A CYCLOTRON TEST SITE FOR NEUTRINO EXPERIMENTS AND RADIOISOTOPE PRODUCTION

Main Goal: Construction of a cyclotron accelerators able to deliver 10 mA of proton beam

DAEδALUS: A Path to Measuring $\delta_{CP}$ Using Decay-at-Rest Neutrino Sources, by J. Conrad & M. Shaevitz

- 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
The DAEDALUS Neutrino Source

$\pi^+$ decay-at-rest (DAR) beam:

$$p + C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+ \leftrightarrow e^+ \bar{\nu}_\mu \nu_e,$$

Shape driven by nature!
Only the normalization varies from beam to beam

A great place to search for

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$\bar{\nu}_e$ is absent in the flux:
look for its appearance!
\[ \delta = \pi/2 \]
\[ \delta = 0 \]

**8 km**
- Constrains Initial flux
- Constrains rise of probability wave

**20 km**
- Osc. maximum at \( \sim 40 \text{ MeV} \)

- Near Neutrino Source
- Mid-distance Neutrino Source
- Far Neutrino Source

- Three Identical Beams
- Single Ultra large Detector
  - With Free Protons as IBD
  - \((\overline{\nu}_e + p \rightarrow e^+ + n)\) Targets

**Flux (arb. units)**
- Energy [MeV]
The duty factor is flexible, but beam-off is needed.
Cyclotrons: Viable technology?

PSI is current world power leader in this energy range

\(~ 1.4 \text{ MW average, 590 MeV protons}\)

Extrapolation to higher power?

Problems:

1. space-charge at injection

2. Clean extraction… max loss 200 W (\(\sim 10^{-4}\))
Proposed Solution: $\text{H}_2^+$ ions

- Two protons for every ion (1 emA = 2 pmA)
- Perveance of 5 emA $\text{H}_2^+$ at 35 keV/amu same as 2 emA of 30 keV protons
  - Axial injection of 2 emA protons at 30 keV is well within state of the art
- Extraction with stripping foil
  - Clean turn separation is not needed, only high-acceptance extraction channel
DAEdALUS Superconducting Ring Cyclotron has been investigated and Main technical problems set!

Coils and cryostat by J. Minervini (MIT), Stripper foil H. Okuno (Riken), Space Charge A. Adelman (PSI), Injection F. Meot (BNL)
IsoDAR (Isotope Decay At Rest)

- Proton beam into neutron-producing target
- Secondary neutrons into ~50 kg pure $^7$Li blanket
- $^8$Li decay produces $\bar{\nu}_e$, high beta endpoint energy
  - Good for discriminating background
- As with DAEdALUS, use IBD in liquid scintillator
  - Good spatial, energy resolution

GOAL: SEARCH STERILE NEUTRINO
Injector Cyclotron, normal conducting coils 60 MeV/amu, peak current 5 mA H$_2^+$

- Axial injection by spiral inflector
- Extraction by Electrostatic Deflectors

IsoDAR
NEEDS CW BEAM
POWER 600 KW!
arXiv: 1207.4895
Beam dynamic simulations made by A. Adelman and J. Yang at PSI, by OPAL code including space charge effects. Cyclotron magnetic field map supplied by Catania Team.
Beam dynamic simulations made by A. Adelman and J-Yang at PSI, by OPAL code including space charge effects cyclotron magnetic field map supplied by Catania Team

Radial particle distributions (last 4 turns)
Stripper to remove the halo beam on the septum

Deflector septum 0.5 mm thick

Extraction efficiency 99.98%, if beam power is 600 kW on the septum 120 W!
Injection test at “Best Cyclotron Inc.” site in Vancouver
CAPEN Experiment supported by “Commissione 5 INFN”
Central region and Spiral inflector designed by Catania Team
The Vancouver set-up has not the same central region of IsoDAR and Daedalus injector Cyclotron

Construction of a IsoDAR prototype cyclotron is convenient!

Central field 1.07 T
E = 7 MeV/amu
Rex = 0.7 m
This is a dual Cyclotron able to accelerate $H^-$ and ions with $q/A=0.5$ $H_2^+$ and $He^{++}$

