Electron Beam Ion Sources

Günter Zschornack

Dreebit GmbH Dresden

and

Technische Universität Dresden
Department of Physics

and

Helmholtzzentrum Dresden-Rossendorf
Institute of Ion Beam Physics and Materials Research
Why Highly Charged Ions?

Exciting properties of highly charged ions
Properties of Highly Charged Ions

Potential Energy

The potential energy of an ion increases with the degree of ionization.

Example:

$\text{Xe}^{44^+}$ has a potential energy that is \textbf{4200 times higher} than that of $\text{Xe}^{1^+}$

$\text{Xe}^{54^+}$ has a potential energy that is \textbf{16700 times higher} than that of $\text{Xe}^{1^+}$
Properties of Highly Charged Ions

High power Deposition into the Surface

The deposition of potential energy leads to ultrafast intense electronic excitations up to: $10^{12} \ldots 10^{14} \text{ W/cm}^2$
Pathways of Potential Energy

Hollow Atom

$E_{pot}$ pathways

- Backscattered HCIs: <10%
- Low energy electrons (from Auger cascade)
- Inner shell Auger electrons (transition rates $\sim 10^{15}$ s$^{-1}$)
- X-rays (transition rates $\sim 10^8$ s$^{-1}$): <10%
- Secondary electrons, ions, neutrals by potential emission/sputtering (secondary effects): <10%

Fraction of retained potential energy $\rightarrow$ available for surface modifications

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Energy Deposition into Surface

Energy deposition by ions into solids and surfaces

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Highly Charged Ions give higher Yields of Secondary Ions and Secondary Electrons

Properties of Highly Charged Ions
Small Spatial Extent of the Projectiles

The size ratio of a hydrogen-like nickel ion to a neutral hydrogen atom is approximately equal to the size ratio of the planet Neptune to the sun.

(Idea by J. Gillaspy, NIST)
Properties of Highly Charged Ions

Due to their high charge $q$ ions can be accelerated very effectively

$\sim q$ for linear accelerators

$\sim q^2$ for ring accelerators

Example:

$\text{Xe}^{1+}$ and $\text{Xe}^{44+}$ acceleration at $\Delta U = 20$ kV

<table>
<thead>
<tr>
<th>$\Delta U = 20$ kV</th>
<th>Linear Accelerator</th>
<th>Ring Accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Xe}^{1+}$</td>
<td>20 keV</td>
<td>20 keV</td>
</tr>
</tbody>
</table>
| $\text{Xe}^{44+}$| 880 keV            | 38720 keV = 38.72 MeV

(energy gain about factor 2000!)
Applications of HCI

Highly Charged Ions in Basic Research and Industry
Applications of HCI

Highly Charged Ions in Basic Research and Industry

Nanostructuring

Fragmentation of biomolecules

X-ray projection microscopy

Radiation biology

Information storage

Lithography

Medicine: Cancer therapy

Surface analysis (FIB, TOF-SIMS...)

highly charged ions
How to Produce Highly Charged Ions?

**Ion Accelerators** (GSI, TSR HD)
- Stripping
  - Up to bare nuclei at high projectile energies

**ECR Ion Sources**
- Electron Cyclotron Resonance (ECR)
  - Heating of a magnetically confined plasma

**Electron Beam Ion Sources/Traps**
- Ionization in high-dense electron beams
  - Electron beam compression in strong magnetic fields
  - Superconducting or permanent magnets
  - up to small amounts of U\(^{92+}\)

**Laser Ion Sources**
- Pulsed laser irradiation of selected targets
  - Pb\(^{27+}\) etc.
**Electron Beam Ion Trap – Basic Idea**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>up to 200 keV</td>
</tr>
<tr>
<td>Electron beam current</td>
<td>up to A (typically up to some hundreds of mA)</td>
</tr>
<tr>
<td>Source vacuum</td>
<td>$10^{-8}$ mbar up to $10^{-12}$ mbar</td>
</tr>
</tbody>
</table>
## EBIS/T – Short History

### Selected Milestones

<table>
<thead>
<tr>
<th>Year</th>
<th>Place/Name</th>
<th>Device</th>
<th>Ions</th>
<th>Source type (B, trap length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>Dubna (USSR) Donets</td>
<td>IEL I, IEL II</td>
<td>Au$^{19+}$</td>
<td>warm EBIS 0.4 T, 16 cm</td>
</tr>
<tr>
<td>1971</td>
<td>Dubna (USSR) Donets/Pikin</td>
<td>KRION I</td>
<td>C$^{6+}$, N$^{7+}$, O$^{8+}$, Ne$^{10+}$</td>
<td>SC 1.2 T, 1.2 m</td>
</tr>
<tr>
<td>1974</td>
<td>Dubna (USSR) Ovsyannikov/Donets</td>
<td>KRION 2</td>
<td>Ar$^{18+}$, Kr$^{36+}$, Xe$^{54+}$</td>
<td>SC 2.2 T, 1.2 m</td>
</tr>
<tr>
<td>1981</td>
<td>Orsay (France) Arianer</td>
<td>CRYEBIS 1</td>
<td>C$^{6+}$, N$^{7+}$, Ne$^{10+}$, Ar$^{18+}$</td>
<td>SC, 3 T, 1.66 m</td>
</tr>
<tr>
<td>1986</td>
<td></td>
<td>CRYEBIS 2</td>
<td></td>
<td>SC, 5 T, 1.66 m</td>
</tr>
<tr>
<td>1984</td>
<td>Saclay (France) Faure</td>
<td>DIONE</td>
<td>Ar$^{16+}$, Kr$^{30+}$, I$^{41+}$</td>
<td>SC, 6 T, 1.2 m</td>
</tr>
</tbody>
</table>
## EBIS/T – Short History

