A Novel Low Energy Fast Chopper for H- Injectors

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Abstract

The Fermilab H- injector will be upgraded from a Cockcroft-Walton system to a 750 keV RFQ (radio frequency quadrupole) system. Part of the upgrade is the addition of a fast chopper in the LEBT (low energy beam transport) just before the RFQ. The novelty of this chopper is that it reflects rather than deflects beam. It also has low capacitance < 10 pF so that the rise and fall times of the beam pulse are dominated by cabling and the MOSFET switches. In fact, the measured rise and fall time of the chopped beam have been measured and they are better than 150 ns at 15 Hz.

Keywords:

chopper, H- injector, RFQ

1. Introduction

The present Fermilab Cockcroft-Walton H- injectors (called “H-” and “I-”) will be upgraded to a 750 keV RFQ injector with two H- sources during the 2012 year long shutdown. There are many reasons for the upgrade. See ref. (1). The most important one is that the four decades old

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Cockcroft-Waltons were getting difficult to maintain for reliable operations as time passed. The urgency of the situation manifested itself when one of the Cockcroft-Waltons (“I-”) broke in 2009 and took nearly a year to repair. Therefore, it was decided that an RFQ injector would replace them. Table 1 shows the required parameters for the injector.

One difference between the Cockcroft-Walton injector and the RFQ injector is that chopping for the RFQ injector will be done at 35 keV rather than at 750 keV. In the first iteration of the chopper design, a 10" long twin plate electrostatic chopper was placed in the middle of the LEBT (low energy beam transport) for deflecting the beam. Unfortunately, the location of the chopper and the potential well it creates when it is powered will destroy the beneficial effects of H⁻ neutralization. See ref. (2) and (3). In order to keep the H⁻ beam maximally neutralized in the LEBT, the chopper must be placed as close to the RFQ as possible because at this location, the final solenoid focuses the H⁻ beam to a small size and so the effect of de-neutralization is minimal. Therefore, the chopper is installed just before the RFQ. The H-source, LEBT and RFQ shown in Fig. 1 and the zoomed in view of the Einzel lens in the test line (not vacuum tight) is shown in Fig. 2.

The novelty of the chopper discussed in this paper is that it is a reflector rather than a deflector. The idea of using an Einzel lens as a reflector was first suggested to the authors by D. Raparia (BNL).¹ The advantages of the Einzel lens chopper are as follows:

¹It was unknown to the authors at the time that a similar Einzel lens chopper was also pursued and built at KEK. See ref. (4).

Figure 1: The RFQ injector is installed in a test line for qualification tests. The zoomed in view of the Einzel lens at its location upstream of the RFQ is shown in Fig. 2.

- (a) short length. The Einzel lens is 2" long and 1.75" in diameter and is within the design focal length of the solenoid lens.
- (b) simplicity. Unlike a twin plate chopper which may need to have a meander line to match the speed of the H- beam for fast rise and fall times of the beam pulse, it is unnecessary for the Einzel lens chopper.
- (c) low capacitance. The capacitance of the chopper is very low < 10 pF and so the rise and fall times of the beam pulse are dominated by the cabling and the MOSFET switches used in the electronics.

The disadvantage is that the Einzel lens chopper must have a potential

Figure 2: The Einzel lens is located downstream of the final focus solenoid and upstream of the RFQ.

difference a few keV higher than the energy of the H⁻ beam.

2. The Einzel Lens Chopper

The concept of the Einzel lens chopper acting as a chopper for neutron therapy is shown in Fig. 3. It is assumed that the chopper power supply is able to create enough voltage on the lens to reflect the beam. In the present lens design, -38.5 keV is the minimum voltage required. The chopping sequence is as follows:

- (a) The chopper power supply energizes the lens to -38.5 keV stop the first $\sim 40 \mu\text{s}$ of the H⁻ beam from entering the RFQ because it takes this

- amount of time for the H⁻ beam to be fully neutralized in the LEBT.
- (b) The chopper electronics shorts the lens voltage to ground and the H⁻ beam goes into the RFQ for 60 μ s which is the required bunch length for neutron therapy.
 - (c) The chopper power supply re-energizes the lens back to -38.5 kV to stop the H⁻ beam.
 - (d) The H⁻ source arc current is turned off.

Figure 3: In this example which is used for neutron therapy, the H⁻ source is turned on and the first 40 μ s of the H⁻ beam is not transmitted into the RFQ because it takes this amount of time to neutralize the H⁻ beam. Everything is off for the next 60 μ s so that the neutralized beam is sent into the RFQ. After 60 μ s the beam is turned off again by powering the Einzel lens. The cycle repeats after $1/15[\text{Hz}]=67$ ms.

