Highly Charged Ion extraction beamline study for the UNIST-EBIT

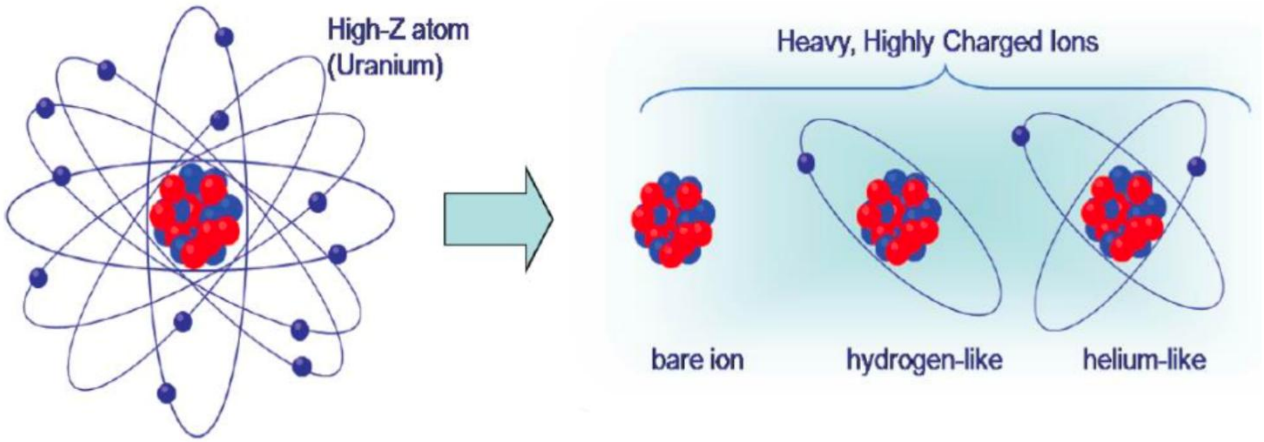
July 11, 2025

Je Hwan Han

Outline

- Highly Charged Ions
- Electron Beam Ion Trap
- Extraction experiment
- Future works

Highly Charged Ion



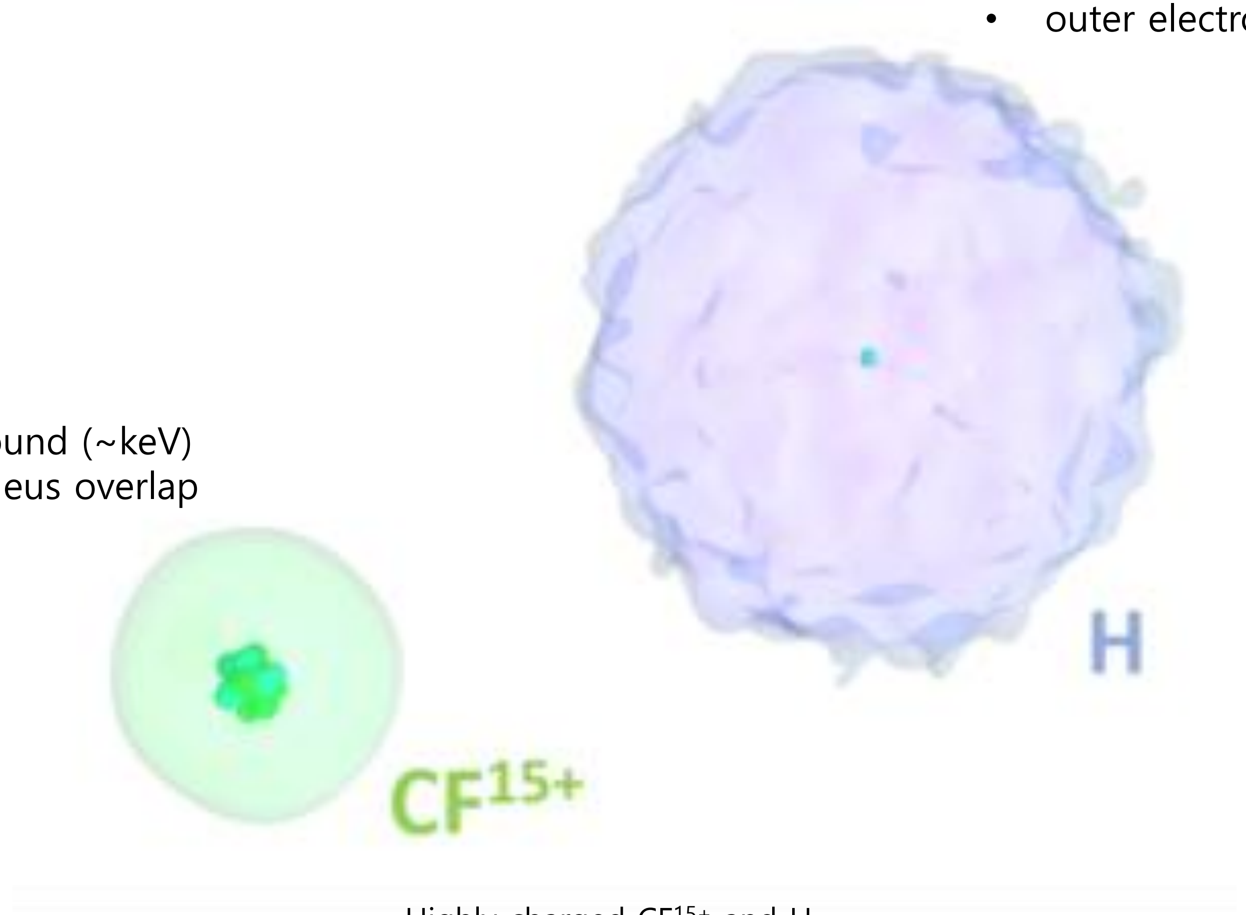
Difference between neutral atom and HCIs

- Atom loses many electrons at high temperatures due to ion-electron collisions.
- Highly Charged Ions (HCIs) constitute a dominant fraction of the visible matter in stars, supernovas, stellar corona, and accretion disks.
- HCIs might have applications in atomic clocks and more accurate measurements of fundamental physical constants. [1]
- Electron Beam Ion Trap (EBIT) is a good laboratory instrument to create, trap, and probe HCIs.

