Status of the accelerators

Danilo Rifuggiato

LNS User meeting
December 2, 2014
Accelerator equipment for ion beam production

450 KV injector
2 sputtering sources

Normal conducting ECR source CAESAR

Superconducting ECR source SERSE
Limited availability of SERSE due to cryogenic problems

Autonomous system based on Helium recondensation

- Dimensioned and designed - cost defined to be around \(300\) k\(\varepsilon\) : project LNS Nuclear Astrophysics
- Realization: a) purchase of cryocoolers done 128 k\(\varepsilon\) b) assembling of cryocoolers and high \(T_C\) current leads \(\rightarrow\) middle of 2015

New beams with CAESAR new injection system

- metallic species through the installation of an oven
- new control system implemented
Tandem upgrade: a new Accelerator Tube n. 1

Tube n. 1 damaged: high residual pressure in the Low Energy section due to vacuum losses

Order to VIVIRAD, France, dated December 20th 2013: 237.000,00 € for 2 accelerator tubes - Delivered in May 2014

Replacement from the L.E. side

Dedicated system manufactured to remove the old tube and assemble the new one

July 9 2014 – The new tube positioned inside the Tandem

Tests are being carried out
Tandem upgrade: Belt → Pelletron conversion

Charging system

HVEC does not produce belts any longer. The insulating material of belts different from the original ones does not resist to temperature and discharges. Belts must have good mechanical and electrical characteristics - No company is available to improve them

**Alternative to the belt: Pelletron by NEC**

Order to National Electrostatic Corporation (NEC, USA) issued in July 2013: 598,845 US$ - Shipment on January 6, 2015 - Installation on January 19, 2015 (if the present tests end positively by Dec 5) Time needed: 2-3 weeks

From the belt
to the Pelletron
Superconducting Cyclotron: Helium liquefier revamping

• **January 1\(^{st}\) 2013** Breakdown of the helium liquefier: turbine found broken due to impurities (Air Liquide diagnosis) – restart on January 15 - Cyclotron operating on January 25

• **May 2\(^{nd}\) 2013** a new failure! Air Liquide inspection: again problems at the turbine - extraordinary maintenance and upgrade (revamping) needed to restore the reliability grade of the past 20 years

• **July 8\(^{th}\) 2013** Economical offer for the revamping operation produced by Air Liquide after a heavy interaction
  Estimated time: 6 months from the order

• **July 20\(^{th}\) 2013** Contract approved by the INFN Executive Board – performance bond and declarations requested to Air Liquide

• **October 8\(^{th}\) 2013** Air Liquide documents ready

• **October 15\(^{th}\) 2013** order issued
Planing documents received from Air Liquide since the order issue (October 15)

1) end of revamping in March 2014
   turbines not repaired, software not ready

2) end of revamping in May 2014
   software malfunctioning

3) end of revamping in July 2014
   problems of vacuum tightness in the turbine

LNS was kept open in August
The Cyclotron cryostat was full of LHe on September 23

Proton beam extracted on October 2
Superconducting Cyclotron

The experimental activity re-started in October 2014 after the liquefier revamping. The program October-December 2014 is being carried out. The program January-April 2015 is close to be published.

In June 2013 beam time was assigned for 1 year. Therefore there are approved experiments until the end of 2015 at least (390 BTU).

Few months before the end of 2015, a new call for proposals will be sent.
Superconducting Cyclotron
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Tandem
After the replacement of Tube n.1, tests are in progress in view of the Pelletron conversion, that will be accomplished in January 2015, as scheduled.

After the Pelletron installation, the approved experiments left (85 BTU) will be performed and a call for proposals will be sent.
The LNS Superconducting Cyclotron

- **Bending limit**: $K = 800$
- **Focusing limit**: $K_{\text{foc}} = 200$
- **Pole radius**: 90 cm
- **Yoke outer radius**: 190.3 cm
- **Yoke full height**: 286 cm
- **Min-Max field**: 2.2-4.8 T
- **Sectors**: 3
- **RF range**: 15-48 MHz

\[
\left(\frac{T}{A}\right)_{\text{max}} = K_{\text{bending}} \left(\frac{Q}{A}\right)^2 \sim 25 \text{ AMeV Au}^{36+}
\]

\[
\left(\frac{T}{A}\right)_{\text{max}} = K_{\text{focusing}} \left(\frac{Q}{A}\right) 100 \text{ AMeV fully stripped}
\]

