First charge breeding of rare-isotope beams with the electron-beam ion trap of the ReA post-accelerator


National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, USA

Outline

- Motivation for a post-accelerator: ReA
- Reacceleration concept
- ReA EBIT charge breeder
- Commissioning results & Outlook
Why do we need to reach those energies?
- Key reactions in nuclear astrophysics.
- Nuclear structure studies near the Coulomb barrier.

How does the whole system work?

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

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

Beam “stopping”
Gas cells

To produce beams of a few MeV/u, rare isotopes are first thermalized in a gas cell...

High-energy stable-isotope beams from 2 coupled cyclotrons transported to a target where rare-isotope beams are produced at high energies
The ReAcceleration concept

**ReA post-accelerator**

- Highly charged ion beam, 12 keV/u x A (2 ≤ A/Q ≤ 5)
- Magnetic sector
- Achromatic Q/A separator
- Electrostatic sector
- Room-temperature RFQ
- Superconducting RF linac
- EBIT charge breeder 1+ → Q+

**Production & In-flight separation**

- Continuous stable heavy ion beam > 80 MeV/u
- Thin foil target
- He gas-cell
- "Stopping" area
- > 80 MeV/u
- < 1 eV
- ≤ 60 keV

**First configuration, ReA3:**

- \(^{48}\text{Ca}\) 0.3 - 6 MeV/u
- \(^{238}\text{U}\) 0.3 - 3 MeV/u

**Final configuration, ReA (x4):**

- \(^{48}\text{Ca}\) 0.3 - 20 MeV/u
- \(^{238}\text{U}\) 0.3 - 12 MeV/u
The beam “stopping” area

Beam thermalization:
- Decelerate the rare-isotope beams
- Reduce the emittance

Thermalization in He gas cell (built at the Argonne Lab.)

Si detector to measure $\beta$-decay activity for particle ID & beam transport optimization

Analyzing dipole magnet

Rare-isotope beams from the production area
DC beams > 80 MeV/u

DC beams < 60 keV
The beam stopping area

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

Analyzing dipole magnet
DC beams < 60 keV
**EBIT charge breeder in the ReA facility**

**Why do we use a charge breeder and why an EBIT?**
- **CB:** Makes compact & cost-efficient.
- **EBIT:** High efficiency → Narrow charge state distribution (less ions lost in many charge states)
- **EBIT:** Fast → (Adjustable) breeding times < 50 ms
- **EBIT:** Low contamination level → Trap can be built in a cryogenic environment (4K)
Charge breeding principle

- Inject singly charged ions in the high-current density electron beam
- Ions trapped by trap electrodes & e-beam space-charge potential
- Highly charged produced by electron-impact ionization
- Pulsed extraction of highly charged ions

Continuous injection and accumulation (~100 ms)

Pulsed extraction (<100 µs)

Axial potential well from the trap electrodes

Radial electron-beam space-charge potential

How do we inject & extract ions?

Over-the-potential barrier injection

Lower-the-barrier extraction

ICIS 2013
Specifications:
- High electron current: < 1.4 A
- E-beam energy: up to 30 keV
- Current density (6T): up to 10000 A/cm² (according to theory, but need good e-beam compression)
- Long trap @ 4 K
ReA EBIT: Double-magnet configuration

Extended low-field region (solenoid):
To ionize 1+ ion before a roundtrip:
Keep e-beam diameter for high electron-ion beam overlap upon injection → High capture probability

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

Extended low-field region (solenoid):
To ionize 1+ ion before a roundtrip:
Keep e-beam diameter for high electron-ion beam overlap upon injection → High capture probability

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

Location of the 2 fields

Ion acceptance Monte-Carlo simulations:

