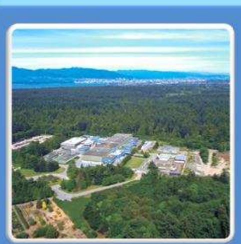
# The Electron Beam Ion Trap at the TITAN Faciliy and Characterization of Extracted Highly Charged Ion Beams



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## Motivations

• Why do we need an Electron Beam Ion Trap (EBIT) at the TITAN Facility ?

• The main purpose of TITAN is to perform high-precision mass measurements ($\delta m/m \leq 10^{-8}$) on short-lived isotopes ($t_{1/2} \geq 10$ ms). The EBIT produces highly charged ions (HCIs) which will boost the precision of such measurements.

• Why do we need to characterize extracted HCI beams ?

• The TITAN EBIT will be receiving online radioactive ion beams from the ISAC facility at TRIUMF. The radionuclides of interest will be of minute quantities. A characterization of HCI beams extracted from the EBIT allows for an understanding of the extraction, trap and beam dynamics necessary to maximize the transfer efficiency of ions towards the Penning Trap.

## TITAN Project

The TITAN (TRIUMF's Ion Trap for Atomic and Nuclear science) experiment at TRIUMF (TRI-University Meson Facility) uses a unique combination of a radio-frequency quadrupole (RFQ), an Electron Beam Ion Trap (EBIT) and a Penning trap to achieve mass measurement with a relative precision of $\delta m/m < 10^{-8}$ on short-lived isotopes (10 ms < $t_{1/2}$ < 1 s).

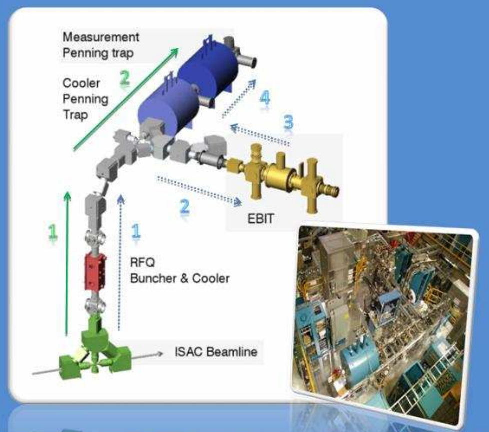


Fig. 1 Main components of the TITAN Experiment. Mass measurements can be performed on singly charged ions (green line) and highly charged ions (blue dashed line) using the EBIT.

The mass is determined from the cyclotron frequency of the ion in the homogenous magnetic field of the Penning trap magnet:

$$w_c = \frac{qB}{m}$$

The use of HCIs will increase the mass measurement resolution by a factor corresponding to the charge state q of the HCI:

$$\frac{m}{\delta m} \propto \frac{qB}{m} T_{rf} \sqrt{N}$$

where $T_{rf}$ is the duration of the radio-frequency excitation and $N$ is the number of measurement cycles.

### Motivations for high precision mass spectrometry

• Shell closure effects, existence and locations of magic numbers far from the valley of stability.
• Test the unitary of the CKM matrix and the CVC hypothesis (Standard Model).
• Study of rp-process waiting-point nuclei.

### Other experimental uses for TITAN

• Collinear laser spectrometry on cooled ion bunches using the RFQ.
• Study of the branching ratio of odd-odd intermediate nuclei in double-beta decay using the EBIT in Penning trap mode.
• X-ray spectrometry of short-lived radioactive nuclei.

## EBIT

The purpose of the TITAN Electron Beam Ion Trap (EBIT) is to trap and charge breed, by electron impact ionization, singly charged ions coming from the RFQ. In the TITAN EBIT, the ions are trapped in the axial and radial direction by electrostatic potentials applied to drift tubes, the space potential of the electron beam as well as a strong magnetic field.

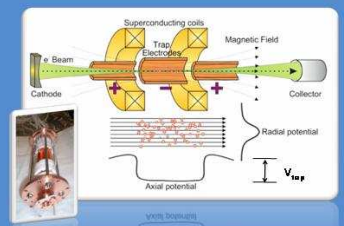


Fig. 2 Simplified diagram of an EBIT. The segmented drift tubes (trap electrodes) of the EBIT provides axial trapping while the Helmholtz coils compresses the electron beam. Radial confinement is provided by the electron beam's space charge. The trap is shown on the left.

| TITAN EBIT Parameters | |
|---|---|
| Maximum Magnetic Field (B) | 6 T |
| Maximum Beam Energy ($E_e$) | 60 keV |
| Maximum Beam Current ($I_e$) | 0.5 A (Upgradable to 5 A) |
| Beam Radius ($r_e$) | 25 µm |
| Beam Current Density ($J_e$) | 30 kA/cm² (Upgradable to 300 kA/cm²) |
| Trap Voltage ($V_{trap}$) | 0 – 1 kV |
| $T_{ion}$ | 100 – 500 eV |
| Number of trapped ions | ~$10^7$ |

Due to the high electron beam current density and energy, the EBIT can produce HCIs within 10 ms. This short breeding time is crucial for high precision mass measurement on short-lived isotopes.

