RF MODELLING OF A HELICAL KICKER FOR FAST CHOPPING*

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Abstract

High intensity proton particle accelerators that support several simultaneous physics experiments require sharing the beam. A bunch by bunch beam chopper system located after the Radio Frequency Quadrupole (RFQ) is required in this case to structure the beam in the proper bunch format required by the several experiments. The unused beam will need to be kicked out of the beam path and is disposed in a beam dumb. In this paper, we report on the RF modelling results of a proposed helical kicker. Two beam kickers constitutes the proposed chopper. The beam sequence is formed by kicking in or out the beam bunches from the streamline. The chopper was developed for Project X Injection Experiment (PXIE).

INTRODUCTION

PIP-II is a proposed high intensity superconducting accelerator to be built in Fermilab to replace the current 40 year old Linac injector of the accelerator complex. The new SRF Linac will secure the required Megawatt beam power required by the laboratory's future experiments, in particular by the Long Baseline Neutrino Experiment (LBNE) [1-2].

PXIE, Project-X injection experiment is planned to test the integrated systems of PIP-II (formerly called Project-X). Among those systems is the chopping mechanism in the Medium Energy Beam Transport (MEBT).

Having the beam shared between several experiments with different bunch sequences (as might happen in the future) puts a stringent specification on the overall bunch sequence supplied by the accelerator. In order to achieve the required bunch sequence, it is planned to have a bunch-by-bunch chopper located in the 2.1 MeV Medium Energy Beam Transport (MEBT) [3].

Figure 1 illustrates the function of the chopper in the MEBT section of PXIE. The beam originates from a 5 mA DC H- source and is then bunched and accelerated by a CW normal-conducting RFQ to energy of 2.1 MeV. A chopper system with a pre-programmed timeline is used then to format the bunch pattern and structure the beam.

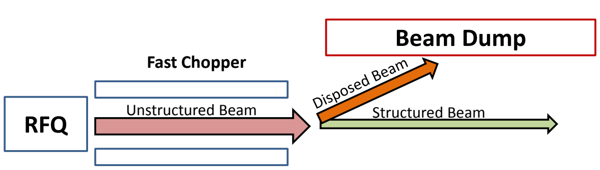

Figure 1: Simplified block-diagram of the Medium Energy Transport (MEBT) of PXIE indicating the function of the chopper.

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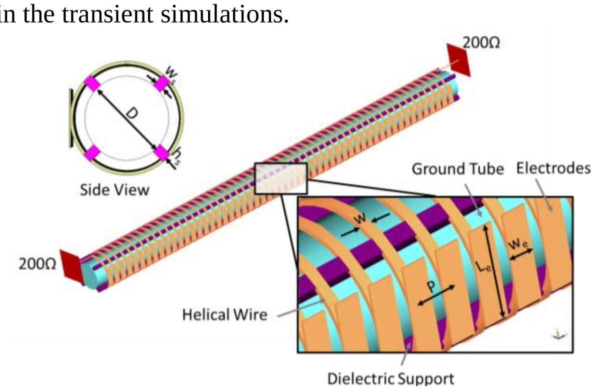
Since the Linac pulsed beam current is limited to 2 mA and the beam current of the ion source can be as high as 5 mA, undesired beam bunches has to be removed by the chopper in normal operating conditions. The unused beam will get disposed in a beam dumb.

GEOMETRY OF THE KICKER

The proposed kicker structure is a pair of traveling wave helices positioned on opposite sides of the beam [4]. The helices are wound with 13 gauge flat wire and are supported above a copper ground tube with four narrow ceramic spacer strips positioned every 90 degrees, as shown in in Fig. 2. Applied kicking voltages propagate along the helix at a speed matching the beam velocity having a beta = 0.0667. Flat, field-shaping electrodes are welded to every turn of wire on the side facing the beam. The resulting helix structure has a 200 Ω characteristic impedance.

Full 3D helical kicker models were built to carry out transient time electromagnetic simulation using CST microwave studio [5]. 200 Ohm excitation ports were used in the transient simulations.



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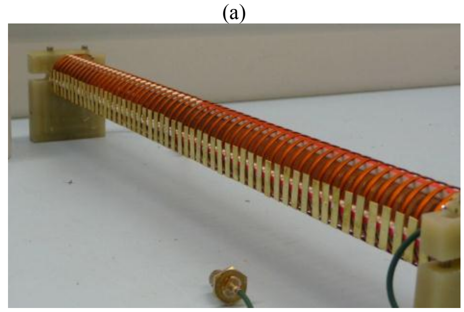


(b)

Figure 2: Geometry of the helical kicker. (a) CST microwave studio simulation model. (b) Picture of the fabricated prototype with N=55, p=0.333, D=0.563, w=0.105, w_s=0.135, h_s=0.189, w_e=0.220 and L_e=0.787 (all dimensions are in inches).