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<tr>
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<th>Device</th>
<th>Ions</th>
<th>Source type (B, trap length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>LLNL (USA) Levine Marrs/Knapp</td>
<td>EBIT-I</td>
<td>Xe(^{54+}), U(^{88+})</td>
<td>SC, 3 T, 2 cm ((E_{(e,\text{max})} = 29) keV)</td>
</tr>
<tr>
<td>1990</td>
<td>LLNL (USA) Marrs/Schneider</td>
<td>EBIT-II (\text{\textbf{(birth of EBIT!})})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>LLNL (USA) Marrs/Schneider</td>
<td>S-EBIT</td>
<td>U(^{92+}), Cf(^{96+})</td>
<td>SC, 3 T, 2 cm ((E_{(e,\text{max})} = 215) keV)</td>
</tr>
<tr>
<td>1999</td>
<td>Freiburg (Germany) Crespo</td>
<td>F/HD-EBIT</td>
<td>Xe(^{54+})</td>
<td>SC, 9 T, 4-30 cm</td>
</tr>
<tr>
<td>2009</td>
<td>Brookhaven (USA) Beebe/Pikin</td>
<td>RHIC-EBIS</td>
<td>Xe(^{36+}) high current EBIS</td>
<td>SC 6 T, 1.5 m</td>
</tr>
</tbody>
</table>
## EBIS/T – Short History

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<tr>
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<th>Device</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>TU Dresden (Germany) Ovsyannikov/Zschornack</td>
<td>Dresden EBIT</td>
<td>$\text{Ar}^{18+}$, $\text{Xe}^{44+}$, $\text{Ir}^{67+}$</td>
<td>warm EBIT, 0.25 T, 2 cm ($E_{(e,\text{max})} = 15$ keV)</td>
</tr>
<tr>
<td>2005</td>
<td>Dreebit GmbH (Germany) Ovsyannikov/Zschornack</td>
<td>Dresden EBIS Dresden EBIS-A</td>
<td>$\text{Ar}^{18+}$, $\text{Xe}^{48+}$, $\text{Ir}^{67+}$</td>
<td>warm EBIS, 0.4/0.6 T, 6 cm ($E_{(e,\text{max})} = 25$ keV)</td>
</tr>
<tr>
<td>2009</td>
<td>Dreebit GmbH (Germany) Ovsyannikov/Zschornack</td>
<td>Dresden EBIS-SC (medical applications and R&amp;D)</td>
<td>$\text{C}^{6+}$, $\text{Ar}^{18+}$, $\text{Xe}^{48+}$</td>
<td>SC, 6 T, 4-30 cm ($E_{(e,\text{max})} = 20$ keV)</td>
</tr>
</tbody>
</table>
EBIT Design

„classical“ cryogenic EBIT

- superconducting coils → (3… 8) T magnetic field
  ⇒ \( j_e > 1000 \text{ A/cm}^2 \)

- highest charge states \( \text{Xe}^{(52…54)^+} \), up to \( \text{U}^{(90…92)^+} \)

- large devices, liquid helium cooling

- latest developments: Refrigerator cooling

room-temperature EBIT

- permanent magnets (SmCo, NdFeB) (250…620) mT at the axis
  ⇒ \( j_e = (200… 600) \text{ A/cm}^2 \)

- bare ions up to \( Z=28 \), \( \text{Kr}^{34+}, \text{Xe}^{(44…48)^+}, \text{Ir}^{67+} \)

- compact, transportable, low initial and maintenance costs, short setup times

latest developments: Refrigerator cooling
There are actually about 60 EBIS/EBIT around the world. (For a list see R. Becker, O. Kester; RSI 81(2010) 02A513)

Most of them are special laboratory constructions.

Worlwide there are only two commercial offerers:

1. **Physics and Technology Livermore (USA)**
   - REBIT (Refrigerated Electron Beam Ion Trap)

2. **DREEBIT GmbH Dresden (Germany)**
   - Dresden EBIT
   - Dresden EBIS
   - Dresden EBIS-A
   - Dresden EBIS-SC
   - Room-Temperature EBIS/T (Refrigerated Electron Beam Ion Trap)
EBIS/T
Different solutions

- Tokyo EBIT
- Dresden EBIT
- Shanghai EBIT
- LLNL EBIT (at the MPI for Plasma Physics Berlin)
Dresden EBIS-SC –
A superconducting EBIS

- L-He free at 4.2K
- electron beam energy up to 30 keV
- electron beam current up to 700 mA
- magnetic field on-axis 6T

Measured ion pulses

<table>
<thead>
<tr>
<th>Ion</th>
<th>Max. Ions/pulse</th>
<th>Max. pulse rate/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁺</td>
<td>3 \times 10⁸</td>
<td>500</td>
</tr>
<tr>
<td>H₂⁺</td>
<td>3 \times 10⁸</td>
<td>1000</td>
</tr>
<tr>
<td>C⁴⁺</td>
<td>8 \times 10⁸</td>
<td>10</td>
</tr>
<tr>
<td>C⁶⁺</td>
<td>4 \times 10⁸</td>
<td>10</td>
</tr>
<tr>
<td>Ar¹⁶⁺</td>
<td>2 \times 10⁷</td>
<td>2</td>
</tr>
<tr>
<td>I⁴⁺</td>
<td>1 \times 10⁶</td>
<td>1</td>
</tr>
</tbody>
</table>
The intended purpose of an EBIS is to produce highly charged ions. For a certain ionisation stage q two opposite processes take place in the electron beam:

