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STATUS OF THE IsoDAR HIGH-CURRENT H_2^+ CYCLOTRON (HCHC-XX) DEVELOPMENT

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Abstract

The potential existence of exotic neutrinos beyond the three standard model neutrinos is an important open question in particle physics. IsoDAR is a cyclotron-driven, pure electron-antineutrino source with a well-understood energy spectrum. High statistics of anti-electron neutrinos can be produced by IsoDAR, which, when coupled with an inverse beta decay detector such as the LSC at Yemilab, is capable of addressing observed anomalies attributed to sterile neutrinos at the 5 sigma level using electron-flavor disappearance. To achieve this high significance, the IsoDAR cyclotron must produce 10 mA of protons at 60 MeV. This is an order of magnitude more current than any commercially available cyclotron has produced. To achieve this, IsoDAR takes advantage of several innovations in accelerator physics, including the use of H_2^+ and RFQ direct injection, paving the way as a new high power accelerator technology. These high currents also allow for new experiments in dark matter, as well as high production rates of rare isotopes such as ^{225}Ac and ^{68}Ge.

INTRODUCTION

The design of the IsoDAR experiment is set to produce a high flux of anti-electron neutrinos using a compact system that will be in close proximity to a kiloton scale, underground neutrino detector, see Figure 1.

Leading exclusions of sterile neutrinos could be provided by this experiment over five years, in which the IsoDAR

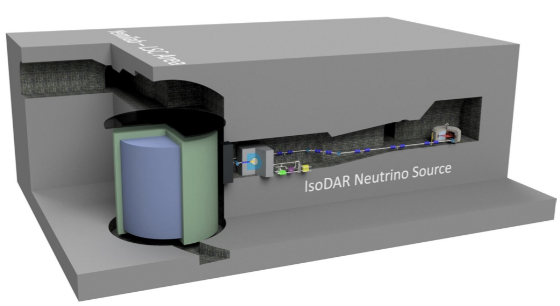

Figure 1: Diagram showing the layout of the IsoDAR experiment. The experiment uses an H_2^+ ion source, which is directly injected into a cyclotron, which accelerates the H_2^+ up to 60 MeV. The H_2^+ is stripped into protons before colliding with the a beryllium target, producing neutrons. The neutrons are absorbed by a highly pure ^{7}Li sleeve, which then undergoes beta decay, and produces anti-electron neutrinos. These neutrinos can then be detected by the nearby detector via inverse beta decay (IBD).

experiment could provide a five-sigma exclusion over several anomalies [1]. However, two conditions must be met:

1. The accelerator must be sufficiently compact to be constructed underground in close proximity to the detector, preventing the use of a separated sector cyclotron [2].
2. The accelerator must provide 10 mA of protons at 60 MeV.

The use of H_2^+ can be used to alleviate space charge in the beam. This is critical for maintaining beam quality in low energy, high intensity regions. Another is the use of a Radio Frequency Quadrupole (RFQ) direct injection system that bunches the beam and leads to higher transmission through the system.

However, high power cyclotrons have applications beyond the particle physics scope. The most common use of cyclotrons is to produce medical isotopes. Rare isotopes are often prohibitively expensive to produce, limiting treatment options for those who require them. The IsoDAR cyclotron can address the bottlenecks of this industry, and help produce large yields of currently rare medical isotopes.

PATH TO HIGHER CURRENTS

Use of H_2^+

The Coulomb repulsion between ions within a beam can lead to emittance and beam size growth. This is particularly important in low energy regions. Most modern cyclotrons accelerate H^- ions, which allows convenient extraction using a stripping foil. However, there are significant advantages to accelerating and extracting H_2^+. This allows twice as many protons to be accelerated with limited space charge effects. The H_2^+ is later run through a stripping foil, which removes the molecular electrons and leaves protons, effectively doubling the beam current.

RFQ Direct Injection

Following the production of H_2^+ is extraction system with four electrodes which is designed to steer and shape the beam in order to properly match the desired input parameters of the RFQ and maximize end-to-end transmission.

The beam is injected as direct current (DC), however as it traverses the RFQ the beam is bunched by the shaped electrodes and RF acceleration. While the beam is only accelerated from 15 keV to 60 keV, the primary purpose of the RFQ is to act as a beam buncher. The RFQ converts the DC beam into a 32.8 MHz beam to match the frequency of the cyclotron. Transmission from ion source to the end of the RFQ has been calculated to be >90% [1].

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The high bunching efficiency of the RFQ allows for higher phase acceptance by the cyclotron. Because the beam is properly bunched, a higher fraction of the beam is put within the phase acceptance window of the cyclotron, allowing for a higher fraction of the beam to be accelerated, and preventing loses early on. Being as efficient as possible with the beam is important to limit space charge in low energy regions, as well as reducing the strain on our filament driven ion source.