Capture eff. Monte-Carlo sims

@1A: >75% for <5 π mm mrad

Prefered B-field distribution

Current density:
~5000 A/cm²

Emittance (σmm mrad)
The electron gun

- Thermionic electron gun
- Ba-dispenser cathodes
- Modular cathode assembly

Includes:
- Anode
- Focus elec.
- Cathode

6 mm in diameter cathode

\(~ 900 \text{ mA current thru 4-T field}~

Perveance of the e-gun \(~ 1.7 \mu \text{P}~

\[\text{Emitted current [mA]}\]

\[\text{Extraction voltage [V]}\]

- Slow extraction voltage increase
- Fast increase

Poster by Stefan Schwarz
WedP06
Reacceleration of stable-isotope beams

**Dec. 2012:** Demonstrated charge breeding of Rb\(^+\) stable-isotope ions from the offline source in the beam stopping area.

**April 2013:** Reacceleration of \(^{85}\)Rb\(^{27+}\) & \(^{87}\)Rb\(^{28+}\) with the RFQ & SRF cavities.

Q/A spectrum of charge bred Rb

Q/A separator magnet current [A]

- E-beam energy: 19.5 keV
- E-beam current: 100 mA
- Accumulation / breeding time ~500 ms
- Magnet: 2 T (coils) - 2 T (sol.)

*Energy spectrum of reaccelerated \(^{87}\)Rb\(^{28+}\) with Si detector after LINAC*
April 2013: Charge breeding of $^{76}\text{Ga}$ [$t_{1/2}=33 \text{ sec}$]
Reacceleration of rare-isotope beams

**April 2013:** Reacceleration of $^{76}$Ga$^{24+}$ & $^{76}$Ga$^{25+}$ to 1 MeV/u

$\beta$-decay energy spectrum after reacceleration

![Diagram of the experimental setup](image)

- **Q/A separator**
- **EBIT**
- **RFQ**
- **SRF cryomodules**
- **β-decay counter**
- **Gas-cell stopper**

**Graph:** $^{76}$Ga$^{24+}$ β-decay energy spectrum after reacceleration.
**Delivery of rare-isotope beams**

**3 weeks ago:** First beam delivery to users for studies of nuclear reactions

**ANASEN:** Array for Nuclear Astrophysics Studies with Exotic Nuclei

Charge breeding and reacceleration of $^{37}\text{K}^{17+}$ [$t_{1/2} \sim 1$ s] to 2.3 MeV/u

---

**Charge state distribution after Q/A separator**

- $^{37}\text{K}^{17+}$ (He-like)
- Charge state distribution after Q/A separator

**ANASEN gas chamber (prop. counter)**

- Signature of $^{37}\text{K}^{17+}$
- $^{13}\text{C}^{6+}$
- $^{37}\text{Cl}^{17+}$

**Total E (chan)**

---

**ANASEN**
Measured charge breeding efficiency

Efficiency in single charge states of $^{39}$K stable-isotope beams
- Measured with a Faraday cup after Q/A separator
- Injected ion beam current $< 600$ epA

Field configuration 4T (coil) – 2T (sol.)
Electron-beam current: 750 mA
Electron-beam energy: 15.5 keV
Accumulation/Breeding time $\sim 100$ ms

Capture efficiency:
Sum over all charge states
$\sim 25\%$

With very careful tuning:
Capture eff.: $\sim 33\%$

Does this make sense?
- From electron-beam size measurements, average current density, $J \sim 400$ A/cm$^2$.
- For beam acceptance $> \text{injection beam emittance (ion-electron overlap)}$, Geometrical Eff. $\sim 1$.

**Total Eff. $\sim$ Capture Eff. by ionization**

$$1 - \exp[-\sigma_{1-2} \, t_{rt} \, J/e]$$

$t_{rt}$: Interaction time of $1^+$ ions with e-beam before they can exit the trap.