Proton beam is extracted by stripper at 28 MeV

$H_2^+, D^+, He^{++}$ are extracted by Electrostatic deflector at 7 MeV/amu
### Cyclotron parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R axial hole</td>
<td>29 mm</td>
</tr>
<tr>
<td>R pole</td>
<td>800 mm</td>
</tr>
<tr>
<td>N. Sectors</td>
<td>4</td>
</tr>
<tr>
<td>Hill width</td>
<td>$30^\circ \div 36^\circ$</td>
</tr>
<tr>
<td>Valley gap</td>
<td>1400 [mm]</td>
</tr>
<tr>
<td>Pole gap</td>
<td>60 [mm]</td>
</tr>
<tr>
<td>Diameter</td>
<td>2800 [mm]</td>
</tr>
<tr>
<td>Full height</td>
<td>1800 [mm]</td>
</tr>
<tr>
<td>Total weight</td>
<td>52 [tons]</td>
</tr>
<tr>
<td>Vacuum</td>
<td>$10^{-5}$ Pa</td>
</tr>
<tr>
<td>Cavities $\lambda/2$</td>
<td>Double gap</td>
</tr>
<tr>
<td>Acc. Voltage</td>
<td>70 [kV]</td>
</tr>
<tr>
<td>Main Coil size</td>
<td>200x240 [mm$^2$]</td>
</tr>
<tr>
<td>2nd Coil size</td>
<td>30x240 [mm$^2$]</td>
</tr>
</tbody>
</table>

### Parameters for ions with $q/A=0.5$, $H_2^+$, $He^{++}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{inj}}$</td>
<td>70 [keV]</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>7 [MeV/amu]</td>
</tr>
<tr>
<td>$B_0$</td>
<td>1.08 [T]</td>
</tr>
<tr>
<td>$B_{\text{max}}$</td>
<td>1.90 [T]</td>
</tr>
<tr>
<td>RF Harmonic</td>
<td>4th</td>
</tr>
<tr>
<td>Freq.</td>
<td>32.5 [MHz]</td>
</tr>
<tr>
<td>Main coil curr. density</td>
<td>2.8 [A/mm$^2$]</td>
</tr>
<tr>
<td>2nd coil curr. density</td>
<td>-1.1 [A/mm$^2$]</td>
</tr>
</tbody>
</table>

### Parameters for proton beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{inj}}$</td>
<td>40 [keV]</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>28 [MeV]</td>
</tr>
<tr>
<td>$B_0$</td>
<td>1.12 [T]</td>
</tr>
<tr>
<td>$B_{\text{max}}$</td>
<td>2.0 [T]</td>
</tr>
<tr>
<td>RF Harmonic</td>
<td>2nd</td>
</tr>
<tr>
<td>Freq.</td>
<td>34.3 [MHz]</td>
</tr>
<tr>
<td>Cur. density</td>
<td>2.3 [A/mm$^2$]</td>
</tr>
<tr>
<td>Main coil</td>
<td>4 [A/mm$^2$]</td>
</tr>
<tr>
<td>2nd coil</td>
<td>2nd</td>
</tr>
</tbody>
</table>
Average field [T]

Isochronism plot

H_2^+, He

Protons

δω/ω₀

0,004

0

-0,004

-0,008

-0,012

0 20 40 60 80

60R [cm]
Acceleration phase

Protons   H₂⁺, He++
Beam Envelope along the extraction channel

E. Deflector

M1  M2

radial envelope

Axial envelope

Large normalised emittance 6.5 p mm.mrad

SIF, Trieste 23-27 Settembre 2013
Cyclotron view with extraction trajectory for H2+ and He++

Stripper extraction (proton beam) is not yet studied

Layout of vacuum chamber with holes for vacuum pumps, RF tuning and trimmer capacitors, diagnostic probes

SIF, Trieste 23-27 Settembre 2013
SIF, Trieste 23 - 27 Settembre 2013

Stem Diameter: 80 mm

Liner Cyl diam.: 288 mm

Length: 764 mm

Valley Height: 1400 mm

Height: 2600 mm

B28 Cavity Performances:
- Resonant Frequency: ≈ 31.7 MHz
- Quality Factor: ≈ 6.869
- Power dissipation: ≈ 10.58 kW
- Max Surface Current: ≈ 49 A/cm
- Max Electric Field: ≈ 5 MV/m
- Voltage Distribution on a gap: ≈ 70-70 kV
- Dee Radial Extension (Length): = 735 mm
- Stem Diameter/Liner Cyl Diameter: = 80/288 mm
- Dee Gap: = 30 mm
Extracted Beam

Holes for the RF Cavities

Central Hole for axial injection
On the other side

For installation at LNS the vertical position is selected, but for commercial use the horizontal installation is the favorite
The central region will be optimised for injection and acceleration of mA beam current of \( \text{H}_2^+ \) and \( \text{He}^{++} \). Unfortunately not fit for \( \text{H}^- \) injection!