**Charge-generating processes**

- Ionisation (ion)
- Charge Exchange (ce)
- Radiative Recombination (RR)

**Charge destructive processes**

- Ionisation
- Charge Exchange
- Radiative Recombination
- Ion loses from the trap
Charge Balance of Ions with the Charge State $q$

**Rate equations**

$$\frac{dn_q}{dt} = n_e v_e \left[ \sigma_{q-1 \rightarrow q}^{\text{ion}} n_{q-1} - \left( \sigma_{q \rightarrow q+1}^{\text{ion}} + \sigma_{q \rightarrow q-1}^{\text{RR}} \right) n_q + \sigma_{q+1 \rightarrow q}^{\text{RR}} n_{q+1} \right]$$

$$- n_0 v_{i\text{on}} \left[ \sigma_{q \rightarrow q-1}^{\text{ce}} n_q - \sigma_{q+1 \rightarrow q}^{\text{ce}} n_{q+1} \right] - f_q^{\text{col}} \left( \frac{e}{kT_{i\text{on}}} \right) \frac{qeU_t}{kT_{i\text{on}}} n_q$$

**Charge-generating processes** (sources for $A^{q+}$)

**Charge destructive processes** (sinks for $A^{q+}$)

- We should consider
  - the electron beam energies
  - the vacuum in the ionization region
  - the excitation functions of individual processes

$U_t$ - depth of the potential wall (radial and axial) trap potential

$kT_{i\text{on}}$ - ion energy
Example:
Ionization of Xenon in a Dresden EBIS-A

Pressure: $2 \times 10^{-9}$ mbar
Electron beam energy: 14 keV
The basic process in the electron beam of an EBIS is **successive electron impact ionization** with an average ionization time for the ionization of ions with the charge state $q$ of

\[
\tau_{q\rightarrow q+1} = \frac{n_q}{f_{q\rightarrow q+1}} = \frac{1}{n_e v_e \sigma_{q\rightarrow q+1}} = \frac{e}{j_e \sigma_{q\rightarrow q+1}}
\]

with the collision frequency

\[
f_{q\rightarrow q+1} = n_e n_q v_e \sigma_{q\rightarrow q+1}
\]

This expressions lead to the **ionization factor**

\[
j_e \tau_{q\rightarrow q+1} = \frac{e}{\sigma_{q\rightarrow q+1}}
\]

i.e. ionization is possible if we have

\[
j_e \tau_{q\rightarrow q+1} \geq \frac{e}{\sigma_{q\rightarrow q+1}}
\]
Ionization Factor vs. Atomic Number and Degree of Ionisation

\[ E_e = 2.7 \cdot E_B \]

Ionization factor (e cm\(^{-2}\))

Z →

- fully ionized
- hydrogen-like
- helium-like
- neon-like
- argon-like
- nickel-like
- krypton-like
Ionization Factor vs. Atomic Number, Degree of Ionization and Electron Energy

According to an idea from Prof. E.D. Donets [Dubna]
The optimal energy for ionizing an ion from the charge state $q$ to $q+1$ is nearly $e$-times the ionization energy of the weakest bound electron.

Ionization starts at the ionization threshold $E_I$. 
Electron Binding Energies
Threshold values for ionization

Graph showing the relationship between ionic change and atomic number, with different threshold values for electron binding energies indicated.
Let's have a look onto the most important physical processes in the electron beam:

- Single ionization
- Double ionization
- Single charge exchange
- Double charge exchange
- Radiative recombination
Basic Physics
Single Electron Impact Ionization

\[ A^{q+} + e^- \rightarrow A^{(q+1)+} + 2e^- \]

The higher the ion charge state, the smaller is the ionization cross section.

\[
\sigma_{q\rightarrow q+1} = 4.5 \cdot 10^{-14} \sum_{i=1}^{N} \frac{\ln \frac{E_e}{E_{nl}}}{E_e \cdot E_{nl}} \text{ [cm}^2\text{]} 
\]

Lotz formula for \( E_e \gg E_{nl} \)
(estimated error: up to 10%;
N: number of subshells)
Basic Physics
Double Electron Impact Ionization

\[ A^{q+} + e^- \rightarrow A^{(q+2)+} + 3e^- \]

The higher the ion charge state, the smaller is the ionization cross section

Shevelko formula

\[ \sigma_{q\rightarrow q+2} = 1.4 \cdot 10^{-19} \frac{N^{1.08}}{(E_q[\text{eV}]/13.6\text{ eV})^2} \left( \frac{U}{U+1} \right)^c \frac{\ln(U+1)}{U+1} \text{[cm}^2\text{]} \]

with

\[ U = \frac{E_e}{E_q} - 1 \]

c=1 for neutrals and c=0.75 for ions

\( E_q \) – sum of the ionization potentials of both weakest bound electrons

\( N \) – number of electrons in the atom/ion
Charge exchange is dominant and the main loss process for highly charged ions.

\[ A^{q+} + A^{p+} \rightarrow A^{i+} + A^{(q+p-i)+} \]

Cross sections are independent on the electron energy.

\[ \sigma_{q \rightarrow q-1} \approx (1.43 \pm 0.76) \cdot 10^{-12} q^{1.17} (E_q [eV])^{-2.76} \text{[cm}^2\text{]} \]

Single charge exchange (Müller and Salzborn)

\[ \sigma_{q \rightarrow q-2} \approx 1.08 \cdot 10^{-12} q^{0.71} (E_q [eV])^{-2.8} \text{[cm}^2\text{]} \]

Double charge exchange
Due to RR processes ionization in an EBIS is more efficient at higher electron energies.

\[ A^{q+} + e^- \rightarrow A^{(q-1)+} + \hbar \omega \]

Charge exchange is strong at low electron energies.

