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MATCHING OF AN RFQ AND MULTICUSP ION SOURCE WITH A COMPACT LEBT*

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Abstract

The IsoDAR project is a neutrino experiment that requires a high current H_2^+ beam at 60 MeV/amu, which will be produced by a cyclotron. A critical aspect of the design is the injection, which comprises an ion source, a compact low energy beam transport section (LEBT), and a radio-frequency quadrupole (RFQ) buncher embedded in the cyclotron yoke. The LEBT is optimized to match the desired input Twiss parameters of the RFQ. Here we report on the latest results from the ion source commissioning, and on the design and optimization of the LEBT with matching to the RFQ. With this ion source, we have demonstrated a 76% H_2^+ fraction at a current density of 11 mA/cm^2 in DC mode. The design of the LEBT includes a chopper, steering elements, and focusing elements, to achieve the desired matching, which, according to our simulations, leads to ~95% transmission from the ion source to the exit of the RFQ.

INTRODUCTION

The IsoDAR cyclotron produces a high power proton beam that when collides with a specially designed target is able to produce a high flux of anti-electron neutrinos. The full IsoDAR system is placed in close proximity to a kiloton inverse beta decay detector. This experiment takes advantage of the high statistics produced by IsoDAR to examine the parameter space in which anomalies have been observed by several neutrino experiments [1, 2].

Most kiloton neutrino detectors are constructed underground to limit backgrounds from cosmic rays. Therefore, to have the IsoDAR cyclotron near one of these detectors, it must be sufficiently compact to be built underground.

In order to produce these high neutrino statistics, a high-power proton accelerator is required. To produce a high-power proton driver, it is necessary to have an ion source which is able to produce a high enough current to compensate for beam losses throughout the system. We have chosen a filament driven multicusp ion source [1] and so it is desirable to run at lower currents to limit the wear on the filament. The higher the wear on the filament, the more often the filament will require replacement. Higher currents in the system will also cause higher amounts of space charge, increasing emittance throughout the beamline. This is particularly important in the low energy regions. Therefore, making the transmission through the system as high as possible is crucial.

This type of ion source was chosen for its low emittance and high species fraction of H_2^+. H_2^+ was chosen as the accelerated beam species to lessen the effects of space charge. It is possible to reduce emittance and beam growth by using H_2^+ as opposed to protons or H^- ions, which are typically accelerated by cyclotrons. They can later be separated into protons using a stripping foil.

Contaminant ions in the beam can be filtered out by the RFQ due to their different charge to mass ratios, however over time this will cause damage to the RFQ electrodes. Therefore, it is important to minimize ion source contaminant species to prevent wear on the RFQ.

Typically, in cyclotrons with an external ion source, a low energy beam transport (LEBT) with multiple focusing magnets is used to axially inject beam into the cyclotron. In this case, beam losses occur from two factors: losses that occur in the beamline, and due to phase acceptance of the cyclotron. Only particles within a certain phase window will be accelerated by the cyclotron. Those outside of that phase window are lost. To address these issues, we have begun the radio frequency quadrupole direct injection project (RFQ-DIP). The compactness of RFQ-DIP compared to a typical LEBT system is shown in Fig. 1.

RFQ-DIP shortens the LEBT system to less than a meter and uses electrostatic lenses as an injection system to the RFQ. The shorter LEBT is complete with diagnostics to better understand the beam being injected into the RFQ.

The RFQ then accelerates the beam up to 70 KeV, acting primarily as a buncher. The frequency of the RFQ is 32.8 MHz to match the frequency of the cyclotron. The matching of the RFQ to the cyclotron and its bunching of the beam will maximize phase acceptance and minimize loses to the beam when entering the cyclotron. Based on our simulations of the RFQ, the beam transmission through the RFQ is over 95% [1].

To achieve this high transmission, the beam parameters of from the LEBT must be well matched to the optimum input parameters of the RFQ. The LEBT must be designed with this in mind.