**Versatility (performance)**

**Reliability (protontherapy)**

**High intensity (radioactive beams)**
Superconducting Cyclotron developed beams

\[ ^4\text{He} 80 \text{ AMeV} \]

\[ ^{112}\text{Sn} 43.5 \text{ AMeV} \]

In red beams with intensity \(10^{12}\) pps
Axial injection allows for intensity enhancement

Compactness makes extraction a critical process: $\varepsilon \approx 50\%$

Inter-turn separation

$$\Delta R = R \cdot \left( \frac{\Delta E}{E} \right) \cdot \left( \frac{1}{\nu_r^2} \right) \cdot \frac{\gamma}{(\gamma + 1)}$$
Increasing the Cyclotron beam intensity

- Septum: directly cooled
- New septum material: W vs. Ta
- Bigger thickness: 0.3 vs. 0.15 mm
  - Extraction efficiency 63% vs. 50%

\[ ^{13}C^{4+} @ 45 \text{ AMeV (EXCYT primary beam)} \]
\[ P_{\text{extr}} = 150 \text{ watt} \quad I = 1020 \text{ enA} = 1.5 \times 10^{12} \text{ pps} \]

The source-cyclotron matching needs to be improved

Beam transport along the injection line is now being considered, following the MSU, JYFL, KVI methods
Physics case demanding high intensity: double $\beta$ decay

\[ 1 / T_{1/2}^{0\nu} (0^+ \to 0^+) = G_{01} \left| M^{\beta\beta0\nu} \right|^2 \left| \frac{m_\nu}{m_e} \right|^2 \]

but one should know **Nuclear Matrix Element** (NME)

\[ \left| M^{\beta\beta0\nu}_e \right|^2 = \left| \left\langle 0_f \right| \hat{O}_e^{\beta\beta0\nu} \left| 0_i \right\rangle \right|^2 \]

A lot of new physics inside

\[ \langle m_\nu \rangle = \sum_i |U_{ei}|^2 m_i e^{i\alpha_i} \]
Double charge exchange reactions \((^{18}\text{O},^{18}\text{Ne})\) and \((^{20}\text{Ne},^{20}\text{O})\) towards the determination of the nuclear matrix element of the double \(\beta\) decay

\[
^{40}\text{Ca}(^{18}\text{O},^{18}\text{Ne})^{40}\text{Ar} \quad \text{exp. DOCET nov.2012}
\]
Extraction by stripping is based on the reduction of magnetic rigidity of the accelerated ion, caused by an increase of charge state or decrease of mass, after crossing a thin carbon foil (stripper).

For light ions at high energies the charge state fraction for $q=Z$ after a stripper with thickness bigger than the equilibrium thickness is >99%
Extraction by stripping: high efficiency >99%

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy</th>
<th>Isource</th>
<th>Iacc</th>
<th>Iextr</th>
<th>Iextr</th>
<th>Pextr</th>
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<tr>
<td></td>
<td>MeV/u</td>
<td>eμA</td>
<td>eμA</td>
<td>eμA</td>
<td>pps</td>
<td>watt</td>
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<tr>
<td>Carbon:</td>
<td>E=15 MeV/u</td>
<td>F(4)=1.74e-7</td>
<td>F(5)=8.35e-4</td>
<td>F(6)=0.99917</td>
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<tr>
<td></td>
<td>E=20 MeV/u</td>
<td>F(4)=2.56e-8</td>
<td>F(5)=3.20e-4</td>
<td>F(6)=0.99968</td>
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<tr>
<td>Oxygen:</td>
<td>E=15 MeV/u</td>
<td>F(6)=2.48e-6</td>
<td>F(7)=3.14e-3</td>
<td>F(8)=0.9969</td>
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<tr>
<td></td>
<td>E=20 MeV/u</td>
<td>F(6)=4.18e-7</td>
<td>F(7)=1.29e-3</td>
<td>F(8)=0.9987</td>
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<tr>
<td></td>
<td>E=30 MeV/u</td>
<td>F(6)=3.50e-8</td>
<td>F(7)=3.74e-4</td>
<td>F(8)=0.9963</td>
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<tr>
<td>Neon:</td>
<td>E=15 MeV/u</td>
<td>F(8)=2.00e-5</td>
<td>F(9)=8.90e-3</td>
<td>F(10)=0.9911</td>
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<tr>
<td></td>
<td>E=20 MeV/u</td>
<td>F(8)=2.66e-6</td>
<td>F(9)=3.26e-3</td>
<td>F(10)=0.9967</td>
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<tr>
<td></td>
<td>E=30 MeV/u</td>
<td>F(8)=2.26e-7</td>
<td>F(9)=9.51e-4</td>
<td>F(10)=0.9991</td>
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</table>

