SPES BEAM DYNAMICS

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B. Chalykh, ITEP, Moscow, Russia
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SPES, acronym of Selective Production of Exotic Species, is a CW radioactive ion beam facility under construction at LNL INFN in Italy.
Outline

• Overview of SPES Project.

• Transport line 1+:
  – Low energy transport and selection;
  – High Resolution Mass Spectrometer;
  – Charge Breeder.

• Transport line n+:
  – Clean the contaminants from CB with MRMS.
  – The new RFQ as new ALPI LINAC injector.

• ALPI LINAC for SPES.
**Premise**

- The LNL group has designed the RFQ for IFMIF EVEDA and the DTL for ESS (more in the main stream of this workshop).
- The post acceleration of SPES requires extremely good magnetic selection, high transmission (precious beam) and very good knowledge of the position of amount and location of beam losses.
- Contaminants give similar problems for radiation protection (MPS and activation in the beam setting steps).
- The approach computational tools (TRACEWIN, $10^5$ macroparticles, accurate field maps..) are almost the same.
The ISOL choice for SPES

Cyclotron → Proton Driver:
70MeV 0.75 mA  2 exit ports

NEW CONCEPT
direct target
Multi-foil UCx
designed to reach $10^{13}$ f/s
0.2 mA 40 MeV

Define a cost-effective facility in the order of 50 M€

SPES direct target/ion source
30g UCx
ISOLDE-type target/source
**SPES scientific and technical collaboration**

**INTERNATIONAL LEVEL**

**EUROPE**

LEA Colliga → France-Italy 
(SPES, SPIRAL2, ALTO, EXCYT, FRIB, Coll. on Det.)

ISOLDE (CERN) → SPES (Italy)

LEA (signed May 2014) → Poland-Italy

MoU (in preparation) → ELI-np - SPES

**NATIONAL LEVEL SPES collaboration**

Second Generation ISOL facilities

European ISOL Roadmap toward EURISOL

**INTERNATIONAL COLLABORATION** on Innovative Itinerant Detectors & on experimental proposals to keep a qualified & competitive level

AGATA, FAZIA, PARIS, NEDA, GASPARD

Italy → France, England, Spain, Poland, Romania, Bulgaria, Turkey, Germany, Croatia, Sweden, Finland, Denmark.

**WORLD**

MoU (signed) → iTHEMBA-Labs - INFN
HRIBF (ORNL)

RIKEN, MSU-FRIBS, RISP-KOREA, BARC, NEW DEHLI, DUBNA, MOSCA

Acc. Technologies & Mechanics 
(INFN divisions and Universities)

Milano, Bologna, LNS, LNL, Pavia, Trento, Palermo.

Physics Programs & Detectors (INFN) 
(Bari, Bologna, Catania, Firenze, Milano, LNL, LNS, Padova, Trento, Napoli)
The use of the continuous beam from the +1 source (LIS, PIS, SIS) maximizes the RNB efficiency but need a CW post accelerator (RFQ and ALPI); this layout also needs a charge breeder chosen to be an ECR that works in continuous.

The energy on the transfer lines are determined by the chosen RFQ input energy \( w_{RFQ} = 5.7 \text{ keV/u} \); namely, all the devices where the beam is approximately stopped (production target, charge breeder and RFQ cooler) lay at a voltage:

\[
e V = \left( \frac{A}{q} \right) w_{RFQ}
\]
The beam preparation scheme satisfies various requirements:

