Acceleration of Heavy Ions generated by ECR and EBIS

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OUTLINE

Ion production in ECR and EBIS is governed by the same collision physics, however with different weights:

1) Stepwise electron impact ionization for producing highly charged ions

2) Charge exchange limits the highest charge states

3) Radiative Recombination (RR) asks for highest electron energies

4) Ion heating by small angle elastic Coulomb collisions raises emittances

5) ion-ion-cooling (gas mixing) improves high charge state performance

The magnetic emittance requires careful design of the LEBT, especially for ECRs.
Recent Results with VENUS in comparison with other high performance sources
SECRAL: IMP, Lanzhou, Zhao et al.
GTS: Grenoble, Hitz et al.

### Venus results

<table>
<thead>
<tr>
<th>f(GHz)</th>
<th>VENUS 28 or 18</th>
<th>SECRAL 18</th>
<th>GTS 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>6' 2850 850</td>
<td>2300 810</td>
<td>1950</td>
</tr>
<tr>
<td>7'</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>12' 860 510</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>14'</td>
<td>514 270</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>16'</td>
<td>270 73</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>17'</td>
<td>36 8.5</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>18'</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>28' 222</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>29'</td>
<td>168</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>30'</td>
<td>116 101</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>31'</td>
<td>86 68</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>34'</td>
<td>41 21</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>37'</td>
<td>12 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38'</td>
<td>12 2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42'</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>33' 205</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34'</td>
<td>202</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35'</td>
<td>175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47'</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50'</td>
<td>1.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Daniela Leitner et al.
example: RHIC EBIS test setup

- Electron gun
- Gate valves
- Superconducting solenoid
- HV feedthroughs
- Drift tubes
- Gate valve
- Cryopump
- Electron collector magnet coil
- Electron collector
- HV break

E. Beebe et al.

Oliver Kester. CB06. 22.-24.05.06. Darmstadt. Germany

Goethe-Universität Frankfurt/M, Germany

Venice, 8-13 June 2009

Reinard Becker, Institut für Angewandte Physik
### EBIS Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>RHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>Au^{32+}</td>
<td>Au^{32+}</td>
</tr>
<tr>
<td>I_e</td>
<td>10 A</td>
<td>10 A (20)</td>
</tr>
<tr>
<td>J_e</td>
<td>\sim 575 A/cm^2</td>
<td>575 A/cm^2</td>
</tr>
<tr>
<td>t_{confinement}</td>
<td>35 ms</td>
<td>35 ms</td>
</tr>
<tr>
<td>L_{trap}</td>
<td>0.7 m</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Capacity</td>
<td>0.51 x 10^{12}</td>
<td>1.1 x 10^{12}</td>
</tr>
<tr>
<td>Au neutralization</td>
<td>70%</td>
<td>50%</td>
</tr>
<tr>
<td>% in desired Q</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Extracted charge</td>
<td>55 nC</td>
<td>85 nC</td>
</tr>
<tr>
<td>Ions/pulse</td>
<td>1.5 \times 10^9 (Au^{32+})</td>
<td>3.3 \times 10^9 (Au^{32+})</td>
</tr>
<tr>
<td>Pulse width</td>
<td>10-20 \mu s</td>
<td>10-40 \mu s</td>
</tr>
</tbody>
</table>

**B field of test EBIS solenoid:** 5 T

**B field of RHIC EBIS solenoid:** 6 T

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E. Beebe et al.

