DAEδALUS SUPERCONDUCTING RING CYCLOTRON TO DELIVER 10 mA PROTON BEAM AT 800 MeV

ECPM
May, 2012

Alessandra CALANNA
MIT/INFN
Primary physics goal: searching for CP-violation in the neutrino sector

- Short baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ experiment with no matter effect
- Novel design which provides high-statistics and low backgrounds
OUTLINE

• Physics Opportunities of DAEδALUS
• Basic Structure of the experiment
• Accelerator requirements
• Status of design
• Critical questions to be answered
• Next steps
DAEδALUS: experiment overview

Accelerator Complex (LNS-CSFNSM expertise)

**DAEδALUS**

- Far accelerator (5MW)
- Mid accelerator (2MW)
- Near accelerator (1MW)

**Near**:
- $1.27 \Delta m^2_{\text{atm}}$ L/E
- $\sim 0$
- Constrains flux

**Mid**:
- $\sim \pi/4$
- CPV L-dependence

**Far**:
- $\sim \pi/2$
- Oscillation max

**Vis source**

**Normal conducting Cyclotron**

**Superconducting Ring Cyclotron**

Gd-doped H2O detector
SOURCE & INJECTION CHANNEL

Accelerator Complex (LNS-CSFNSM expertise)

VIS source → Normal conducting Cyclotron → Superconducting Ring Cyclotron

Prof. L. Calabretta’s talk
Stay tuned!
DAEδALUS: experiment overview

Duty factor: 20%

proton beam 800 MeV @ 5 MW
proton beam 800 MeV @ 2 MW
proton beam 800 MeV @ 1 MW

osc max (π/2) at 40 MeV
off max (π/4) at 40 MeV
Constrains flux

H₂O w/ Gd
DAEδALUS: idea of dimensions

It could be

Because there is nothing like An existing detector
There is no creation of $\overline{\nu}_e$!
Since neutrinos do not travel as purely electron, muon or tau neutrinos, distances can provide information on:

- Beam-on background: 1.5 km cyclo
- Oscillation max: 8 km cyclo
- Disappearance: 20 km cyclo

3 distances can provide information on:

- Beam-on background: 1.5 km cyclo
- An oscillation wavelength of about $\pi/4$ at 50 MeV: 8 km cyclo
- Oscillation max: 20 km cyclo
Water provides target of a free proton for the inverse beta decay (IBD) interaction

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

Produces Cherenkov ring

Doped water with Gadolinium enhances the neutron capture signal

IBD interactions are identified via a coincidence signal
And in the Ultra-large detector era? We are already there!

>70% coverage $\delta$ at $5\sigma$!

With the courtesy of Prof. J. Conrad
ACCELERATOR REQUIREMENTS

What proton energy is required?
There is a "Delta plateau" where you can trade energy for current to get the same rate of v/MW

<600 MeV too little $\pi^+$ production

>1500 MeV energy goes into producing other particles besides $\pi^+$ at a significant level

DAEdALUS needs 1-1.5 MW proton beam @ 800 MeV

duty cycle= 20% $\rightarrow$ peak power 5-8 MW $\rightarrow$ Peak current 6-10 mA
Our Needs vs. Existing Machines

- LAMPF (Linac: 800 MeV, 1 mA)
- PSI (Cyclotron: 590 MeV, 2.3 mA)
- SNS (Linac: 1 GeV, 1 mA)

If we accelerate protons

If we accelerate H2+
POSSIBLE TECHNOLOGIES

- Superconducting linacs \(\rightarrow\) the most conservative technology option but they are expensive.

- Space and cost constraints suggest that high-power cyclotrons could be a less expensive option.

- Compact cyclotrons for protons – MMC – Stacked cyclotrons have been evaluated.

- FFAG very interesting, but not yet proven.

The Multi Mega Watt Cyclotron (MMC) accelerating \(\text{H}_2^+\) has 2 main advantages:
- Space charge effects reduced by a factor of \(\sqrt{2}\) with respect to proton beam
- Extraction by stripping foil
WHY STRIPPER EXTRACTION

Experience at PSI (best performing cyclotron existing). They have 99.98% of extraction efficiency. Our goal is to match their result (extraction with deflector)

- No interference with injection trajectory

- It is possible to accept an energy spread 0.5-1%

- No septum needed

- High binding energy, so we can use higher magnetic fields than TRIUMPH
MMC-R Superconducting Ring Cyclotron

- H2+ injected in the ring cyclotron at 60MeV/n
- Last closed orbit at 800MeV
- Isochronous field. Average field ≈2T
- Simulation done with OPERA3D:
  - Design the structure
  - Define materials
  - Design coils
  - Define mesh
  - Solve through Tosca (FEM)
  - Elaborate and visualize results with Post-Processor
  - Optimization process

- To accelerate H2+ the magnetic field is 2 times higher than for protons → superconducting coils
- Losses have to be limited to a few hundred watts in total
MMC-R Superconducting Ring Cyclotron

8 SUPERCONDUCTING sector magnets:

View of 1/16 of the cyclotron: median plane is above the upper hill

Sector Weight < 450 tons

Pole gap = 80mm

Half height 2.8m

Inner Yoke

Pole

Hill

Outer Yoke

Outer radius ≈ 7m
The different cross section is needed to guarantee enough space in the center region for the RF Cavities installation (and maybe is not enough!)