1. The zone with worst radiation protection issues is reduced by means of the first isobar selection (resolution R=1/200).
2. After that with an RFQ cooler the beam energy spread and transverse emittance are reduced both for further separation and to cope with the charge breeder acceptance (about 5 eV).
3. HRMS and MRMS (high and medium resolution mass spectrometers, R=1/40000 and R=1/1000 respectively) are used to select the RNB (with good transmission) and to suppress the contaminants from the charge breeder source.
4. Both the HRMS and the MRMS are installed on a negative voltage platform, to decrease the beam geometrical emittance, the relative energy spread and to keep the dipole field in a manageable range (>0.1 T).
5. The 7 m long RFQ has an internal bunching and relatively high output energy; this easies the setting and allows 90% transmission into ALPI longitudinal acceptance (constraint deriving from quite long ALPI period, 4 m).
6. An external 5 MHz buncher before the RFQ will be available for specific experiments (at the price of about 50% beam transmission).
7. The dispersion function is carefully managed in the various transport lines; where possible the transport is achromatic, otherwise the dispersion is kept low (in particular at RFQ input D=0, D' is about 50 rad).
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- Resonators: low-beta upgrade and E-Upgrade (+2 high-b cryostats)
- New quads with higher gradient (20→25 T/m) to optimize T
- RN Beam Diagnostics
- Cryogenics and cryostats upgrades
- Vacuum system replacement
- New controls (RF, diagnostics, magnets, access, vacuum)

- New HEBT to Hall III, low energy 1+ line, EXCYT spectrometer.
- Charge breeder and dedicated 1+ source
- MR Mass Spectrometer
- Transport to ALPI (lenses, bunchers, ...)
- New NC RFQ
SPES Layout
3° Hall

ALPI
PIAVE
TANDEM

NEW INJECTOR AND LINES

- Resonators: low-beta upgrade and E-Upgrade (+2 high-b cryostats)
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ALPI UPGRADE

- New HEBT to Hall III, low energy 1+ line, EXCYT spectrometer.
- Charge breeder and dedicated 1+ source
- MR Mass Spectrometer
- Transport to ALPI (lenses, bunchers, ...)
- New NC RFQ
- **Resonators**: low-beta upgrade and E-Upgrade (+2 high-b cryostats)
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- **New HEBT** to Hall III, low energy 1+ line, EXCYT spectrometer.
- **Charge breeder** and dedicated 1+ source
- **MR Mass Spectrometer**
- **Transport** to ALPI (lenses, bunchers, ...)
- **New NC RFQ**
• Usage of short electrostatic triplets (for little areas)
• 1/200 via D1 dipole. Isotopes from isobars separation
• HRMS to CB
• Wien Filter as a pre-mass separator.
• Usage of dipoles for bending magnets in order to control the dispersion.

To CB

Wien Filter

From Cyclotron

1/200 analyzer dipole
Input used for 1+ Beam:

- Mass 132 A 1+
- Voltage 40 kV
- RMS norm. Emittance 0.007 mmmrad Geom=8.6 mmmrad, Geom 99%=70 mmmrad, $\Delta E = \pm 20$ eV. Brho=0.33088485 Tm
- CEA TraceWin code
- Fields Maps for long Electrostatic quads and Wien Filter. Short triplets with hard edges.
From target to beam cooler

Wien Filter

1/200 Dipole

Dipole 90 deg to RFQ cooler

$D_x = 0$
HRMS physics design

Preliminary analysis (LNS-LNL)
Input parameters:
- **Energy** = 260 keV
- **$\Delta \theta$** = 4 mrad
- **$\Delta E$** = ± 5 eV
- **Emittance** 99% = 5.7π mm mrad

Linear design mass resolution: 1/60000 (eng. design: 1/25000)

Inspired to CARIBU-HRMS, ANL (USA)

**SPES RFQ Beam Cooler parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Range</td>
<td>5-200 amu</td>
</tr>
<tr>
<td>Transverse Emittance Injected beam</td>
<td>30 π mm mrad @ 40 keV</td>
</tr>
<tr>
<td>Emittance Reduction factor</td>
<td>10 (max)</td>
</tr>
<tr>
<td>Buffer Gas</td>
<td>He @ 273 K</td>
</tr>
<tr>
<td>Beam Intensity</td>
<td>50-100 nA $\rightarrow$ $x10^{13}$ pps</td>
</tr>
<tr>
<td>Energy spread</td>
<td>&lt; 5 eV</td>
</tr>
<tr>
<td>RF Voltage range</td>
<td>0.5 - 2.5 kV (1 kV at q=0.25)</td>
</tr>
<tr>
<td>RF Frequency range</td>
<td>1 - 30 MHz (3.5 - 15 MHz at q=0.25)</td>
</tr>
<tr>
<td>RFQ gap radius (ro)</td>
<td>4 mm</td>
</tr>
<tr>
<td>RFQ Length (total)</td>
<td>700 mm</td>
</tr>
<tr>
<td>Pressure Buffer Gas (He) range</td>
<td>0.1 - 2.5 Pa</td>
</tr>
<tr>
<td>Ion energy during the cooling</td>
<td>100 - 200 eV</td>
</tr>
</tbody>
</table>