Highly Charged Ion

Atom
- size: ~100 pm
- outer electron weakly bound (~10 eV)

HCI
- size: a few pm
- positive charge
- strongly electron bound (~keV)
- strong electron-nucleus overlap

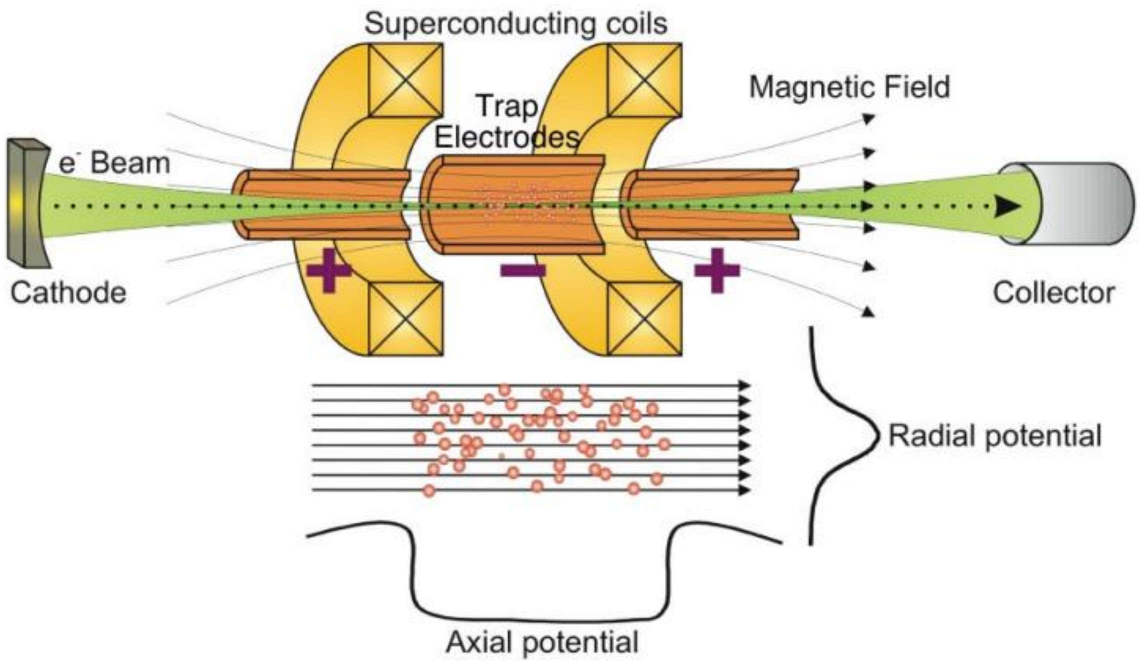


Highly charged CF^{15+} and H

https://qsnet.org.uk/highly-charged-ion-clock/

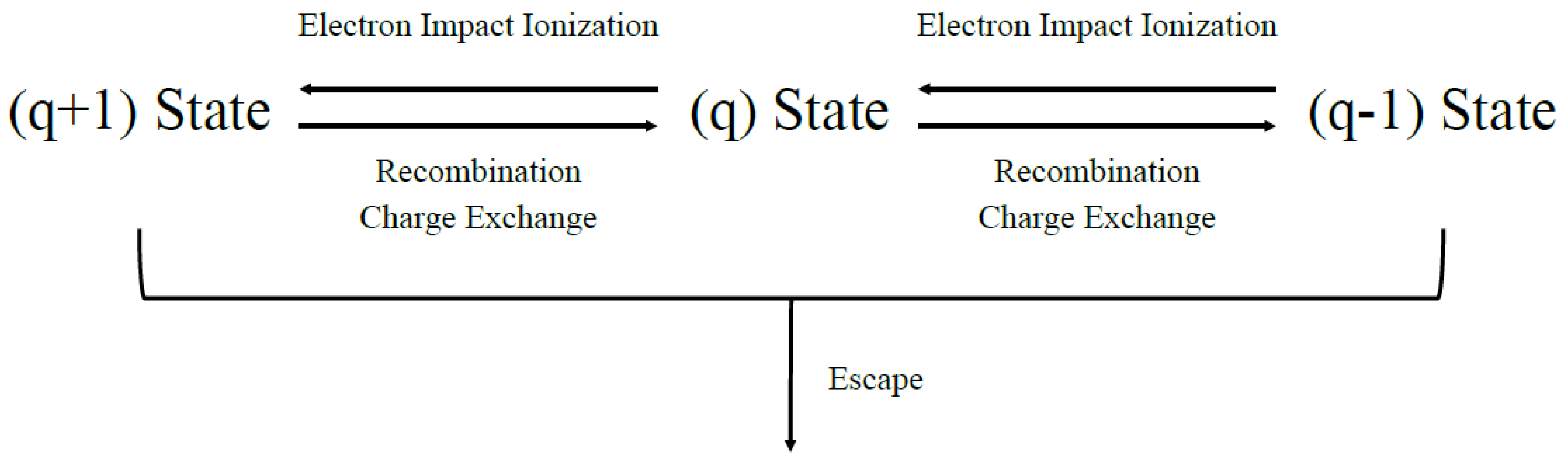
What is an Electron Beam Ion Trap?

- Compact in size and can produce uniform and steady-state HCI plasmas.
- Selective charge state production by electron beam energy.
- Easy detection in trap region by using Helmholtz or permanent magnets.



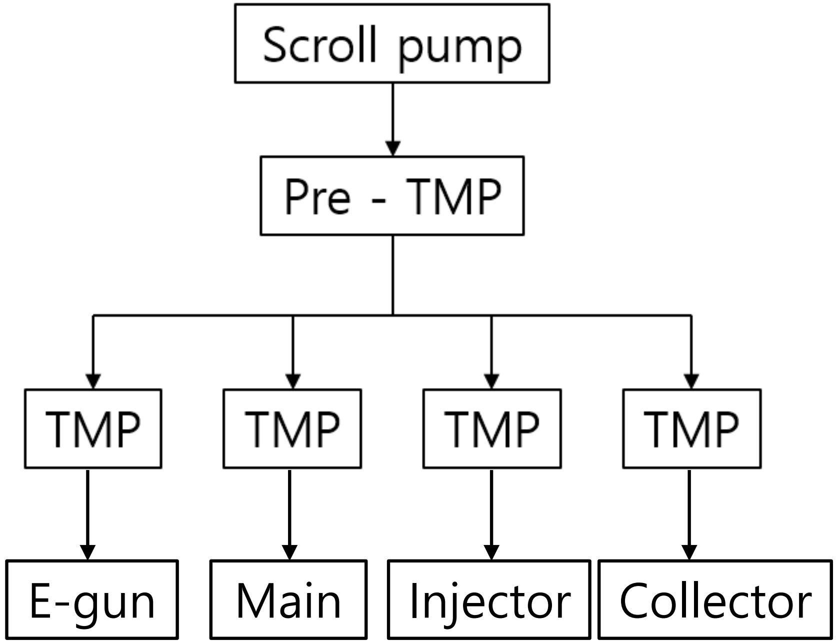
Trapping the HCIs in the EBIT

What is happening in EBIT?