Oliver Kester. CB06. 22.-24.05.06. Darmstadt, Germany
Charge balance

\[
\frac{dn_i}{dt} = n_e n_e \left[ \sigma_{i-1 \rightarrow i}^{\text{ion}} n_{i-1} - \left( \sigma_{i \rightarrow i+1}^{\text{ion}} + \sigma_{i \rightarrow i-1}^{\text{RR}} \right) n_i + \sigma_{i+1 \rightarrow i}^{\text{RR}} n_{i+1} \right] \\
- n_{o \nu_{\text{ion}}} \left[ \sigma_{i \rightarrow i-1}^{\text{chex}} n_i - \sigma_{i+1 \rightarrow i}^{\text{chex}} n_{i+1} \right] \\
- \nu_{\text{coll}} \exp \left\{ \frac{ieU_w}{kT_{\text{ion}}} \right\} n_i \\
- \nu_i \frac{ieU_w}{kT_{\text{ion}}} n_i
\]

Growth by ionisation
Loss by ionisation
Loss by radiative radiation
Win from radiative radiation
Loss by charge exchange
Win from charge exchange
Loss of confinement of heated ions
Lotz cross sections

Approximate ionisation energies, ionisation cross sections and required jτ-values for bare ions

\[
\sigma_{i \rightarrow i+1} = 4.5 \times 10^{-14} \sum_{nl} \ln \left( \frac{E_e}{E_{i,nl}} \right) \left[ \text{cm}^2 \right]
\]

<table>
<thead>
<tr>
<th>Ion</th>
<th>( E_i ) [eV]</th>
<th>( \sigma ) [cm(^2)]</th>
<th>( j^*\tau ) [Cb/cm(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(^{6+})</td>
<td>490</td>
<td>7.7 \times 10^{-20}</td>
<td>2.1</td>
</tr>
<tr>
<td>N(^{7+})</td>
<td>666</td>
<td>4.2 \times 10^{-20}</td>
<td>3.8</td>
</tr>
<tr>
<td>O(^{8+})</td>
<td>870</td>
<td>2.4 \times 10^{-20}</td>
<td>6.5</td>
</tr>
<tr>
<td>Ne(^{10+})</td>
<td>1360</td>
<td>1 \times 10^{-20}</td>
<td>16</td>
</tr>
<tr>
<td>Ar(^{18+})</td>
<td>4400</td>
<td>9.5 \times 10^{-22}</td>
<td>170</td>
</tr>
<tr>
<td>Kr(^{36+})</td>
<td>17600</td>
<td>6 \times 10^{-23}</td>
<td>2700</td>
</tr>
<tr>
<td>Xe(^{54+})</td>
<td>39700</td>
<td>1.2 \times 10^{-23}</td>
<td>13600</td>
</tr>
<tr>
<td>Pb(^{82+})</td>
<td>91400</td>
<td>2.2 \times 10^{-24}</td>
<td>72300</td>
</tr>
<tr>
<td>U(^{92+})</td>
<td>115000</td>
<td>1.4 \times 10^{-24}</td>
<td>115000</td>
</tr>
</tbody>
</table>
Charge exchange

The approximation formula of Salzborn and Müller is based on many measurements with low charge states, however, we have nothing better!

\[ \sigma_{i \rightarrow i-1} = 1.43 \times 10^{-12} i^{1.17} P_0^{-2.76} \left[ \text{cm}^2 \right] \]

In EBIS/T the pressure usually is low enough to avoid CX, only dangerous for extremely high charge states, where ion cooling becomes necessary.

In ECRs CX usually limits the build up if higher charge states and produces the wide range of charge state with almost identical abundance.
Charge exchange versus Ionisation

Vacuum pressure at which gain by ionization equals the loss by charge exchange for lead ion.
Radiative Recombination

RR is time-reversed photo-ionisation. Therefore RR cross sections may be calculated from cross sections for photo ionisation, which is a well established procedure (T. Stöhlker):

\[
\sigma_{nl}^{ph}(k) = \left( \frac{4\pi \alpha a_0^2}{3} \right) \frac{n^2}{Z^2} \sum_{l'=l \pm 1} \frac{l_+}{2l + 1} (1 + n^2 \kappa^2) \times |g(n,l;\kappa,l')|
\]

\[
\sigma_{nl}^{RR}(k) = \frac{(hv)^2}{k^2} \frac{1}{2m_e c^2} \sigma_{nl}^{ph}(k)
\]
“Balance energy” at which the gain by ionization equals loss by radiative recombination for lead ions
Heating

