Nuclear Physics Seminar, University of Warsaw
13 October 2022

Overview of the New Radioactive Ion Beam Accelerator Complex RAON in Korea

Byungsik Hong

Center for Extreme Nuclear Matters (CENuM), Korea University

for Rare Isotope Science Project (RISP), IBS

Outline

1. Overview of RISP
2. Accelerator system
3. RI & experimental systems
4. Status of beam commissioning and summary

Part 1.

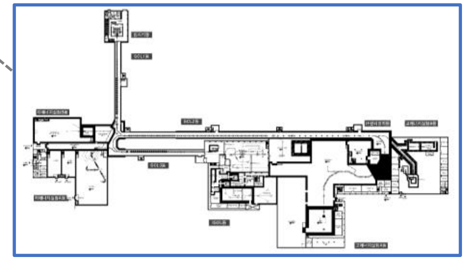
Overview of RISP

Overview of Rare Isotope Science Project (RISP)

- Goal: To build a heavy-ion accelerator complex RAON for rare isotope science research
  - **RAON**: **R**are isotope **A**ccelerator complex for **ON**-line experiments
- Budget: Total KRW 1,518 B (~U$ 1.2 B for 1 U$=KRW 1,300) for phase I
  - Accelerator & experimental facilities: ~U$ 400 M
  - Civil engineering & conventional facilities: ~U$ 800 M, including ~U$ 270 M for purchasing land
- Project period: 2011-2022 (1st phase), 2023-2029 (2nd phase for high-energy Linac)

System installation project

Development, installation, and commissioning of the accelerator systems that provides the high-energy (200 MeV/u) and high-power (400 kW) heavy-ion beams



Facility construction project

Construction of the research and supporting facility to ensure the stable operation of the heavy-ion accelerator, experimental systems, and to establish a comfortable research environment in Korea

◐ **Providing high-quality RI beams by ISOL & IF**

ISOL: direct fission of ^{238}U by 70 MeV proton beams
IF: 200 MeV/u ^{238}U (intensity: 8.3 pμA)

◐ **Providing high-intensity neutron-rich beams**

For example, ^{132}Sn with energy up to 250 MeV/u and intensity up to 10^9 particles per second

◐ **Providing more exotic RI beams**

Combination of ISOL and IF

Layout

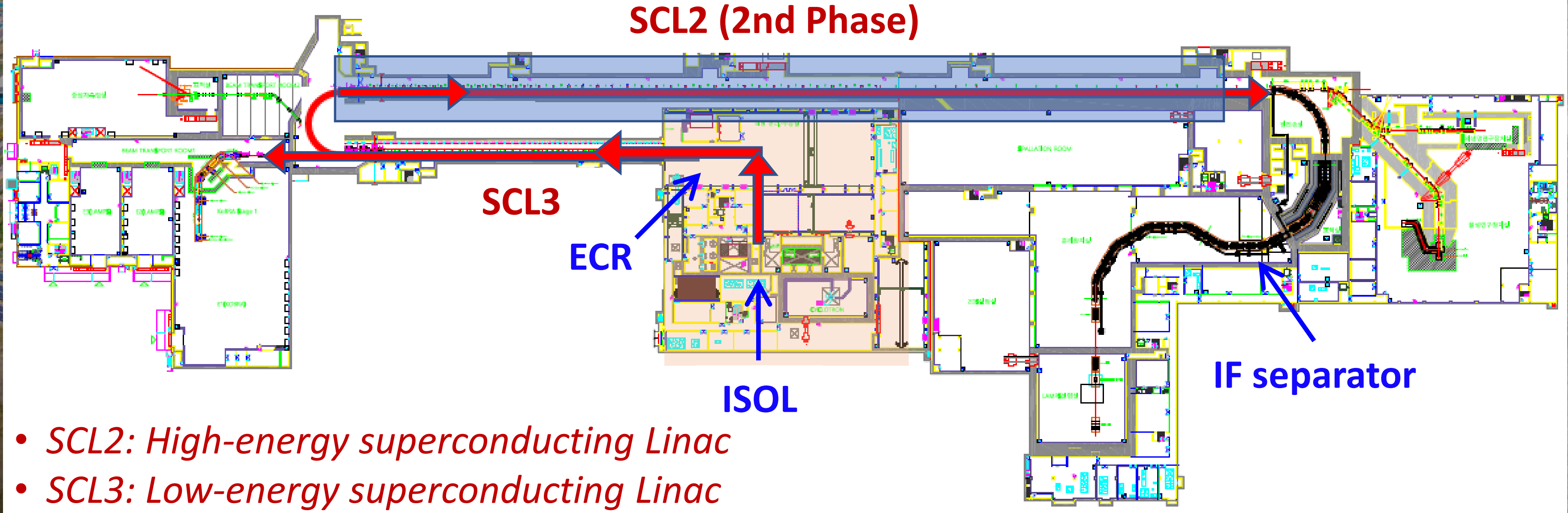
- Campus area : 952,066 m^2 including the reservation area of 144,640 m^2
- Building area : 76,259 m^2 for 11 Bldgs. (Total floor area of 116,252 m^2)

RAON

Scientific goals

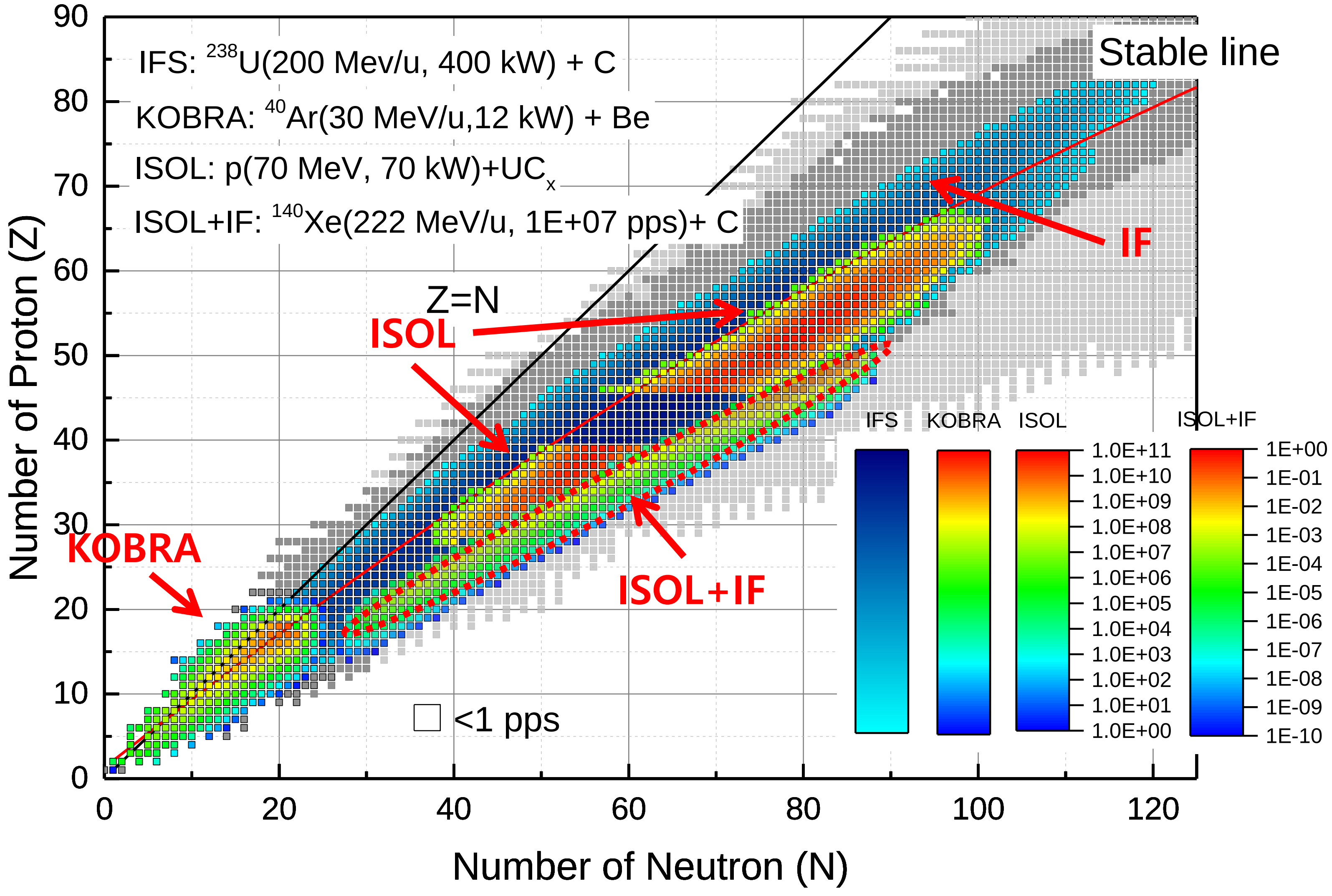
RIB production methods at RAON

	KoBRA	ISOL	IF separator
RIB production & acceleration mode	ECR (SIB) → SCL3 → KoBRA Prod. Target (RIB)	Cyclotron (p) → TIS (RIB) → SCL3	ECR (SIB) / ISOL (RIB) → SCL3 → SCL2 → IF (RIB)
Production mechanism	Direct reactions, Multi-nucleon transfer	p induced U fission	PF, U fission
RIB energy	< a few tens MeV/u	> a few keV/u	< a few hundreds MeV/u



- *SCL2: High-energy superconducting Linac*
- *SCL3: Low-energy superconducting Linac*

