Beam parameters and physics opportunities
- or why an upgraded EBIS and a buncher should be considered

J. Cederkall, Lund University
What has been achieved? What is next?

- Some goals for HIE-ISOLDE with attempt at a combined physics–and-machine view
- What is the current status?
- What can we do next?
- Which generic developments could/should we focus on?
Some physics for accelerated RIBs

- Shell evolution and isotopic chains
- The heaviest elements
- Shapes and shape co-existence
- Nuclear astrophysics (R- and rp-processes)
- Halos and few particle interactions
- …
REX-ISOLDE and HIE-ISOLDE (evolution…)

- Semi-continuous beam (release time in ms range)
- Emittance ~35 π mm mrad @ 60 keV
- Occasionally not isobarically nor molecularly clean beams.
## Table 1.1: Requested beam characteristics at HIE-ISOLDE.

<table>
<thead>
<tr>
<th>Beam parameter</th>
<th>Description or value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>continuous from $&lt; 0.7$ to at least $10$ MeV/ nucleon</td>
</tr>
<tr>
<td>Beam spot diameter</td>
<td>$&lt; 1 - 3$ mm FWHM</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>$&lt; 1 - 3$ mrad FWHM</td>
</tr>
<tr>
<td>Micro-bunch structure(^{\text{a}})</td>
<td>no requirement of micro-bunching to bunch at $&lt; 1$ ns FWHM with $\sim 100$ ns bunch spacing</td>
</tr>
<tr>
<td>Macro-bunch structure(^{\text{a}})</td>
<td>longer pulse lengths or cw operation</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td>Absolute energy resolution(^{\text{b}})</td>
<td>no specific details given</td>
</tr>
</tbody>
</table>

\(^{\text{a}}\) The time structure of the beam is determined by the charge breeder and the REX front end, see Figure 2.4.

\(^{\text{b}}\) No system currently exists to measure the absolute beam energy; time-of-flight systems are being discussed.
Effusion, diffusion and decay

K. Peräjärvi et al. NIM B 204 (2003) 272
The combined time structure

Semi-continuous beams already from the primary target.

Fig. 1. The time structure of the PS-BOOSTER proton pulses is illustrated. A standard proton pulse \((N)\) contains up to \(3 \times 10^{13}\) protons distributed in 20 bunches over 2.4 \(\mu\)s. In the staggered mode \((S)\) three groups of 5 bunches are extracted at time intervals ranging from 5 to 500 \(\mu\)s (maximum pulse intensity: \(2.2 \times 10^{13}\) ppp). The maximum proton pulse intensity is obtained by immediate extraction of the last synchrotron \((S4)\).

Fig. 6. The ionic current of \(^{190}\)Hg as recorded with a 0.5 mm metallic needle is shown for different proton beam intensities in the staggered mode (a) \(9 \times 10^{12}\), (b) \(1.5 \times 10^{13}\) and (c) \(2.1 \times 10^{13}\) proton per pulse. The parameters of the release function from which the release time is calculated were fitted to these data. The timing of the 8 proton pulses in the 19.2 s cycle is shown.

J. Lettry et al. NIM B 126 (1997) 170
The pulse structure

Fig. 2.4: REX beam time structure. Figure courtesy of J. van de Walle.
The pulse structure

- **Maintain driver flexibility in any upgrade**
  - Target response is different for different elements and can be used to improve beam purity

- **Provide user interface for beam gate control**

Fig. 2.4: REX beam time structure. Figure courtesy of J. van de Walle.
Target development for future improved yields?

LIEBE target

\[
\begin{align*}
&y = -0.0718x^2 + 15.898x - 868.32 & \text{ABRABLA 2.0GeV-4uA} \\
&y = -0.0704x^2 + 15.68x - 861.98 & \text{FLUKA 2.0GeV-4uA} \\
&y = -0.074x^2 + 16.486x - 906.85 & \text{FLUKA 1.4GeV 2uA}
\end{align*}
\]

The principle

Worst case:
assume ca 10 mm
ca 30 mm
Δφ= (14 - 5 ) deg

ca 15 mm
Kinematics

Galilean transformation $\rightarrow$ Max scattering angle

$V_{\text{cm}}$

$v_{\text{part}}(\text{cm})$

Backward branch

Forward branch

$tangent$

$v_{\text{part}}(\text{lab})$

$v_{\text{part}}(\text{cm})$
Kinematics I

$^{110,108,106}\text{Sn}$ on $^{58}\text{Ni}$ at 2.8 MeV/u

Energy in lab vs scattering angle

Measurement

Calculation

high cross section

$^{110}\text{Sn}$

$^{58}\text{Ni}$

Energy in lab vs scattering angle
Cross section for a $2^+$ and $4^+$ excitation
Sn-110 and Pb-206

Indirect detection
Energy spread and beam spot size


C-12 (3+)

