Operation of an ECRIS Charge State Breeder at TRIUMF

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TRIUMF

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1. Introduction

2. set –up

3. charge breeding results with stainless steel plasma chamber
   - efficiency
   - purity
   - beam transport

4. first results with aluminum plasma chamber
   - efficiency
   - purity

5. beam purification tools

6. summary
layout of the ISAC facility
Charge State breeding at ISAC

Requirements:

- M/Q < 30 with additional stripping after first acceleration stage (150 keV/u)
- M/Q < 7 without additional stripping
- ion velocity: 2 keV/u
- transversal emittance for highly charged ions: \( \leq 30 \pi \) mm mrad

Incoming beam:

- singly charged ions continuous beam
- typical emittance < 20 \( \pi \) mm mrad @ 30 keV
- beam intensity: 1 \( \ldots > 10^8 \) ions/sec
modified 14.5 GHz PHOENIX ECR ion source from Pantechnik
2 step deceleration for the injection of singly charged ions
2 step acceleration scheme for the extraction of the highly charged ions
Aluminum plasma chamber
<table>
<thead>
<tr>
<th>isotope</th>
<th>q</th>
<th>A/q</th>
<th>efficiency [%]</th>
<th>I (in) [1/s]</th>
<th>background [pA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>46K</td>
<td>9</td>
<td>5.11</td>
<td>0.5</td>
<td>4.0E4</td>
<td>340</td>
</tr>
<tr>
<td>64Ga</td>
<td>13</td>
<td>4.92</td>
<td>0.7</td>
<td>8.4E4</td>
<td>150</td>
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<tr>
<td>64Ga</td>
<td>14</td>
<td>4.57</td>
<td>0.75</td>
<td>8.4E4</td>
<td>210</td>
</tr>
<tr>
<td>74Br</td>
<td>14</td>
<td>5.28</td>
<td>3.1</td>
<td>3.2E7</td>
<td>10000</td>
</tr>
<tr>
<td>74Br</td>
<td>15</td>
<td>4.93</td>
<td>2.1</td>
<td>3.2E7</td>
<td>25</td>
</tr>
<tr>
<td>78Br</td>
<td>14</td>
<td>5.57</td>
<td>4.5</td>
<td>2.8E7 AlBr</td>
<td>20</td>
</tr>
<tr>
<td>74Kr</td>
<td>15</td>
<td>4.93</td>
<td>6.2</td>
<td>2.1E6</td>
<td>25</td>
</tr>
<tr>
<td>76Rb</td>
<td>15</td>
<td>5.07</td>
<td>1.68</td>
<td>3.8E6</td>
<td>15</td>
</tr>
<tr>
<td>80Rb</td>
<td>13</td>
<td>6.15</td>
<td>1.17</td>
<td>5.7E7</td>
<td>35</td>
</tr>
<tr>
<td>80Rb</td>
<td>14</td>
<td>5.71</td>
<td>1.1</td>
<td>5.7E7</td>
<td>70000</td>
</tr>
<tr>
<td>122Cs</td>
<td>19</td>
<td>6.42</td>
<td>1.1</td>
<td>3.1E5</td>
<td>6</td>
</tr>
<tr>
<td>124Cs</td>
<td>20</td>
<td>6.2</td>
<td>1.37</td>
<td>2.75E7</td>
<td>50</td>
</tr>
</tbody>
</table>
$^{78}\text{Br}^{14+}$ (1E6 ion/s) A/q = 5.57 amu/e injected as AlBr from ZrC target accelerated to 5MeV/u measured at TIGRESS detector background ≈ 20 pA
beam purity

energy spectrum after scattering from a gold foil (77 µg/cm²) at 1.5 MeV/u

A/q=5.78

52Cr⁹⁺

133Cs²³⁺

A/q=6.33

19F³⁺

38Ar⁶⁺

57Fe⁹⁺

133Cs²¹⁺

A/q=5.6

28Si⁵⁺

56Fe¹⁰⁺

84Kr¹⁵⁺
Measured beam current relative to the current after the CSB on several Faraday cups. The theoretical value for the LEBT assumes charge exchange at a pressure of $2 \times 10^{-7}$ T over 25 m. Cross sections from F. Ames et al., High Energy Phys Nucl Phys. 31 (2007) 211, ECRIS’06 proc.
charge exchange

scan of MEBT dipole

$^{40}\text{Ar}^{7+}$

$^{56}\text{Fe}^{10+}$

$^{133}\text{Cs}^{23+}$
Cs$^{23+}$ beam profile (blue) at ILT:RPM44  (focal plane of first bender in front of RFQ)
The center of the beam has been moved in horizontal (x) direction to show more beam components.
Aluminum plasma chamber first try

mass spectrum with stainless steel and aluminum plasma chamber

Additional peaks from Al chamber Cl^{n+}, most other peaks remain

higher total beam current
aluminum plasma chamber efficiency

80Rb charge state distribution from Al plasma chamber with different injection/extraction voltage

charge breeding efficiency of radioactive ions from stainless steel and aluminum plasma chamber

increase of efficiency

<table>
<thead>
<tr>
<th></th>
<th>steel</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{K}^9+$</td>
<td>0.67%</td>
<td></td>
</tr>
<tr>
<td>$^{46}\text{K}^9+$</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>$^{80}\text{Rb}^{15+}$</td>
<td>4.5% (6.5%)</td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Rb}^{15+}$</td>
<td>1.68%</td>
<td></td>
</tr>
<tr>
<td>$^{124}\text{Cs}^{20+}$</td>
<td>1.37%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
aluminum plasma chamber second try

mass spectrum after exchange of all electrodes to aluminum and coating plasma chamber and iron with pure aluminum

peaks from $^{56}$Fe, $^{52,53}$Cr... missing or reduced

$\Rightarrow$ new test with $^{76,94}$Rb

background identified
$^{76}$Rb$^{15+}$ A/q=5.06
$^{61}$Ni$^{12+}$, $^{76}$Se$^{15+}$, $^{76}$Ge$^{15+}$

