

# TOOLS FOR THE DEVELOPMENT AND APPLICATIONS OF THE IsoDAR CYCLOTRON\*

L. H. Waites<sup>†</sup>, J. Alonso, J. M. Conrad, D. Koser, D. Winklehner  
Massachusetts Institute of Technology, Cambridge, MA, USA

## Abstract

The IsoDAR cyclotron is a 60 MeV cyclotron designed to output 10 mA of protons in order to be a driver for a neutrino experiment. However, this high power can be used in other useful and important applications outside of particle physics. The IsoDAR cyclotron accelerates  $H_2^+$ , which allows the beam to be highly versatile and important for the development of high-power targets. This could help alleviate a bottleneck in the medical isotope community. IsoDAR could also be used for the development of materials. The accelerator system uses many new tools, including novel methods of applying machine learning, as well as several of the uses of this new technology. With these applications and tools, the IsoDAR cyclotron can have an important impact on the accelerator, medical, and physics communities.

## INTRODUCTION

The IsoDAR cyclotron is designed to be a high-power cyclotron producing a high flux of anti-electron neutrinos. The high flux of neutrinos is generated in close proximity to a kiloton neutrino detector. This is laid out Schematically in Fig. 1. The accelerator system in conjunction with the neutrino detector would undergo a sterile neutrino experiment, providing a 5-sigma exclusion over a large parameter space after 5 years [1]. To achieve this result, the accelerator faces two major design constraints:

1. The accelerator is required to be built in an underground mine in close proximity to a kiloton scale neutrino detector. Therefore, the accelerator must be compact in size. This prevents use of a large separated sector cyclotron [2].
2. The accelerator must produce 10 mA of 60 MeV protons (600 kW of beam power). This is an order of magnitude higher than commercially available compact cyclotrons, typically used for medical isotope production, can deliver [3]. Several new techniques were used to address these constraints, including the acceleration of  $H_2^+$  and radio-frequency quadrupole (RFQ) direct injection.

The high current capabilities of IsoDAR mean that it could be transformative for applications outside of neutrino and particle physics. For example, the production of rare medical isotopes has reached a bottleneck due the limitations of targets and the current limit of cyclotrons. The high current capabilities of IsoDAR have the potential to relieve this bottleneck by making medical isotope production more cost efficient, while simultaneously enabling new

developments for high-power targets. Similarly, the IsoDAR cyclotron has the potential to more quickly evaluate materials used in nuclear reactors.

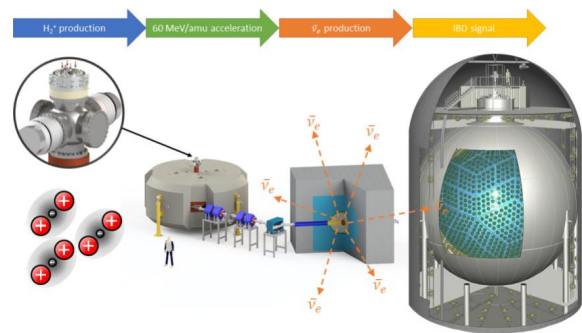


Figure 1: Schematic showing the full IsoDAR experiment including  $H_2^+$  ion source, accelerator, target, and kiloton neutrino detector [4].

## Use of $H_2^+$

One of the major limitations of reaching high currents in compact cyclotrons is the effect of space charge on beam and emittance growth. The coulomb repulsion between ions in the beam cause the beam to expand

The IsoDAR cyclotron accelerates  $H_2^+$  ions, decreasing the charge per ion, and thus limiting the effects of space charge on the beam. Once extracted, the  $H_2^+$  beam is run through a stripping foil, removing electrons and separating the  $H_2^+$  beam into protons. This process allows twice as many total protons to be accelerated with less of an effect from space charge, allowing the IsoDAR cyclotron to reach higher currents than traditional cyclotrons.

## RFQ Direct Injection

The IsoDAR cyclotron uses the novel approach of RFQ direct injection. After the ion source is a short tetrode extraction system that shapes and steers the beam into the RFQ. The RFQ then acts primarily as a buncher, creating a beam frequency of 32.8 MHz to match with the cyclotron. Transmission of the RFQ has been calculated to be over 90% [1]. Because the beam is highly bunched by the RFQ before its injection into the cyclotron, phase acceptance in the cyclotron will lead to far fewer losses early on. The high throughput of the system also leads to less strain on the filament of the ion source, prolonging filament lifetime.

The RFQ direct injection system is also far more compact than a traditional LEBT. The use of a single transport and bunching system, rather than a series of focusing magnets needed for a LEBT, reduces the size of the system, making installation in difficult places such as an underground mine more practical.

\* This work was supported by NSF grants PHY-1505858 and PHY-1626069, as well as funding from the Bose Foundation.

<sup>†</sup> lwaites@mit.edu

## TOOLS

### *Use of Machine Learning for RFQ Optimization*

The multiple design parameters of the RFQ (i.e. cell number, cell size, vane voltage, etc.) span a large possible parameter space. To better understand this space, and decrease computational needs, machine learning techniques have been used to generate surrogate models for our RFQ.

For this work, we describe two separate cases:

- A model to optimize the input Twiss parameters of the RFQ from the ion source.
- A model to optimize the full RFQ design.

Creating a surrogate model for the full RFQ design requires 14 input parameters, as well as a dataset large enough to provide sufficient information for machine learning algorithms. Modelling the beam from the input Twiss parameters requires only 2 input parameters to the surrogate model, making it less computationally expensive.

Using the well-established code RFQGen [5] a training dataset is generated. The inputs into RFQGen are parameterized for the surrogate model to decrease the computation time for training the machine learning algorithms. This dataset is then used to create a surrogate model of the RFQ. The surrogate model can rapidly evaluate different design parameters and generate simulated outputs. The RFQ design is optimized by calling the surrogate model in order to find the best parameters for the RFQ.