**L. Calabretta**

Typical voltage fluctuation frequency: 200-300 Hz, <<10 kHz

Electrostatic Plates to correct the voltage ripple of the H.V. platform

Electrostatic Plates to correct the ± 750 V to correct ± 5 V platform ripple
HRMS physics design

preliminary analysis (LNS-LNL)
Input parameters:
- Energy = 260 KeV
- $\Delta \theta = 4$ mrad
- $\Delta E = \pm 5$ eV
- Emittance99% = $5.7\pi$ mm mrad

Linear Design Mass resolution: 1/60000
(eng. design: 1/25000)

COOLBEAM experiment financed by INFN-CSN5, 2012→2015
Collaboration: LNL-LNS, Mi Bicocca

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<tr>
<td>Beam Intensity</td>
<td>50-100 nA $\rightarrow$ $x10^{11}$ pps</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$&lt; 5$ eV</td>
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SPES Layout: zoom on 3° hall
ECR-type Charge Breeder

- CB based on ECR technique
- Developed by LPSC (LEA-COLLIGA coll.)
- Design 2013, construction 2014

**Features:** 3 coils for axial magnetic field; permanent magnet 6-pole for the radial field (1.2 T at injection, 0.42 T minimum and 0.82T at extraction). Microwaves at ~14.5 GHz and a maximum power of 600 W; operation at 18 GHz also possible.

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>ION</th>
<th>Q</th>
<th>Efficiency [%]</th>
<th>Year Data Source</th>
<th>(M/q)_min</th>
<th>(M/q)_max</th>
</tr>
</thead>
<tbody>
<tr>
<td>138</td>
<td>Xe</td>
<td>20+ (21+)</td>
<td>10.9 (6.2)</td>
<td>2012 (2005)</td>
<td>6.57</td>
<td>6.90</td>
</tr>
<tr>
<td>130</td>
<td>132</td>
<td>134</td>
<td>Sn 21+</td>
<td>6</td>
<td>2005</td>
<td>6.19</td>
</tr>
<tr>
<td>98</td>
<td>98</td>
<td>14+</td>
<td>Sr 14+</td>
<td>3.5</td>
<td>2005</td>
<td>7</td>
</tr>
<tr>
<td>94</td>
<td>94</td>
<td>16+(18+)</td>
<td>12 (8.5)</td>
<td>2013</td>
<td>5.22</td>
<td>5.88</td>
</tr>
<tr>
<td>90</td>
<td>99</td>
<td>14+</td>
<td>Y 14+</td>
<td>3.3</td>
<td>2002</td>
<td>6.43</td>
</tr>
<tr>
<td>74</td>
<td>80</td>
<td>10+</td>
<td>Zn 10+</td>
<td>2.8</td>
<td>2002</td>
<td>7.40</td>
</tr>
<tr>
<td>90</td>
<td>81</td>
<td>11+</td>
<td>Ga 11+</td>
<td>2</td>
<td>2002</td>
<td>7.36</td>
</tr>
<tr>
<td>92</td>
<td>34</td>
<td>8+(9+)</td>
<td>16,2 (11,5)</td>
<td>2012 (2013)</td>
<td>3.78</td>
<td>4.25</td>
</tr>
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</table>

A. Galata
Error study performed

Full Electrical fields maps for Multipoles

Input: 0.1 rms transverse norm., 28.44 rms geo. Tot geo emittance 222.7 π mm mrad.

