TEVATRON ELECTRON LENS UPGRADE*

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Abstract

A novel high voltage modulator had been under development for 1.5 years. It was completed, tested on the bench and became a part of the TEL2 system in October 2008. The modulator is used to drive the electron gun anode. We provide technical details on the Stacked Transformer Modulator analyze its performance and discuss the design challenges. The results of the beam studies made possible by the new high voltage modulator are reported.

INTRODUCTION

Electron lenses were installed in the Tevatron for compensation of both long-range and head-on beam-beam effects occurring during the collider operation [1]. The lens employs a low energy β_e=v/c <<1 electron beam, generated by a thermionic gun. The space charge forces of the electron beam 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, an electron 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 $j_e(r)$ [2]. 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 by means of EM forces. The electron guns can be optimized to generate an electron beam with a specific shape of the transverse charge density distribution. The long range beam-beam effects have to be treated bunch-by-bunch. Therefore, the electron gun driver (HV modulator) needs to be capable of varying the electron current on the bunch-by-bunch basis. This technique allows equalizing the bunch-to-bunch differences and optimizing the performance of all of the bunches in multi-bunch colliders.

The HV modulator practically defines what can or cannot be done using an electron lens. The accumulated experience shows that the modulator is one of the most challenging subsystems to design. The recently installed Stacked Transformer Modulator (STM) had three predecessors: a fast ionisation pulser [3], a tetrode modulator [3] (is being routinely used in TEL1 for abort gap cleaning [4]) and a solid state Marx generator [5], [6] . Every upgrade allowed for an overall better performance of the electron lenses which includes peak electron current, pulse rise and fall times, repetition rates flexibility of waveform adjustment and reliability.

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STACKED TRANSFORMER MODULATOR

The modulator must meet the following requirements: 1) have an output peak voltage of at least 6 kV, 2) have a programmable waveform providing an individual voltage for each of 12 (anti)proton bunches spaced 395 ns apart that would be repeated three times for each of the three bunch trains every Tevatron revolution.

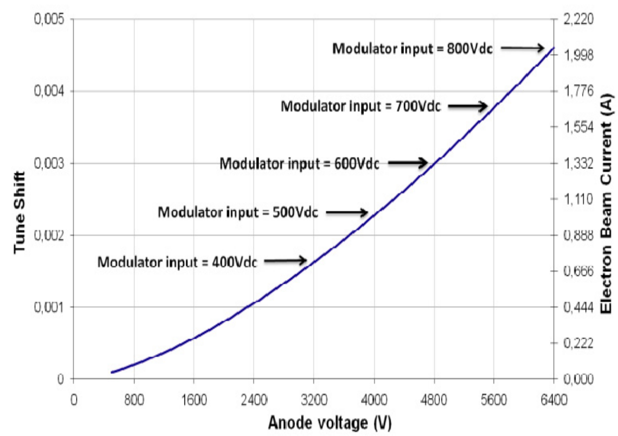

Figure 1: Required anode voltage for a given electron current and tune shift assuming standard TEL2 settings.

The newly commissioned Stacked Transformer Modulator [7] is used to drive the TEL2 electron gun anode (currently of the SEFT type [8]). The new modulator greatly enhances TEL2 capabilities.

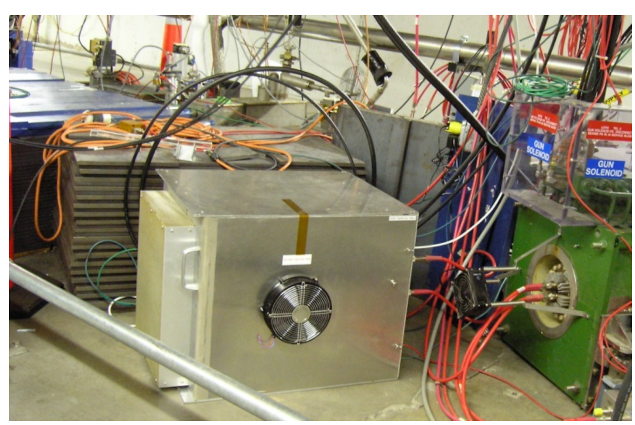

Figure 2: A photograph of the Stacked Transformer Modulator connected to the TEL2 electron gun in the Tevatron tunnel. The green magnet is the TEL2 gun solenoid.

Figure 1 shows the gun anode voltage needed to introduce a certain tune shift. Standard TEL2 settings are assumed [8]. Figure 2 shows the stacked transformer modulator connected to the TEL2 electron gun. Since TEL2 is located very close to the beam dump 6 ft of steel protect the modulator from radiation. As a precaution, the power supply providing power to all the modulator components is turned off by sequencer prior to every store termination. It remains to be seen whether this amount of steel is adequate to protect the electronics. Presently when the protons are dumped at the end of a store and the electronics are not powered down, the CPU in the embedded processor hangs up and needs to be restarted - not simply reset.

