

# Redefinition of Second

SungNam Park

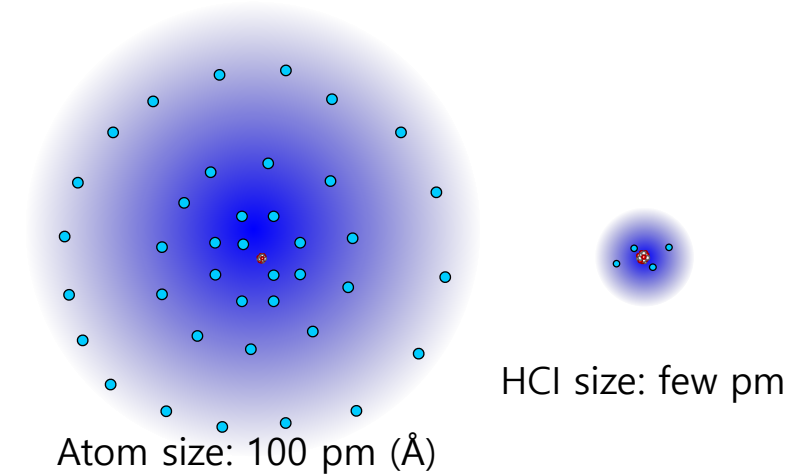
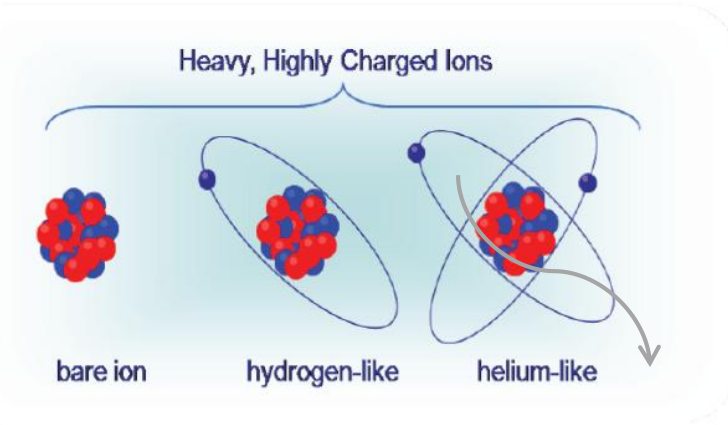
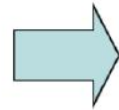
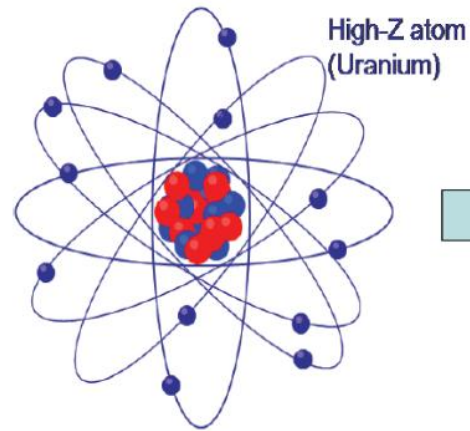
2025.07.11

# Contents

1. Redefinition of Second
2. Current Work at KRISS
3. EBIT
4. Future Vision

# Highly Charged Ions

## Development and Commissioning of a Compact Electron Beam Ion Trap for Highly Charged Ion Studies



### Definition

An HCI is any atom that has been stripped off a large number of electrons ( $Q \gg 1$ ), so that the total energy yielded during re-neutralization ( $E_0$ ) is outside the realm of  $E_0 \gg 10 \text{ eV}$

### Note: Overlap

*multiply charged or multi charged ions* -  $Q = 2 \sim 9$ ,  $E_0 < 1000 \text{ eV}$   
*Very highly charged ions* such as Uranium -  $Q = 92$ ,  $E_0 \sim 750,000 \text{ eV}$

### Scope

Argon losing 13 – 16 electrons.

# Redefinition of Second

Metrologia 61 (2024) 012001 (19pp)

<https://doi.org/10.1088/1681-7575/ad17d2>

## Review

## Roadmap towards the redefinition of the second

N Dimarcq<sup>1</sup>, M Gertsch<sup>2</sup>, G Milet<sup>3</sup>, S Bize<sup>4</sup>, C W Oates<sup>5</sup>, E Peik<sup>6</sup>, D Calonico<sup>7</sup>, T Ido<sup>8</sup>, P Tavella<sup>9,\*</sup>, F Meynadier<sup>9</sup>, G Petit<sup>9</sup>, G Panfilo<sup>9</sup>, J Bartholomew<sup>10</sup>, P Defraigne<sup>11</sup>, E A Donley<sup>5</sup>, P O Hedekvist<sup>12</sup>, I Sesia<sup>7</sup>, M Wouters<sup>13</sup>, P Dubé<sup>2</sup>, F Fang<sup>14</sup>, F Levi<sup>7</sup>, J Lodewyck<sup>4</sup>, H S Margolis<sup>15</sup>, D Newell<sup>5</sup>, S Slyusarev<sup>16</sup>, S Weyers<sup>6</sup>, J-P Uzan<sup>17</sup>, M Yasuda<sup>18</sup>, D-H Yu<sup>19</sup>, C Rieck<sup>12</sup>, H Schnatz<sup>6</sup>, Y Hanado<sup>8</sup>, M Fujieda<sup>8,21</sup>, P-E Pottie<sup>4</sup>, J Hanssen<sup>20</sup>, A Malimon<sup>16</sup> and N Ashby<sup>5</sup>

Progress status: Several other atomic species are being investigated as potential candidates for the next generation, for example  $^{229}\text{Th}^+$ ,  $\text{Lu}^+$ ,  $\text{Cd}$ , and several highly charged ions. The most recent references can be found for example in [Proceedings of the annual IEEE IFCS <https://ieee-uffc.org/symposia/ifcs>, and EFTF conferences [www.eftf.org/](http://www.eftf.org/)].

2025-07-15

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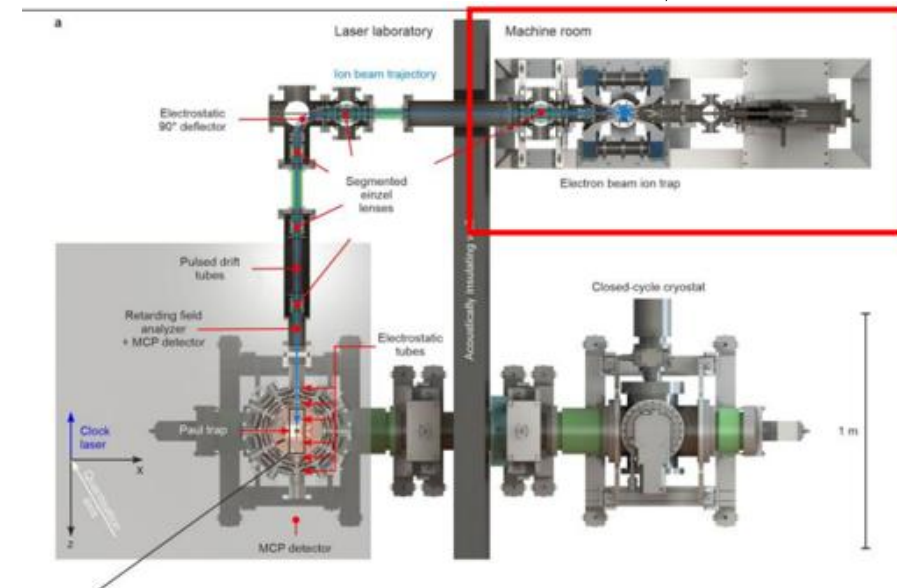
## An optical atomic clock based on a highly charged ion

[Steven A. King](#), [Lukas J. Spieß](#) , [Peter Micke](#), [Alexander Wilzewski](#), [Tobias Leopold](#), [Erik Benkler](#), [Richard Lange](#), [Nils Huntemann](#), [Andrey Surzhykov](#), [Vladimir A. Yerokhin](#), [José R. Crespo López-Urrutia](#) & [Piet O. Schmidt](#) 

[Nature](#) 611, 43–47 (2022) | [Cite this article](#)

9703 Accesses | 90 Citations | 282 Altmetric | [Metrics](#)

Ph.D Thesis



# HCI Candidates

## Periodic table for highly charged ions

Chunhai Lyu<sup>\*</sup>, Christoph H. Keitel, and Zoltán Harman

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

(Dated: April 16, 2025)

Mendeleev's periodic table successfully groups atomic elements according to their chemical and spectroscopic properties. However, it becomes less sufficient in describing the electronic properties of highly charged ions (HCIs) in which many of the outermost electrons are ionized. In this work, we put forward a periodic table particularly suitable for HCIs. It is constructed purely based on the successive electron occupation of relativistic orbitals. While providing a much-simplified description of the level structure of highly charged isoelectronic ions – essential for laboratory and astrophysical plasma spectroscopies, such a periodic table predicts a large family of highly forbidden transitions suitable for the development of next-generation optical atomic clocks. Furthermore, we also identify universal linear  $Z$  scaling laws ( $Z$  is the nuclear charge) in the so-called “Coulomb splittings” between angular momentum multiplets along isoelectronic sequences, complementing the physics of electron-electron interactions in multielectron atomic systems.

