STATUS OF PXIE 200 OHM MEBT KICKER DEVELOPMENT*

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Abstract

The proposed Project X machine at Fermilab must deliver a widely varying bunch pattern to provide beam to several experiments quasi-simultaneously. H- Beam is delivered to the 2.1 MeV Medium Energy Beam Transport (MEBT) section at 162.5 MHz continuous wave (CW) by a radio frequency quadrupole magnet (RFQ). Unnecessary beam bunches will be selectively chopped out in the MEBT by two identical choppers on a bunch-by-bunch basis and stopped by an absorber. The Project X Injector Experiment (PXIE) will be the test bed to demonstrate a chopper's ability to form an arbitrary bunch pattern. Presently two kicker system versions are under development. One proposed version is a 50 Ω structure driven by a ±250 V linear amplifier. The second proposed version is a 200 Ω helical, microstrip line structure driven by a 500 V bipolar switch. This paper describes the development status of the 200 Ω version and includes the design concept, comparison of 3D modelling work with prototype measurements, 200 Ω hardware description and progress with the driver.

SYSTEM REQUIREMENTS

The challenge for this application is the bandwidth requirement to chop beam continuously. Beam will be delivered to a number of experiments "at the same time", so kicking patterns would vary depending upon the needs of the experiments. Thus, the frequency at which bunches change from being kicked in and out will vary from 1 to 35 MHz average and 81.25 MHz peak for about 20 alternating bunches. This 200 Ω chopper offers a design solution by taking advantage of reduced power requirement and includes the development of a suitable driver.

Beam beta in the MEBT is .067 at 2.1 MeV, so the kicker can be a traveling wave structure (the "kicker") to slow down the propagating voltage pulse to match the beam velocity. The chopper consists of two 50 cm long traveling wave kickers parallel to each other on opposite sides of the beam. Applied voltage to the parallel kickers will always be of opposite polarity.

The MEBT's lattice allows for a chopper either to apply a voltage to only kick beam out to the absorber (the unipolar scheme), or to kick beam both in and out with opposite polarity voltages (the bipolar scheme). The unipolar scheme requires applying 0 V and 500 V and the bipolar scheme ±250 V. Voltage tolerance is ±25 V.

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SYSTEM DESIGN

Component power dissipation is a big issue, and current flowing in the kicker does nothing to kick beam. These facts made it appealing to design a higher impedance system than 50 Ω. Power delivered to the load is a factor of four lower at 200 Ω, and the kicker structure's RF I^2R losses in the vacuum are lower by a factor of 16 (all other physical characteristics being the same). The downside is that all system components need to be developed. Figure 1 is the block diagram of intended system.

Helical Kicker

Meander line kickers have been implemented. However, limited power handling and evident pulse distortion suggested considering alternatives. Helical structures have also been built [1]. Constructing a cylindrically helical, 175 Ω microstrip line demonstrated promising results. Subsequent ~200 Ω versions with good mechanical uniformity resulted in good enough performance to proceed with the 200 Ω idea.

The helical wire is #13 flat magnet wire (.105" x .041") held above a copper ground tube by four ceramic spacers. This wire size was chosen to be stiff to hold its shape yet easy enough to wind tightly on a mandrel by hand. Electrodes, each 2-cm wide and .61 cm long, are attached to each turn of wire at the point closest to the beam. Beam aperture between the two facing helices is 16 mm. Figure 2a shows a photograph of a kicker prototype.

The single helix electrical characteristics and performance are affected when the two helices are positioned alongside each other, as in Fig. 2a, and driven with opposite polarities. The electrical effects are that impedance is lowered and propagation velocity reduced at the 3-5% level. Also, the helix microstrip line alone exhibits 900 MHz bandwidth but drops to about 600 MHz due to the second helix's proximity. Therefore, electrical measurements of a single helix are only valid when a zero voltage plane is installed to electrically mirror the missing helix. A metal surface positioned at beam-centre needs to extend the length of the helix, be parallel to the electrodes and grounded to the copper ground tube at both ends.

Magnetic coupling of the helical microstrip line geometry affects its characteristic impedance. The geometry for this 200 Ω helix would be 140 Ω line if laid out flat.

Estimated RF I^2R losses in the wire are about 6 W. However, the design requirements call for handling 40 W of inadvertent beam striking each helix. The ceramic spacers supporting the helix will conduct the heat to the copper ground tube. This nominal 1" diameter copper

