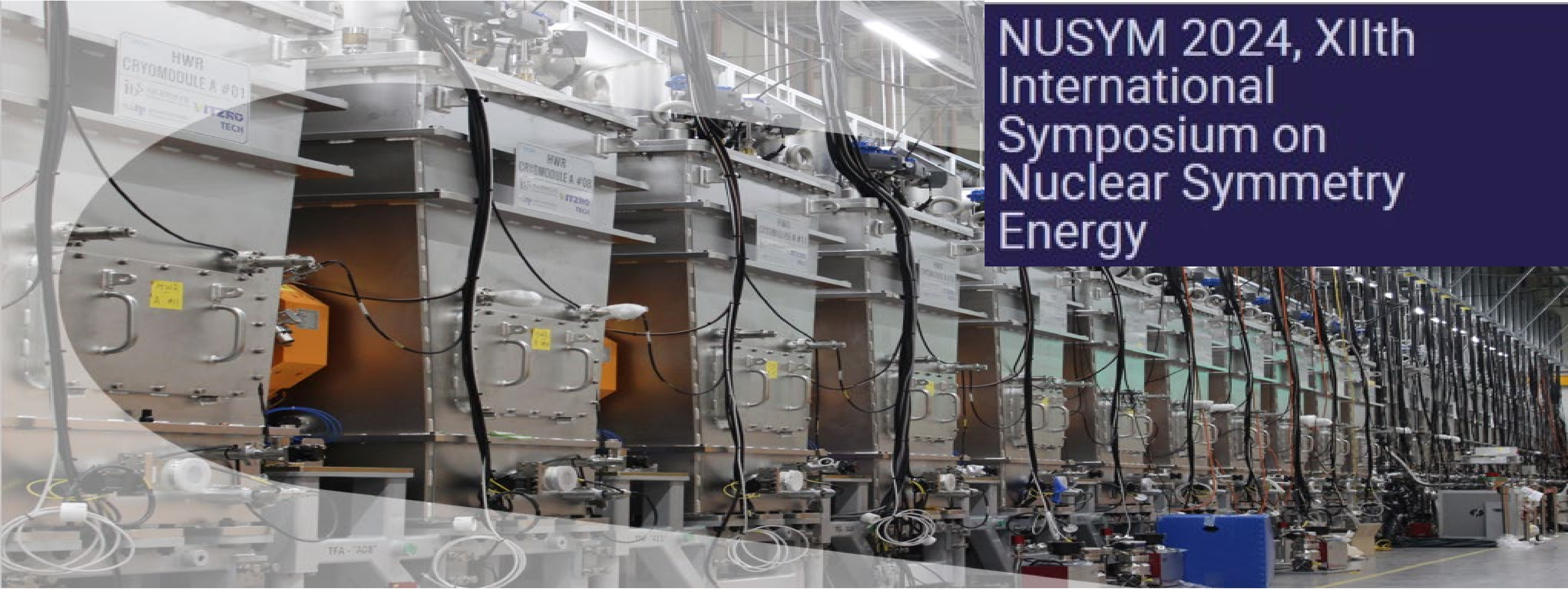

NUSYM 2024, XIIth International Symposium on Nuclear Symmetry Energy

iRIS Institute for Rare Isotope Science

Status of the RAON Facility

Taeksu Shin
Institute for Rare Isotope Science, IBS

Sep 11, 2024 at CAEN

RAON (Rare isotope Accelerator complex for ON-line experiments)

RAON

Accelerator complex
ISOL + In-Flight Fragmentation

Origin of Matter

- Nuclear Astrophysics
- Nuclear Matter
- Super Heavy Element Search
- High-precision Mass Measurement

Properties of Exotic Nuclei

- Nuclear Structure
- Electric Dipole Moment and Symmetry
- Hyperfine Structure Study

Applied Sciences

- Bio-Medical Sciences
- Material Sciences
- Neutron Science

Rare Isotope Accelerator complex

1. Cyclotron for ISOL
2. Superconducting Linac for Post-acceleration of RIB and In-Flight Fragmentation

Brief History of RAON : RISP and IRIS

Institute for Rare Isotope Science

2011~
2023

2011

- '11.02 Conceptual Design Report(CDR)
- **'11.12 Rare Isotope Science Project(RISP) Launched**
- '13.09 Technical Design Report (TDR)
- '14.02 Contract of Purchasing Land, Shindong

2015

- '16.12 RFQ Ion Bean Extracted
- '17.02 Civil Construction Project Started
- '17.06 Ground Breaking Eng. Completed
- '19.04 Move RISP office in Shindong Site
- '19.09 1st SRC Cryomodule Installed(QWR)

2019

2023

- '20.09 Completed QWR Installation
- '21.06 RAD Safety Permission Acquired
- **'22.07 Institute for Rare Isotope Science(IRIS) begin**
- '22.12 Completed Stage-1 of RISP
- **'23.05 Commission of SCL3 Accelerator**
- '23.12 Call for Proposals

RAON Rare Isotope Accelerator Complex

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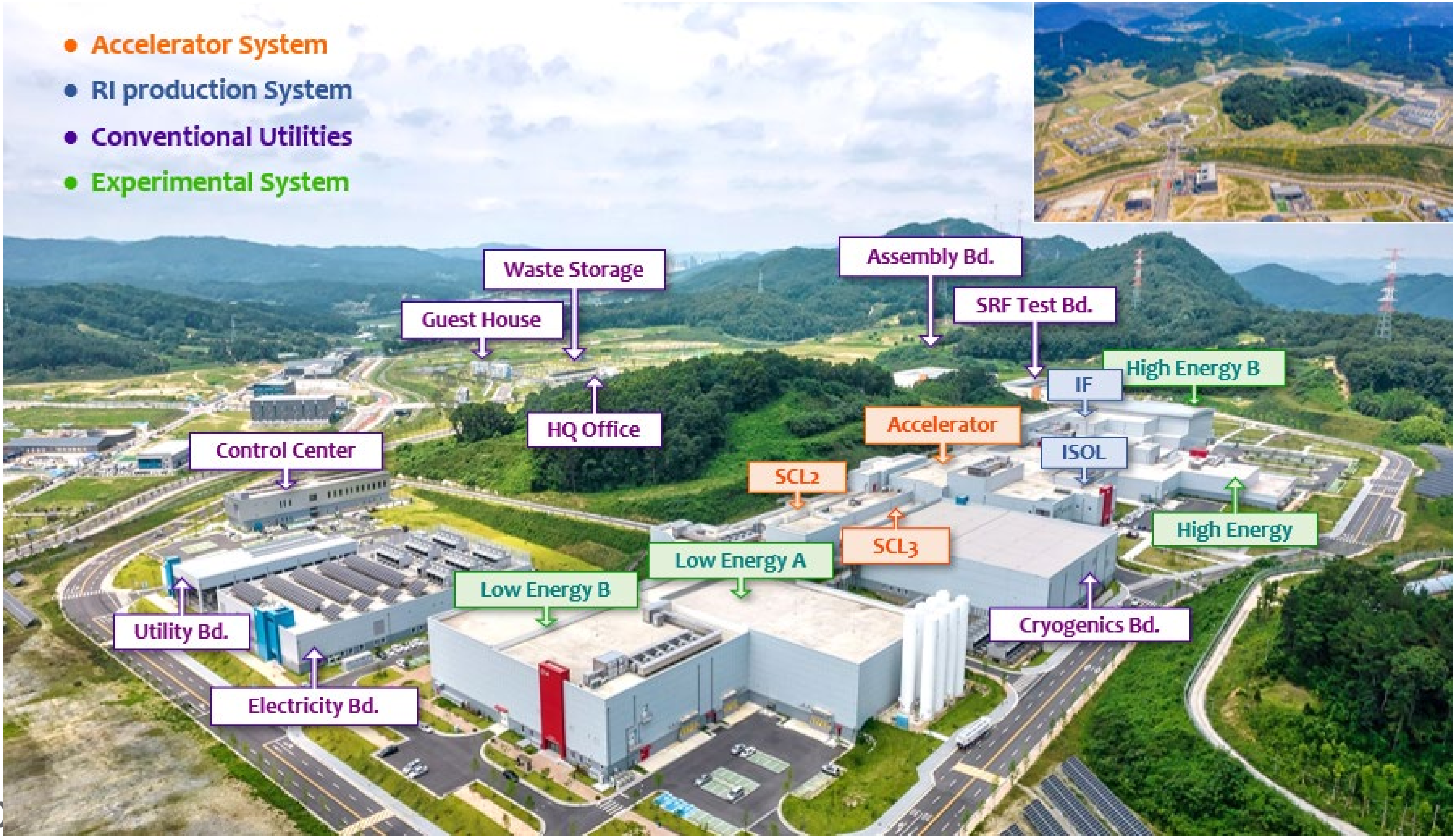
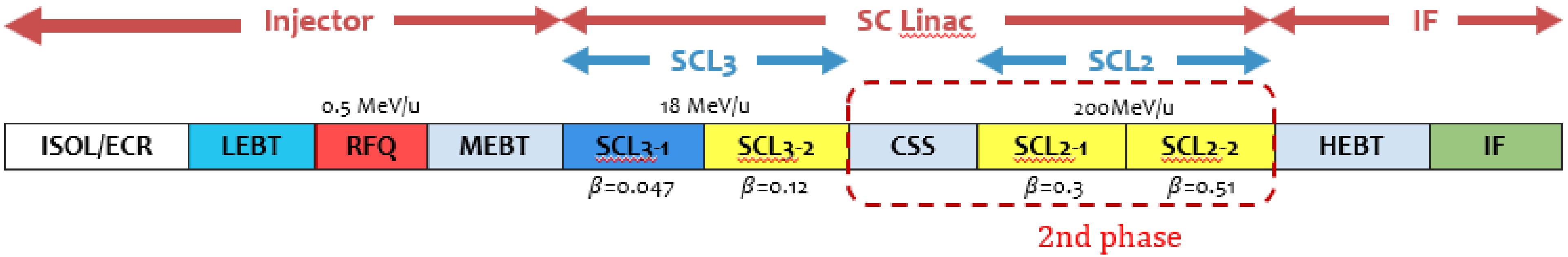
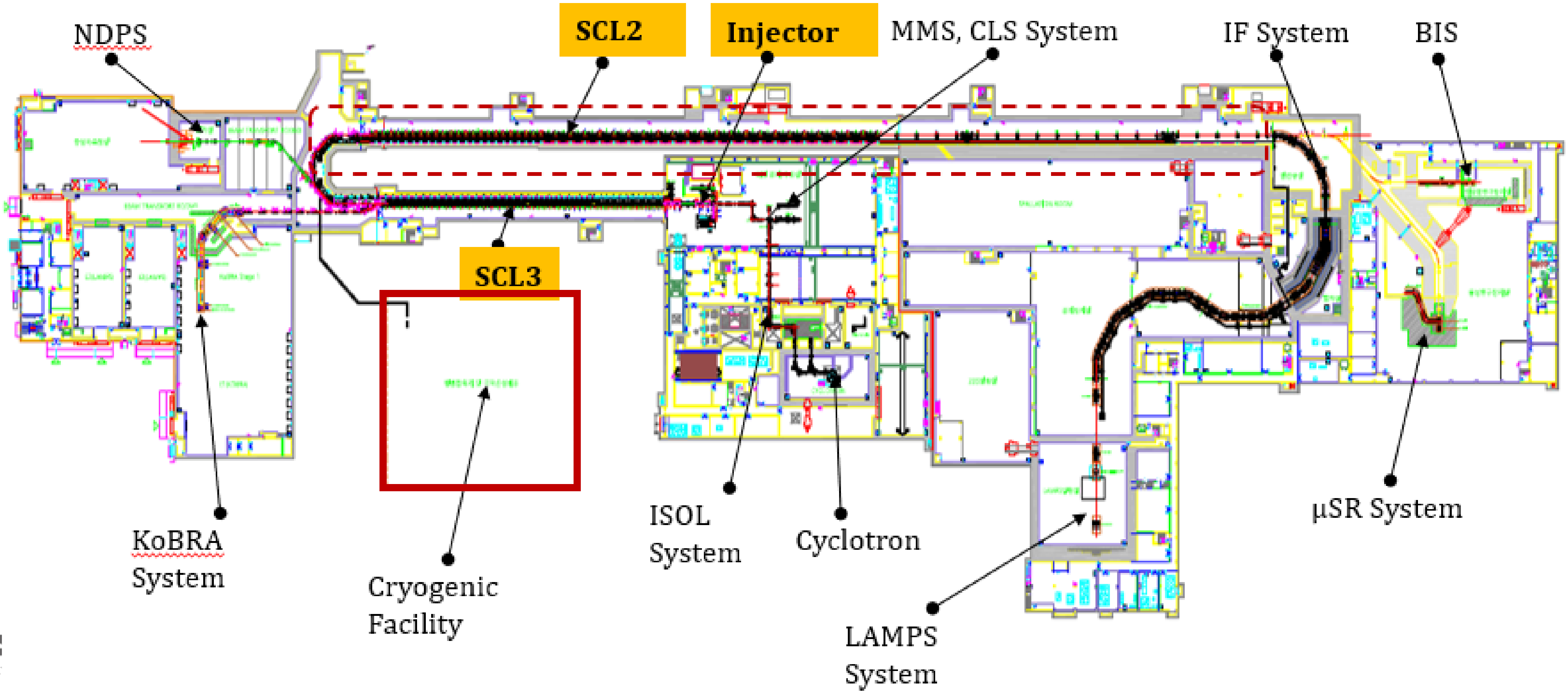