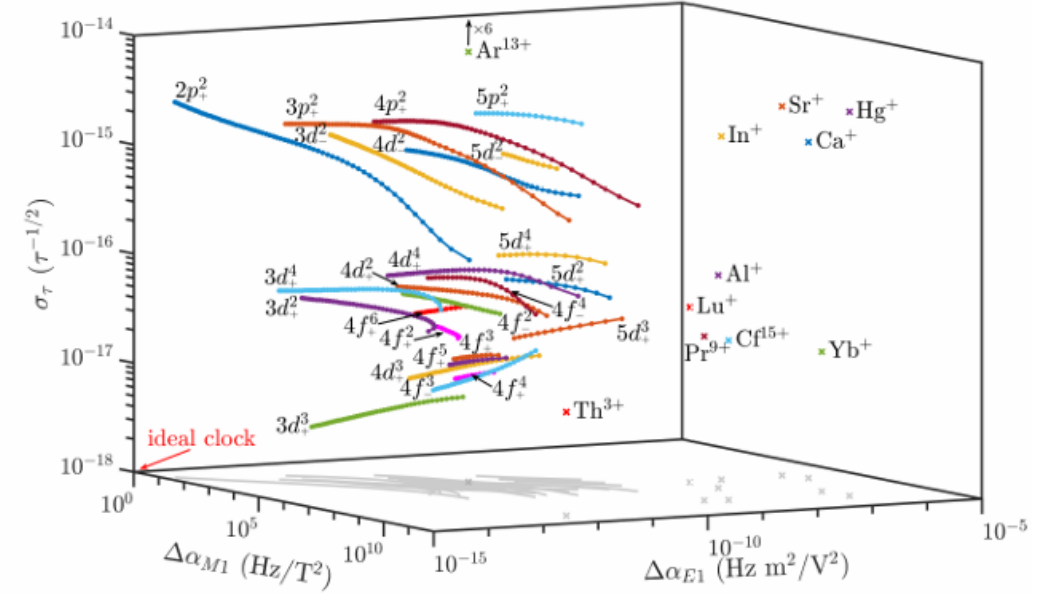
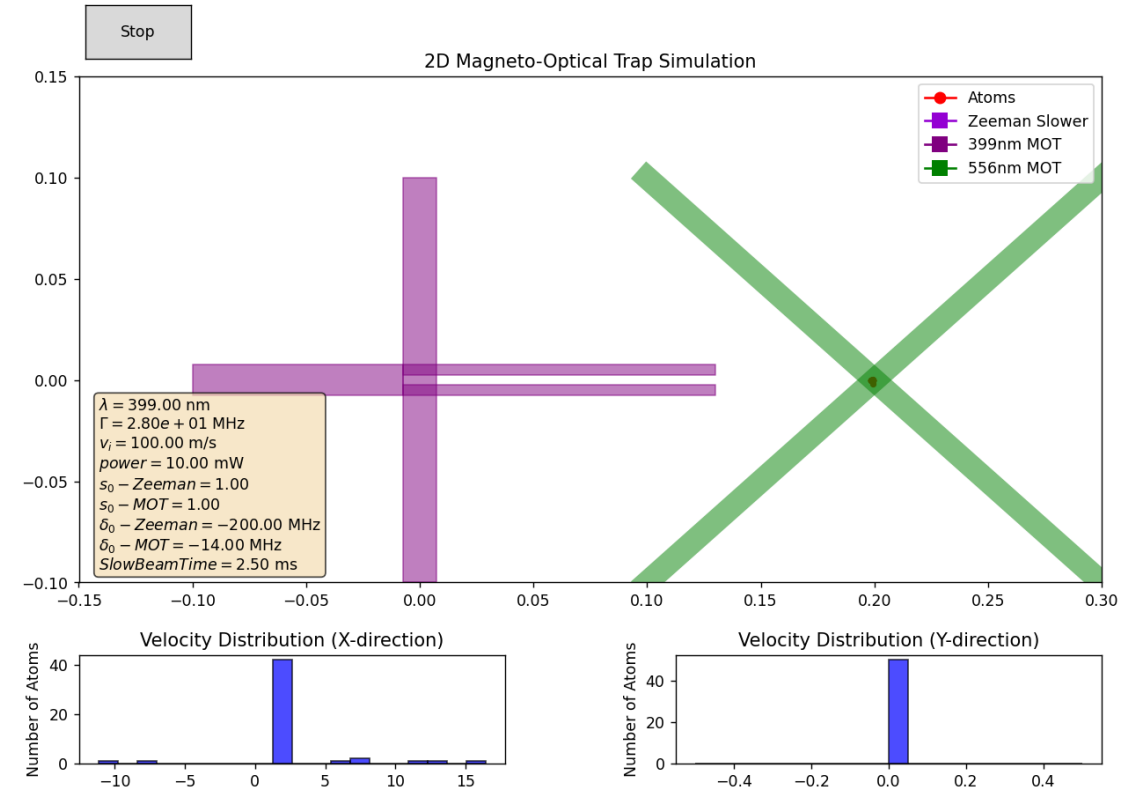
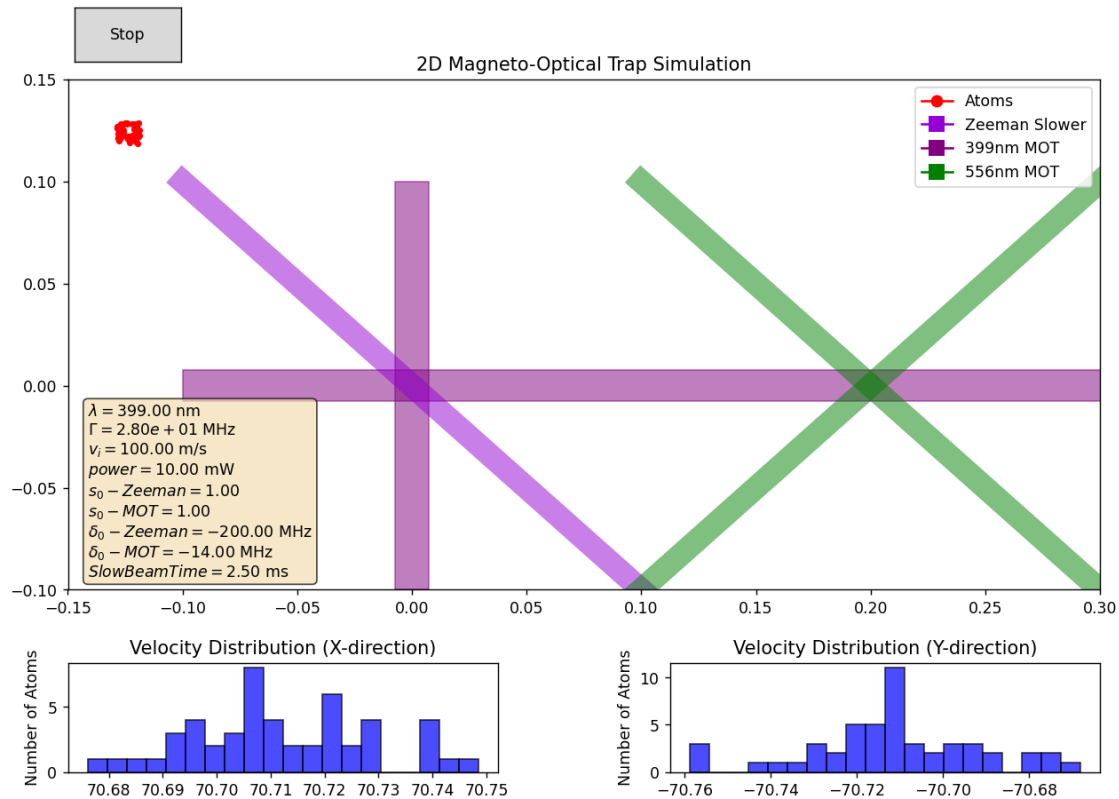


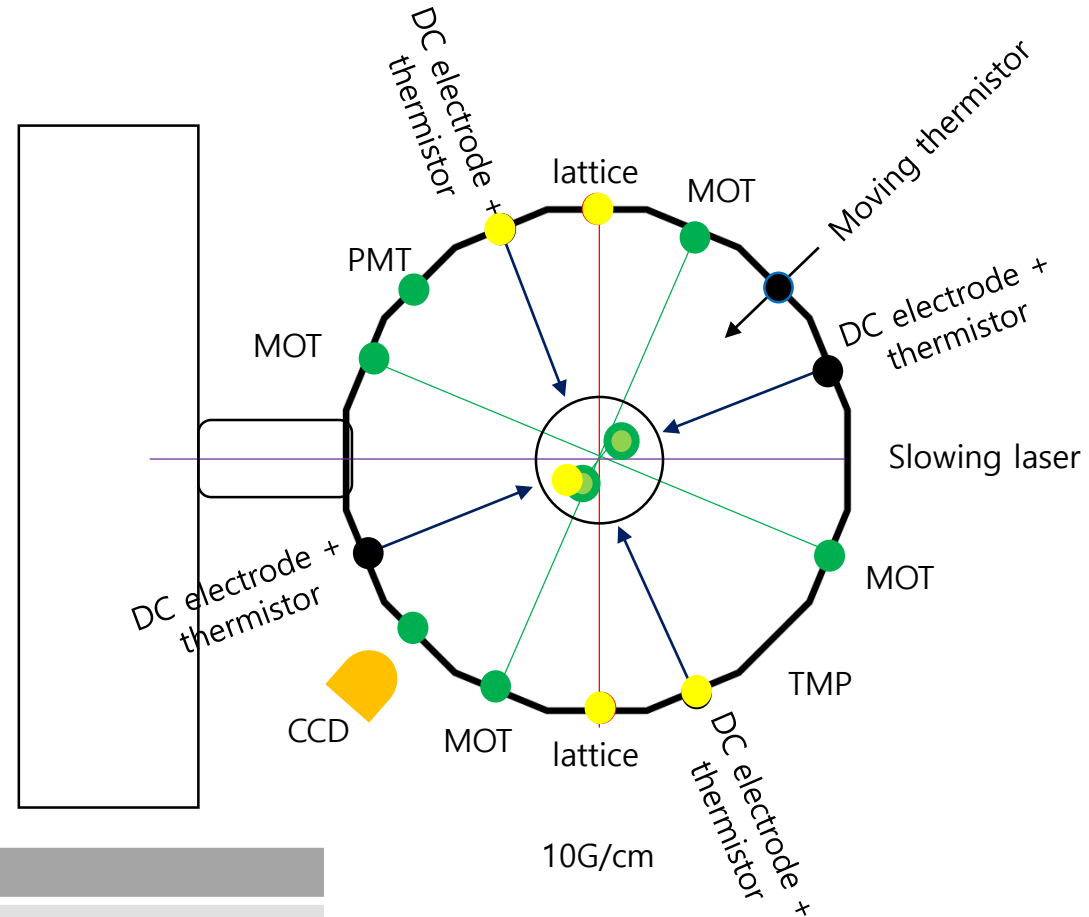
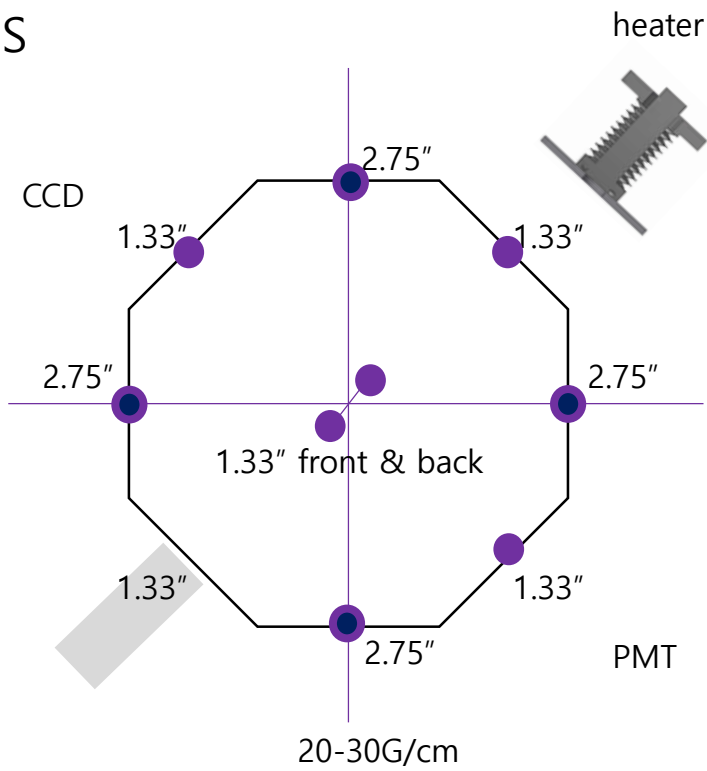
Figure 3. **Superior clock properties of HCI clock candidates.** The projected instability  $\sigma_\tau$ , differential magnetic- ( $\Delta\alpha_{M1}$ ) and electric-dipole ( $\Delta\alpha_{E1}$ ) polarizability of over 700 HCI clock candidates are plotted, with the grey lines and crosses being their projections in the  $x - y$  plane. Each line corresponds to a relevant isoelectronic sequence denoted by the colored cells in the periodic table Fig. 1. The values for state-of-the-art singly charged ion clocks [12, 42],  $\text{Ar}^{13+}$  [11],  $\text{Pr}^{9+}$  [43],  $\text{Cf}^{15+}$  [44], and nuclear clock  $^{229}\text{Th}^{3+}$  [45] are presented for comparison.