Expected RIBs from RAON

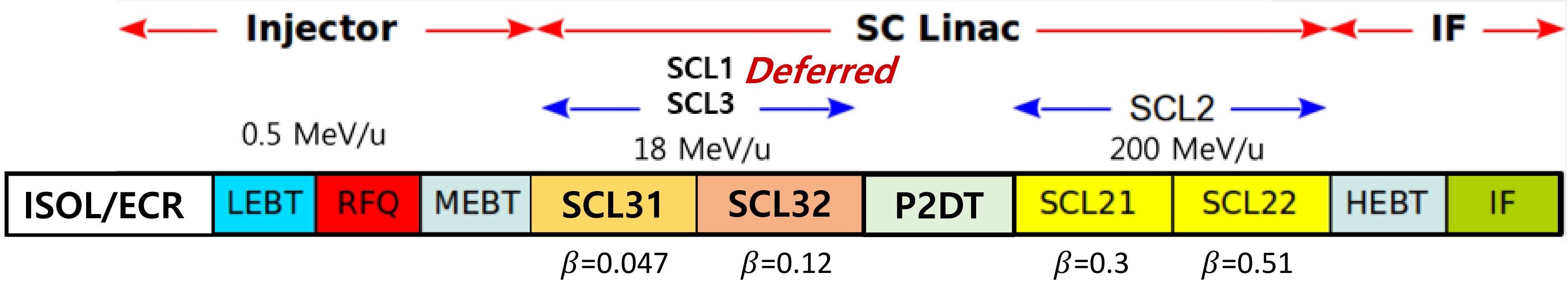


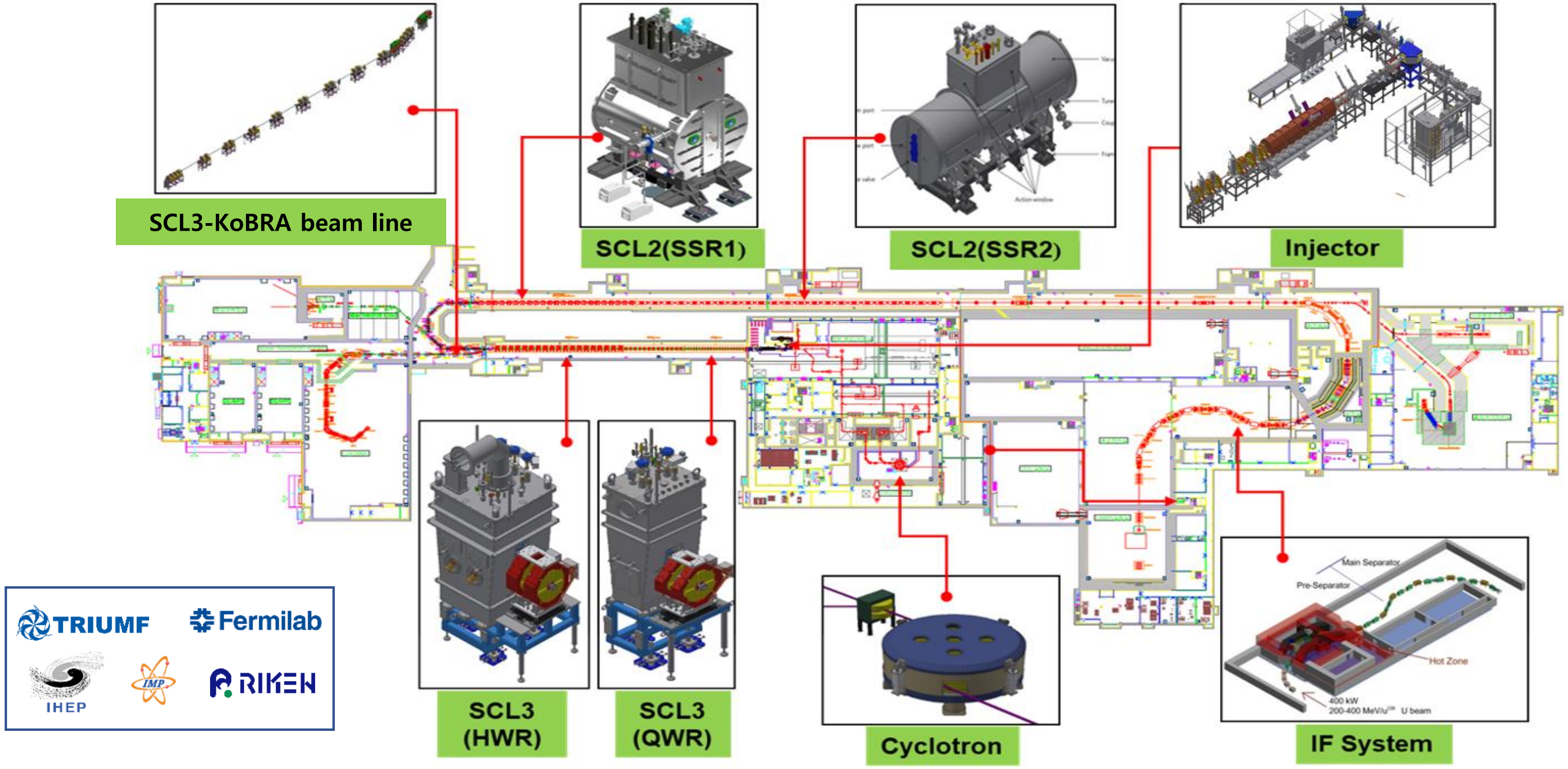
- RAON is going to eventually combine ISOL and IF to provide more exotic RIBs.
- RAON is expected to access to more neutron-rich regions of the nuclear chart.

Part 2.

Accelerator system

Accelerator system (Overview)



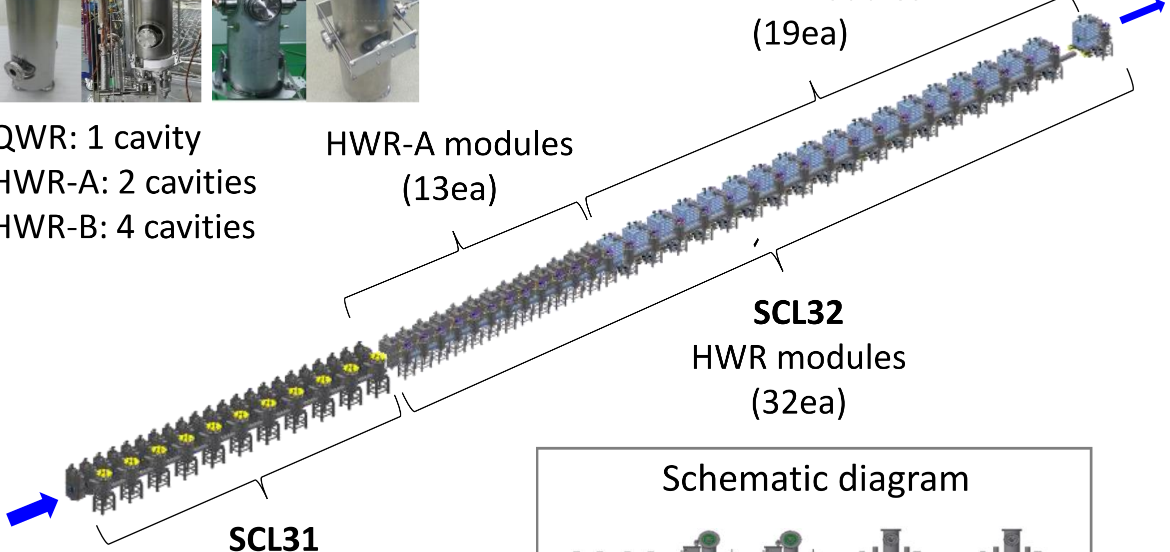


- **Phase I (~2022)**
  - Installation and beam commissioning of the injector, SCL3 and ISOL
  - Installation and machine commissioning of all experimental systems & IF separator
- **Phase II (~2029)**
  - R&D, construction, installation and beam commissioning of SCL2

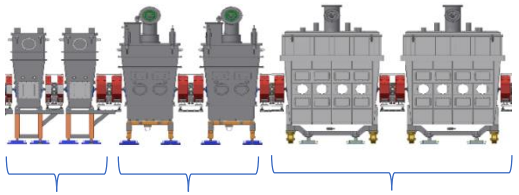
Accelerator system (Overview of SC Linacs)

SCL3 (Phase I)

QWR: 1 cavity
HWR-A: 2 cavities
HWR-B: 4 cavities

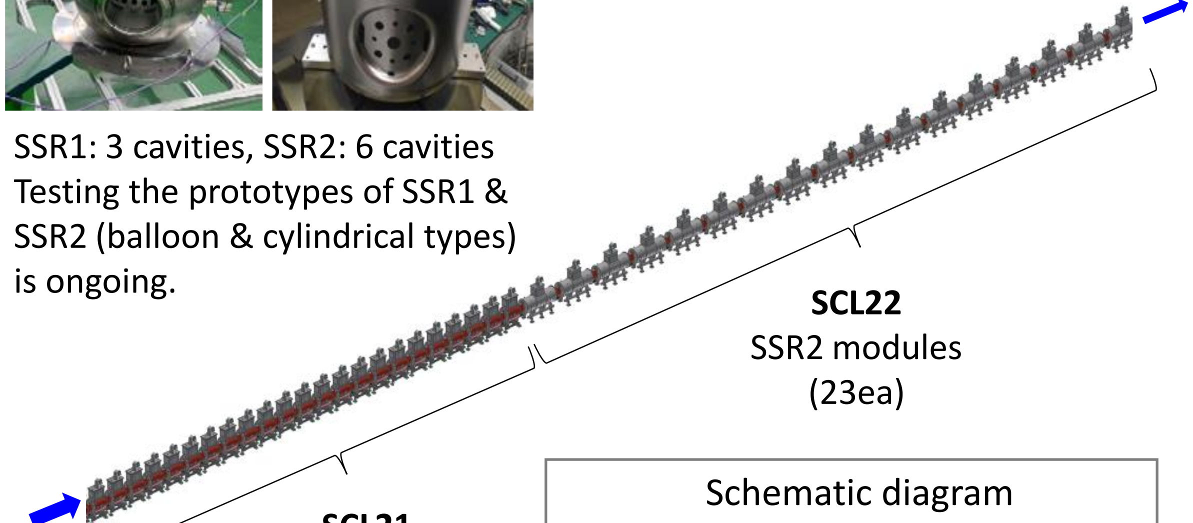


Schematic diagram

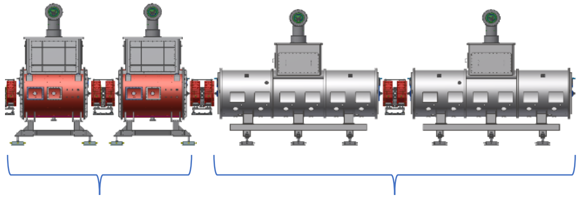


SCL2 (Phase II)

SSR1: 3 cavities, SSR2: 6 cavities
Testing the prototypes of SSR1 & SSR2 (balloon & cylindrical types) is ongoing.



