High-Mass Beam Delivery to ISAC-II

Science Forum, 13th Feb 2012

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The Charge State Booster

Modified 14.5 GHz PHOENIX ECR ion source from Pantechnik

Inject 1+ ions, extract n+ ions

Reduces A/q from <238 to <30 (7) for acceptance into RFQ (MEBT)

Advantages:
- Continuous output (DC beam)
- High intensity capability
- No pre-bunching/cooling required

Issues:
- Efficiency <5%
- Stable backgrounds at all A/q
TRIUMF’s High Mass Task Force:

**Accelerator Division:** Friedhelm Ames, Rick Baartman, Bob Laxdal, Marco Marchetto, Colin Morton, Victor Verzilov

**Science Division:** Barry Davids, Adam Garnsworthy, Greg Hackman

**Mandate:**

“To develop hardware and techniques to deliver beams with $A/q > 30$ from the CSB to high energy users.”
High Energy Users = Mostly ISAC-II Facilities
Hardware Modifications and Upgrades

**CSB**
- Eliminate Stainless Steel from the inside shielding to enable uninterrupted operation

**MEBT Dipoles**
- Upgrade of power supplies, increase A/q transport from 6 to 7

**Accelerator Scaling**
- Software/controls addition to scale all tuning elements to desired A/q value

**Upgrade beam diagnostics**
- Tbragg Detector in ISAC-II
- Prague Station in ISAC-I

**CSB Webpage**
- Quick and easy calculation of possible contaminants and opportunities
The problem has been divided into two parts:

Stage 1: CSB-LEBT-RFQ-MEBT-DTL
- Time-of-flight separation in LEBT
- Pre-buncher phase used to tune for selection
- Prague Diagnostic station used for setup
- Theoretical: 1/1000 resolution in A/q
For electrostatic acceleration,

\[
E = \frac{1}{2} m v^2 = \frac{1}{2} A m_0 v^2 = q V_{\text{bias}}, \quad \text{so} \quad \frac{A}{q} = \frac{2 V_{\text{bias}}}{m_0 v^2}
\]

\[
\frac{\Delta (A/q)}{A/q} = 2 \frac{\Delta v}{v}
\]

- \(\Delta v\) results in \(\Delta t\) from MHB to RFQ:

\[
\Delta t = \frac{\Delta v}{v} t = \frac{\Delta v}{v} \frac{l}{v}, \quad \text{so} \quad \frac{\Delta v}{v} = \Delta t \frac{v}{l}
\]

- RFQ acceptance:

\[
\Delta t_{\text{accept}} = \frac{\Delta \varphi_{\text{accept}}}{\omega_{\text{RFQ}}} = \frac{\pi}{4} \omega_{\text{RFQ}}
\]

- Result? \(~1/1000\) resolution in \(A/q\):

\[
\left. \frac{\Delta (A/q)}{A/q} \right|_{\text{accept}} = 2 \Delta t_{\text{accept}} \frac{v}{l} = 2 \frac{\Delta \varphi_{\text{accept}}}{\omega_{\text{RFQ}}} \frac{\beta c}{l}
\]

\[
= 2 \left( \frac{\pi}{4} \right) (0.0021)(3 \times 10^8 \text{m/s})
\]

\[
= \frac{2 \pi (35 \times 10^8 \text{ s}^{-1})(5.5 \text{m})}{2 \pi (35 \times 10^8 \text{ s}^{-1})(5.5 \text{m})} = 0.08\%
\]
For electrostatic acceleration,

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\[ \Delta\left(\frac{A}{q}\right) = 2 \frac{\Delta v}{v} \]

\( \Delta v \) results in \( \Delta t \) from MHB to RFQ:

\[ \Delta t = \frac{\Delta v}{v} t = \frac{\Delta v}{v} \frac{l}{v}, \text{ so } \frac{\Delta v}{v} = \Delta t \frac{v}{l} \]

RFQ acceptance:

\[ \Delta t_{accept} = \frac{\Delta \varphi_{accept}}{\omega_{RFQ}} = \frac{\pi}{4} \frac{\omega_{RFQ}}{\omega_{RFQ}} \]

Result? \( \sim 1/1000 \) resolution in \( A/q \):

\[ \frac{\Delta (A/q)}{A/q} \bigg|_{accept} = 2 \Delta t_{accept} \frac{v}{l} = 2 \frac{\Delta \varphi_{accept}}{\omega_{RFQ}} \frac{\beta c}{l} \]

\[ = 2 \left( \frac{\pi}{4} \right) (0.0021)(3 \times 10^8 \text{ m/s}) \]

\[ = 2 \left( \frac{\pi}{4} \right) (0.0021)(3 \times 10^8 \text{ s}^{-1})(5.5 \text{ m}) = 0.08\% \]
Time-of-flight separation in LEBT