Meanwhile, several prototypes of different dimensions have been built to the helical structure. Figure 2(b) shows a prototype built to the structure with the following parameters; 55 turns, P=0.333, D=0.563, w=0.105, w_s=0.135, h_s=0.189, w_e=0.223 and L_e=0.787 (all dimensions are in inches).

ANALYSIS AND MEASURMENTS

In order for the kicker to be synchronized with the beam, the electromagnetic wave propagating through the structure should have identical velocity to the beam one. The group velocity of the H- beam exiting the RFQ at 2.1 MeV is 0.0667. So basically the helix pitch needs to be adjusted to get the electromagnetic wave slowed down to propagates at this group velocity. The structure is also required to satisfy the 200 Ohm characteristic impedance design goal.

The fabricated prototype has been tested with a narrow pulse excitation of 2 ns in width and 1 ns in rise/fall time. The measured output pulse came after 27.1 ns delay, while the simulated pulse had slightly shorter delay of 26.3 ns, as shown in Fig. 3. In simulation we tried to mimic the measurement environment and the structure was simulated open to air. In fact, the effective delay value is 26.1 ns after accounting for a 1 in long input/output coaxial cables that were used to excite the structure in simulation. The 0.8 ns difference between the simulated and measured transmission pulse delays might be due to some uncertainties in the dielectric properties of the dielectric supports. We have used in this prototype Mica of dielectric constant 6.

The group velocity of the kicker prototype is 0.0594 (simulated) versus 0.0579 (measured) which is lower than the targeted value; 0.0667, but we intended to use this case to verify correspondence between simulation and measurements. This case shows that we need to increase the pitch of the structure to increase the group velocity of electromagnetic wave.

Three cases of different pitch values for the helical kicker were simulated and the results are summarized in Table 1. In order to meet the required group velocity, it is inferred that we should use a pitch of 0.376 in. Unfortunately, changing the pitch will change not only the group velocity but also the characteristic impedance.

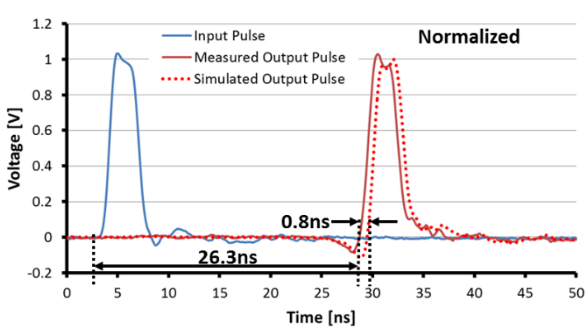


Figure 3: Measured versus simulated transient response of the helical kicker.

Table 1: Summary of the delay and group velocity for various simulated helical choppers of different pitch.

	L, Delay	β_g
P=0.333"	465.2 mm, 26.1 ns	0.05941
P=0.370"	516.89 mm, 26.2 ns	0.06576
P=0.450"	628.77mm, 26.4ns	0.07939

In order to optimize the structure for both group velocity and characteristic impedance, the optimization cycle shown in Fig. 4 were followed, where we changed just two parameters; the pitch P and the height of the dielectric support h_s. Few design iterations were then needed to reach the optimized structure with P=0.425 in and h_s=0.285.

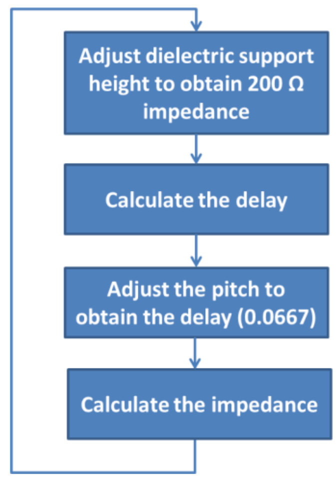
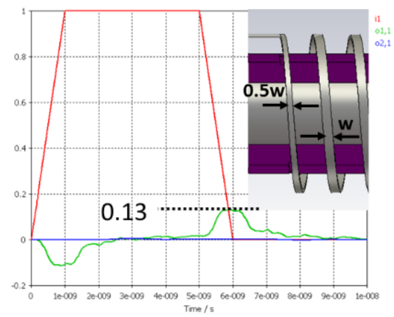


Figure 4: Flow chart of the optimization procedure for the helical kicker.

DESIGN OF END SECTION

The end sections of the helical kicker need special attention. Inductive coupling of adjacent wires raises the helix uniform characteristic impedance to its 200 Ohm level. The ends lack this coupling where the impedance tapers down roughly by 25%. One of the design goals of the structure was to minimize the reflections the transmitted pulse sees at input and output of the structure. We have investigated several options in order to adjust the characteristic impedance specifically at both ends of the structure to minimize input and output pulse reflections.

