EBIS/T Charge Breeders at Rare Isotope Beam (RIB) Facilities

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...with a focus on post-acceleration...
Fundamental research in nuclear physics and astrophysics require rare isotope beams with energies from a few to tens of MeV/u. This is different from their production energy.

After production, rare isotopes often need to be reaccelerated with a “post-accelerator.”

Common techniques exist to produce rare isotopes:

- **Target spallation, fragmentation by light ions (e.g., protons) (Isotope Separation On-Line (ISOL))**
  - Accelerator → Target (low energy) → Separator → RIB → Post-accelerator
  - e.g., CERN, TRIUMF, RISP

- **Photon-induced (tens of MeV electrons) fission**
  - Accelerator → e-beam → Converter → Target (low energy) → Separator → RIB → Post-accelerator
  - e.g., ARIEL (TRIUMF)

- **Fission from a (radioactive) source**
  - Fission → Catcher (low energy) → Separator → RIB → Post-accelerator
  - e.g., CARIBU

- **Projectile fragmentation/fission of heavy ions at high energy (~100 MeV/u)**
  - Accelerator → Target → Separator → Catcher (low energy) → Separator → RIB → Post-accelerator
  - e.g., NSCL/FRIB
What is charge breeding?

- A cost effective way to reach high beam energies is to increase the charge of the accelerated ions
- A charge breeder converts beams of ions of low charge state into multiply charged ion beams before re-acceleration
- The typical breeding techniques are:
  - Foil or gas stripping
    » Several stripping stages may need to be added at different beam velocities for high efficiencies (complex and expensive…)
  - Electron Cyclotron Resonance Ion Source (ECRIS)
  - Electron-Beam Ion Source/Trap (EBIS/T)

**ECRIS CB scheme**

\[
\text{RIB (1+)} \quad \rightarrow \quad \text{Charge breeder} \quad \rightarrow \quad \text{RIB (Q+)} \quad \rightarrow \quad \text{Q/A separator} \quad \rightarrow \quad \text{RFQ + linear accelerator} \quad \rightarrow \quad \text{RIB (Q+)}
\]

\[
< 60 \text{ keV} \quad \rightarrow \quad \text{RFQ + linear accelerator} \quad \rightarrow \quad \text{MeV/u}
\]

Using an ECRIS or an EBIS/T is typically more cost-efficient than stripping targets…

**EBIS/T CB scheme** (typically, a cooler-buncher trap is added for pulsed injection, and high efficiency)

\[
\text{Continuous RIB (1+)} \quad \rightarrow \quad \text{Accumulate & bunch} \quad \rightarrow \quad \text{Cooler-buncher trap} \quad \rightarrow \quad \text{Charge breeder} \quad \rightarrow \quad \text{Q/A separator} \quad \rightarrow \quad \text{RFQ + linear accelerator} \quad \rightarrow \quad \text{RIB (Q+)}
\]

\[
< 60 \text{ keV} \quad \rightarrow \quad \text{RFQ + linear accelerator} \quad \rightarrow \quad \text{MeV/u}
\]
EBIS/T breeders for post-acceleration

Worldwide: 5 EBIS/T breeders for reacceleration of rare isotopes: 3 operations & 2 being implemented
EBIS/T breeding principle

- Produce & trap highly charged ions with a high-current density electron beam
- 3 main components: e-gun, trap + “strong” magnet, e-collector
- Axial ion confinement provided by a potential well (trap electrodes)
- Radial ion confinement by the electron-beam space-charge potential
- Magnetic field: Electron-beam compression for Ionization by electron impact
- Small charge capacity, but generally sufficient for RIB (from a few to $10^7$ ions/s)
- Low contamination

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**Diagram:**
- Electron gun cathode
  - $\Phi \sim$ Several mm
- Electron beam
  - $\Phi \sim 1 - 0.2$ mm
- Trap electrodes
- Magnetic field, up to several Tesla
- Electron collector
- Injection $A^+$
- Extraction $A^{Q+}$
- Radial space-charge potential from the electron beam
- Axial potential well from the trap electrodes
- Highly charged ions