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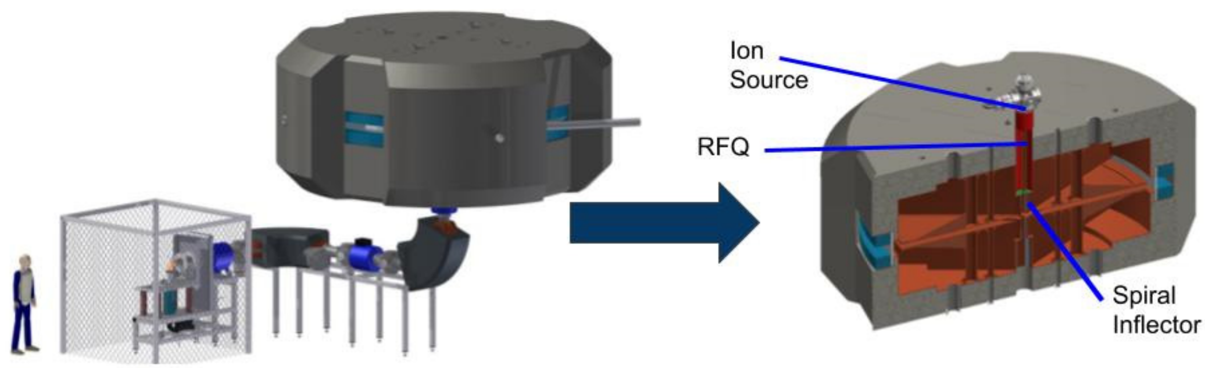

Figure 1: Comparison of the IsoDAR cyclotron with LEBT (Left) and RFQ direct injection system (Right.) Also labelled is the ion source and spiral inflector [3].

LEBT REQUIREMENTS

The LEBT is a series of electrostatic lenses which connect the ion source to the RFQ. The electrodes shape and steer the beam into the RFQ to match the desired Twiss parameters at the RFQ entrance. See Fig. 2.

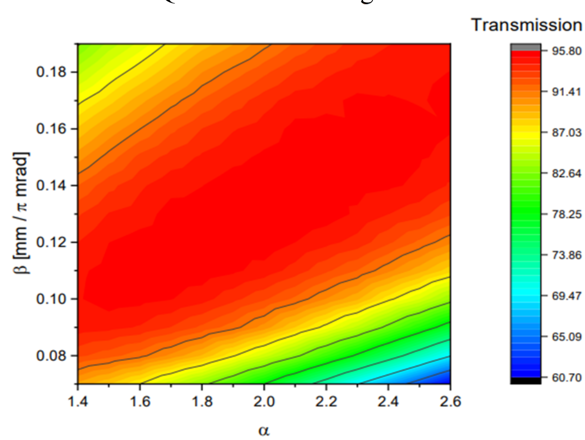

Figure 2: Temperature plot of transmission through the RFQ based on input Twiss Parameters.

However, there are several constraints on the LEBT to make the best possible design.

- The output energy of the LEBT must be 15 KeV. This constrains the maximum voltages on the power supplies and focusing electrodes within the system.
- The electrodes within the LEBT must be sufficiently far apart to prevent sparking when in vacuum.
- The electrodes should be constrained to the length of a 6-way cross to keep costs down and the system mechanically feasible.
- The LEBT should have a diagnostics section which includes 4 button pickups, and an ACCT, Faraday cup, and additional port for pumping.
- The LEBT must be separated from the rest of the beamline by a gate valve.
- There must be a capability of small angle steering to ensure alignment with the RFQ. This requires 2 sets of magnetic steerers for x, x', y, y' adjustment.
- The LEBT must include a chopper to pulse the beam for commissioning and machine protection.

