Methods for Characterizing Rare Isotope Beams at the REX/HIE-ISOLDE Linear Accelerator

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Beam Quality

- **Beam Intensity Optimization**
  - Slow extraction
  - Charge-breeding performances

- **Transverse properties**
  - Quadrupole-scan
  - Trace space reconstruction

- **Beam Purity**
  - EBIS partial pressures
  - Rare contaminants

- **Longitudinal properties**
  - Beam energy distribution
  - Bunch structure
Experimental Hall

Low Energy RIB
E < 60 keV

General-Purpose Separator

p+ at 1.4 GeV

High-Resolution Separator

REX-ISOLDE

HIE-ISOLDE
Beam Quality

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- EBIS partial pressures
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- Quadrupole-scan
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Longitudinal properties
- Beam energy distribution
- Bunch structure
LaB6 cathode: $I_e < 250 \text{ mA (} j < 100 \text{ A/cm}^2\text{)}$, $U_{\text{gun}} < 5 \text{ kV}$

IrCe cathode: $I_e < 300 \text{ mA (} j < 400 \text{ A/cm}^2\text{)}$, $U_{\text{gun}} < 6.5 \text{ kV}$
Non-adiabatic immersed electron gun

- Immersed electron gun positioned in low B-field (few hundred Gauss)
- Reduce cyclotron motion with local magnetic element
- Produce a laminar beam that is thereafter adiabatically compressed by main B-field

A. Pikin et al., “A method of controlling the cyclotron motion of electron beams with a non-adiabatic magnetic field”, accepted PRAB
**Technique** Discretization of the axial energy distribution and solve all $V_{\text{barrier}}(t_i)$ (barrier step-function) to obtain a constant escape rate.

Ion energy distribution may be assumed a Maxwell-Boltzmann with 3 DoF: 

$$f(E_i) = \frac{2}{kT_i} \frac{E_i}{\pi k T_i}^{1/2} \exp\left(- \frac{E_i}{kT_i} \right)$$

Reduction of contamination via delayed extraction of the beam of interest (high CS) can be improved, notably with higher current density.

Axial energy distribution

**Technique**: Variation of REXEBIS extraction potential and monitoring of escaped ions to reconstruct the axial energy distribution.

**Energy dynamics**

\[
\frac{dk_B T_i}{dt} = \left( \frac{dk_B T_i}{dt} \right)^{\text{Spitzer}} + \left( \frac{dk_B T_i}{dt} \right)^{\text{Ionisation}} + \sum_j \left( \frac{dk_B T_i}{dt} \right)^{\text{Transfer}} - \left( \frac{dk_B T_i}{dt} \right)^{\text{Escape}}
\]

- **Capture**
- **Time-of-Flight** measured after the \(A/q\)-Separator when gating with the outer barrier.

- **Ionic axial energy distribution** measured at REXEBIS extraction, as a function of the electron beam current.

**Graphs**
- **Left**: Beam intensity vs. time.
- **Right**: Area-normalized intensities vs. axial energy.
**EBISIM package** collection of tools for simulating the evolution of the charge state distribution inside an Electron Beam Ion Source / Trap (EBIS/T) using Python. [GitHub](https://github.com/HPLegion/ebisim#readme). Developed by Hannes Pahl (CERN).

**EBISIM code: Charge state and energy dynamics**

**Figure** Electron impact cross sections

**Figure** Charge state distribution versus breeding time

**Figure** Energy-scan across DR resonances.

Charge dynamics:

\[
\frac{dN_q}{dt} = \frac{j_e}{e} f_{i,e} \left( N_{q-1} \sigma_{q-1}^{\text{EI}} - N_q \sigma_{q}^{\text{EI}} + N_{q+1} \sigma_{q+1}^{\text{RR}} - N_q \sigma_{q}^{\text{RR}} + N_{q+1} \sigma_{q+1}^{\text{DR}} - N_q \sigma_{q}^{\text{DR}} \right) 
+ \sum_j f_{i,j} \left( n_j \nu_{q+1} N_{q+1} \sigma_{q+1}^{\text{CX}} - n_j \nu_q N_q \sigma_{q}^{\text{CX}} \right) + N_q R_q^{\text{source}} + N_q^{\text{source}}
\]
Measurement of the charge state relative abundancies and comparison with EBISIM code featuring dielectric recombination effects in REXEBIS.