This curve is telling us that for $400$ A/cm$^2$, we can only expect at most $\sim 30\%$. We are here !!!
Calculated capture efficiency

- From electron-beam size measurements, average current density, $J \sim 400 \text{ A/cm}^2$
- For beam acceptance > injection beam emittance (ion-electron overlap), Geometrical Eff. $\sim 1$

Total Eff. $\sim$ Capture Eff. by ionization $= 1 - \exp[-\sigma_{1-2} t_{\text{rt}} J/e]$

$t_{\text{rt}}$: Interaction time of 1+ ions with e-beam before they can exit the trap.

This curve is telling us that for 400 A/cm$^2$, we can only expect at most $\sim 30\%$.

We are here!!!

How can we get to 80\%, at least?
The Key: High e-beam current density = High efficiency

Charge breeding efficiency vs. e-beam current and radius

- Eff: 30%; 330 A/cm²
- Eff: 80%; 1545 A/cm²

Acceptance > Emittance
Fixed trap length: ~ 644 mm

3 basic strategies:
- Compress e-beam radius with **stronger B field**
- Increase e-beam current with **larger cathode**
- Or both → **Higher compression (6T) & Higher current (1.4A) ← Plan for next months!**
ReA EBIT becoming operational
   → Demonstrated charge breeding of rare-isotope beams.

Commissioning will continue over the next year...
   → Higher e-beam current density for higher capture efficiency
   → Map contamination-free Q/A regions to deliver clean beams to users

Start in 2014 an early science program with reaccelerated beams

Thank you.
May 2014: EBIS/T Symposium & Workshop on Applications of HCI

International Symposium
Electron Beam Ion Sources and Traps, EBIS/T14
May 18-22, 2014
National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, MI, USA

Workshop on Applications of Highly Charged Ions (HCI App)
May 22-24, 2014
National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, MI

Website online soon:
www.nscl.msu.edu

The 12th International symposium on Electron Beam Ion Sources and Traps (EBIS/T14) was held at the National Superconducting Cyclotron Laboratory at Michigan State University in May 2014.

Program
NSCL is a rare-isotope accelerator facility conducting advanced nuclear astrophysics, accelerator physics, and related nuclear physics. It is home to the nuclear physics graduate program ranked #1 by US News & World Report.

Registration
The EBIS/T symposium is intended to provide a forum for discussion and exchange of ideas.

Submit abstract
Topics to be covered:
1. New EBIS/T facilities
2. Atomic spectroscopy of highly charged ions (e.g., laser, ion trap)
3. Charge exchange recombination
4. Surface interactions with highly charged ions
5. Charge breeding of stable and radioactive isotopes
6. New EBIS/T designs
7. Detectors for spectroscopy
8. Medical applications

We look forward to seeing you at Michigan State University.

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University is a rare-isotope accelerator facility conducting advanced research in fundamental nuclear science, nuclear astrophysics, accelerator physics, and related instrumentation technologies. It is home to the nuclear physics graduate program ranked #1 by US News & World Report and was recently selected by the Department of Energy (DOE) to establish the national user facility for Rare Isotope Beams (FRIB) for basic research with rare-isotope beams.

The NSCL is currently in the final commissioning phase of an electron-beam ion trap (EBIT) and a high-resolution charge-over-mass (Q/A) separator. The EBIT will primarily be used as a charge breeder to provide highly charged ion beams of radio-nuclides to the NSCL's ReA post-accelerator. This workshop on "Applications of Highly Charged Ions" is intended to provide a forum for open discussions on opportunities to utilize the ReA EBIT and Q/A separator as a user facility for science with highly charged ions. The uniqueness of the system could be the combined use of rare isotopes and highly charged ions for specialized applications.

The workshop will focus on:
- The use of (stable and radioactive) highly charged ions for science outside of nuclear physics, such as accelerator physics, mass spectrometry, material science, biophysics or medical physics, and others,
- Discussing the potentials and needs of highly charged ion facilities like the NSCL's ReA EBIT to enhance research in those fields.

