

A FAST INJECTION KICKER SYSTEM FOR THE TEVATRON

C. Jensen, R. Reilly, B. Hanna, Fermilab*, Batavia IL USA 60510

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 system design tradeoffs needed to meet these goals will be discussed. These include the system topology, the system impedance and the number of magnets. 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 396 ns bunch spacing. The protons are injected as 4 bunches during a 1.25 μ s flattop, with a 375 ns rise time. This is done 9 times with a gap of 2.6 μ s left at the end for the abort kicker rise time. The pbar injection kicker was successfully upgraded in 1995 to perform the above injections for pbars. 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 lattice; 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.

2 SYSTEM DESIGN

Once the physics specifications had been set for kick strength and aperture, several different power supply and magnet configurations were investigated. The three parameters that needed to be defined were the topology of the system, the impedance of the system and the number of magnets in the Tevatron lattice.

The most common way to operate a kicker system is with a single pulse supply and an unbalanced magnet. In that case, the magnetic material is C shaped and one of the magnet conductors connects to the pulse supply common and magnet case. In a balanced kicker system there are two pulse supplies and a balanced magnet. Each conductor of the magnet is connected to a pulse supply and the commons of the pulse supplies are connected to the magnet case. The magnetic material completely surrounds both conductors; the air gap is between the conductors. In this way each pulse supply provides energy to fill half of the air gap with magnetic field. The magnet fill time can be reduced by 50% over an unbalanced system of the same impedance [1] if both supplies are connected at the same end and two load resistors are connected at the other.

Essentially, twice the peak power is supplied to fill the air gap with magnetic energy. This balanced system was also used for the pbar injection kicker upgrade in 1995 [2].

There were constraints on the impedance of the system. First, the impedance needed to be a sub-multiple of our standard 50 Ω high voltage cable, Times [3] #AA-5966. This cable would be used in 182 m lengths for the pulse forming line and 39 m lengths to connect the pulse supply to the magnet. Second, for long lifetime, the AA-5966 cable and the Isolation Design connectors have a maximum voltage of \sim 65 kV. Finally, the thyatron enclosure parasitics and thyatron turn on characteristics have an impact on performance through the choice of impedance. In the simple approximation that the thyatron has a practically instantaneous turn on and is simply an equivalent series inductance, then clearly, a higher system impedance gives a faster rise time. However, this approximation is very poor with fast rise times.

Given these parameters and constraints, 16.7 Ω and 12.5 Ω systems were investigated further. While the 16.7 Ω system assumed a single (unbalanced) pulsed supply, the 12.5 Ω system assumed two (balanced) positive and negative pulse supplies because of the longer magnet fill time. SPICE was used to model simplistic systems to determine magnetic field rise time. In addition, the length of individual magnets was varied from 1 m to 1.6 m; this varied the number of magnets from three to five. A balanced system with an impedance of 12.5 Ω and a magnet length of 1 m was required to meet the rise time specification of 113 ns. A peak current of 1600 A and a charging voltage of 40 kV were required to get the kick strength.

Although the system impedance and topology were determined, there was considerable uncertainty in achieving the power supply and magnet performance. The thyatron and enclosure required a maximum rise time of 42 ns (1% - 99%). The magnet required a 70 ns fill time with low dispersion. Significant money and effort were spent to build prototypes starting three years before operation was required. Since the magnet is covered in a companion paper [4], the remainder of this paper will focus on the power supply.

2.1 Thyatron Enclosure Design

The first decision was the kind of switch. The repetition rate is 36 shots spaced approximately 4 seconds apart once every 8 hours for 36 x 36 operation. Many more shots will be used during tune up. So, this system was designed for a 10 year lifetime of 10^5 shots. In the pbar kicker system, spark gaps were used as switches. However, the proton system requires 10 times the lifetime and only half the current of the pbar system, so a thyatron was chosen.

Fermilab is operated by University Research Association Inc. under Contract No. DE-AC02-76CH03000

We had a thyatron enclosure from the MI project so we made some modifications and performed several tests. The CX1268 thyatron was recommended by Marconi Applied Technology (née EEV) [5]. This is a two gap thyatron, without a drift space, rated at 45 kV and 10 kA with a grid structure that allows for heavy pulse triggering. The original housing was for a 25 Ω system using a CX1668 [6]. This provided us with an opportunity to learn of the limiting performance of this housing. It was modified so that it could take the shorter CX1268 and run with either 4 x 50 Ω cables (12.5 Ω) or 2 x 50 Ω cables (25 Ω). The cables were connected to the anode and charged with a DC supply. The output cables connected the cathode through 15 m of cable to the loads. We used two spare 25 Ω loads which have ~ 60 nH of series inductance, ~ 50 pF of parallel capacitance and a built in current viewing resistor (CVR). Measurements were made on the CX1268 in a 25 Ω system and then the impedance was changed to 12.5 Ω. The reservoir was kept constant to eliminate that variable. The only change was the number of cables to and from the pulser. The same CVR and load were used for measuring the output current in both cases.

