Developing a High Power Cyclotron
To Drive Sub Critical Reactor

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Summary/Outlook
(courtesy M. Seidel PSI, IPAC2010)

• the PSI accelerator delivers **1.3 MW** beam power; loss: \(\sim 10^{-4}\); average reliability is **90%**; **25-50 trips** per day; grid-to-beam power conversion efficiency is **32%** considering RF systems only; \(\sim 15\%\) including everything

• upgrade to **1.8 MW** is under work; new resonators Inj II; new 10’th harmonic buncher; completion planned for 2013

• cyclotron concept presents an effective option **to** generate high power beams, for example for ADS applications [e.g. **1 GeV/10 MW**]

2011 1.42 MW!
DAEALUS, a Decay-At-rest Experiment for CP studies At the Laboratory for Underground Science, provides a new approach to the search for CP violation in the neutrino sector. The design utilizes high-power proton beam to produce neutrino beams with energy up to 52 MeV from pion and muon decay-at-rest.

The experiment searches $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for at short baselines corresponding to the atmospheric $\Delta m^2$ region. The $\bar{\nu}_e$ will be detected in the 300 kton fiducial volume Gd-doped water Cerenkov neutrino detector proposed for the Deep Underground Science and Engineering Laboratory (DUSEL), via inverse beta decay.
Lay-out of DAEβALUS experiment. Three proton sources are used to send neutrino at a 300 kton water Cerenkov detector placed at 1.5 km underground.
We can know the distance for an event by the timing.
DAEδALUS needs 1 ÷ 2 MW proton beam @ 800 MeV

The beam time structure being 100 msec beam on, 400 msec beam off duty cycle= 20% → peak power 5÷10 MW → Peak current 6÷12 mA

- **Superconducting linacs provide the most conservative technology option but they are expensive**

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

We propose a Multi-Megawatt Cyclotron Ring (MMC), to accelerate $H_2^+$ for two main reasons:

- **Vantages of stripper extraction vs. the Electrostatic Deflectors extraction**

- **Space charge effects reduced by a factor $\sqrt{2}$ vs. proton beam**
Main Downtime Causes
- electrostatic elements
- controls problems
- cooling/site power
- RF not prominent!

Performance 2009
Reliability: **89.5%**
Beam trips: **25..50 d^{-1}**

PSI-HIPA operational data 2009, courtesy of M. Seidel PSI
The cyclotrons system is designed to deliver proton beam 10 mA @ 800 MeV duty cycle 20%, average power <1.6 MW> Stripper extraction

< 1 mA> H2+ 800 MeV/n 8 MW peak

< 1 mA> H2+ 60 MeV/n <120 kW>/600 kW peak

Space Charge effects, Electrostatic Deflectors

Superconducting Coils, Losses due to residual gas
The cyclotron complex here presented is designed to deliver a proton beam at 800 MeV with peak current of 10 mA. If duty cycle is 20% → the average beam power is 1.6 MW.
The beams delivered by the sources are chopped, to reduce the duty cycle at \( \sim 77\% \).

The power of the 3 cyclotron is reduced from 15.6 MW \( \rightarrow \) 10 MW.

6.5 mA of proton \( \rightarrow \) 5.2 MW delivered by each Ring Cyclotron.

3.25 mA of H\(_2^+\) delivered by each cyclotron Injector.
In case of failure, or ion source maintenance, it is possible to increase the duty cycle of the chopped source at 100% to maintain the beam power greater than 10 MW!

3.25 mA of H$_2^+$ delivered by each cyclotron injector.

The acceleration time along the injector cyclotron is approximately 12 $\mu$sec, so the chopping time structure will be 8 $\mu$sec Beam ON and 4 $\mu$sec Beam Off.

The beam loading is not a problem.

6.5 mA of proton or 5.2 MW delivered by each ring cyclotron.
Expected feedback time $< 100 \, \mu\text{sec}$

Bunch separation 20 nsec, Bunch length $< 1$ nsec

 SRC Transit time $\approx 50 \, \mu\text{sec}$

Power stability $<10^{-4}$ Feasible

The voltage to chop the beam is some kV and is applied using fast switch with rise time $<100$ nsec
test run: stable operation at 2.3mA
courtesy of M. Seidel PSI
Cyclotron allow for a Fast Control of beam intensity.

