PROGRESS WITH ELECTRON BEAM SYSTEM FOR THE TEVATRON ELECTRON LENSES*

V. Kamerdzhiev[#], G. Kuznetsov, G. Saewert, V. Shiltsev, FNAL, Batavia, IL 60510, USA

Abstract

The Tevatron Electron Lenses (TELs) were installed to mitigate the effects of electromagnetic long-range and head-on interactions of high intensity proton and antiproton beams. These phenomena account for significant beam loss and lifetime limitations in the Tevatron Collider operation. The electron guns and their drivers are key components of the TELs. They define the possible modes of operation and overall performance of the TELs. We report on the recent development of the electron guns and the gun driver for the Tevatron Electron Lenses.

INTRODUCTION

Electron lenses were proposed for compensation of both long-range and head-on beam-beam effects in the Tevatron collider [1]. The lens employs a low energy $\beta_e=v/c <<1$ electron beam whose space charge forces act on the high-energy hadron beam. These forces are linear at distances smaller than the characteristic beam radius $r < a_e$ but scale as $1/r$ for $r > a_e$. Correspondingly, such a lens can be used for linear and nonlinear beam-beam compensation depending on the beam-size ratio a_e/σ and the current density distribution $j_e(r)$.

To keep the electron beam straight and its distribution unaffected by its own space-charge and the EM fields of the circulating beam, the electron beam is immersed in a strong magnetic field. The conventional solenoids generate up to 4.5 kG in the electron gun and collector regions, while the superconducting (SC) main solenoid generates up to 65 kG in the interaction region.

The electron beam acts on high-energy beams only through EM forces. The electron guns can be optimized to generate the electron beam with a specific shape of the transverse charge density distribution. Furthermore, the electron gun driver (HV modulator) needs to be capable of varying the peak electron current on the bunch-to-bunch basis. This will equalize the bunch-to-bunch differences and optimize the performance of all of the bunches in multi-bunch colliders. The modulator must meet the following requirements: 1) have an output peak voltage of at least 5 kV, 2) have a programmable waveform providing an individual voltage for each of 12 (anti)proton bunches spaced 396 ns apart that would be repeated three times for each of the three bunch trains on every Tevatron revolution.

ELECTRON GUNS

Both TELs are now equipped with SEFT electron guns for optimal long-range compensation [1]. An electron gun with a Gaussian like profile, designed for head-on compensation, was successfully tested on the test bench. We also built and tested a prototype of the grid-controlled e-gun.

Gaussian electron gun

Fig. 1 shows the transverse electron beam profile generated with the Gaussian electron gun. The profile and microperveance (1.2) measured on the test bench agree very well with the ones predicted by numeric simulation performed using UltraSam code. We plan to use this gun for head-on compensation studies relevant for LHC beam-beam compensation [2].

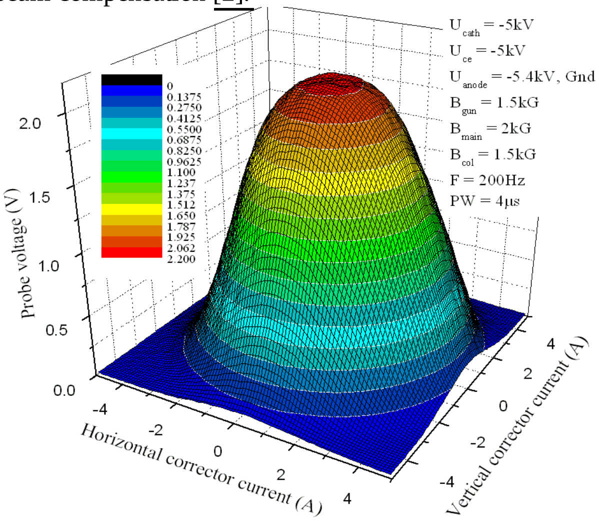

Figure 1: Transverse charge density distribution measured on the test bench. Gaussian electron gun.

Grid controlled gun

Since the e-gun driver performance is the major limiting factor for the TEL operation we looked at the possibility to use an electron gun controlled by a grid. This approach represents a tradeoff between the driver output voltage and e-beam profile quality. If successful the driver output voltage can be lowered to a few hundred volts making its design much less challenging. The grid in the first prototype consists of eight wires shaped with a spherical radius of 11.5 mm to match the convex cathode having 10.8 mm radius. The results of the test bench measurements are shown in Fig. 2. The e-gun generated 2.3 A of peak electron current at 200 V on the grid with respect to the cathode. Although the gun is capable of generating significant electron current at low grid voltage the e-beam profile features the expected wire shadows and additional non-uniformity. The wire shadows are expected to average out as the e-beam rotates inside the main solenoid. Numerical simulations need to be performed to

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[#]vsevolod@fnal.gov

study the effect of the e-beam profile on proton beam lifetime prior to using this e-gun for beam-beam compensation

