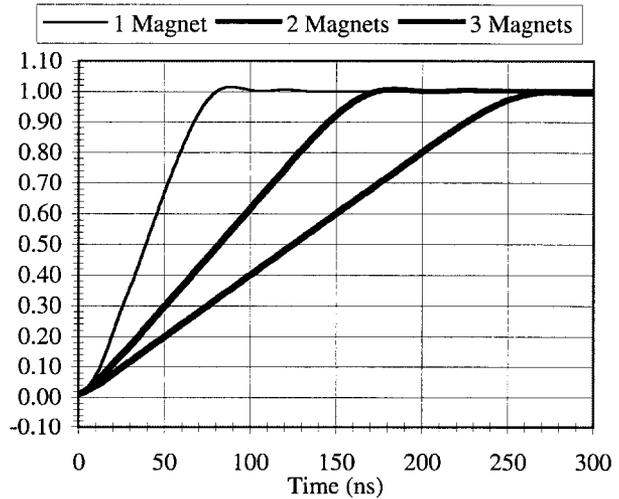


Figure 3, Normalised Integrated Field vs. Time, Zero Time is set to 1% of Flattop

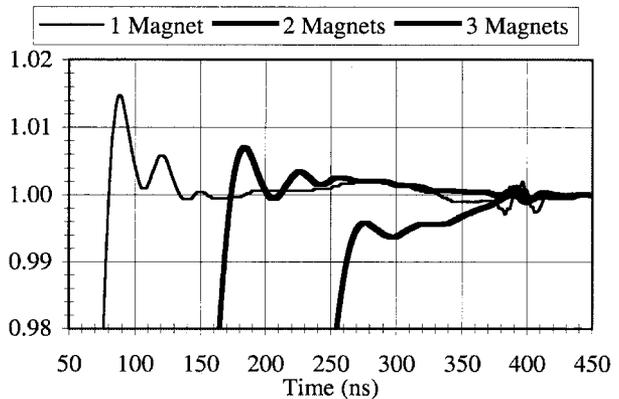


Figure 4, Normalised Integrated Field vs. Time, Expanded Vertical Scale, Zero Time is set to 1% of Flattop

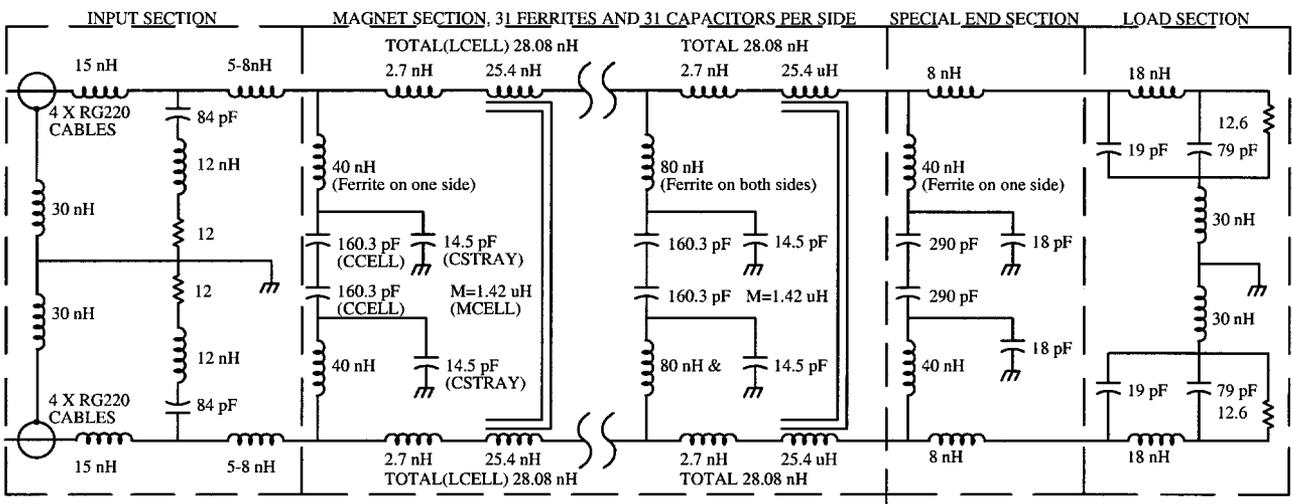


Figure 2, Equivalent Circuit of Magnet, All parameters are based on experimental measurements