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HIGH-CURRENT H_2^+ BEAMS FROM A COMPACT CYCLOTRON USING RFQ DIRECT INJECTION*

D. Winklehner†, J. M. Conrad, D. Koser, J. Smolsky, L. H. Waites
Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract

For the IsoDAR experiment in neutrino physics, we have developed a compact and cost-effective cyclotron-based driver to produce very high intensity beams. The system will be able to deliver continuous wave (cw) particle beam currents of > 10 mA of protons on target in the energy regime around 60 MeV. This is a factor of 4 higher than the current state-of-the-art for cyclotrons and a factor of 10 compared to what is commercially available. All areas of physics that call for high cw currents can greatly benefit from this result; e.g. particle physics, medical isotope production, and energy research. This increase in beam current is possible in part because the cyclotron is ab-initio designed to include and utilize so-called vortex motion, which allows clean extraction. Such a design process is only possible with the help of high-fidelity particle-in-cell codes, like OPAL. Another novelty is the use of an RFQ embedded in the cyclotron yoke to bunch the beam during axial injection. Finally, using H_2^+ relieves some of the space charge constraints during injection. In this paper, we will give an overview of the project and then focus on the design and simulations of the cyclotron itself. We will describe the pertinent physical processes, computational tools, and simulation results. At the end, we will describe how we are including machine learning in the simulation effort, for error analysis, sensitivity studies and machine tuning assistance.

INTRODUCTION

The main motivation behind the development of the IsoDAR high-current compact cyclotron is in neutrino physics. The IsoDAR experiment [1, 2] is a proposed search for so-called *sterile neutrinos*, a hypothetical new particle that could explain anomalies in recent neutrino oscillation experiments [3]. In order to be decisive within 5 years of running, on the order of 10^{23} $\bar{\nu}_e$ (electron-antineutrinos) need to be produced in a high power target over the experiment lifetime. To do this a 60 MeV proton driver beam with cw current of 10 mA is required. Because the accelerator and target need to be installed close to a large underground neutrino detector, compactness is of the utmost importance and a compact cyclotron was chosen to produce the driver beam. However, 10 mA is an order of magnitude higher than off-the-shelf cyclotrons in the medical isotope industry can deliver and a factor four higher than the current record held by PSI Injector II [4] (a larger, 4-sector cyclotron).

The main challenge in scaling up the beam current from the state-of-the-art is *space charge* – the Coulomb repulsion of positive charges in the beam. This effect leads to beam- and emittance growth and ultimately to particle losses on the surrounding accelerator hardware. It is most problematic at low energies (e.g. in the LEBT and during injection through the spiral inflector). Another challenge is the small phase window for acceleration in a cyclotron not using stripping extraction (as is done for H^- machines, for example). Only about 20° of the RF period should be populated. Ultimately, both effects may lead to halo particles in between turns, which in turn leads to activation of the electrostatic extraction septum. We have addressed these challenges through the following innovations:

1. Accelerating 5 mA of H_2^+ instead of 10 mA of protons leads to the same number of nucleons on target at half the electrical current.
2. Injecting and pre-bunching via a Radio-Frequency Quadrupole (RFQ) partially embedded in the cyclotron yoke (see Fig. 1).
3. Designing the cyclotron main acceleration to optimally utilize *vortex motion*, leading to clean extraction.

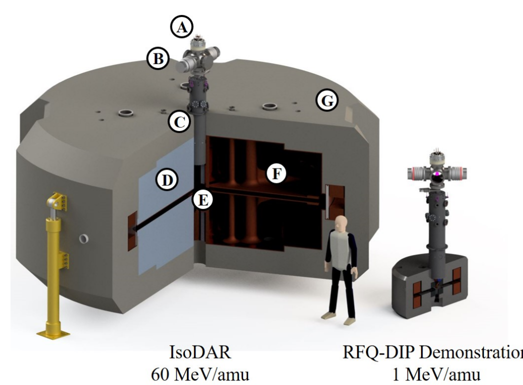

Figure 1: CAD rendering of the IsoDAR 60 MeV/u cyclotron (left) and the RFQ-Direct (axial) Injection Prototype (RFQ-DIP) (right). Labelled items are: A - ion source, B - LEBT, C - RFQ embedded in the cyclotron yoke, D - magnet pole, E - central region with spiral inflector, F - RF cavity (double-gap), G - return yoke.

Beyond particle physics, a compact cyclotron capable of delivering cw beam currents of this magnitude has applications in medical isotope production [5, 6], material research [7, 8] and, if paired with another cyclotron, also for energy research [9, 10]. See also Ref. [11].

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† winklehn@mit.edu

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THE ISODAR CYCLOTRON

Overview

A schematic of the IsoDAR cyclotron layout can be seen in Fig. 1 (left). The system has been described in detail in Refs. [12–14]. It consists of an ion source, a short electrostatic extraction system and Low Energy Beam Transport (LEBT), an RFQ buncher-accelerator embedded in the cyclotron yoke, and the compact isochronous cyclotron accelerating the beam to 60 MeV/u. We are describing the individual components in the following subsections. At each step, we have performed high-fidelity particle-in-cell simulations to demonstrate the feasibility of the design, which we will describe in the respective places.