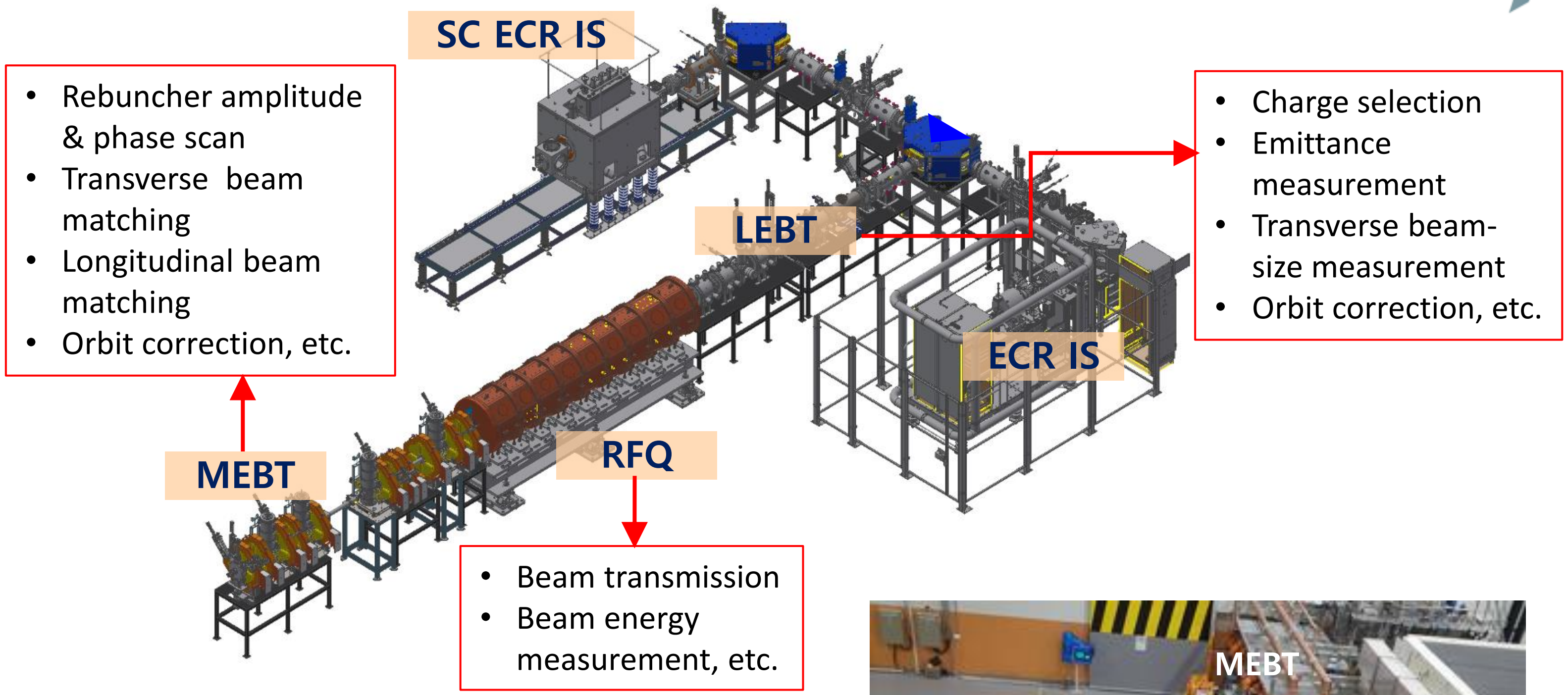
Schematic diagram



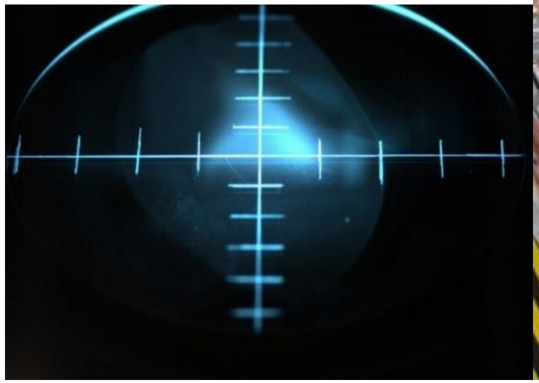
- *SSR2: 23 for acceleration and additional 2 for bunching*

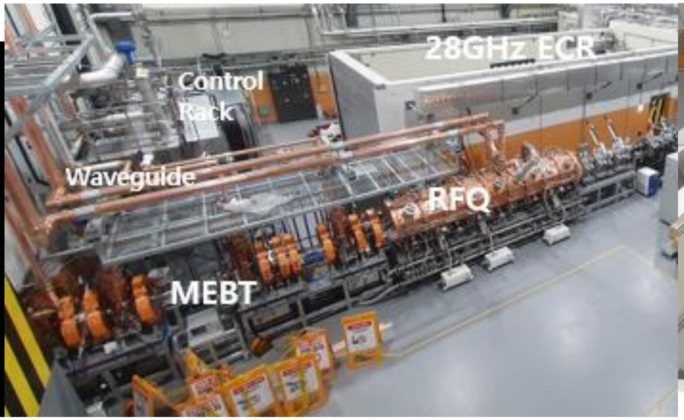
Injector system

- Two ECR IS's
  - 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 efficiency ~98%
  - CW RF power 94 kW (SSPA: 150 kW)
- MEBT (E = 500 keV/u)
  - Four RF bunchers (SSPA: 20, 15, 2 X (4 kW))
  - Simple quadrupole magnets, Instrumentation
- Beam commissioning since Oct. 2020

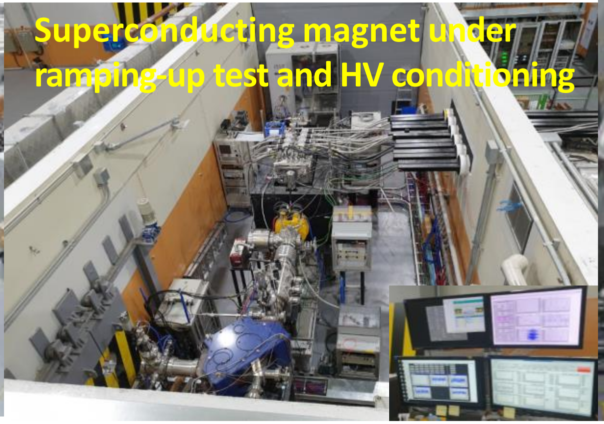


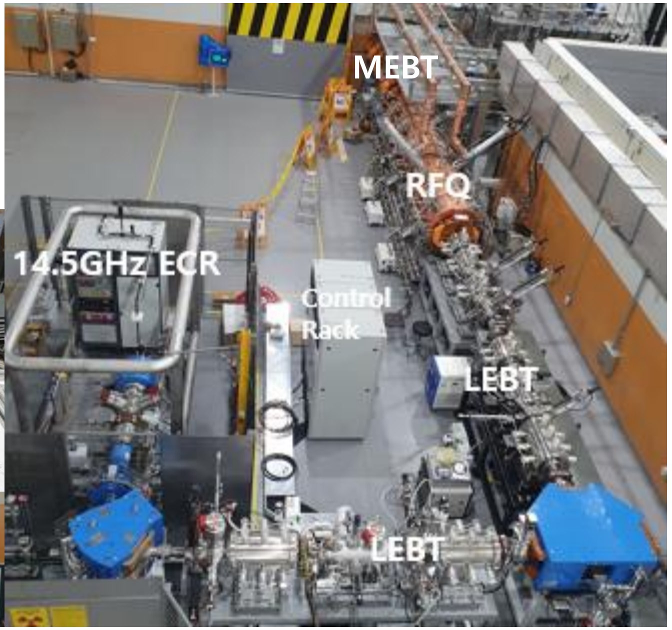
Ar^{8+} 10μA @ Beam Viewer('21)





28 GHz SC ECR IS

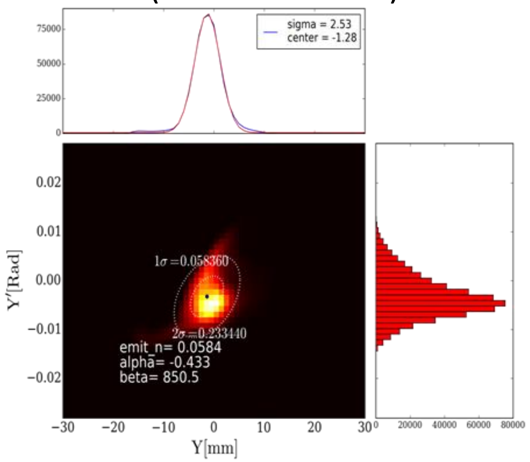




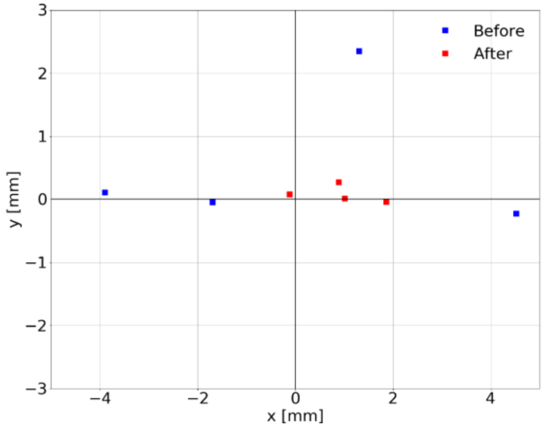
Injector beam commissioning

Parameter	Value
[Beam Properties]	
Frequency	81.25 MHz
Particle	H^{1+} to $^{238}U^{33+}$
Input energy	10 keV/u
Input current	0.4 mA
Input emittance	0.012 cm·mrad
Output energy	0.507 MeV/u
Output emittance	0.0125 cm·mrad
Transmission	~98% (simulation)
Duty factor	100%