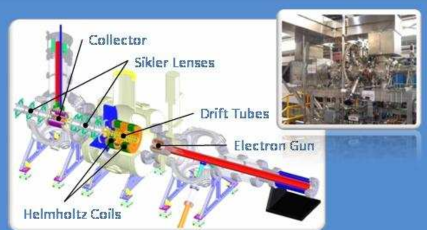


Fig. 3 Cut-out of the TITAN EBIT

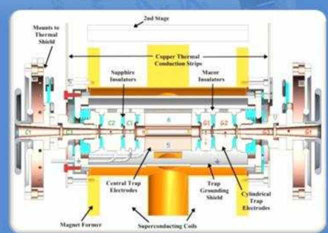


Fig. 4 Cross-sectional overview of the TITAN EBIT trap electrodes. The radially segmented octupole trap electrodes labeled one through eight are located in the center, with the electron gun-side cylindrical electrodes on the right, and the collector-side cylindrical electrodes on the left. The pieces separating the electrodes (light blue) are the sapphire insulators, which provide good thermal conduction, with the larger spacers (white) being Macor-material insulators.

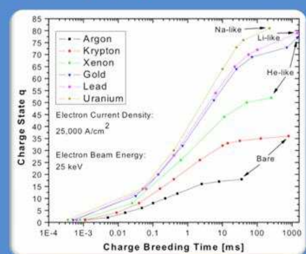


Fig. 5 Charge breeding time for different charge states of various elements. Starting with singly charged ions in the EBIT, an intense electron beam is turned on and directed towards the trap where the ions quickly become ionized to higher charge states. The time required for reaching higher charge states increases exponentially until no more electrons are orbiting the ion's nucleus.

### Extraction Scheme

The trapped ions can be extracted from the EBIT in two different modes:

• Pulsed

By lowering the potential of the drift tube nearest the collector below the potential of the central drift tube at a regular frequency up to 100 Hz, the HCIs are expulsed from the trap towards the collector in bunches at regular intervals.

• Leaky (continuous)

The potential of the drift tube nearest to the collector is lowered to a potential in between its original value and the one on the central drift tube and keep fixed. This results in a continuous stream of HCIs emerging from … pared to the pulsed mode.

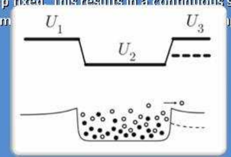


Fig. 6 Potentials on trap drift tubes in trap (solid line) and leaky (dashed line) modes.

## Emittance Measurements

### Theory

• Longitudinal emittance

$$\varepsilon = \Delta E \cdot \Delta t$$

Where ΔE is the energy spread and Δt is the time spread of the ion bunch.

• Transverse emittance

$$\varepsilon = \pi \cdot r \cdot r'$$

Where *r* is the ion beam source radius and *r'* is the divergence of the beam.

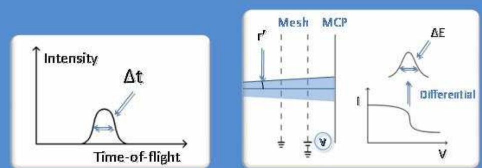


Fig. 7 Methods to measure the time spread Δt and energy spread ΔE of an extracted ion bunch.

### Experimental setup

We are planning to measure the emittance of HCI beams extracted from the EBIT using Time-of-Flight Mass Spectroscopy (TOFMS) combined with ion deflection plates.

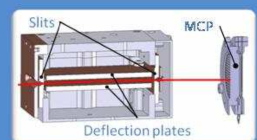


Fig. 8 Ion deflection box and MCP. As the ions enter the box, the first set of slits will filter a small subsection of the pulse. Depending on the applied potentials on the deflector plates, the trajectory of the ions will bend and a select few will past the second set of slits at the end of the box. By knowing the applied potentials, we can extract the divergence of the beam for that subsection.

• Advantages

• Charge resolution (TOF)
• Able to resolve specific *m/q* ratios for sufficiently low ion temperature in the trap.


Fig. 9 SIMION simulation of the extraction of HCIs through the main components of the TITAN EBIT

## Plans

### Offline measurements

For emittance measurements of the extracted HCI beam, the EBIT can be run offline (disconnected from the ISAC beamline) using either a gas injection system or a 5 keV Ion source.