The use of an RFQ direct injection system also leads to a far more compact system than a traditional LEBT design. This allows for easier installation in compact regions such as an underground mine.

Use of Machine Learning for RFQ Optimization

An RFQ design can be represented as a point in a very large parameter space who's dimensions include factors such as vane voltage, cell number, cell size, and input beam parameters. This is difficult to design by hand due to the size of the parameterspace. To accelerate this process (*audible groan), we used machine learning techniques to create surrogate beam dynamics models for the RFQ, which could then be coupled with an optimizer. We used for this for two scenarios:

1. Optimize the beam input from the tetrode extraction system into a fixed RFQ.
2. Optimize the full RFQ design.

We modeled the beam inputs with only the Twiss parameters of the beam to fully describe its profile. To model the full RFQ design we required 14 input parameters. This requires a much larger dataset to train the machine learning algorithms, but covers a much larger space.

We generated a training dataset using RFQGen [3].The inputs are parameterized, then used to generate this data are used for the inputs for the surrogate model. Due to the nature of pretrained ML models, theses could now rapidly simulate the beam dynamics through the specified RFQ. The RFQ design can then be optimized by tuning these input parameters in order to match the desired beam dynamics through the RFQ.

Surrogate models were generated using a Polynomial Chaos Expansion (PCE) using the the UQ tool kit made by sandia labs [4] and a Deep Neural Network (DNN) which was produced using tensorflow [5]. To mimic a similar neural network architecture used in accelerators found in Ref. [6], we used a neural network with structure 14-10-20-20-14 and use an Adam optimizer with a learning rate of .001.

We were then able to use these surrogate models to alter the design of the RFQ and tetrode extraction system. We were able to optimize the designs based on the output beam dynamics of the RFQ, for which we then used a bayesian optimizer [7]. The optimizer would return the best design inputs to the surrogate model, which then described an optimium design. For a more detailed look at this process, see Ref. [8].

MEDICAL ISOTOPE PRODUCTION

PET scans and alpha therapies have gained a lot of attention due to their ability to potentially transform cancer treatment and diagnostics. However, these treatments are still prohibitively expensive for many of those who require them. This expense is partially driven by the high cost of production for these radio-isotopes.

To produce more of these isotopes the problem is simple in concept: more protons on target, at higher energies. This unfortunately does not fully reflect reality. Higher protons on target means higher power, which in turn leads to thermal constraints in the target. To keep the target from being damaged or destroyed, these thermal constraints need to be well managed and understood.

The IsoDAR cyclotron would have record setting power and protons on target. Compared to comercial devices, seen in Table 1, the IsoDAR cyclotron would have a higher power by an order of magnitude.

Table 1: Comparison of commercial cyclotrons from IBA with the IsoDAR cyclotron, from Ref. [9].

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

This higher power clearly leads to more protons on target. However, this high power also exceeds any thermal constraints of the target. However, because IsoDAR extracts H_2^+, it is possible to easily split the beam to defuse this power. Using a system including a double focusing dipole magnet and stripping foil, it is possible to break the beam up into several lower power, controlled parts, as seen in Figure 2. This would provide a perfect testbed for the research and development of high power targets, as this system would provide variable power to multiple stations that could be used to produce isotopes, develop and test new targets, or run new experiments. Not only this, but the power could be adjusted in a modular and continous way.

This would provide multiple targets with acceptable levels of power, while also utilizing the full potential of the IsoDAR cyclotron.

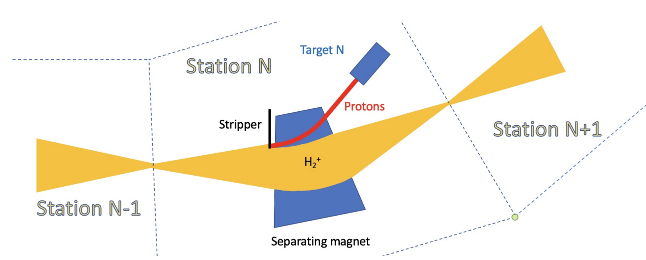

Figure 2: Diagram showing the H_2^+ beam from the IsoDAR cyclotron iteratively being broken up across several (n) stations. Taken from Ref. [10]

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CONCLUSION

While originally intended for an ambitious particle physics experiment, the IsoDAR cyclotron is capable of also making changes in the medical isotope field. We have taken advantage of several new developments and technologies in order to design a higher power, compact cyclotron. Our of H_2^+ mitigates space charge as well as allows it to be a testbed for target research. Our use of an RFQ-direct injection system also provided an example of using machine learning in accelerators. Coupling these technologies will help pave the way for new developments in multiple fields.

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