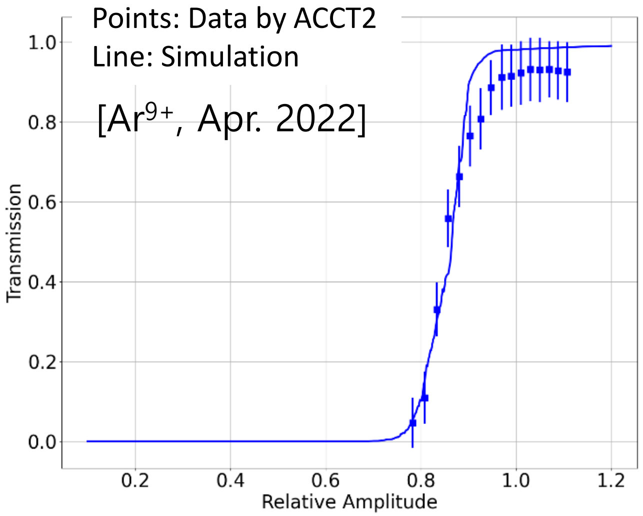
LEBT Beam emittance
(Allison scanner)

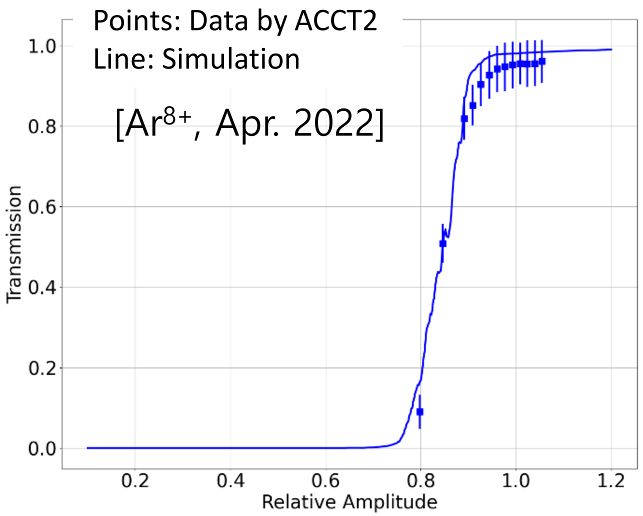


LEBT orbit correction



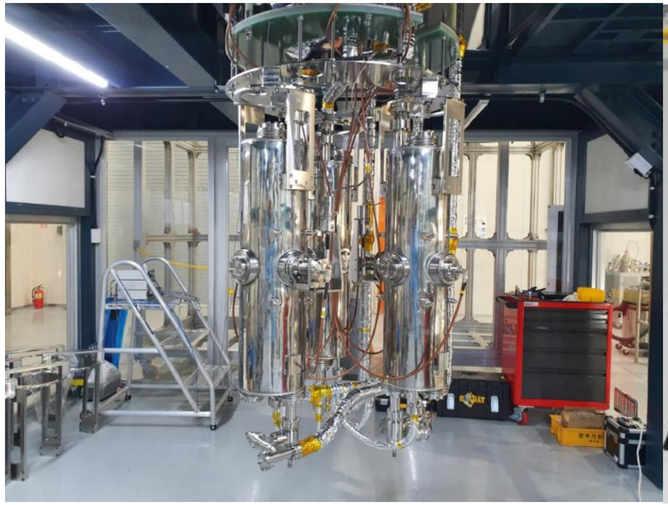
- Beams
  - Ar^{9+} (~30 μA) & Ar^{8+} (~47 μA): 100 μs long pulsed beam
  - Repetition rate: 1 Hz
- EPICS basis control system
- RFQ transmission
  - Measured by ACCTs in LEBT & MEBT (Error bar: 3σ)
  - Ar^{9+} (91.9% w/ σ=1.9%) & Ar^{8+} (95.4% w/ σ=1.3%)
- Energy
  - 507 keV/u by ToF using the two BPMs in MEBT

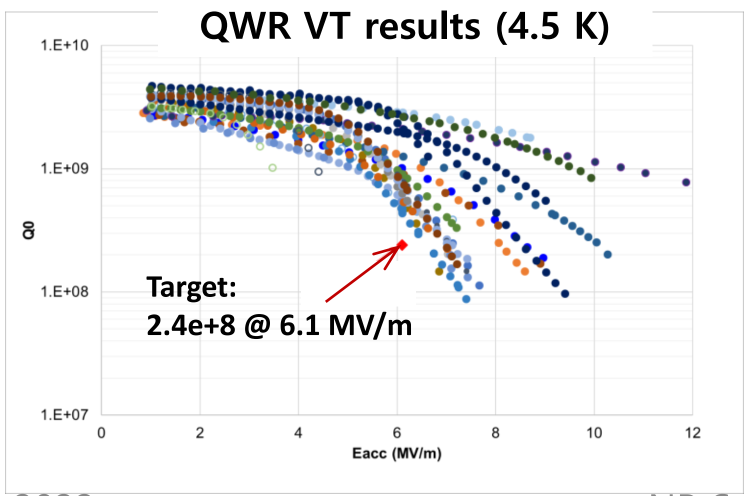


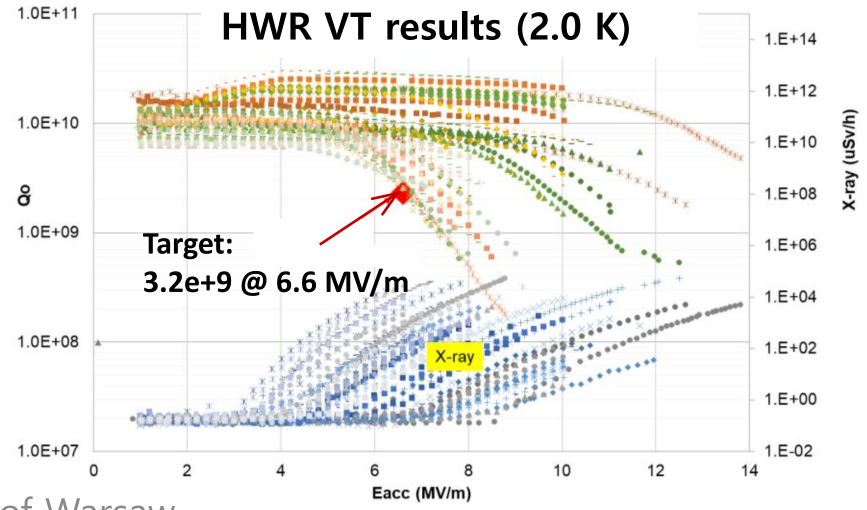


SRF test facility and QC

- Processing the performance tests of SCL2 and SCL3 cavities & modules at cryogenic temperature
- Onsite test facility: 3 vertical test (VT) pits with 3 cavities per pit and 3 horizontal test (HT) bunkers
- It can cover all RAON cavities: QWR (81.25 MHz), HWR (162.5 MHz) and SSR1/SSR2 (325 MHz)







SCL3 and cryoplants

- Cryomodules (CM) & warm sections were assembled in the clean booth in the tunnel.
- Total counts of particles for the size > 0.5 µm/10 min. were less than 30.

SCL3 (2021)

- Cryoplants
  - SCL3 (4.2 kW @ 4.5 K), SCL2 (13.5 kW @ 4.5 K)
  - Two plants combined through the distribution box. If one plant down, the other can be maintained cold. (We operate either SCL2 & 3 together or just one.)

