On-line Operation of the EBIT Charge Breeder of the ReA Post-Accelerator


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PART I

- Motivation for a post-accelerator: ReA
- Reacceleration concept
- ReA EBIT charge breeder

PART II

- Results of on-line operation:
  - Charge-breeding efficiencies
  - Stretching of EBIT pulses (ejected ion time distributions)
  - Contamination study

Conclusion

Started on-line operation in Sept 2015
ReA: Reaccelerator of rare isotopes

National Superconducting Cyclotron Lab. @ MSU
- User facility producing rare-isotope beams by projectile fragmentation.

ReA @ NSCL
- Post-accelerator built for reacceleration of rare-isotope beams to several MeV/u.

Why do we need to reach this energy regime?
- Key reactions in nuclear astrophysics
- Nuclear structure studies

How does the entire system work?

Acceleration (>80 MeV/u):
- ECR ion source
- + coupled cyclotrons

Production (>80 MeV/u):
- Projectile fragmentation & in-flight separation

“Low” Energy Beam Area
(≈ several MeV/u)

Beam “stopping”

High Energy Beam Area

Target, e.g., beryllium
NSCL rates ≤ 10⁹ pps
The ReAcceleration concept

ReA post-accelerator

- Magnetic sector
- Electrostatic sector
- Achromatic Q/A separator
- 'Mass' slit
- Energy slit

• Continuous beam injection into BCB
• Pulsed EBIT injection & ejection frequency: 2 - 7 Hz
• $2 \leq A/Q \leq 4$
• Silicon $\beta$-decay counters integrated to Faraday cups.

First device in ReA
New beam bunched (accumulates and bunches)

*Production & In-flight separation

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

Target

He-gas cell

Thermalized-beam area

Current configuration, ReA3

Light ions: 0.3 - 6 MeV/u ($^{48}$Ca)

Heavy ions: 0.3 - 3 MeV/u ($^{238}$U)
Why do we use an EBIT Charge Breeder?

- High efficiency (narrow charge state distributions; less ions lost in many charge states)
- Fast & variable breeding times (~10 ms up to 1 s; for charge-state optimization)
- High beam purity (low contamination level)
- Variable ejected ion distribution in time (extracted pulse widths) (~20 µs up to ~100 ms)

Improve S/N ratio!
Working principle of an EBIT

What is an Electron-Beam Ion Trap (or Source)?
- Produce & trap highly charged ions with a high-current density electron beam
- 3 main components: e-gun, trap + “strong” magnet, e-collector
- Magnetic field: Electron-beam compression & Ionization by electron impact
- Axial ion confinement provided by a potential well (trap electrodes)
- Radial ion confinement by the electron-beam space-charge potential

![Diagram of an EBIT setup]

- Electron gun cathode $\Phi \sim 6\, \text{mm}$
- Electron beam
- Trap electrodes
- Magnetic field, up to several Tesla
- Electron collector
- Highly charged ions $A^+$
- Hair-like electron beam $\Phi \sim 100\, \mu\text{m}$
- Radial space-charge potential from the electron beam
- Axial potential well from the trap electrodes
- Pulsed injection $A^+$
- Pulsed extraction $A^{Q+}$
The ReA EBIT

Key parameters
- Magnetic field for operation: 4 T
- Electron-beam current < 1.4 A
- Current density: ~170 A/cm² for 300 mA (stable 24/7 operation)
- E-beam energy < 30 keV (e.g., Ne-like U⁸²⁺)
- Length of the trapping region: 0.64 m
- Cold trap structure at 4 K

Trap structure
* 1.2 m long
* 23 Ti electrodes
How do we inject & extract ions?

**Pulsed injection scheme**

- **Pulsed injection**
  - Open the trap with a square pulse (step function)
  - Decrease a barrier potential

- **Charge breeding**
  - Inject
  - Breeding
  - Extract
  - Inject
  - Breeding
  - Extract

- **Pulsed extraction**
  - Inject
  - Breeding
  - Extract

**Natural width of an extracted ion pulse**

- Typical pulse width (~20 \( \mu s \)) defined by the time taken by the trapped ions to freely exit the trap.
- In many cases, instantaneous rate of each pulse is too high for nuclear-physics experiments.
- New extraction schemes being developed to spread in time pulses by tens ms → Results at the end...

**Extracted \( K^{10+} \) after the Q/A separator**

- MCP voltage signal [V]
  - Time [\( \mu s \)]
  - "Natural" width ~ 20 \( \mu s \)
ReA officially started (on-line) operation in September 2015

- Delivered pilot beams of stable-isotope → BCB: $^{39}$K, $^{85}$Rb
- Delivered 7 rare-isotope beams: $^{46}$Ar, $^{46}$K, $^{34}$Ar, $^{47}$K, $^{37}$K, $^{75}$Ga, $^{77}$Br.
- Efficiency measurements conducted with stable and rare isotopes after the Q/A separator.
- Pulse stretching tests performed with reaccelerated beams delivered to experiments (during operation).