A. Lapierre, ICIS 2019, Slide 5
ReA EBIT

Post-acceleration concept with ReA at the NSCL/MSU

- Pulsed EBIT injection & ejection frequency: 2 - 30 Hz
- $A/Q \leq 4$

RIB production by fragmentation & In-flight separation

- Continuous stable heavy ion beam $>80$ MeV/u

Current configuration, ReA3
- Light ions: 0.3 - 6 MeV/u ($^{48}$Ca)
- Heavy ions: 0.3 - 3 MeV/u ($^{238}$U)

Config. under construction, ReA6
- Light ions: 0.3 - 12 MeV/u
- Heavy ions: 0.3 - 6 MeV/u

He-gas cell

Thermalized-beam area

Flooding cooling & buncher

RT RFQ

MHB

12 keV/u

600 keV/u

~up to 6 MeV/u

SRF LINAC

Energy slit

Magnetic sector

Electrostatic sector

FC/DC 4

'Mass' slit

Achromatic, Nier-type $Q/A$ separator

Energy slit

Continuous beam

Continuous stable heavy ion beam

Target

He-gas cell

Thermalized-beam area

FC/DC 1

FC 2

$\leq 60$ keV

RFQ Paul trap filled with He gas

Beam cooler-buncher

1+ $\rightarrow Q+$

$Q/A$ separator

$\leq 60$ keV

CM 1

CM 2

CM 3

RIB production by fragmentation & In-flight separation
ReA EBIT at NSCL/MSU

Operational since 2015

Key parameters
- Magnetic field: 4 T
- Electron-beam current ~300 – 600 mA
- E-beam energy < 15.5 keV
- Current density: ~200 A/cm² for 300 mA
- Length of the trapping region: 0.64 m
- Cryogenic trap structure

Developed in collaboration with MPIK, inspired by the Livermore EBIT

Radial ports for spectroscopic access
How do we inject and extract ions?

Ions are trapped in the axial direction in a potential well created with 2 barriers.

**Pulsed injection for high efficiency**

- Decrease a barrier potential
- Pulsed injection

**Time sequence of the barrier potential**

V_{trap}

- Trap opened for extraction with a ramp-like continuous potential function
- Time

**Width of extracted ion pulses**

- Pulse width of ions extracted by opening the trap with a square-shaped potential function \( \sim 20 \, \mu s \)
- Instantaneous rate of each pulse is often too high for many detection systems to detect all ions within this short pulse
- The ion distribution in time can be spread up to \( \sim 100 \, \text{ms} \) using ramp-like potential functions
Breeding efficiency in single charge states of EBIS/T systems in operations

Overall, the average efficiency is ~20%

Higher efficiencies for light ions.

Efficiencies exceeding 30% can be reached with He-like ions (closed electronic shell).

The ReA EBIT often breeds Li-like and He-like ions (A/Q ~ 2.5) to reach high beam energies for the science program.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Breeding time [ms]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>46Ar17+</td>
<td>369</td>
<td>15</td>
</tr>
<tr>
<td>46K18+</td>
<td>369</td>
<td>6</td>
</tr>
<tr>
<td>37K17+</td>
<td>369</td>
<td>8</td>
</tr>
<tr>
<td>34Ar15+</td>
<td>125</td>
<td>26</td>
</tr>
<tr>
<td>47K17+</td>
<td>350</td>
<td>21</td>
</tr>
<tr>
<td>47K17+</td>
<td>260</td>
<td>34</td>
</tr>
<tr>
<td>23Mg12+</td>
<td>800</td>
<td>15</td>
</tr>
<tr>
<td>72Se25+</td>
<td>230</td>
<td>29</td>
</tr>
<tr>
<td>45K17+</td>
<td>260</td>
<td>30</td>
</tr>
</tbody>
</table>