Cold box

Warm compressors

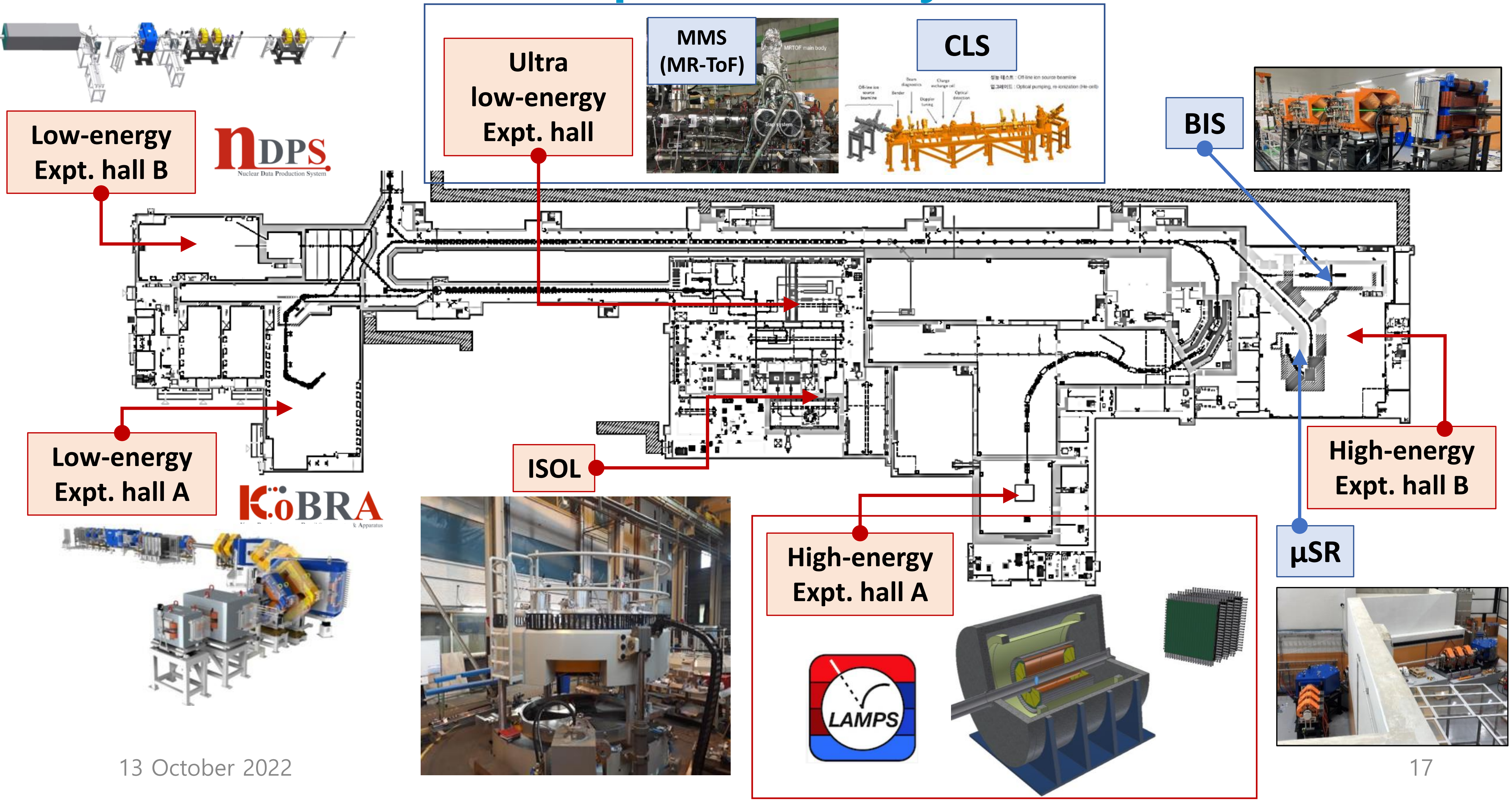
LHe Dist. box

- SCL3 cryoplant
  - Installation completed in 2021
  - SAT completed in July 2022
  - Cooldown started in Sep. 2022
  - RF conditioning in the end of Sep. 2022
  - Beam commissioning in Oct. 2022 (Goal: Beam injection to the first 5 modules)
- SCL2 cryoplant
  - Commissioning ongoing

Part 3.

RI & experimental systems

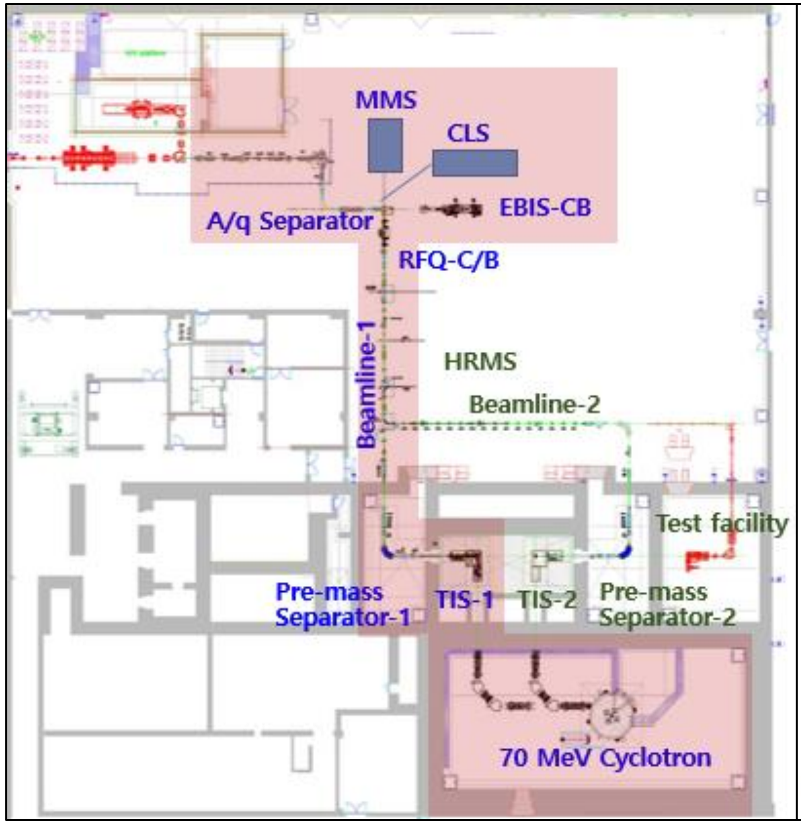
Overview of experimental systems

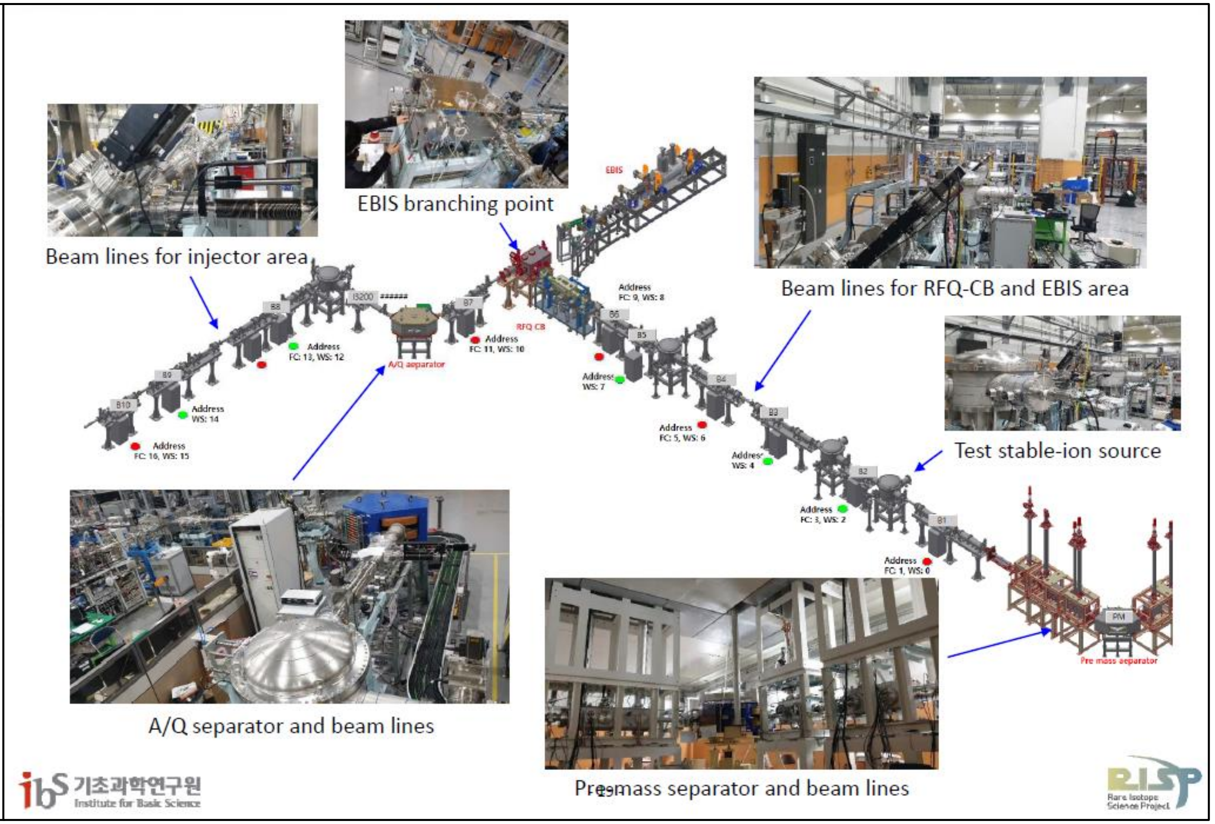


RAON ISOL system

Target Ion Source ($^{132}Sn^{1+}$, 20 keV) → Pre-Separator ($m/\delta m \simeq 400$) → RFQ Cooler-Buncher (3π mm mrad, < 5 eV) → EBIS ($^{132}Sn^{33+}$, 10 keV/u) → A/q Separator ($m/\delta m \simeq 250$) → Post Linac (Charge state n+)

- Driver beam: p, $35 \leq K \leq 70$ MeV with $\gtrsim 50$ kW
- Target: SiC, BN, UC_X, MgO, etc. (CaO, BeO later)
- Ion Source: Surface, RILIS, Plasma
- RIB: $6 \leq A \leq 250$, $10 \leq K \leq 80$ keV, 10^8 pps (Sn), Purity > 90% @ Exp.
- Incident to RFQ with 10 keV/u
- Full remote maintenance system with TIS modularization



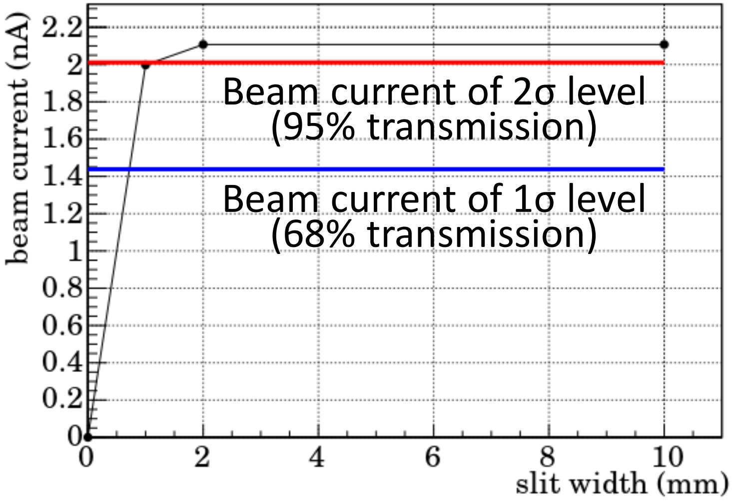


◐ ISOL beamlines including sub-systems were commissioned with Cs ions in 2021 (next slide).