**Figures of merit:**
- Effective electron beam current density
- Space charge energy correction
- Electron energy spread

**Experimental setup** $^{39}\text{K}^q$ for $q = 13...17 \ @ 4 \text{ keV/u}$. RR = 1 Hz; Breeding time = 995 ms; $I_\text{e} = 50 \text{ mA}$. Potential use for charge state selectivity.

**EBIS plasma: Dielectronic recombination process**

**Introduction (3/3)**

**Rare Contaminants**

**Charge-breeding performances**

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**Electron beam**

- **K-shell**
- **L-shell**
- **$A^q + e^- \rightarrow [A^{q-1}]^* \rightarrow A^{q-1} + h\nu$**

**Potential use for charge state selectivity**

$A^q + e^- \rightarrow [A^{q-1}]^* \rightarrow A^{q-1} + h\nu$
EBIS plasma: Space charge potential

Space charge potential from the electron beam only.

With uniform e-beam:

\[
\phi(r) = U_t - \phi_0 \cdot \begin{cases} 
2 \ln \frac{r}{r_c} - \frac{r^2}{r_c^2} + 1 & , |r| \leq r_c \\
2 \ln \frac{r}{|r|} & , |r| > r_c 
\end{cases}
\]

Space charge potential including ion beam compensation.

Gauss law:

\[
\nabla \cdot \mathbf{E} = \frac{\partial}{\partial r} \left( r \frac{\partial \phi(r)}{\partial r} \right) = e \varepsilon_0 (n_e(r) - \sum_i \sum_q q_i n_i q(r))
\]

Using Boltzmann distribution:

\[
n_i(r, t = \infty) = n_i(0) \exp \left( - \frac{Q_i \phi(r)}{k_B T_i} \right)
\]

Convergence inspection:

\[
N_i(r > r_c) \propto \int_{r_c}^{+\infty} n_i(r) dr \\
\propto \int_{r_c}^{+\infty} r^{1-2Q_i \phi_0/(k_B T_i)} dr
\]

Use Riemann criteria
EBIS plasma: Extracted beam properties

Average radius of the ion cloud versus temperature.

Ion cloud characteristic radii:

\[ r_i = \int_{R_i} r^2 n_i(r) dr \]

\[ r_i^{\text{rms}} = \sqrt{\int_{R_i} r^3 n_i(r) dr} \]

Deduction of the overlap factor between electron and ion distributions.

Normalized emittance of extracted beam in a field free region.

Transverse emittance in EBIS (Cartesian):

\[ \varepsilon_x = \sqrt{\frac{k_B T_i}{2 m_i v_x^2}} \left[ (r_i^{\text{rms}})^2 - \frac{r_i^2}{\pi} \right] \]

Conservation of canonical momentum

\[ \varepsilon_x^2 (B = 0) = \varepsilon_x^2 (B = B_d) + \frac{Q^2 B_d^2}{16 m_i^2 v_x^2} (r_i^{\text{rms}})^4 \]
Measurement of the overlap factor

**Experimental setup** Neutral gas injection of $^{129}$Xe. Electron beam with a current of 200 mA and energy about 6 keV. Axial energy scans with varying breeding time.

- **Method**
  Fitting of three free parameters, using the lower gamma incomplete function:
  
  \[
  f(U) = I_0 (1 - \gamma \left( \frac{q U - E_0}{k_B T_i} \right)^5)
  \]

- **Results**
  Estimate of the ion temperature. Deduce the ion radial distribution. Calculate of the overlap factor.

- **Conclusion**
  The ion cloud remains confined within the electron beam. Heating rate:
  - Measured: 3.5 keV/s
  - From Landau-Spitzer: 2.4 keV/s
**Estimation of the effective electron current density**

**Objective** Estimate the effective electron current density $j_{\text{eff}}$, when comparing the measured charge state distributions with the EBISIM code.