# Mobile Clock

## LVIS(Low Velocity Intense Source) using Yb atom



For LVIS



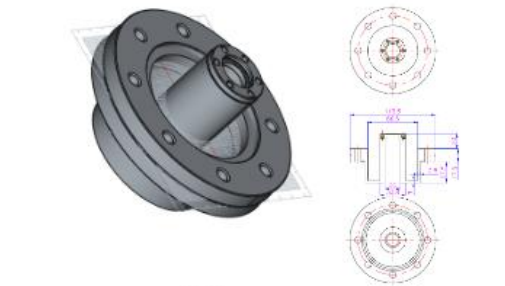
| 399 coating non-magnetic viewport 2.75"  | 4            |  |
|--|--------------|--|
| 399 coating non-magnetic viewport 1.33"  | 5            | Ion source쪽 없음, front, back(16 chamber side) |
| 556 coating non-magnetic viewport 2.75"  | 2            |  |
| 556 coating non-magnetic viewport 1.33"  | 4            |  |
| 399 coating non-magnetic viewport 1.33"  | 5            | LVIS 용 velocity 측정용 4개 (수직, 22.5도 + PMT)     |
| 556 coating non-magnetic viewport 1.33"  | 2            | CCD + PMT                                    |
| <del>759 bare window 표면이 가장 부드러운 것</del> | <del>2</del> | <del>임시</del>                                |
| Blank                                    | 4            | DC electrode + thermistor                    |
| 2025-07-15 Blank                         | 1            | Moving thermistor                            |



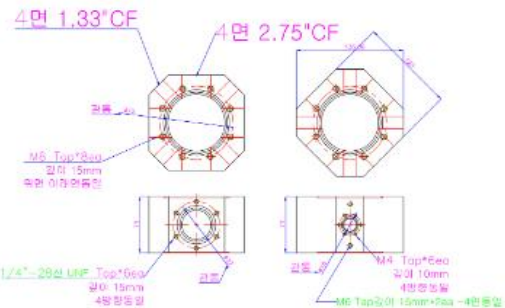
# 25.04.04 16-side coil flange

## LVIS 시스템 챔버 부속품 5종 제작사양서

### 1. 8각 챔버 Magnetic Field Flange + Bobbin.

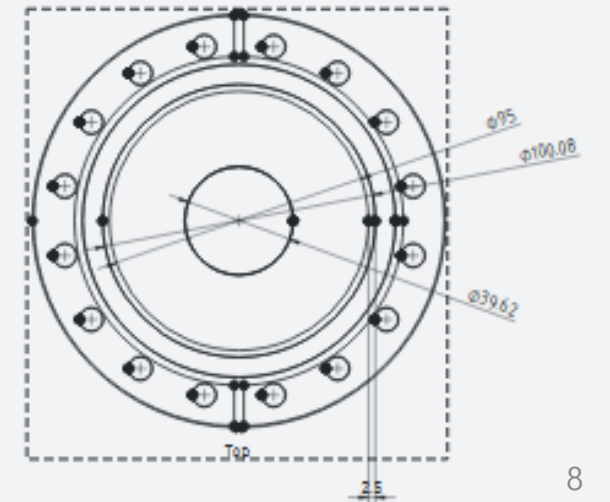
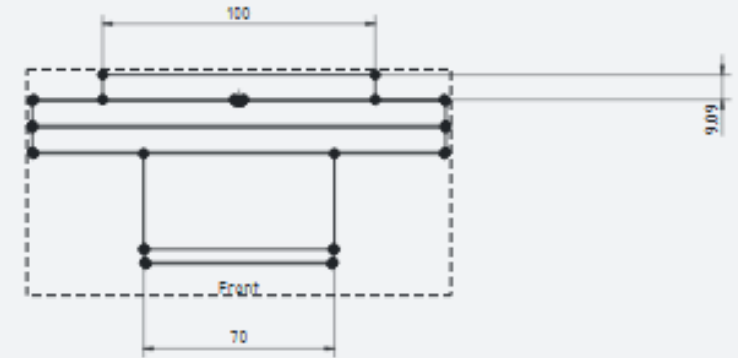
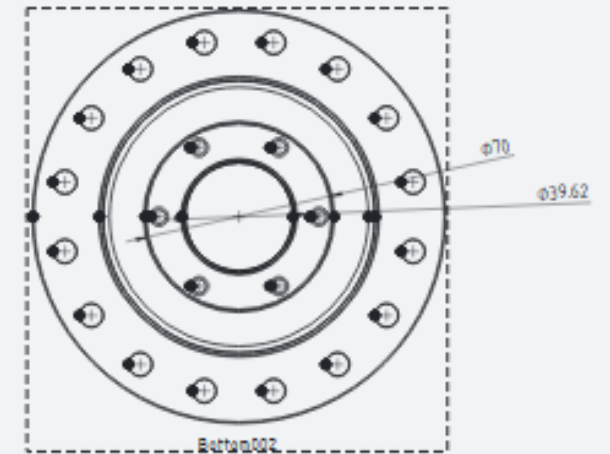
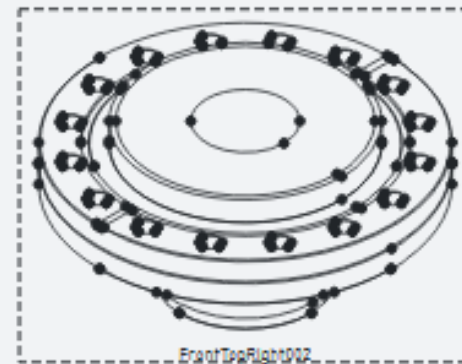
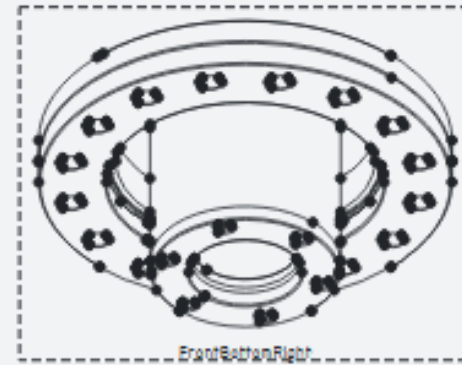
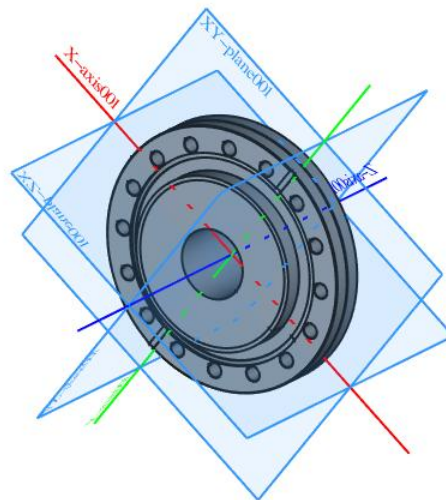
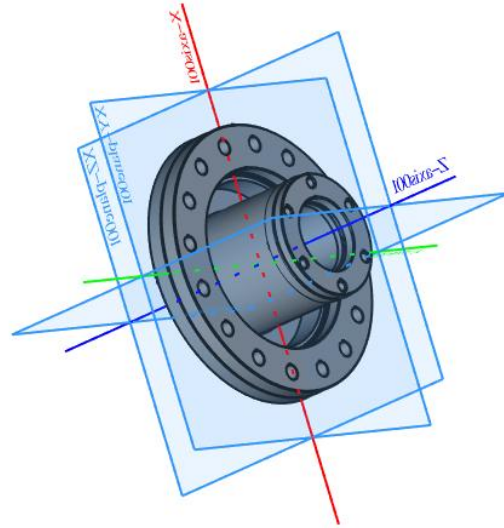


