Acceleration of Heavy Ions generated by ECR and EBIS

R. Becker, Goethe-Universität, Frankfurt, Germany

O. Kester, NSCL, MSU, USA
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.

<table>
<thead>
<tr>
<th>f(GHz)</th>
<th>VENUS 28 or 18</th>
<th>SECRAL [3,8]</th>
<th>GTS [11]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>6$^+$</td>
<td>2850</td>
<td>2300</td>
</tr>
<tr>
<td></td>
<td>7$^+$</td>
<td>850</td>
<td>810</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>12$^+$</td>
<td>860</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>14$^+$</td>
<td>514</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>16$^+$</td>
<td>270</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>17$^+$</td>
<td>36</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>18$^+$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>28$^+$</td>
<td>222</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>29$^+$</td>
<td>168</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>30$^+$</td>
<td>116</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>31$^+$</td>
<td>86</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>34$^+$</td>
<td>41</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>37$^+$</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>38$^+$</td>
<td>7</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>42$^+$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>33$^+$</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td></td>
<td>34$^+$</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35$^+$</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47$^+$</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50$^+$</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

4kW 28 GHz
770 W 18 GHz

Uranium

Analyzed Current [µA]

Mass to Charge Ratio

Daniela Leitner et al.

Goethe-Universität Frankfurt/M, Germany

Venice, 8-13 June 2009

Reinard Becker, Institut für Angewandte Physik
example: RHIC EBIS test setup

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
### Example: RHIC EBIS Test Setup

![Image of test setup](image)

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

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

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 $j\tau$-values for bare ions

<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$^5^+$</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>
The approximation formula of Salzborn and Müller is based on many measurements with low charge states, however, we have nothing better!

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

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

![Graph showing the relationship between pressure (in mbar) and Pb Charge states for different current densities (10 A/cm² and 100 A/cm²).](image-url)
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):

\[
\sigma_{nl}^{\text{ph}}(k) = \left( \frac{4\pi\alpha a_0^2}{3} \right) \frac{n^2}{Z^2} \sum_{l'=l\pm1} \frac{l_{>}}{2l + 1} (1 + n^2 \kappa^2) \times |g(n,l;\kappa,l')|
\]

\[
\sigma_{nl}^{\text{RR}}(k) = \frac{(h\nu)^2}{k^2} \frac{1}{2m_e c^2} \sigma_{nl}^{\text{ph}}(k)
\]
RR versus Ionisation

“Balance energy” at which the gain by ionization equals loss by radiative recombination for lead ions

Electron energy (eV)

Pb Charge states

Goethe-Universität Frankfurt/M, Germany

Venice, 8-13 June 2009

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Heating

Radial well voltages $U_w = kT_i$ 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

![Graphs showing relative abundance vs. \( j \tau \) (Cb/cm²)](image)

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Charge state breeder setup

- Post accelerator or experiment
- Low energetic $q^+$ ions
- Isotopes from 1+ ion source
- Analyzing magnet
- Buffer gas emittance cooler
- Switch yard
- Low energetic 1+ ions
- EBIS/T ECRIS

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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:

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

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

<table>
<thead>
<tr>
<th>( r ) (m)</th>
<th>( \varepsilon_{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

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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.