ISOL SIB commissioning

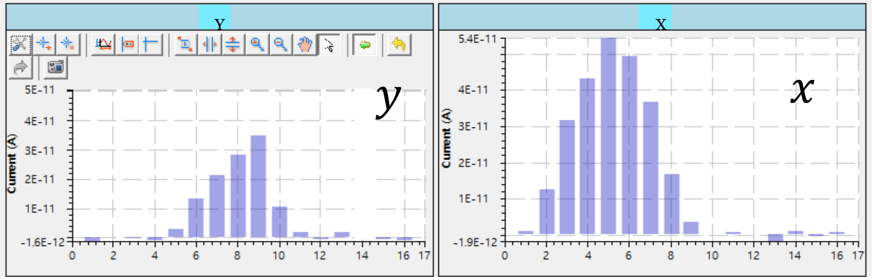
Target Ion Source ($^{133}Cs^{1+}$, 20 keV) → Pre-Separator ($m/\delta m \simeq$1,000) → RFQ-CB (>10^8 ions/bunch) → EBIS (>15% $^{133}Cs^{27+}$, A/q<6) → A/q Separator ($m/\delta m \simeq$ 250) → Post Linac ($^{133}Cs^{27+}$, 10 keV/u)

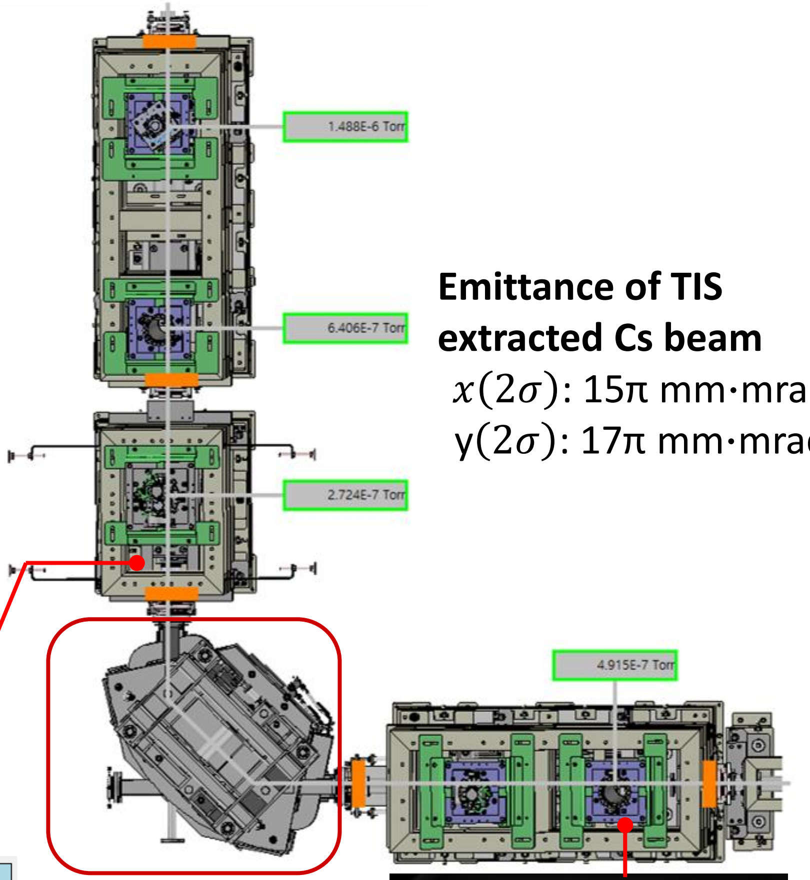
Beam size measurement by F2 slit

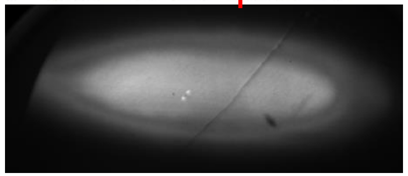


- Horizontal beam size ~2 mm (2σ)
- Mass-resolving power of Pre-mass separator ~1,000 (2σ)

Cs⁺ Beam profile (Wire Grid)

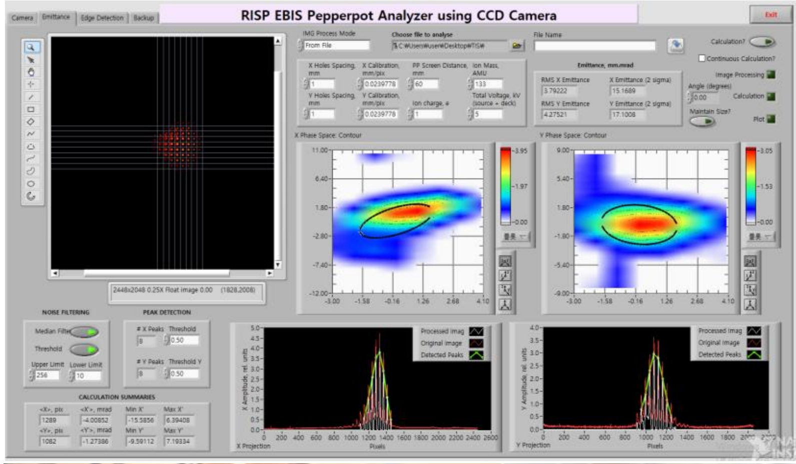


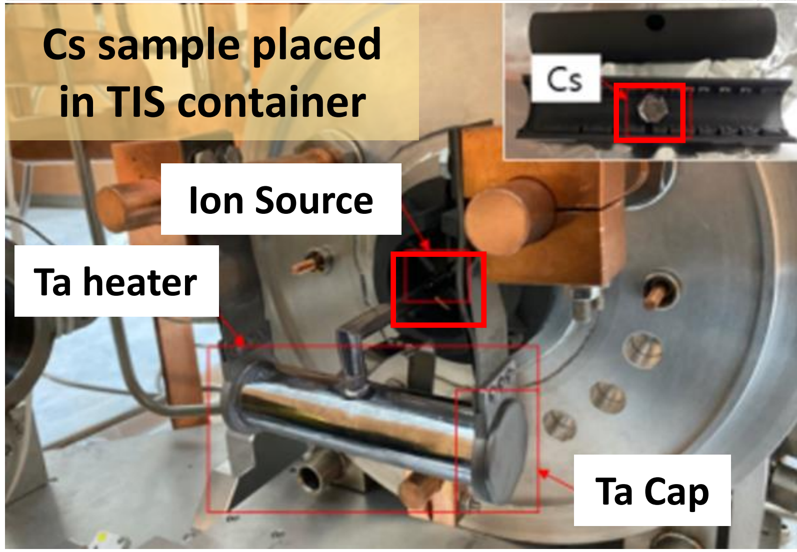




Beam viewer
x ~40 mm, y ~ 15 mm

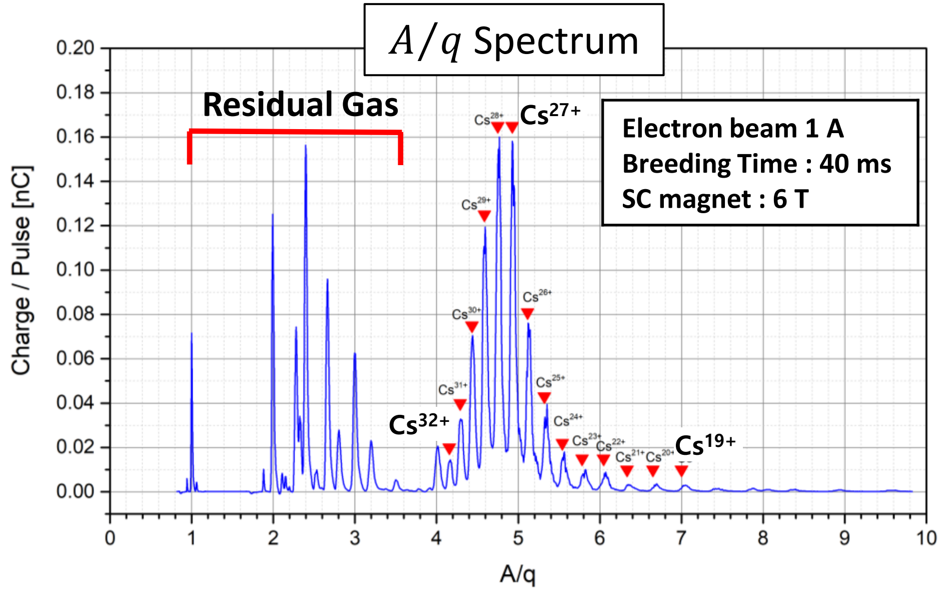
Emittance of TIS extracted Cs beam
$x(2\sigma)$: 15π mm·mrad
y(2σ): 17π mm·mrad