8각 챔버 magnetic field flange



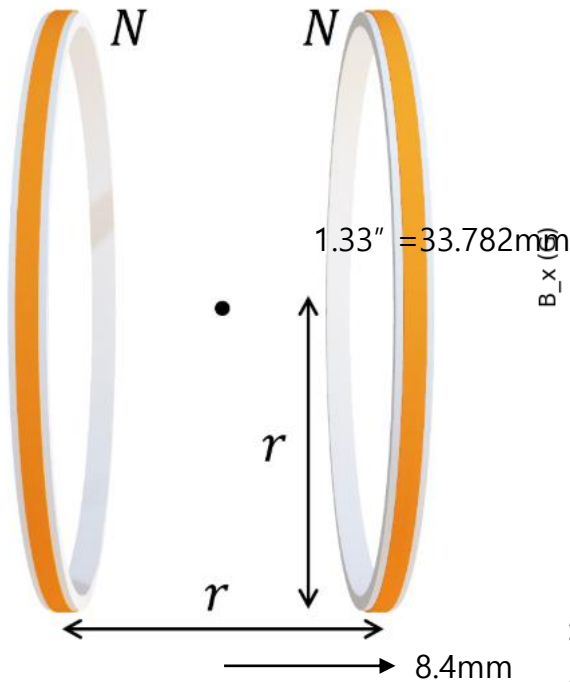
8각 챔버 규격

재질: Titanium Grade 2





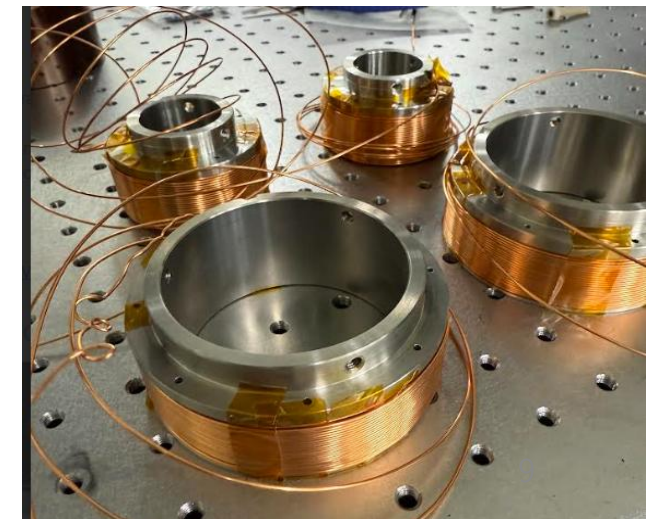
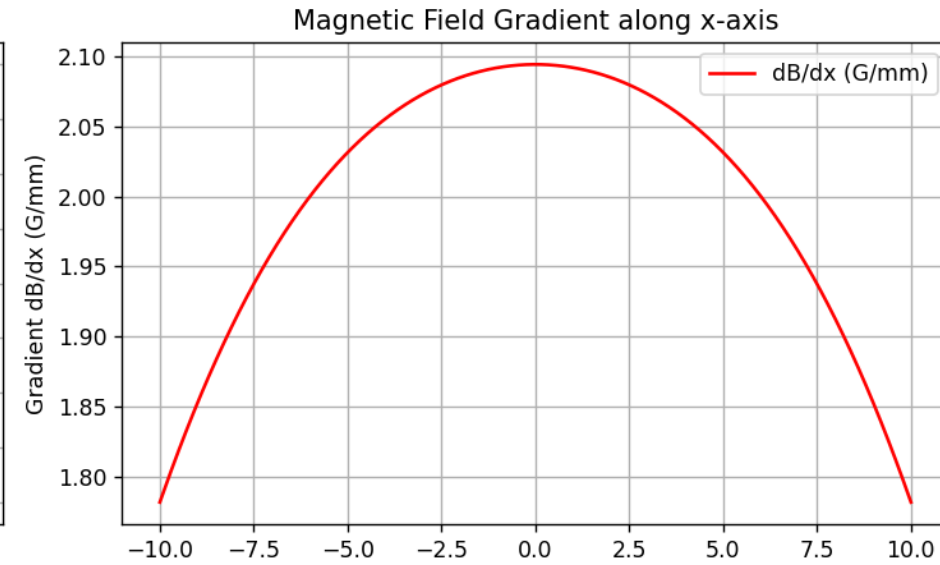
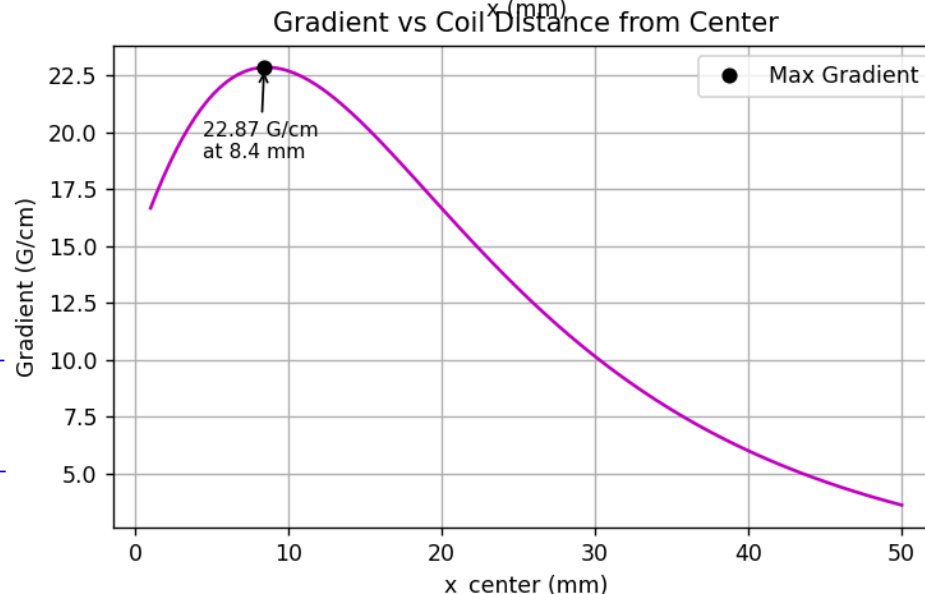
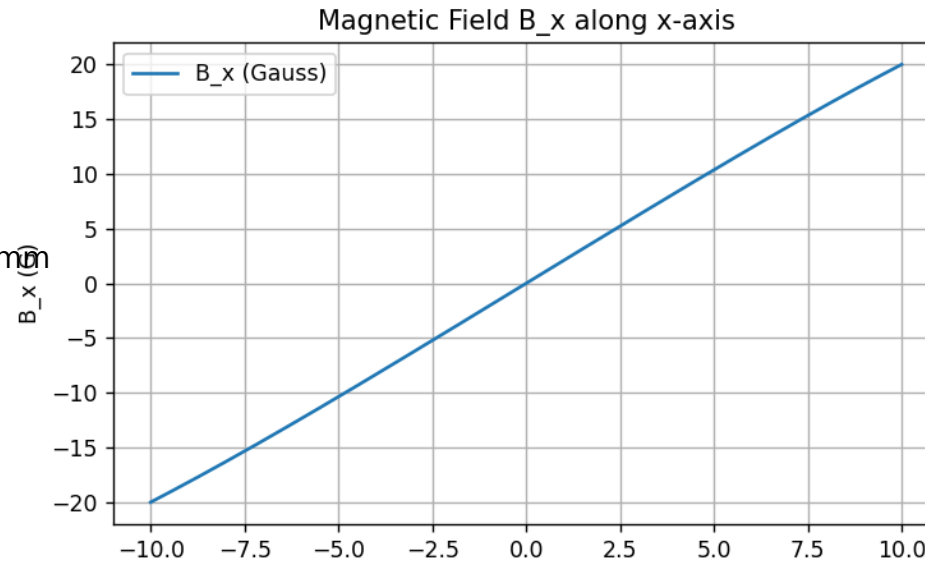
# Mobile Clock – MOT Coils



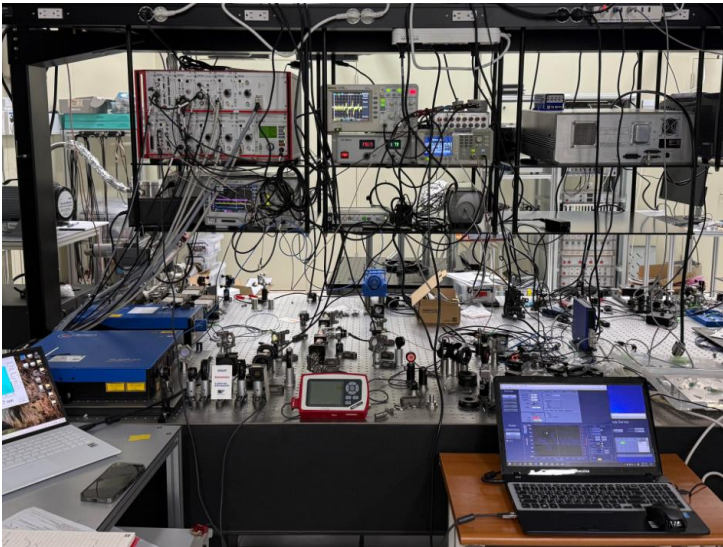
64m, ~1.4 Ohm

Current: 0.6A  
 Total turns (N): 325 turns  
 Number of winding lines on x-direction: 13 turns  
 Number of layers on y-direction: 25 layer  
 Total wire length: 63.30 meters  
 Power consumption: 0.4875 Watts

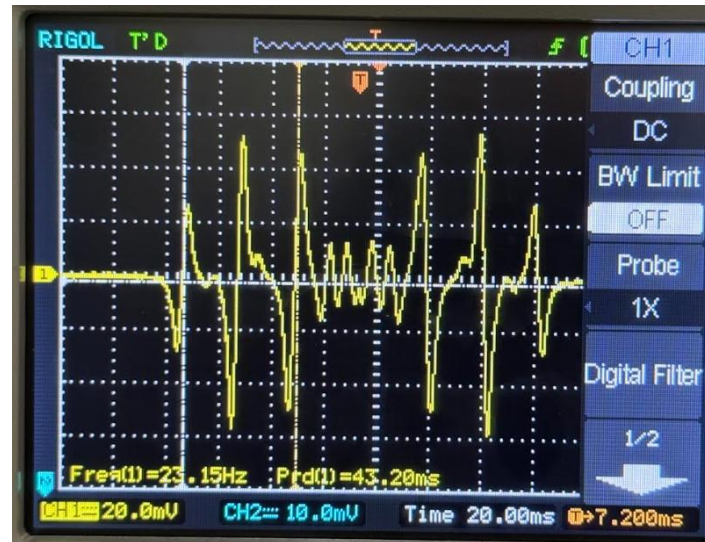
B-field at -5 mm: -10.37 G  
 B-field at +5 mm: 10.37 G  
 Gradient between  $\pm 5$  mm: 20.74 G/cm