Ion Source

To produce the needed DC current of 12 mA of H_2^+ at the required low emittance and high beam purity, a new filament-driven multicusp ion source was built at MIT (MIST-1) and recently commissioned at 25 % of its final power. The highlights of the commissioning were > 1 mA H_2^+ current in a Faraday cup right after the extraction system, 80 % H_2^+ fraction (see Fig. 2), and emittances as low as 0.05 π-mm-mrad (RMS, normalized) at the source exit [15]. This emittance was determined by comparison of full simulations of our test-stand with experimental results. We simulated the ion source extraction using IBSimu [16] and the subsequent diagnostic beam line using WARP [17]. The simulations were in good agreement with the experiments [15]. For the matching of the ion source to the RFQ, we have designed a new extraction system and LEBT. This compact system comprises an Einzel lens, electrostatic steering and chopping, as well as magnetic steerers, final focusing into the RFQ with a solenoid, and several beam diagnostics [18].

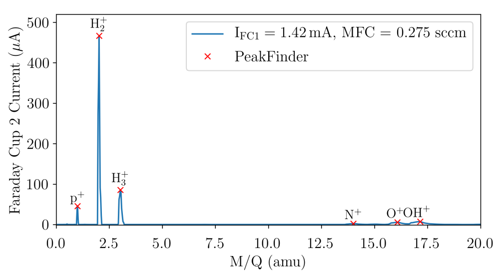

Figure 2: Mass spectrum recorded during the MIST-1 commissioning at 25 % power. H_2^+ is the dominant species with 80 % fraction. From [15].

Table 1: RFQ Parameters

Parameter	Value	Parameter	Value
Ion type	H_2^+	Beam current	10-20 mA
Frequency	32.8 MHz	Duty factor	100 % (cw)
E_{in}	7.5 keV/u	E_{out}	35 keV/u
RF power	≤ 6 kW	Length	1.4 m

RFQ Direct Injection

The RFQ direct injection scheme was presented in detail elsewhere [13, 19]. Here, a 7.5 keV/u H_2^+ beam is injected into an RFQ, which is partially embedded in the cyclotron yoke. The RFQ is an efficient buncher and also moderately accelerates the beam to 35 keV/u. The latest RFQ technical design can be found in Ref. [20], an optimization study of the input power coupling in Ref. [21], and a detailed analysis of the thermal properties and cooling in Ref. [22]. The main RFQ parameters are listed in Table 1 and a CAD rendering is shown in Fig. 3. The cyclotron frequency of 32.8 MHz can be matched by the RFQ through use of a *split-coaxial* RFQ design, in which pairs of vanes are attached to the entrance and exit flange, respectively, rather than radially to the tank walls. This yields a low frequency while maintaining a small diameter (needed for insertion into the cyclotron). Mechanical stability and frequency detuning due to RF heating have been investigated and are within manageable limits. Our loop coupler study shows a RF power below 6 kW. The simulated beam input (matching the ion source and LEBT simulations) and output parameters are listed in Table 2 for 90 % transmission. Here the entrance and exit gap fields (longitudinal and transverse), as well as space charge were taken into account. Once the beam has left the RFQ, it diverges quickly in the longitudinal and transverse directions. To compensate, the RFQ exit is brought as close as possible to the median plane and an additional electrostatic quadrupole channel is installed between RFQ exit and spiral inflector.

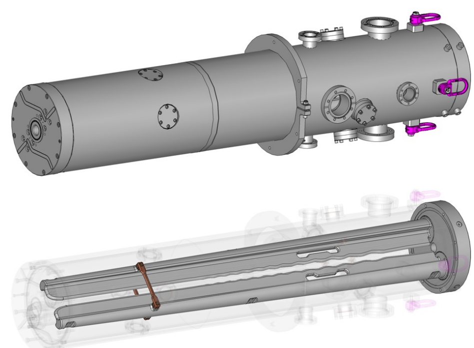

Figure 3: (upper) The split-coaxial RFQ. Note the absence of extruded flanges in the lower half where the structure is embedded in the cyclotron. (lower) Two vanes are attached to the entrance flange, the other two are attached to the exit flange, giving the split-coaxial structure. Note the additional structural bridges (copper color).

