

# UPDATED PHYSICS DESIGN OF THE DAE $\delta$ ALUS AND IsoDAR COUPLED CYCLOTRONS FOR HIGH INTENSITY H $_2^+$ BEAM PRODUCTION\*

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## Abstract

The Decay-At-rest Experiment for  $\delta_{CP}$  violation At a Laboratory for Underground Science (DAE $\delta$ ALUS) and the Isotope Decay-At-Rest experiment (IsoDAR) are proposed experiments to search for CP violation in the neutrino sector, and “sterile” neutrinos, respectively. In order to be decisive within 5 years, the neutrino flux and, consequently, the driver beam current (produced by chained cyclotrons) must be high. H $_2^+$  was chosen as primary beam ion in order to reduce the electrical current and thus space charge. This has the added advantage of allowing for stripping extraction at the exit of the DAE $\delta$ ALUS Superconducting Ring Cyclotron (DSRC). The primary beam current is higher than current cyclotrons have demonstrated which has led to a substantial R&D effort of our collaboration in the last years. We present the results of this research, including tests of prototypes and highly realistic beam simulations, which led to the latest physics-based design. The presented results suggest that it is feasible, albeit challenging, to accelerate 5 mA of H $_2^+$  to 60 MeV/amu in a compact cyclotron and boost it to 800 MeV/amu in the DSRC with clean extraction in both cases.

## INTRODUCTION

### Physics Motivation

The standard model of particle physics includes three so-called “flavors” of neutrinos:  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ , and their respective anti-particles. These particles can change flavor (neutrino oscillations), a process that can be described using a mixing matrix. This necessarily means that neutrinos must have a small mass [1]. In addition, some experiments aimed at measuring these oscillations in more detail have shown anomalies that led to the postulation of so-called “sterile” neutrinos which would take part in the oscillation, but, contrary to the three known flavors, do not interact through the weak force [2]. Another important question is whether the three neutrino model can give rise to a CP-violating phase  $\delta_{CP}$  [3], which might explain the matter-antimatter asymmetry in the universe today. DAE $\delta$ ALUS [4, 5] and IsoDAR [6] are proposed experiments to search for CP violation in the neutrino sector, and sterile neutrinos, respectively. In the following, we will give a brief overview of the facilities and identify and discuss the most critical aspects.

\* Work supported by NSF under award #1505858.

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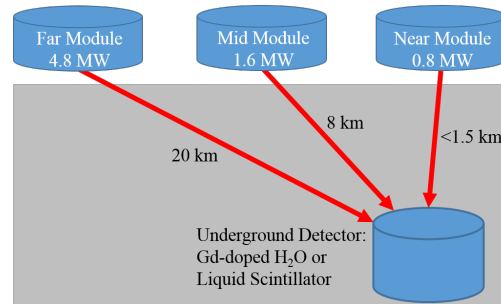


Figure 1: Schematic of the layout of DAE $\delta$ ALUS accelerator modules. The powers at the respective modules, are average values based on a 20% duty cycle.

### Facilities Overview

In the DAE $\delta$ ALUS concept (described in detail in [4, 5]), three accelerator modules are placed at distances 1.5, 8, and 20 km from a large detector (see Figure 1). As the neutrino oscillation probability depends on  $L/E$ , the ratio of neutrino energy to the distance traveled [1], this scheme can work as follows: The near module constrains the flux, the mid module constrains the rise of the probability wave and the far module measures the oscillation maximum. Each of these modules consist of one or more chains of cyclotrons, as depicted in Figure 2. The neutrino distribution from the production target is more or less isotropic, which means the number of produced neutrinos needs to increase with distance if one wants to keep statistics up. Hence the higher power of the far site which will be reached by using several modules. In this way, DAE $\delta$ ALUS can be used to measure a  $\delta_{CP}$  dependent maximum of the oscillation curve. Figure 2 shows schematically the main parts of DAE $\delta$ ALUS:

1. Ion source
2. Low Energy Beam Transport (LEBT)
3. DAE $\delta$ ALUS Injector Cyclotron (DIC)
4. Medium Energy Beam Transport (MEBT)
5. DAE $\delta$ ALUS Superconducting Ring Cyclotron (DSRC)
6. High Energy Beam Transport (HEBT)
7. Neutrino production target