Accelerator





Accelerator: SCL2 & SCL3

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Injector | SC Linac | IF

SCL3 | SCL2

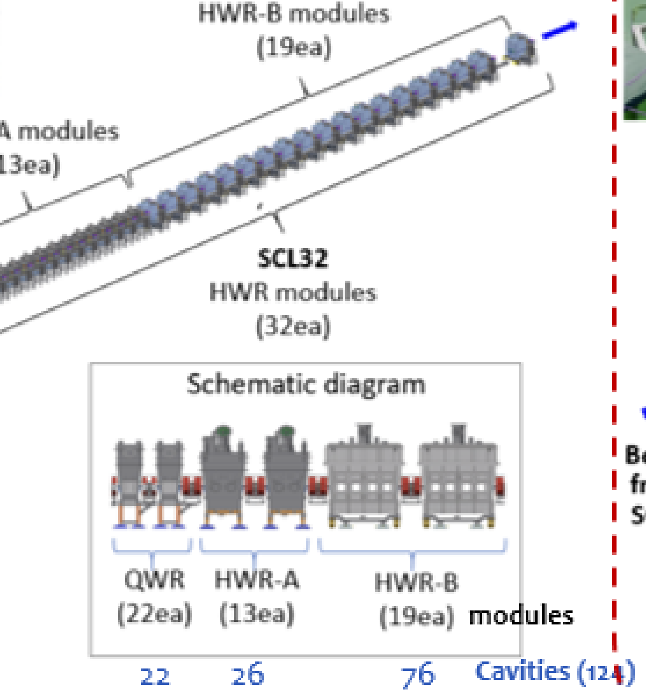
0.5 MeV/u | 18 MeV/u | 200MeV/u

ECR	LEBT	RFQ	MEBT	SCL31	SCL32	CSS	SCL21	SCL22	HEBT	IF

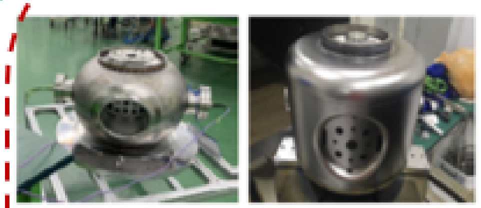
ISOL → LEBT

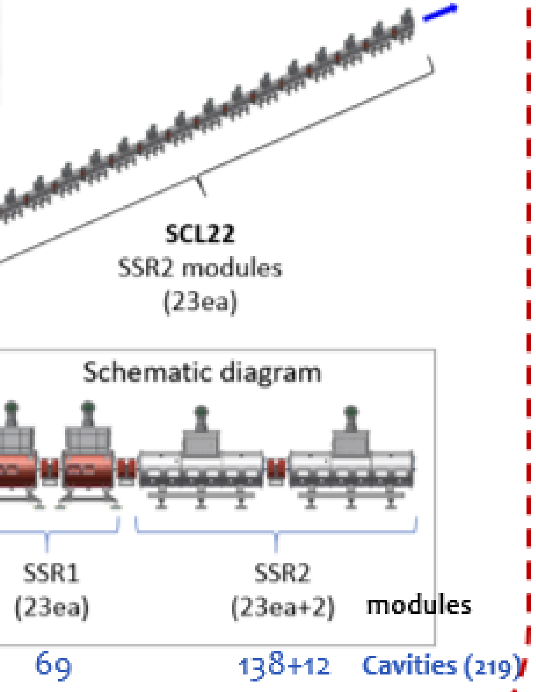
2nd phase

SCL3



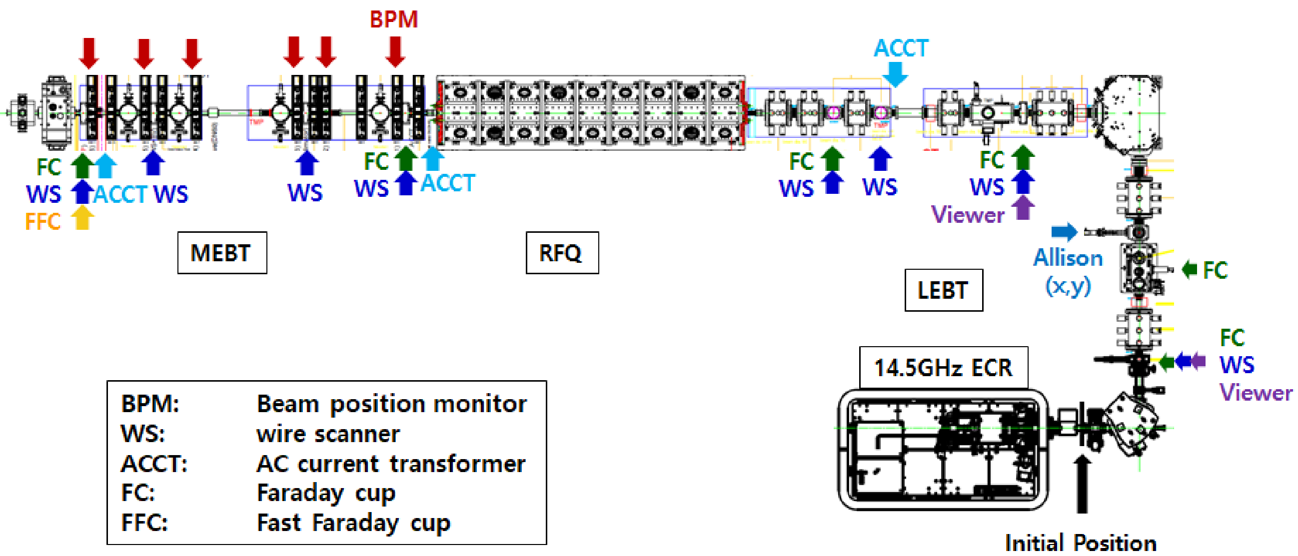
SCL2



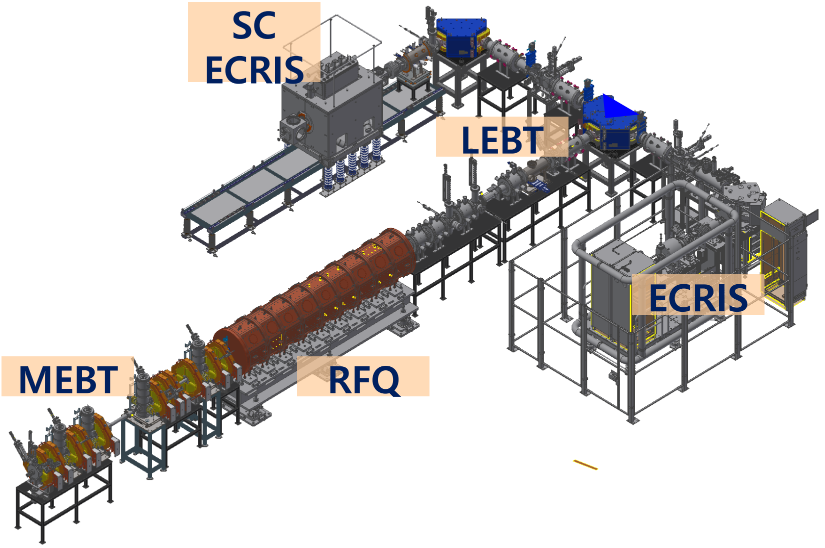


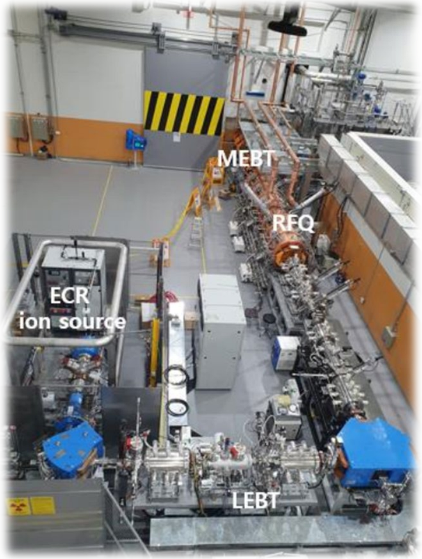
Accelerator: Injector

- **Two ECR-IS on high voltage platforms**
  - 14.5 GHz ECR ion source
  - 28 GHz superconducting ECR ion source
- **LEBT (E = 10 keV/u)**
  - 10 keV/u, Dual bending magnet
  - Chopper & Electrostatic quads, Instrumentation
- **RFQ (E = 500 keV/u)**
  - 81.25 MHz, Transmission Eff. ~98%
  - CW RF Power 94 kW (SSPA: 150 kW)
- **MEBT (E = 500 keV/u)**
  - Four RF bunchers (SSPA: 20, 15, 2×4 kW)
  - Simple quadrupole magnets, Instrumentation



[Beam Diagnostics in injector]





Ion	Argon	Neon	Oxygen	Helium	Proton
A (Q)	40 (8, 9, 11)	20 (4)	16 (6)	4 (2)	1(1)
Current [μA]	50, 30, 50	40	40	50	50 ~ 160

- Injector: 14.5 GHz ECR (10keV/u),
  LEBT (charge selection, matching),
  RFQ (507 keV/u, 98% transmission),
  MEBT (matching)
- Injector beam commissioning:

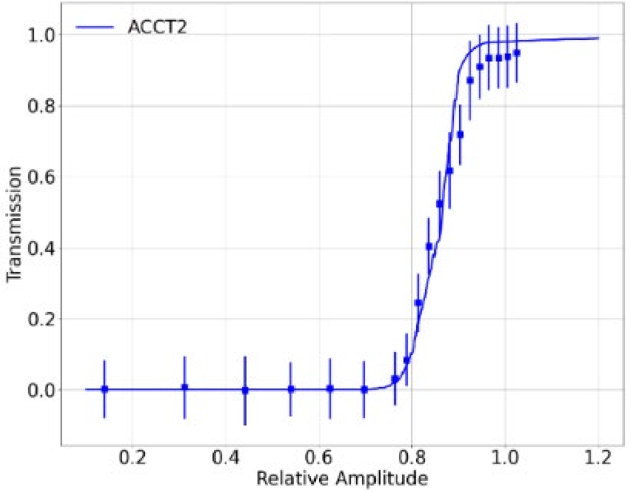
Accelerator: RFQ

- RFQ set point: beam transmission measured by ACCT in LEBT and MEBT.
  - Low RFQ transmission for Ne beams ⇒ main issue in injector beam commissioning with Ne beams
  - Different set values for the same A/Q (Ar8+, Ne4+): Need more study

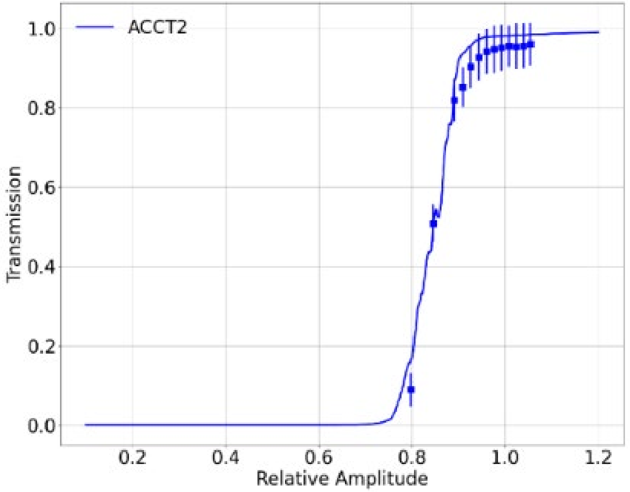
[Installed RFQ and MEBT]

	Ar(Q=9)	Ar(Q=8)	Ne(Q=4)
Transmission	**93.4%**	**95.4%**	**85.7%**
RF set value	**51.5 kW**	**62.9 kW**	**67.4 kW**

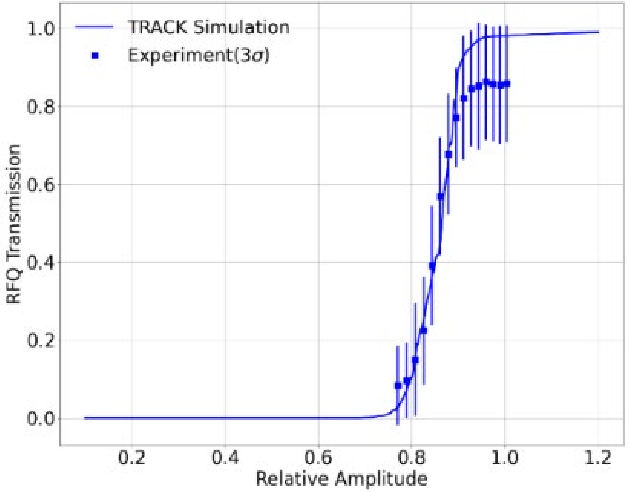
[RFQ set-point for Ar (9+)]



[RFQ set-point for Ar (8+)]



[RFQ set-point for Ne (4+)]



Cryoplants

- SCL3 cryoplant (4.2 kW @ 4.5 K)

Compressors and Oil Removal System (WCS)

Cold Box(CB)

- SCL2 cryoplant (13.5 kW @ 4.5 K)

Compressors and Oil Removal System (WCS)

Cold Box (CB)
(Left warm side, right – cold side)

Accelerator: QWR & HWR for SCL3

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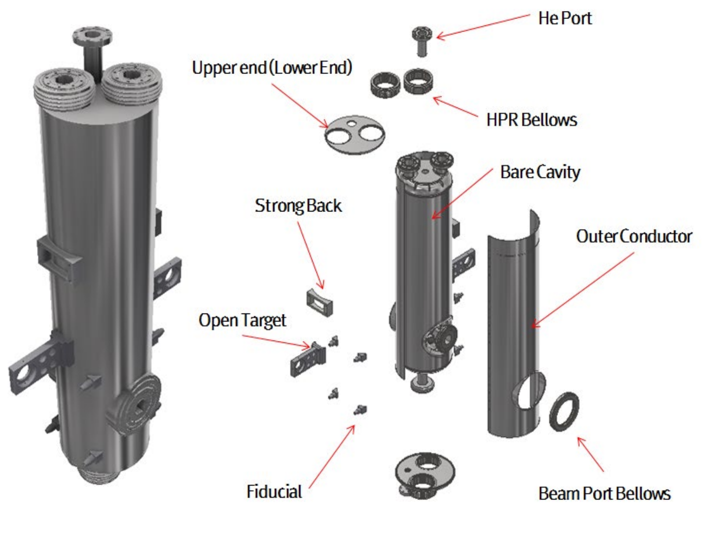