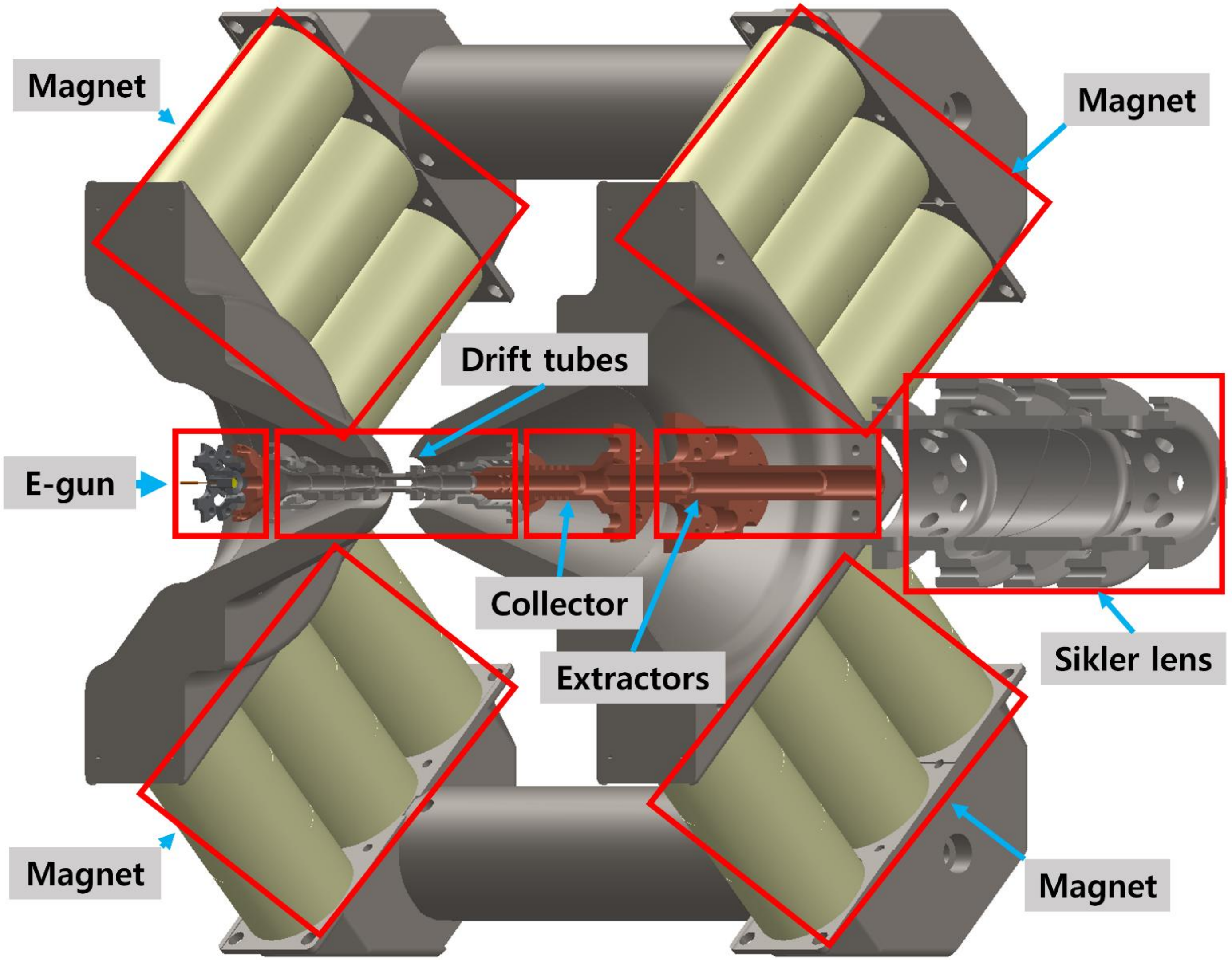


Charge state q will be estimated by considering Electron Impact Ionization, Radiative Recombination, and Charge Exchange. [2]