Mg-28 (9+)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>66Ni16+</td>
<td>4.5</td>
<td>4.47</td>
<td>0.2</td>
</tr>
<tr>
<td>9Li3+</td>
<td>6.9</td>
<td>6.72</td>
<td>0.5</td>
</tr>
<tr>
<td>132Sn31+</td>
<td>5.5</td>
<td>5.49</td>
<td>0.4</td>
</tr>
<tr>
<td>78Zn20+</td>
<td>4.3</td>
<td>4.27</td>
<td>0.3</td>
</tr>
</tbody>
</table>

J. A. Rodriguez Rodriguez et al. priv comm.
Energy spread and beam spot size


C-12 (3+)

Mg-28 (9+)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>66Ni16+</td>
<td>4.5</td>
<td>4.47</td>
<td>0.2</td>
</tr>
<tr>
<td>9Li3+</td>
<td>6.9</td>
<td>6.72</td>
<td>0.5</td>
</tr>
<tr>
<td>132Sn31+</td>
<td>5.5</td>
<td>5.49</td>
<td>0.4</td>
</tr>
<tr>
<td>78Zn20+</td>
<td>4.3</td>
<td>4.27</td>
<td>0.3</td>
</tr>
</tbody>
</table>

J. A. Rodriguez Rodriguez el al. priv comm.
Statistics now and then

25% of HIE data

In total ~150 larger statistics

100% of REX data
Statistics now and then

25% of HIE data

100% of REX data
What is accessible with a generic approach to HIE-infrastructure?

Now: Coulomb excitation or neutron transfer, e.g. protons come out from a d-target.
What new is accessible with a generic approach to HIE-infrastructure?

Proton transfer, i.e. neutrons come out from a d-target

Need for neutron detectors which preferably use time-of-flight and good start time, or separator alt. spectrometer
What is accessible with a generic approach to HIE-infrastructure?

...including rp-process via surrogate methods.
Single particle dominated states

For two particles outside a core:

\[ H = \sum_{k=3}^{A} [T_k + U(\vec{r}_k)] + \sum_{k=3}^{A} \sum_{l=k+1}^{A} W(\vec{r}_k, \vec{r}_l) - \sum_{k=3}^{A} U(\vec{r}_k) \]

\[ H_{core} \]

\[ = \sum_{k=1}^{2} [T_k + U(\vec{r}_k)] + \sum_{k=1}^{2} \sum_{l=k+1}^{A} W(\vec{r}_k, \vec{r}_l) - \sum_{k=1}^{2} U(\vec{r}_k) \]

\[ H_{0}^1 + H_{0}^2 \text{ independent motion} \]

\[ H_{12} \text{ interaction} \]

\[ H_{12} = \sum_{l=3}^{A} W(\vec{r}_1, \vec{r}_l) - U(r_1) + \sum_{l=3}^{A} W(\vec{r}_2, \vec{r}_l) - U(r_2) + W(\vec{r}_1, \vec{r}_2) \]

\[ \approx 0 \]

\[ = V(\vec{r}_1, \vec{r}_2) \]
Single particle dominated states

\[ E = \langle \Phi_{J,T}^0 | H | \Phi_{J,T}^0 \rangle = \langle \Phi_{J,T}^{\text{core}} | H_{\text{core}} | \Phi_{J,T}^{\text{core}} \rangle \]

\[ + \langle \Phi_{J,T}^{\alpha_1,\alpha_2} | H_1 + H_2 | \Phi_{J,T}^{\alpha_1,\alpha_2} \rangle \]

\[ + \langle \Phi_{J,T}^{\alpha_1,\alpha_2} | V(\vec{r}_1, \vec{r}_2) | \Phi_{J,T}^{\alpha_1,\alpha_2} \rangle \]

Transfer reactions

Angular momentum transfer: \( l = q \times R \), with \( q \) the transferred momentum.

Cross section \( \sim 1 \text{ mb} \)
Target thickness 100 \( \text{ug/cm}^2 \) to \( \text{mg/cm}^2 \)
Intensity \( \sim 10^4 \text{ pps} \)

One can show that transferred angular momentum maps onto the scattering angle.
Angular distributions from (d,p)

Muehlleer et al.
Phys. Rev. 159, 1043 (1967)
Maximum energy

- Phase 1A (CM1)
- Phase 1B (CM2)
- Phase 2A (CM3)
- Phase 2B (CM4)
- Phase 3 (not planned)

MeV/u vs. A/q

Maximum energy

![Graph showing maximum energy vs. A/q for different phases of HIE-ISOLDE upgrade. The graph includes lines for Phase 1A (CM1), Phase 1B (CM2), Phase 2A (CM3), Phase 2B (CM4), and Phase 3 (not planned). The red arrow indicates the maximum energy achieved.]
EBIS current situation

Breeding time (s)

0.0001 0.001 0.01 0.1 1

- O
- Na
- K
- Kr
- Sb
- Pb

Courtesy F. Wenander
EBIS current situation

Breeding time (s)

- O
- Na
- K
- Kr
- Sb
- Pb

Pb-208: A/q = 4.5 >> q = 46

Courtesy F. Wenander
EBIS current situation

Breeding time (s)

q

Pb-208: A/q = 4.5 >> q = 46

- O
- Na
- K
- Kr
- Sb
- Pb

Courtesy F. Wenander
EBIS current situation

Pb-208: $A/q = 4.5 >> q = 46$
EBIS current situation

![Graph showing the current situation of EBIS with two peaks labeled 224Ra52+ and 224Ra52+ with self and slow extraction.