- $j_{\text{eff}} = 600 \text{ A/cm}^2$ for $I_{\text{e}} = 300 \text{ mA}$.
- $j_{\text{eff}} = 400 \text{ A/cm}^2$ for $I_{\text{e}} = 200 \text{ mA}$.

**Method**
Measurement of the charge state distribution of $^{129}\text{Xe}^{q+}$ for different breeding time.

**Result**
Deduce the effective electron current density from a least-square minimization between the EBISIM code and the measurements.

**Conclusion**
- $j_{\text{eff}} = 600 \text{ A/cm}^2$ for $I_{\text{e}} = 300 \text{ mA}$.
- $j_{\text{eff}} = 400 \text{ A/cm}^2$ for $I_{\text{e}} = 200 \text{ mA}$.

Decreasing trend can be explained with reduced overlap factor.
Beam Quality

Beam Intensity Optimization
- Slow extraction
- Charge-breeding performances

Transverse properties
- Quadrupole-scan
- Trace space reconstruction

Beam Purity
- EBIS partial pressures
- Rare contaminants

Longitudinal properties
- Beam energy distribution
- Bunch structure
Abundant contamination

**Technique** Variation of REX A/q-Separator magnet, monitoring of current passing through slit on Faraday cup. Simplified model:

\[
\frac{dN_q}{dt} = \frac{I_e}{e} \frac{p}{k_B T_i} L_d \left[ f_{q-1} \sigma_{q-1} - f_q \left( \sigma_q^{\text{EI}} + \sigma_q^{\text{RR}} \right) + f_{q+1} \sigma_{q+1}^{\text{RR}} \right]
\]

<table>
<thead>
<tr>
<th>Element</th>
<th>Density [mm⁻³]</th>
<th>Pressure [mbar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>4.0 .10⁷</td>
<td>1.6 .10⁻¹⁰</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.5 .10⁷</td>
<td>6.0 .10⁻¹¹</td>
</tr>
<tr>
<td>Carbon</td>
<td>6.0 .10⁷</td>
<td>2.4 .10⁻¹⁰</td>
</tr>
<tr>
<td>Neon</td>
<td>2.0 .10⁶</td>
<td>8.0 .10⁻¹²</td>
</tr>
<tr>
<td>Argon</td>
<td>5.0 .10⁶</td>
<td>2.0 .10⁻¹¹</td>
</tr>
</tbody>
</table>

A/q-scan measured with a Faraday cup. \( I_e = 200 \text{ mA}, E_e = 6 \text{ keV} \).
From epA to single-ion detection

**Objective** Anticipate on the beam purity and probe A/q-areas where Faraday cups do not allow for identification.

**Technique** Instead of varying REX A/q-Separator magnet, all necessary beam optics and RF, from REXEBIS to the Si detector, are scaled for each A/q step.

Experimental setup in 2020, using non-adiabatic gun with IrCe cathode at higher electron beam density:

- Confirmation of the capability to probe rare contaminants.
- Residual gas ions were accelerated through the RFQ and acquired on a large Si detector installed directly afterward.
- Intensities are representative of reality.
Rare contaminants

Method $A/q$-scan measured with a silicon detector. $I_e = 200$ mA, $E_e = 6$ keV.

Application Investigation on the presence of Ir or Ce from the electron gun cathode using the silicon detector energy histograms.

Results
- Correlation with neighboring CS
- Poor energy resolution
- Negligible Ir/Ce contamination
- Cathode can be used
Beam Quality

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- Quadrupole-scan
- Trace space reconstruction

**Longitudinal properties**
- Beam energy distribution
- Bunch structure
HIE-ISOLDE

REX LINAC basic parameters

- $f = 101.28$ MHz
- Four-rod $\lambda/2$ RFQ and Buncher
- IH-structure
- Three 7-Gap resonators
- 9-Gap resonator ($f = 202.56$ MHz)

HIE LINAC basic parameters

- 4 high-$\beta$ cryomodules ($\beta_g = 10.3$)
- 20 quarter-wave resonators ($f = 101.28$ MHz)
- 4 superconducting solenoids

$^{23}$Na$^{9+}$ @ 10.43 MeV/u reached in November:
- REXTRAP+REXBIS efficiency: 17.7%
- LINAC transmission: 81%
Method

- Measurement of transverse beam profiles at the same location, with a Faraday cup for pA current range or a silicon detector below 1 fA.
- Bias and exclusion (threshold) analysis.