Table 2: Simulated Beam Parameters Before and After RFQ

Parameter	Before	After
$E_{kin,mean}$	7.5 keV/u	33.3 keV/u
ϵ_x (RMS, n.)	0.19 π-mm-mrad	0.25 π-mm-mrad
ϵ_y (RMS, n.)	0.19 π-mm-mrad	0.22 π-mm-mrad
ϵ_z	DC Beam	0.03 MeV-deg

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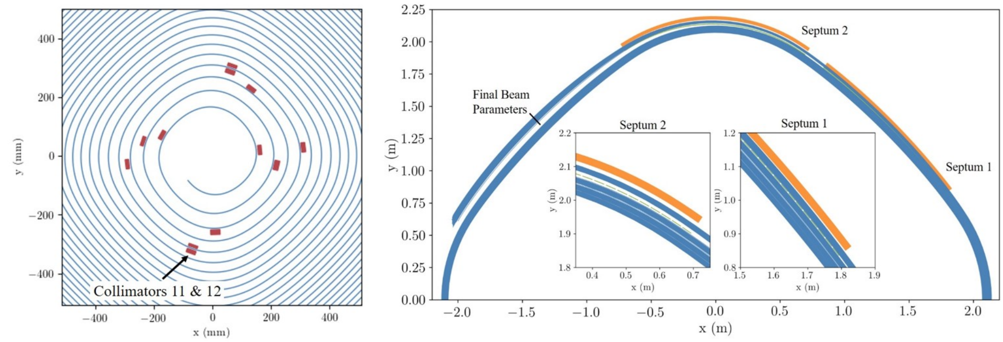

Figure 4: (left) Collimators in the central region. (right) Final turns with electrostatic extraction channels. From [14].

Cyclotron

The IsoDAR cyclotron is a room-temperature, isochronous, compact cyclotron that operates in the 4th harmonic at 32.8 MHz. Four double-gap RF cavities with peak voltage from 70 kV at the center up to 250 kV at the outermost radius yield high energy gains per turn. Collimators that are placed in the central region clean up beam halo that develops when an initially mismatched beam undergoes vortex motion. For a detailed explanation of this longitudinal-radial space-charge coupling effect see Ref. [14] and references therein. The latest collimator placement is shown in Fig. 4(left). Total beam loss on these collimators is about 29 % and the energy of particles lost stays below 1.5 MeV/u (well below activation threshold). All simulations of the cyclotron were performed with the well-established OPAL code [23]. Note that we are not yet using the 6D phase space distribution resulting from RFQ simulations as input to the cyclotron simulations. Bunches of 2e5 macroparticles are then simulated during acceleration to 60 MeV/u. At the extraction radius of approximately 2.1 m, we use a 3D model of the extraction septa to generate a field, which is loaded into OPAL and to place collimator objects to cound particle losses in this region. This can be seen in Fig. 4 (right). The beam parameters at beginning and end of the simulations are listed in Table 3. Losses amount to less than 50 W (a factor four below the safety limit determined at PSI for Injector II) while we can smoothly increase turn separation up to the point where magnetic channels can safely be introduced.

Table 3: Simulated Beam Emittances (RMS, Normalized) in the First and Last Turn of the Cyclotron

Parameter	**Turn 1**	**Turn 103**
$E_{kin,mean}$	194 keV/u	62.4 MeV/u
$\epsilon_{rad.}$	0.14 π-mm-mrad	3.8 π-mm-mrad
$\epsilon_{long.}$	0.02 MeV-deg	0.1 MeV-deg
$\epsilon_{vert.}$	0.59 π-mm-mrad	0.44 π-mm-mrad

MACHINE LEARNING

We used Machine Learning (ML) in two places during the design and simulation process: The RFQ design and optimization [24], and for Uncertainty Quantification (UQ) of the cyclotron [14]. In both cases, we create datasets by random sampling the hyperspace made up by design variables of interest and running the usual simulations codes (RFQ: PARMTEQM, GFQGen, WARP, Cyclotron: OPAL). Using these datasets, we then train Surrogate Models (SM), either with Neural Nets or Polynomial Chaos Expansion, to predict the output beam parameters. The SM executes much faster than the original simulation codes. We used multiobjective optimization (Bayesian optimizer) to find the best RFQ cell-, and input beam parameters [24]. For the cyclotron, we used the SM for uncertainty quantification, using Sobol indices, to show that the design does not strongly depend on small variations of the input beam [14].

CONCLUSION

We have presented a mature design for a compact cyclotron, able to deliver 5 mA of 60 MeV/u H_2^+ beams, which can be stripped into a 10 mA, 60 MeV proton beam. The use of H_2^+ alleviates charge concerns, while aggressive prebunching through a 32.8 MHz split-coaxial RFQ, embedded in the cyclotron yoke increases the amount of beam that can be captured within the small phase acceptance window of the accelerator. These, together with a high acceleration gradient, carefully placed collimators in the first 5 turns, and the vortex effect then lead to good turn separation at 60 MeV/u and let us extract beam with predicted losses in the electrostatic extraction channels below 50 W. The design has been thoroughly tested through highly accurate PIC simulations using WARP and OPAL and the final steps to close the full start-to-end simulation chain (handing over full 6D phase space distributions from one software to the next after the spiral inflector) are currently being taken. Finally, a prototype to demonstrate the feasibility of RFQ injection and the onset of vortex motion is currently under construction.

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