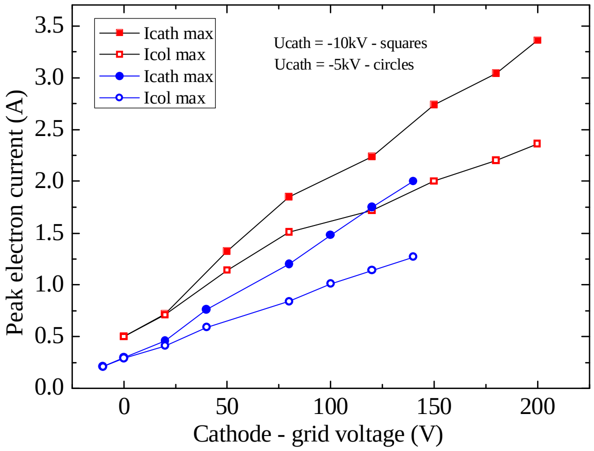

Figure 2: Measured volt-ampere curve of the grid controlled electron gun.

THE MARX GENERATOR

The solid state Marx generator, currently employed in TEL2, was built by Stangenes Industries [3]. The pulse rise time is adequate and the pulse-to-pulse amplitude is stable. Switching losses in the IGBTs limit the output voltage to 5 kV at the nominal rep rate of 50 kHz [4].

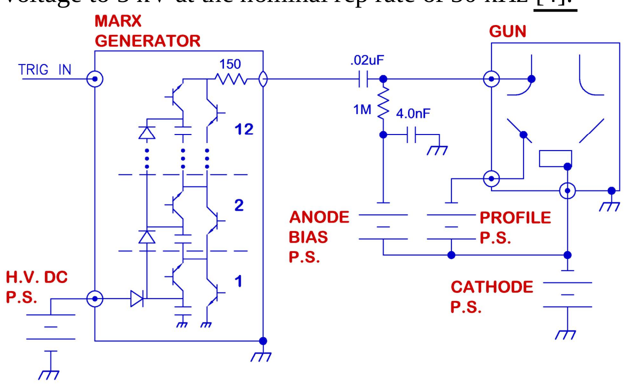

Figure 3: Electron gun driving scheme using the Marx generator.

The Marx generator allowed for single bunch beam-beam compensation in the Tevatron. However, this particular version does not have the potential to become operational e-gun driver for beam-beam compensation of more than two bunches.

STACKED TRANSFORMER MODULATOR

Generator Design Concept

The basic design of the modulator shown in Fig. 4 is a “stack” of 5 pulse transformers connected such that the primary windings are driven independently at ground level, and the secondary windings are connected in series. The primary drive circuit is an H-bridge that connects the input DC voltage across the primary either positively, negatively or with zero volts. The capacitor in series with the primary automatically averages the primary voltage to zero regardless of the waveform duty factor.

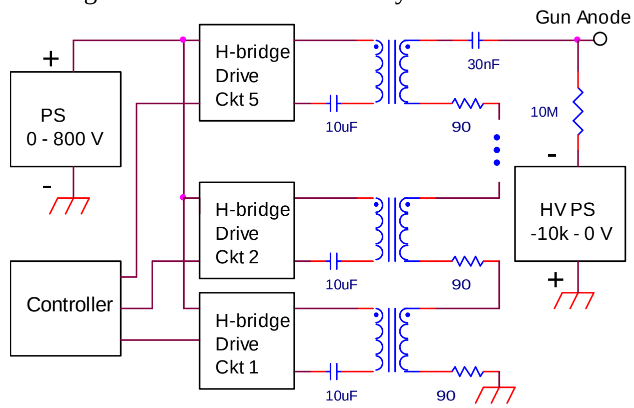

Figure 4: Modulator circuit topology.

The modulator output voltage at any given time is the sum of voltages from the five secondaries. The result over one 12-bunch cycle is a bipolar waveform that is AC coupled to the anode, see Fig. 5. A DC offsetting voltage is summed with this AC signal at the anode with a DC value such that the most negative swing of the AC waveform just cuts off the electron emission in the gun. The most positive value of the AC waveform is that required for the most tune shift.

Design Considerations

The output load of this modulator is a 60 pF electrode capacitance. The fundamental problem for this application is dealing with parasitics both inductance and capacitance. Parasitic inductance in series with the output limits bandwidth and degrades the waveform. Parasitic capacitance degrades the waveform as well, and it must be charged and discharged with every pulse. The resulting dissipated power in the resistance in series with parasitic capacitance is a major design issue at these voltages and switching speeds. Stacking pulse transformers for this application has the appeal that (1) they can deliver high duty factor waveforms, and (2) circuitry and total component surface area driven at high rates to elevated voltages is minimized which also minimizes power loss.

Transformer parasitics accumulate quickly with each additional transformer. Therefore, the transformer was sized to minimize parasitics, not for high power handling. Ceramic Magnetics, Inc., core material MN8CX was chosen for its low loss in the 1 MHz range and reasonably high permeability. Electrical tests verified predictability of pulse transformer modeling. Numerous iterations were done at the design level using various core geometries and transformer winding combinations. It was estimated the use of five transformers could comfortably meet the design requirements. Inserting resistors of the proper value between each secondary winding very effectively dampens and shapes the output waveform.