Two types of machine learning algorithms are used for generating surrogate models of the RFQ: Polynomial chaos expansion (PCE) and a deep neural net (DNN). The PCE was integrated using the UQ tool kit by Sandia Labs [6] and the DNN was integrated using TensorFlow [7]. The deep neural net has a node structure of 14-10-20-20-14 and uses an Adam optimizer with a learning rate of .001. This structure corresponds to a similar DNN used for accelerators in [8].

Surrogate models are generated using these methods which are then used to predict alternate designs. The alternate designs are evaluated based on the output beam parameters of the RFQ. The output beam parameters are optimized using a Bayesian optimizer [9] in order to find the best RFQ design or set of input Twiss parameters.

### *Use of OPAL for Spiral Inflector Injection Simulation*

A difficult to simulate region of the IsoDAR system is the spiral inflector. This is the point in the central region in which the beam is injected, and changes planes from being axial to the cyclotron, to being in the midplane. This is done using two spiral electrodes held at a high potential difference.

In order to properly simulate this region, the particle in cell (PIC) code OPAL [10, 11] was used. OPAL was developed specifically for accelerator applications and is highly parallelizable. OPAL was upgraded to include a new field solver, along with a new geometry class, which together can model the complex boundary conditions which are

present in the spiral inflector system. This code has been benchmarked against experimental results and has shown to accurately reproduce the trajectories of particles through the spiral inflector.

## APPLICATIONS

### *Medical Isotope Production*

Nuclear Medicine has exciting applications including new means of fighting cancer with alpha therapies, as well as diagnostic tools such as positron emission tomography (PET). However, in order for medical isotope treatments to be used in a clinic, the radionuclides must first be produced. These radioactive isotopes are produced at accelerator complexes that typically use cyclotrons to accelerate H-, then strip the H- to protons. The proton beam produced by the cyclotron system then collides with a target, producing radioisotopes. The target is then chemically separated to isolate the isotopes of interest to the medical community.

The IsoDAR cyclotron can produce currents an order of magnitude higher than comparable commercially available cyclotrons, as seen in Table 1.

Table 1: Comparison of IsoDAR Cyclotron with IBA C30 [3]

Parameter	IsoDAR	IBA C30
Energy (MeV/nucleon)	60	30
Proton Current (mA)	10	1.2
Beam Power (kW)	600	36
Outer Diameter (m)	6.2	3

These higher currents allow for more protons on target, leading to more nuclear reactions and higher yields of rare isotopes. However, the high power can overwhelm the thermal constraints of the target. This is a major bottleneck for medical isotope production. There are two mitigations to this:

- Maintaining lower power on target by using less than the total available power.
- Developing new target designs which are capable of absorbing higher power beams.

The IsoDAR cyclotron can support both mitigations without significantly compromising its power. This is due in large part to its acceleration and extraction of  $H_2^+$ .  $H_2^+$  is separated into protons using a stripping foil to remove the electrons. Because the charge to mass ratio of protons is approximately half that of  $H_2^+$ , a proton beam will bend more in the same magnetic field as will an  $H_2^+$  beam. One could imagine using this effect with a double focusing dipole magnet and using a stripper foil to break off a controlled fraction of the beam. The remaining fraction of this beam could then go on to the following station, and this process could be repeated iteratively. See Fig. 2.

At each of these stations, the proton beam would be impinging on a different target. Because the power of the proton beam is easily variable, the power on target can be kept

below the thermal constraints. Each station would be a useful tool for the development of new high-power targets, as it can easily modify the power of the proton beam without the need for any external changes to the beamline. During the target development and testing period, the proton beam current can be increased or decreased as needed.

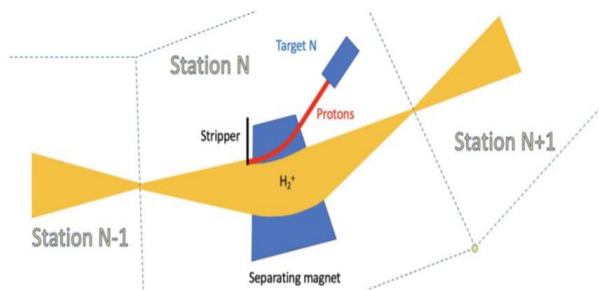


Figure 2: A dipole magnet station used to separate an  $H_2^+$  beam. The remaining  $H_2^+$  can be refocused using a double focusing dipole and move on to the next station (N+1). This can be done iteratively, creating multiple ion proton beams on target.

### Materials Science

Inside a fusion or advanced fission power plant the materials used in construction undergo an extreme environment. This represents one of the most urgent challenges in nuclear power. In order to properly equip these powerplants, it is crucial to understand how these materials may change under large amounts of radiation damage. To replicate this environment in a safe, cost effective, and accurate way, proton beams from 10-30 MeV can be used to irradiate materials.

Protons can accurately reproduce the wide range of recoil energies and transmutation effects that are seen in a nuclear reactor [12].

Proton beams with high currents have been used to evaluate materials used in nuclear power plants [12, 13]. With use of a high-power beam, it is possible to replicate the radiation damage done in a nuclear reactor with an order of magnitude less time [14]. This process can be made more widely available to groups outside of national laboratories by the relatively small footprint and low operating cost of a cyclotron.

### CONCLUSION

New techniques that are being used to develop this high-power cyclotron, including machine learning, new  $H_2^+$  acceleration, and RFQ direct injection, are important developments in accelerator physics. While initially designed for a neutrino experiment, the IsoDAR cyclotron's high current and use of  $H_2^+$  makes it a perfect tool for the production of medical isotopes, the development of high-power targets, and for materials science.

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