Design and test of the CANREB-EBIS

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TRIUMF
ARIEL Extension

- Advanced Rare IsotopE Laboratory
- New facility to expand capabilities of TRIUMF

- E-linac (photo-fission)
  - Isotope distribution
  - Neutron heavy isotopes
  - More controlled
ARIEL Extension

- Advanced Rare IsotopE Laboratory
- CANadian Rare isotope beam with EBIS (CANREB)
- Charge breeder and high resolution mass separator
  - Efficient filtering
  - Efficient post acceleration
CANREB

Charge Breeding

CANREB EBIS

RF Quadrupole Buncher

Energy and mass selection

Beam of desired species

Nier-spectrometer

MB\(^{90}\)

Isotopes
Electron Beam Ion Source (EBIS)

The cryogenic MPIK-EBIS are based on the MPIK-EBIT design and equipped with spectroscopic diagnostics.
MPIK Electron beam ion traps

Cryogenic, superconducting EBITs at MPIK: HD, FLASH, Hyper + TRIUMF, CANREB, MSU

Mini-EBITS for Blaum division, PTB and Petra-III

- Facility at MPIK supports Pfeifer and Blaum division
- Out of ~20 research EBITs worldwide, 10 are at or come from MPIK
Challenges and requirements

- $A/Q \leq 7$
- 10-20% in charge state distribution
- 100 Hz repetition rate
- Isotopes with lifetimes down to few ms
- $10^6$ ions/bunch, energy $< 15$ keV, long. length 1 $\mu$s, 90% acceptance
- **Emittance** energy $< 14$ keV $\times Q$, energy spread $dE < 100$ eV, bunch up to 1 ms
- **EPICS controls**, compatible to TRIUMF control system
CANREB EBIS Requirements

- Accepts beams with a phase space area of $5\pi$

$10^6$ ions in bunch
• Must reach a mass-to-charge ratio ≤ 7 within 10 ms
• Charge state is about 6+ for potassium
• Extraction must contain 10-20% in desired charge state
• $\Delta E < 100$eV (for the next device)

$\sim 10^5$ ions in desired charge state
Design

Collector manipulator

Cryo head

Gun manipulator

Rare ions

Electron gun

Collector

Superconducting Helmholtz coils
Design
Simulations aimed at optimization of
• electron beam for higher currents
• ion injection and extraction efficiency
Electrostatic simulation

- Set of 9 individually biased drift tubes
- Central drift tube has eight radial RF electrodes
Collector uses water cooling for 3 kW DC thermal load
Electrostatic simulation

Specified for TRIUMF for 18 kV drift tube bias, but capable of higher values
Magnetostatic simulation

- 6 T central magnetic field
- Helmholtz configuration
Electron beam simulations with TriCOMP, COMSOL, SimIon
- Space charge limited Pierce gun design
- Non-immersed
Magnetostatic simulation

- Ratio of $B_{\text{trap}}/B_{\text{cathode}}$ maximizes beam compression
- Iron reduces B field from superconducting coils

- Non-immersed design for very high compression
Emission parameters:

- Cathode radius: 3mm
- Maximum beam current: 1.0 A
- Bucking coil 8000 A×windings, trim coil -400 A×windings
Electron trajectories

Examples for three complete electron trajectories

~0.1 mm
At 1 A space charge potential on axis surpasses -1 kV
Injection (without ionization)

1.5 mm at trap center

If not optimized:
Comparison of injected ion distribution (blue) to 0.1 mm radius electron beam (red)

Start at 750 mm
Herrmann radius and acceptance

The electron beam radius (containing 80% of the electrons) can be calculated in the magnetic field, using Herrmann’s formula:

\[
r = r_B \sqrt{0.5 + \sqrt{0.25 + \frac{8m_e k_B T_c r_c^2}{e^2 B^2 r_B^4}} + \frac{B_c^2 r_c^4}{B^2 r_B^4}}
\]

\[
r_B = \sqrt{\frac{I m_e}{\pi \varepsilon_0 v e B^2}}
\]

A maximum acceptance can be estimated by calculating the geometric phase space area of the non-compensated electron beam:

\[
\alpha = \pi \frac{r^2}{\sqrt{2U}} \left( B \sqrt{\frac{Q}{M}} + \sqrt{\frac{Q B^2}{4M} + \frac{j}{2v \varepsilon_0}} \right)
\]

I = electron beam current  
\( j = \) electron beam current density  
\( v = \) electron velocity  
B = magnetic flux density on axis  
Tc = cathode temperature  
rc = cathode radius  
Bc = cathode magnetic flux density  
Q/M = ion charge over mass in As/kg  
U = ion acceleration potential  
e = electron charge  
me = electron mass  
\( \varepsilon_0 = \) vacuum peritivity  
kB = Boltzmann constant
Example calculations of time-of-flight (TOF):

• Kinetic energy in the trap: 500 eV
• TOF for 2 x 78 mm: 2.2 µs (M = 20); 5.8 µs (M = 132)
• TOF for 2 x 116 mm: 3.3 µs (M = 20); 8.6 µs (M = 132)
At each time step check ion status and update charge state based upon ionization probability.