As DAE $\delta$ ALUS is a big project, it makes sense to look for a staged approach and physics that can be done with only part of it. In this case using only the DIC and replacing the DSRC with a different production target comes to mind. This is IsoDAR, a search for sterile neutrinos. Here the primary H $_2^+$  beam at 60 MeV/amu is used to produce  $\bar{\nu}_e$  through isotope-decay-at-rest. In both experiments, the primary ion beam

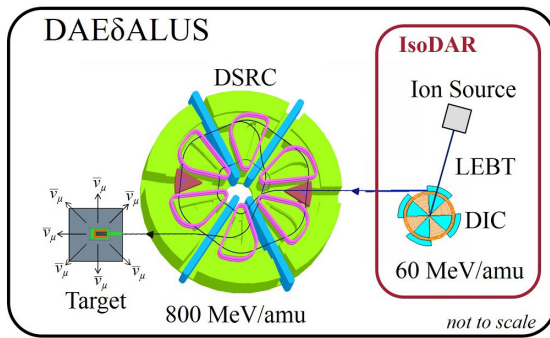


Figure 2: Cartoon picture of one single DAE $\delta$ ALUS module with the injector part that can be used for IsoDAR highlighted on the right.

current needs to be very high in order for the measurements to be conclusive within a certain time span. The nominal current is 5 mA. IsoDAR will operate with a 90% duty cycle, DAE $\delta$ ALUS with 20%. Clearly the target design is a major challenge for beam powers of 600 kW and 1.6 MW, respectively. However, for the sake of brevity and to keep with the topic of the conference, we will abstain from a discussion of the targets and instead point to the references given throughout this text. Similarly, we will not consider the MEBT and HEBT here as they are not considered high-risk. Instead, in the following section, we will discuss the ion source, LEBT, DIC and DSRC in more detail (henceforth called the “driver”).

## MOTIVATION OF DESIGN PARAMETERS

As the isodar front-end and cyclotron are, for all intents and purposes, identical to the DAE $\delta$ ALUS front-end and DIC, we will discuss IsoDAR first and consider only the DSRC in the subsequent DAE $\delta$ ALUS section.

### IsoDAR

Recently, the DAE $\delta$ ALUS Collaboration published a Conceptual Design Report (CDR) for the technical aspects of the IsoDAR project [7], in which the project is discussed in much detail. The important parameters of the front end and cyclotron are summarized in Table 1. From beginning to end, the driver consists of 1.) an ion source, 2.) a LEBT with buncher, and 3.) a compact isochronous cyclotron.  $H_2^+$  was chosen as primary beam ion because of the reduction in electrical beam current vs. particle current (after stripping),

Table 1: Important parameters for the IsoDAR driver.

| Parameter                 | Value    | Parameter                 | Value        |
|---------------------------|----------|---------------------------|--------------|
| Ion                       | $H_2^+$  | Ion Source                | Multicusp    |
| $I_{\text{source, nom.}}$ | 35 mA DC | Injection                 | Spiral Infl. |
| Cycl. Freq.               | 42.1 MHz | Harmonic                  | 6            |
| Cycl. Type                | Compact  | $E_{\text{max}}$          | 60 MeV/amu   |
| Extraction                | Septum   | $I_{\text{cycl., extr.}}$ | 5 mA avg.    |

Figure 3: 1-RMS beam radii for a matched beam in IsoDAR, starting at 193 keV/amu. Collimators are placed in turn 10 ( $\approx 3$  MeV/amu) which clean up beam halo, and only reduce the beam current from 6.5 mA to 5.0 mA. Data from [11].

which reduces space charge effects. At the same time the magnetic rigidity of the beam increases, which has to be taken into account during injection. The main challenges were identified as

1. Production of necessary initial current in the ion source.
2. Beam injection into the cyclotron through a spiral inflector of appropriate size to accommodate high rigidity.
3. Focusing and matching in the first 10 turns.
4. Ultra-low-loss extraction from the cyclotron.

**About items 1. and 2.** In the summers of 2013 and 2014 we tested  $H_2^+$  ion production, LEBT and cyclotron injection in collaboration with Best Cyclotron Systems, Inc. (BCS). The results were published in [8] and can be summarized as such: An off-resonance ion source like the one we tested (Versatile Ion Source - VIS) can provide the necessary  $H_2^+$  ion flux, but only marginally and through pushing the source to its limits. Consequently, we are now investigating alternatives to the VIS and conventional LEBT system. We are pursuing two avenues:

- We are currently building a new multicusp ion source at MIT called MIST-1 [9], which is optimized for  $H_2^+$ .
- We are investigating the use of an RFQ to directly inject a highly bunched beam into the spiral inflector [10]. Funding for a first RFQ injector was obtained and the first phase (design study) will commence this fall.