The beam current of each cyclotron can be fast modulated to control the power.
Beam losses vs. Energy (H2+, I=2.5 mA, 4 MW)

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

High energy gain/turn is useful to reduce beam losses present simulation <3 MeV/turn>

\[ T = \frac{N}{N_0} = \exp(-3.35 \times 10^{16} \int \sigma_i(E) \, P \, dl) \]
\[ \sigma_i(E) \approx 4\pi a_0^2 \left( \frac{v_s}{v} \right)^2 (Z_t^2 + Z_t/Z_i) \]

\[ Z_t = 1 \]
To deliver a proton beam with 10 mA peak current we have to accelerate an H$_2^+$ beam with a 5 mA peak current.

The Generalized Perveance is the parameter which measure the space charge effect, it is defined by this formula [M. Reiser]:

$$K = \frac{qI}{2 \cdot \pi \cdot \varepsilon_o \cdot m \cdot \gamma^3 \beta^3}$$

<table>
<thead>
<tr>
<th></th>
<th>$E_p=30$ keV, $E_{H_2}=30$ keV</th>
<th>$E_p=30$ keV, $E_{H_2}=70$ keV</th>
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<tbody>
<tr>
<td></td>
<td>$\beta_p = 1.414 \beta_{H_2}$</td>
<td>$\beta_p = 0.926 \beta_{H_2}$</td>
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<tr>
<td>Proton 10 mA</td>
<td>$K_p = 1.245 \times 10^{-3}$</td>
<td>Proton 2 mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K_p = 0.249 \times 10^{-3}$</td>
</tr>
<tr>
<td>H2+ 5 mA</td>
<td>$K_{H_2} = 0.881 \times 10^{-3}$</td>
<td>H2+ 5 mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K_{H_2} = 0.247 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$K_{H_2}/K_p = 0.707$</td>
<td></td>
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<tr>
<td></td>
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<td>$K_{H_2}/K_p = 0.992$</td>
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</table>
Cyclone-30 is able to delivers up to 2 mA

- 15 mA high-brightness $\text{H}^-$ source
- Reduce $\text{H}^-$ stripping losses
  - Differential pumping
  - Compact design
  - Axial bore elements in separate housing at atmospheric pressure (no outgassing)
- Two pairs of steering magnets for beam alignment at inflector
- Cyclotron iron is used as return yoke for the solenoid
- Magnetic shielding of turbo-pumps
H$_2^+$ Max current 3.25 mA: Without buncher
Current delivered by the H$_2^+$ ion source must be 60 mA, assuming phase acceptance ± 10°

With buncher, the current requested from the source should be <30 mA!
Preliminary test at Catania VIS source 20 mA!

Serious problem at the injection due to the thermal losses and space charge effect!

85% beam lost @ injection
7 mA at 2$^{nd}$ post
<1400 W @ 200 keV

15 mA at 1$^{st}$ post
<1050 W @ 70 keV

Extraction effic. > 99.95%
Beam power 400 kW
Power lost 200 W

5 mA at 3$^{rd}$ post
1750 W @ 350 keV
Versatile Ion Source (VIS)
Developed at LNS-Catania
by Gammino, Ciavola, Celona et Al.

VIS could deliver more than 30 mA of H2+ adjusting some parameters like: RF Power, Vacuum Pressure, Position of the permanent magnets, increasing the extraction hole.

Next summer we will perform a test, at the test stand of Best Cyclotron Company, under construction in Vancouver and using the Catania source.
Main parameters are extrapolated from existing commercial compact cyclotron: C30 and TR-30

Injection energy and acceleration voltage are higher vs. C30/TR-30
60 MeV/n after 110 turn vs. 150, or 8.8 μsec vs. 8.1 μsec

The space charge regime is the same of PSI cyclotron, we expect similar feature of phase compression from initial 20° to 2°-4° at extraction.
Beam emittance $6.4 \pi \text{ mm.mrad}$, off center + $3\text{mm}$ at orbit of $1\text{ MeV/n}$
Yoke