Injection efficiency simulation considers time-dependent ionization events.
Ionization simulations

Evolving charge state of ions as they enter the trap

Runge-Kutta ionization state evolution including electron impact ionization and radiative recombination
Capture simulation

Ionization probability time based upon overlap of phase space area

Relative abundance

Time (s)
First Results

Injected $K^+$ ion

Ion reaches trap center after 6μs

Time after injection (μs)
Results for capture efficiency

With increasing ionization stage, injected ion catching improves
Charge breeding simulation

![Graph showing relative abundance over breeding time for Hg$^{29+}$ and Hg$^{35+}$]
Breeding times required for $A/q=7$

$A/q = 7$

$I = 550$ mA

$E_{e^-} = 2500$ eV

Charge state $q$ vs. Breeding time (s)
Acceptance and beam radius

**Electron beam current density**

Average $z < 0.1$ m: 12189 A/cm$^2$

**Electron beam radius (Herrmann)**

- **Electrons:**
  - $T_c = 1200$ K
  - $I = 1$ A
  - $E = 10$ keV
  - $r_c = 0.0254/8$ m
  - $B_c = 0.0015$ T

Average $z < 0.1$ m: 51 μm

**Maximum geometric acceptance**

(for Herrmann radius)

- **Ions:**
  - $M = 20$
  - $U = 15$ kV

Average $z < 0.1$ m: 7.5 π μm
Electron gun

- $r_c = 3.175$ mm
- max. emission $I_c > 1$ A
- Soft iron shield

Dispenser-type Ba M-coating thermoionic cathode
Electron collector

- HV feedthroughs
- Coil leads
- Extractor
- Ions
- Back shield
- Collector coil
- Collector electrode
- Front shield
- Suppressor
- Electron beam
- Water
Electron collector
Drift tube assembly

- Trap region length 80-270 mm
- 4 K operation
- Fast HV switching in sub-μs range possible
Drift tube supports

- Sapphire insulator
- OFHC copper holder
- Slotted apertures
Drift tubes, electrode assembly

- Sapphire insulators
- Slotted apertures
- OFHC copper holder
- Sapphire insulator
Drift tubes, electrode assembly
Slotted central drift tube

central drift tube

assembly with leads
Drift tube assembly in magnet bore

OFHC cooling anchor to 4 K

ceramic insulator

sapphire

Macor
Assembly phase
Assembly lab
First beam 3.3.2017

First beam
3.3.2017
CAREB-EBIS
Leigh, Michael, Christian, We, Stepan
First 1 A beam!
Measured permeance

\[ k_1 = (3.887 \pm 0.0024) \cdot 10^{-6} \frac{A}{V^{3/2}} \]
Radiative recombination

\[ E_p = E_e + E_B \]
$E_e = 5.5$ keV
$B = 4.5$ T
$V = -100$ V
$I = 300$ mA
Spache charge shift

Shifts of RR peaks with beam current show value of space-charge potential

$E_e = 5.8 \text{ keV}$
$B = 4.5 \text{ T}$
$V = -100 \text{ V}$
Space charge shift

Shifts of RR peaks with beam current show value of space-charge potential

\[ \Delta V_e = (-1.639 \pm 0.070) \frac{\text{eV}}{\text{mA}} \]
Space charge shift

Shifts of RR peaks with axial-well depth show ion space charge compensation

\[ E_e = 5.5 \text{ keV} \]
\[ B = 4.5 \text{ T} \]
\[ V_{CDT} = 2.5 \text{ kV} \]
\[ I = 812 \text{ mA} \]

\[ \Delta V_i = (-0.763 \pm 0.035) \frac{\text{eV}}{V} \]
Summary

- Design, construction and assembly of CANREB-EBIS
- Test up to 4.5 T
- Emission currents up to 1 A with 6 mm diameter cathode

- Pervance determination
  \[ k_1 = (3.887 \pm 0.0024) \cdot 10^{-6} \frac{A}{V^{3/2}} \]

- Space charge potential determination dependence
  - electron beam current
    \[ \Delta V_e = (-1.639 \pm 0.070) \frac{eV}{mA} \]
  - trap potential depth
    \[ \Delta V_i = (-0.763 \pm 0.035) \frac{eV}{V} \]
Support frame
Final tests before shipping
Table-top EBITs for PTB, Petra-III, MPIK
Mini EBITs

- HCl cloud
- Water cooling
- NdFeB magnets
- Electron gun
- Drift-tubes
- Electron beam
- Water-cooled collector
- HCl extraction optics
Mini EBITS

- 8.1 x 10^{-9} mbar
- 1.9 x 10^{-9} mbar
- 3.6 x 10^{-9} mbar
- 1.1 x 10^{-9} mbar

Signal [a. u.]

q/m [e/u]
Off-axis electron gun
Off-axis electron gun

Photon beam
Fluorescence of He-like O$^{6+}$ 1s-3p

Miniature PolarX-EBIT successfully operating with synchrotron radiation at BESSY-II
Outlook

• Preparation for HV-floating operation
• Tests of injection from laser ion source
• Test of gas injection system
• Transfer to TRIUMF
CANREB EBIS Team
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