- $^{12}$C, q=4+, E=30 MeV/u
- $^{18}$O, q=6+, E=60 MeV/u
- $^{20}$Ne, q=4+, E=20 MeV/u
Beam dynamics calculations are necessary to ascertain the feasibility of extraction by stripping. In particular, the beam envelope has to be evaluated.

![Graph showing beam dynamics parameters](image-url)
Design of magnetic channels for beam focusing
From electrostatic extraction to extraction by stripping

A new cryostat

Conceptual design study accomplished in collaboration with MIT.

Report delivered on Oct. 31

Liquid nitrogen shield to be enlarged

LHe Cryostat to be modified

α-Coil layers to be removed
Agreement with MIT

Statement of Work
for
Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare (INFN)

Title: Conceptual Design of a Superconducting Magnet for the LNS Cyclotron

Tasks

• Magnetic design
deviation from the present form factors of the alpha and beta coils

• Conceptual design
  NbTi cable ans superconducting coils
  Cryostat
  Structural analysis
  Cryogenic consumption

• Preliminary schedule and cost estimate for design and manufacturing
Study of a new superconducting magnet
Study of a new superconducting magnet
The whole upgrade

Looking for intensity

- New s.c. magnet: cryostat with coils
- Stripper system
- Magnetic channels
- New liner
- Source-Cyclotron matching
- Cyclotron-Magnex beam line

Looking for reliability

- New trim coils
- RF cavities insulators
- New power supplies
- New Helium liquefier

Roughly estimated cost

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Superconducting magnet</td>
<td>5.4 M€</td>
</tr>
<tr>
<td>“Intensity” equipment</td>
<td>2.2 M€</td>
</tr>
<tr>
<td>“Reliability” equipment</td>
<td>4.5 M€</td>
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<tr>
<td>Total</td>
<td>12.1 M€</td>
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</table>
Cryostat design study: 09/2014 - 06/2015
Equipment construction: 10/2015 - 12/2017
Dismantling: 07/2017 - 12/2017
Assembling: 01/2018 - 12/2018
Commissioning: 01/2019 - 04/2019
Production Target: 0.5, 1.5, 2.5 mm Be

20° beam line - HODO

CHIMERA beam line
<table>
<thead>
<tr>
<th>primary beam</th>
<th>beam</th>
<th>intensity (kHz/100W)</th>
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<tbody>
<tr>
<td>18O 55 AMeV</td>
<td>16C</td>
<td>120</td>
</tr>
<tr>
<td>setting 11Be</td>
<td>17C</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>13B</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>11Be</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>10Be</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>8Li</td>
<td>20</td>
</tr>
<tr>
<td>18O 55 AMeV</td>
<td>14B</td>
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</tr>
<tr>
<td>setting 12Be</td>
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<tr>
<td></td>
<td>9Li</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>6He</td>
<td>12</td>
</tr>
<tr>
<td>13C 55 AMeV</td>
<td>11Be</td>
<td>50</td>
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<tr>
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<tr>
<td>36Ar 42 AMeV</td>
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<tr>
<td></td>
<td>35Cl</td>
<td>50</td>
</tr>
<tr>
<td>20Ne 35 AMeV</td>
<td>18Ne</td>
<td>50</td>
</tr>
<tr>
<td>setting ne18</td>
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<td>20</td>
</tr>
<tr>
<td></td>
<td>21Na</td>
<td>100</td>
</tr>
<tr>
<td>70Zn 40 AMeV</td>
<td>68Ni</td>
<td>20</td>
</tr>
</tbody>
</table>

Beams to be delivered in 2014-2015 to approved experiments

\[ ^{16}\text{C} \text{ (CHIMERA)} \]

\[ ^{68}\text{Ni} \text{ (CHIMERA)} \]

\[ ^{8}\text{He} \text{ (CHIMERA)} \text{ new} \]

\[ ^{14}\text{Be} \text{ (test experiment)} \text{ new} \]

\[ ^{38}\text{S} \text{ (MAGNEX)} \text{ new} \]
Thank you