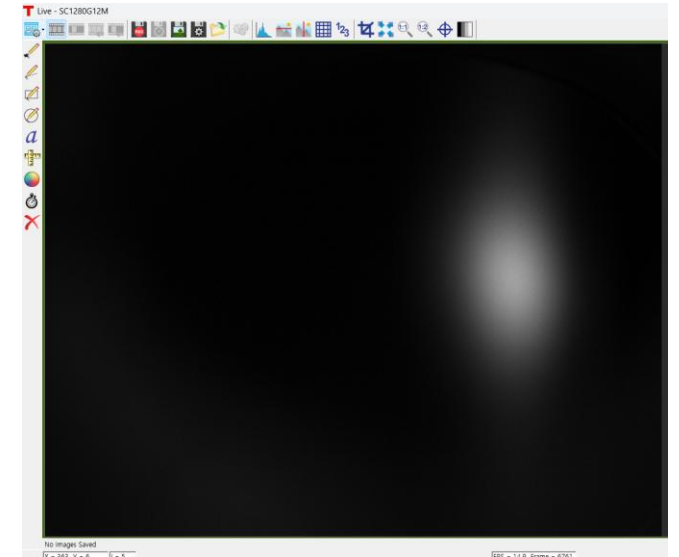
# Mobile Clock – Laser Setup



399nm Yb atom

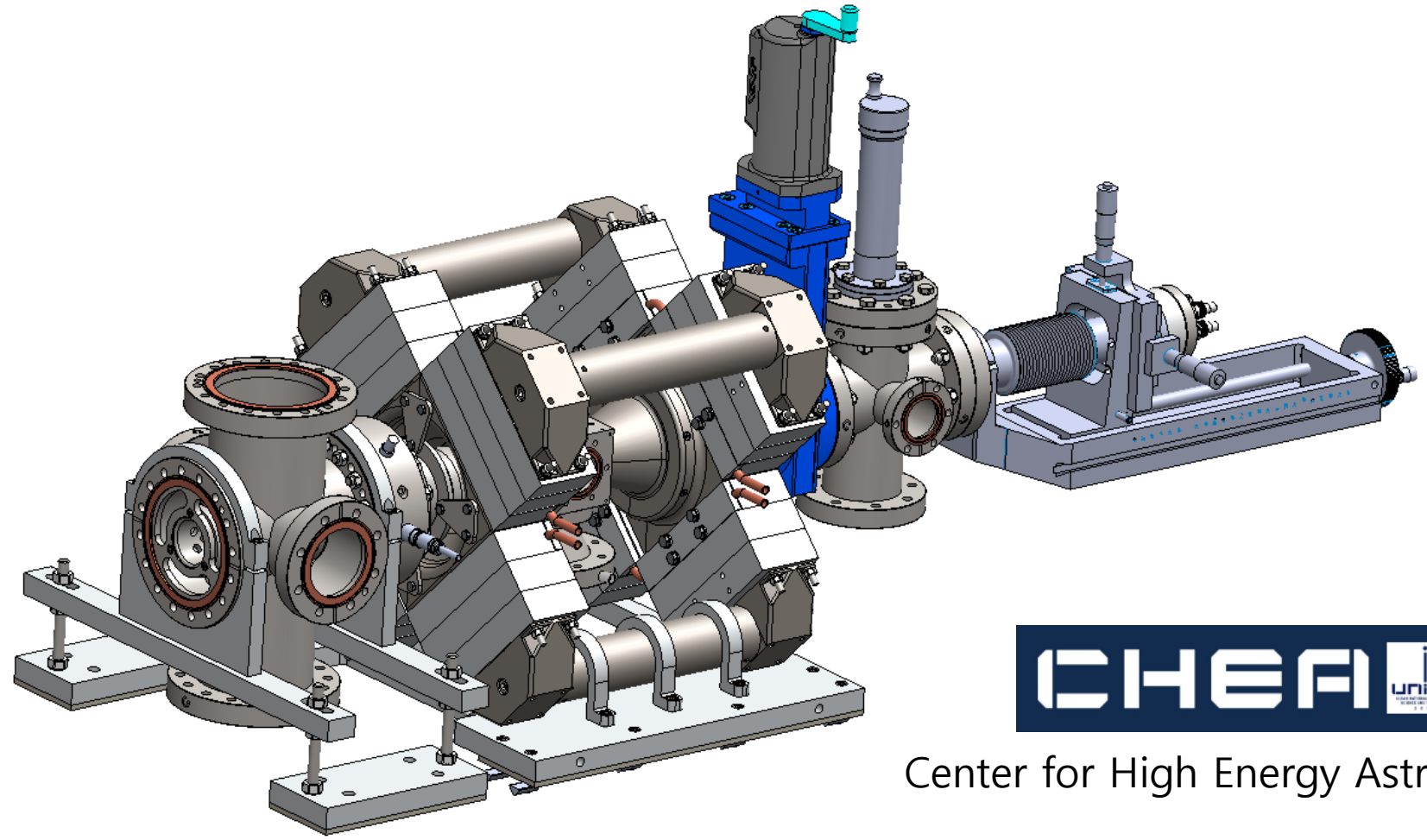
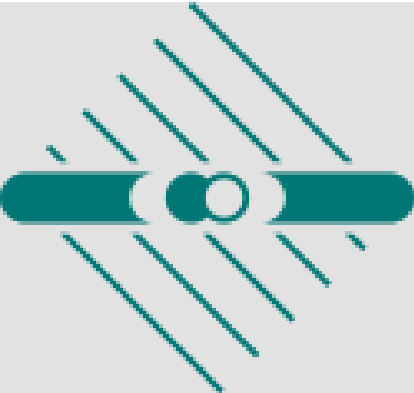


Error Signal



CCD Camera Image of Yb atoms

# UNIST-EBIT (Electron Beam Ion Trap)

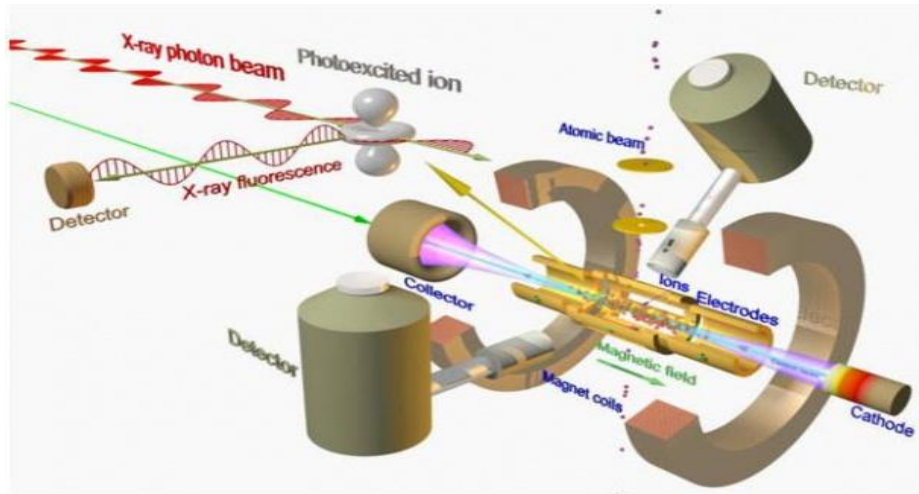


Center for High Energy Astrophysics

Max Planck Institute of Nuclear Physics

# What is Electron Beam Ion Trap?

- **Electron beam ion** sources and **trap**s(EBIS/Ts) are the device which create and study highly charged ions (HCIs) ([1] p1763)
- Distinction between EBISs and EBITs([1] p1763 – p1764)
  - EBISs are used to deliver ions to other experiments while
  - EBITs are used for in situ studies of the ions.

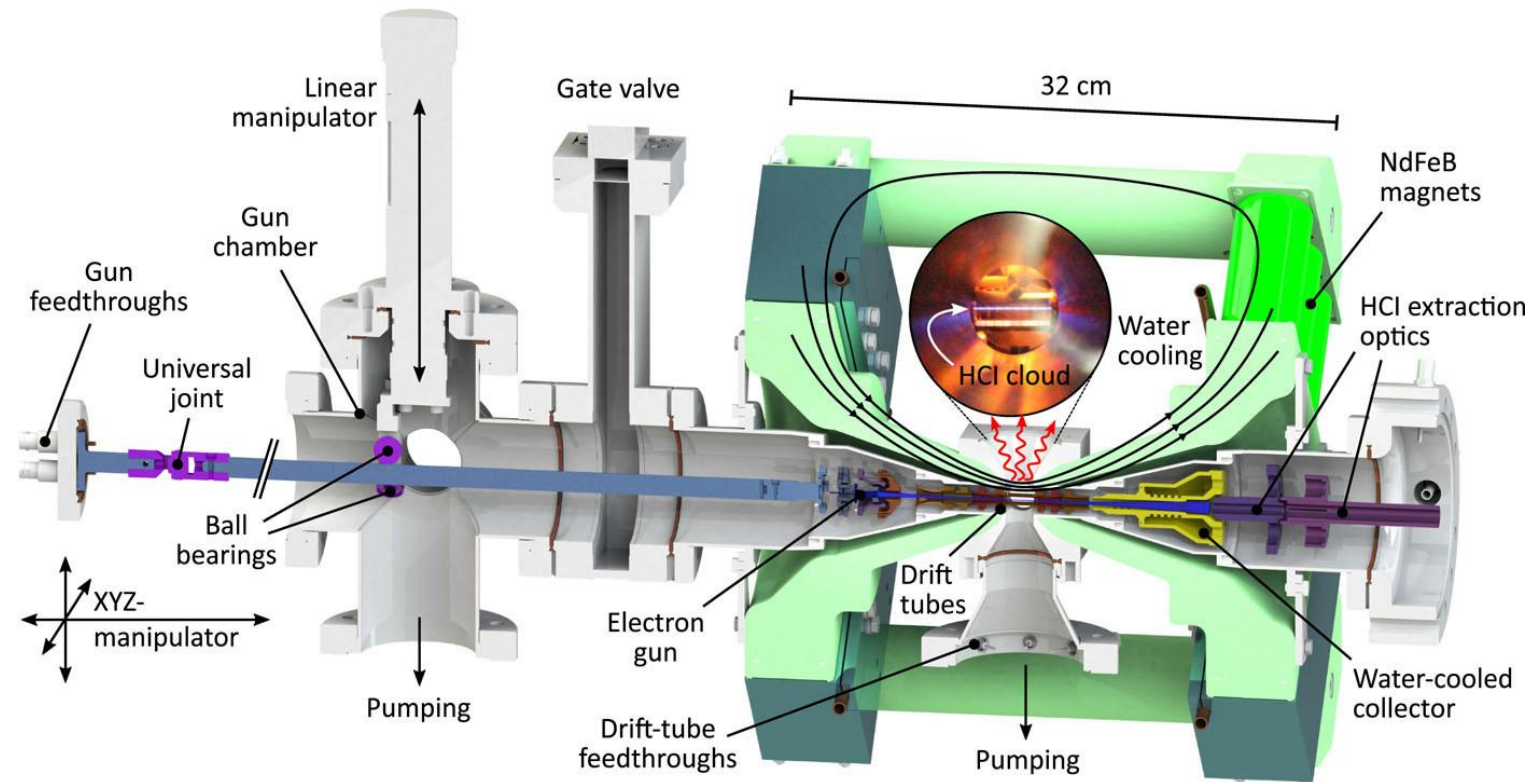


## Abbreviation

- EBIS – Electron Beam Ion Source
- EBIT – Electron Beam Ion Trap
- HCI – Highly Charged Ion