**Result** Capability to measure transverse profiles of very low intensity ion beams.
**HIE-ISOLDE: Transverse beam properties characterization**

**Experimental setup** \(^{39}\text{K}^{10+} @ 3.82 \text{ MeV/u}\), thin-slits and quadrupoles are used to probe the transverse phase-space for two ranges of intensity.

**Treatment when using Faraday cup as beam collector**

Exclusion ellipse: deduce a threshold from the evolution of the second derivatives of the Twiss parameters.

**Left:** Double-slit scan using Faraday cup (>10 epA). **Right:** Silicon detector (<1 eFA).

**Technique**

With the double-slit scan, the transverse phase-space is sliced twice. Beamlet acquired via a silicon detector or a Faraday cup.

**Result**

Validation of the new methodology with very low intensity ion beams. Correlation of the results for the two ranges of intensity.

"Characterization of the transverse properties of very low intensity ion beams at the REX/HIE-ISOLDE LINAC", N. Bidault, et al., NIM-A, in-review.
HIE-ISOLDE: Transverse beam properties characterization

Experimental setup $^{39}$K$^{10+}$ @ 3.82 MeV/u, thin-slits and quadrupoles are used to probe the transverse phase-space for two ranges of intensity.

Method

With the quadrupole scan the transverse phase-space is sliced once and rotated.

Results

<table>
<thead>
<tr>
<th>Plane</th>
<th>Parameter</th>
<th>Value SD</th>
<th>Value FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-plane (a)</td>
<td>$\beta_x$ [mm.mrad$^{-1}$]</td>
<td>4.8(5)</td>
<td>5.1(5)</td>
</tr>
<tr>
<td></td>
<td>$\gamma_x$ [mrad.m^{-1}]</td>
<td>0.21(3)</td>
<td>0.20(3)</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{SD/FC}(\sigma_1^x)$</td>
<td>0.988</td>
<td></td>
</tr>
<tr>
<td>y-plane (b)</td>
<td>$\beta_y$ [mm.mrad$^{-1}$]</td>
<td>2.4(3)</td>
<td>2.8(3)</td>
</tr>
<tr>
<td></td>
<td>$\gamma_y$ [mrad.m^{-1}]</td>
<td>0.25(11)</td>
<td>0.23(9)</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{SD/FC}(\sigma_1^y)$</td>
<td>0.984</td>
<td></td>
</tr>
</tbody>
</table>

Tomography

Reconstruction of the trace space from the quadrupole-scan

Intensity          Purity          Transverse Properties          Longitudinal Properties
Beam Quality

**Beam Intensity Optimization**
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- Charge-breeding performances

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- EBIS partial pressures
- Rare contaminants

**Transverse properties**
- Quadrupole-scan
- Trace space reconstruction

**Longitudinal properties**
- Beam energy distribution
- Bunch structure
HIE-ISOLDE: Beam energy distribution measurement

**Technique**
Use of an HEBT dipole as energy-spectrometer and three vertical slits. Acquisition of the beamlet current with a silicon detector.

Measurements using the three HEBT dipoles confirmed to be similar.

The energy spread derived is overestimated depending on the beam transverse emittance and the spacing between the 1-mm vertical slits.

Proven capability to measure the energy distribution of very low intensity ion beams.

**Method**
Estimation the inherent spread introduced by the thin slits in the measurement channel and deconvolution on typical energy distribution measured from a RIB.
HIE-ISOLDE: Longitudinal phase-space characterization

\[ \varepsilon(z_0) : \gamma_z (\Delta t)^2 + 2\alpha_z \Delta W/A + \beta_z (\Delta W/A)^2 = \varepsilon_z \]

\[ R_{\text{ir}}(E_0) = \begin{pmatrix} 1 & 0 \\ 1 - 2\pi f_0^2 E_0 T_L \sin(\varphi) & 1 \end{pmatrix} \]

\[ R_{\text{in}}(L) = \begin{pmatrix} 1 & -\frac{ML}{\beta \gamma (\gamma + 1) L^2} \\ 0 & 1 \end{pmatrix} \]

Experimental setup \( ^{20}\text{Ne}^{8+} \) @ 6.64 MeV/u, 10 superconducting cavities (SCC) at nominal accelerating phase, 1 SCC acting as a buncher at zero-crossing phase.