We started by looking at the option of gradually changing the wire width at the input and output turn such that it starts as a fraction of the normal wire width w and is gradually changed to w by the end of the turn. Figure 5 demonstrates the input pulse reflections in three cases for 0.5w, 0.25w, and 0.1w. The input pulse reflections can be decreased from 0.13 to 0.10 upon changing the wire width from 0.5w to 0.1w. However, changing the wire width was not favored as it will really imply getting the wire to a very narrow width.



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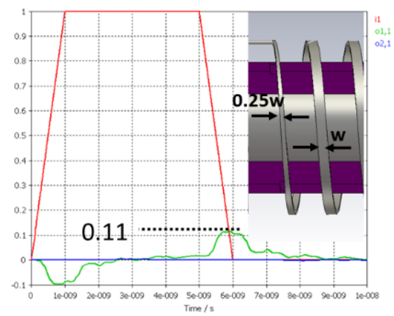

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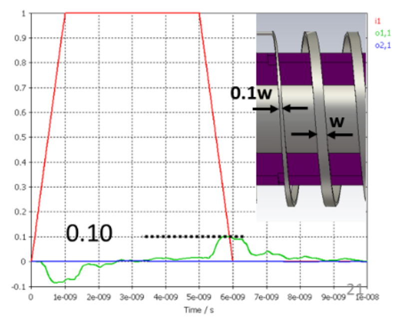


(c)

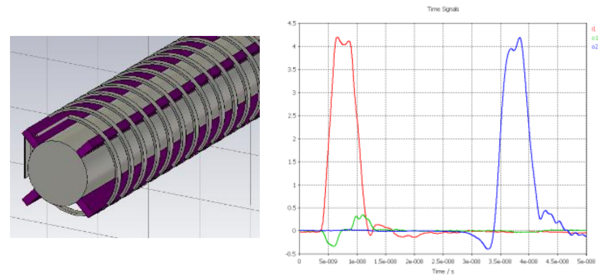
Figure 5: End effects compensation by reducing the wire width at the last half turns (a) 0.5w. (b) 0.25w. (c) 0.1w.

The second option was to change the effective wire height above ground. Upon flaring the ground tube, or making a step changing the height we basically could achieve the same effect and compensate for the change in characteristic impedance at both end sections.

Figure 6 illustrates three cases for a regular uniform ground tube in (a), a flared one in (b), and finally a stepped ground tube in (c). Flaring or stepping the ground tube happened for just 2 turns.

We used in this case an actual pulse excitation and monitored both the reflected and transmitted pulses. It is clear that both the flared and the stepped ground cases would exhibit lower reflections as shown in Figure 6(b) and (c), respectively, when compared to the regular uniform ground case in (a).

Finally, we have investigated the effect of enclosing the structure in a metallic box of dimensions 7.1 in x 4.67 in. Transient time simulations has shown that the dispersion of the pulse propagating along the structure got relatively improved, and no changes were observed for the delay or the characteristic impedance due to the box.



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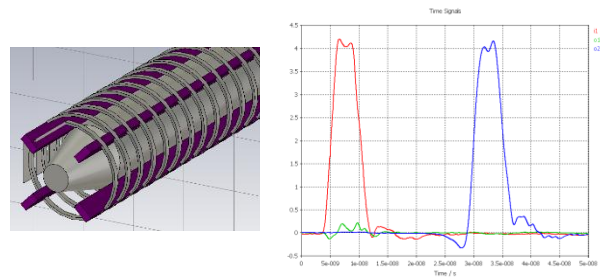

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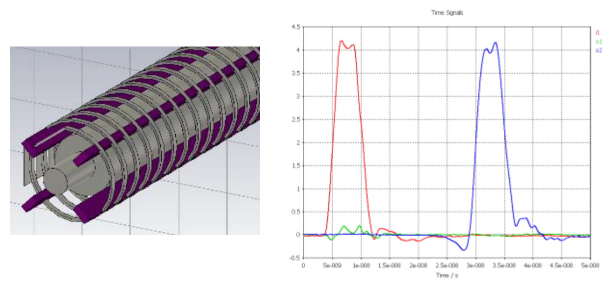

(c)

Figure 6: End effects compensation by changing the height to ground. (a) Straight ground tube. (b) Flared ground tube. (c) Stepped ground tube.

CONCLUSION

The helical kicker has been thoroughly modelled. Pitch of 0.425 in is recommended to match the beam velocity with dielectric support height of 0.285 in to get the 200 Ω characteristic impedance. Modelling reveals that the chosen grounded enclosure's dimensions has negligible effects on the structure performance. End effects could be compensated by flaring or stepping the ground for a couple of turns at the ends.

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