F. Wenander JINST5 C10004 (2010)
Sn-110, (d,p) kinematics

110Sn inv. (d,p)

- Protons from 110Sn inv. (d,p) at 10 MeV/u
- 111Sn from inv. (d,p) at 10 MeV/u

Lab. energy (degrees) vs Lab. angle (degrees)
Particle – $\gamma$ coincidence and Doppler shift

Time

Background from deposited beam

Prompt

Energy vs time

Prompt

PRL 98, 172501 (2007)

\[ FWHM = 16.4 \text{ keV} \quad \chi^2 = 1.11 \]

\[ FWHM = 23.0 \text{ keV} \quad \chi^2 = 0.72 \]

\[ FWHM = 17.2 \text{ keV} \quad \chi^2 = 1.16 \]

\[ FWHM = 28.3 \text{ keV} \quad \chi^2 = 1.21 \]
Recoil detection

G. Wilson et al.
TOF spectrometers etc...

M. Rejmund et al. NIMA 621 558 (2010)
New ideas…

Proposal for a design study using SC elements

Explore new design concept using SC coils and RF cavities. Produce a compact, efficient and high-selectivity recoil separator. Study size, weight, efficiency, selectivity, cost and running cost.

SC solenoids
- Combined function magnets for bending and focussing
- High fields ~ 8 T

SC RF cavities
- High gradients ~ 10 MV/m
- HTS materials (> 77 K)
- Rebuncher ~ 10 MHz

Example – Ring concept

SEC
R [m]
0.5 - 1 m
B [T]
2 - 6
f₀ [MHz]
10 - 40
f_k [kHz]
100 - 3000
Storage t [μs]
0.5 - 10

Ismael Bravo, Olof Tengblad
100 ns Buncher

@0.1c gives 3m flight path
Resolution in spectrometer and Si-setup

Table 2
Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to 10°. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_i/A$ (MeV)</th>
<th>$\theta_{lab}$</th>
<th>Origin of contribution</th>
<th>$\Sigma_{quad}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Delta \theta$</td>
<td>$\Delta p$</td>
</tr>
<tr>
<td>p($^{12}$Be, $^{11}$Be)d</td>
<td>30</td>
<td>1.07°</td>
<td>172</td>
<td>147</td>
</tr>
<tr>
<td>p($^{12}$Be, $^{11}$Be)d</td>
<td>15</td>
<td>1.06°</td>
<td>84</td>
<td>71</td>
</tr>
<tr>
<td>p($^{77}$Kr, $^{76}$Kr)d</td>
<td>30</td>
<td>0.16°</td>
<td>1404</td>
<td>811</td>
</tr>
<tr>
<td>p($^{77}$Kr, $^{76}$Kr)d</td>
<td>10</td>
<td>0.10°</td>
<td>334</td>
<td>143</td>
</tr>
<tr>
<td>d($^{76}$Kr, $^{77}$Kr)p</td>
<td>10</td>
<td>0.21°</td>
<td>1140</td>
<td>614</td>
</tr>
</tbody>
</table>

Table 3
Major contributions in keV to the resolution of the excitation energy spectra of single neutron pickup and stripping reactions in inverse kinematics, where the light particle is detected in a silicon detector. Symbols as described in text and Table 2.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_i/A$ (MeV)</th>
<th>$\theta_{lab}$</th>
<th>Origin of contribution</th>
<th>$\Sigma_{quad}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Delta \theta$</td>
<td>$\Delta E_f$</td>
</tr>
<tr>
<td>p($^{12}$Be, d)$^{11}$Be</td>
<td>30</td>
<td>19.0°</td>
<td>136</td>
<td>74</td>
</tr>
<tr>
<td>p($^{12}$Be, d)$^{11}$Be</td>
<td>15</td>
<td>17.8°</td>
<td>66</td>
<td>72</td>
</tr>
<tr>
<td>p($^{77}$Kr, d)$^{76}$Kr</td>
<td>30</td>
<td>15.0°</td>
<td>124</td>
<td>55</td>
</tr>
<tr>
<td>p($^{77}$Kr, d)$^{76}$Kr</td>
<td>10</td>
<td>6.0°</td>
<td>26</td>
<td>24</td>
</tr>
<tr>
<td>d($^{76}$Kr, p)$^{77}$Kr</td>
<td>10</td>
<td>155.3°</td>
<td>52</td>
<td>93</td>
</tr>
</tbody>
</table>
What is next?

- **Bunch beam for any form of TOF measurement or timed injection**
  - time-of-flight dependent detectors (eg. for neutrons)
  - spectrometer/recoil separator
  - ring

- **Upgrade EBIS**
  - reach higher charge states for heavy nuclei quicker
  - higher charge states can reduce pressure on accelerator to reach highest voltages for all cavities.

- **Pre-studies already exists but need to be a priority for next step for the high-energy program together with higher intensity**