Theory from Stobbe (for fully ionized atoms)

\[ \sigma_{q \rightarrow q-1}^{RR} = 2.10 \cdot 10^{-22} \frac{E_0^2}{nE_{cm}(E_0 + n^2E_{cm})} \text{[cm}^2\text{]} \]

\[ \sigma_{q \rightarrow q-1}^{RR} = \frac{8\pi}{3\sqrt{2}} \alpha \chi_q(E_e) ln\left(1 + \frac{\chi_q(E_e)}{2(n + (1 - W_n) - 0.3)}\right) \]

Theory from Kim and Pratt (for all ions)

\[ \chi_q(E_e) = (Z + q)^2 \frac{13.6 \text{ eV}}{4E_e} \]

where

- \( E_0 \) – binding energy of the hydrogen-like ground-state ion
- \( n \) – main quantum number of the shell where the electron is captured
- \( E_{cm} \) – CM collision energy between electrons and ions
- \( W_n \) – ratio of the number of unoccupied states to the total number of states in the subshell
- \( \alpha \) – fine structure constant
- \( \chi_q(E_e) \) – capture cross section
- \( \lambda_e \) – Compton-wavelength
Balance between ionization and radiative recombination for lead ions
(after: R. Becker; ICIS 2009, Gatlinburg)

Ion loss ratio:

\[ R = 2 \cdot 10^{-13} n_e \frac{q^2}{\sqrt{E_e}} \left[ \frac{\text{cm}^3}{\text{s}} \right] \]
Capture of an electron from the continuum at simultaneous excitation of a second electron and following deexcitation (photon emission).

\[ A^{q+} + e^- \rightarrow [A^{(q-1)+}]^* \rightarrow A^{(q-1)+} + \hbar \omega \]

Capture of an electron from the continuum at simultaneous excitation of a second electron and following deexcitation (photon emission).

\[ R_{DR} = 6 \cdot 10^{-10} N \left( \frac{q}{E_e} \right)^{3/2} \sqrt{E_q} e^{-\frac{E_q}{E_e}} \left[ \frac{cm^3}{s} \right] \]

Ion loss ratio

N – number of electrons in the outermost occupied shell

E_q – ionization energy of the ion with the charge q
The total number of ions stored in an EBIs is determined by the electrical trap capacity $C_{el}$.

**Assumption:**

Homogeneous electron beam passing an ion trap of the length $L$ with an electron beam current $I_e$. The electron energy is $E_e$.

With

$$I_e = \frac{dQ}{dt}, \quad v_e = \frac{dx}{dt}, \quad v_e = \sqrt{\frac{2E_e}{m_e}} \quad \Rightarrow \quad \Delta Q = \frac{I_e \Delta x}{v_e} = \frac{I_e L}{\sqrt{2E_e m_e}}$$

follows

$$C_{el} = 1.05 \cdot 10^{13} \frac{I_e[A] \ L[m]}{\sqrt{E_e[eV]}}$$
EBIS: Basic Properties

Electrical trap capacity

\[ C_{el} = 1.05 \cdot 10^{13} \frac{I_e[A]}{\sqrt{E_e[eV]}} \cdot f \cdot \alpha \]

For practical purposes we must consider

- the charge compensation \( f \) (\( f < 1 \)) of the electron beam,
- the fraction \( \alpha \) of ions with a certain ion charge state in the ion charge state spectrum of the produced ions.

Example:

Trap capacity of the Dresden EBIS-SC at different electron beam currents and different electron beam energies.
**EBIS: Basic Properties**

Electron beam: space charge potential

### Radial trap potential

\[
V_e(r) = \begin{cases} 
  U_e \left( \frac{r}{r_e} \right)^2 & \text{für } r < r_e \\
  U_e \left( 2 \ln \frac{r}{r_e} + 1 \right) & \text{für } r > r_e
\end{cases}
\]

with

\[
U_e = \frac{I_e}{4\pi \varepsilon_0 v_e} = \frac{1}{4\pi \varepsilon_0} \cdot \sqrt{\frac{m_e}{2}} \cdot \frac{I_e}{\sqrt{E_e}}
\]

For estimations we get:

\[
U_e = \sqrt{\frac{30 I [A]}{\sqrt{1 - \left( \frac{E_e [keV]}{511} + 1 \right)^{-2}}} [V]}
\]

**Example:**

**Radial trap potentials** in a Dresden EBIT.

The potential of the drift tubes is superimposed by \( U_e \) in the center of the electron beam.
Equation of motion for $r$

$$\frac{d^2 r}{dt^2} = \frac{eI_e}{2\pi\varepsilon_0 v_z rm_e} + \frac{e^2}{4m_e^2} \left( \frac{B_c^2 r_c^4}{r^3} - B_z^2 r \right)$$

$B_c$ – B-field at the cathode
$r_c$ – cathode radius

Assuming $B_c = 0$ exists a stationary solution of the above equation. The solution corresponds to an equilibrium flow of the electrons with constant radius, the so-called Brillouin-Flow.