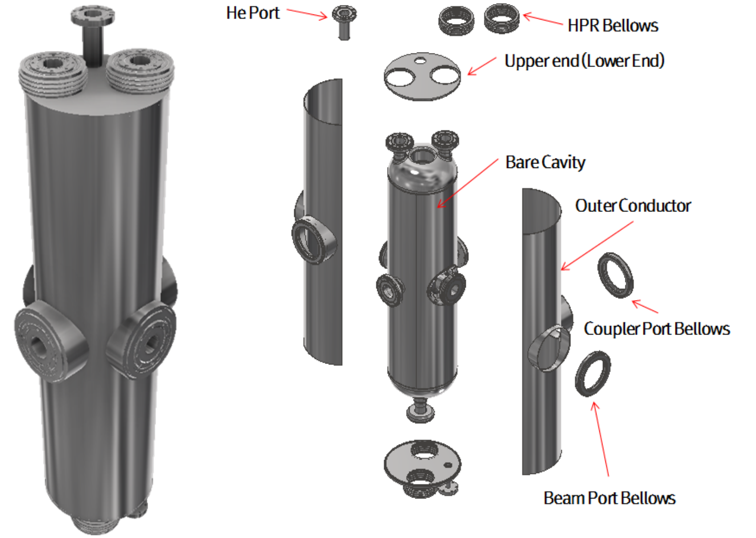

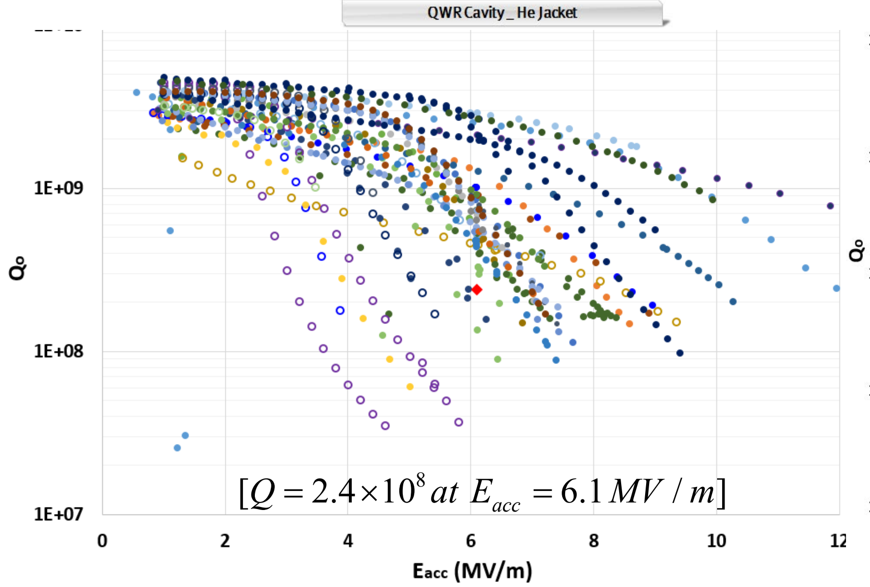

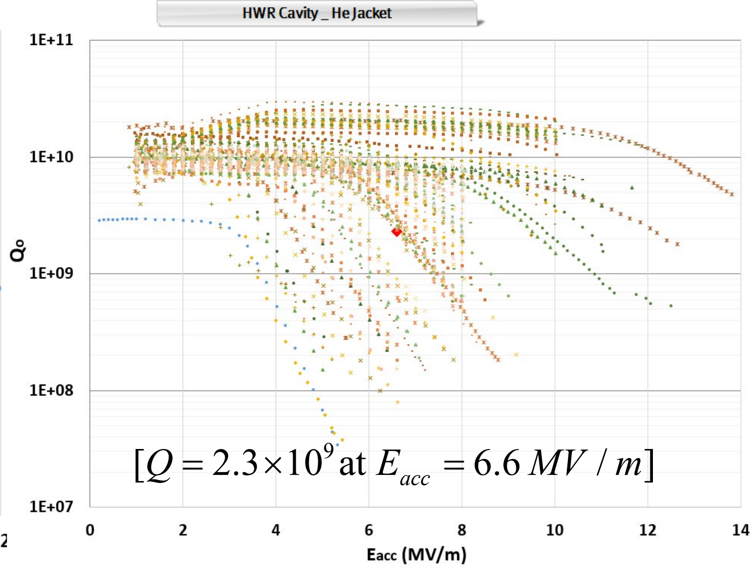

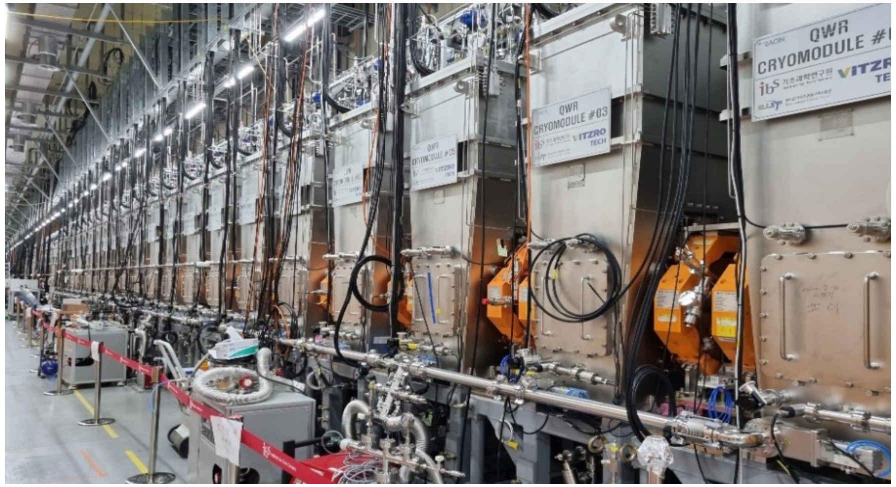

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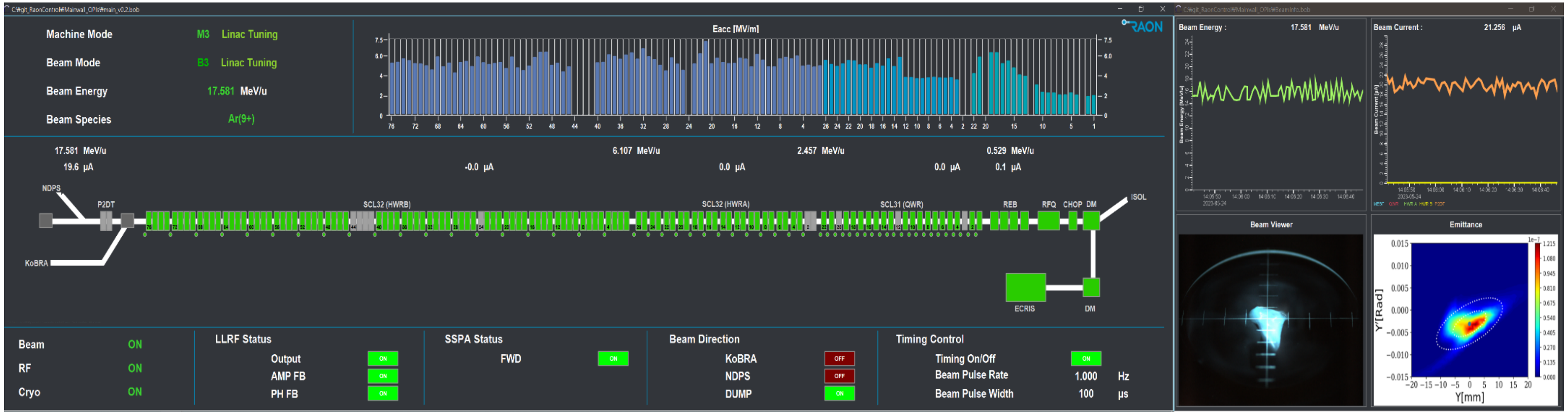
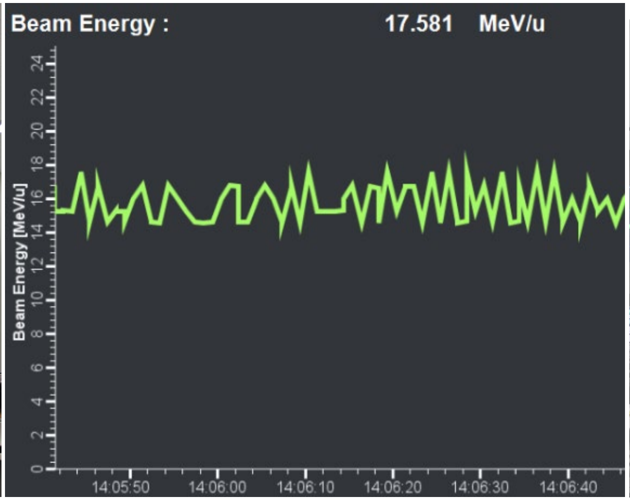
1st SCL3 Beam Commissioning in 2023



Ar^{9+} beams accelerated by entire SCL3(QWR/HWR) on May 23, 2023



SCL3 Beam Operation in 2024

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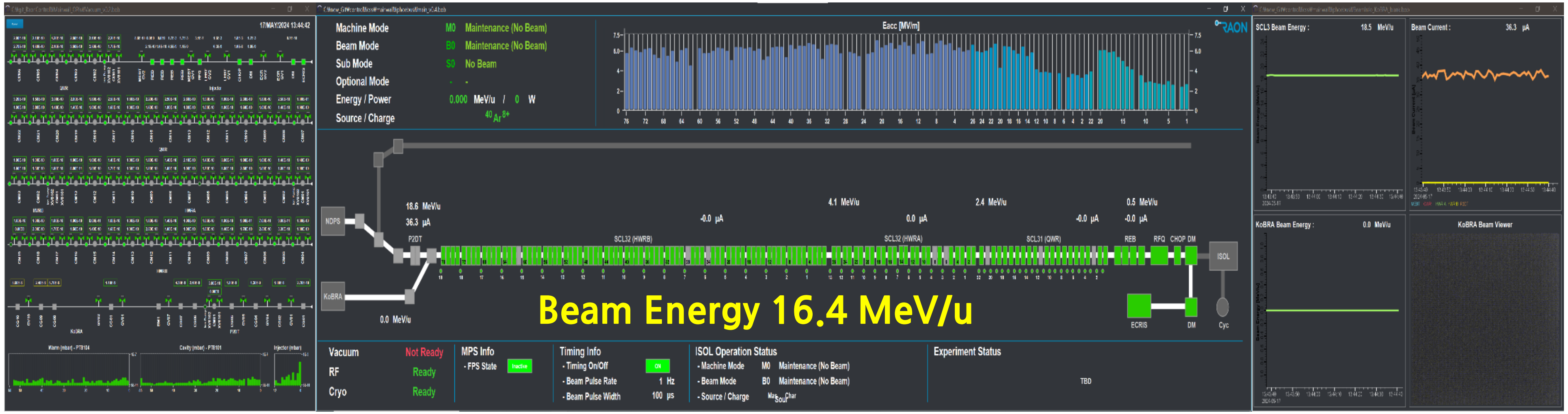
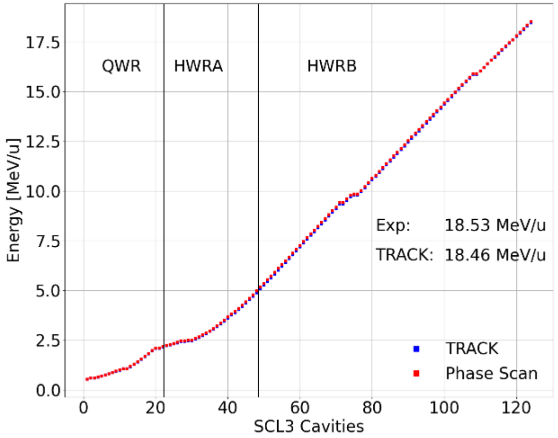
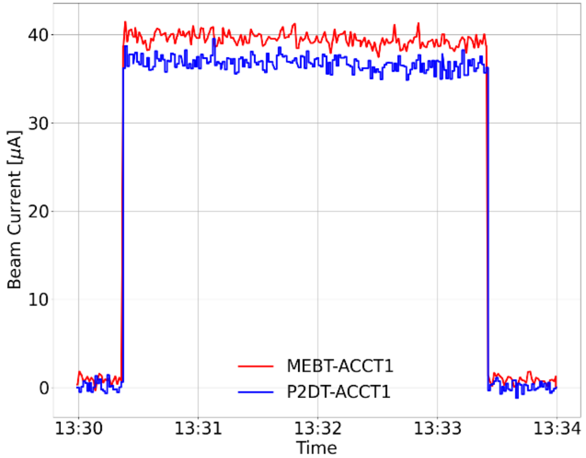


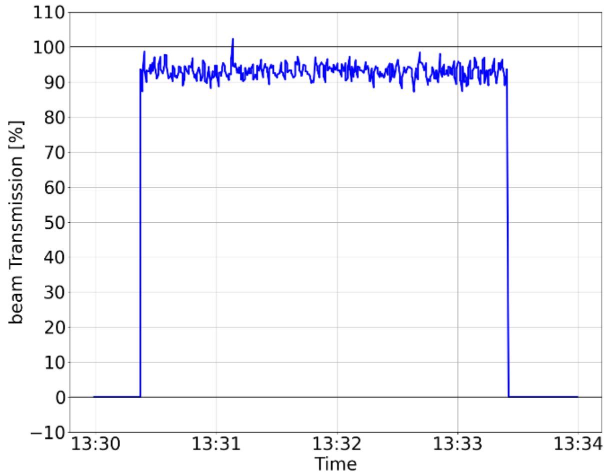
$^{40}Ar^{8+}$ beam accelerated by the entire SCL3(QWR/HWR) on May 17, 2024



[Energy in SCL cavities]



[Beam current measured by ACCT in MEBT and P2DT]



[Beam transmission through SCL3]

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Experimental Systems

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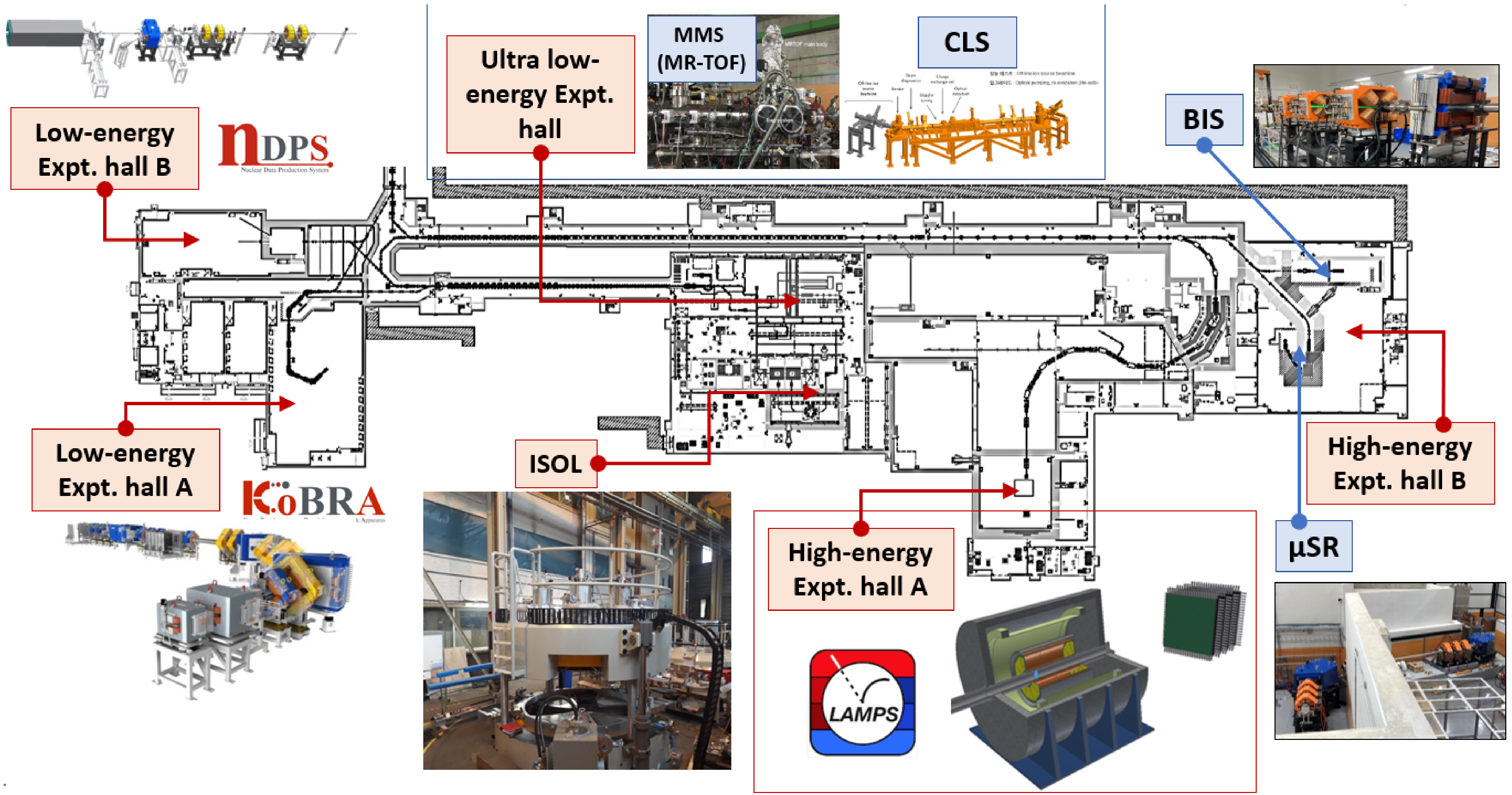

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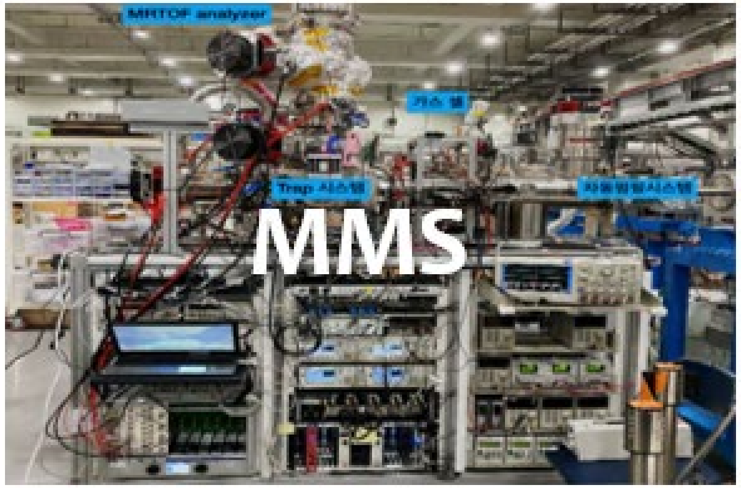
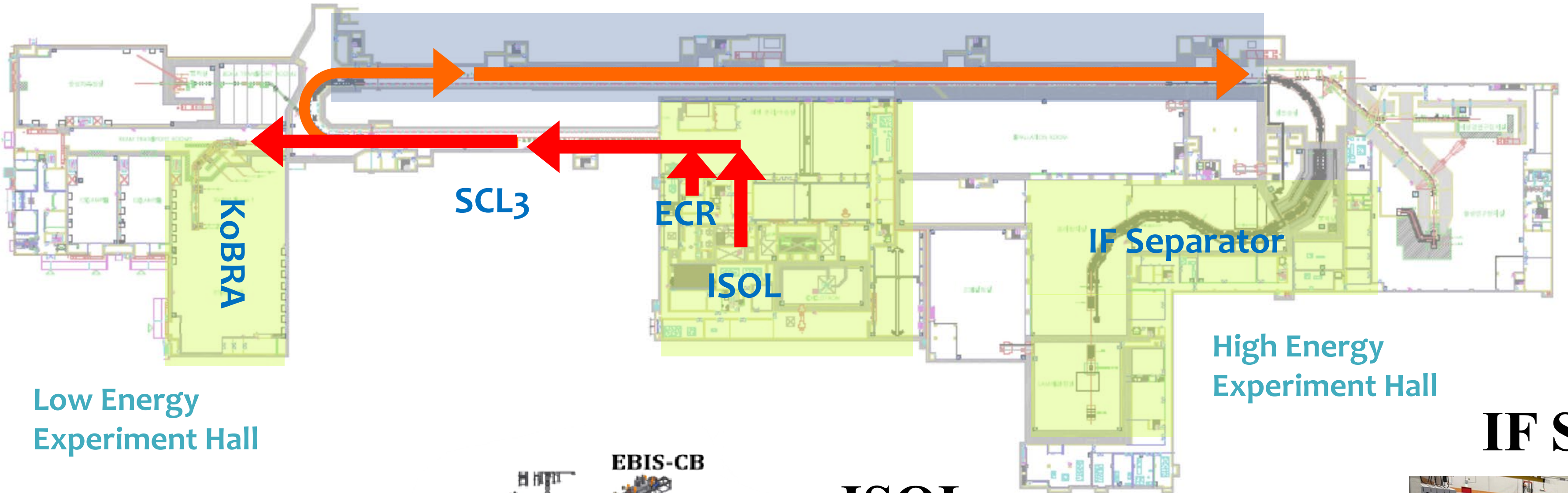
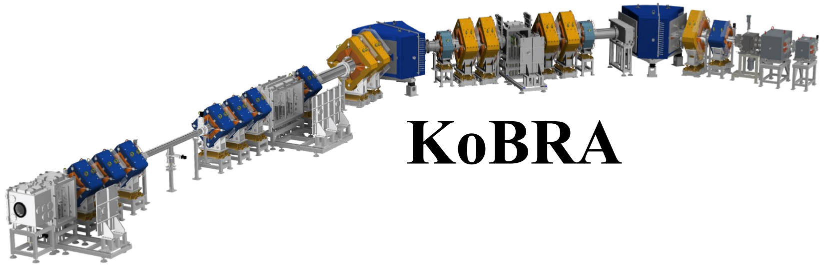
Experimental Systems

