Update on DAEδALUS and IsoDAR: Coupled cyclotrons for high intensity $\text{H}_2^+$ beam production

Daniel Winklehner, MIT
Outline

Introduction
- 3-Page Neutrino Crash-Course
- DAEALUS & IsoDAR Facilities Overview

The Design
- Challenges
- Recent Tests/Experiments
- Recent Simulations

Outlook
- Next Steps
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Neutrinos in the Standard Model

- Part of lepton weak doublets
- Three flavors (+ anti-particles)
- Only interact through weak force (CC, NC) (no e/m, no strong force, no mass)
- E.g.: Beta – decay:

Source: symmetrymagazine.org
Neutrinos Oscillations

- Seen 1998 in SuperK experiment
- Confirmation by SNO in 2001
- KamLAND measurements of electron antineutrino disappearance from a reactor (2003) (picture)

- Mixing:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
U = \begin{pmatrix}
c_{12}c_{13} & s_{12}s_{13}e^{i\delta} & s_{13}e^{i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}
\end{pmatrix}
\]

- Mass!
- CP violation?
Sterile Neutrinos

- The width of the Z boson shows us that there are only 3 flavors of neutrinos that interact via the weak force.
- Reactor experiments indicate that there is a deficit in the electron flavored neutrinos.
- Calibration source experiments confirm this.
- Data from low L/E oscillation experiments observe ~3 sigma excess in $\nu_e$ and $\bar{\nu}_e$.
- Other type of neutrino could participate in oscillation $\rightarrow$ Sterile Neutrinos.

Graph showing the behavior of different types of oscillations with $E_{cm}$ and $\sigma_{had}$.
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DAEδALUS – CP Violation – $\bar{\nu}_e$ appearance
DAEδALUS + IsoDAR

DAEδALUS

Target

800 MeV/amu

DSRC

IsoDAR

Ion Source

LEBT

DIC

60 MeV/amu

not to scale
IsoDAR – Sterile $\nu$’s – $\bar{\nu}_e$ disappearance

Search for oscillations at short distances and low energy

1 kton detector

16.5 m
IsoDAR – Sterile $\nu$'s – $\bar{\nu}_e$ disappearance

Search for oscillations at short distances and low energy

1 kton detector

(3+1) Model with $\Delta m^2 = 1.0 \text{ eV}^2$ and $\sin^2 2\theta = 0.1$

Oberved/Predicted

$\bar{\nu}_e$

$\nu_e$

$\bar{\nu}_e$

$\nu_e$

$^7\text{Li Sleeve}$

$^9\text{Be Target}$

Protons

16.5 m
Challenges

• In order to yield results within a reasonable time-frame, we would like to have 10 mA of protons on target for 5 years continuously.

• IsoDAR: 90% duty cycle, DAEδALUS: 20%.
  – Clearly targets are going to be an issue at 600 kW and 1.2 MW, respectively.
  – Columbia University and Bartoszek engineering are working on this, not part of this talk, but understood to be a challenge.
Challenges

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• Main Challenge to consider: Space Charge!
  – Mitigate by accelerating $\text{H}_2^+$
  – Half the electrical current for same particle current (protons after stripping)
  – Higher rigidity has to be accounted for.
Going from End to Start

DAEδALUS

DSRC

Ion Source

LEBT

DIC

Target

800 MeV/amu

60 MeV/amu

not to scale
• Previously: 8 sector design
• Have solid beam dynamics calculations using OPAL for 8 sector. Stationary distribution develops, stripping extraction of $\text{H}_2^+$ yields excellent extraction efficiency.
• After magnet design study by PSFC (MIT) we changed design to 6-sector.
• 6-Sector beam dynamics pending.
• Main challenge: Vibrational states.

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<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<td>Ion</td>
<td>$\text{H}_2^+$</td>
<td>Injection</td>
<td>Radial</td>
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<tr>
<td>Cycl. Freq.</td>
<td>42.1 MHz</td>
<td>Harmonic</td>
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<td>Extraction</td>
<td>Stripping</td>
<td>$I_{\text{cycl., extr.}}$</td>
<td>5 mA avg.</td>
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Conceptual Layout of IsoDAR Driver

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<tr>
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<td>Septum</td>
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Immediate Concerns with High Intensity?

- 600 kW beam power
  → Worry about *uncontrolled* beam losses in the Cyclotron.

- 7 – 10% injection efficiency
  → Need 35-50 mA at injection to extract 5 mA.