![Diagram](image.png)
Charge-breading efficiency of stable-isotope beams

Measure ion-beam currents

\[
\text{Eff in SCS} = \frac{I_{\text{out}}^i}{Q_i} \frac{I_{\text{in}}}{I_{\text{in}}}
\]

\[\text{Eff in ACS} = \text{Sum over all SCS eff.}\]

Ratio of # extracted ions to # injected ions.

Caution: Does NOT include BCB efficiencies

<table>
<thead>
<tr>
<th>Element</th>
<th>Electron Inj.</th>
<th>Inj. Brd.+ej.</th>
<th>Max. ACS (Max. CS)</th>
<th>ACS Isotope current freq. time SCS eff.[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(39\text{K}\ (15+))</td>
<td>302(10)</td>
<td>13(1)</td>
<td>6.98</td>
<td>110+23</td>
</tr>
<tr>
<td>(85\text{Rb}\ (27+))</td>
<td>333(10)</td>
<td>37(2)</td>
<td>7.12</td>
<td>110+20</td>
</tr>
<tr>
<td>(133\text{Cs}\ (38+))</td>
<td>573(10)</td>
<td>15(1)</td>
<td>7.00</td>
<td>110+23</td>
</tr>
</tbody>
</table>

Charge-state distributions: \(39\text{K}\ & \ 85\text{Rb}\)

ACS efficiency: \(81(7)\) %

\(39\text{K}^{15+}\) \(\sim 25\%\)

ACS efficiency: \(75(4)\) %

\(85\text{Rb}^{27+}\) \(\sim 24\%\)

Ne-like
### Charge-breeding efficiency of rare-isotope beams

#### Measure $\beta$-decay rates

![Image of a machine with labels and arrows indicating direction and measurements.]

**SCS eff** = \( \frac{R_{\text{out}}}{R_{\text{in}}} \)

#### SCS efficiency

<table>
<thead>
<tr>
<th>Element</th>
<th>Electron Brd.+Ej. SCS</th>
<th>ACS</th>
<th>ACS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
<td>current [mA]</td>
<td>time [ms]</td>
<td>eff.[%]</td>
</tr>
<tr>
<td>$^{46}\text{Ar}^{17+}$</td>
<td>364(10)</td>
<td>369+122</td>
<td>15(1)</td>
</tr>
<tr>
<td>$^{46}\text{K}^{18+}$</td>
<td>367(10)</td>
<td>369+122</td>
<td>6(1)</td>
</tr>
<tr>
<td>$^{37}\text{K}^{17+}$</td>
<td>569(10)</td>
<td>369+122</td>
<td>8(3)</td>
</tr>
<tr>
<td>$^{34}\text{Ar}^{15+}$</td>
<td>347(10)</td>
<td>125+65</td>
<td>26(2)</td>
</tr>
<tr>
<td>$^{47}\text{K}^{17+}$</td>
<td>332(10)</td>
<td>350+100</td>
<td>21(2)</td>
</tr>
</tbody>
</table>

Caution: Does NOT include BCB efficiencies & corrected for decay losses

#### Charge-state distributions: $^{34}\text{Ar}$ & $^{47}\text{K}$

**$^{34}\text{Ar}$**

ACS efficiency: 72(7) %

$^{34}\text{Ar}^{15+}$ ~26%

**$^{47}\text{K}$**

ACS efficiency: 65(9) %

He-like $^{47}\text{K}^{17+}$ ~21%

**Graphs:**
- **$^{34}\text{Ar}$**
  - Efficiency [%] vs Charge state, $Q$
  - ACS efficiency: 72(7) %
  - $^{34}\text{Ar}^{15+}$ ~26%

- **$^{47}\text{K}$**
  - Efficiency [%] vs Charge state, $Q$
  - ACS efficiency: 65(9) %
  - He-like $^{47}\text{K}^{17+}$ ~21%
Stretching of EBIT pulse widths

Spreading in time the distribution of the ejected ions from the EBIT is important to reduce the instantaneous rate delivered to experiments.

- Instantaneous rate $\rightarrow$ # of ions per pulse width
- Each ion must arrive at the user’s detector outside the dead time of the DAQ system

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**Conventional extraction**

- Trap opened with a square pulse (step function)

**Ramp**

- Trap opened with a continuous voltage function, resembling a ramp
Pulse stretching – The Ramp

**Trap physics → Highly charged ions confined to the bottom of the axial trapping potential**
- To optimize time spread: fast barrier potential drop to reach ion position, and then slow decrease
- Best functions: Exponential or logarithmic ejection ramps
- Ion distributions (pulse widths) stretched from ~20 μs up to ~70 ms
- Two-peak structure may be caused by two potential regions in trap (?).