Input Twiss parameters from simulation of CB. Spread of 5 eV. Brho = 0.076 Tm

Slits for beam selection, 1/166 sep
Beam optics of MRMS

In figure are reported 3 beams, with the same emittance, injected separated by $\frac{1}{1000}$ in mass. After the MRMS the beams are fully separated in X. RMS Tr. Norm. Input Emittance 0.1 mmmrad.

Dipoles
- $R=750$ mm
- $\Phi=90^0$
- Edge=33.35 °
- $B=0.2$ T
- Gap=$\pm\ 35$ mm
- $R_{sex}=1474$ and 828 mm
- Field homogeneity $10^{-4}$
  (in $\pm 180$ mm hor, $\pm 35$ mm ver)

Electrostatic multipoles elements
In the center (bore beam diameter=300 mm)

Beam Envelopes

In figure are reported 3 beams, with the same emittance, injected separated by $\frac{1}{1000}$ in mass. After the MRMS the beams are fully separated in X. RMS Tr. Norm. Input Emittance 0.1 mmmrad.
Transport Line to SPES RFQ

Magnetic Line with Magnets and Solenoids

TFQ

ECR ion source

Tape System

Mass Separator

CB

1+ Stable Source
New RFQ Injector for ALPI

- Energy 5.7 → 727.3 keV/A [β=0.0395] (A/q=7)
- Beam transmission >95%
- $\varepsilon_{\text{long, RMS, out}} = 0.15$ ns*keV/u.
- L=695 cm (6 modules)
- Intervane voltage 63.8 – 85.8 kV
- RF power (four vanes) 100 kW.
- Mechanical design takes advantage of IFMIF experience (LNL, INFN_Pd, Bo, To) for up to 1 mA

### Parameter (units) Design Value

| Operational mode | CW               |
| Frequency (MHz)   | 80.00            |
| Injection Energy (keV/u) | 5.7 (β=0.0035) |
| Output Energy (keV/u) | 727 (β=0.0395) |
| Accelerated beam current (μA) | 100 |
| Charge states of accelerated ions (Q/A) | 7 – 3 |
| Inter-vane voltage V (kV, A/q=7) | 63.8 – 85.84 |
| Vane length L (m) | 6.95             |
| Average radius $R_0$ (mm) | 5.33 – 6.788 |
| Synchronous phase (deg.) | -90 – -20 |
| Focusing strength B | 4.7 – 4 |
| Peak field (Kilpatrick units) | 1.74 |
| Transmission (%) | 95               |
| Output Long. RMS emittance (mmrad) / (keVns/u)/(keVdeg/u) | 0.055 / 0.15 / 4.35 |

See Talk of A. Palmieri
New RFQ Injector for ALPI

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See Talk of A. Palmieri

Mechanical layout of the RFQ (tank module ≈1.2 m)
Table 2: RFQ design parameters

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</tr>
<tr>
<td>Vane radius ρ to average radius ratio</td>
<td>0.76</td>
</tr>
<tr>
<td>Modulation factor m</td>
<td>1.0 – 3.18</td>
</tr>
<tr>
<td>Min small aperture a (mm)</td>
<td>2.45</td>
</tr>
<tr>
<td>Total number of cells</td>
<td>321</td>
</tr>
<tr>
<td>Synchronous phase (deg.)</td>
<td>-90 – -20</td>
</tr>
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<tr>
<td>Transmission (%)</td>
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</tr>
<tr>
<td>Input Tr. RMS emittance (mrmrad)</td>
<td>0.1</td>
</tr>
<tr>
<td>Output Long. RMS emittance (mrmrad)</td>
<td>0.055 / 0.15 /</td>
</tr>
<tr>
<td></td>
<td>4.35</td>
</tr>
</tbody>
</table>

Figure 1: The main RFQ parameters vs. length.
Design parameters
RFQ Mechanical concept

Bolted electrodes, copper plated 304L tank, metallic circular joints, brazing of electrodes and other components before assembly

Tank inner radius 375 mm, 40 mm thickness
Electrode assembly concept
To be compared with the case without buncher: total losses 93-94\% after the RFQ, output longitudinal emittance 0.067 \(\pi\) mmmrad.