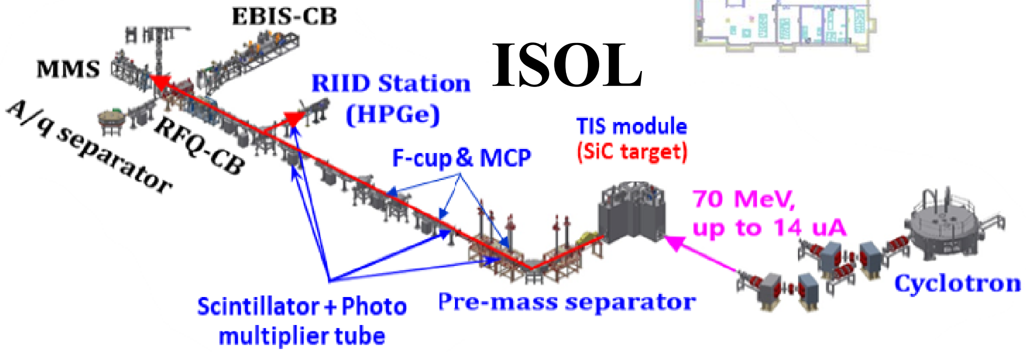


RIB Production of RAON

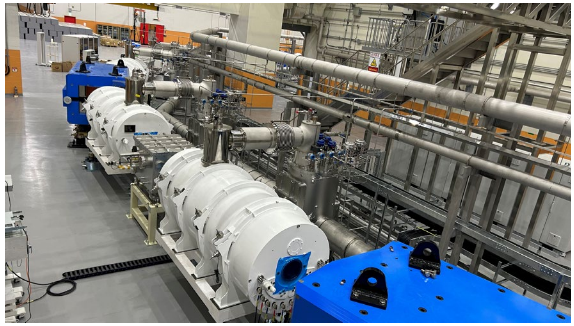
	KoBRA	ISOL	IF Separator
RIB Production & Acceleration Mode	ECR (SIB) → SCL3 → KoBRA production target	Cyclotron (p) → TIS (RIB) → SCL3	ECR (SIB) or ISOL (RIB) → SCL3 → SCL2 → IF (RIB)
Production Mechanism	Direct reactions & Multi Nucleon Transfer	p induced fission of U	Projectile Fragmentation (U fission)
RIB Energy	< a few tens of MeV/u	> a few keV/u	< hundreds of MeV/u



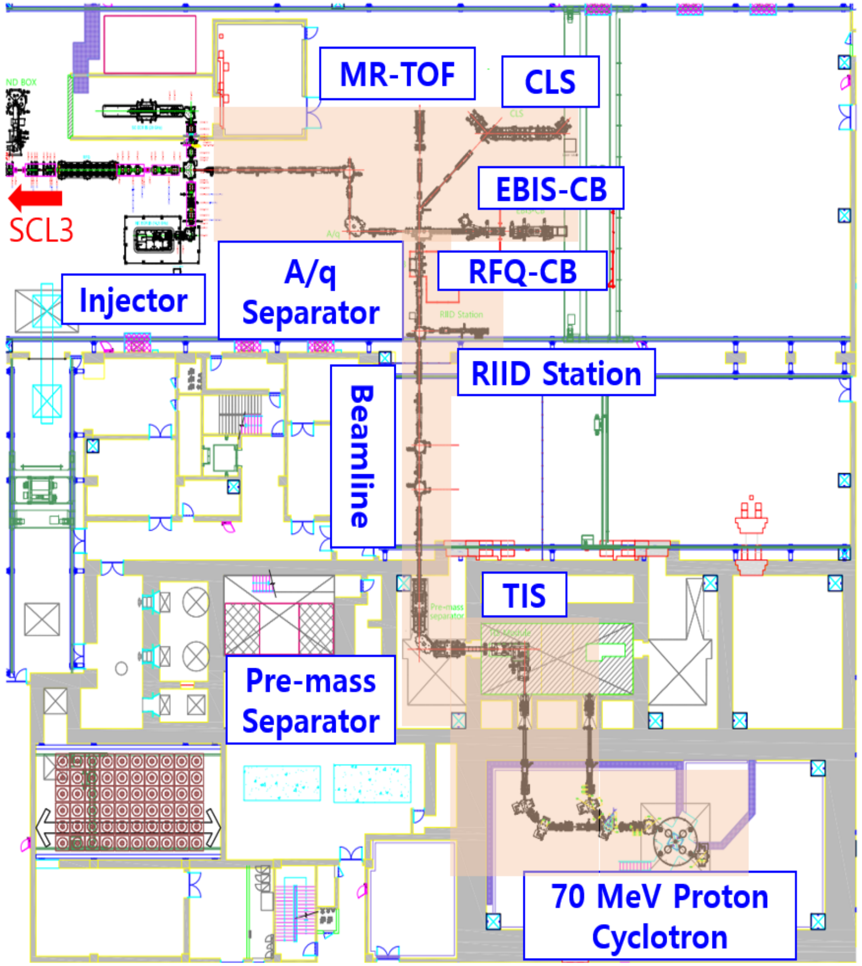




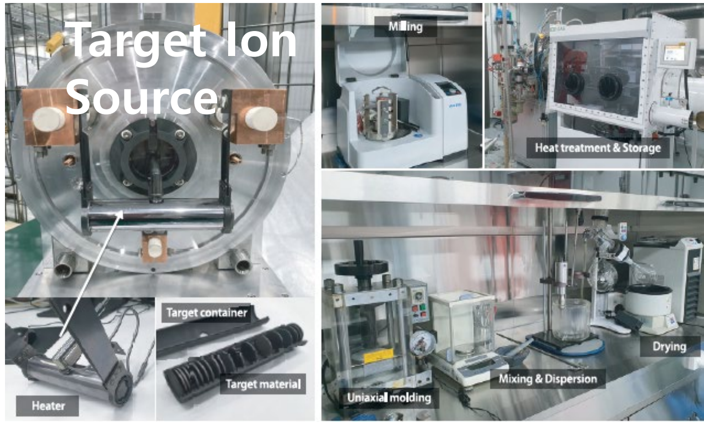
IF Separator



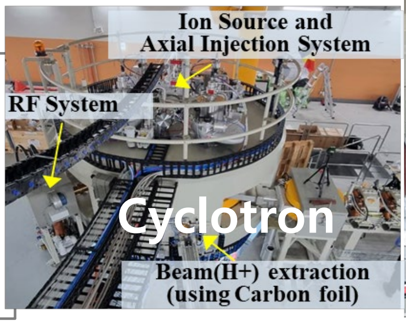
ISOL System



- U fission target for **80 < A < 160** neutron-rich isotope production and delivery
- Driver using Cyclotron : proton 40<K<70 MeV, up to 0.75 mA
- Target: UCx & non-fissile target (SiC, BN, MgO, LaC_2, TiC, CaO etc)
- Ion source : SIS, RILIS, FEBIAD
- Pre-mass separator, Rm ~400
- RIB: 10< K< 60 keV, up to 40 pi mm mrad, 10^8 pps(Sn), > 90% purity @Exp.
- RFQ-Cooler/buncher + EBIS charge breeder
- A/q separator, $R_{A/q}$ ~250
- 10 keV/u, A/q<6 to RFQ of post accelerator (SCL3) for RIB acceleration
- Remote handling system for TIS/module

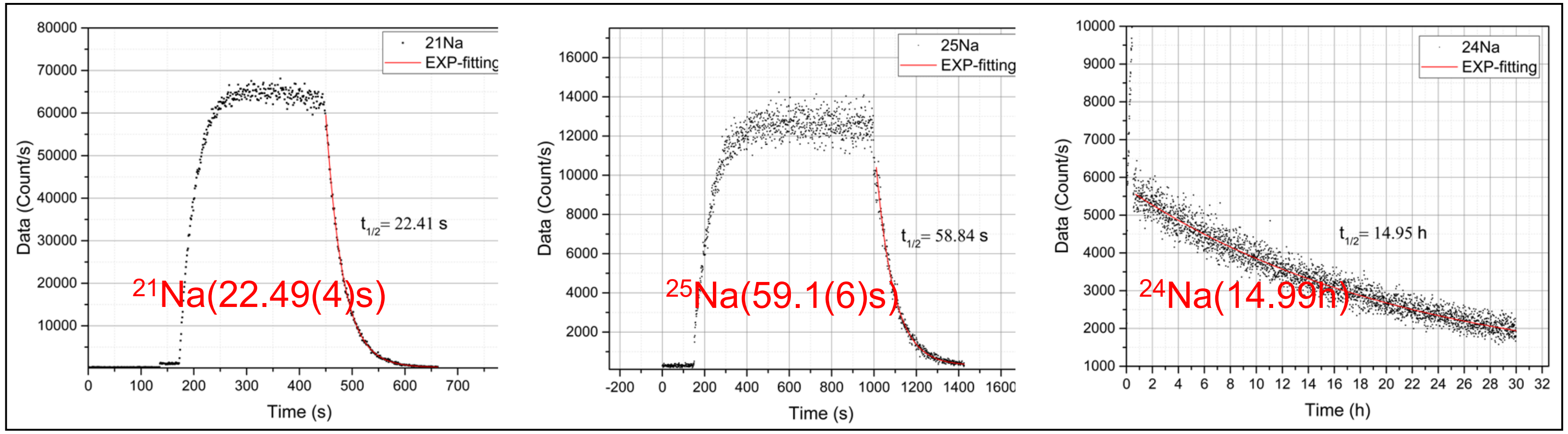


- ~ 2021.05, ISOL system installation and performance tests using a test ion source
- ~ 2022.12, ISOL system integration and stable beam commissioning
- 2022.10, 70 MeV Cyclotron SAT
- 2023.03 ~, Initial RI beam (Na) commissioning using a SiC target
- 2023.06 ~, RI beam (Na) transport to ISOL beamline, RIID, RFQ-CB, EBIS charge breeder and MMS

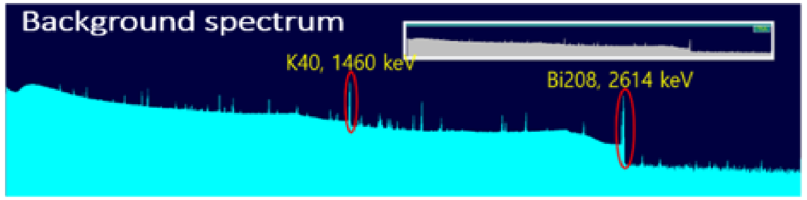


1st ISOL RIB Commissioning in 2023

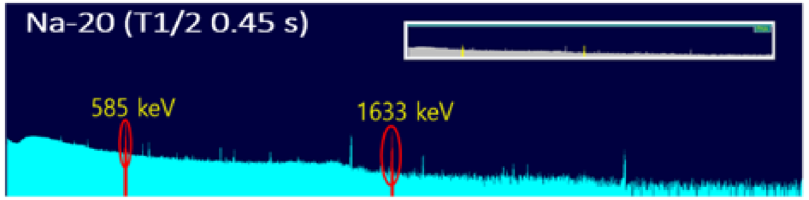
The first RI production and transport at ISOL on March 3, 2023



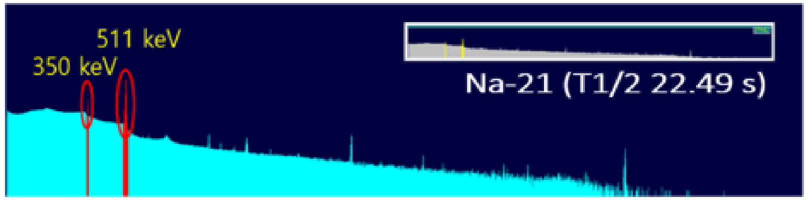
Half-lives of Na isotopes measured by using scintillators & PMT



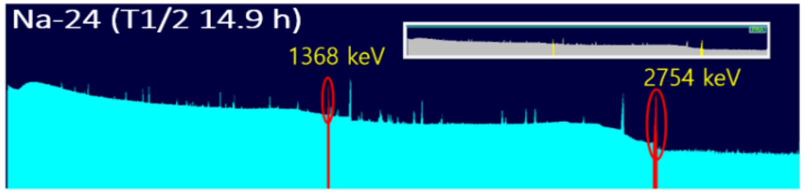
< Measurement of 534,632 sec >



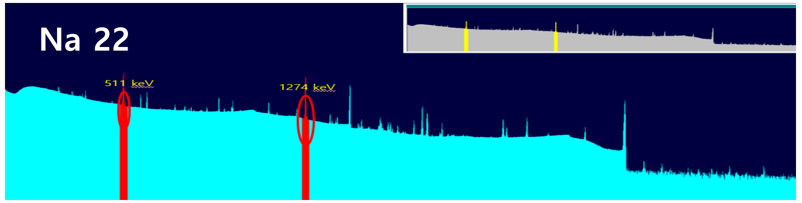
< 2uA p+ irradiated 3,180 sec, measured 3,260 sec >