Furthermore, during the BCS tests, we could show that a large (1.6 cm gap) spiral inflector could be built and operated at up to  $\pm 12$  kV. 6 mA of a DC  $H_2^+$  beam were injected through the spiral inflector and results compared well with simulations.

**About items 3. and 4.** In a previous publication, it was shown through particle-in-cell (PIC) simulations using OPAL [12] that, starting at 1.5 MeV/amu, a stationary distribution in the horizontal plane could be achieved through vortex-motion [13]. Through collimation at low energy and tuning of the RF phase, it was possible to keep the predicted

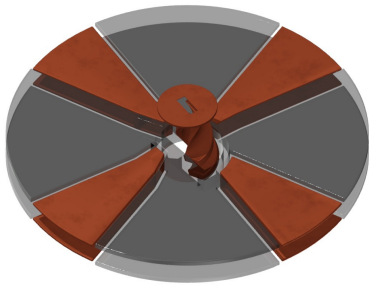


Figure 4: Preliminary CAD model of the IsoDAR central region.

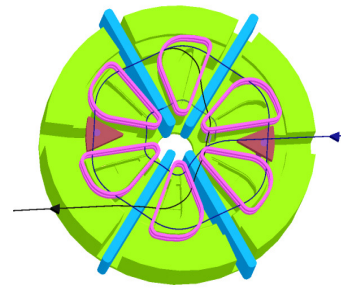


Figure 5: Preliminary CAD model of the DSRC with injection and extraction trajectories.

beam loss on the septum below 200 W. In the past few months, these simulations were extended to lower energies and matched distributions were found down to energies of 193 keV/amu. An example is shown in Figure 3. Note that the steep increase in longitudinal direction at the end stems from a resonance, which is expected to be suppressed in future design iterations of the magnetic field. The vertical beam size is fairly large in the first few four turns and then decreases rapidly. We are currently in process of designing a central region that can accommodate this large beam. The present state of the design is depicted in Figure 4.

### DAEδALUS

The DAEδALUS design was reviewed in detail in [4] and the most important parameters of the DSRC are listed in Table 2. The superconducting ring cyclotron will take the 60 MeV/amu beam from the IsoDAR-like front-end and boost it to 800 MeV/amu. Detailed simulations were performed and the results published in [13]. These simulations showed that a stationary distribution forms in the DSRC which can then be extracted very cleanly through stripping extraction. A model of the current design of the DSRC can be seen in Figure 5.

### CONCLUSION

DAEδALUS and IsoDAR are ambitious experiments aiming at discovering CP violation in the neutrino sector and the existence of sterile neutrinos, respectively. The requirement of 5 mA of  $H_2^+$  has led to a substantial R&D effort on which was reported here. We have identified the injection of the necessary current into the compact DIC (almost identical to the IsoDAR main cyclotron) as the main challenge and have

Table 2: Important parameters for the DAEδALUS driver. Note that the DIC parameters are identical to the IsoDAR parameters listed in Table 1.

| Parameter   | Value     | Parameter          | Value       |
|-------------|-----------|--------------------|-------------|
| Ion         | $H_2^+$   | Injection          | Radial      |
| Cycl. Freq. | 42.1 MHz  | Harmonic           | 6           |
| Cycl. Type  | Ring      | $E_{max}$          | 800 MeV/amu |
| Extraction  | Stripping | $I_{cycl., extr.}$ | 5 mA avg.   |

shown preliminary experimental studies and simulations that will soon lead into a full start-to-end simulation treatment of the system. The experimental high intensity injection studies showed that a spiral inflector with the required large size for the higher magnetic rigidity of the  $H_2^+$  beam can be built and operated. Simulations using OPAL with the new spiral inflector option compared well to these studies and systematic injection simulations using beam currents up to the required injection currents are on the way. Parallel to the conventional LEBT front end, we have just begun a full investigation of using an RFQ for direct axial injection of a bunched beam into the spiral inflector.

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