2.1. The Einzel Lens

The dimensions of the Einzel lens were optimized in SIMION (5) so that the voltage on the lens that can stop 35 keV beam is < 40 kV and that its transverse size is large enough so that it does not clip the beam when it is turned off. For the beam pipe that is 4" in diameter, the simulations found that the lens that is 2" long and 1.75" in diameter fits the criteria. In this case, the simulated minimum potential difference that reflects 35 keV is $|-38|$ keV. The reason why the potential is 3 kV higher than the energy of the beam is because the potential at the center of the lens is lower by 3 kV compared to the surface of the lens. In practice, the required potential is -38.5 kV.

2.2. Mechanical Design

The mechanical drawing of the Einzel lens and its final assembly is shown in Fig. 5. The lens is made of stainless steel and is held in place by welding the lens to the center conductor of the high voltage feedthroughs. The feedthroughs are CeramTec model number 21183-01-W which are rated for a maximum voltage of 50 kV.

2.3. Chopper Electronics

The Einzel Lens Chopper requires a switching system that features fast rise and fall times, stable voltage level settings, and the ability to modify beam pulse lengths over a wide range at a 15 Hz rate. The circuit chosen for this application is a relatively simple push-pull circuit utilizing solid-state high voltage switches. Solid state switches were chosen because they exhibit

Figure 4: This is a longitudinal cross sectional view of the beam pipe and the Einzel lens. The magnetic field from the last solenoid focuses the 35 keV H- beam (blue) into the entrance of the RFQ when the Einzel lens is off. When the Einzel lens is on, it acts like a mirror on the H- beam by reflecting the beam away from the RFQ.

the required ON/OFF capability (as opposed to say, a thyratrons ON only action). See Fig. 6.

This relatively simple circuit operation is complicated by the fact that the stray capacitances in the circuit are comparable to the load capacitance. At the same time, when the load capacitance is charged and discharged, the stray capacitances are also charged and discharged in parallel with the load and therefore, increases the circuit RC time constants. The full spice model is shown in Fig. 7 with the stray capacitances arbitrarily set to 10 pF and

Figure 5: The drawing of the Einzel lens (1.75 ID) and how it is attached to the end of the LEBT and to the entrance of the RFQ (left). And the various views of it after final assembly (right).

1 pF. The stray capacitances are modeled as capacitances attached to the switches but are in fact spread over the whole circuit enclosure with the bulk of the stray capacitance coming from the switches themselves.

2.3.1. Circuit operation

When the circuit is initially energized, the load voltage will rise to ~ -19 kV due to the voltage divider action of the Off resistances of the switches. The Einzel lens being used for tests has operated to 45 kV with no sparking

Figure 6: The basic Einzel chopper electronics circuit.

and so there are no expected problems when running it at 19 kV.

Operationally, the Lens ON switch SW1 is turned on and the load is charged to shut off the beam. When it is required for beam to be transmitted to the RFQ (LENS OFF), SW1 is turned off and SW2 is turned on to discharge the load. When the desired amount of beam is achieved, SW1 and SW2 are cycled again to stop the beam acceleration. The ideal lens voltage waveform is shown in Fig. 9 in conjunction with the Source Extractor and Arc Current waveforms to illustrate the overall pulsed source operation.

There is time between 15 Hz beam pulses for all of the various capacitances to charge to the voltage levels dictated by the voltage divider resistances. Thus when the charging switch section is activated initially to charge the load (i.e. Lens ON), the required charging current is reduced compared to

Figure 7: The full spice model of the chopper electronics.

the current required during the second Lens ON event. Four current toroids have been placed to monitor the various currents during operation: one to monitor the total current through the storage capacitor C1 (I_{total}), one to monitor the current through the SW1 section (I_{chg}), one to monitor the current through the SW2 section (I_{dischg}) and one to monitor the Load current (I_{load}). Typical currents from each of these monitors are shown in Fig. 10.

It is not easy to monitor the lens voltage directly. Any typical high voltage probe has capacitance comparable to the lens capacitance and will

Figure 8: The spice output voltage waveform on the Einzel lens (left) and the initial beam ON settling time (right).

severely affect the circuit operation. For example, the Hewlett-Packard and Northstar probes used for these tests exhibit 10 pF and 15 pF respectively. Furthermore, probe calibration over the wide frequency range is very difficult. There are no plans to try to implement voltage monitoring unless it is found to be absolutely necessary.

2.3.2. The solid state switches

The switches used for this application were acquired from Diversified Technologies Inc. They supplied switch assemblies rated at 50 kV/50 A. The switch assemblies come complete with control and driver electronics, and cabling. The assemblies were installed into a custom enclosure that will be mounted directly above the RFQ beam line and as physically close to the Einzel lens as reasonably possible. Each switch assembly exhibits ON/OFF resistances of 750Ω/150MΩ respectively. The current rise times have been measured to be ~ 60 ns.

Figure 9: The conceptual timing diagram required for chopper operations.