IF 5 MHz buncher on:

Transmission 45% chopper,
Transmission RFQ output 43% emittance long rms 0.0371 \(\pi\) mmmrad.

Total amount of space occupied by the beam due to quad errors
Beam Optics of Transport line from CB via RFQ with static errors study

<table>
<thead>
<tr>
<th>Quad error type</th>
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<tbody>
<tr>
<td>Misalignement</td>
<td>0.15</td>
</tr>
<tr>
<td>Tilt</td>
<td></td>
</tr>
<tr>
<td>Gradient error</td>
<td>0.3%</td>
</tr>
<tr>
<td>Multipolar components</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

With this set of Errors we get an average of 7.4% of losses out of RFQ
New CR21 CR22

New HEBT to 3° hall

New Position for PIAVE QWR

New RFQ injector

PIAVE QWRs new position

2 new bunchers

4 new triplets

From 3° hall reshaping

4 m

3.5 m
ALPI LINAC for SPES case A/q=7

- Input energy from new RFQ: 93.9 MeV ($\beta=0.0395$) = 0.711 MeV/A.
- Output energy from CR21: 1285 MeV ($\beta=0.143$) around 9.7 MeV/A.
- Input Transverse emittance of 0.12 mmmrad RMS norm.
- Global transmission from CB to Experimental Hall: 0.95 (RFQ)*0.95(ALPI)=0.9=90%.
- Simulation software: Tracewin with full RF fields Maps for cavities.

ALPI Input Phase Space

ALPI Output Phase Space
Beam Optics from RFQ to Experimental Hall for $A/q=7$

Max G = 20 T/m

5% Losses

B. Chalykh
Beam Optics from RFQ to Experimental Hall for $A/q=7$

Max $G=25$ T/m

3% Losses

B. Chalykh
ALPI long acceptance plot

ALPI tunnel

Inside the cryostat
Energy from SPES Post-Accelerator as function of A/q

Preliminary results from alpi performances with 2 cavities off (margin), Low Beta=5 MV/m, Medium Beta=4.3 MV/m, High Beta=5.5 MV/m
Conclusions

• SPES post accelerator beam design has involved the study of many critical devices, and the overall optimization to distribute the criticality.
• The beam transport lines from CB to ALPI are specified and we are tendering the magnets.
• SPES cyclotron and building will be delivered March 2015
• The mechanical design of RFQ and HRMS will be completed during 2015; procurement procedure will follow within 2015.

The background
ALPI PIAVE accelerates ions up to Gold, energies up to 10 MeV/u, is the largest superconducting linac for ions in Europe.
Three projects are active in this moment for the development of high intensity linear accelerators in INFN

IFMIF EVEDA (International Fusion Material Facility)
MUNES (Multidisciplinar Neutron Source)
ESS (European Spallation sources) design

About 30 persons involved, 20 FTE, 10 dedicated contracts, dedicated funds from MIUR of about 30M€

The sections indicated in the map are involved
IFMIF-EVEDA RFQ (built by INFN)

- The most powerful RFQ beam (650kW)
- 130 mA deuterons accelerated
- 5 MeV final energy
- 9.8 m length, 18 brazed modules
- Due in Rokkasho March 2015

The 130 mA 9 MeV prototype built in EU and commissioned in JA
ESS: our contribution

• INFN in charge of design and prototypes, in kind contribution to be decided in the next months
  • Drift Tube Linac (3.6-90 MeV)
  • Operating frequency 352.2 MHz
  • 65 mA protons
  • Duty cycle up to 7%
Choice of $A/q$

Effective TTF in ALPI:
Energy gain per charge state/\( V T \cos(\phi_s) \)