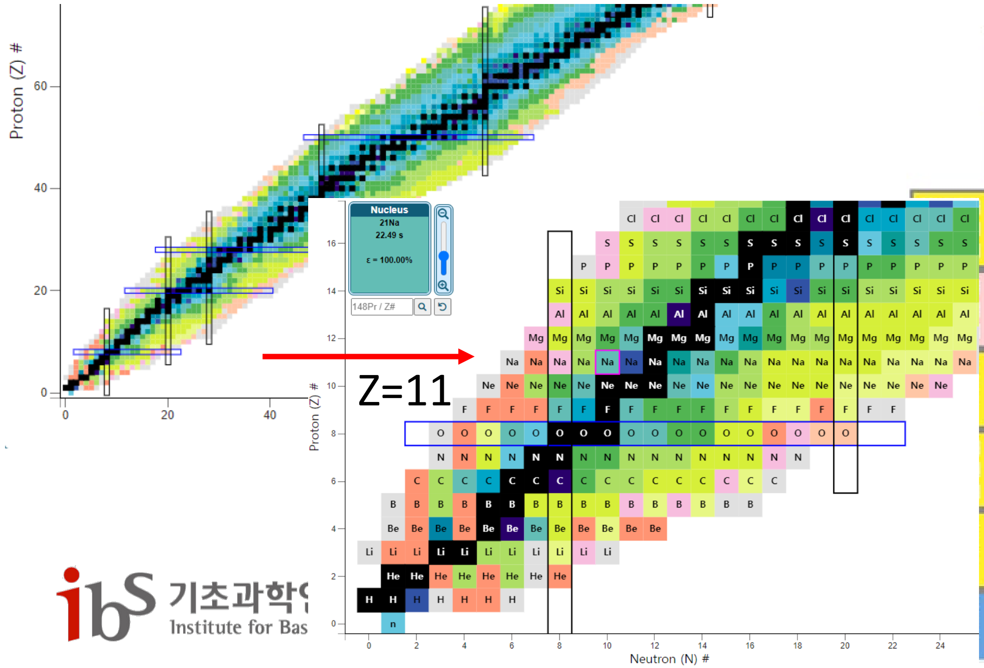


< 1.71uA p+ irradiated 1,000 sec, measured 1300 sec >



< 1.7uA p+ irradiated 1,060 sec, measured 489,146 sec >



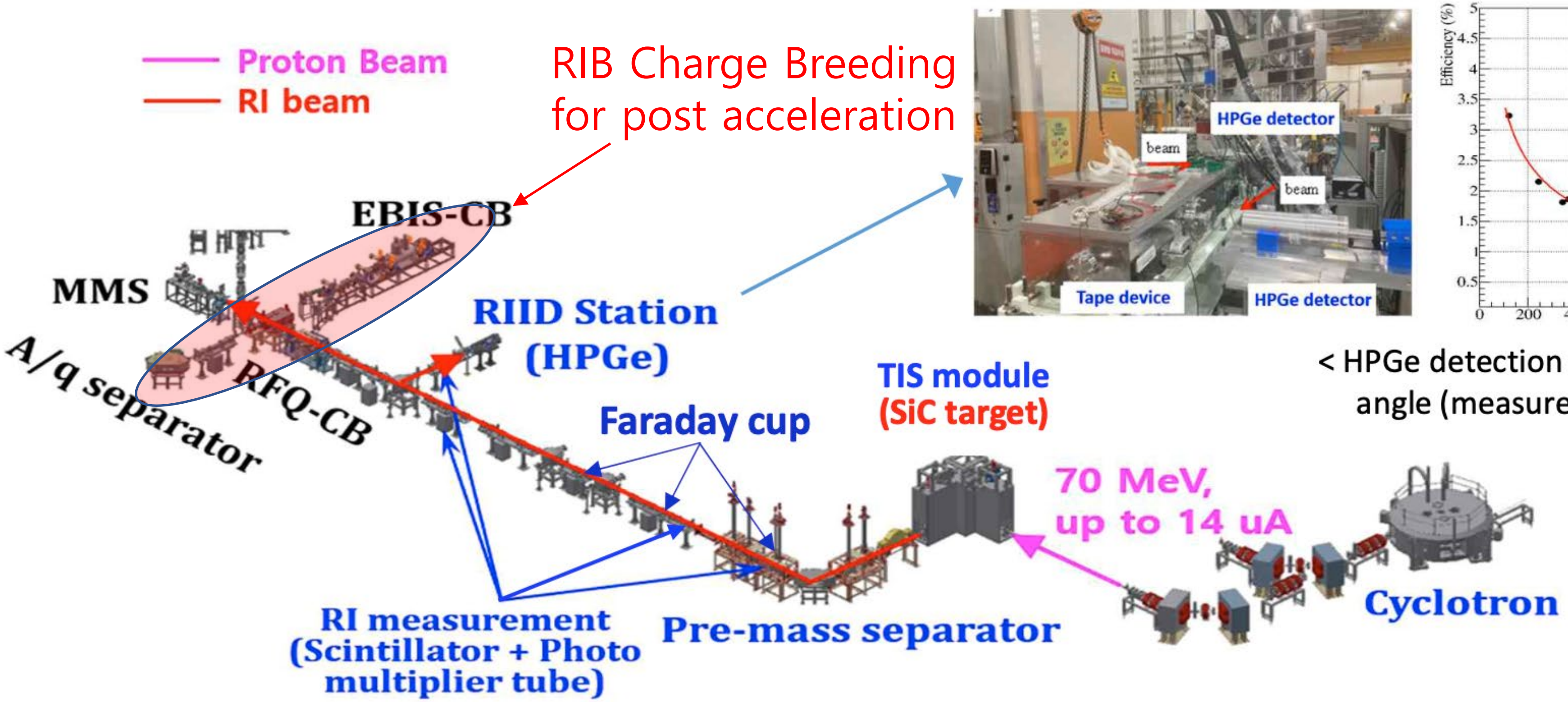


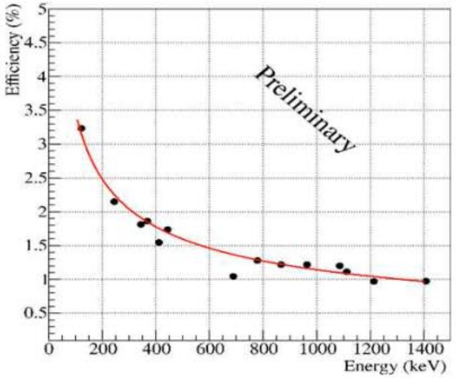
Si- 22 29ms	Si- 23 42.3ms	Si- 24 140.5ms	Si- 25 220ms	Si- 26 2.2453s	Si- 27 4.15s	Si- 28 92.223	Si- 29 4.685	Si- 30 3.092
Al- 21 p 6.4E-22s	Al- 22 91.1ms	Al- 23 446ms	Al- 24 2.053s *130.9ms	Al- 25 7.183s	Al- 26 71.7E5y	Al- 27 100	Al- 28 2.245m	Al- 29 6.56m
Mg- 20 90.8ms	Mg- 21 122ms	Mg- 22 3.8755s	Mg- 23 11.317s	Mg- 24 78.99	Mg- 25 10.00	Mg- 26 11.01	Mg- 27 9.458m	Mg- 28 20.915h
Na- 19 p 150ns	Na- 20 447.9ms	Na- 21 22.49s	Na- 22 2.6027y	Na- 23 100	Na- 24 14.997h *20.18ms	Na- 25 59.1s	Na- 26 1.077s	Na- 27 301ms
Ne- 18 1.6654s	Ne- 19 17.22s	Ne- 20 90.48	Ne- 21 0.27	Ne- 22 9.25	Ne- 23 37.24s	Ne- 24 3.38m	Ne- 25 602ms	Ne- 26 197ms
F - 17 1.075m	F - 18 1.830h	F - 19 100	F - 20 11.163s	F - 21 4.158s	F - 22 4.23s	F - 23 2.23s	F - 24 390ms	F - 25 80ms
O - 16 99.757	O - 17 0.038	O - 18 0.205	O - 19 26.88s	O - 20 13.51s	O - 21 3.42s	O - 22 2.25s	O - 23 97ms	O - 24 65ms
N - 15 0.364	N - 16 7.13s	N - 17 4.173s	N - 18 619ms	N - 19 271ms	N - 20 130ms	N - 21 83.0ms	N - 22 24ms	N - 23 14.1ms

ISOL RIB Commissioning Preparation

ISOL RI Beam Commissioning

- Stable beam tuning using $^{39}K^{1+}$ with energy of 20 keV before RI beam experiment
- Low density SiC target (density 1.8 g/cm3) / Surface ion source
- Proton beam : 70 MeV, up to 14 μ A, non-wobbling (beam profile at Proton module X 35 mm, Y 30 mm)
- TIS temperature : target < 1,600 °C (prevent for Si evaporation), Ion source 1.500 ~ 1,800 °C
  - Joule heating of the target heater was controlled according to the proton beam current
- Targeted isotopes : Na, Al and Li…
- RI confirm (in RIID) and evaluation of beam transmission efficiency

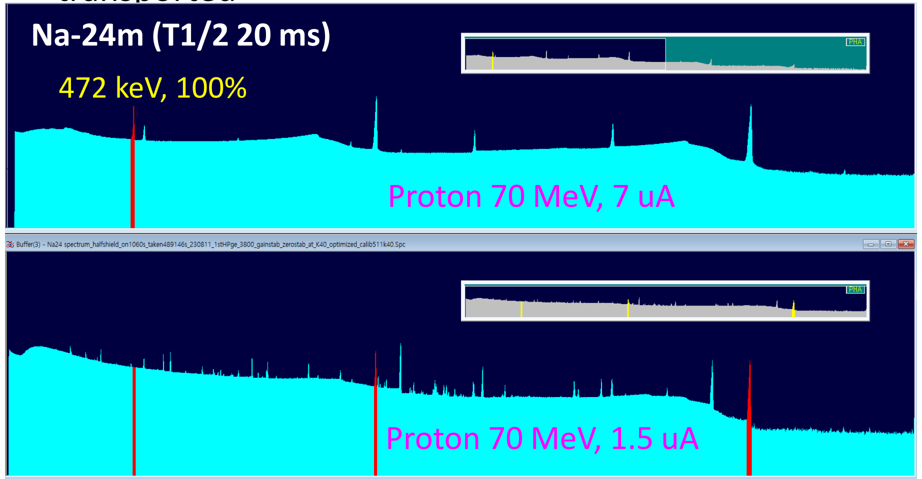




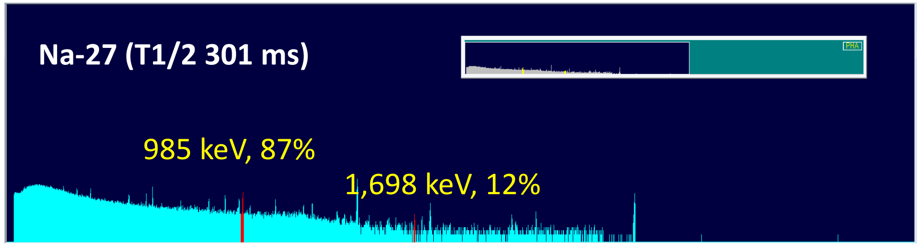
< HPGe detection efficiency including the solid angle (measured using a 152Eu source) >

ISOL RIBs in 2024

- **Measurement of short-lived Na beams**
  - Proton beam : 70 MeV, 7 μ A
  - **Na-24m ($T_{1/2}$ 20 ms) & Na-27 ($T_{1/2}$ 301 ms) detected at RIID**
  - RIs with very short half-lives can be produced and transported

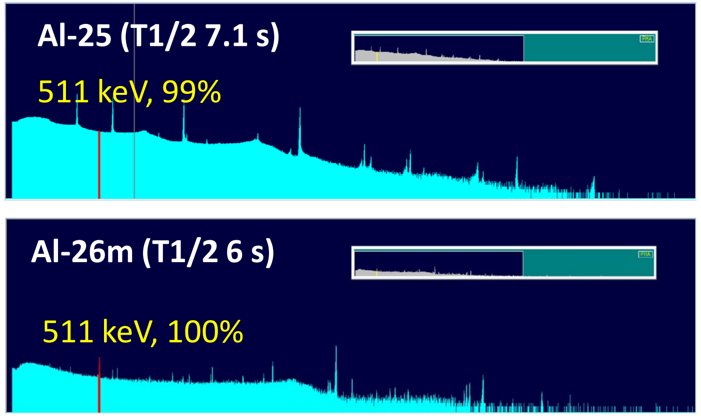


< Gamma spectrum of Na-24 measured by HPGe >
Proton 7 uA (upper) & 1.5 uA (lower)

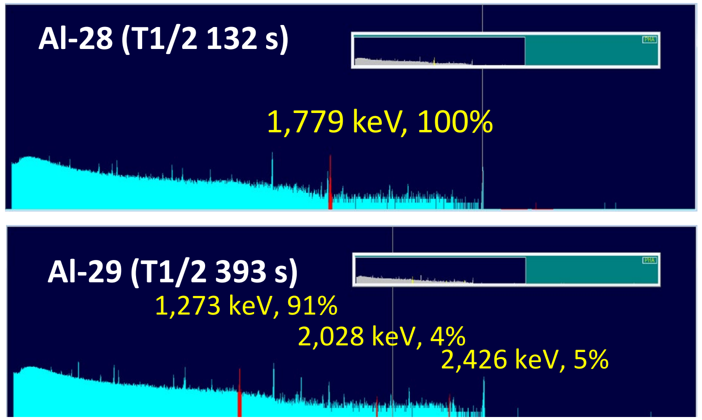


< Gamma spectrum of Na-27 measured by HPGe >

- **Aluminum isotopes**
  - Release of Al isotopes is very slow
  - Low ionization efficiency with a surface ion source
  - Al yield is low (in SiC target)



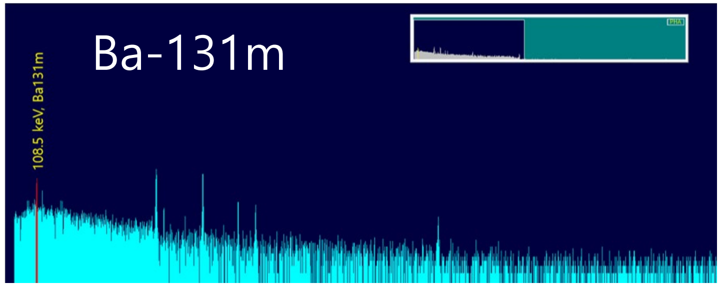
< Gamma spectrum of Al-25(upper) & Al-26m(lower) >

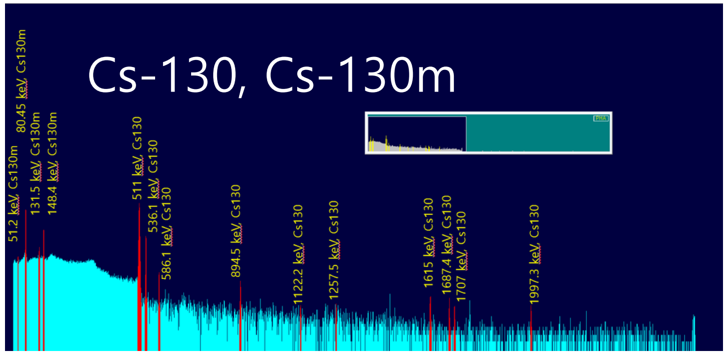


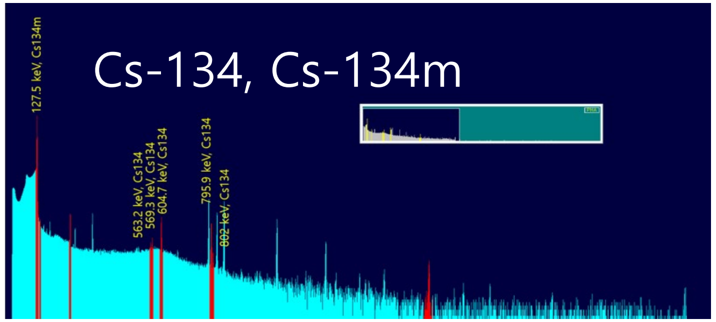
< Gamma spectrum of Al-28(upper) & Al-29(lower) >

SiC Target

- LaC_2 target in ISOL TIS and Cs130, Cs130m, Ba131m, Ba133, Ba133m, Cs134, Cs134m, Cs135m, Ba135m, Cs136, Ba137m, Cs138, Cs138m observed using HPGE