It was somewhat surprising that there was no substantial change in current rise time when the impedance was changed, 17±1 ns (10%-90%). The measurements showed little change when done at the same peak current or the same charge voltage. EEV later found a similar result [5] using a CX1268 in a 16.7 Ω system but with a different housing and with saturating ferrite cores.

There are many possible explanations for our results. The thyatron ionizing grid in our case has a small DC current instead of a large pulse current. The stray capacitance of the thyatron cathode to ground might have been the limiting factor. The thyatron was not di/dt limited as doubling the voltage doubled the di/dt, but did not change the rise time. The conclusion of EEV on their data was that the current rise time was limited by the housing inductance. However, the thyatron and housing do not seem series inductance limited in our case. If that were the case, the rise time should have changed substantially with an impedance change and it did not.

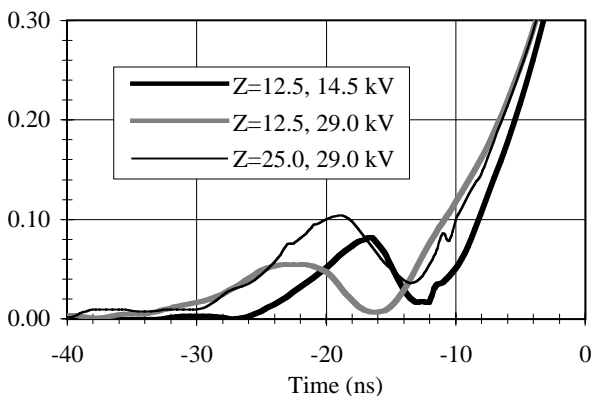


Figure 1, Current Measured in Original Housing
Zero Time Is Set to 50% of Flattop.

One thing that did change with impedance was the amplitude of the pre-pulse, Figure 1. It was a lower percentage in the lower impedance systems when either the charging voltage or the peak current was held constant. The pre-pulse amplitude was 10% for the 25 Ω system compared to 8% for the 12.5 Ω system. This reduction of pre-pulse was also one of the reasons for going with a non drift space thyatron. From these test results, we decided to reduce the cathode housing capacitance, reduce the series inductance and build in the possibility for triggering both grids to reduce the rise time.

To reduce cathode capacitance and series inductance, the design was changed from a coaxial housing to a re-entrant housing. The cathode enclosure to case distance was increased by 50% over the original housing distance even though the peak voltage was reduced from 65 kV to 45 kV. The thyatron was fitted with a 5" diameter current return shield, 80% of the original housing diameter. In this way the current path from the anode through the thyatron to the cathode and back through the return shield had a minimal inductance while maintaining the reduced cathode capacitance. Electric field simulations of the thyatron in the return shield were also done to determine the closest spacing.

The cathode capacitance was then measured to be ~ 140 pF in air (~ 265 pF in Fluorinert FC-40). The equivalent inductance of the thyatron during conduction was measured by using a 2" diameter conductor in place of the thyatron. The total inductance was measured to be ~ 80 nH, of which 30 nH is estimated to be from the input and output connectors. The inductance is now ~30% of the original housing and the capacitance is now ~70% of the original housing. A section through the enclosure is shown in Figure 2.

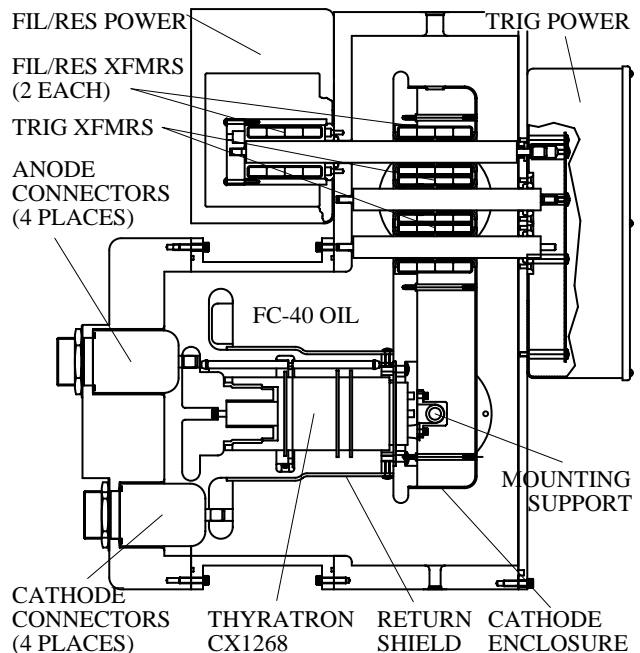


Figure 2, Thyatron and Final Enclosure

Test results in the new housing using the same set up as the original housing gave about the same rise time. The pre-pulse in the new enclosure is now smaller than before and it is closer to the main pulse. The change in position of the pre-pulse is probably due to the increase in the reservoir voltage made possible by resonant charging.

