DREEBIT-Electron Beam Ion Sources and Traps
for Applications in Accelerator Physics

Speaker:
Mike Schmidt
DREEBIT GmbH
and
Dresden University of Technology
Agenda

Why Highly Charged Ions
  Properties, Production, Sources of HCI

EBIS/T Short History
  Selected Milestones

DREEBIT Ion Sources
  Room Temperature and Superconducting Ion Sources

Product Portfolio
  Ion Beam Optics and Diagnostics

Applications
  Charge Breeding and Medical Particle Therapy

References
  National and International Customer-specific Irradiation Facilities

Resumé
Why Highly Charged Ions?

Properties of highly charged ions
Properties of Highly Charged Ions
Extremely Compact Accelerator Structures are possible

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

$\sim q$ for electrostatic accelerators
$\sim q^2$ for circular accelerators

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

<table>
<thead>
<tr>
<th>$\Delta U = 20 \text{ kV}$</th>
<th>electrostatic accelerator</th>
<th>circular accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe $^{1+}$</td>
<td>20 keV</td>
<td>20 keV</td>
</tr>
<tr>
<td>Xe $^{44+}$</td>
<td>880 keV</td>
<td>38720 keV = 38,72 MeV</td>
</tr>
</tbody>
</table>

(energy gain about factor 2000!)
The deposition of potential energy leads to ultrafast intense electronic excitations. Energy density: $10^{12} \ldots 10^{14}$ W/cm$^2$
Energy deposition by ions into solids and surfaces

- 500 eV Xe\(^{q+}\)
- 5 keV Xe
- 100 MeV Xe

Potential energy vs. log \(E_{\text{kin}}\)
- Nuclear
- Electronic

Typ. 10 nm
Properties of Highly Charged Ions

HCl give higher Yields of Secondary Ions and Electrons


Total electron yields vs ion charge state q
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

**Laser Ion Sources**
- Pulsed laser irradiation of selected targets

- **up to U^{92+}**
- Ar^{16+}, Ta^{38+}, Au^{41+}
- up to small amounts of U^{92+}
- Pb^{27+} etc.
## 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>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>
<tr>
<td>1986</td>
<td></td>
<td>CRYEBIS 2</td>
<td></td>
<td>SC, 5 T, 1.66 m</td>
</tr>
</tbody>
</table>
## EBIS/T – Short History

### Selected Milestones

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<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 $(E_{(e,max)} = 29 \text{ keV})$</td>
</tr>
<tr>
<td>1990</td>
<td>LLNL (USA) Marrs/Schneider</td>
<td>EBIT-II (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 $(E_{(e,max)} = 215 \text{ keV})$</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

### Selected Milestones

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<tr>
<th>Year</th>
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<th>Device</th>
<th>Ions</th>
<th>Source type (B, trap length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>TU Dresden (Germany) Ovsyannikov/Zschornack</td>
<td>Dresden EBIT</td>
<td>Ar^{18+}, Xe^{44+}, Ir^{67+}</td>
<td>warm EBIT 0.25 T, 2 cm (E_{(e,\text{max})} = 15 \text{ keV})</td>
</tr>
<tr>
<td>2005-2008</td>
<td>Dreebit GmbH (Germany) Ovsyannikov/Zschornack</td>
<td>Dresden EBIS Dresden EBIS-A</td>
<td>Ar^{18+}, Xe^{48+}, Ir^{67+}</td>
<td>warm EBIS, 0.4/0.6 T, 6 cm (E_{(e,\text{max})} = 25 \text{ 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>C^{6+}, Ar^{18+}, Xe^{48+}</td>
<td>SC, 6 T, 4-30 cm (E_{(e,\text{max})} = 20 \text{ keV})</td>
</tr>
</tbody>
</table>
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.

Two commercial supplier worldwide:

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
   (Refrigerated Electron Beam Ion Trap)
Room Temperature EBIS/T

DREEBIT Ion Sources

DREEBIT GmbH

slide 13 / 27
Dresden EBIS-SC (superconducting)

DREEBIT Ion Sources

- 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 10^9</td>
<td>500</td>
</tr>
<tr>
<td>H(_2^+)</td>
<td>3 \times 10^9</td>
<td>1000</td>
</tr>
<tr>
<td>C(^{4+})</td>
<td>8 \times 10^8</td>
<td>10</td>
</tr>
<tr>
<td>C(^{6+})</td>
<td>4 \times 10^8</td>
<td>10</td>
</tr>
<tr>
<td>Ar(^{16+})</td>
<td>2 \times 10^7</td>
<td>2</td>
</tr>
<tr>
<td>I(^{43+})</td>
<td>1 \times 10^6</td>
<td>1</td>
</tr>
</tbody>
</table>
# 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>
</tr>
<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>
Ion Optics and Diagnostics
DREEBIT Product Portfolio

- Einzel lense
- Deflector
- Ion beam deceleration/acceleration system
- ExB Particle separator (Wien Filter)
- Faraday Cup
- Quadrupole Beam Bender
- Retarding Field Analyzer
- Pepperpot Emittance Meter...
q/A Analysis with a Wien filter
Ion Irradiation Facilities
DREEBIT Product Portfolio

Ion Irradiation Facility S

Ion Irradiation Facility L
Ion Irradiation Facilities
DREEBIT Product Portfolio

Equipment:

- 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

Ion beam diagnostics: Faraday cups, MCP detector on request

Mass separation: double focusing analyzing dipole magnet

Ion Irradiation Facility L
Cat.No.: 10001
Applications
Charge Breeding
Applications
Charge Breeding: Gold

q/A analysis

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

Description:

\[
dN_{q+}/dt = \lambda_{q-1} \cdot N_{q-1} - \lambda_q \cdot N_q + \lambda_{q+1} \cdot N_{q+1}
\]
Medical Particle Therapy

Hadron Therapy

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Problem:
A magnetic analyser selects individual q/A ratios, \( \text{C}^6+, \text{N}^7+, \text{O}^8+ \) can not be separated, (q/A = 0.5)!

ECR ion sources work at about \( 10^{-6} \) mbar, mixing of C, N, and O in the plasma.
Simplification of Therapy Facilities by using an EBIS

Advantages:
- only one ion source
- only 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
Simplification of Therapy Facilities by using an EBIS

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the beam quality is improved,
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First Experiments at HIT in 2013!
Dresden EBIS/T systems have been successfully commissioned and operated at Low Energy Beamlines, but can also be used as ion sources for:

1. Cyclotrons
2. Synchrotrons
3. Synchro-Cyclotrons
4. Cyclotron Driven Linac
5. Dielectric Wall Accelerator
6. Direct Driven Accelerator
7. Fixed Field Alternating Gradient Accelerator
Thank you

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R&D

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