• For electrostatic acceleration,

\[ E = \frac{1}{2} mv^2 = \frac{1}{2} Am_0 v^2 = qV_{bias}, \text{ so } \frac{A}{q} = \frac{2V_{bias}}{m_0 v^2} \]

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\[ \Delta t_{accept} = \frac{\Delta \varphi_{accept}}{\omega_{RFQ}} = \frac{\pi}{4} \frac{\omega_{RFQ}}{A / q} \]

• Result? \( \sim 1/1000 \) resolution in \( A/q \):

\[ \left. \frac{\Delta(A / q)}{A / q} \right|_{accept} = 2 \Delta t_{accept} \frac{v}{l} = 2 \frac{\Delta \varphi_{accept}}{\omega_{RFQ}} \frac{\beta c}{l} \]

\[ = 2 \left( \frac{\pi}{4} \right) (0.0021)(3 \times 10^8 \text{ m/s}) \]

\[ = 2 \frac{(\pi / 4)(0.0021)(3 \times 10^8 \text{ m/s})}{2\pi (35 \times 10^8 \text{ s}^{-1})(5.5 \text{ m})} = 0.08\% \]
Time-of-flight separation in LEBT

For electrostatic acceleration,

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\[ \Delta t = \frac{\Delta v}{v} t = \frac{\Delta v}{v} \frac{l}{v}, \text{ so } \frac{\Delta v}{v} = \Delta t \frac{v}{l} \]

RFQ acceptance:

\[ \Delta t_{accept} = \frac{\Delta \varphi_{accept}}{\omega_{RFQ}} = \frac{\pi}{4} \]

\[ \frac{\Delta (A/q)}{A/q}_{accept} = 2 \Delta t_{accept} \frac{v}{l} = 2 \frac{\Delta \varphi_{accept}}{\omega_{RFQ}} \frac{\beta c}{l} \]

Result? \( \sim 1/1000 \) resolution in \( A/q \):

\[ = 2 \left( \frac{\pi}{4} \right) \left( 0.0021 \right) \left( 3 \times 10^8 \text{ m/s} \right) \]

\[ = \frac{2 \pi (35 \times 10^8 \text{ s}^{-1}) (5.5 \text{ m})}{2 \pi (35 \times 10^8 \text{ s}^{-1}) (5.5 \text{ m})} = 0.08\% \]
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\[ \Delta (A / q) = 2 \frac{\Delta v}{v} \]

\Delta v \text{ results in } \Delta t \text{ from MHB to RFQ:}

\[ \Delta t = \frac{\Delta v}{v} t = \frac{\Delta v}{v} l, \text{ so } \frac{\Delta v}{v} = \Delta t \frac{v}{l} \]

RFQ acceptance:

\[ \Delta t_{accept} = \frac{\Delta \phi_{accept}}{\omega_{RFQ}} = \frac{\pi}{4} \frac{\omega_{RFQ}}{\omega_{RFQ}} \]

Result? \( \sim 1/1000 \) resolution in \( A/q \):

\[ \frac{\Delta (A / q)}{A / q} \bigg|_{accept} = 2 \Delta t_{accept} \frac{\nu}{l} = 2 \frac{\Delta \phi_{accept}}{\omega_{RFQ}} \frac{\beta c}{l} \]

\[ = 2 \left( \frac{\pi}{4} \right) (0.0021)(3 \times 10^8 \text{ m/s}) \]

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\[ \Delta t = \frac{\Delta v}{v} t = \frac{\Delta v}{v} \frac{l}{v} \text{, so } \frac{\Delta v}{v} = \Delta t \frac{v}{l} \]

RFQ acceptance:

\[ \Delta t_{\text{accept}} = \frac{\Delta \varphi_{\text{accept}}}{\omega_{RFQ}} = \frac{\pi}{4} \frac{\omega_{RFQ}}{\omega_{RFQ}} \]

\[ \frac{\Delta(A / q)}{A / q} \bigg|_{\text{accept}} = 2 \Delta t_{\text{accept}} \frac{v}{l} = 2 \frac{\Delta \varphi_{\text{accept}}}{\omega_{RFQ}} \frac{\beta c}{l} \]

\[ = 2 \left( \frac{\pi}{4} \right) (0.0021)(3 \times 10^8 \text{ m/s}) \frac{1}{2\pi (35 \times 10^8 \text{ s}^{-1})(5.5 \text{ m})} = 0.08\% \]
• For electrostatic acceleration,

\[ E = \frac{1}{2} m v^2 = \frac{1}{2} A m_0 v^2 = q V_{\text{bias}}, \text{ so } \frac{A}{q} = \frac{2 V_{\text{bias}}}{m_0 v^2} \]