Method Energy spread measurement.
Method Time structure measurement.


<table>
<thead>
<tr>
<th>Beam Property</th>
<th>From ( \Delta W )</th>
<th>From ( \Delta t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_z [\pi, \text{ns, keV/u}] )</td>
<td>1.25(8)</td>
<td>1.18(10)</td>
</tr>
<tr>
<td>( \alpha_z )</td>
<td>-3.54(30)</td>
<td>-4.68(50)</td>
</tr>
<tr>
<td>( \beta_z [\text{ns/(keV/u)}^{-1}] )</td>
<td>0.0183(20)</td>
<td>0.0194(30)</td>
</tr>
<tr>
<td>( \gamma_z [\text{keV/u, ns}^{-1}] )</td>
<td>970(40)</td>
<td>1110(50)</td>
</tr>
</tbody>
</table>
Summary

Analysis of REXEBIS performance and produced ion beam quality

- Estimation of REXEBIS electron current density for the new electron gun
- Capability to measure rare contaminants over wide A/q range
- Access to ion distribution of axial energy

Post-accelerated ion beam characterization

- Reliability on transverse beam profile measurements in the sub-femto A range
- Method for probing the transverse beam properties at very low intensity
- Consolidation of beam energy measurement technique
- Method for characterizing the longitudinal phase-space at very low intensity
Thank you for your attention

This work is the result of a collaborative effort involving in particular the following teams at CERN:

**ISOLDE Operation (BE-ISO-OP):**
- Miguel Luis BENITO
- Eleftherios FADAKIS
- Simon MATAGUEZ
- Emiliano PISELLI
- Jose Alberto RODRIGUEZ
- Erwin Siesling

**Beam Physics (BE-ABP):**
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- Hannes PAHL
- Alexander PIKIN
- Fredrik WENANDER

**Beam Instrumentation (BI):**
- William ANDREAZZA
- Enrico BRAVIN
- Sergey SADOVICH
Non-adiabatic immersed electron gun

**Design**

- Post anode
- Iron ring
- Anode
- Wehnelt
- $\phi=2$ mm IrCe cathode

Post anode used to adjustment the phase of cyclotron wrt iron ring for different beam currents

**Results**

- **Current and losses**
  - $I_e$ well behaved to 300 mA
  - <15 uA anode losses
  - <100 uA losses on drift tube in front of suppressor

- **EBIS breeding efficiency**
  - 19.7% for $^{39}$K$^{1+}$ to $^{39}$K$^{10+}$
  - Almost as high as for old gun

- **Effective current density**
  - $T_{\text{breed}}=44$ ms for $^{133}$Cs$^{1+}$ to $^{133}$Cs$^{31+}$
  - $j_e$ estimated to ~400 A/cm$^2$

- **Problems**
  1. Excessively high cathode work function (activation not helpful)
  2. Electron beam losses rises exponentially when $I_e > 300$ mA. Believed to be caused by back-scattered or elastically reflected electrons from the collector region.
Silicon Detector specifications

Figures Diagram of the Silicon Detectors DAQ at HIE-ISOLDE.

<table>
<thead>
<tr>
<th>Type</th>
<th>Canberra’s model</th>
<th>Radius [mm]</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PD50-11-300RM</td>
<td>4.0</td>
<td>Energy [keV] Time [ns]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>TMPD50-16-300RM</td>
<td>4.0</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>PD600-20-300RM</td>
<td>13.8</td>
<td>20</td>
</tr>
</tbody>
</table>

Table Basic parameters of 300 µm-thick PD-PIPS detectors used at HIE-ISOLDE (*²⁴¹Am, 5.486 MeV alphas).