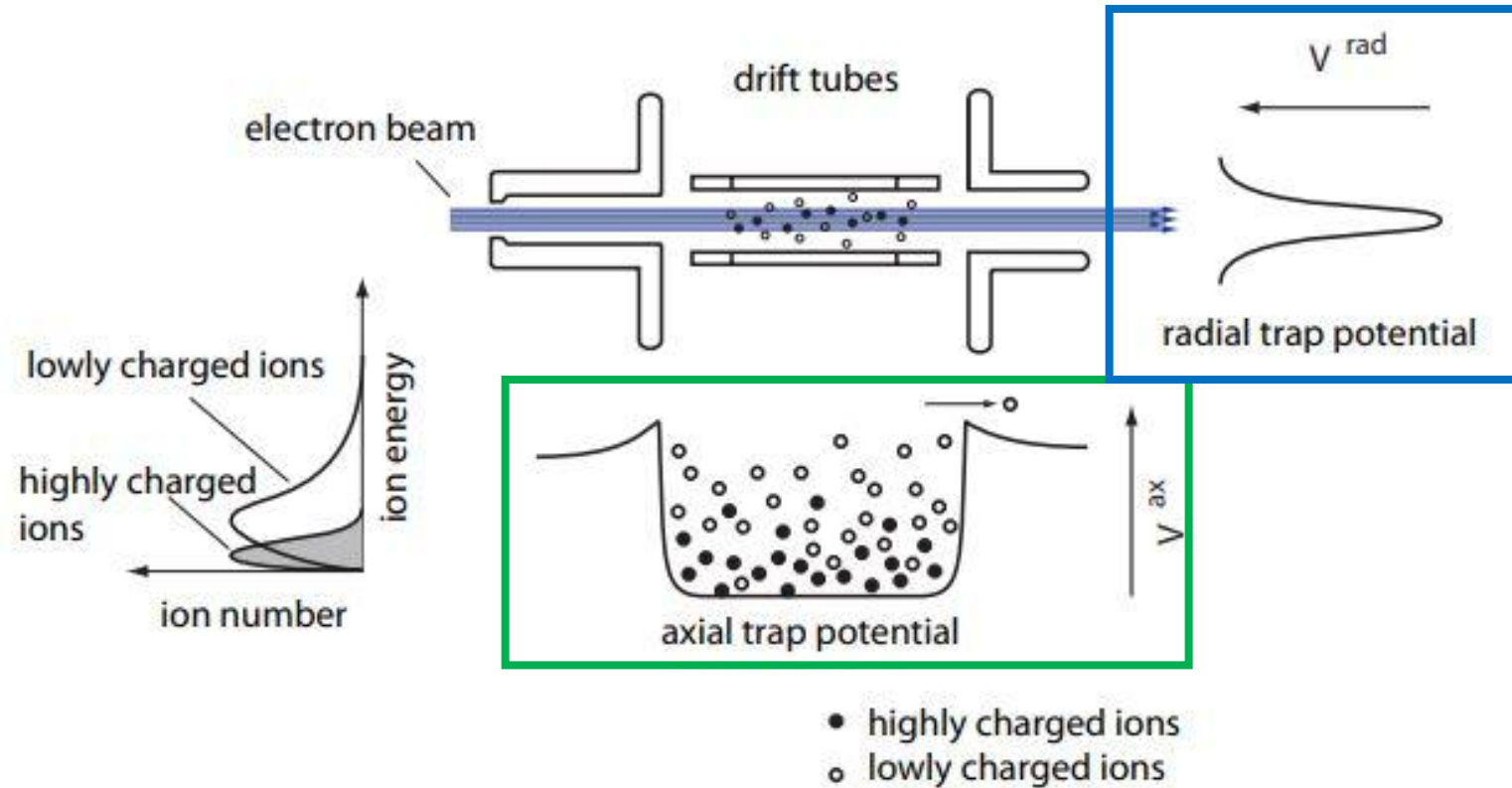


# Overview of UNIST-EBIT



- Low-maintenance
- Table-top
- Magnetic structure: 72 permanent magnets, soft iron/magnetic steel yoke
- 0.86T at trap center
- Tunable electron beam energy to 8 keV
- Electron beam current up to > 80mA
- Excellent optical access, opening angle of 58 degree

# Trapping the ions



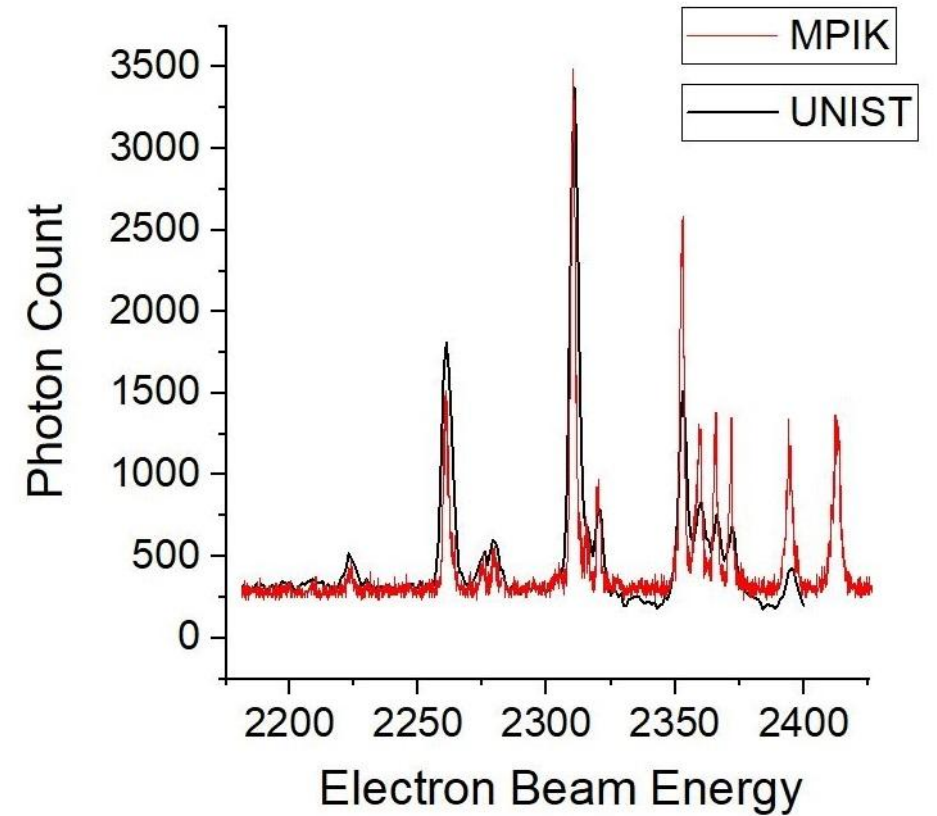
**Radial Trapping** – Space charge of the electron beam & **Axial Trapping** – Potential well by the drift tubes.



# UNIST-EBIT

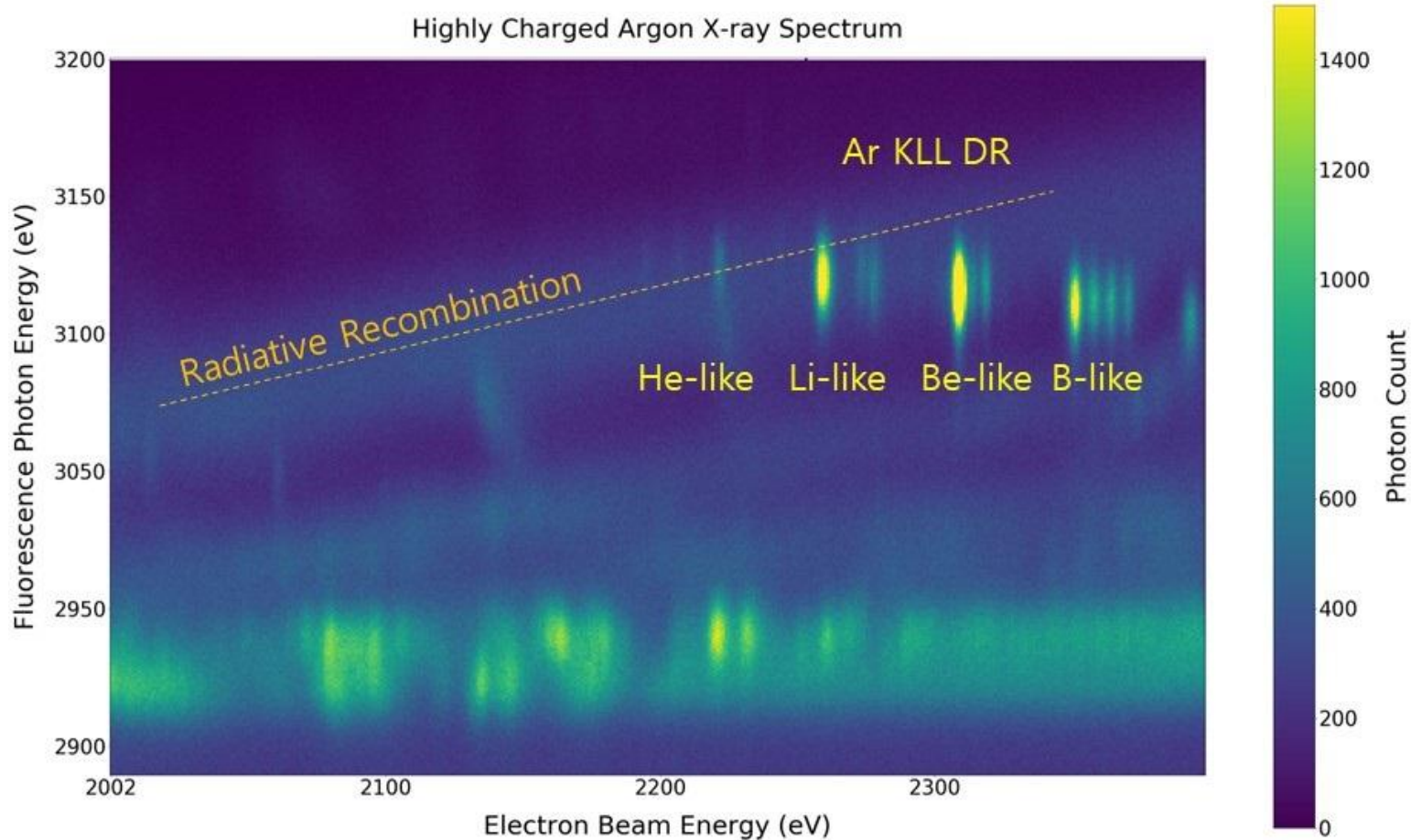


Highly Charged Argon Spectrum



UNIST EBIT Works!