- Space Charge in Cyclotron.
  - More Space Charge in Spiral Inflector.
  - Space Charge in LEBT.
  - Space Charge Compensation in LEBT?

- Can we transport that much without emittance becoming larger than acceptance?

- Can we produce that much in source?
Immediate Concerns with High Intensity?

- 600 kW beam power $\rightarrow$ Worry about *uncontrolled* beam losses in the Cyclotron.

- 5 – 10% injection efficiency $\rightarrow$ Need 50 mA at injection to extract 5 mA.

- Space Charge
  - More Space Charge in Spiral Inflector.
  - Space Charge in LEBT.
  - Space Charge Compensation in LEBT?

- Can we transport that much without emittance becoming larger than acceptance?

- Can we produce that much in source?

**Tests/Experiments**

**Simulations**

**Comparison**
Injection Tests at Best Cyclotron Systems, Inc.

Versatile Ion Source (VIS) loaned from INFN
Cyclotron + Teststand provided by Best Cyclotron Systems, Inc. (BCS)
Injection Tests
Injection Tests

- First, look at beam through spiral inflector
- 8 mA before, 7.5 mA inside \(\rightarrow\) 94% transmission
- Then accelerate
- Unfortunately, RF system did not manage to get to full power, only 50 out of 70 kV Dee voltage
- Measured beam currents on radial probes
Injection Tests

- First, look at beam through spiral inflector
  - 8 mA before, 7.5 mA inside
    → 94% transmission
- Then accelerate
- Unfortunately, RF system did not manage to get to full power, only 50 out of 70 kV Dee voltage
- Measured beam currents on radial probes

  Accelerated 100 µA for four turns in test cyclotron @50 kV V_{Dee}
Good agreement of LEBT Simulations/Exp.
Good agreement of LEBT Simulations/Exp.
• At position of Probe 1
• Noticeable shoulder on the right, due to insufficiently accelerated ions
• Overall good qualitative agreement
• FWHM not in as good agreement, most likely due to probe geometry.
Summary of Tests

- We did beam tests with a slightly modified version of the IsoDAR Spiral Inflector at BCS in Vancouver.
- Showed > 95% transmission at 6-8 mA
- Showed ~1% acceptance (~100 μA) in RF bucket (due to reduced $V_{\text{Dee}}$)
- Compares well with simulations.
- OPAL runs with up to 50 mA show reduction in Transmission + RF Capture from ~10% to ~5%. This will be addressed:
  - Final IsoDAR Spiral Inflector will be slightly larger.
  - Central region will have better vertical focusing.
  - Cyclotron will run 4 double gap cavities in 6\textsuperscript{th} harmonic.
  - Simulations can be tuned better to match highest intensity (for now, just used beam values from BCS tests to match results).
- Finally, close start-to-end gap by using spiral inflector results in main cycl.
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• Previously, we showed simulations using the PIC code OPAL (see tomorrow’s talk by A. Adelmann) for both DIC and DSRC [Yang et al.]

• For the DIC these started at 1.5 MeV/amu.

• Showed formation of a stationary, almost round, horizontal particle distribution (vortex motion) from initially mismatched distribution,

• Showed good turn separation at extraction (beam losses on septum < 200 W)
Current Simulation Work - DIC

- Extension of previous work down to 193 keV/amu (Jakob Jonnerby: Masters Thesis, PSI/ETHZ)
- Similar behavior as before, but larger
- Collimators at ~3 MeV/amu cutting beam from 6.5 mA to 5 mA to clean up halo.
- Turn separation not as good as before, need to optimize collimator placement.
- Larger vertical size in very first turns. Gap of RF cavity 30 mm, barely fits through.
Current Simulation Work – Spiral Inflector

- Based on BCS Tests we are currently in the process of designing a new central region for the DIC/IsoDAR to match LEBT beam to cyclotron simulations.
- Spiral Inflector model by Grazia D’Agostino, INFN.
- Very preliminary, tedious process.
- First single particle results
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• This fall we are commencing the first phase of the RFQ study (funding obtained)
  – Simulations & Design
  – Build Test stand and RFQ
  – Commission and Test

• We will continue developing the OPAL injection simulations
  – Finish design of first iteration spiral inflector and central region
  – Continue systematic study of bunched beam injection into cyclotron and subsequent acceleration to full energy
  – Start-to-end simulations of both front end options

• Parallel: Target design (Columbia, Bartoszek Engineering)
References