2.2 Resonant Charging Supply Design

A resonant charging scheme was adapted for two reasons. First, it allows the reservoir to be raised on the thyatron to achieve a faster rise time while maintaining a given pre-fire rate. Second, it could be used to achieve voltage balance on the positive and negative pulse forming lines by using a transformer and a single supply. This system operates with a complete discharge; all the energy in the low voltage storage capacitor is transferred to the pulse forming lines.

The resonant charging system consists of a standard 5 kV capacitor charging supply, a 20 uF, 5kV storage capacitor, a primary side switch, a dual secondary step-up transformer, output diodes and output snubbers. The primary switch is two Mitel (GEC) DGR820 6 kV phase control thyristors in series with a DF654 3 kV fast diode. This gives adequate voltage margin at 5 kV and provides for fast turn off. The use of a lower charging supply voltage and a single thyristor was considered. There are twelve of the 5 kV supplies in use at Fermilab, so another power supply type was operationally undesirable.

A charging time of 300 us was chosen to allow the pulse forming line to settle to less than 1% of the final value before the thyatron fires. The turns ratio was chosen early on as 1:12:12. This gave the flexibility to operate up to 60 kV if the design had changed. Given the turn ratio, the charging time and the pulse forming line total capacitance, the leakage inductance of the transformer was determined. The tank was specified to have all of the secondary diodes, secondary snubber, fault terminations and output monitors in the same oil as the transformer. The pulse forming cables plug directly into Isolation Design [7] D-1023 sockets on the top of the tank and the resonant supply is also mounted directly on top of the tank. This makes a very compact package that can be easily exchanged when required.

The charging transformer and tank were designed by Stangenes Industries. The transformer was required to have a balanced turns ratio, secondary 1 to secondary 2, with at most a 0.5% difference. All the units had a measured difference between secondary 1 and secondary 2 of less than 0.1% and performed well.

3 PERFORMANCE

One of the hard parts of this project was measuring the performance of the system. We relied on custom, built in capacitive pickups in the magnet [4]. The response of the installed systems, shown in Figure 3, was calculated using a spreadsheet and the measured magnet input and output voltages.

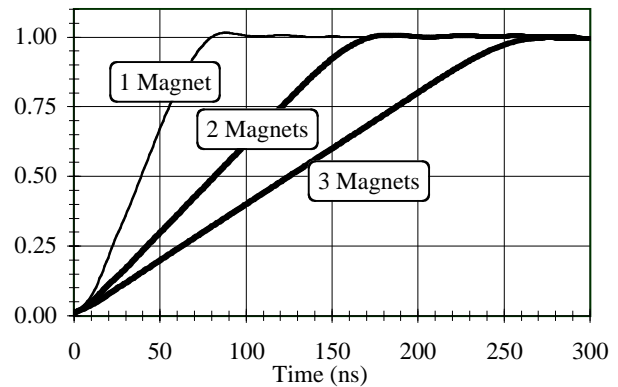


Figure 3, Measured Rise Time
Zero Time Is Set To 1% of Flattop

The initial design for the magnets called for them to be potted in silicon rubber. However, the installation schedule was very tight and the system performance was somewhat uncertain. There exist several kicker magnets in the Main Injector that have a fluorinated oil from 3M as a dielectric. This dielectric has a boiling point below water and can therefore be easily baked out of a vacuum system. We installed the magnets in the Tevatron and then filled them with Fluorinert FC-40. The performance was then measured with beam and found to be good. If performance had been poor, we could have modified the magnets in place and continued with a limited interruption in commissioning.

The plan is to drain the FC-40 and pot the magnets as soon as there is adequate down time. This has now become even more pressing as beam losses have been found to break down small amounts of FC-40 into caustic and toxic compounds. A special filter material from 3M has been installed to break down these compounds until we can proceed with the potting. The system has been operational in the Tevatron since July 2000.

4 ACKNOWLEDGEMENTS

Thanks to George Krafczyk and Darren Qunell for many useful discussions and to Dirong Chen and Clifford Foster for their excellent assembly work.

5 REFERENCES

- [1] Lou Reginado, LLNL, Private communications
- [2] J. Dinkel, et. al., "Development of a High Quality Kicker Magnet System", PAC 1993, Washington May 1993, pp1357-1359
- [3] Times Microwave Systems, Wallingford CT 06492
- [4] C. Jensen, B. Hanna, R. Reilly, "A Fast Injection Kicker Magnet for the Tevatron", PAC 2001, Chicago June 2001
- [5] Ron Sheldrake, Paul Robinson, Marconi Applied Technology, Private communications
- [6] D. Qunell, C. Jensen, D. Tinsley, "Kicker System for 8 GeV Protons", PAC 1997, Vancouver, June 1997, pp1287-1289
- [7] Isolation Design, Sunnyvale CA