**Stretched ion (time) distributions accelerated to experiments**

**(a)** Si detector in SHIP (GPL)
- Trap open for ion release
- Trap closed
- **Exp. function**
- Ion counts
- EBIT extraction time [ms]

**(b)** Si detector in JENSA
- Trap open for ion release
- Trap closed
- **Log. function**
- Ion counts
- EBIT extraction time [ms]
In stretched extraction, ions of low charge state are ejected first compared to high-Q ions

- Ions of low charge states are less bound to the trapping potential.
- “Feature” can be used for beam purification.
- **Red:** \(^{13}\text{C}\)-only ion distribution by blocking \(^{39}\text{K}\) from BCB \(\rightarrow\) EBIT contamination, only.
- **Blue:** Ion distribution cleaned by delaying the RFQ on-time period to prevent \(^{13}\text{C}\) acceleration.
Conclusion

- ReA EBIT started (on-line) in September 2015
- Charge breeding efficiencies in single charge states, up to 25 %
- Efficiency over all charge states ~76 %
- Ion distributions stretched up to 70 ms

Future work:
- Investigate ion losses
- Stable operation with 1 A (higher current densities and beam acceptance)
- More uniform ion distributions

Thank you.
Back-up slides
The beam “stopping” area

The purpose of beam thermalization

- Decelerate the rare isotopes.
- Reduce emittance to 2 mm mrad (95%, 30 keV) for eff. beam transport to ReA and low-energy facilities.
- Equipped with alkali ion source for pilot beam production.

He gas cell (Argonne lab) [Gas + Degrader] Si det. measure β activity for particle ID & beam transport optimization

DC beams < 60 keV

Separator dipole magnet

Rare-isotope beams from the production area

DC beams > 80 MeV/u
Beam cooler buncher for pulsed injection

He-gas-filled radio-frequency quadrupole (RFQ) ion trap (Paul trap)

- NEW device added to help improve EBIT injection efficiency for low-current electron beams
- Started operation in September 2015
- Efficiencies between 50% - 100% (depend on injection optics)
- Equipped with alkali ion source for production of pilot beams

*After mass separation with separator magnet

DC beams < 60 keV

Pulsed beam to EBIT < 60 keV
Some imperfections...

- Magnetic field is not homogenous within ± 3%
- Combined with the e-beam space-charge potential, central electrostatic potential experienced by ions in the trap is non-uniform (*does not seem to impede charge breeding*...).
Typical operational parameters

Injection energy $< 40$ keV
Ejection energy $= 12$ keV/u $\times A/Q$ (def. by RFQ velocity accept.)
Efficiencies in single charge states $\sim 10 – 25\%$
Breeding time $< 369$ ms
Ejection time $< 125$ ms
**E-beam current** $\sim 300 - 600$ mA
E-beam density $\sim 174 - 329$ A/cm$^2$
**E-beam energy** $\sim 15.5$ keV
Field configuration: 4T - 4T
Trapping region: 0.64 m

- Electron current can reach up to $\sim 1.4$ A. Due to beam instabilities, the current is kept low during operation.
Measured radius of the electron beam by x-ray imaging

**X-ray pinhole camera installed on a radial port of the EBIT**

![X-ray camera](image)

\[ r_e(80\%) \sim 212(19) \, \mu m \text{ for } 800 \, mA \text{ in } 4 \, T \]

\[ j_e \sim 454(83) \, A/cm^2 \text{ for } 800 \, mA \text{ in } 4 \, T \]

Pulse stretching – The Ramp

- Output of the (voltage) amplifier can be controlled by an Arbitrary Function Generator (AFG).
- Using specialized Controls apps, extraction ramp functions can *easily* be uploaded to an AFG: multi-segments Lin, Exp, Log, etc.

Snap shot of a Controls app.

![Graph showing Logarithmic Ramp function](image)
Pulse stretching – Latest result of the Train

Ion (time) distribution of $^{40}\text{Ar}^{17+}$ accelerated to an MCP in front of the AT-TPC experiment.

- Amplifier applied voltage to the extraction potential barrier
- $\sim$1 - 2 $\mu$s trap opening time, spaced by 100 $\mu$s
- Up to 70 pulses within 15 ms (each micropulse containing a few ions)
- Try to develop...faster HV switch to inject pulses into RF cycles of RFQ ($\sim$60 ns, 100 kHz)
Identifying contaminants is essential to eliminate them & provide rare-isotope beams of high purity.