Steering and Chopping of the Beam

While mechanical alignment is maintained by precision engineering, in the case that the LEBT is misaligned to the RFQ at the sub-millimeter level, an additional degree of freedom can be used to ensure alignment. The LEBT is a series of electrodes held at different potentials. These electrodes are cylindrically symmetric, and so the electric field acting on the beam is dependent only on the radial and longitudinal position. One way to steer the beam is to break this symmetry. By cutting one of these electrodes in half and adding a small potential difference to one of the half-lenses, the centroid of the beam will be adjusted in a way proportional to the potential difference between the two halves.

To move the beam in a single direction, the electrode must be cut into halves. To move in two directions, say x and y simultaneously, the electrode would be needed to be cut into quarters. Therefore, in order to have all the steering required for the LEBT, there would need to be either 2 electrodes cut into quarters, or 4 electrodes cut into halves. However, having steering too early in the beamline will cause aberrations and emittance growth as the beam travels through more focusing elements.

Using this technique at a higher voltage causes the potential difference between the two half electrodes to be so high that the beam is unable to travel down the beamline. This is referred to as “chopping” the beam. When one of the shells is grounded at high frequency, the beam can be chopped into different pulses. This chopping is essential for testing the RFQ-DIP project at different total currents, as well as for machine protection for elements further down the beamline. This style of chopping is similar to work which was done with the ion source at the SNS [4].

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Another means of steering the beam is using magnetic steerers. These are 4 coils placed outside the beamline in a square shape that can create a small dipole field to help steer the beam in the x and/or y directions. This has several advantages over electrostatic steering (so long as the steerers are sufficiently far from any equipment that their magnetic field does not cause interference). Their being external to the beamline allows easier access for maintenance or positional changes outside of vacuum. There is also no danger of arc between electrodes, because the magnetic field is generated by a current running through a coil, not a potential difference between two nearby electrodes. There are a maximum of 2 required for steering the beam. The effects of these magnetic steerers on the beam dynamics simulations can be seen in Fig. 3.

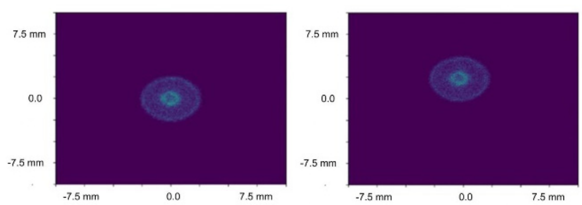

Figure 3: Beam dynamics simulation from WARP using a magnetic steerer 75 mm from the RFQ to steer beam in the +y direction.

Beam Dynamics Simulations

The beam dynamics of the LEBT were done using two simulation codes: IBSimu [5] and WARP [6, 7]. IBSimu was used in the region close to the plasma meniscus due to the accuracy of its plasma model. However, for long beamlines IBSimu can be computationally expensive. To speed up the design process, the particle distribution from IBSimu is transferred to WARP after 3 cm. Identical electrode geometries and potentials are used in both codes. The beam dynamic simulation from WARP can be imported into a CAD model for visualization, as seen in Fig. 4. The beam parameters are then printed at the entrance to the RFQ.

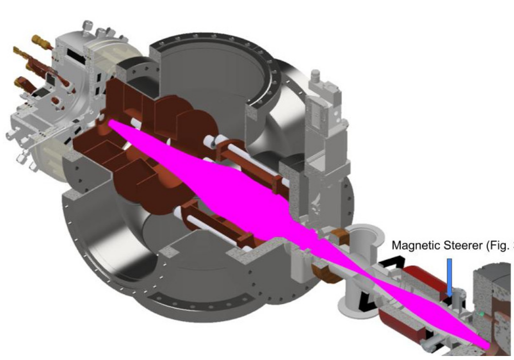

Figure 4: Beam dynamics simulation from WARP (purple) imported into ¾ cut CAD model of ion source and LEBT. The magnetic steerer used in the simulation for Fig. 3 is labelled.

To generate this plot an idealized distribution was used. The LEBT design was intended to match these parameters and was able to do so in addition to having a lower emittance, as shown in Table 1.