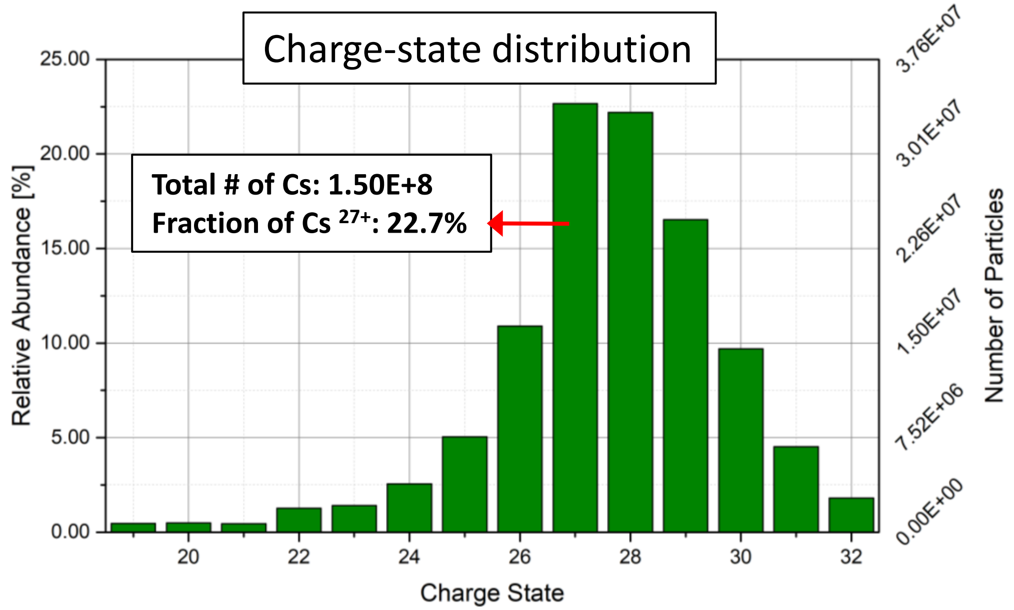


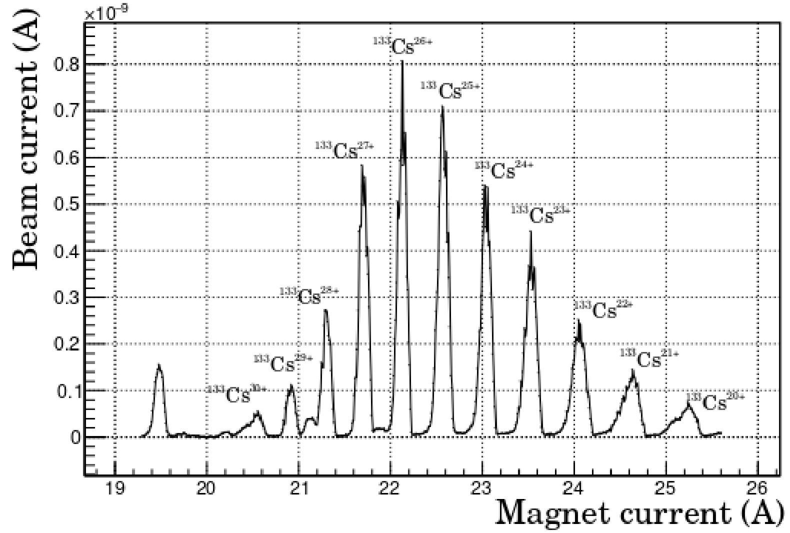


ISOL SIB commissioning

Target Ion Source ($^{133}Cs^{1+}$, 20 keV) → Pre-Separator ($m/\delta m \simeq$1,000) → RFQ-CB (>10^8 ions/bunch) → EBIS (>15% $^{133}Cs^{27+}$, A/q<6) → A/q Separator ($m/\delta m \simeq$ 250) → Post Linac ($^{133}Cs^{27+}$, 10 keV/u)







- A/q spectrum and resolving power (preliminary)
  - Momentum dispersion of A/q magnet: 1.244 m
  - Beam size in $2\sigma \sim \pm 5$ mm from the slit-width dependence of beam current → Mass-resolving power ~250 (2σ)
- With much more careful tuning, the higher mass-resolving power of ~400 in 2σ can be achieved.

RAON Cyclotron

- Specifications
  - Proton beams at 35~70 MeV
  - Maximum beam current: 0.75 mA
  - Two beamlines to the ISOL TIS bunker

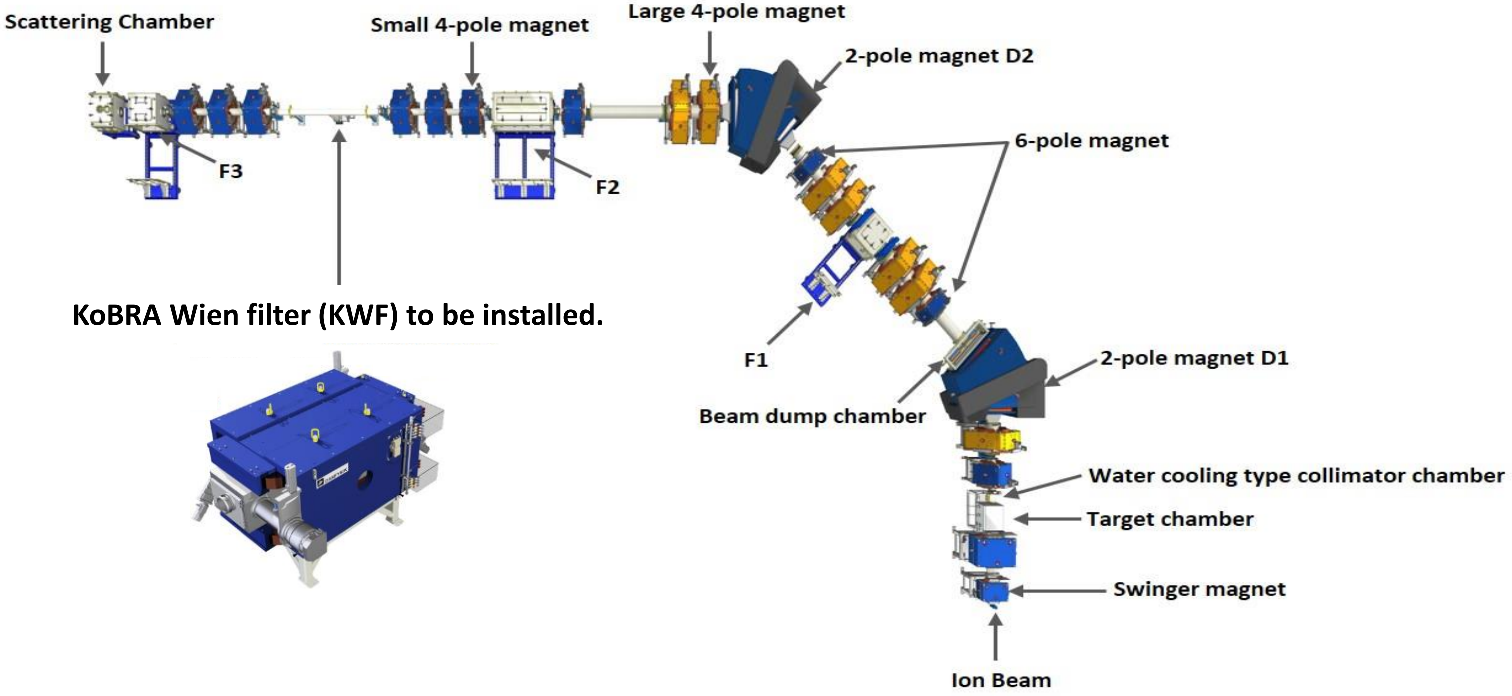
- History
  - Jun. 2019: Contract with IBA
  - Apr. 2020: Design finalized
  - Jun. 2021: Factory Acceptance Test (FAT)
  - Aug. 2021: Shipping
  - Nov. 2021~**Apr. 2022: Installation**
  - Oct. 2022: Site Acceptance Test (SAT) (plan)
  - Still need to finalize the interface between cyclotron and ISOL

Cyclotron

Cyclotron beamline installation

KoBRA

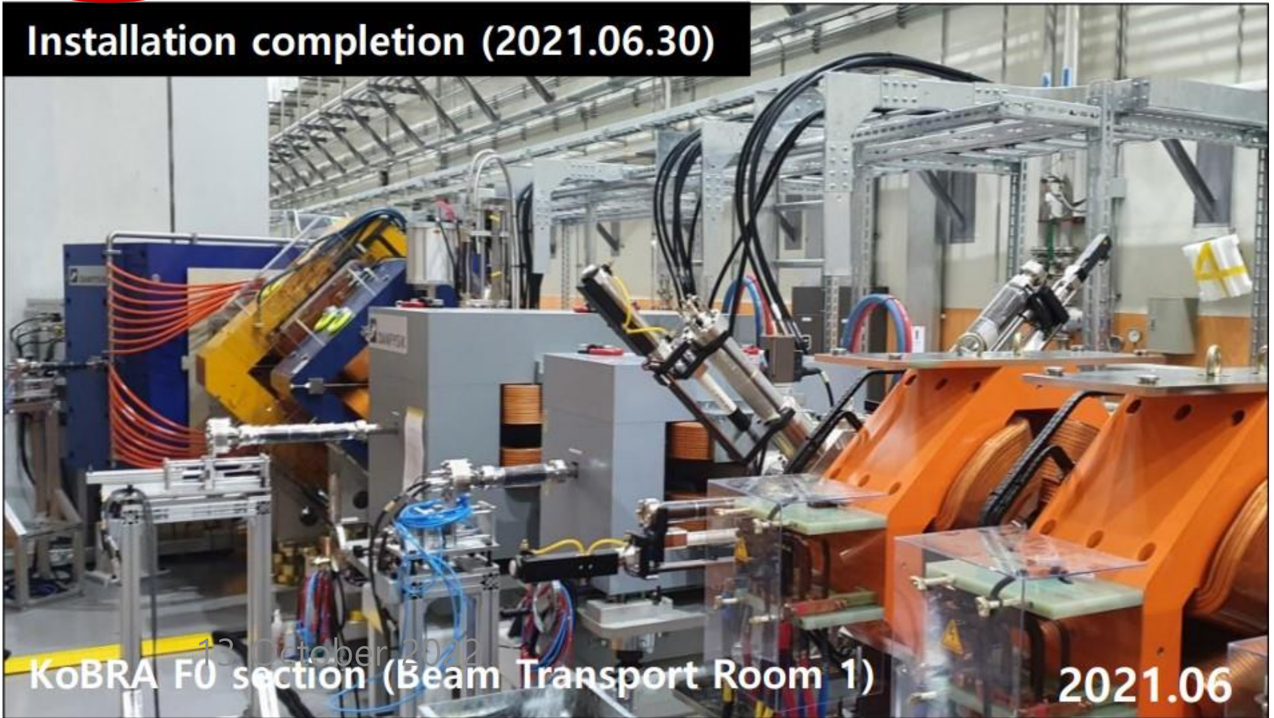
- **Ko**rea **B**road acceptance **R**ecoil spectrometer & **A**pparatus
- Instrument for nuclear structure and nuclear astrophysics using stable or RI beams in the energy range of 1~40 MeV/u
  - Stable ions up to ~40 MeV/u from ECR IS ($\lesssim$ 40 MeV/u for $A \leq 40$ and $\lesssim$ 20 MeV/u for $A \geq 100$)
  - RIB production at a few MeV/u using the stable ion beams from ECR IS
  - Role of the recoil mass separator for RIBs from ISOL at beam energies less than a few MeV/u