We obtain:

$$B = B_B = \frac{1}{r} \left( \frac{2I_e m_e}{\pi\varepsilon_0 v_z |e|} \right)^{1/2} \quad \text{and} \quad r_B = \frac{1}{B_B} \left( \frac{2I_e m_e}{\pi\varepsilon_0 v_z |e|} \right)^{1/2}$$

For a Brillouin flow all electrons have a constant distance to the beam center. Thereby the Lorentz force caused by the magnetic field is compensated by the space charge and the centrifugal force of the rotating electrons.
Electron beam dynamics, considering

- a magnetic field at the cathode,
- thermal effects at the cathode due to filament heating up to the temperature $T_c$,
- interactions between the electrons

lead to a corrected electron beam radius (smaller than $r_B$)

→ Herrmann Theory

*(G.Herrmann; J.Appl.Phys., 29 (1958) 127)*
Electron beam radius, enclosing 80% of the beam

\[ r_e = r(0) \cdot \sqrt{\left(1 - \frac{r_0}{r(0)}\right)^2 + \frac{2}{1 + \frac{B_C^2 r_C^4}{B_z^2 r_0^4}} \left(\frac{v_e \tan \gamma}{\frac{e}{m_e} B_z} \right)^2} \]

and

\[ r_0 = r_B \left(\frac{1}{2} + \frac{1}{2} \left[1 + 4 \left(\frac{8 k T_C r_C^2 m_e}{e^2 B_z^2 r_B^4} + \frac{B_C^2 r_C^4}{B_z^2 r_B^4}\right)^{1/2}\right]^{1/2}\right) \]

with
- \( r(0) \) – beam radius at the cathode
- \( \gamma \) – angle deviation from the source axis

* (G. Herrmann; J. Appl. Phys., 29 (1958) 127)
Electron beam density determines the ionization rate → investigation necessary for understanding the ionization process

- Dresden EBIT:
  \[ r_{80\%} = 89\pm4 \text{ µm}; \ j_e = 96\pm9 \text{ A/cm}^2 \]
  @ E\text{e} = 7.8 \text{ keV}; I_e = 30 \text{ mA}

Generally:
electron beam diameter
(40...200) µm

CCD image

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.
Electron Beam Ion Sources

Production of HCI

Electron-impact ionization: It is hot in the ion trap

> 100,000,000 K

Conditions as at the border of a black hole...

The electron beam energy of an EBIS can be adjusted with a precision of eV

→ Selective excitation and preparation of atomic states and ion charge states

Electron beam scalpel
EBIS: Basic Properties

- Ion beam properties
  - Pulse form and width
  - Emittance
  - Energy spread
  - Extracted ions (see later)
Three operation modes:

1. **Permanently opened trap – transmission mode**
   The trap is permanently open and ions are produced in the electron beam without axial trapping.
   This mode delivers **high currents of the lowest charged ions (nA ... µA)**.

2. **Partially closed trap – leaky mode**
   Selecting a low axial potential wall a certain amount of ions with adequate kinetic energy can surpass the potential wall and are extracted continuously.
   This mode delivers **ions with preferentially low up to intermediate ion charge states (up to nA) and a low fraction of higher ion charge states**.

3. **Periodically opened and closed trap – pulsed mode**
   The potential wall is high enough to trap all ions axially. Periodical opening of the trap releases pulses of ions extracted with typical pulse lengths in the order of some microseconds and allow to produce **highest currents of highly charged ions (up to µA per pulse)**.
Particularities of EBIT/EBIS puls form – classical extraction

**FWHM is in the order of µs**

Ion paths in the moment of ion extraction

Ion extraction

**Ion pulses from the Dresden EBIS-A**
Trap length – 6 cm

---

**FWHM is in the order of µs**

Ion paths in the moment of ion extraction

**Ion extraction**

**Ion pulses from the Dresden EBIS-A**
Trap length – 6 cm
FIG. 3. Extracted ionic charges per Ar$^{16+}$ pulse in dependence on the extraction time $t_{\text{extr}}$ ($U_0=4.0$ kV, $I_e=24$ mA, $t_{\text{cyc}}=100$ $\mu$s, $t_{\text{wait}}=1$ s, $p=3.1 \times 10^{-9}$ mbar). The solid line is a guide to the eye.

Short time ion pulse extraction from the Dresden electron beam ion trap$^a$

U. Kentsch,$^1$ G. Zschornack,$^{2b}$ A. Schwan,$^1$ and F. Ullmann$^1$

$^1$Dreebit GmbH, D-01109 Dresden, Germany
$^2$Institute of Applied Physics, Dresden University of Technology, D-01062 Dresden, Germany
One of the requirements for the applications of EBIS with synchrotrons are flat-top pulses.

Controlling properly $U_B$ flat-top pulses with FWHM to at least 100 $\mu$s can be formed.
Particularities of EBIT/EBIS Emittance

90° Bending magnet

Einzel lens
Dresden EBIS-A

Position 1
CCD camera

Position 2
Faraday cup

Mirror
Phosphor screen + MCP
Pepperpot mask

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Particularities of EBIT/EBIS Emittance

The scheme of the Pepper-Pot Emittance Meter is pictured in figure 2. The incoming particle beam passes the Pepper-Pot mask and is separated into several beam spots. The particles hitting the MCP create an electron current which is amplified passing the two micro channel plates. The electrons are then accelerated towards the phosphor screen. The visible light spots created at the phosphor screen are detected after 90° deflection by a CCD camera.