$^{94}$Rb$^{15+}$ A/q=6.26
$^{69}$Ga$^{12+}$, $^{94}$Mo$^{15+}$, $^{107}$Ag$^{17+}$,
$^{113}$In$^{18+}$, $^{119}$Sn$^{19+}$, $^{132}$Xe$^{21+}$,
New diagnostics for particle identification

- Stopping gas counter in ISAC-II experimental hall
- Particle ID from $\Delta E-E$ after acceleration
- Tolerant of high count rates
- Thickness can be adjusted by varying gas pressure
In flight purification

using LINAC chain as mass filter \((M/\Delta M \approx 1000)\)
additional stripping at 1.5 MeV/u to \(^{94}\text{Rb}^{22+}\)

Before final filtration
In flight purification

using LINAC chain as mass filter ($M/\Delta M \approx 1000$) additional stripping at 1.5 MeV/u to $^{94}\text{Rb}^{22+}$

Before final filtration
In flight purification

using LINAC chain as mass filter ($M/\Delta M \approx 1000$)
additional stripping at 1.5 MeV/u to $^{94}$Rb$^{22+}$

Before final filtration

After final filtration
new tools: CSB calculator

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: 94  Rb  Show A/Q values

Rb has an atomic number 37
94Rb has an atomic mass of 93.926405 u.

The CSB BCR source has an Aluminum liner.
The resolving power of the magnet immediately following the CSB is 1/100

Blue font indicates species which can currently be delivered to ISAC II (i.e. have an A/Q value between 5 and 6.4 only).
"Possible Companions" includes any stable species with an A/Q value within +/- 0.5% (1/100 resolving power of magnet) of the species of interest. Obviously not all of these stable species will be present and the amount of each species will depend on the operating conditions of the CSB (temperature/pressure etc.) as well as the recent CSB history (i.e. isotopes recently injected into the beam).
Red font indicates elements which are known to come from the CSB. (Residual gases and the material of the CSB itself).
The masses used here to calculate A/q values are taken from the AME2003 atomic mass evaluation available at http://www.nndc.bnl.gov/masses.
The plot on the right is of the Charge-State Booster Background Intensity as measured on August 13th 2012.

<table>
<thead>
<tr>
<th>Species Charge State</th>
<th>A/Q Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>94Rb 14</td>
<td>6.708</td>
</tr>
</tbody>
</table>

Possible Companions

<table>
<thead>
<tr>
<th>Zn10+ = 6.692</th>
<th>Sc11+ = 6.720</th>
<th>Si12+ = 6.720</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni12+ = 6.686</td>
<td>Cu13+ = 6.695</td>
<td>Zn14+ = 6.708</td>
</tr>
<tr>
<td>Cu16+ = 6.708</td>
<td>Zn16+ = 6.708</td>
<td>Cu18+ = 6.720</td>
</tr>
<tr>
<td>Fe18+ = 6.720</td>
<td>Fe20+ = 6.720</td>
<td>Fe22+ = 6.720</td>
</tr>
<tr>
<td>Fe24+ = 6.720</td>
<td>Fe26+ = 6.720</td>
<td>Fe28+ = 6.720</td>
</tr>
<tr>
<td>Fe30+ = 6.720</td>
<td>Fe32+ = 6.720</td>
<td>Fe34+ = 6.720</td>
</tr>
</tbody>
</table>

Note: The table and diagram represent the possible companions and the background intensity of the Charge-State Booster.
new tools: CSB calculator
new tools: CSB calculator
Summary

• charge breeding of radioactive ions
  • 2.0% efficiency for $^{124}\text{Cs}^{20+}$ (A/q = 6.2), 4.5% efficiency for $^{80}\text{Rb}^{15+}$ A/q=5.33 6.2% for $^{74}\text{Kr}^{15+}$
  • higher efficiency at higher injection energy
  • injection of molecular ions $\Rightarrow$ beam purification from isobars
  • acceleration of $^{76,80,94}\text{Rb}^{14,15+}$ and $^{78}\text{Br}^{14+}$

• background reduction methods
  • Aluminum coated plasma chamber
  • “In flight” purification in LINAC chain
  • new diagnostics
  • new software tools (CSB calculator, automatic accelerator scaling routines)

• plans for the future
  • continue optimizing the system with radioactive ions, short half lives
  • further optimization of breeding and accelerator efficiency
  • background reduction ??
next generation charge state breeder

Possible strategies for improved ECR charge breeder

• efficiency
  • higher voltage at charge breeder
    ➢ floating RFQ and / or charge breeder
    ➢ new RFQ with higher velocity acceptance
  • new ECR source design
    ➢ symmetric magnetic field at injection
    ➢ higher and/or dual frequency plasma heating

• beam transport
  • relocate charge breeder closer to accelerator
  • improve vacuum in beam line for low energy highly charged ions

• purity
  • ultra high vacuum source and ultra pure support gas
    ➢ will reduce only some gaseous impurities
  • high resolution mass separator after charge breeding (ΔM/M >1000)
    ➢ limited by source emittance
Thank you!

Merci!