Topics to be covered:
1. Charge breeding research
2. Material and surface science
3. Medical applications
4. Biophysics
5. Mass spectrometry: Penning trap & accelerator
Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

Ion sources

Coupling line

K1200

Stripping foil

$^{86}\text{Kr}^{34+}$, 155 MeV/u

Production target

Be, 480 mg/cm²

K500

$^{86}\text{Kr}^{14+}$, 14 MeV/u

A1900

Focal plane
Commissioning results

Transverse emittance measurements with Pepperpot-meter

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

Emittance vs charge state

Unnormalized emittance [$\pi$ mm mrad]

Extracted beam energy: 29.228 keV x Q

Preliminary
A feel about the breeding time...

M. W. Froese, M Master Thesis, University of Manitoba (based on R. Becker’s CBSIM program)

Note: Recombination with beam electrons and charge exchange with atoms and molecules not included
Injection modes

Three modes of injection to produce stable-isotope and rare-isotope beams

→ Gas injection
→ Inject singly charged stable-isotope ions from offline ion sources
→ Inject rare-isotope beams from the beam stopping area
**Charge-over-mass (Q/A) separator**

**Double-focusing spectrometer**

**Design parameters**
- Resolving power ~100 at 120 $\pi$ mm mrad
- Achromatic within $\Delta E/E \sim 3\%$
- Accept EBIT beams of large energy spread

**EBIT charge breeder**

- Superconducting magnet (6 T)
- Electron gun (<5A)
- Test beam ion source
- Electron collector
- 45° electrostatic bends
- 90° dipole magnet

**Energy acceptance profile (He$^+$ beam)**

- Current after magnet (pA)
- Beam energy (keV)
- $\Delta E \sim 600$ eV @ 20 keV
Delivery of rare-isotope beams

Total beam energy vs. energy loss in the ANASEN gas chamber (prop. counter)

No K beam

With K beam

Signature of $^{37}\text{K}^{17+}$
Contamination measurements

- Rare isotopes injected at low rates (< $10^6$ ions/sec)
- Delivering clean beams to users is important
- **Program:** Quantify Q/A regions the least contaminated with single-ion counting techniques

Q/A scans with a high-sensitivity ammeter

Many Q/A regions with a level of contamination of < 0.1 pA

To give an example how critical it is to deliver clean beam...
- $^{37}$K$^{17+}$ : 1000 pps.
- Request < 1% of $^{37}$Cl (not met)
- Request < 50% for low-Z ions
From the stopping area to ReA

To post-accelerator built on an elevated platform

Analyzing magnet
Calculated capture efficiency

- Effective current density seen by energetic ions (operation condition), \( J_{\text{eff}} \approx 350 \text{ A/cm}^2 \)
  - Measurements and simulations of charge breeding times
  - Finite-element simulations of the electron gun (see S. Schwarz’s. poster)
  - Electron-beam size measurements

\[ t_{\text{rf}}: \text{Interaction time of 1+ ions with the e-beam before they can exit the trap.} \]

For such e-beam radius: Acceptance > injected beam emittance \( \Rightarrow \) Geo. Efficiency = 1

To a good approximation: **Efficiency \( \approx 1 - \exp[-\sigma_{1-2} t_{\text{rf}} J_{\text{eff}}/e] \)**
Calculated capture efficiency

Capture efficiency of injected ions [%]
Electron-beam current density [A/cm²]

How can we get to 80%, at least?

We are here!!!
- \( t_{rt} \approx 41 \mu m \) (K+)
- Roundtrip trap length: \( 2 \times 644 mm = 1.3 m \)
- Kinetic energy in the trap: \( \sim 200 \text{ eV} \)

Conclusion: Calculations indicate we have reached the maximum efficiency for \( J_{eff} = 350 \text{ A/cm}^2 \)
Facility for Rare Isotope Beams (FRIB)

In 2008, NSCL & MSU selected to establish the US facility (FRIB) for science with rare-isotope beams → Completion ~2022

The two NSCL coupled cyclotrons will be later replaced by a 400-kW superconducting heavy-ion “driver” linac.