# Highly Charged Argon Spectrum with the UNIST-EBIT



## KLL Dielectronic Recombination(DR)

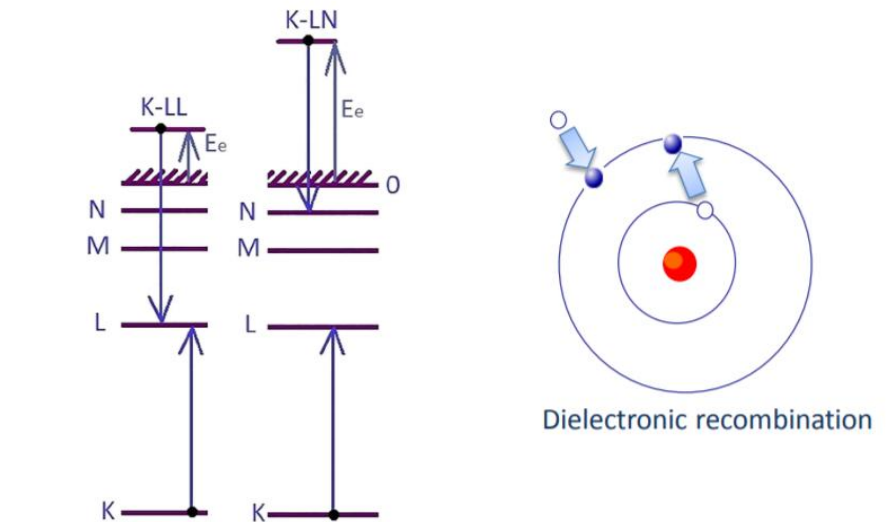


FIGURE 1 Examples of dielectronic recombination processes (K-LL, K-LN)

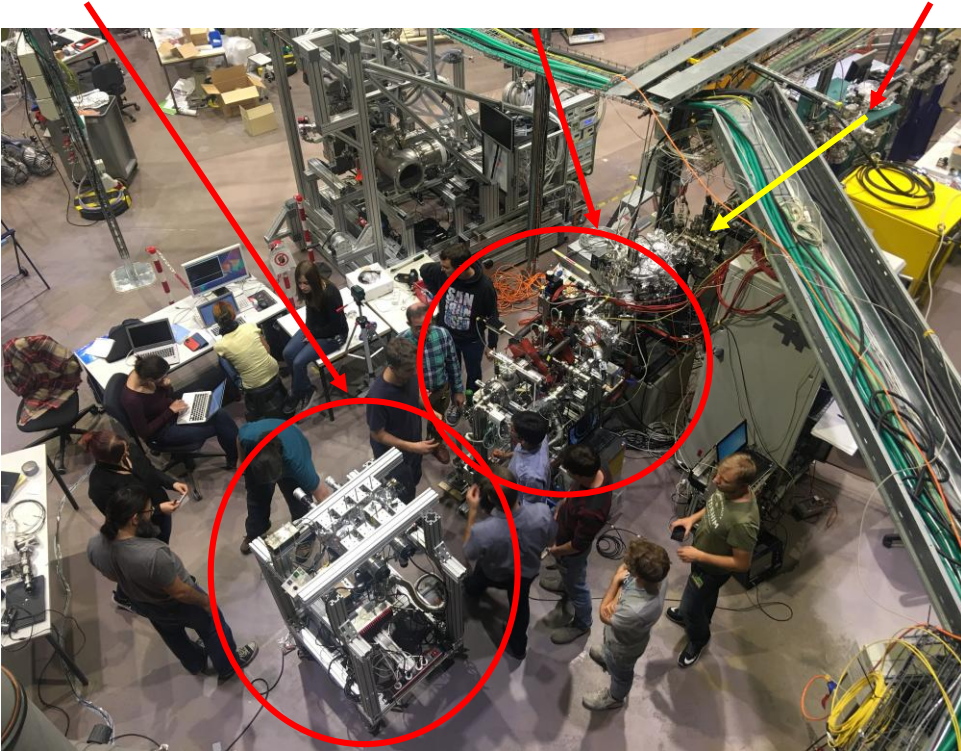


# Learning Laboratory Astrophysics

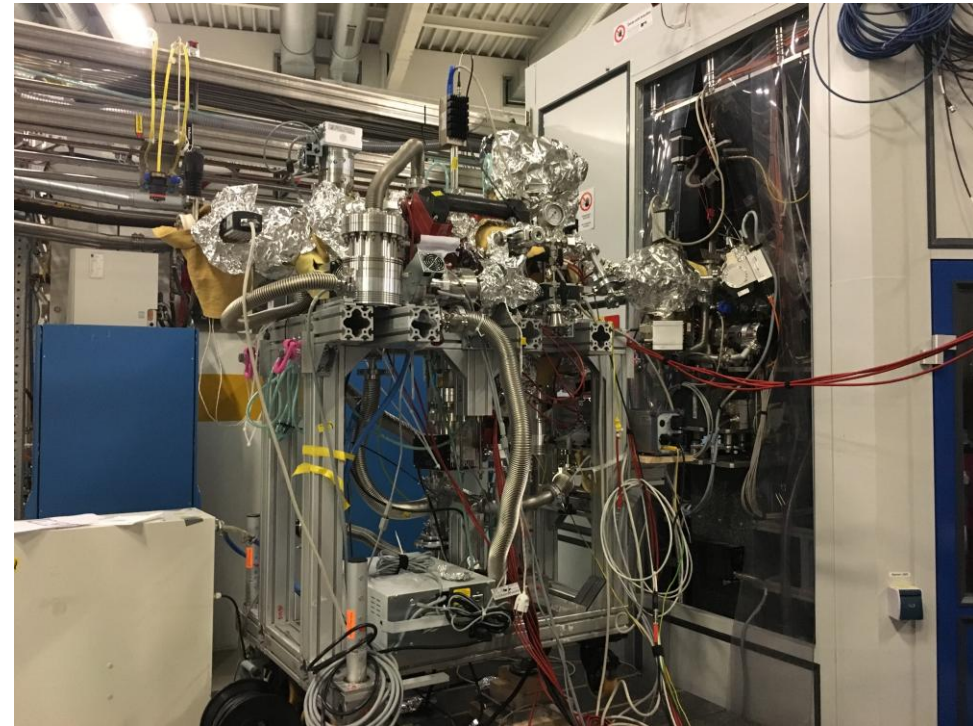
NASA gas cell

MPIK Polar-X EBIT

BESSYII Beamline



BESSY II Experiment 2017.10  
MPIK / NASA / LLNL ...



PETRAIII P04 Beamtime  
2018.11.29 – 2018.12.05

# PAL-XFEL Experiment

PAL-XFEL (Pohang Accelerator Laboratory X-ray Free Electron Laser)

[PAL-XFEL Beam Times: 2022.01.26 ~ 2022.01.27 2 shift(12hours) x 2 days(10:00 ~ 22:00)]



| Parameter                            | Unit    | Value   |
|--------------------------------------|---------|---|
| Electron beam energy                 | GeV     | $\leq 10.0$   |
| Photon energy                        | keV     | 2.2 – 15  |
| Energy bandwidth                     |         | $< 0.4\%$   |
| Pulse duration                       | fs      | 25 (FWHM)   |
| Photons per pulse                    | #/pulse | $> 1.0 \times 10^{11}$  |
| Repetition rate                      | Hz      | 60  |
| X-ray beam size<br>(at XSS beamline) |         | $\sim 300 \mu\text{m} \times 300 \mu\text{m}$ (unfocused) @ 9.7 keV<br>$\sim 10 \mu\text{m} \times 10 \mu\text{m}$ (focused by beryllium CRL) |
| Minimum undulator gap                | mm      | 8.30  |
| Undulator period                     | mm      | 26.0  |
| Undulator length                     | m       | 5.0   |
| Effective B-field                    | T       | 0.812   |
| Undulator parameter ( $K$ )          |         | 1.973   |
| Phase jitter                         | deg     | $< 7.0$   |
| Number of undulators                 |         | 20  |



# PAL-XFEL Beamline Experiment (Movement)



Package of the EBIT (UNIST)



5-ton Truck (Due to the Rack height)

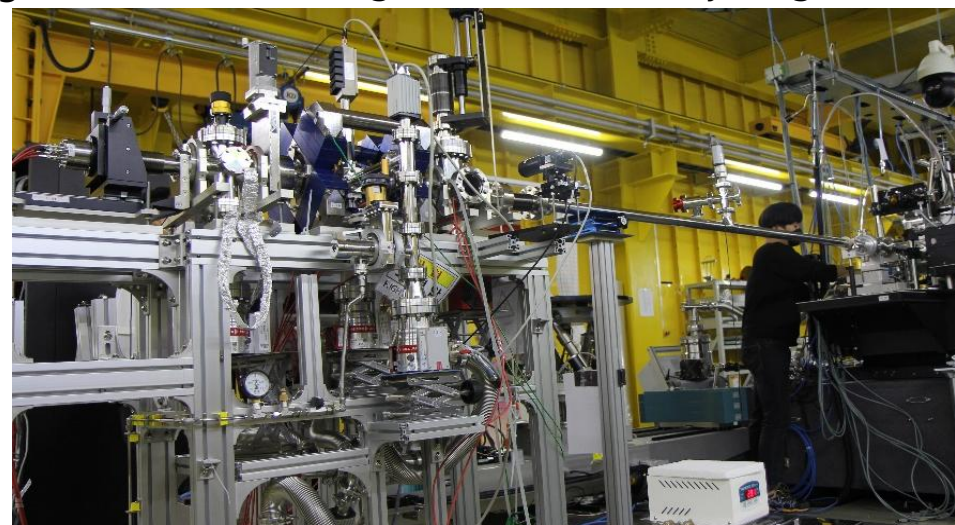


Package of the EBIT (everything)