The challenge is to deliver a programmable, high duty factor waveform at high enough voltage with sufficiently fast rise time and keep internal power dissipation manageable. Pulse transformers are capable of producing fast enough rise times. Stacking a number of transformer secondary windings in series produces higher voltage. H-bridges drive the primary windings [7].

The STM consisting of 5 transformer modules was designed and built at Fermilab. It was tested on the bench with a load identical in its electrical characteristics to the electron gun anode prior to the installation in the Tevatron tunnel. The flatness of the pulse flat top was found to be better than 3V/ns after a voltage transition of about 5 kV.

The built in digital controller takes care of proper timing including synchronization with the machine RF, provides interface for configuring the HV waveform parameters, reading back of vital device parameters (core and heat sink temperatures, average current in each transformer etc.)

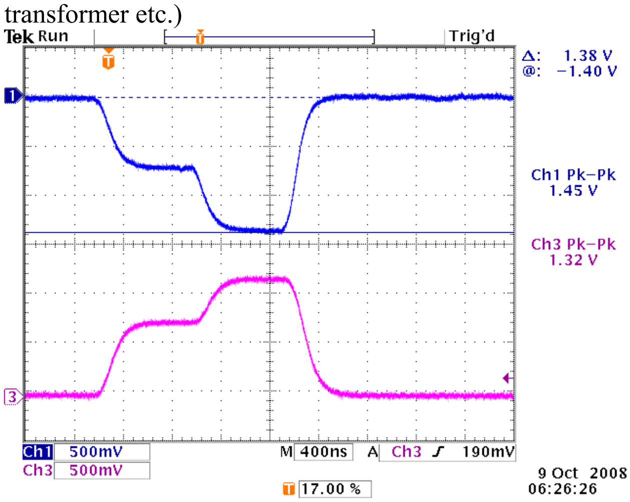

Figure 3: Electron current waveforms at the cathode (Ch1) and the collector (Ch3). Different polarity is due to the current transformer (CT) wiring. The CT calibration is 1 V/A.

The STM is fully integrated into the accelerator controls system and thus all its functions can be controlled remotely. Figure 3 shows sample electron current waveforms recorded at the TEL2 electron gun and collector during STM commissioning. The modulator was programmed to deliver 0.7 A of peak electron current at one flat top and 1.4 A at another. Each flat top is long enough to cover two (anti)proton bunches. The waveform was repeated each Tevatron revolution period.

Figure 4 shows the electron current waveforms intended for single bunch beam-beam compensation. In this case the electron beam was not only measured by the CTs but was also detected by means of a capacitive pickup installed in the TEL2 vacuum chamber.

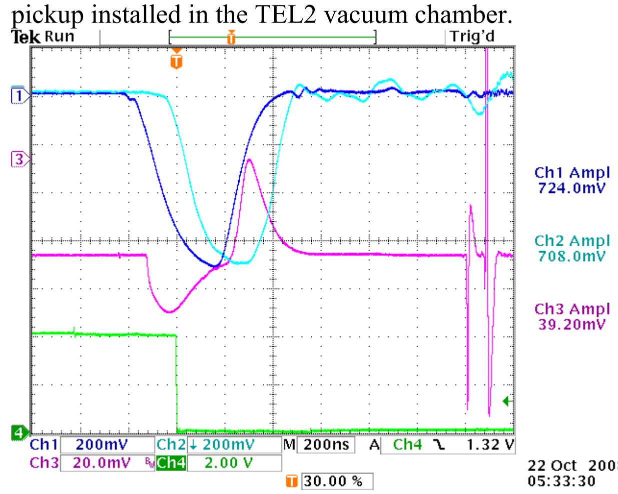

Figure 4: Electron pulse set up for a single bunch tune shift. Ch1 and Ch2 show the electron currents at the cathode and the collector. Ch3 shows the electron pulse, an antiproton bunch and a proton bunch as detected by a capacitive pickup. For clarity the electron pulse is timed to the abort gap and the pickup signal bandwidth is limited to 20 MHz.

Figure 5 serves as an illustration of the STM ability to deliver adjustable voltage and consequently electron current levels. The final voltage levels depend on how many transformers contribute to the output and are discrete by design at any given input voltage, common to all the transformer modules. Sixteen discrete voltage levels are definable between minimum and maximum output. Sixteen levels is the result of employing 5 transformers having two different turns' ratios. The voltage of each level is proportional to the DC input. It was agreed that 16 different levels would provide enough adjustable resolution. The curve of Figure 1 shows that the slope at 5 kV output is twice that at 1kV. Therefore, the resolution is desirable when higher voltages are required. However, in practice the levels are programmed first and then the input voltage is ramped up resulting in controlled electron current ramp seen by individual (anti)proton bunches.