UNIST-EBIT

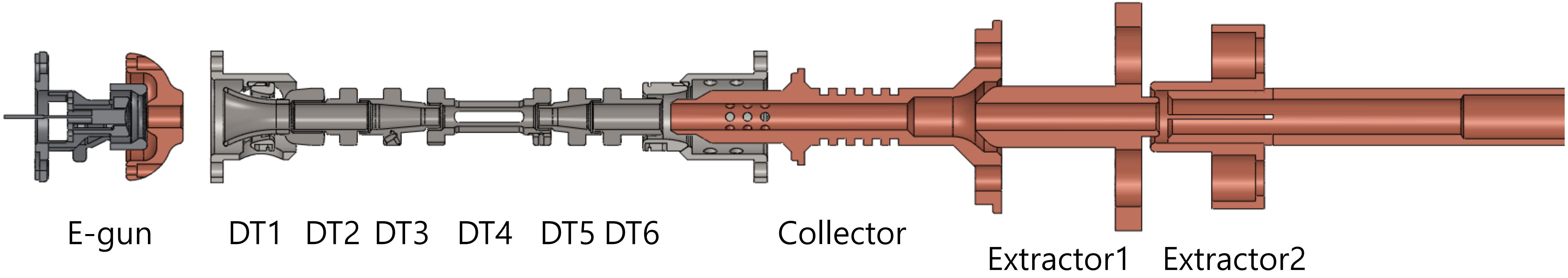


UNIST-EBIT vacuum system

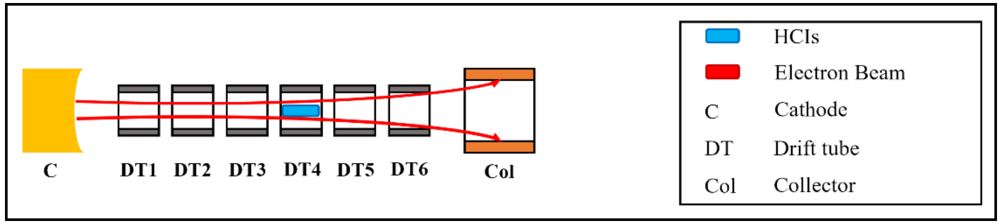


Schematic of UNIST-EBIT

UNIST-EBIT

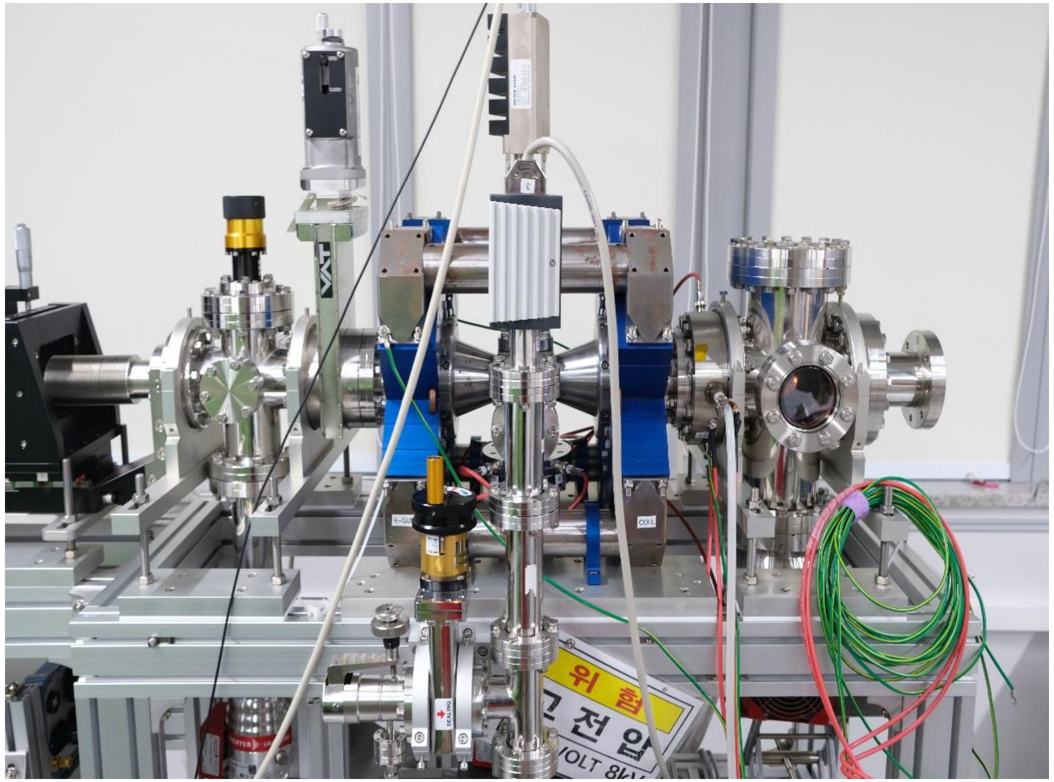


Inner component schematic of UNIST-EBIT



UNIST-EBIT

- Compact tabletop device.
- Tunable electron beam energy up to 8 keV.
- Electron beam current up to > 80 mA.
- Use 72 permanent magnets, soft iron/magnetic yoke.
- 0.84 T at trap center.
- Excellent optical access, opening angle of 58 degrees.



UNIST-EBIT

Herrmann radius

Herrmann radius is the beam radius when the electron beam flow as ideal flow with considering the temperature and magnetic field at cathode and trap center. [3]

$$r_B = \sqrt{\frac{2m_e I_b}{\pi \epsilon_0 v_e e B^2}}$$

$$r_H = r_B \sqrt{\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{8 m_e k_B T_c r_c^2}{e^2 B^2 r_B^4} + \frac{B_c^2 r_c^4}{B^2 r_B^4}}}$$

r_B : Brillouin radius
r_H : Herrmann radius

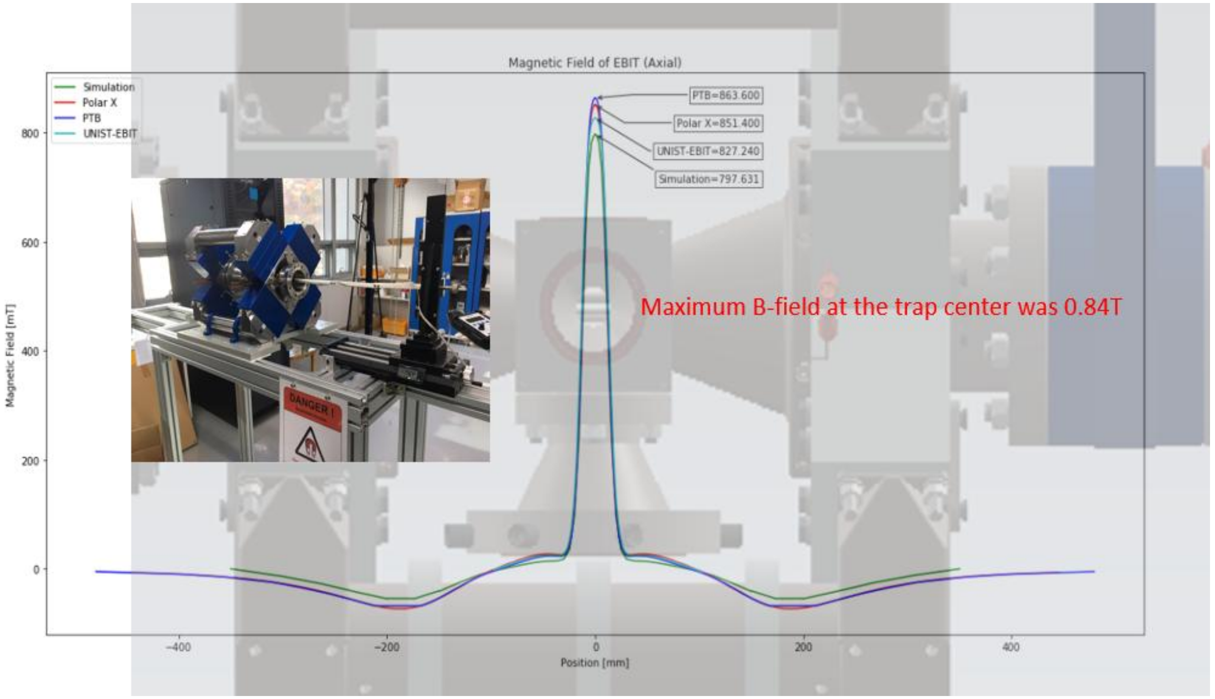
Parameter	Value
Electron beam current : I_b	80 mA
Electron beam energy : E_b	5 keV
Cathode temperature : T_c	1400 K
Magnetic field at cathode : B_c	100 μT
Magnetic field at trap center : B	0.86 T
Velocity of electron : v_e	4.1939*10^7 m/s
Radius of cathode : r_c	0.001702 m
Current Density	500 A/cm^3
Electron Density	$7 \times 10^{11}\ \mathrm{cm}^{-3}$

Parameter	Value
r_B	32.471 μm
r_H	72.147 μm

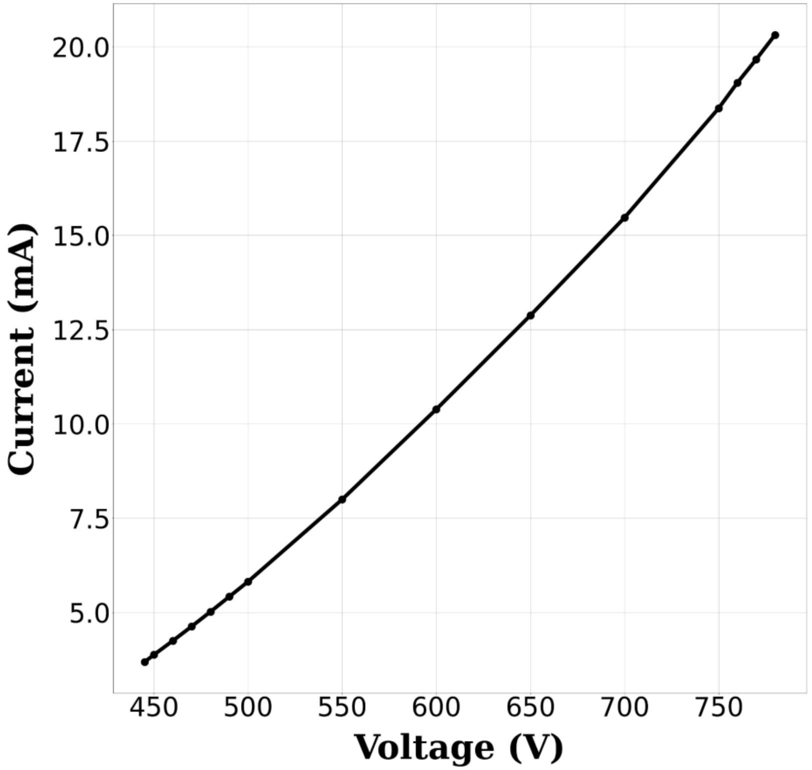
UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY 2007