Table 1: Comparison of Input Twiss Parameters

Parameter	LEBT Output	Baseline
Norm. RMS emittance	0.157 π mm mrad	0.3 π mm mrad
Alpha	2.1	2.1
Beta	0.13 mm/ mrad	0.17 mm/ mrad

Steering was tested using both electric and magnetic steerers. Magnetic steering fields were calculated using COMSOL [8] and then the field was imported into WARP.

The final electrode in the LEBT is split into halves to be used as an electrostatic chopper. One half shell of the lens is connected to a MOSFET, which grounds the electrode on command to chop the beam. The potential difference between the grounded and HV shell causes the beam to terminate on the grounded shell. The electrode is water cooled to prevent any thermal damage from chopping the beam.

Because the diagnostic section requires a long drift period before entering the RFQ, an additional solenoid is added before the RFQ entrance. This solenoid field was calculated with COMSOL [8] and imported into the warp code. The solenoid provided an additional degree of freedom for focusing the beam into the RFQ. The full diagnostic section including solenoid and magnetic steerers is show in Fig. 5.

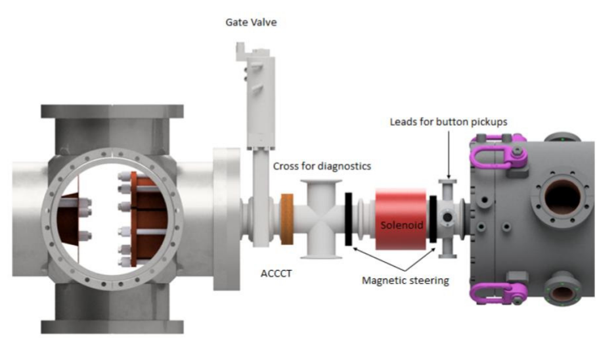

Figure 5: Layout of diagnostic section of LEBT.

CONCLUSION

The LEBT is well matched to the input parameters of the RFQ. This will ensure high transmission and beam quality through the RFQ. This is essential to reduce the strain on the ion source filament, reduction of wear on the RFQ, and to have the highest possible transmission through the cyclotron. In addition to this, the LEBT allows for beam diagnostics before the RFQ, steering, and chopping capabilities. These pieces make the LEBT a crucial part of the RFQ-DIP project.

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REFERENCES

[1] D. Winklehner *et al.,* “High intensity cyclotrons for neutrino physics”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 907, pp. 231-243, Nov. 2018. doi:10.1016/j.nima.2018.07.036

[2] A. Diaz, C. A. Argüelles, G. H. Collin, J. M. Conrad, and M. H. Shaevitz, “Where are we with light sterile neutrinos?”, *Physics Reports*, vol. 884, pp. 1–59, Nov. 2020. doi:10.1016/j.physrep.2020.08.005

[3] M. Abs *et al.,* "IsoDAR@ KamLAND: a conceptual design report for the technical facility”, unpublished. arXiv:1511.05130

[4] S. Nath *et al.*, “Beam Behavior Through The SNS Chopper System”, in *Proc. 21st Linear Accelerator Conf. (LINAC'02)*, Gyeongju, Korea, Aug. 2002, paper MO440, pp. 130–132.

[5] T. Kalvas, O. Tarvainen, T. Ropponen, O. Steczkiewicz, J. Ärje, and H. Clark, “IBSIMU: A three-dimensional simulation software for charged particle optics”, *Review of Scientific Instruments*, vol. 81, no. 2, p. 02B703, Feb. 2010. doi:10.1063/1.3258608

[6] A. Friedman *et al.*, “Computational Methods in the Warp Code Framework for Kinetic Simulations of Particle Beams and Plasmas,” *IEEE Transactions on Plasma Science*, vol. 42, no. 5, pp. 1321–1334, May 2014. doi:10.1109/tps.2014.2308546

[7] 2021 Warp, http://warp.lbl.gov/

[8] COMSOL Multiphysics v. 5.4., www.comsol.com