The emittance of the beam can be determined from the position, the size, and the shape of the light spots.

Display of the results after calculation
Particularities of EBIT/EBIS Emittance

Dresden EBIS-A

For comparison:

Dresden EBIS-SC about 30 mm mrad for $I_e = 300$ mA
Particularities of EBIT/EBIS Energy spread

The differentiation of the measured curves gives

- The energy spread
- The total beam energy of the analyzed ion beam.

![Diagram of EBIT/EBIS setup]

- Retarding field analyzer
- HV grid
- Grounded grid
- Faraday cup
- Collimator including two diaphragms
- Support

The graph shows the differential intensity of ions with respect to the beam energy. The energy spread is indicated by the width of the peaks, and the total beam energy can be determined from the area under the curve.
Particularities of EBIT/EBIS Energy spread

Dresden EBIS-A $\text{Ar}^{8+}$

Total ion beam energy (shifts due to different depths of the beam Coulomb potential)

Energy spread of $\text{Ar}^{8+}$ (the energy spread is below 1 eV/u in any case)
EBIS: Diagnostics
Processes in the ion source

- q/A analysis
  - Dipole magnet
  - Wien filter

- X-rays (UV, EUV, visible light)
  - energy dispersive spectroscopy
  - wavelength dispersive spectroscopy
  - time-resolved spectroscopy

June 2, 2012
EBIS: Diagnostics

q/A Analysis

- Beamline positioning units
- Signal interface units
- Power and vacuum control unit
- High voltage terminal shielding

High voltage power supplies

Ion deceleration lens system

Large target chamber, customer specifications on request

Transfer chamber

Dresden EBIS-A

Ion beam guiding components: Einzel lenses, ion deflectors

1 m

Mass separation: double focusing analyzing dipole magnet

Ion beam diagnostics: Faraday cups, MCP detector on request

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Objective: charge state separated ion beam

Lorentz force = centripetal force

\[
q \cdot v \cdot B = \frac{mv^2}{r}
\]

- Ion charge state separation

\[
\frac{q}{A} = \frac{2 \cdot U}{r^2 B^2}
\]
q/A analysis: dipole magnet
Examples for ion charge state spectra

Ion extraction spectra measured with a Faraday cup after ion charge state separation.
q/A analysis: dipole magnet time-resolved ion charge state spectra

Signal intensity of individual ion charge states measured at different ionization times → reveals the evolution of charge states in the trap

Further analysis allows for
- characterizing the charge balance inside the trap
- estimating the ionisation factor of the source
- determining electron impact ionisation cross sections.

Dresden EBIT Fe<sup>q+</sup>
The Wien Filter is a particle separator with a crossed magnetic and electric field configuration providing mass and charge state separated beams of excellent quality at small spatial dimensions (15cm \times 20cm \times 20cm). With the Wien filter as an ion source add-on an very compact device is available substituting a complete standard beamline setup with a space consuming dipole magnet and other necessary equipment. The Wien filter can be used as stand-alone solution for various beam line setups. In dependence on the installed mass- and charge state-separating aperture a resolution of better than 80 is available.
EBIS: Diagnostics
q/A Analysis with a Wien filter
q/A analysis: Wien filter
Examples for ion charge state spectra

Dresden EBIT
Xenon

Closed atomic shells
q/A analysis: Wien filter
Examples for ion charge state spectra

Dresden EBIT Hydrogen

Dresden EBIT Neon
## Pulsed mode (ions/pulse)

<table>
<thead>
<tr>
<th>Ion</th>
<th>EBIT</th>
<th>EBIS-A</th>
<th>EBIS-SC</th>
<th>EBIT:EBIS-A:EBIS-SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>C⁴⁺</td>
<td>24.000.000</td>
<td>80.000.000</td>
<td>900.000.000</td>
<td>1 : 3 : 38</td>
</tr>
<tr>
<td>C⁶⁺</td>
<td>10.000.000</td>
<td>30.000.000</td>
<td>400.000.000</td>
<td>1 : 3 : 40</td>
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<tr>
<td>Ar¹⁶⁺</td>
<td>900.000</td>
<td>7.800.000</td>
<td>250.000.000</td>
<td>1 : 9 : 278</td>
</tr>
<tr>
<td>Ar¹⁷⁺</td>
<td>45.000</td>
<td>1.400.000</td>
<td>22.000.000</td>
<td>1 : 31 : 489</td>
</tr>
<tr>
<td>Ar¹⁸⁺</td>
<td>6.000</td>
<td>90.000</td>
<td>1.500.000</td>
<td>1 : 15 : 250</td>
</tr>
<tr>
<td>Xe⁴⁴⁺</td>
<td>10.000</td>
<td>700.000</td>
<td>10.000.000</td>
<td>1 : 70 : 1000</td>
</tr>
</tbody>
</table>
Beams of molecular fragments

**Propane \( \text{C}_3\text{H}_8 \)**

Extraction of all molecular fragments

\( \text{C}_x\text{H}_y \)

- \( x = 1 \ldots 3 \)
- \( y = 1 \ldots 9 \)
- \( y = 9: \) protonation

A unique possibility to form beams of exotic molecular fragments
For an x-ray detector the following count rate can be expected

\[ \dot{N}_q = \varepsilon \frac{\Omega}{4\pi} V j_{\omega q} n_q \sigma_{q}^{exc} \]

\[ \dot{N}_q = \varepsilon \frac{\Omega}{4\pi} l I_{e\omega q} n_q \sigma_{q}^{exc} \]

The emitted radiation power can be estimated as

\[ P = \dot{N}_q E_{if e} \]

For individual dipole lines radiation power on the order of nW was recorded.
EBIS: X-Ray Diagnostics

X-ray output

EBIS are excellent sources of X-rays from highly charged ions.