3. Chopper Beam Tests

In the chopper beam tests, the RFQ has been removed and a fast Faraday cup (6) has been installed 11" from the downstream flange of the lens, and a toroid called Z:LTOR is mounted 50" from the lens. See Fig. 11. The fast Faraday cup has a bandwidth of 15 – 20 GHz and its signal is connected to a Tektronix oscilloscope with a bandwidth of 500 MHz.

3.1. Timings

The voltage pulses on the Einzel and its effect on the beam current is shown in Fig. 12. Looking at Z:ATOR which is the beam current upstream of the lens, it is clear although Z:ATOR shows beam within the first Einzel lens voltage pulse, the lens has stopped the beam from going through it because Z:LTOR remains at 0 V. It is not until the voltage pulse goes to zero that beam goes through, i.e. Z:LTOR is no longer zero. Finally, when the second voltage pulse is applied, the beam is stopped again — Z:LTOR goes to zero — despite Z:ATOR being non zero.

Figure 10: The plots of the total current I_{total} through the storage capacitor C, I_{chg} through SW1, I_{dischg} through SW2 and I_{load} through the load.

3.2. Voltage needed for stopping beam

The voltage required to stop 35 keV H- beam is between -38 kV and -39 kV. In practice, the stopping voltage has been set to -38.5 kV which is very close to -38 kV calculated using SIMION discussed in section 2.1. Fig. 13 shows that beam leaks out of the Einzel lens when the voltage is set to -38 kV, while at -39 kV, the beam is completely stopped.

An interesting effect on Z:ATOR when the H- beam is reflected is shown in Fig. 14. Toroids are directional devices and so the “backwards” moving H- beam will reduce the measured current. The reduction in Z:LTOR current is the result of this effect.

Figure 11: (a) The test line used to demonstrate chopping consists of the Einzel lens connected to the end of the LEBT, a fast Faraday cup and a toroid. (b) A zoomed in view of the Einzel lens connected to the end of the LEBT.

3.3. Rise and fall times

The rise and fall times of the chopped H- beam are measured with the fast Faraday cup. The measured rise time is ~ 138 ns and the fall time is ~ 81 ns. See Fig. 15. The rise time is longer than the fall time because the total capacitance, due to stray capacitances being charged, is larger than the capacitance being discharged. See the basic chopper electronics circuit diagram in Fig. 6 circuit and section 2.3. The main contributor to the RC time constants which affect the rise/fall times are the resistance of the MOSFET switches and the capacitance of the system. Each pad contributes 150Ω and so for a stack of 5 pads, each stack contributes 750Ω . It is conceivable to short out one pad of each stack to reduce the rise/fall times, however, these times are already within the requirements for chopped beam. Note: the vacuum pressure in the LEBT is about 2.5×10^{-6} Torr in these experiments.

Figure 12: The Einzel lens voltage and the toroid signals.

Figure 13: (a) When the Einzel lens voltage is below $|-38|$ kV, some beam leaks out (b) the beam is completely stopped when the voltage on the Einzel lens is above $|-38|$ kV.

4. Conclusion

The Einzel lens chopper together with its electronics has met the requirements needed for operations. There was an initial fear that this type of chopper will be prone to sparking but it has not been the case. The question about the robustness and reliability of the electronics can only be answered after a few years of operation. Whatever the future may be, it is necessary for this system to work for the next decade until Project X stage 1 becomes

Figure 14: The measurement on Z:LTOR clearly shows that the beam is chopped to a width of $43 \mu\text{s}$ downstream of the Einzel lens. The current measured on Z:ATOR is smaller when the lens reflects the H- beam because toroids are sensitive to beam direction. The rolls in the toroid signals come from the low pass filters of the toroid amplifiers.

a reality when it replaces the present Linac.

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References

- [1] C. Tan, et al., The 750 keV RFQ injector upgrade, Tech. rep., Fermilab (2012).
URL <http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=3646>
- [2] M. Reiser, et al., Theory and Design of Charged Particle Beams, 2nd Edition, Wiley-VCH, 2008.
- [3] J. Alessi, et al., H- source and low energy transport for the BNL RFQ preinjector, in: AIP Conf. Proc., Vol. 210, 1990, pp. 711 – 716.
- [4] T. Adachi, et al., A solid-state Marx generator driven Einzel lens chopper, Re. Sci. Inst. 82 (083305).
- [5] SIMION.
URL <http://simion.com>
- [6] High Power Fast Faraday Cup R&D.
URL <http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=866>

Table 1: Injector Parameters

Parameter	Value	Units
Input energy	35	keV
Output energy	750	keV
Ouput H- current	> 40	mA
Output pulse length	$4 - 60$	μs
Repetition rate	15	Hz
Required rise and fall time of beam pulse	< 150	ns

Figure 15: The rise and fall times of the chopped H- beam. The traces have been averaged 16× and background subtracted.