• Gas Injection System

The gas injection system injects a fine stream of atoms into the trap from a side port of the magnetic chamber. These atoms can be used for charge breeding measurements and as a cooling gas for incoming ions from either the ISAC beamline or ion source.

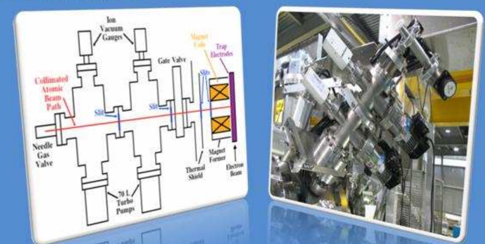


Fig. 10 The two-stage differentially pumped gas injection system. This system can be used to inject a collimated atomic beam of neutral gas or sublimated elements to the trapping region (located on the right in purple), which then becomes ionized and trapped.

•5 keV Ion Source

An ion source will be connected to the EBIT beamline and used to inject singly charged ions up to 5 keV into the EBIT. This will be used to test the optics in the beamline during injection and the trapping potentials of the drift tubes while performing all the regular measurements on the HCI beam emittance parameters (described below).

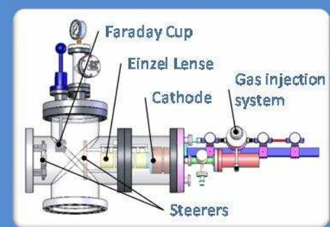


Fig. 11 Upper components of EBIT Ion Source

### HCI beam emittance parameters to be studied

• Ion temperature
• Number of trapped ions
• Injection pressure or ion beam injection density
• Ion charge stage
• Magnetic field
• Electron beam energy, current and radius ($r_e$)
• Trapping potentials and extraction scheme

The first two parameters to be analysed will be the temperature and the charge states of the extracted HCIs.

• Temperature

The temperature is primordial in determining the transverse emittance (as seen below) and crucial for good transmission of the HCI beam towards the detectors or Penning trap. Reducing it improves the mass measurement sensitivity in the Penning Trap.

$$\varepsilon = \pi \cdot r_0 \cdot \sqrt{\frac{k \cdot T_i}{q \cdot U}}$$

Fig. 12 The expected un-normalized transverse emittance of an EBIT/S. This can be calculated from the properties of the trapped ions, where $T_i$ is the temperature of the trapped ions, $r_0$ is the radius of their confinement volume, $U$ is the acceleration potential, and $q$ is the ion charge.

• Charge states, magnetic field and $r_e$

The transverse emittance is a function of the source radius which varies for different charge states, EBIT's magnetic field and beam radius. Hence, studying how these parameters changes the beam emittance is of fundamental importance.

## What do we expect ?

From past experiments with various other EBITs, we can predict a few parameters we except to see from the TITAN EBIT.

| Expected parameters of the TITAN EBIT | |
|---|---|
| Energy Spread (ΔE) | ~20 q eV |
| Extracted number of HCI | ≈ $10^6$ ions/s (Pulsed mode) |
| Transverse Emittance | ≤ 30 π mm mrad |
| Longitudinal Emittance | 8 x $10^{-5}$ q eV s |
| Breeding Time | 1 ms ≤ t ≤ 1 s |

For instance, if we extract a pulse of $Ne^{10+}$ ions from the EBIT, the resulting energy spread from this bunch will be around 200 eV. It is to be noted that this value is for a non-compensated electron beam. Otherwise, the energy spread can easily double or more depending on the degree of compensation.

The size of the transverse emittance can also be affected by the charge breeding time and electron beam current, increasing if either of them increases.

The charge state distribution cannot be predicted accurately and will only be known once the first measurements with either an X-ray detector or TOF with a Wien filter is done.

## Summary & Outlook

The TITAN EBIT will produce the most intense electron beam currently available and will be used to charge breed radioactive ions from the ISAC facility at TRIUMF. Used in unison with the Penning Trap, these HCIs will be used for high-precision mass measurements on short-lived isotopes.

Before becoming fully operational to receive the online radioactive beam from ISAC, calibration and testing of the EBIT will need to be performed. While offline, the EBIT will either use the gas injection system or the 5 KeV ion source as ion sources for testing purposes. The first of these measurements will be on the transverse and longitudinal emittances while simultaneously testing the optics of the EBIT.

Once the testing is completed, integration of the EBIT with the rest of the TITAN experiment will be done. The first online measurement will start shortly afterwards with $^{74}Rb$, which will help in refining measurement of the CKM matrix and fundamental symmetries in the Standard Model.

Fig. 13 The Titan group

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