LaC2 Target

KoBRA Spectrometer

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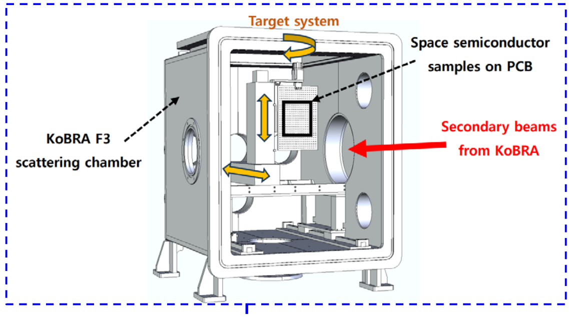
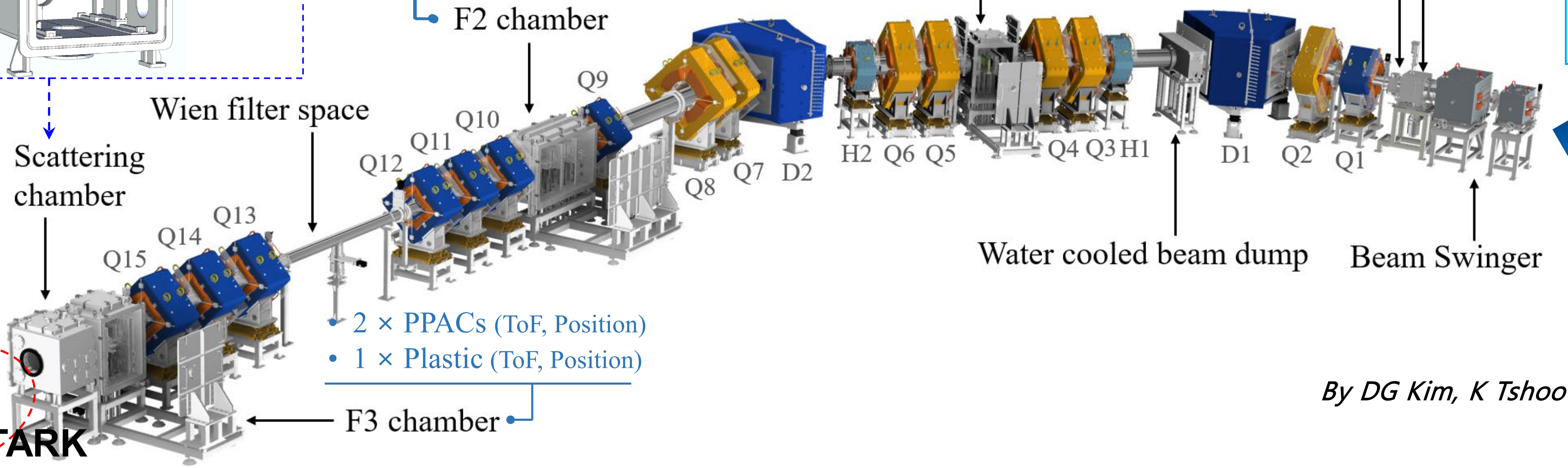
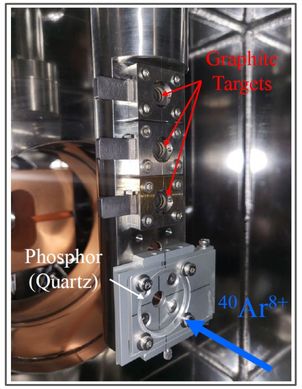
KoBRA Experimental Setup

- 2 × Large Area PPACs (Bρ, Position)
- 1 × Homogeneous Degrader (RI Separation)
- 1 × Plastic (Intensity)
- 1 × Phosphor (Beam Centering)



- 2 × PPACs (ToF, Position)
- 1 × Plastic (ToF, Position)





Target Ladder

$^{40}Ar^{8+}$ from SCL3
E = 18.5 MeV/u
I = 5 pnA

- 2 × PPACs (ToF, Position)
- 1 × Plastic (ToF, Position)

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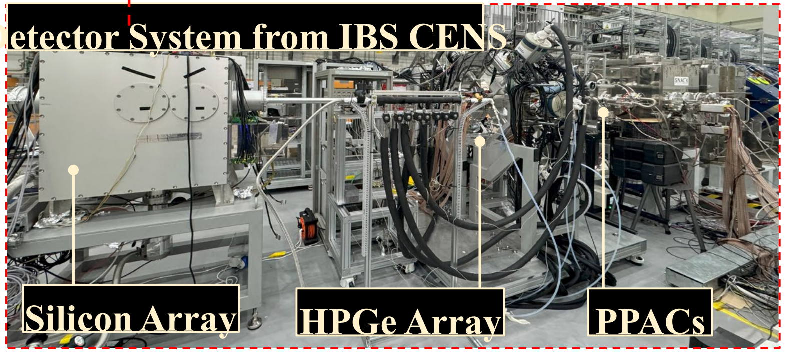
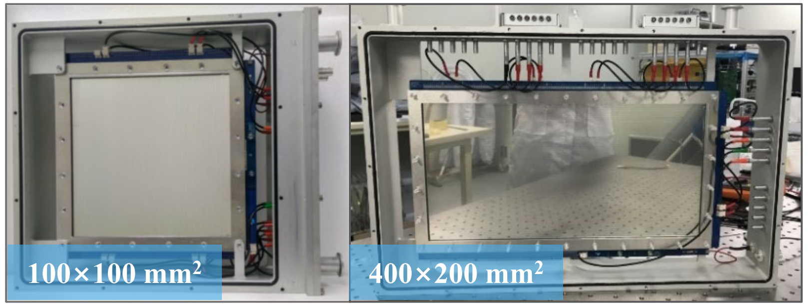
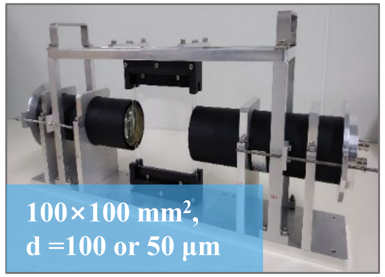
CENS STARK

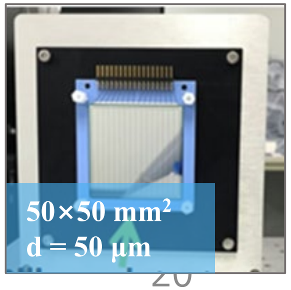




Parallel-Plate Avalanche Chambers (PPACs)



Plastic Scintillator



Silicon Strip Detector

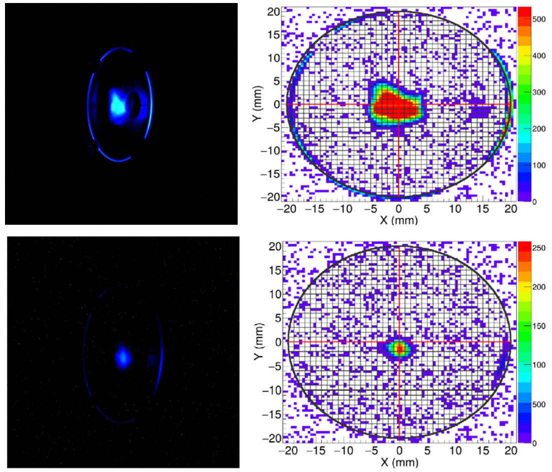
KoBRA Spectrometer

Institute for Rare Isotope Science

2024. 05. 01 ~ 2024. 08. 31.

Beam size & Transmission after SCL3-KoBRA Beamline

Beam Phosphor Image at KoBRA F0



$^{40}Ar^{8+}$ Primary Beam

$\sigma_x = 1.93 \pm 0.01$ mm
$\sigma_y = 1.78 \pm 0.01$ mm

$\sigma_x = 0.99 \pm 0.01$ mm
$\sigma_y = 0.90 \pm 0.01$ mm

$T_{eff} = \sim 3\% \rightarrow \sim 87\%$

Main Trouble Shootings

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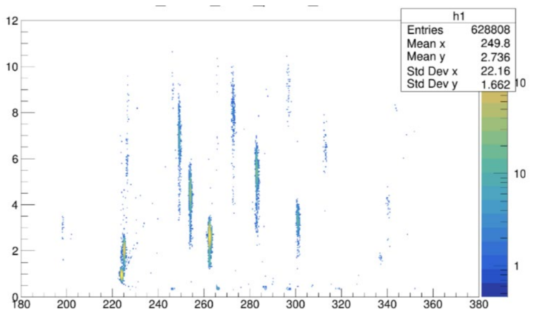
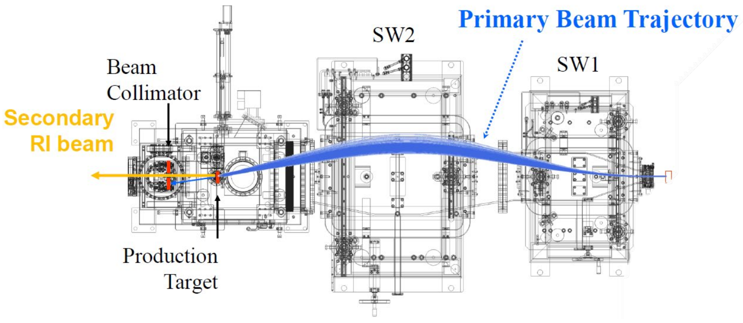
Primary Beam Rejection for Contamination of ^{40}Ar Various Charge States

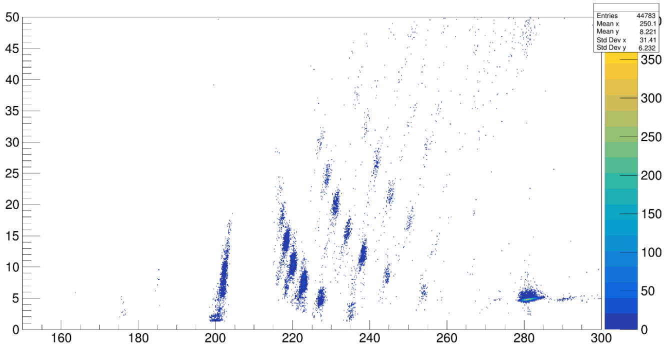


Particle Identification (Z ≤ 5) with Primary Beam Stop at Beam Phosphor (SiO2, 1 mm)

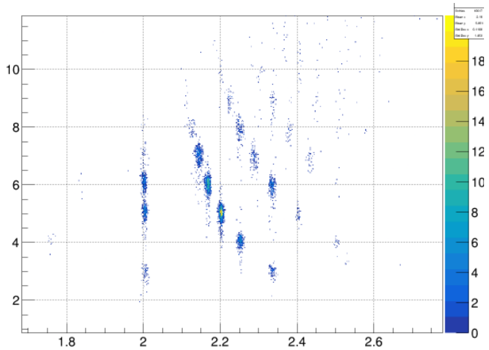


Primary Beam Rejection with Beam Swinger Magnet & Collimator

ΔE-ToF Measurement with Silicon Detector



Distorted ΔE – ToF plot



Return to Normal ΔE by Changing Si Detector

KoBRA Spectrometer

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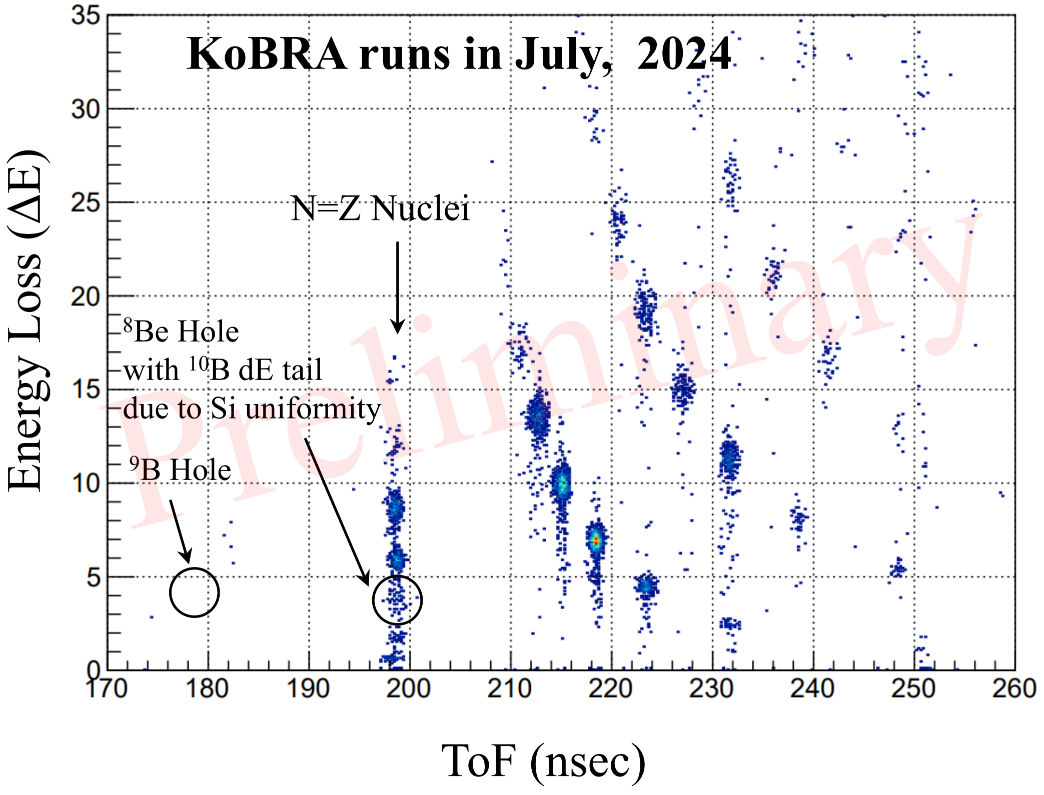
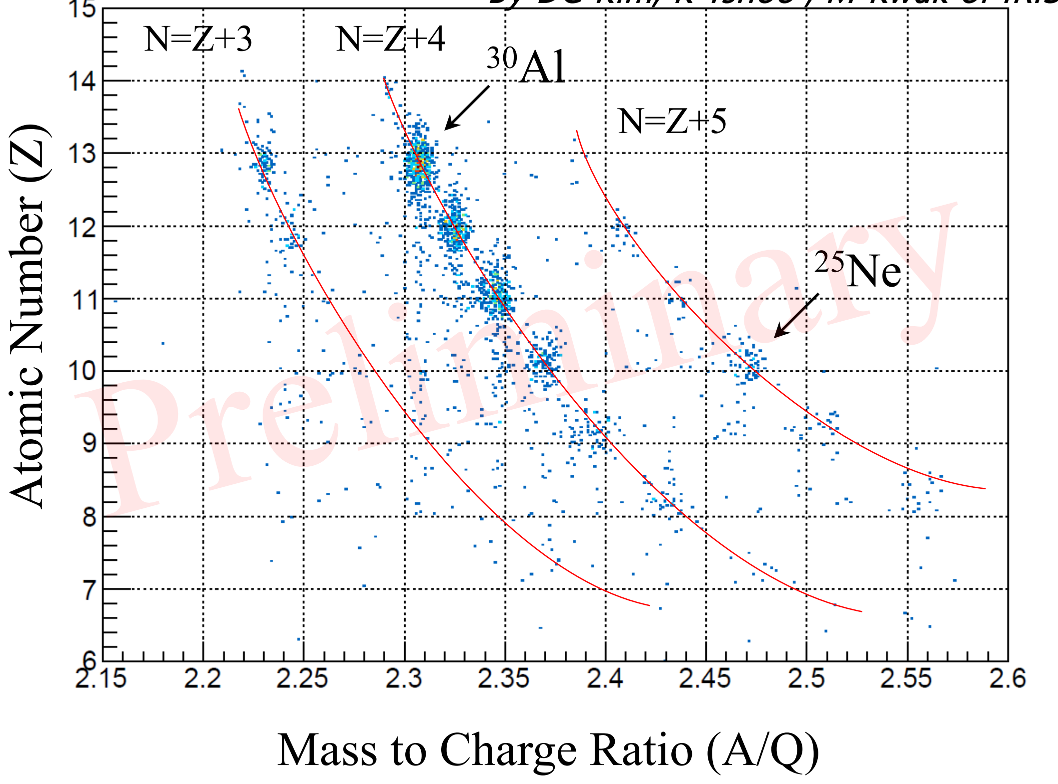