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• Result? \( \sim 1/1000 \) resolution in \( A/q \):

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\[ = 2 \left( \frac{\pi}{4} \right) (0.0021)(3 \times 10^8 \text{m/s}) \frac{0.08}{2\pi(35 \times 10^8 \text{ s}^{-1})(5.5 \text{m})} = 0.08\% \]
Techniques for Filtration of Cocktail Beams

The problem has been divided into two parts:

**Stage 1:**
CSB-LEBT-RFQ-MEBT-DTL
- Time-of-flight separation in LEBT
- Pre-buncher phase used to tune for selection
- Prague Diagnostic station used for setup
- Theoretical: 1/1000 resolution in A/q

**Stage 2:**
DSB-SCLINAC-SEBT-Experiment
- Stripping foil at 1.5MeV/u (Optional)
- Change in A/q and differential TOF
- DSB slits used for selection
- TBragg detector used for setup
- Theoretical: 1/800 resolution in A/q
• Change in charge states of all components

• Stripping (degrading) introduces a $\Delta \nu$ by energy loss

• $\Delta \nu$ results in $\Delta t$ from stripper to buncher

• Result: $\sim 1/800$ resolution in $\nu$:

$$\frac{\Delta \nu}{\nu} \bigg|_{\text{accept}} = \frac{\pi/6 (0.056)(3 \times 10^8)}{2\pi (106 \times 10^6)(10)} = 0.13\%$$
Diagnostics

- Si detectors (incl. Rutherford scattering and ΔE-E telescope)
- Bragg detector
- Prague multi-purpose station
- Future RIB detection
Multi-purpose detector station:

- Faraday cup, low-intensity purity monitor, beta/gamma counters for RIB identification
- Mimics filtration of the second half of the accelerator chain
- Allows rapid characterization of beams – crucial for development, setup and tuning
Tbragg Detector in SEBT3

- Determines Z (1/66 resolution) and Energy (1% resolution) of the beam constituents
- Can handle >5000 pps
- MIDAS experiment with user-friendly ‘custom page’ web interface. Provides scalers of the individual components
$^{94}\text{Rb}^{22+}$ at TBragg detector

Before final filtration

After final filtration
No DSB Stripping required

$^{75}$Rb rate ~ 10-100 pps

Ratio of 1:10 in A=75. $^{75}$Rb was 7% of total cocktail
No DSB Stripping required

$^{75}\text{Rb}^{13+}$ rate $\sim$ 10-100 pps

Ratio of 1:10 in A=75. $^{75}\text{Rb}$ was 7% of total cocktail
The Yields from ISAC are impressive.

High-Powered Nb for neutron-deficient

UCx for neutron-rich
Beam Delivery Prospects, Rb Example

Efficiency of 0.001 delivery from ISAC to SEBT

Minimum Intensity of 100pps for Coulomb excitation

Minimum Intensity of 1000pps for transfer reactions

$^{75}\text{Rb}$ to $^{98}\text{Rb}$ should be possible
Stable beam background from CSB is between:
\( \sim 2 \times 10^{-11} \text{ enA } \sim 8 \times 10^6 \text{ pps} \)
and
\( \sim 2 \times 10^{-9} \text{ enA } \sim 8 \times 10^8 \text{ pps} \)

Overwhelming background

Experiments are Impossible
Filtration techniques reduce stable beam background to between:
\(~ 5 \times 10^4\) pps
and
\(~ 1 \times 10^6\) pps

Minimum Intensity of 100pps for Coulomb excitation

Minimum Intensity of 1000pps for transfer reactions

Background still overwhelming
Filtration techniques reduce stable beam background to between:
\(~ 5 \times 10^4\) pps and \(~ 1 \times 10^6\) pps

Minimum Ratio of 1:10 for Coulomb excitation and Transfer reactions

\(^{76}\text{Rb}\) to \(^{96}\text{Rb}\) possible for Coulomb excitation and transfer reactions