Excl. the buncher efficiency
ReA EBIT at NSCL/MSU

Modified the abundance of the first $^{38}$K isomer in a beam

- The isomer and ground state cannot be separated due to insufficient mass resolving power before injection and after extraction
- $^{38}$K ground-state half-life $\rightarrow$ 8 minutes (decays to $^{38}$Ar)
- $^{38}$K isomer half-life $\rightarrow$ 1 sec (decays to $^{38}$Ar)
- By changing the breeding time from 150 ms to 1.5 s, isomer ratio modified from 41% to 17%
- Needed for nuclear structure physics to identify events caused by the isomer only

REX-EBIS at ISOLDE/CERN

- REX-EBIS is part of the ISOLDE facility at CERN
- RIB are produced by the ISOL technique (1.4-GeV proton beam, up to 2 μA)
- Over the years, worked on many areas of development…
  - Hadron (carbon) therapy
  - High-compression electron gun
  - Slow-ion extraction
  - DR

REX-EBIS is a mature system, operational since ~2003, its success inspired the construction of the newer systems

Key parameters
- Magnetic field: 2 T
- Electron-beam current ~200 – 500 mA
- E-beam energy ~5 keV
- Current density: ~100 – 250 A/cm²
- Length of the trapping region: 0.8 m
- Room-temperature trap structure
- Gas-filled cooler-buncher Penning trap

To HIE linear accelerator, energies up to ~11.2 MeV/u (A/q = 2.5)
REX-EBIS at ISOLDE/CERN: $^{11}$C for hadron therapy

- Performed feasibility studies for an EBIS/synchrotron-based hadron therapy facility with $^{11}$C ($Q=6+$) to provide beam intensities of $10^{10}$ ions/s
- Why $^{11}$C? Is radioactive, can be used to measure doses in real-time by Positron Emission Tomography
- A limitation of synchrotrons: they have long injection times (> 1 sec) because of multi-turn acceleration to reach high energies of up to ~400 MeV/u
- Using $^{13}$C, studied pulsed and continuous ion injection for long confinement times: measured efficiencies of less than 1% in both cases

EBIS injection schemes studied by the CERN group

- $^{11}$CO gas
- Condensate molecular $^{11}$CO gas
- Fast charge breeding during the LINAC injection time

Propose two efficient options for carbon therapy with an EBIS

REX-EBIS at ISOLDE/CERN: MedEGun

- Requirements for carbon therapy with a \textit{non-superconducting} LINAC
  - Rate: $10^8$ C$^6^+$ ions / pulse
  - Extraction rep. rate: 300 – 400 Hz

- Developed a high-compression gun (MedEGun) to reach an electron-beam current density of $\sim 5000$ A/cm$^2$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{medegun_diagram.png}
\caption{Diagram of MedEGun}
\end{figure}

Recent results with TWINEBIS
- Electron-beam current: 1.5 A
- Magnetic field: 2 T
- E-beam energy: 5 keV
- Electron-beam losses $< 1$ mA
- Current density: \textbf{Looks promisingly}!

- Time-of-flight measurements planned to measured charge state distributions and determine the current density

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
Parameter & Design Value \\
\hline
Main magnet & 5 T \\
Trap length & 0.25 m \\
Electron current & 1 A \\
Current density & 4.5 kA/cm$^2$ \\
Electron energy & 7.5 keV \\
Capacity C$^6^+$ & $1 \times 10^9$ ions/pulse \\
Repetition rate C$^6^+$ & 440 Hz \\
\hline
\end{tabular}
\end{table}

R. Mertzig et al. NIM A, 859 102 (2019)
Slowly releasing ions is critical to limit the instantaneous ion rate delivered to users.

The axial energy distribution of the trapped ions.

The “optimum” time-dependent voltage function was numerically calculated to release the trapped ions with square-shaped distribution in time.

Pulse widths were extended from ~200 μs up to 2 ms, over the maximum possible length of the RFQ pulse.