iBAL INTENSE BEAM AND ACCELERATOR LABORATORY

UNIST-EBIT

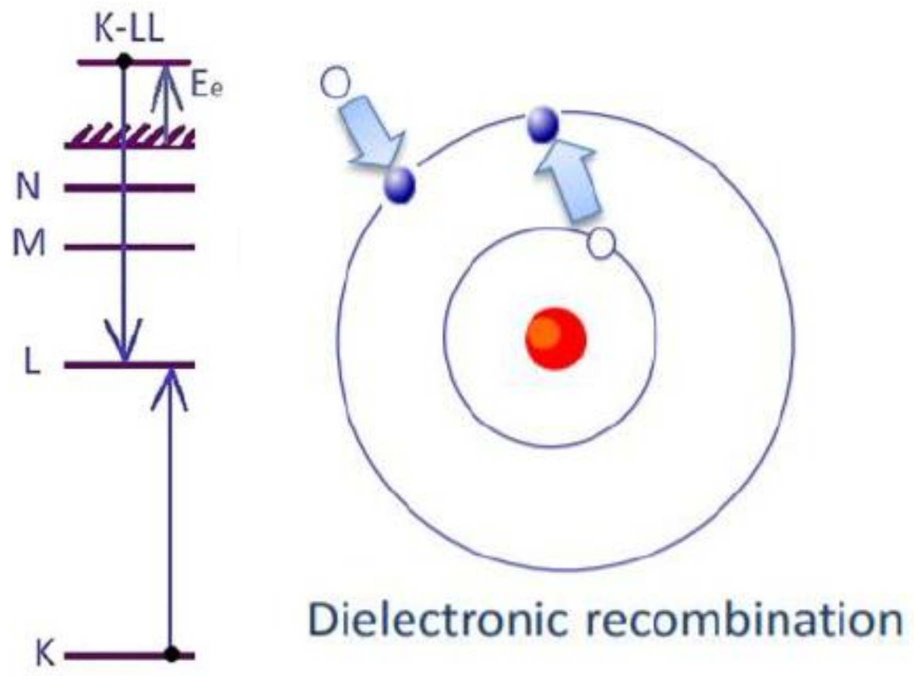


Magnetic field of UNIST-EBIT

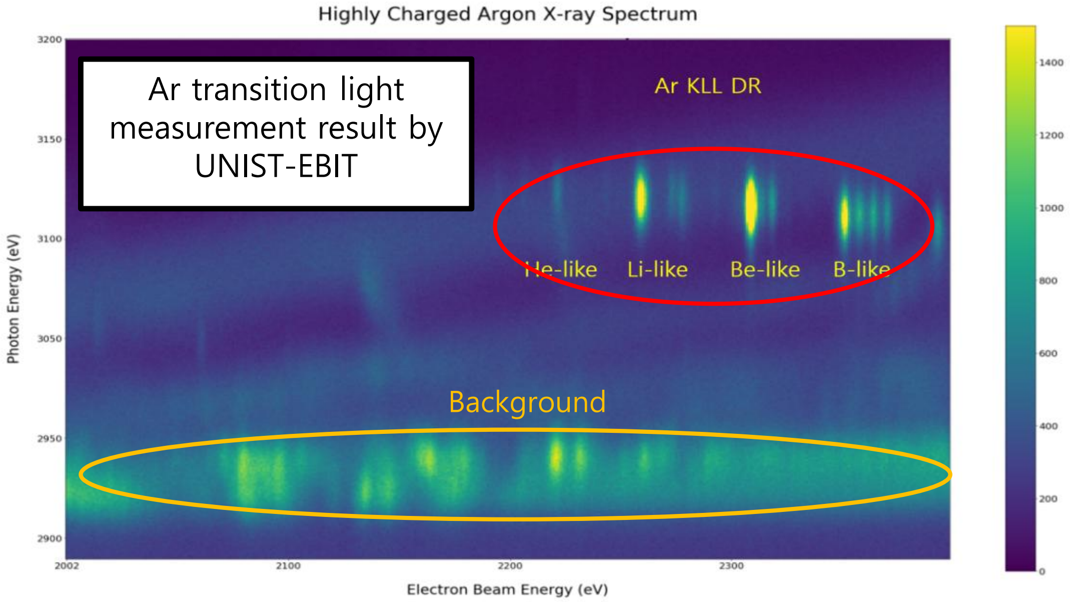


Perveance of UNIST-EBIT cathode

UNIST-EBIT

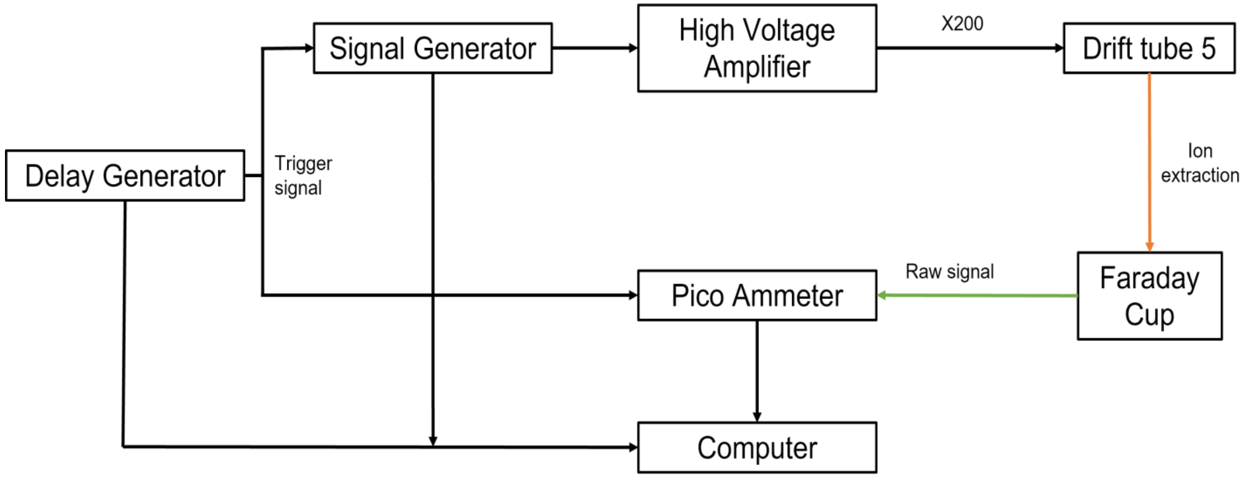


KLL Dielectronic Recombination (DR) schematic.