Compensation is defined by entering the descriptions of waveforms of switching patterns for each slot of time for 16 time slots by means of the ACNET controls interface. This means of inputting waveforms as required for compensation is somewhat tedious although flexible. This interface was intended to provide a temporary means of controlling the installed modulator before a more automated process can be developed. The first 12 switching pattern descriptions correspond to those for the 12 bunches in a pulse train.

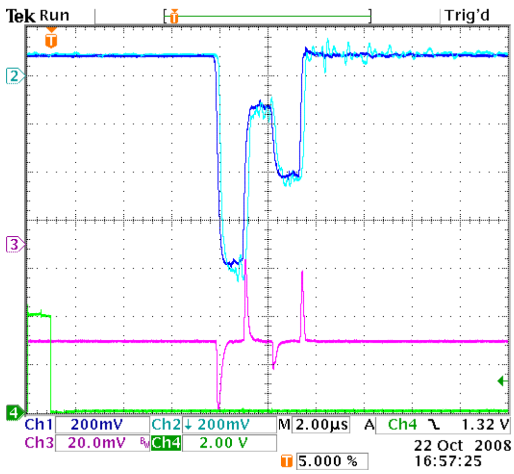

Figure 5: Example of an electron current waveform. Ch1 and Ch2 show the electron currents at the cathode and the collector. Ch3 shows the electron pulse as detected by a capacitive pickup.

(The last four need not have voltage defined at all.) Measurements of bunch-by-bunch tunes reveal that the pattern of required tune shifts among the three trains is very much the same. The 12-bunch compensation waveform can then be chosen to be output for any of the three equally spaced 12-bunch trains of (anti)protons in the Tevatron. This provides the maximum flexibility to influence tunes of the 36 bunches. In other words, the waveform pattern can be applied to only the first, second or third train, any 2 trains in combination, or all three. The STM can handle the resulting repetition rates and duty factors.

Figure 6 depicts the electron current waveforms along with the pickup signal recorded while performing a bunch-by-bunch tune scan during an HEP store [9]. TEL2 was set up to act on proton bunches 2 and 3. This simple procedure allows exploring available tune space without risking high beam losses (positive tune shifts for protons, negative for antiprotons).

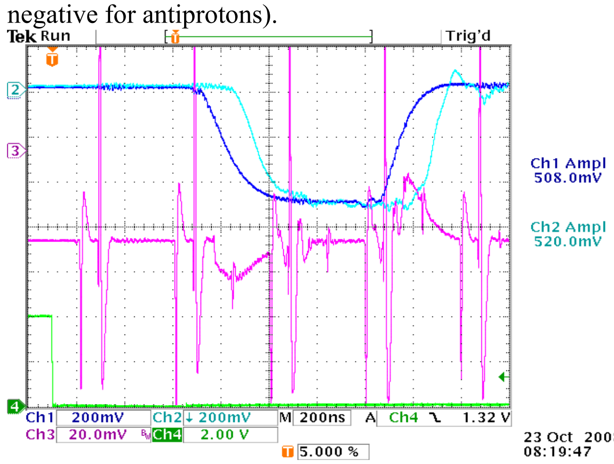

Figure 6: Electron pulse set up for two-bunch tune shift. Ch1 and Ch2 show the electron currents at the cathode and the collector. Ch3 shows the electron pulse and the antiproton and proton bunches as detected by the pickup. For clarity the pickup signal bandwidth is limited to 20 MHz.

SUMMARY

The novel Stacked Transformer Modulator designed and built at FNAL to drive the TEL electron gun was successfully commissioned. The new HV modulator allows much greater flexibility and precision in generating electron current waveforms. The STM can output complex waveforms with 16 definable voltage levels proportional to the input DC voltage with output voltage up to 6.4 kV. Faster pulse rise and fall times and much higher repetition rates are of great advantage for future experimental beam-beam studies. When properly tuned, TEL2 does not cause any measureable increase in beam Schottky power. TEL2 equipped with the new HV modulator was used in numerous beam studies without disrupting HEP operation of the Tevatron. Both experiments continued taking data. Though significant luminosity improvements could not be achieved due to the absence of strong long-range beam-beam effects in the Tevatron at the time, the study results were in good agreement with theoretical expectations. The ability of TEL2 in its current configuration to shift tunes of individual bunches in a well controlled manner can be used not only for active compensation of beam-beam effects but also for performing tune scans to verify theoretical models.

The magnetic and vacuum systems of TEL2 were also used for experimental studies of electron columns [10].

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