Radial well voltages $eU_w = kT_i$ to trap multiply charged ions heated by electrons of energy 1 keV (dashed lines) and 10 keV (full lines), typical for ECR and EBIS/T.
Results of CBSIM
Charge state breeder setup

- Post accelerator or experiment
- Low energetic $q^+$ ions
- Isotopes from 1+ ion source
- Analyzing magnet
- Low energetic 1+ ions
- Buffer gas emittance cooler
- Switch yard
- EBIS/T ECRIS
Reinard Becker, Institut für Angewandte Physik
Goethe-Universität Frankfurt/M, Germany
Venice, 8-13 June 2009

Charge breeding

ECRs and EBIS have become popular as „charge breeders“. Nevertheless these are still ion sources for highly charged ions, but the problem of generating simple or difficult or rare singly charged ions has been „outsourced“ – leave the hard work to the specialist!

ACCU-EBIS

TOFEBIS-COOLER

Magnetic Emittance

The conservation of the magnetic moment (Busch’s theorem) results in skew trajectories outside of the magnetic field. When this beam is treated as a round one, it has a considerable “magnetic“ emittance:

\[ \varepsilon_{\text{abs}} = \frac{\pi}{4} \sqrt{\frac{2eq}{M}} \frac{Br^2}{\sqrt{U_0}} \ [m] \]

For modern ECR and EBIS \( B_z = 3 \text{T} \) and \( U_0 = 20 \text{ kV} \). For bare nuclei we then obtain:

<table>
<thead>
<tr>
<th>( r ) (m)</th>
<th>( \varepsilon_{\text{abs}} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-3} )</td>
<td>( 5.2 \times 10^{-6} )</td>
</tr>
<tr>
<td>( 10^{-2} )</td>
<td>( 520 \times 10^{-6} )</td>
</tr>
</tbody>
</table>

Note that dimension \( m \) for the emittance gives the same numbers as the old fashioned \( \text{mm} \times \text{mrad} \) *)

EBIS beam are usually smaller than 1 mm, therefore the magnetic emittance will be negligible in contrast to ECRs, where special attention must be given to transport such a beam through a LEBT, especially, when this is including an analyzing magnet for mass separation.

Accelerator applications

ECR is an intense dc source, with afterglow also for ms pulses.

EBIS is an intense pulsed source – exceeding ECRs in pulse current and charge-to-mass - ratio. Dc beams at low intensity have ultra-low emittances.

ECR, dc beams: cyclotrons (all over the world)

ECR, pulsed beams: Synchrotrons (CERN, NIRS, GSI)

EBIS, pulsed beams: Synchrotrons (Dubna, BNL)

EBIS, dc beams: atomic physics studies (Frankfurt, SNLL, KSU)
Charge selection in LEBT

**EBIS:**
- REX-ISOLDE
- MSU ReA3

**ECRIS:**
- TRIUMF charge state booster
BNL LEBT without charge selection
Matching to the accelerator

pre-bunching scheme

multi harmonic buncher

RFQ

linac or cyclotron

ISAC facility (TRIUMF), ReA3 (MSU)

HMI (Berlin)

RFQ-bunching scheme

RFQ with shaper and buncher

linac or cyclotron

REX-ISOLDE (CERN)

GSI (High charge state injector), BNL (RHIC EBIS injector)
Conclusions

EBIS and ECR are complementary ion sources for accelerators, either as primary sources or as charge state breeders:

EBIS is naturally a pulsed source with high intensity (mA) in short (10 – 100 µs) pulses of highest charge states.

ECR are naturally dc sources of high intensity for medium charge states.

The atomic collision physics is the same in both sources, however with different influence of charge exchange and radiative recombination, due to vacuum pressure and electron energy distribution.