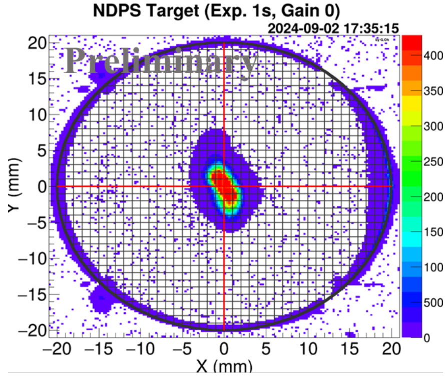


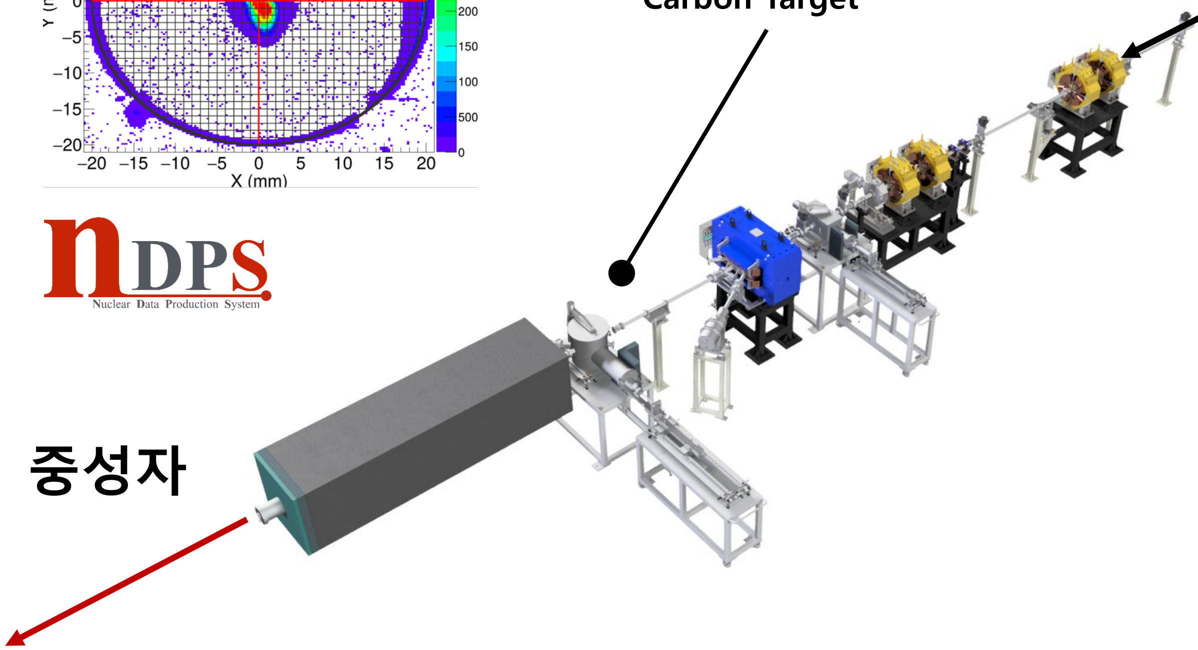
- ✓ Magnetic Rigidity Setting for ^{10}B (one of the N=Z Nuclei)
- ✓ without F1 Al degrader & PPACs
- ✓ $\Delta p/p = 0.2\%$
- ✓ ToF Measurement
  - Two PPACs between F2 and F3 ($\sigma_{time} \sim 250$ psec)
- ✓ ΔE Measurement
  - Si Strip Detector (50 μm, $\sigma_E \sim 1\%$)

- ✓ Magnetic Rigidity Setting for ^{25}Ne
- ✓ With F1 PPACs (functions as a energy degrader)
- ✓ $\Delta p/p = 8\%$ (full momentum acceptance)
- ✓ ToF Measurement
  - Two PPACs between F2 and F3 ($\sigma_{time} \sim 250$ psec)
- ✓ ΔE Measurement
  - Si Strip Detector (50 μm, $\sigma_E \sim 1\%$)

NDPS(Neutron Data Production System)

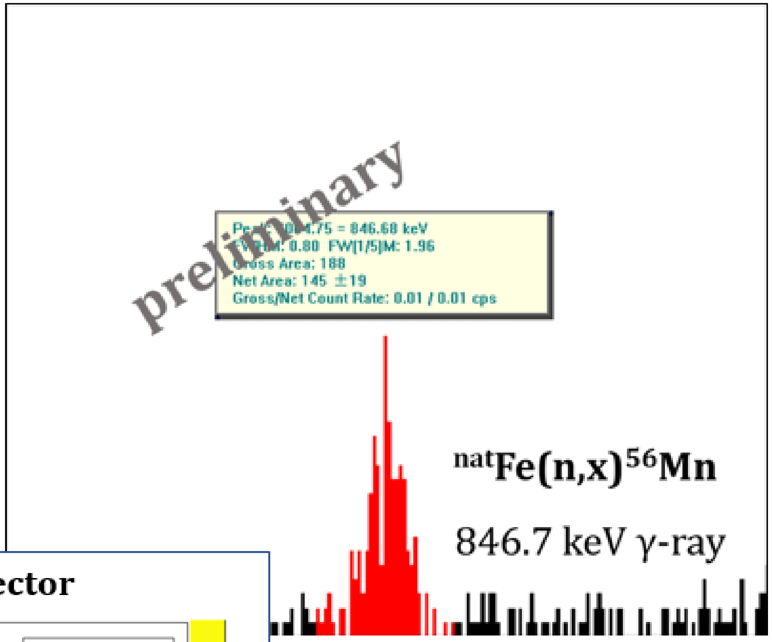
- ❖White neutrons produced by 50 MeV/u deuteron beams from SCL3
- ❖Monoenergetic neutrons, by using proton beams of 20-80 MeV/u from SCL3

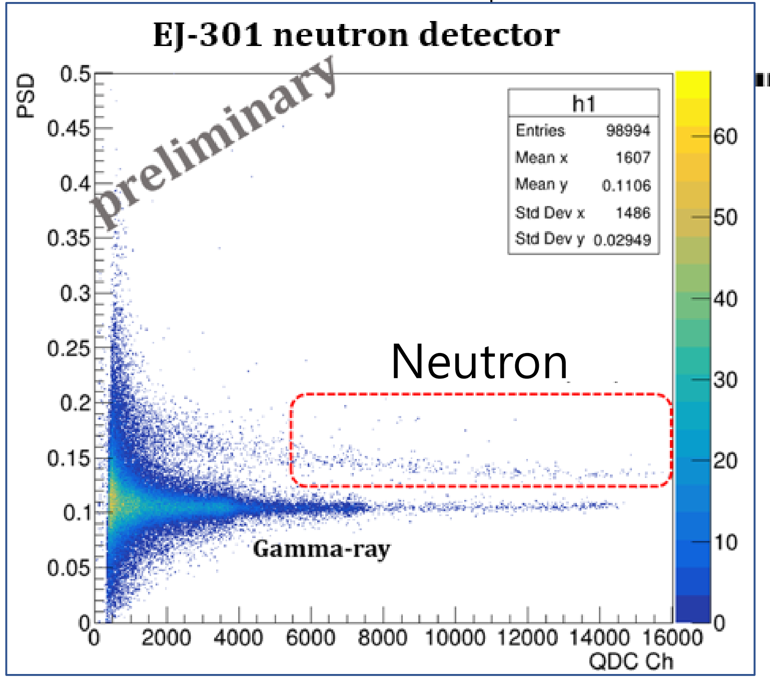




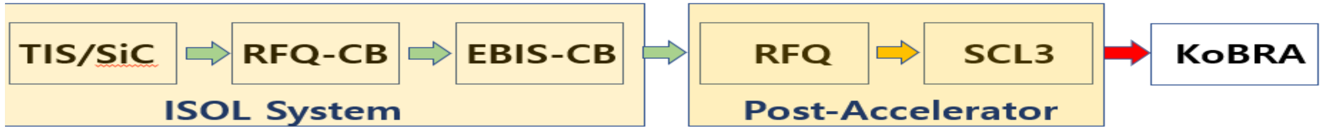
By CM Ham, G Oh of IRIS

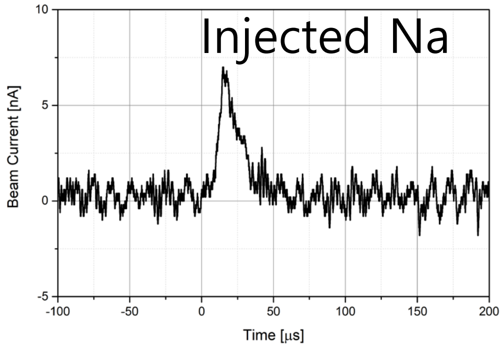
Fe foil + HPGe detector

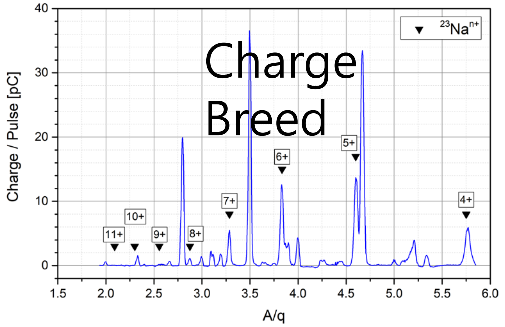


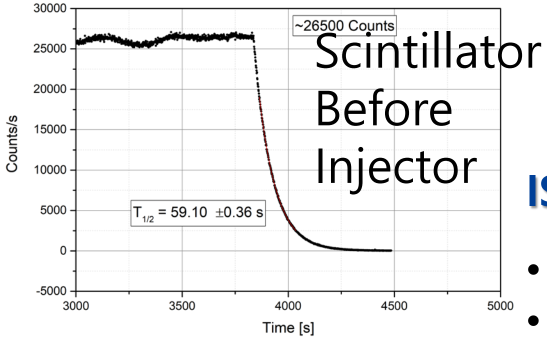


Post-acceleration of IOSL RIB($^{25}Na^{5+}$) to KoBRA

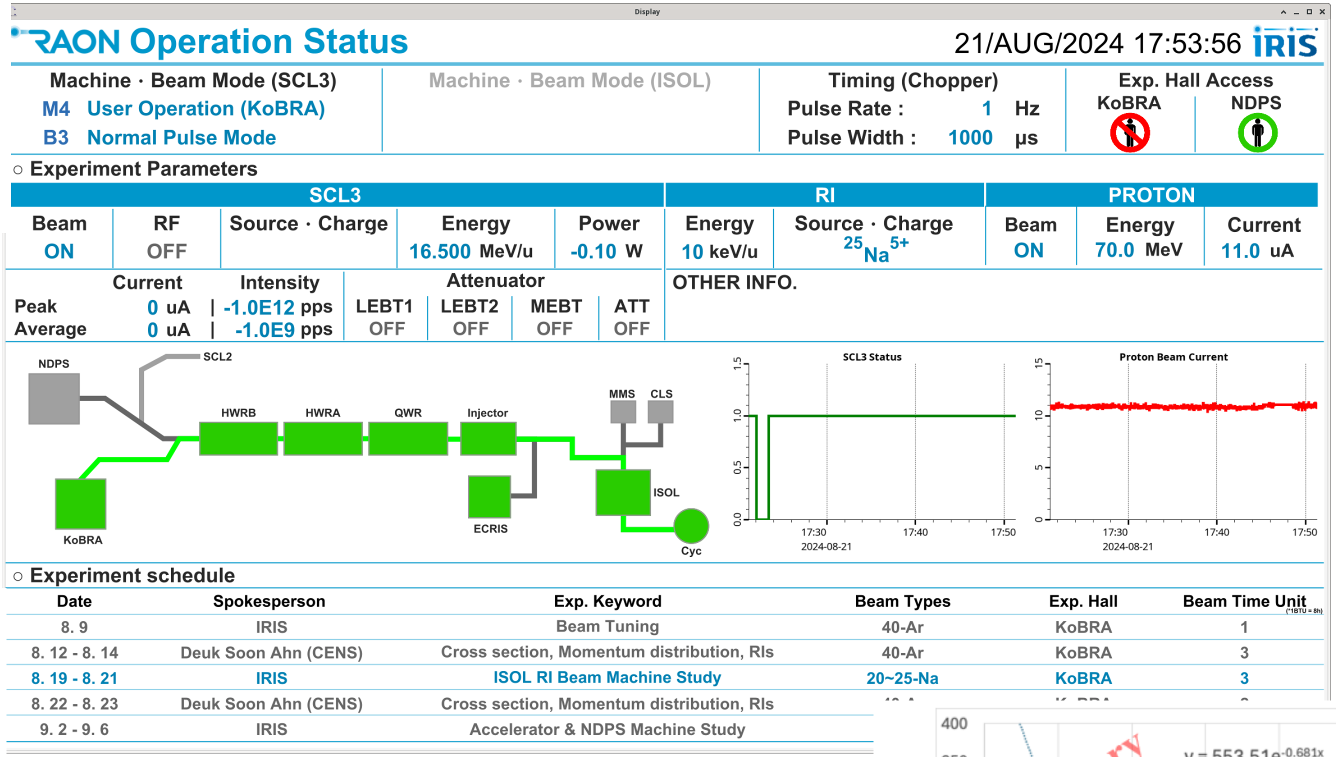








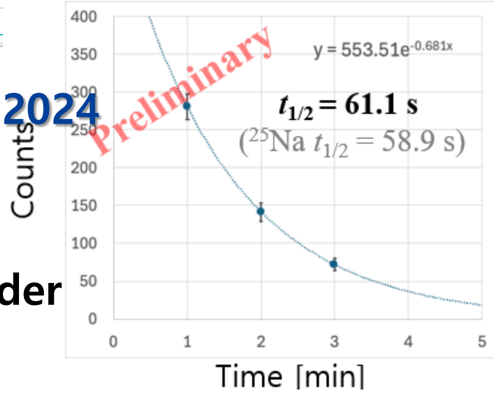
By KH Yoo of IRIS

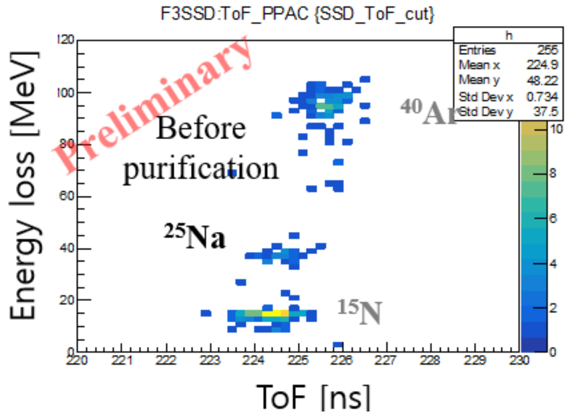


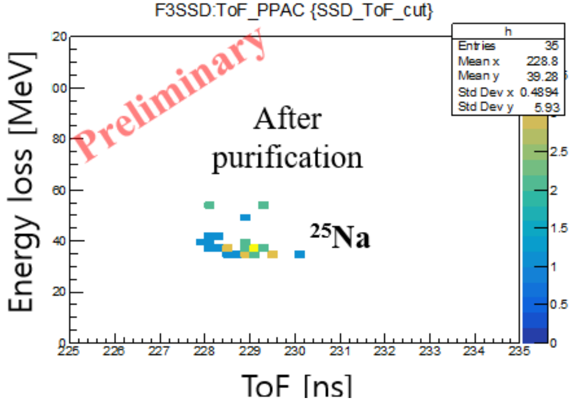
Date	Spokesperson	Exp. Keyword	Beam Types	Exp. Hall	Beam Time Unit
8. 9	IRIS	Beam Tuning	40-Ar	KoBRA	1
8. 12 - 8. 14	Deuk Soon Ahn (CENS)	Cross section, Momentum distribution, RIs	40-Ar	KoBRA	3
8. 19 - 8. 21	IRIS	ISOL RI Beam Machine Study	20~25-Na	KoBRA	3
8. 22 - 8. 23	Deuk Soon Ahn (CENS)	Cross section, Momentum distribution, RIs			
9. 2 - 9. 6	IRIS	Accelerator & NDPS Machine Study			