NOTE: Isobars from the ISAC target are not considered here and may also be overwhelming.
Filtration techniques reduce stable beam background to between:
\(~ 5 \times 10^4\) pps
and
\(~ 1 \times 10^6\) pps

Minimum Ratio of 3:1 for Fusion evaporation reactions

\(^{78}\text{Rb}\) to \(^{84}\text{Rb}\) possible for fusion-evaporation reactions

NOTE: Isobars from the ISAC target are not considered here and may also be overwhelming.
Implications for Current LOI (Nov 2012)

With our new understanding of the true performance, Only 1 minimum yield satisfied (Background conditions not considered)

<table>
<thead>
<tr>
<th>Proposal/LOI</th>
<th>Target</th>
<th>Ion Source</th>
<th>Element</th>
<th>Isotope</th>
<th>Established Yield (Y. Station)</th>
<th>EEC Priority</th>
<th>Dvipmt Priority</th>
<th>Notes</th>
<th>Charge State (1)</th>
<th>Charge State (2)</th>
<th>A/q (1)</th>
<th>A/q (2)</th>
<th>Contaminant</th>
<th>Intensity (Cont.)</th>
<th>Required Min. Intensity (SEBT)</th>
<th>Expected Intensity (SEBT)</th>
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<td>Molecule broken in CSB</td>
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<tr>
<td>S1187</td>
<td>UC</td>
<td>FEBIAD</td>
<td>O</td>
<td>22O</td>
<td>1</td>
<td>I</td>
<td></td>
<td></td>
<td>Molecule broken in CSB</td>
<td>4+</td>
<td>4+</td>
<td>5.502</td>
<td>22Ne</td>
<td>?</td>
<td>1.00E+03</td>
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<td>C</td>
<td>19C</td>
<td>1</td>
<td>I</td>
<td></td>
<td></td>
<td>Molecule broken in CSB</td>
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<td>3+</td>
<td>6.667</td>
<td>None</td>
<td>-</td>
<td>1.00E+03</td>
<td></td>
</tr>
</tbody>
</table>

Either: modification to physics aims of these experiments considering true yields/BGs
Or, New experiments considering true yields/backgrounds likely using less exotic beams
Charge-State Booster Page

The Charge-State Booster (CSB) is intended to produce radioactive ion beams in charge states greater than 1+. Stable isotopes are also ionized and produced by this device so must be considered when selecting which beam to extract. This page may help identify which charge-state might be the cleanest.

Select Mass and Element: [ ] [ ] Show A/Q values
The first filter applied is for $^{94}$Rb$^{15+}$, A/Q of 6.261. A resolving power of 1/25 is used to transport the cocktail through the DSB section here. The green windows indicate the resolving power of the RFQ pre-buncher (1/1000) for the first A/q and the DSB pre-buncher (1/400) for the second A/q. Percentage energy loss used is 1.7