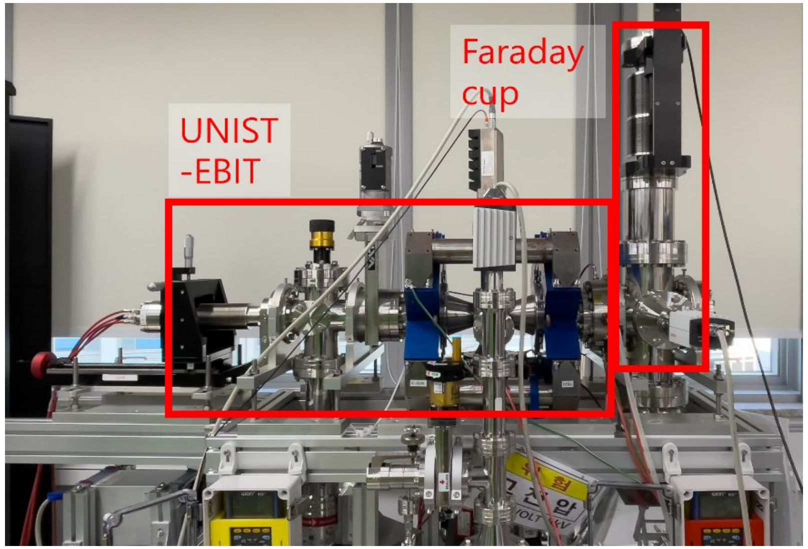


With the observation of KLL DR lines, we can specify the charge state of the argon ions.

Extraction experiment setup



Scheme of measuring the total current of HCIs



UNIST-EBIT with Faraday cup

- Establish the total automatic control system with EPICS.
- Measure the total current of HCIs with a Faraday cup.
- Make ion beam pulse with signal generator by control the DT5.
- Measure the current of three different types of extraction modes.

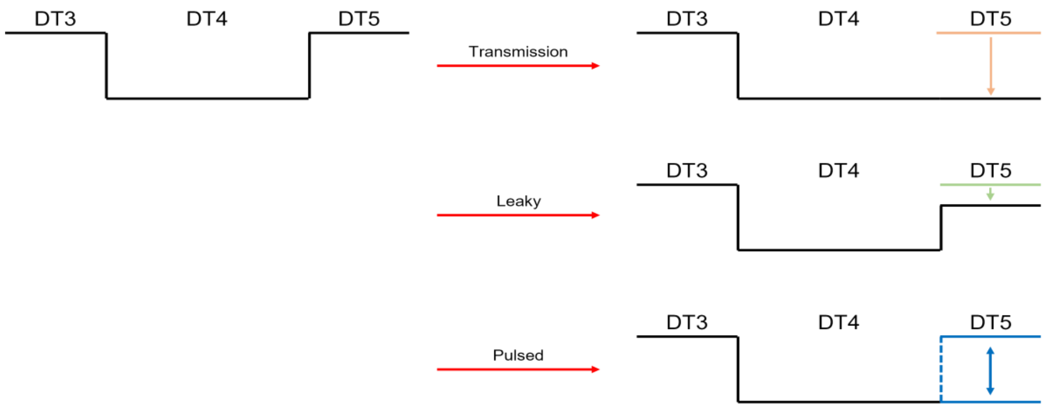
Extraction experiment setup

Component	Voltage (V)
Cathode	-594
Focus	-900
Anode	180
DT1	900
DT2	650
DT3	1876
DT4	1776
DT5	1876
DT6	20
Collector	0
Extractor1	-2000
Extractor2	-2400

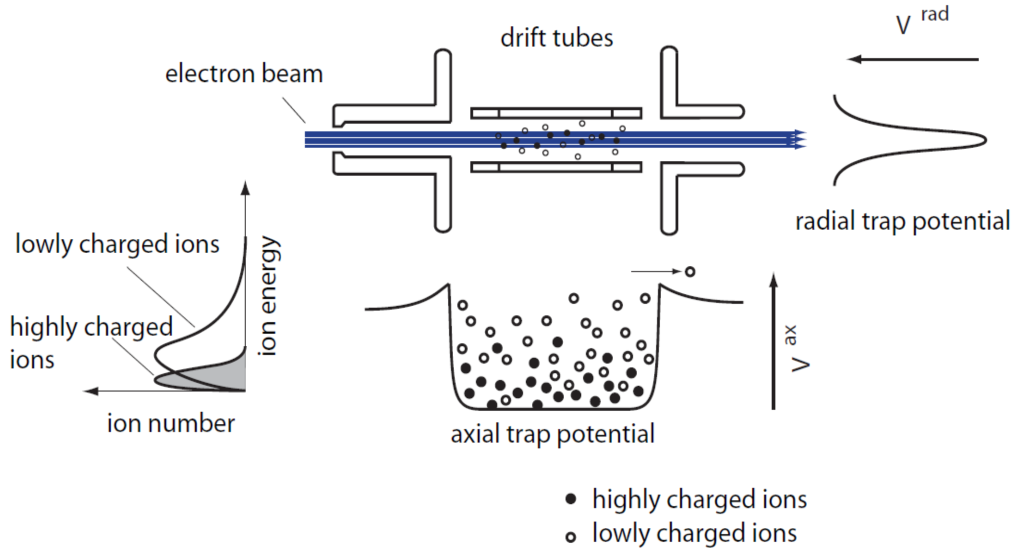
Electron Gun	
Heating voltage	7.1 V
Heating current	1.41 A
Electron beam current	10.1 mA

Vacuum Chamber	Vacuum level (mbar)
E-gun	9.73e-09
Injector	5.65e-08
Collector	1.54e-09

Extraction experiment setup



Electrical scheme of extraction mode



Trapping HCIs and LCIs in EBIT [4]

- Three extraction modes; Transmission, Leaky, and Pulsed mode.[5]

Trap Capacity Estimation

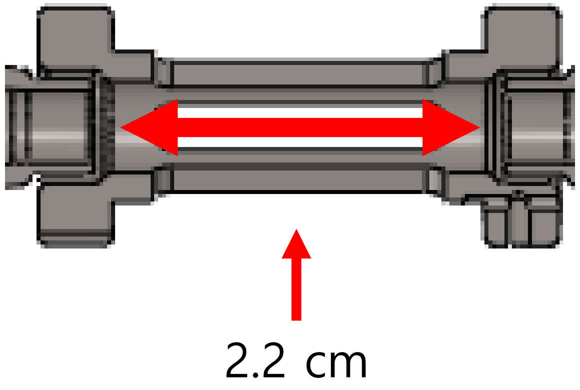
Trap capacity means the total amount of charge that can stably trap in the trap region. [4]

$$I_e = \frac{dQ}{dt}, \qquad v_e = \frac{dx}{dt} = \frac{\sqrt{2E_e}}{m_e}$$

$$\Delta Q = \frac{I_e \Delta x}{v_e} = \frac{I_e L}{\sqrt{2E_e/m_e}} \qquad L = trap\ length\ , 2.2\ \mathrm{cm}$$