<table>
<thead>
<tr>
<th>ion</th>
<th>transition $i \to f$</th>
<th>$E_{if}$/eV</th>
<th>$A_{if}$/eV/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar$^{16+}$</td>
<td>$2p(^1P_1) \to 1s(^1S_0)$</td>
<td>3138.8</td>
<td>0.073</td>
</tr>
<tr>
<td>Xe$^{26+}$</td>
<td>$3d(^1P_1) \to 2p(^1D_2)$</td>
<td>4159.6</td>
<td>0.208</td>
</tr>
<tr>
<td>Xe$^{36+}$</td>
<td>$3d(^1P_1) \to 2p(^1S_0)$</td>
<td>4366.8</td>
<td>0.372</td>
</tr>
<tr>
<td>Xe$^{44+}$</td>
<td>$3d(^1P_1) \to 2p(^1S_0)$</td>
<td>4558.0</td>
<td>0.321</td>
</tr>
</tbody>
</table>

X-ray output from the Dresden EBIT
X-rays from highly charged ions
radiation power of the Dresden EBIT

The graph shows the most dominant dipole transitions for DE in case of 3 different ion species:

- EBIS-A: \( \times 10 \)
- EBIS-SC: \( \times 200 \)

\( \rightarrow \) higher transition power

\[
P[W] = \frac{\text{photons}}{s} \times \frac{E[\text{eV}]}{e[\text{As}]} \]
Z-dependence allowed and forbidden transitions
HFS, QED, parity violation

Table III. The Z-dependence of the probabilities of allowed and forbidden transitions, hyperfine interaction, QED effect, relativistic effects and parity violation effect along the Hydrogen iso-electronic sequence.

With higher atomic number the intensity of otherwise weak transitions increases.

For highly charged ions otherwise forbidden transitions can become dominant.

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Physics Based on Electron Beam Ion Traps*  
Yuming Zou1,2* and Roger Hutton3

1The Key Lab of Applied Ion Beam Physics, The Ministry of Education, China  
Modern Physics Institute, Fudan University, Shanghai 200433, China  
2Astronomy Department, Lund University, BOX 43, SE-221 00 Lund, Sweden
X-rays: excitation vs. ionisation

excitation cross-section for 
\[ 2p(^{1}S_{0}) \rightarrow 3d(^{1}P_{1}) \]
vs.
L-shell ionisation cross-section in Xe\(^{44+}\)
Transition energies in one- and two-electron systems can be calculated very precisely.

Therefore hydrogenn-like ions are excellent sources for well known x-ray transitions: Lyman lines.
Wavelength X-ray spectroscopy: Xenon

\[ E: \ 3s - 2p \]
\[ F: \ 3d - 2p \]
Energy and Wavelength X-ray spectroscopy: Iron

- Diagram showing X-ray spectroscopy of iron
- LiF (200) crystal analysis
- Fe (C₅H₅)₂ molecule structure
- Energy level diagram for iron
X-Ray Spectroscopy: Scatterplot
Time-resolved x-ray spectroscopy

Time-resolved energy dispersive x-ray spectroscopy on xenon ions
Time-resolved KKL-DE x-ray spectroscopy

KLL $\text{Kr}^{28+}$

(fixed electron beam energy, but x-rays as a function of the ionization time)
Applications of highly charged ions (examples)
Applications of highly charged ions (examples)

Nanostructuring

FIB, Surface analysis

Particle Therapy

Charge Breeding
Nanostructuring with highly charged ions

**Ion Implantation**
- Nanocrystals by Implantation and Annealing
- Focused Ion Beam Synthesis of Nanostructures
- Magnetic Nanostructures

**Ion Beam Sputtering**
- Focused Ion Beam Direct Writing
- Self-Organized Periodic Nanopatterns

**Highly Charged Ions**
- Local Modification of Surface Structure by Electronic Excitation
- Nanodots/pits by Single Ion Impact

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FZD Ringvorlesung 2009/10

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Nanostructuring with HCI

Surface Modifications Induced by Potential Energy

**HOPG**
- Conductor
- AFM: flat surface
- STM: nanodots
  → HCl impact modifies electronic structure of surface

**KBr**
- Insulator
- Nanopits
  → HCl impact induces desorption

**CaF₂**
- Insulator
- AFM: nanodots
  → HCl impact modifies crystal structure of surface

- HOPG, 150 eV Ar²⁺, \( E_{\text{pot}} = 1000 \text{ eV} \)
- CaF₂, 5.4 keV Xe³⁶⁺, \( E_{\text{pot}} = 27.8 \text{ keV} \)
- KBr, Xe³⁴⁺, 24 keV, \( E_{\text{pot}} = 20 \text{ keV} \)

New properties:
- morphologic
- electric
- optic

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June 2, 2012
Focussed Ion Beams

FIB
(Focused Ion Beam)
### A new class of FIB

<table>
<thead>
<tr>
<th>Feature</th>
<th>New Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectiles</td>
<td>Almost all elements of the periodic table, in particular noble gases</td>
</tr>
<tr>
<td>Charge State</td>
<td>Free choice of projectile charge state</td>
</tr>
<tr>
<td>Sputter Yield</td>
<td>Variable, according to the kinetic and potential energy</td>
</tr>
<tr>
<td>Implantation</td>
<td>Variable implantation depth, according to the kinetic projectile energy</td>
</tr>
</tbody>
</table>

**Implantation in Si:**
Realization of different implantation depths due to different ion charge states at a fixed ion acceleration potential.
A new class of FIB
By using DREEBIT ion sources

Production of ion beams with different ion charge states with diameters in the micrometre up to nanometre region.