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Niels Bidault, Jose Alberto Rodriguez, Miguel Lozano, Sergey Sadovich,
Slow Extraction of Charged Ion Pulses from the REXEBIS, arXiv:1808.02713v1

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(a) Slow Extraction of $^{140}\text{Sm}^{34+}$ time structure. (b) $^{132}\text{Xe}^{32+}$ resulting time structures lengthening, acquired with the MCP, when extending the extraction voltage step-function from 1.0 ms to 2.5 ms (0.25 ms steps).
DR is a resonant process, where a free electron of the beam is captured by an ion in a multi-excited state.

Performed simulations and measurements to study KLL resonances in K to increase production of single charge states.

By varying the e-beam energy over resonances, the production of certain charge states was observed to increase by up to 50% in K^{14+}.

Process still being investigated to increase breeding efficiencies during operation.

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CARIBU EBIS

- CARIBU (Californium Rare Isotope Breeder Upgrade) is a 1 Ci $^{252}$Cf source providing rare isotope beams to ATLAS (Argonne Tandem Linac Accelerator System)
- Before acceleration through ATLAS to energy up to ~15 MeV/u, rare isotopes are bred with an EBIS
- CARIBU EBIS is a start-of-the-art breeder, developed in collaboration with Brookhaven lab.

Key parameters
- Magnetic field: 5.5 T
- Electron-beam current ~ 1 - 2 A
- E-beam energy ~8 keV (< 15 keV)
- Current density: ~300 – 600 A/cm$^2$
- Length of the trapping region: ~0.5 m
- Room-temperature trap structure
- RFQ Paul trap filled with He gas

Operational since 2016


A. Lapierre, ICIS 2019, Slide 16
Have been focusing on isotopes in the mass range A~140 u (Tc, Ru, Cs, Ce, Pr, etc.)

Typically breed high A/Q ≤ 7, with breeding time ~20 ms

Efficiencies single-charge states of ~20%; overall charge state efficiencies of ~90%

Have excellent vacuum (<10^{-10} Torr)

Use slow extraction of ~5 ms by pushing ions out of the trap with a time-dependent logarithmic voltage function

• TRIUMF is building the ARIEL project (Advanced Rare Isotope Laboratory)
• ISOL facility (Cyclotron, 500-MeV protons, ≤100 μA)
• ARIEL will increase TRIUMF’s capabilities with photo-fission with an electron linac (30 MeV, 10 mA)
• Building CANREB (CANadian Rare isotope facility with Electron Beam ion source) to provide reaccelerated beams with an EBIS
• CANREB EBIS developed in collaboration with MPIK

Key parameters
• Magnetic field: 6 T
• Electron-beam current ~ up to 1 A
• E-beam energy: 8 keV for operation
• Expected current density: ~5500 A/cm²
• Length of the trapping region: up to 26 cm
• Cryogenic trap structure

- Built to charge breed ions of $A/Q \leq 7$ for reacceleration up to $\sim 11$ MeV/u (ISAC II)
- Demonstrated a 1-A electron beam in a 6-T field
- Includes radial ports for spectroscopy: observed x-rays from HCl and measured breeding times
- Being installed, will start commissioning soon with stable Cs from their He-gas-filled RFQ Paul trap
- Commissioning on-line by the end of the year.

M. Pereira-Wilson et al. IPAC Conf. Proceedings, 2018
The RISP project (Rare Isotope Science Project) is being implemented in Korea.

- ISOL facility: Cyclotron, 70-MeV protons with 10 kW on target (1st phase, 2020)
- As part of RISP, RAON accelerator (Rare isotope Acc. Complex for ON-line exp’ts)
- Incl. an EBIS system and an RFQ Paul trap cooler-buncher
- First RIB beams ~2021
RISP/RAON EBIS

- Similar in design to the CARIBU EBIS
- Electron gun tested up to ~2 A (designed for 3 A)
- Did excellent work on vacuum by adding high-capacity ZAO NEG panels: ~10^{-11} Torr in trap
- Expect first breeding off-line tests with stable Cs by end of 2019
- On-line commissioning in 2021

Key parameters
- Magnetic field: 6 T
- Electron-beam current: 3 A
- E-beam energy: 20 keV
- Current density: ~500 A/cm²
- Length of the trapping region: ~0.8 m
- Warm trap structure

Slowly releasing ions from an EBIS/T is critical to limit the instantaneous ion rate delivered to users.