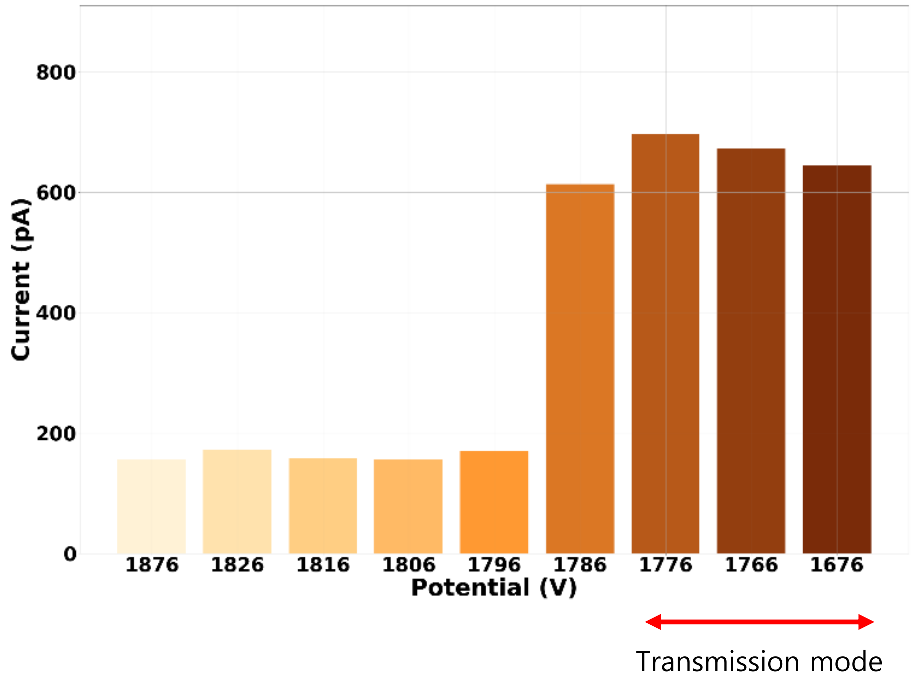
$$C_e \approx 1.05 * 10^{13} \frac{I_e(\mathrm{A}) L(\mathrm{m})}{\sqrt{E_e(\mathrm{eV})}}$$

$$C_e = 4.792 * 10^7 \qquad I = 7.677\ \mathrm{pA}$$

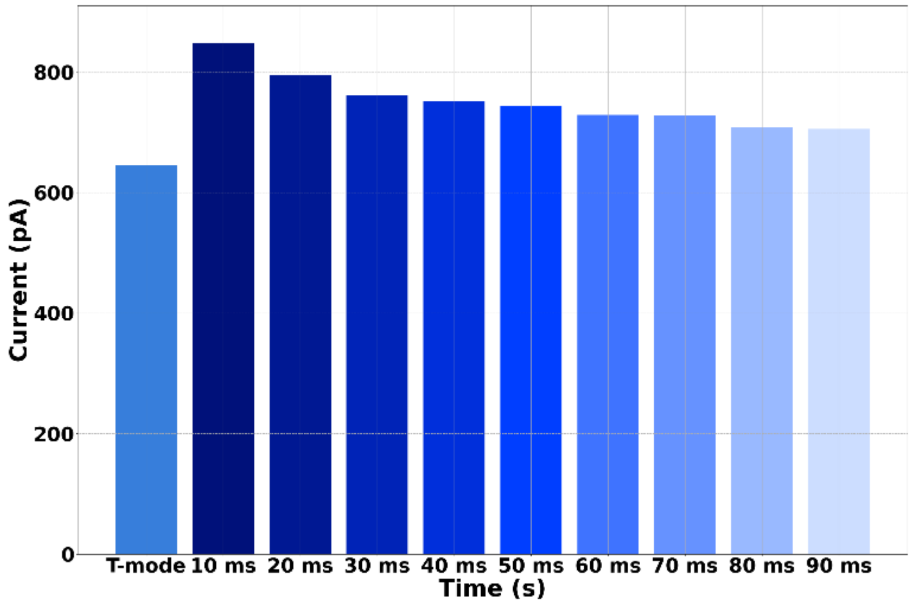


*integration time with 1s.

Extraction experiment results

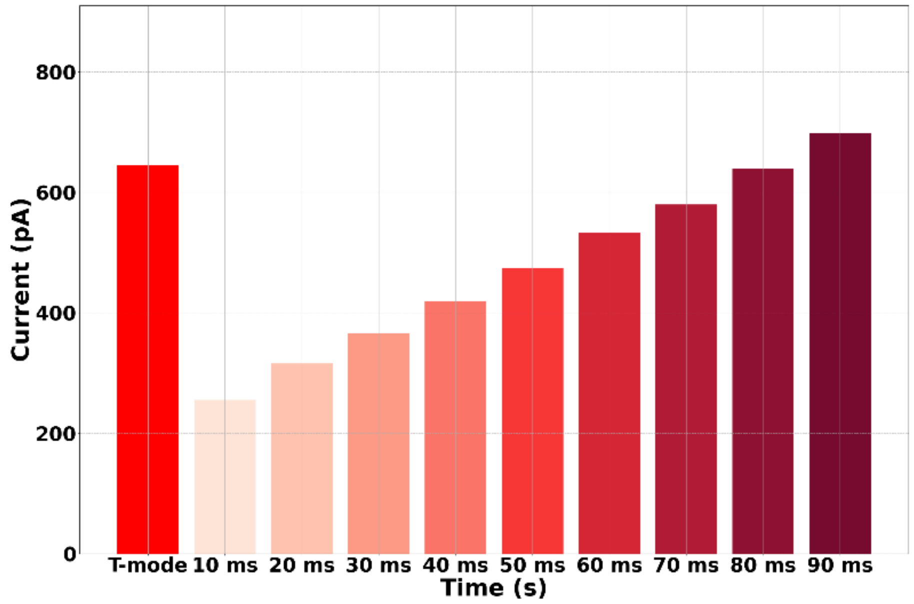


Measured currents for various DT5 potentials (Transmission and Leaky modes).