A solution for a dual operation is to use a central region optimised for \( \text{H}^- \) and usable also for injection of \( \text{He}^{++} \), but this solution allow accelerating low beam current for \( \text{He}^{++} \) (10-100 microA)

The fast switch from a beam to the other, few hours, has to be optimised

Red curve 2\(^{\text{nd}}\) harmonic proton, green curve 4\(^{\text{th}}\) harmonic D, He Kleeven, Nantes Cyclotron

Switch from \( \text{H}^- \) to \( \text{He}^{++} \), and delivering the highest beam current is feasible opening the cyclotron and replacing the central region, expected time for this operation less than “one day”
Beam from SI
Back-integrated orbit
Our Goal is to accelerate an H2+ beam with a current of 5 mA

To achieve this goal we use our present existing Versatile Ion Source with some upgrading to deliver a beam current of about 50 mA

A new injection beam line, including a RF buncher have to be build MIT supply the fund to build the new beam line

The cyclotron is designed by INFN but will be built by BEST Cyclotron Inc. System, agreements are in progress
Beam current in the territory of 1-2 mA of proton beam are accelerated by commercial cyclotrons (2.1 $\pi$ mm.mrad nor.)

The use of H2+ beam and an higher injection energy should allow to increase this beam current (<1 $\pi$ mm.mrad nor.)

Expected bottle neck are the Buncher efficiency, electrostatic Spiral Inflector and central region acceptance

Preliminary injection tests are in progress at Best Lab

Study of a new generation of magnetic Spiral Inflector using Permanent magnet is in progress

Injection of H- beam current in excess of 1 mA and acceleration up to 28 MeV is an additional commercial goal
How we can use this cyclotron, after our research activities?

The cyclotron will be able to supply
Proton beam 1 mA @ 28 MeV
and/or Deuteron beam @ 14 MeV, Helium beam @28 MeV

current intensity depends from the central region
and from the ion sources

Straightforward application is radioisotope production

Physics Department of Catania University is interested to
develop a laboratory for radioisotope purification
Cyclotron produced Tc$^{99m}$

- The supply of Tc99m for Nuclear Medicine procedures has been interrupted several times recently and this has prompted the development of accelerator techniques for the production of Tc99m. The figure below indicates the production yields for the process \[ p + \text{Mo}^{100} \rightarrow \text{Tc}^{99m} + 2n. \]
### Direct Production of Tc99m

<table>
<thead>
<tr>
<th>Cyclotron</th>
<th>Energy on Target (MeV)</th>
<th>Yield (mCi)</th>
<th>Mo99:Tc99m Activity Ratio at EOB</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEST 14p</td>
<td>14</td>
<td>2000 (8000)</td>
<td>0.010</td>
</tr>
<tr>
<td>GE PETtrace</td>
<td>16</td>
<td>2600</td>
<td>0.011</td>
</tr>
<tr>
<td>IBA Cyclone 18</td>
<td>18</td>
<td>3000</td>
<td>0.036</td>
</tr>
<tr>
<td>ACSI TR19</td>
<td>19</td>
<td>4000 (16000)</td>
<td>0.038</td>
</tr>
<tr>
<td>ACSI TR24</td>
<td>24</td>
<td>5600 (22400)</td>
<td>0.270</td>
</tr>
</tbody>
</table>

**TABLE:** Tc99m estimated yields for a production run of 4 hours at 100 and (400) uA.

2000 – 4000 mCi for 2,000,000 population
Central Pharmacy can service need
Physical distillation
In mini hot cell.

Automate

Separation of Mo and Tc specific activity
The separation of the $^{100}$Mo target material and the $^{99m}$Tc is first accomplished by a dry distillation process as shown below. The irradiated target is transported to the processing unit.

The process steps correspond to converting the target material and radioisotope to their oxides, subliming the oxides and differentially distilling the oxides on different columns in the separation unit.

The resulting $^{99m}$Tc oxide is then further purified in small columns for the final $^{99m}$Tc radiochemical.
**Is possible satisfies the needs of Italy with just 6 dedicated cyclotrons like our or also using existing commercial cyclotrons, but ...**

**Distribution must be daily based for 99Tc**

*While the present ⁹⁹Mo distribution is weekly based additional costs and a lot of radioactivity material has to be transported through the country*

**99Tc is a new drug! You need new permission**
Could a high current alpha accelerator be useful?

A 1 mA of He beam can produce a dose of 80 Ci/week
Hospital generators needs a recharge of 0.5÷10 Ci/week
We could supply 160÷8 generators per week
A further interesting reaction is Bi 209 (alpha, 2n) At 211

At 211 decay scheme
$^{210}$At contaminant beta decay to $^{210}$Po. $T_{1/2}$ 138 days. Energy range limited below 30 MeV to avoid this problem.
...And that's all folks!

Thanks for your attention!