Change percentage energy loss in the stripping foil: [1.7 %] Recalculate

<table>
<thead>
<tr>
<th>Species</th>
<th>Charge State</th>
<th>A/Q Value</th>
<th>Possible Companions</th>
</tr>
</thead>
</table>
| $^{94}$Rb | 15 | 0.0% | This A/Q = 6.208  
First A/Q = 6.261  
$^{94}$Rb$^{15+}$ |
| | | | $^{25}$Mg$^{4+}$=6.193  
$^{44}$Ca$^{7+}$=6.225  
$^{50}$Ti$^{8+}$=6.189  
$^{50}$V$^{8+}$=6.190  
$^{50}$Cr$^{6+}$=6.189  
$^{63}$Cu$^{10+}$=6.239  
$^{69}$Ga$^{11+}$=6.212 |
| | | | $^{75}$As$^{12+}$=6.190  
$^{88}$Sr$^{14+}$=6.225  
$^{94}$Zr$^{15+}$=6.206  
$^{94}$Mo$^{15+}$=6.206  
$^{100}$Mo$^{16+}$=6.190  
$^{100}$Ru$^{16+}$=6.190 |
| | | | 107 $^{107}$Ag$^{17+}$=6.234  
$^{113}$Cd$^{18+}$=6.218  
$^{113}$In$^{18+}$=6.218  
$^{119}$Sn$^{19+}$=6.204 |
| | | | 125 $^{125}$Te$^{20+}$=6.191  
$^{131}$Xe$^{21+}$=6.180 |
| | | | $^{132}$Xe$^{21+}$=6.227  
$^{132}$Ba$^{21+}$=6.227  
$^{138}$Ba$^{22+}$=6.214  
$^{138}$La$^{22+}$=6.214  
$^{138}$Ce$^{22+}$=6.214  
$^{144}$Nd$^{23+}$=6.203 |
| | | | 150 $^{150}$Nd$^{24+}$=6.193  
$^{144}$Sm$^{23+}$=6.203  
$^{150}$Sm$^{24+}$=6.193  
$^{151}$Eu$^{24+}$=6.234  
$^{156}$Gd$^{25+}$=6.183  
$^{157}$Gd$^{25+}$=6.223 |
| | | | 156 $^{156}$Dy$^{25+}$=6.183  
$^{162}$Dy$^{26+}$=6.212  
$^{169}$Tm$^{27+}$=6.203  
$^{176}$Yb$^{28+}$=6.229  
$^{175}$Lu$^{28+}$=6.194  
$^{176}$Lu$^{28+}$=6.229 |
| | | | 176 $^{176}$Hf$^{28+}$=6.229  
$^{181}$Ta$^{29+}$=6.186  
$^{182}$W$^{29+}$=6.220  
$^{187}$Re$^{30+}$=6.178  
$^{187}$Os$^{30+}$=6.178  
$^{187}$Os$^{30+}$=6.211 |
| | | | 194 $^{194}$Pt$^{31+}$=6.203  
$^{195}$Pt$^{31+}$=6.235  
$^{200}$Hg$^{32+}$=6.195  
$^{201}$Hg$^{32+}$=6.226  
$^{206}$Pb$^{33+}$=6.188  
$^{207}$Pb$^{33+}$=6.218 |
| | | | 232 $^{232}$Th$^{37+}$=6.217  
$^{238}$U$^{38+}$=6.210 |
| | 19 | 1.6% | This A/Q = 4.901  
First A/Q = 6.261  
$^{94}$Rb$^{15+}$ |

$^{25}$Mg$^{5+}$=4.953  
$^{44}$Ca$^{9+}$=4.842  
$^{50}$Ti$^{10+}$=4.951  
$^{50}$V$^{10+}$=4.952  
$^{50}$Cr$^{10+}$=4.951  
$^{63}$Cu$^{14+}$=4.881  
$^{69}$Ga$^{15+}$=4.952  
$^{88}$Sr$^{18+}$=4.841  
$^{94}$Zr$^{19+}$=4.900  
$^{94}$Mo$^{19+}$=4.900  
$^{100}$Mo$^{20+}$=4.952  
$^{100}$Ru$^{20+}$=4.952  
$^{107}$Ag$^{22+}$=4.817  
$^{113}$Cd$^{23+}$=4.866  
$^{113}$In$^{23+}$=4.866  
$^{119}$Sn$^{24+}$=4.911  
$^{125}$Te$^{25+}$=4.953  
$^{131}$Xe$^{26+}$=4.991  
$^{131}$Xe$^{27+}$=4.806  
$^{132}$Xe$^{27+}$=4.843  
$^{132}$Ba$^{27+}$=4.843  
$^{138}$Ba$^{28+}$=4.883  
$^{138}$La$^{28+}$=4.883  
$^{138}$Ce$^{28+}$=4.883  
$^{144}$Nd$^{29+}$=4.920  
$^{150}$Nd$^{30+}$=4.954  
$^{144}$Sm$^{29+}$=4.920  
$^{150}$Sm$^{30+}$=4.954  
$^{151}$Eu$^{30+}$=4.987  
$^{151}$Eu$^{31+}$=4.826  
$^{156}$Gd$^{31+}$=4.986
Calculated charge states, $A=94$

After stripping at 1.5 MeV/u

Fraction, %

Charge state, $q$

94Rb
94Mo
• Look for first A/q value with low CSB Background

• Best situation is when no DSB stripping is required

• Consider charge state fractions of main contaminants

• Filter plot will indicate the level of BG reduction achievable

• Every beam is a unique case
Dramatic improvement in delivered beam quality has been achieved through new hardware and filtration techniques.

Electron Beam Ion Source (EBIS) for charge-breeding included in CANREB CFI funding application led by St. Mary’s and Manitoba.

Some opportunities for experiments exist with the present facility before CANREB comes online in 2016.
CANRadian Rare isotope facility with Electron-Beam ion source

First beams ~2016

Saint Mary’s University, University of Manitoba and Advanced Applied Physics Solutions, Inc. in collaboration with the University of British Columbia, University of Guelph, Simon Fraser University, and TRIUMF
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Thank you!

Merci