Current density 3400A/cm²
Area 30x24cm² or 15x48cm²

The winding of the cable could be a blocking point for cooling reasons
Huge forces developed
The longest straight arms of the coils will be connected with a plate passing between the upper and lower hill. This will be necessary to cancel the expansion magnetic forces which tend to make the coil round.

On the coil surface $B_{mod_{\text{max}}} \approx 6T$
MMC-R COILS

<table>
<thead>
<tr>
<th></th>
<th>DSRC</th>
<th>RIKEN-SRC</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Force *</td>
<td>3.7</td>
<td>3.3</td>
<td>MN</td>
</tr>
<tr>
<td>Radial shifting force *</td>
<td>2.7</td>
<td>0.36</td>
<td>MN</td>
</tr>
<tr>
<td>Azimuthal shifting force *</td>
<td>0.2</td>
<td>0</td>
<td>MN</td>
</tr>
</tbody>
</table>

With the courtesy of PSFC MIT Engineering Group

First evaluations on how the cryostat could be constructed

Axial Supports (2 by 3)
Radial/Lateral Tripod
Lateral Supports (2 by 2)
Total 16 Supports
MMC-R OPTIMIZATION RESULTS

All dangerous resonances are crossed quickly. Walkingshaw resonance is NOT crossed at the end of acceleration.

±0.5% between isochronous and calculated values. We need $10^{-4}$. 
B_{\text{max}} \text{ on a patch on the median plan} \ 6.05 \text{T}

B_{\text{min}} \text{ on a patch on the median plan} \ -2.5 \text{T}

1 \text{ Electrostatic Deflector} + 4 \text{ Magnetic channels for the injection}
Beam losses vs. Energy (H2+, I=8 mA, 12.8 MW)

- P=2E-8 mbar
- P=1E-8 mbar
- TRIUMF, P=2E-8 mbar

Residual Gas composition

H₂ 100%

\[ T = \frac{N}{N_0} = \exp \left( -3.35 \times 10^{16} \int \sigma_i(E) P \, dl \right) \]

\[ \sigma_i(E) \approx 4\pi a_0^2 \left( \frac{v_o}{v} \right)^2 \left( Z_t^2 + Z_j/Z_i \right) \]

\[ Z_t = 1 \]

With the courtesy of L. Calabretta
INFN-LNL
3 major blocking points in the design

- The variable cross-section that could cause complications on the LHe cooling system
- Huge residual radial FORCE that pushed outward the coil
- Not enough SPACE left between two contiguous sectors to install RF cavities PSI like
We need an exact symmetry 8 only above 400MeV/amu

-> the coil was divided in two zones. Fixing a point on the center of the hill where there is the last closed orbit, the tip of the coil was tilted by 4deg. Same with the contiguous coil ring, which was tilted by -4deg.

Constant cross-section of the coil, which is parallel to the median plane.
The stopping band resonance for a six sector machine is $\gamma = 3$

Why don’t use a 6-sector cyclotron?

Before we planned to use SCOILS and 4 empty valleys to install vacuum pumps. Since now we have coils parallel to mp and empty space in the center of the hill to install cryogenic panels, it is possible to explore the 6 sector option.

- No more issue for the RF cavities installation
- Easier study for injection system
- Sector shape similar to Riken

Constant cross-section of the coil, which is parallel to the median plan.
OTHER APPLICATIONS

Layout of a production plant

5 cyclotrons drive 4 ADS

2.5 MW

Each ADS is driven by 3 accelerators. Beam stability increases and decreases the number of beam trips

12.5 MW

APS Meeting, March 31st 2012

With the courtesy of L. Calabretta
SUMMARY

- DAEδALUS is an antineutrino experiment
- DAEδALUS results combined with other experiments will provide real improvement in the knowledge of the of $\delta_{cp}$
- A Superconducting Cyclotron has studied to produce the proton beam needed
- $H_2^+$ is the accelerated particle
- Applications in ADS filed

First 2 years of study confirm the feasibility of the project
In Ancient Greece,
DAEδALUS was the mythical patron of those
Who made wonderful things out of objects at hand