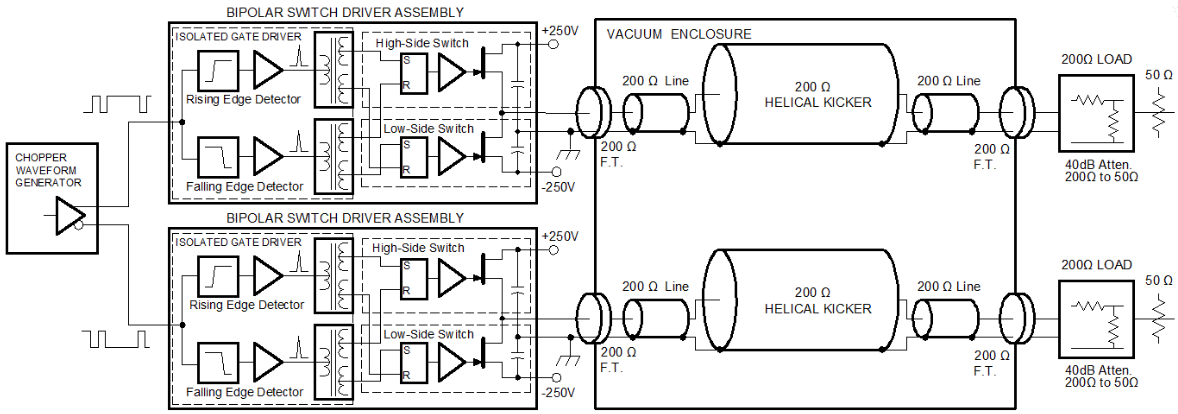

Figure 1: 200 Ω chopper electrical system block diagram. Two such systems are called for in the MEBT. Both driver and load are to be physically very close to the feed throughs.

tube is to be water cooled. The ceramic chosen is a type of machinable AlN having 50 W/m/K thermal conductivity available from Ceramic Products, Inc. Vacuum compatible epoxy is to be applied between all ceramic to copper surfaces to assist thermal conduction. The wire is estimated to rise <10°C but has yet to be confirmed by testing.

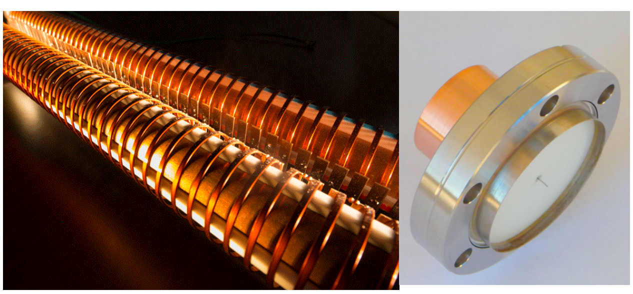

Figure 2: Hardware photos. a) Prototype kicker assembly. b) Cylindrical 200 Ω vacuum feed through.

The helix was modelled with 3D and 2D codes to determine wire height and helix pitch to achieve the desired characteristic impedance and traveling wave velocity. Agreements with a prototype helix were within 3-5%, but not quite good enough to provide precise dimensions. However, sensitivity data was obtained and then used to make adjustments to wire height and pitch of an existing prototype. A helix is in fabrication now with these adjustments.

Voltage tests revealed reflections from the far end of the helix in excessive of 10%, and TDR measurements revealed the characteristic impedance tapers down within the last turn or so at the ends to about 150 Ω. Modelling was used to evaluate optional solutions. The choice was to increase the impedance of the last turn by increasing the wire/ground spacing by 75%. This was done by decreasing the ground tube diameter under the last turn. Figure 4 shows the test result of applying this correction along with other minor adjustments achieving reflection level of ±3%.

Chopper Driver

The approach taking for the 200 Ω chopper driver was to develop a bipolar switch DC coupled to the helix. The required switching rates are those mentioned earlier, and rise/fall times need to be less than 2 ns, 5%-95%. Switching losses must be considered for the average rate of 35 MHz and are not trivial. A transistor's capacitive switching losses are CV^2f in a bipolar switch topology and amount to 3.5 W switching 100 V but 88 W switching 500 V having 10 pF Coss. The appeal to build a bipolar switch as a chopper driver was: (1) it has the DC coupled advantages; (2) designing a circuit from scratch for 200 Ω is easier than for 50 (at least in principle), and (3) the very low capacitance of available GaN FETs from Polyfet Devices, Inc. There is no single transistor available that can switch 500 V and handle its own capacitive switching losses at 35 MHz; but these FET losses come down with V^2 when connected in series to share voltage.

Current development effort is on a bipolar driver using cascode switches. Five FETs would be necessary per switch for 500 V with currently suitable and available FETs. The cascode switch is a modular design to allow for a variable number of common gate stages. A bipolar switch assembly is shown in Fig. 3 composed of 3-FET cascode switches.

Figure 1 shows the driver's major circuit blocks. The high-side switch floats with the load, so gate signal isolation must be designed for the maximum transient immunity of >250 kV/µs—well beyond commercial isolator ICs. (Low jitter fiber optic receivers are too physically large.) Narrow voltage pulses are generated at the ground-level from input rising and falling edges. These pulses set and reset latches on the cascode switches' control level that, in turn, reconstruct the ground-level chopper signal waveform and preserve timing information. Dead time is a settable parameter necessary to prevent shoot-through current. The cascode control board level includes a discrete GaN FET driver circuit, again. Not shown in any diagram is a 1 MHz, regulated AC voltage distribution system that delivers power to every isolated circuit board. Both high and low-

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side switches are totally isolated from power/ground. Thus, the driver can be biased with bipolar voltages or with a voltage offset from ground.