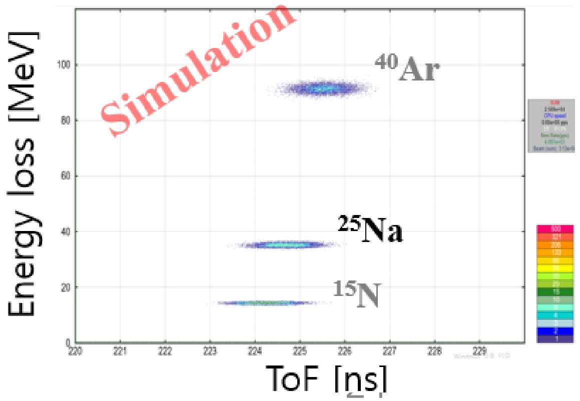
ISOL $^{25}Na^{5+}$ beam post-accelerated on Aug. 2024

- Beam Energy after SCL3: ~16.5 MeV/u
- ^{25}Na, ^{40}Ar, ^{15}N were identified in KoBRA
- ^{25}Na was purified by using energy degrader at KoBRA
- Decay curve of beta ray was measured





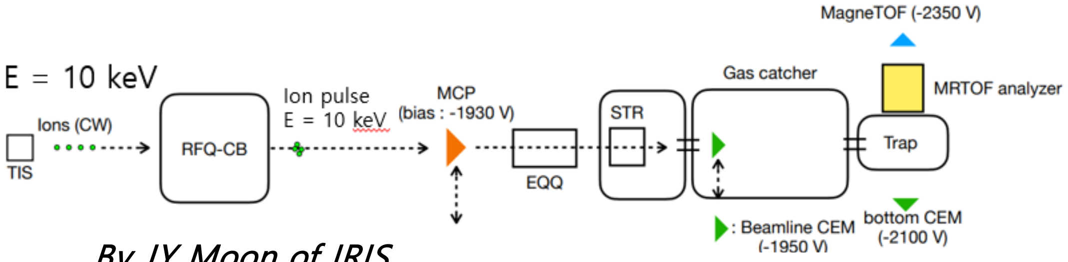




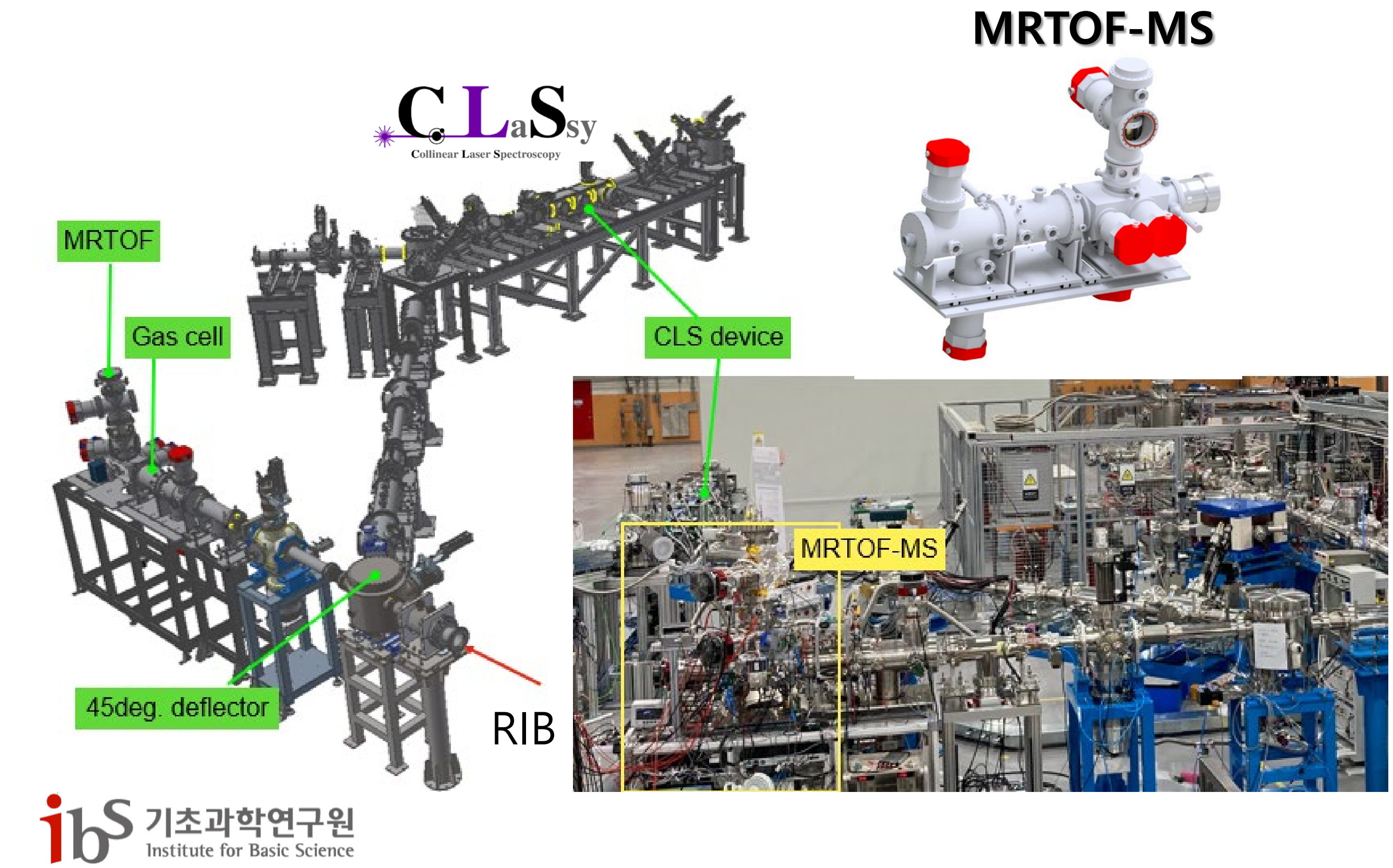
By MS Kwak of IRIS

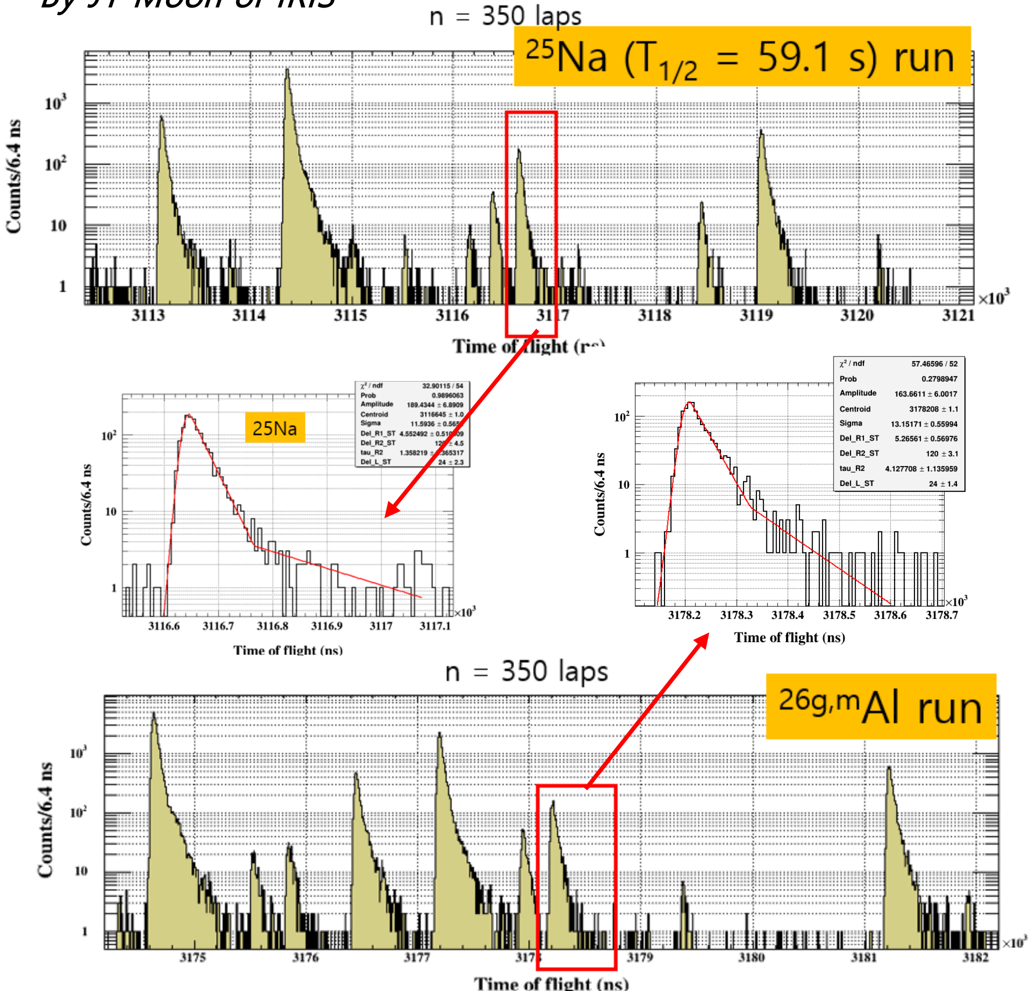
ISOL Beam to MRTOF-MS

MRTOF-MS consists of three subsystems :
- Gas cell (or catcher), Trap system: Buffer-gas collision, ion thermalization
- MRTOF analyzer : Multi-reflection, mass measurement



By JY Moon of IRIS





ISOL Beam to CLS

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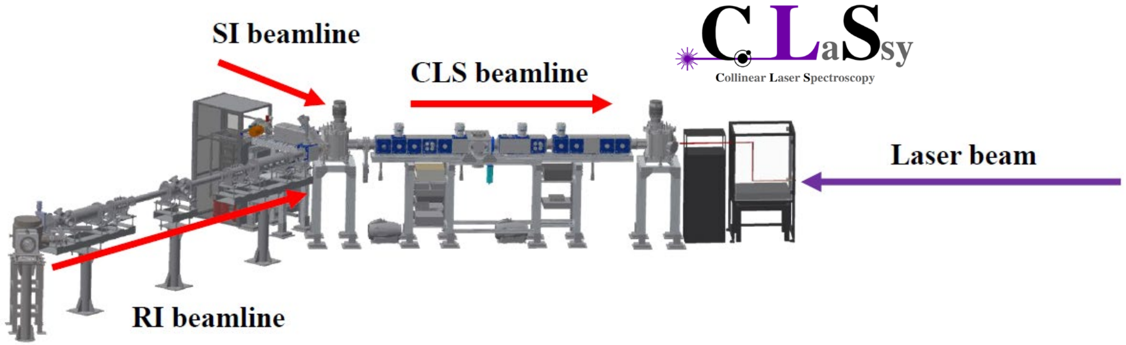
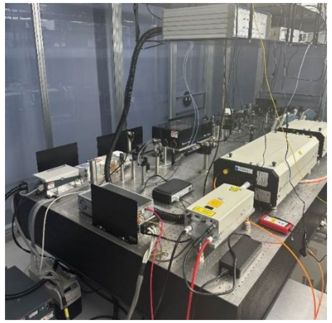
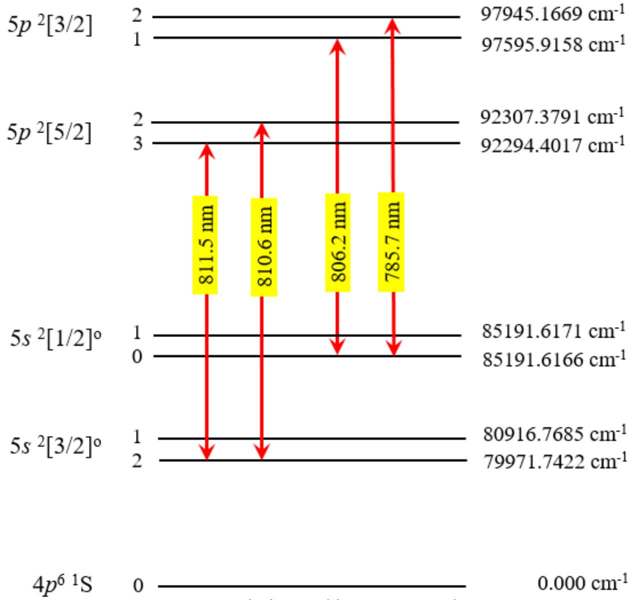


Laser system





Kr transition lines under test

Kr(offline source) test runs recently and ISOL Na beam to CLS in Oct 2024

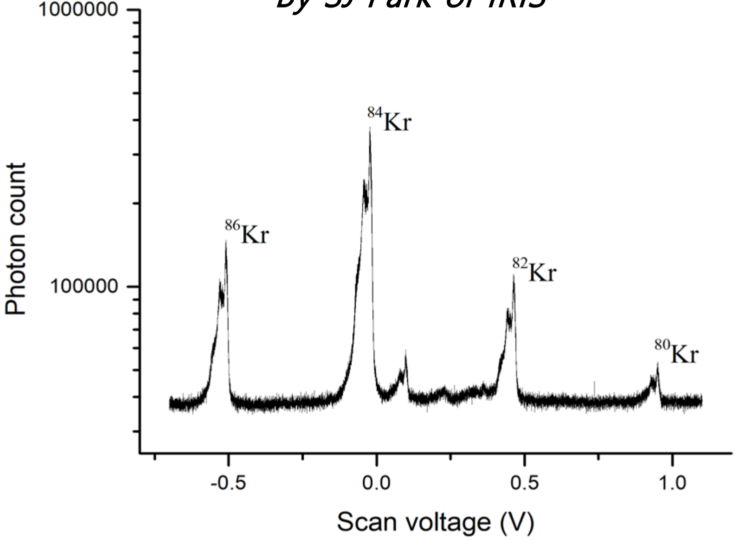
CLaSsy (formerly **CLS) beamline parameter**

- Ion beam energy : 20 keV
- Alkali vapor used for neutralization : Rb
- Neutralization efficiency : 50 %
- Intensity for neutral atom beam : ~ 40 nA
- Laser power at the input port : 0.8 mW
- Laser frequency spread : Δ10 MHz
- Laser frequency : 369159.859 GHz
- Scan step voltage : 0.0001 V
- Scan dwell time : 40 ms

Laser parameter

- Wavelength (vac) : 811.513132 nm
- Wavelength (air) : 811.289558 nm
- Resonance frequency : 369 424.038 GHz
- Laser frequency : 369 159.859 GHz
- Doppler shift : -265.179 GHz
- Natural linewidth : 5.7 MHz
- Differential Doppler shift : 6.6 MHz/V

By SJ Park of IRIS



Kr absorption lines @ 811.5 nm (preliminary)

Stable isotopes of krypton

Nuclide	Z	N	Isotopic mass	Half-life	Spin & Parity	Natural abundance	
^{78}Kr	36	42	77.92036634	$9.2 \pm 1.3\times10^{21}$ y	0+	0.00355	0.355%
^{80}Kr	36	44	79.91637794	stable	0+	0.02286	2.286%
^{82}Kr	36	46	81.91348115	stable	0+	0.11593	11.593%
^{83}Kr	36	47	82.91412651	stable	9/2+	0.11500	11.500%
^{84}Kr	36	48	83.91149773	stable	0+	0.56987	56.987%
^{86}Kr	36	50	85.91061062	stable	0+	0.17279	17.279%

Summary

- The first commissioning of the SC Linac(SCL3), ISOL & KoBRA done in 2023 and 2024
- ISOL RIBs were produced from SiC & LaC_2 in 2024 and RIBS from UCx is expected in 2026
- KoBRA spectrometer produced and identified the secondary isotopes in low-mass area
- For the first time in RAON, ISOL RIB($^{25}Na^{5+}$) was accelerated by SCL3 and transported to KoBRA with energy of 16.4 MeV/u
- MRTOF-MS is to measure RI beam from ISOL and CLS is preparing for RI beam laser spectroscopy
- The first call for proposals was done in Dec 2023 for domestic users(recommended by Science Advisory Committee) and finished 2 user experiments using SCL3 Ar beam and KoBRA, July to August, 2024