The transformers are wound on Nomex 418 insulation in air and are wound slightly differently from each other. Transformers beginning with #1 have progressively thicker insulation between primary and secondary in consideration of dielectric strength required for windings that are close to the output. Transformers #1-3 are wound 1:1, while #4 and #5 are wound 2:1.

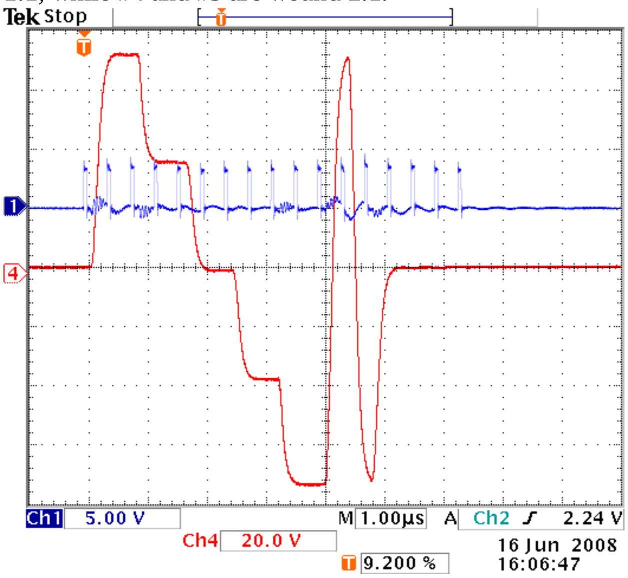

Figure 5: The output waveform of the stacked transformer modulator.

The two transformers at the highest output voltage level have very low parasitic capacitance and provide higher settable resolution of the output voltage, since their voltage contribution is half of the others. The slope (dA/dV) of the e-gun's Volt-Ampere curve is twice at 5 kV as it is at 1 kV, so having this added resolution is more beneficial at higher electron current.

Performance

Fig. 5 shows the modulator performance with only drivers for transformers #1 and #2 operational so far. Transformers #3, #4 and #5 are installed with their primaries shorted and grounded in order to impose their parasitics on the circuit and contribute 0 V. Temporary resistors are installed between secondaries. The output is a dummy load of 100 pF.

Fig. 5 shows the modulator driven over one waveform cycle delivering 3200 V peak-to-peak with 800 V incremental values. Channel 1 displays 16 timing triggers of which the first 12 correspond to the eventual 12 (anti)proton bunches. Channel 4 is the output voltage monitored at 20:1, but with a -7.5% scale factor error. The primary input DC voltage is at maximum, 800 VDC. Initiated by the first timing trigger both #1 and #2 are driven on positively, and the output goes to +1600 V; after 792 ns #2 is driven to 0 V, and the output drops to 800 V; and so on. At the 11^{th} trigger the output is driven from -1600 V to +1600 V for 396 ns; at the 12^{th} back to -1600 V for 396 ns and finally to 0 V. Demonstrated is worst case performance when multiple transformers are driven on simultaneously. The measured flat top voltages 320 ns after switching on simultaneously have a slope of 1V/ns for 80 ns after triggers 11 and 12.

Hardware assembly

Fig. 6 shows a picture of the 27"Wx19"Dx20"H enclosure partially assembled. It is designed to control the flow of air to cool upwards of 1.8 kW of dissipated power distributed between H-bridge FETs, transformer cores and the secondary side resistors.

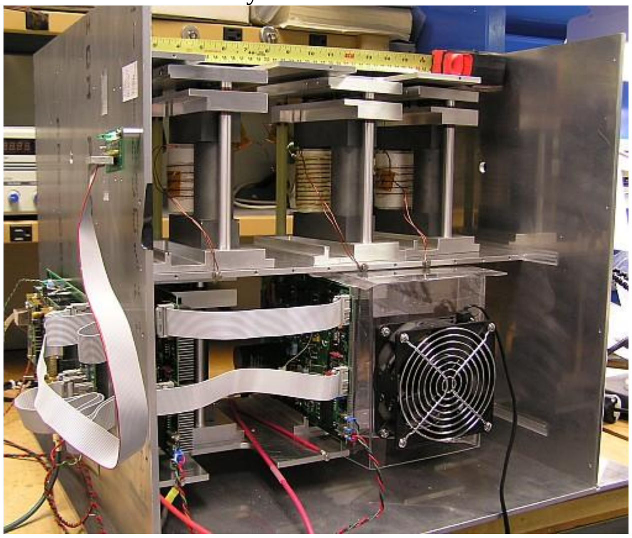

Figure 6: Photo of the stacked transformer modulator.

SUMMARY

The Gaussian electron gun has been successfully tested and is ready for installation. The grid controlled gun showed promising performance, however the effects of the non-uniform e-beam profile on proton lifetime need to be studied before installation. The Marx generator is available for single bunch beam-beam compensation studies. Construction of the stacked transformer modulator is close to completion. Sufficient testing has been done to demonstrate the design concept works and the critical components perform within anticipated limits. This modulator will make 36 bunch beam-beam compensation possible in the Tevatron.

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