GANIL, through the EMILIE project, is developing a “debuncher” ion trap to capture the short ion pulses from an EBIS/T breeder and stretch upon extraction the distribution of the ions in time.

Debuncher is a linear Paul Trap with DC central segments.
Electron String Ion Source (ESIS) is similar to an EBIS/T...

In an ESIS, the collector is modified to include electrodes to reflect electrons on multiple passes to increase the electron current density.

ESIS group is involved in $^{11}$C therapy research using a synchrotron.

Scheme: Intend to produce $^{11}$C from an ISOL target through methane gas ($^{11}$CH$_4$)

Gas collected in a cryogenic trap, $^{11}$C ionized to 1+ in an EBIS

After mass separation, inject into an ESIS for ionization to $^{11}$C$^{6+}$ before acceleration

Currently conducting experimental feasibility studies (measuring efficiencies)

The MPIK in Heidelberg has developed multiple compact *table-top* room-temperature EBITs used for atomic spectroscopy and mass measurements.

**Key parameters**
- Magnetic field: 0.86 T
- Electron-beam current: 80 mA
- E-beam energy: 10 keV
- Estimated current density: ~500 A/cm²
- Length of the trapping region: ~2 cm
- Warm trap structure

Those EBITs are not coupled to RIB facilities, developed an “in-trap” laser ablation technique for injection of long-lived rare isotopes.

Technique consists of moving near the electron beam a wire whose tip contains material that is ablated with a laser beam.

Proof-of-principle measurements made with stable Holmium…

Charge state distribution from extracted ions… that works.
Conclusion

- EBIS/T are more and more used at RIB facilities for post-acceleration: 2 new EBIS being commissioned (CANREB & RAON)

- Over the years we have seen R&D on…
  - Using EBIS/T for carbon therapy
  - Developing a high-current density electron gun
  - Increasing the breeding efficient using dielectronic recombination
  - Changing the abundance of an isomer by varying the breeding time
  - Stretching the width of the pulses ejected from EBIS/T (in-trap and debuncher)
Acknowledgment


Thanks to you…
Back-up
Target spallation, fragmentation by light ions (e.g., protons) (Isotope Separation On-Line (ISOL))

Photon-induced (tens of MeV electrons) fission

Fission from a (radioactive) source

Projectile fragmentation/fission of heavy ions at high energy (~100 MeV/u)
In an EBIS/T charge breeder…

- Ions confined in a trap and ionized by an electron beam
- Small charge capacity, but generally sufficient for RIB (from a few to $10^7$ ions/s)
- High electron-current density for fast and variable breeding times
- Low level of contamination
- Generally more efficiency than ECRIS (they can reach good efficiency too!)
- Small ion-beam emittances (energy spread and transverse emittance)

Analogy by Jose Crespo
Charge Breeders

- **Electron-Cyclotron Resonance Ion Source (ECRIS)**
  - Ions confined in a plasma and ionized by electrons heated by RF wave
  - **Can capture and store lots of charge (high charge capacity)**
  - Low electron-current density $\rightarrow$ Long breeding times
  - High contamination level (not convenient for RIB, produced in small quantities)
  - Large emittances (energy spread and transverse emittance)

Analogy by Jose Crespo
New EBIS source built for high charge capacity

Key parameters

- Magnetic field: 4 - 5 T
- Electron-beam current ~ 4 A (Max, 10 A)
- E-beam energy: up to 15 keV
- Expected current density: ~230 A/cm²
- Length of the trapping region: up to 0.7 cm
- Up to $10^{10}$ ions per sec for light ions (e.g., Ne$^{8+}$)