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IsoDAR: A High Power Cyclotron for Neutrino Physics and Beyond

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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 KamLAND, 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.

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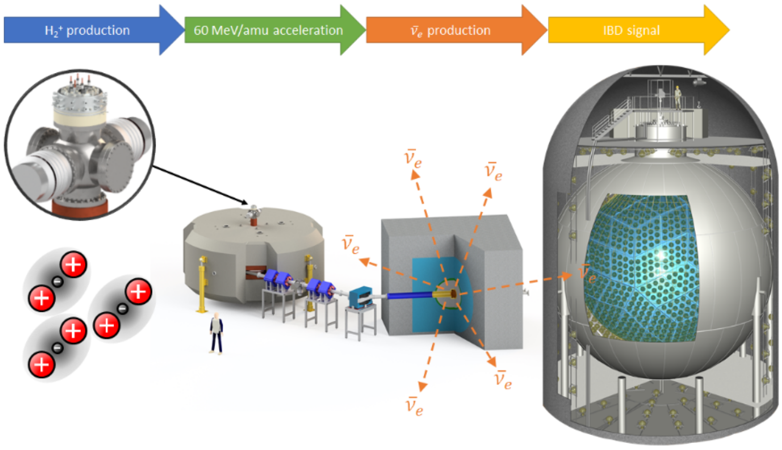

Figure 1: Diagram showing the layout of the IsoDAR experiment. The experiment uses an H_2^+ ion source, which is directly injected into a cyclotron, which accelerates the H_2^+ up to 60 MeV. The H_2^+ is stripped into protons before colliding with the a beryllium target, producing neutrons. The neutrons are absorbed by a highly pure Li^7 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).

1. Introduction

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

This experiment would provide world leading exclusions of sterile neutrino measurements. Over five years, the IsoDAR experiment could provide a five-sigma exclusion over several anomalies [1]. To achieve this ambitious goal, 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.

To provide these two conditions there were several innovations in accelerator technology. First, the use of H_2^+ 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.

The high power and versatility provided by the IsoDAR cyclotron can be used in a context beyond neutrino physics. In fact, the most common use of cyclotrons is to produce medical isotopes. Unfortunately, many rare isotopes are prohibitively expensive to produce. The IsoDAR cyclotron can address the bottlenecks of this industry, and help produce large yields of currently rare medical isotopes.

2. Path to higher currents

2.1 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. Typical modern cyclotrons accelerate H^- ions, and extract using a stripping foil. However, the IsoDAR cyclotron accelerates and extracts H_2^+. This allows twice as many protons to be accelerated with effectively half the total current that would be used in an H^- beam. The H_2^+ is later run through a stripping foil, which removes the molecular electrons and leaves protons.

2.2 RFQ Direct injection

Following the production of H_2^+ in the ion source is a tetrode extraction system. This steers and shapes the beam in order to ensure it is properly injected into the RFQ with high transmission.

Once the direct-current (DC) beam is injected into the RFQ, the shaped electrodes and RF accelerate and bunch the beam. 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].

The high bunching efficiency of the beam is important to the phase acceptance in the cyclotron. By having the beam properly bunched, a higher fraction of the beam is put within the phase acceptance window of acceptance for the cyclotron. This prevents beam loses early in the accelerating process, allowing for less required current in these 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.

2.3 Use of Machine Learning for RFQ optimization

An RFQ has several design parameters which determine its function. This includes factors such as vane voltage, cell number, cell size, and input beam parameters. Because the design space is so vast, we find that designing a system by hand can be very difficult. To speed up this process, 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 two parameters, the Twiss parameters of the beam. 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. The model can then 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 [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 [8].

3. Medical Isotope Production

PET scans and alpha therapies have the potential to transform cancer treatment. However, in many cases these treatments are still prohibitively expensive. One of the major factors in this expense is the cost of production of the isotopes used in these treatments.

To produce more of these isotopes the problem is simple: more protons on target, at higher energies. The solution however, is not so simple. Higher protons on target means higher power, which in turn leads to thermal constraints in the target. A massive bottleneck in the field is due to the lack of high power targets.

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 [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. But a distinct property of the IsoDAR cyclotron prevents this engineering problem. IsoDAR extracts H_2^+. Using a system including a double focusing dipole magnet and stripping foil, it is simple 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.

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

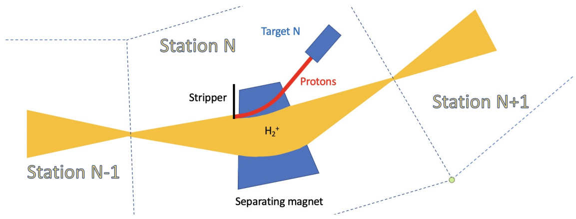

Figure 2: Diagram showing the H_2^+ beam from the IsoDAR cyclotron iteratively being broken up across several (n) stations. Taken from [10]

4. 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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