Q/A separator measures the Q/A:

\[ B \propto \sqrt{\frac{A}{Q}} \]

Fixed RFQ accel. energy: \[ E_{RFQ} = 600 \text{ [keV/u]} \times A \]

By scanning the field of Q/A sep. and measuring beam energy with Si det., the A and Q/A can be disentangled.

**Typical EBIT contaminants:**
- Na, Cl → NaCl (fingerprint?)
- Si → Aluminized mylar tape adhesive
- F → Scroll-pumps: Bearing lubricant & tip seal (Teflon)
- S → Dichronite UHV bearing lubricant (WS₂)
- Ba, W → Dispenser cathode (not detected !!!)
- Cu → Collector, anode...

**All stable isotopes of C, N, O, Ar → Residual “air”**
Contamination measurements

- Trying quantifying contaminants by measuring beam current with high sensitivity with Faraday cup.
- Using a commercial low-noise ammeter with long averaging $\rightarrow \sim 10$ efA; 6000 pps for $Q=10$. 

![Graph showing contamination measurements with ions identified and their corresponding currents.](image)
Commissioning results

Transverse emittance measurements with Pepperpot-meter

$K^{18+}$ beam on MCP viewer

Unnorm. rms emittance [mm mrad]

Emittance vs charge state

Extracted beam energy: 29.228 keV $\times Q$

Preliminary
The beam “stopping” area

**Second beam line:**
- Equipped with offline (surface) ion source (e.g., K, Rb...)
- For commissioning purposes

Analyzing dipole magnet
DC beams < 60 keV
ReA EBIT: Double-magnet configuration

**Solenoid: Long low-field region**
To maximize ionization of 1+ ions within a roundtrip:
Keep e-beam diameter for high electron-ion beam overlap upon injection → High capture probability

**Helmholtz coils: Short high-field region**
Reduce e-beam diameter for high current density → High charge states and fast charge breeding

Over-the-potential barrier injection
"Quasi-continuous"

Monte-Carlo simulations of capture eff.:
E. Gavartin – M.Sc. Thesis, MSU,
K. Kittimanapun – PhD, MSU.

Capture efficiency from Monte-Carlo simulations
@1A: >80% for <3 π mm mrad
High-current electron gun to maximize the capture efficiency of injection ions

- Thermionic electron gun
- Ba-dispenser cathodes
- 6-mm in diameter
- Modular cathode assembly

Modular ass’y includes:
- Anode
- Focus elec.
- Cathode

E-beam current vs. extraction voltage

Demonstrated stable operation up to ~ 1.4 A (4 T)

Pervance ~ 1.7 A/V$^{3/2}$
- Voltage amplifier applies voltage to the extraction potential barrier.
- Output voltage of the amplifier controlled by an Arbitrary Function Generator (AFG)
Time stretching of EBIT extracted pulses

Measured with a microchannel plate after the Q/A separator

Peak intensities normalized to 1

Width ~ 10 μs

Train

Each pulse is ~2-μs long and contains only a few ions

Each pulses spaced by 100 μs (variable)

Time [ms]

No clear discernable difference in efficiency for different parameters

- Electron-beam current
- Injected beam intensity (stable vs. rare)
- Reasons for ion losses being investigated...
Pulse stretching – First tests of the Ramp

Lots of tests with $^{40}$Ar$^{16+}$ (residual gas) accelerated to AT-TPC ion chamber...

“Gentle” Lin. slope

2-point linear ramp, first try

2-point linear ramp, second try

Ramp with lower end

Steep Lin. slope

Small Exp. decay constant

Exp -1 t

Exp -1.5 t

Exp -1.7 t

Exp -2 t

Exp -2.5 t

Large Exp. decay constant

Exp -3 t
Injection sources

**Different sources of injection to produce stable-isotope and rare-isotope beams**

- Gas injection inlet (removed due to gas freezing on shields)
- Inject singly charged stable-isotope ions from off-line sources (plasma and alkali ion sources)
- Inject rare-isotope beams from the beam stopping area
- **Message: injection of multiple beams (elements) from different sources.**
Facility for Rare Isotope Beams (FRIB)

In 2008, NSCL & MSU selected to establish the US facility (FRIB) for science with rare-isotope beams → Early completion ~2020

- The two NSCL coupled cyclotrons will be later replaced with a 400-kW superconducting heavy-ion “driver” linac.
- FRIB will increase the current production rates of rare isotopes by up to 2-3 orders of magnitude < $10^{12}$ pps
Charge-over-mass (Q/A) separator

Double-focusing (achromatic) spectrometer

(Nier-Johnson geometry)

Design parameters

- Measured resolving power (beam size: 90% of particles): \((A/Q)/\Delta(A/Q)\approx 400\)
- Achromatic within \(\Delta E/E\approx 3\%\)
- Measured EBIT energy spread: \(\sim 30 \text{ eV per } Q\)
  (300 eV for Ne\(^{10+}\))