2025-07-15

Vacuumize + E-gun Heating

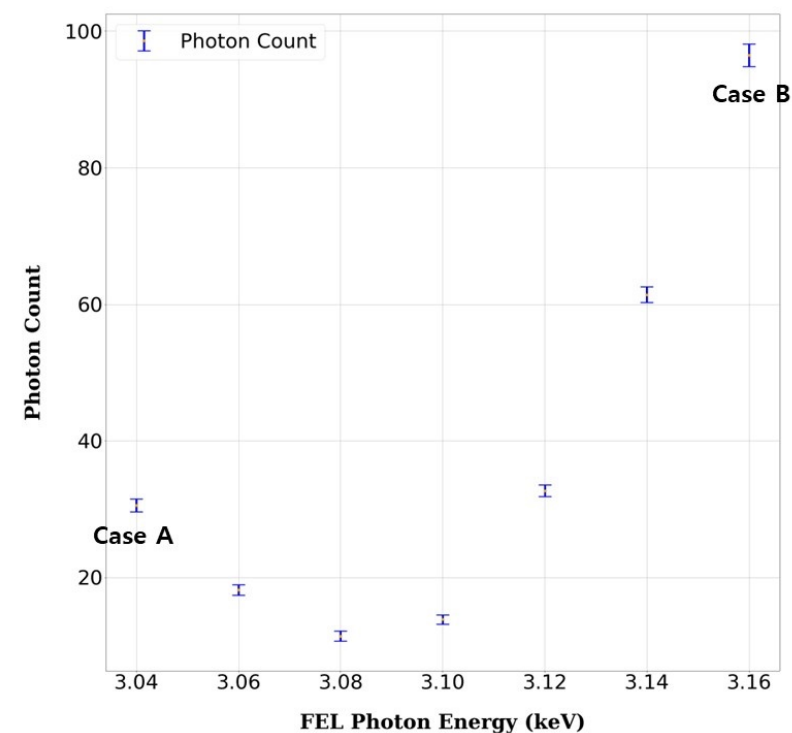
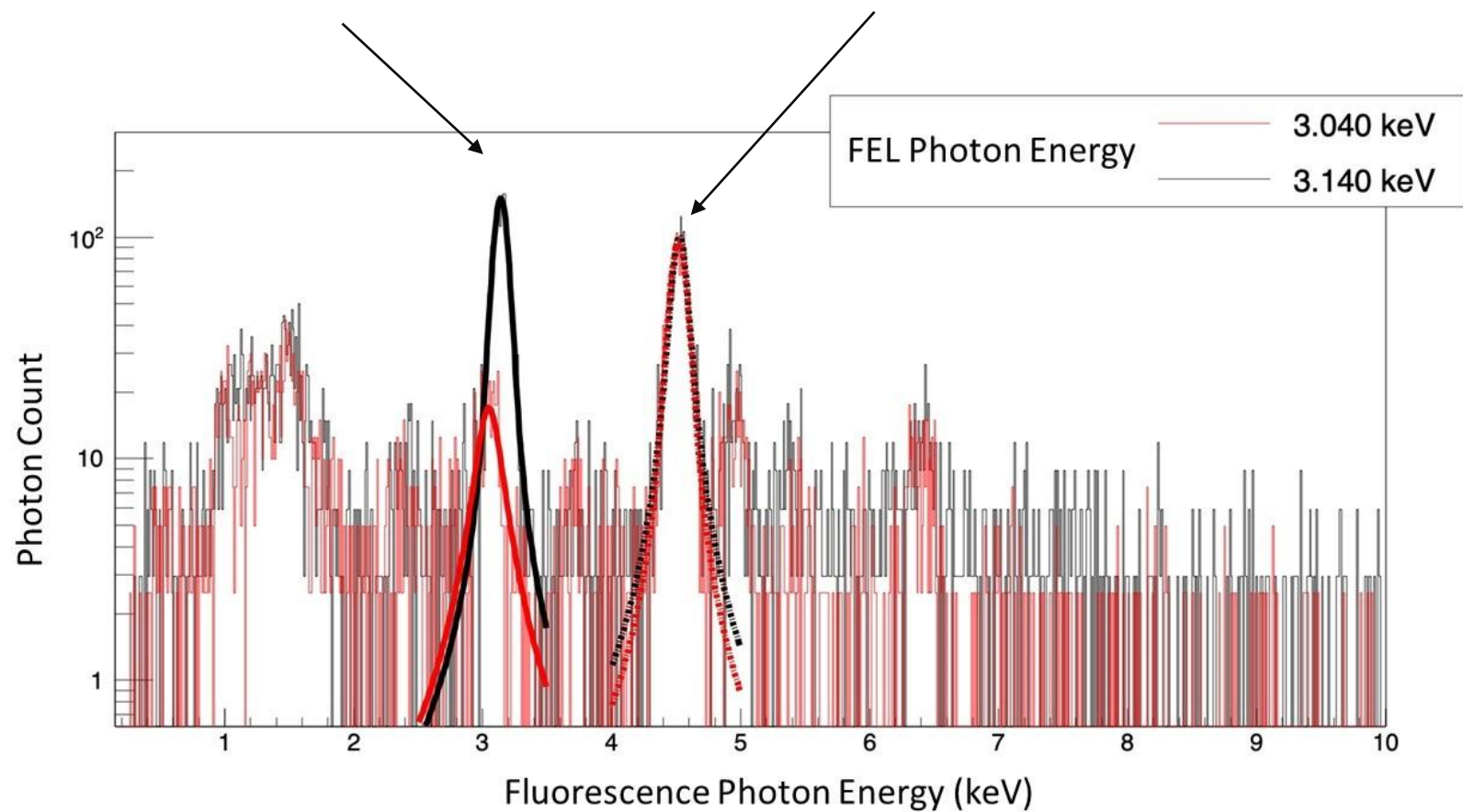


Connection to the PAL-XFEL Beamline

# PAL-XFEL Beamline Experiment

Highly Charged Argon Fluorescence

Titanium Line





# Future Vision

|          |  |
|----------|--|
| 연구주제     | <p>고전리 이온 연구팀</p> <ol style="list-style-type: none"> <li>1) EBIS system 확장 (이온원)</li> <li>2) 이온 트랩 (정지 이온)</li> <li>3) 양자 공정 빔 라인 (저에너지 이온)</li> <li>4) 우주 방사선 (고에너지 이온)</li> </ol> <p>비고: Th 원자시계 연구도 가능 (Trap 방식, 타겟 방식 등)</p>   |
| 연구목표     | <p>고전리 이온 기초연구 수행</p> <ol style="list-style-type: none"> <li>1) EBIS system의 안정성을 위한 back-up system + R&amp;D 용도를 위한 추가적인 EBIS 개발. → 미국 FRIB처럼 빔 전류 상승용도 [1]</li> <li>2) Isotope shift 등과 같은 기초 과학 연구 [2-3]</li> <li>3) 중이온가속기만 가능한 고전리 이온 양자 공정 빔라인 [4]</li> <li>4) 해외 의존도를 줄이는 국내 중이온 우주 방사선 빔 라인</li> </ol>                               |
| 배경 및 필요성 | <p>고전리 이온에 대한 이해도가 증가하며 산업에서도 고전리 이온을 활용한 기술개발이 하나둘씩 확장하는 중이다. 대표적으로 국내 대기업도 구하지 못하는 ASML의 노광장비는 고전리 이온에서 빛을 만들어낸다. 이 밖에 암 치료에도 피폭 방사선을 줄이는 용도로 고전리 이온이 사용된다. 최근에는 양자 공정에 관한 연구들이 해외에서 진행 중이며, 우주 반도체 테스트를 위해서도 고전리 이온은 필수적이다. 표준과학연구원의 광시계 그룹에 오게 된 이유도 고전리 이온은 차세대 원자시계 후보 중 하나이기 때문이다. [5] 이에 고전리 이온 연구에 대한 투자도 국가가 고려해 볼 수 있다고 생각한다.</p> |

|             |  |
|-------------|--|
| 아이디어명       | 우주방사선 표준 실험을 위한 국산 중이온 방사선 시험 인프라 개발 전략  |
| (대표) 제안자    | 박 성 남  |
| 배경 및 필요성    | <p>○ 우주 활동의 확대와 함께 우주방사선의 영향에 대한 연구 필요</p> <ul style="list-style-type: none"> <li>- JEDEC JESD57 <ul style="list-style-type: none"> <li>* 반도체 소자의 단일입자효과(SEE) 방사선 영향 평가</li> </ul> </li> <li>- ESCC21500 (ESA) <ul style="list-style-type: none"> <li>* 유럽 우주 부품의 신뢰성 확보를 위한 방사선 시험 기준</li> </ul> </li> <li>- MIL-STD-883, Method 1019.7 <ul style="list-style-type: none"> <li>* 미 국방성 우주전자기기용 방사선 시험 기준</li> </ul> </li> </ul> |
| 현황 및 문제점    | <p>2022년 2월 8일, SpaceX Starlink 위성 49기 중 40기 손실<br/> → 원인: 태양 폭풍에 따른 지구 대기 팽창 및 저궤도 위성 궤도 이탈<br/> → 참조 논문: "How Geomagnetic Storms Affect the Loss of Starlink Satellites in February 2022?" (2025.1.13)</p> <ul style="list-style-type: none"> <li>- 국내 중이온 기반 우주방사선 실험 인프라 부재</li> <li>→ 세트렉아이, QRT 등 민간기업 모두 해외 시험에 의존</li> </ul>   |
| 추진방안 및 계획   | <p>완성된 고전리 이온원(EBIT) 기반 인프라 단계적 확장</p> <ul style="list-style-type: none"> <li>- 1차 확장 (~3억): 이온 전하 상태(charge state) 분리 기술 구현</li> <li>- 2차 확장: 가속관 도입 → 고에너지 중이온 빔 생성 가능</li> </ul>  |
| 활용방안 및 기대효과 | <p>○ 고전리 이온 연구 인프라 확보</p> <ol style="list-style-type: none"> <li>1. 차세대 원자시계 연구</li> <li>2. 기초과학 및 핵·물리 연구</li> <li>3. 반도체 리소그래피</li> <li>4. 양자 공정 기술 개발</li> <li>5. 우주 방사선 평가</li> </ol>  |

# Future Vision

출연(연) 박사후연구원 연수성과 공모전 <창의도전형 연구아이디어> 부문 발표 일정을 아래와 같이 안내드리오니

대표제안자께서는 발표심사 당일 늦지 않도록 협조 부탁드립니다.

○ 대표제안자: 한국표준과학연구원 박성남(개인)

○ 일시: 2025.7.24.(목), 15:40~15:55

- 15:40~15:50(10분): 발표

- 15:50~15:55(5분): 질의·응답

○ 대기장소: 세종국책연구단지 연구지원동(A동) 2층 화상회의실1

\* 발표시간 30분 전에 대기장소 도착 필수

## 창의도전형 연구아이디어 제안서(본문)

| 아이디어명    | 우주방사선 표준 실험을 위한<br>국산 중이온 방사선 시험 인프라 개발 전략   |
|----------|--|
| (대표) 제안자 | 박 성 남  |
|          | <p>○ 우주 활동의 확대와 함께 우주방사선의 영향에 대한 연구 필요</p> <p><b>배경 및 필요성</b></p> <p>우주방사선 중 HZE(고질량, 고에너지) 이온은 전체의 1%에 불과하지만, Single Event Effect(SEE)를 유발해 위성 시스템에 영구적 손상을 초래</p> <p>Noise on SOHO/LASCO imager during Nov. 8-9, 2000 solar particle event (Credit: NASA Electronics Parts &amp; Packaging Program)</p> <ul style="list-style-type: none"> <li>- JEDEC JESD57 <ul style="list-style-type: none"> <li>* 반도체 소자의 단일입자효과(SEE) 방사선 영향 평가</li> </ul> </li> <li>- ESCC21500 (ESA) <ul style="list-style-type: none"> <li>* 유럽 우주 부품의 신뢰성 확보를 위한 방사선 시험 기준</li> </ul> </li> <li>- MIL-STD-883, Method 1019.7 <ul style="list-style-type: none"> <li>* 미 국방성 우주전자기기용 방사선 시험 기준</li> </ul> </li> </ul> <p><b>현황 및 문제점</b></p> <p>현행 우주방사선 표준은 중이온 기반 시험을 필수로 규정</p> <p>○ 2022년 2월 8일, SpaceX Starlink 위성 49기 중 40기 손실<br/>→ 원인: 태양 폭풍에 따른 지구 대기 팽창 및 저궤도 위성 궤도 이탈<br/>→ 참조 논문: "How Geomagnetic Storms Affect the Loss of Starlink"</p> |