Valley

Holes for RF and vacuum pump
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Einj</th>
<th>Emax</th>
<th>800 MeV/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;R_{\text{inj}}&gt;$</td>
<td>2 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt;B&gt;$ at $R_{\text{inj}}$</td>
<td>1.07 T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pole Gap</td>
<td>80 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hill width</td>
<td>$\sim 20^\circ$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer radius</td>
<td>$\leq 7.5$ m</td>
<td></td>
<td>$&lt; 6$ m</td>
</tr>
<tr>
<td>Flutter</td>
<td>1.4 ÷ 1.97</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>4 Cavities type</td>
<td>Pill Box</td>
<td>2 Cavities type</td>
<td>Double gap</td>
</tr>
<tr>
<td>RF</td>
<td>49.2 MHz</td>
<td></td>
<td>6$^{\text{th}}$</td>
</tr>
<tr>
<td>V-peak</td>
<td>1000 kV</td>
<td></td>
<td>$2.6 \div 4.5$ MeV</td>
</tr>
<tr>
<td>$\Delta R$ at $R_{\text{inj}}$</td>
<td>$&gt; 20$ mm</td>
<td>$\Delta R$ at $R_{\text{ext}}$</td>
<td>3.2 mm</td>
</tr>
</tbody>
</table>

\[
\frac{dR}{dN} = R \frac{E_g}{E} \frac{\gamma}{\gamma + 1} \frac{1}{v^2}
\]
Effect due crossing
Walkinshaw resonance

With courtesy of J.J. Yang & A. Adelman
Simulation of space charge effects made by OPAL code (PSI)

Bunch length 6° RF

With courtesy of J.J. Yang & A. Adelman

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Stripper foil

Steering/focusing Magnetic Channel

Extraction trajectories with ±0.7% energy spread

Trajectory and Beam envelope verified by A. Adelman, J.J. Fang, PSI
space charge with short bunches – new regime, circular beam distribution

in theory

strong space charge within a bending field leads to rapid cycloidal motion around bunch center [Chasman & Baltz (1984)]

→ bound motion; circular equilibrium beam distribution

in practice

PSI’s Injector II cyclotron → circular bunch shape observed; same regime desirable in Ring (10’th harmonic buncher)

[courtesy of R. Doelling]
Stripper position is chosen to achieve:
- Beam extracted
- Good beam envelope
- No interference with injection devices
- Magnetic Field positive

H$_2^+$ beam
Stripper foil
emerging protons

If B=4 kGauss
Re=4.5 mm

3.2 MW Proton beam, release on the stripper
58W/16 mm$^2$ = 3.5 W/mm$^2$
PSI Rotating target 4.75 W/mm$^2$, life >10000 h
3.2 MW beam @ 800 MeV Xing a stripper foil 2 mg/cm² thick
Power lost due to nuclear interaction ~ 58 W

The electrons removed by the strippers have a full power of
3.2 MW*Mₑ/Mₑᴴ₂=3.2/(2*1822)=880 W !

This is the main source of stripper damage

But, electrons can be stopped before strike the stripper

<table>
<thead>
<tr>
<th>Ion</th>
<th>Beam energy</th>
<th>Foil thickness</th>
<th>Beam current</th>
<th>Electrons energy</th>
<th>Electrons power</th>
<th>Mean life</th>
<th>Mean life</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁻</td>
<td>520 MeV</td>
<td>2 mg/cm²</td>
<td>0.5 mA</td>
<td>285 keV</td>
<td>285 W</td>
<td>180 mAh*</td>
<td>360 h</td>
</tr>
<tr>
<td>H₂⁺</td>
<td>1600 MeV</td>
<td>2 mg/cm²</td>
<td>&lt;2&gt; mA</td>
<td>440 keV</td>
<td>880 W</td>
<td>58 mAh</td>
<td>26 h</td>
</tr>
</tbody>
</table>

Stripper Thickness can be also thinner, because lower H₂⁺ neutralization

H⁻ = (p+e+e) → p, e, e is a two steps process (p+e+e) → H + e → p, e, e
H₂⁺ = (p+p+e) → p, p, e is a single step process, low probability for → H + p

* Yuri Bylinsky, Triumf
Coil cross section at $R=4390$ mm
Coil Size
17 x 27 cm²
Current density
5000 A/cm²

Coil Size
20 x 30 cm²
Current density
<4000 A/cm²

B_{max} = 6.3 T at inner radius
Main Problems:
- Increase the field at outer radii;
- Increase the field at inner radii;
- Few iron at R=300 cm;
- Few space at inner radii to install the Pill Box RF cavity
- increase $\nu_z > 0.5$
New Coil Configuration

Coil Size 200 x 300 mm², I≤38 A/mm²

Injection Energy increased from 50 MeV/amu → 60 MeV/amu
...And that's all folks!

Thanks for your attention!