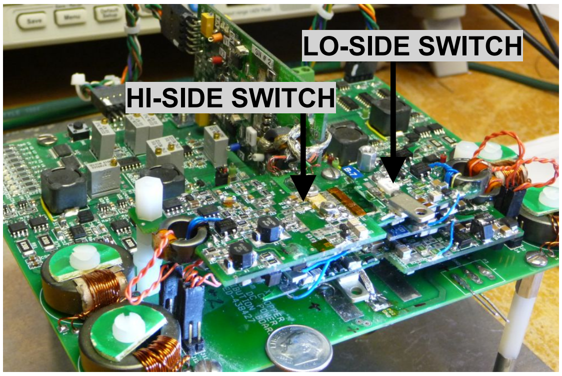

Figure 3: Bipolar switch composed of 3-FET cascode switches mounted to power distribution board.

200 Ω Lines, Feed Throughs and Load

This design is sensitive to reflections at impedance discontinuities particularly downstream of the helix. Reflections are re-reflected off the driver because of its very low impedance. Modelling verified a flat 200 Ω microstrip as the best line type to match to the helix. Feed throughs were custom made by MPC Products, Inc., and designed having isolated, cylindrical 200 Ω geometry; see Fig. 2b. Finally, the 200 Ω load was made by Elab, Inc. utilizing commercial attenuators but includes an input compensation network to minimize reflection.

PRELIMINARY RESULTS

Figure 4 is the through-voltage measurement observed at the 200 Ω load/attenuator output revealing the degree to which the 200 Ω transmission lines and load are matched to the helix. The major reflections are due to helix end effects that are not completely eliminated. Figure 5 shows the hardware included in this measurement. An assembly is currently being constructed that will include the feed throughs.

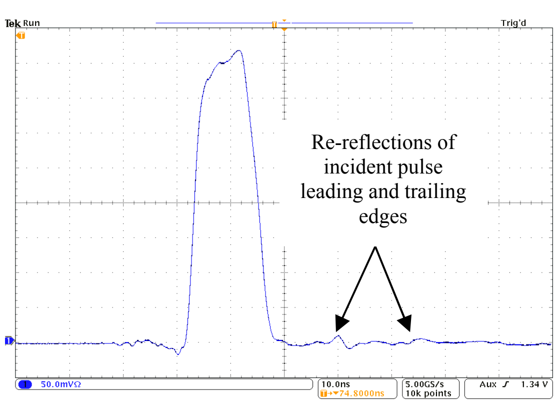

Figure 4: Through-voltage of incident pulse and all re-reflections. Reflection levels are ±3%.

Development efforts first investigated a cascode switch using 5 FETs and achieved 480 V but had issues. These were addressed and incorporated into the current design. A single stage bipolar switch was assembled to demonstrate switching to at least 100 V. This circuit (in Fig. 5) was successfully tested at 35 MHz CW and switches at 81 MHz easily for PXIE's 2 μs requirement. Current efforts are with 3-FET cascode switches in a bipolar assembly, but results are two preliminary to report.

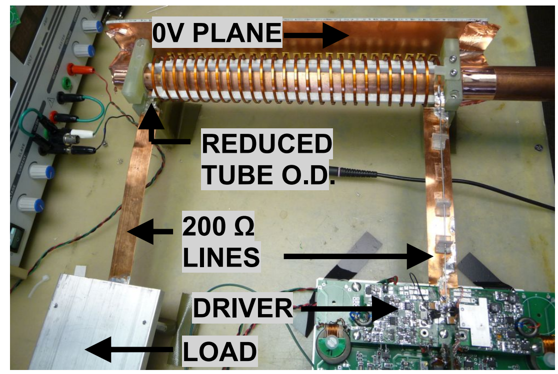

Figure 5: Reflection test setup. Helix is a 26 cm long prototype driven by 100 V (alt. ±50 V) bipolar switch.

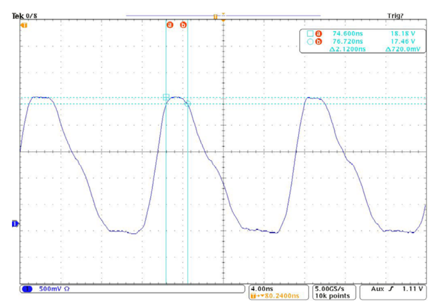

Figure 6: Helix through-voltage driven 0-100V, at 75 MHz. Bipolar switch driver is composed of 1-FET switches: <2 ns rise time (5-95%), fall time includes 2.4 ns dead time, 2.1 ns flattop.

SUMMARY

A 200 Ω microstrip line helix has been demonstrated to be a viable kicker option. Reflections are manageable. GaN FETs have been shown to be a good choice for a fast switch driver. A 100 volt single stage bipolar switch has been built and tested successfully for the continuous and burst mode operation requirement. A 300 volt 3-stage bipolar cascode switch is presently under development.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J.S. Lunsford, el al., "Versatile H+ beam chopper system at LAMPF", IEEE Trans. on Nucl. Sci., Vol. NS-26, No. 3, June 1979.