<table>
<thead>
<tr>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithography</td>
</tr>
<tr>
<td>Nano Engineering</td>
</tr>
<tr>
<td>Photonic Structures</td>
</tr>
<tr>
<td>Materials Characterization</td>
</tr>
<tr>
<td>Micro-Machining</td>
</tr>
<tr>
<td>Quantum Dots</td>
</tr>
<tr>
<td>Radiation Biology</td>
</tr>
<tr>
<td>Surface Analytics</td>
</tr>
</tbody>
</table>
Xe - FIB

Worldwide first SEM-figures produced with a Xe ion beam!

lattice width 2 \( \mu \text{m} \)
Time-of-Flight Secondary Ion mass Spectrometry

TOF-SIMS
## Time of Flight Secondary Ion Mass Spectroscopy

<table>
<thead>
<tr>
<th>Anwendungen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductor industry</td>
</tr>
<tr>
<td>Surface analysis</td>
</tr>
<tr>
<td>&quot;Soft matter“ applications (bio materials, polymers, ... )</td>
</tr>
<tr>
<td>Materials science</td>
</tr>
<tr>
<td>Basic research</td>
</tr>
<tr>
<td>Classical industry (glass, paper, metal, ceramics, ... )</td>
</tr>
<tr>
<td>Analysis of contaminations, adhesion, friction, corrosion, diffusion, cell chemistry, bio compatibility</td>
</tr>
</tbody>
</table>
Applications of HCI
Applications of HCI TOF-SIMS

Non-cleaned Si-surface

Excitation with xenon ions

Positive ions

negative ions
Applications of HCI: TOF-SIMS
Medical Particle Therapy

Hadron Therapy

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Cancer - a Worldwide Problem

- Cancer is the the second most common cause of death and about 33% of all inhabitants of the EU will confront some kind of cancer in their life.

- About 45% of cancer patients can be treated, mainly by surgery and / or radiation therapy [S.Peggs, PAC07, June 25'07]

- Hadron therapy with protons and carbon ions is - taken its success rate - the second most successful technique in cancer treatment, outmatched only by surgery.

- Until 2005 about 40,000 patients worldwide were treated by particle therapy at 22 PT centers (Europe, USA, Japan, China, South Africa). The number of treated patients is constantly increasing.
Advantages of Therapy with Ion Beams

It is possible to focus carbon ions with great precision directly onto the tumor. Therefore, only the tumor is damaged irreversibly but the healthy tissue remains intact.

Another advantage is the high biological efficiency of carbon ions, causing more damage in the tumor cells than other kinds of irradiation.
Problem:
A magnetic analyser selects only individual q/A ratios, i.e. C$^{6+}$, N$^{7+}$ and O$^{8+}$ can not be separated by the magnet (q/A = 0.5)!

ECR ion sources are plasma ion sources working at vacua in the order of $10^{-6}$ mbar, i.e. there already is a mixing of C, N, and O in the plasma.
Simplification of Therapy Facilities by using a New Kind of Ion Source

**Advantages:**
- only one ion source
- one separation magnet
- shorter LINAC
- no stripper
- lower injection energy
- single-turn injection (at 4 MeV/u)
- smaller synchrotron magnets
- lower power consumption

- the complexity of the irradiation facility decreases,
- the beam quality is improved,
- costs can be reduced
Particle therapy

**Cyclotrons**
- IBA (Belgium)
- SIEMENS (Germany)
- HITACHI (Japan)
- MITSUBISHI (Japan) a.o.

**Synchrotrons**
- SIEMENS (Germany)
- HITACHI (Japan)
- MITSUBISHI (Japan) u.a.

**CYCLINACs**
- ADAM (Switzerland; CERN)

**DDA, DWA**
- SIEMENS (Germany)
- some institutes (USA, Japan)

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Today

Future

- Cyclotron
- Synchrotron
- Pulsed at high frequencies
- Cyclotron driven linac
- FFAG
- Dielectr. wall linacs
- Lasers
- Plasma wake field
Charge Breeding
Charge Breeding

q/A analysis

Evolution of the ion charge states Au\(^{38+}\) to Au\(^{48+}\)

Description:

\[ \frac{dN_{q+}}{dt} = \lambda_{q-1} \cdot N_{q-1} - \lambda_q \cdot N_q + \lambda_{q+1} \cdot N_{q+1} \]
Charge Breeding

Electron impact ionisation cross-sections for charge bred gold ions

$E_e = 11.5\, \text{keV}$
Charge Breeding: Gold

The diagram shows the x-ray spectrum for Au$^{8+}$ and I$^{8+}$ with their respective transitions labeled. The EBIT + LMIS Injection and EBIT Background are indicated. The x-axis represents the x-ray energy ($E_{x-ray}$) in keV, ranging from 1 to 15 keV, while the y-axis represents the counts ranging from 0 to 500.
Thank you ... and thanks to the team!