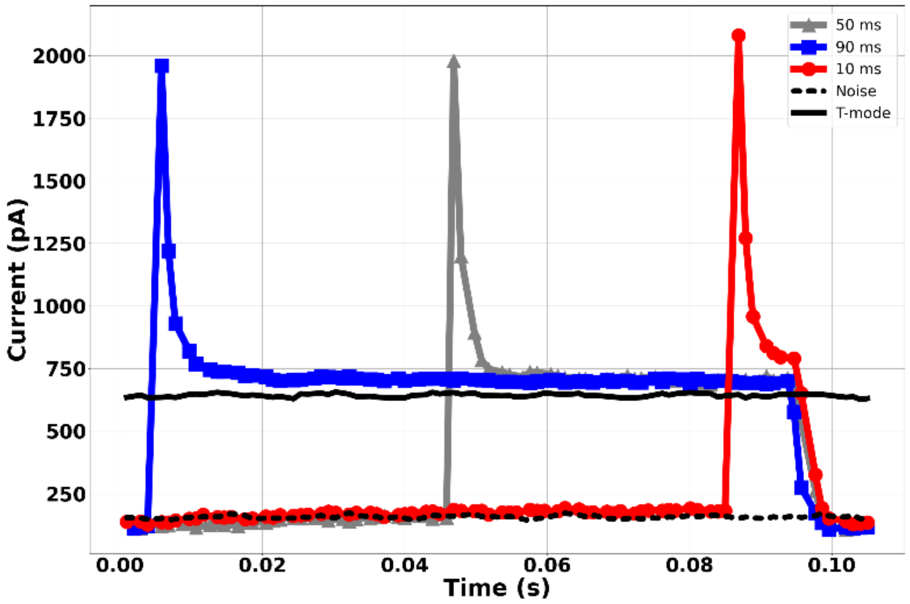


Average currents for different trap opening durations in the Pulsed mode.

Extraction experiment results

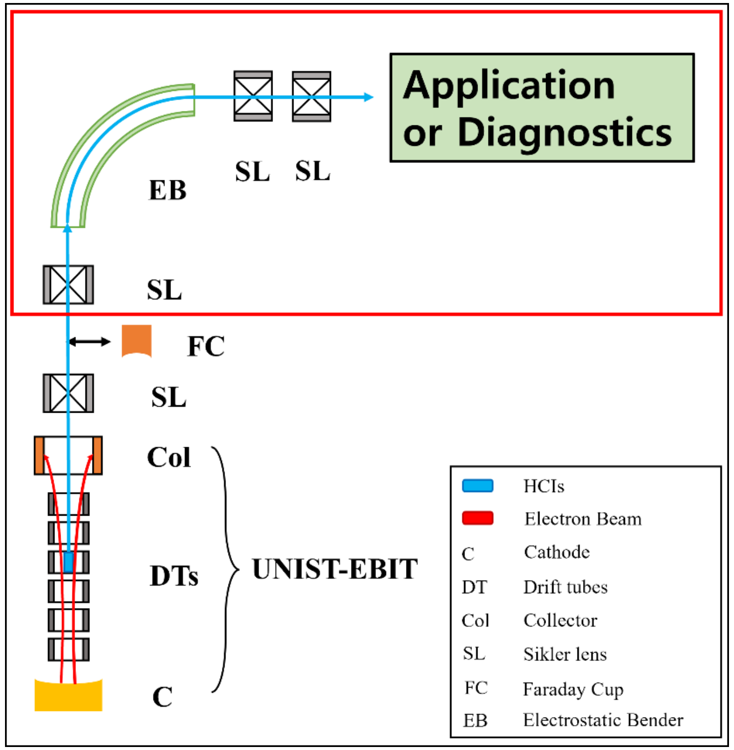


Average currents over the whole cycle
for different trap opening durations in the Pulsed mode.

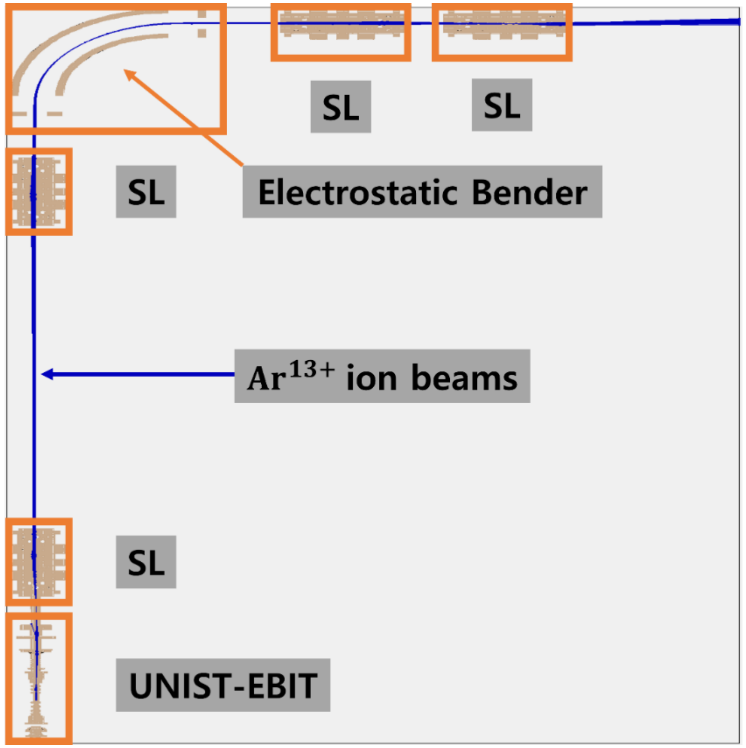


Measured current traces for different trap opening durations
with 0.16 ms integration time.

Extraction beamline simulation



Scheme of UNIST-EBIT Upgrade



Extraction beamline SIMION simulation for bending and deceleration.

Future works

- Design the alignment system.
- Inject and produce highly charged iron ions to obtain X-ray spectrum data.
- Installation and conditioning of the off-axis gun.
- UNIST-EBIT extraction beamline will provide a specific charge state with the specific energy needed for other applications.
- Using trigger to synchronize trap open and picoammeter.

Applications

- Ion Clock
- Astrophysics spectroscopy
- Quantum nano fabrication
- Satellite target experiment
- Semiconductor Lithography
- QED test / Dark matter search

References

[1] King S A, Spieß L J, Micke P, Wilzewski A, Leopold T, Benkler E, Lange R, Huntemann N, Surzhykov A, Yerokhin V A et al. 2022 Nature 611 43–47

[2] F.Currell and G.Fussmann,“Physics of Electron Beam Ion Traps and Sources,” IEEE Transactions on Plasma Science, vol. 33, no. 6, pp. 1763–1777, 2005.

[3] G. Herrmann, “Optical theory of thermal velocity effects in cylindrical electron beams,” Journal of Applied Physics, vol. 29, no. 2, pp. 127–136, 1958.

[4] Zschornacka, G., M. Schmidt, and A. Thorn. "Electron beam ion sources." arXiv preprint arXiv:1410.8014 (2014).

[5] P. Micke et al., Rev. Sci. Instrum. 89, 063109 (2018).