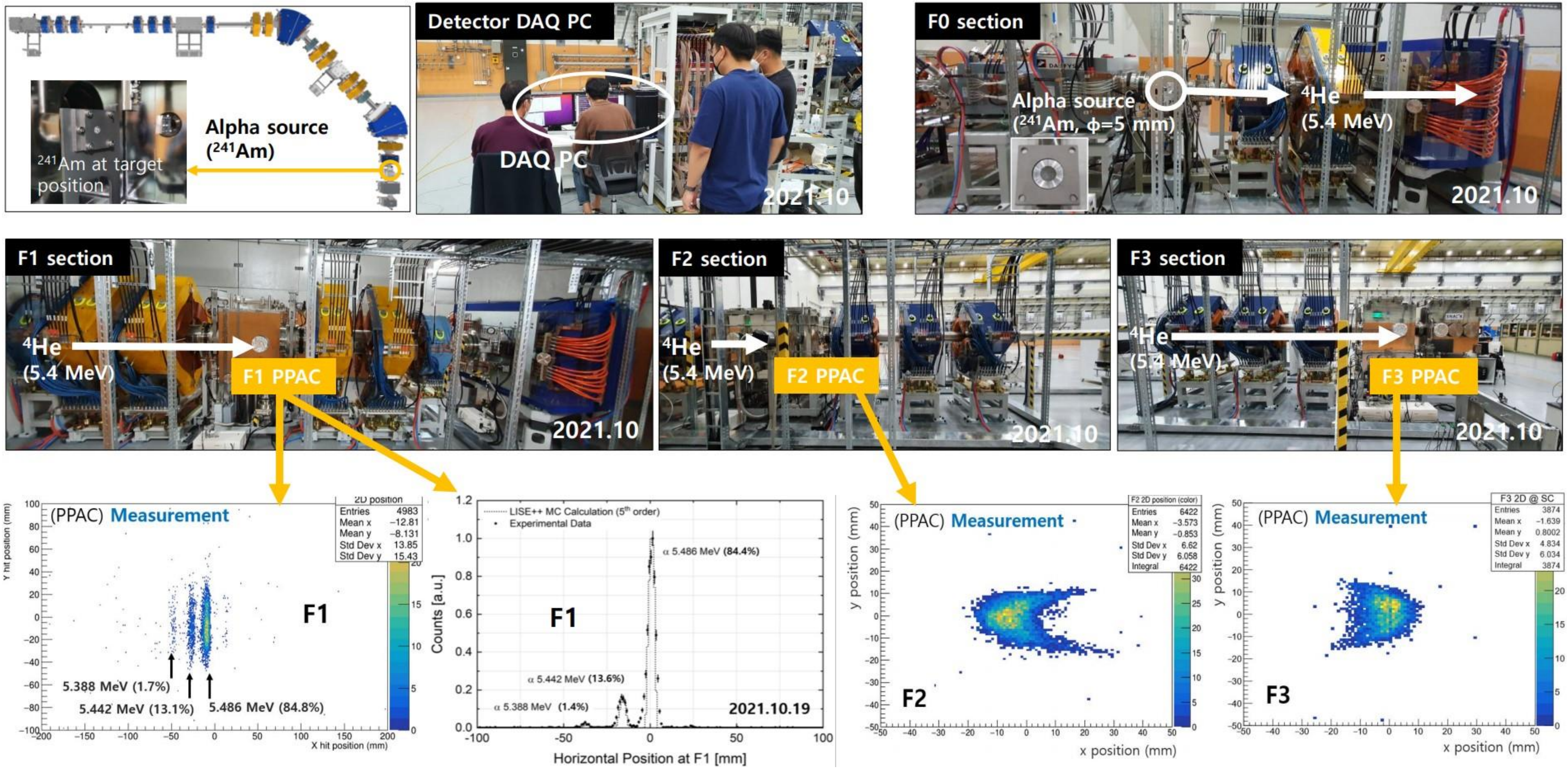
KoBRA Wien filter (KWF) to be installed.

Magnetic rigidity	0.25 – 3.0 Tm
Angular acceptance	80 mrad (H) 200 mrad (V)
Momentum acceptance	8%
Momentum resolving power at F1	2100 at 2 mm beam size
Mass resolving power (with Wien filter)	750 at 2 mm beam size
Beam swinger	up to 12 degree for 3 Tm
High order correction	up to 4^{th} order
Degrader at F1	Homogeneous

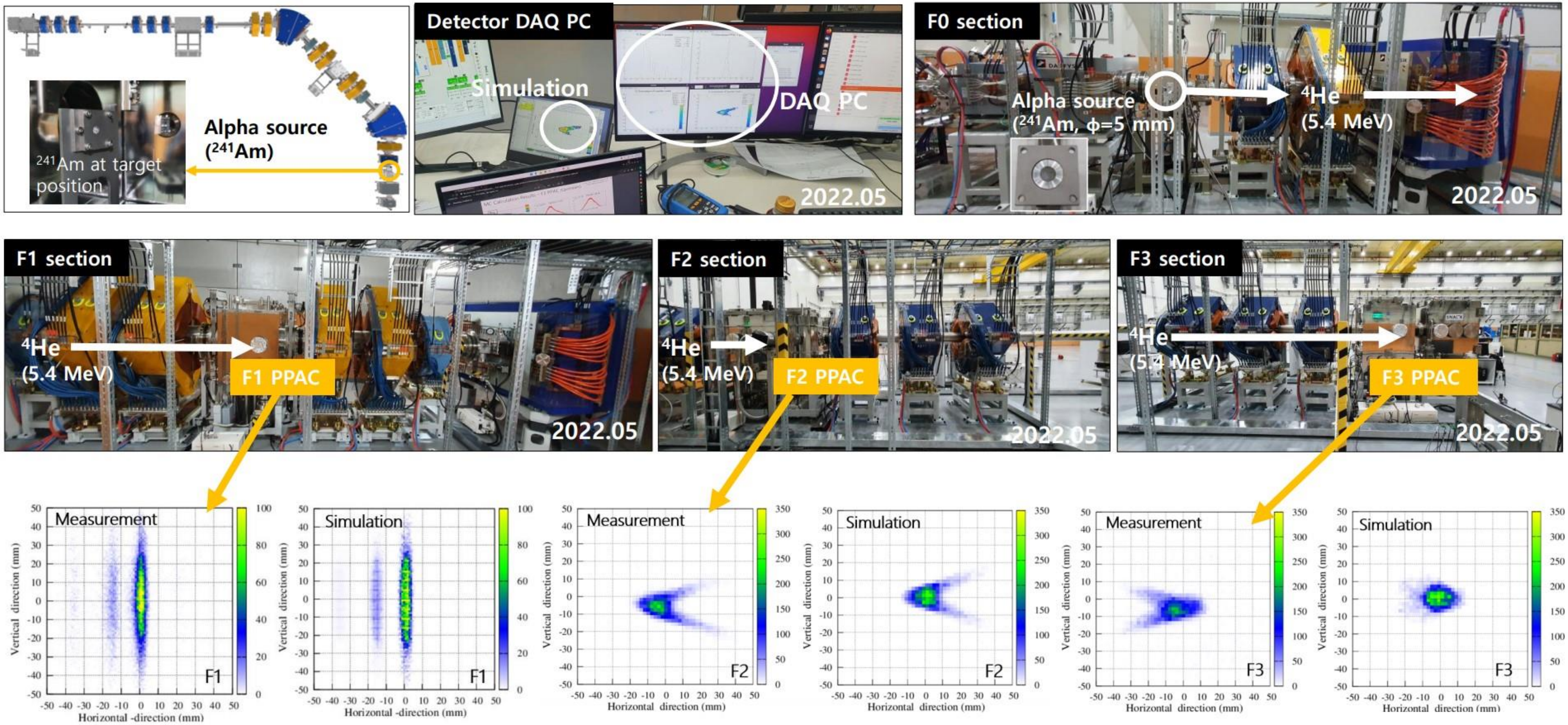
RAON KoBRA



SNACK: **S**ilicon detector array for **N**uclear **A**strophysi**C**s study at **K**oBRA


Alpha source
(^{241}Am)
^{241}Am at target position
Detector DAQ PC
DAQ PC
2021.10
F0 section
Alpha source
(^{241}Am, ϕ=5 mm)
^{4}He
(5.4 MeV)
2021.10
F1 section
^{4}He
(5.4 MeV)
F1 PPAC
2021.10
F2 section
^{4}He
(5.4 MeV)
F2 PPAC
2021.10
F3 section
^{4}He
(5.4 MeV)
F3 PPAC
2021.10
(PPAC) Measurement
F1
5.388 MeV (1.7%)
5.442 MeV (13.1%)
5.486 MeV (84.8%)
X hit position (mm)
Y hit position (mm)
LISE++ MC Calculation (5th order)
Experimental Data
α 5.486 MeV (84.4%)
α 5.442 MeV (13.6%)
α 5.388 MeV (1.4%)
2021.10.19
Counts [a.u.]
Horizontal Position at F1 [mm]
(PPAC) Measurement
F2
x position (mm)
y position (mm)
(PPAC) Measurement
F3
x position (mm)
y position (mm)

KoBRA

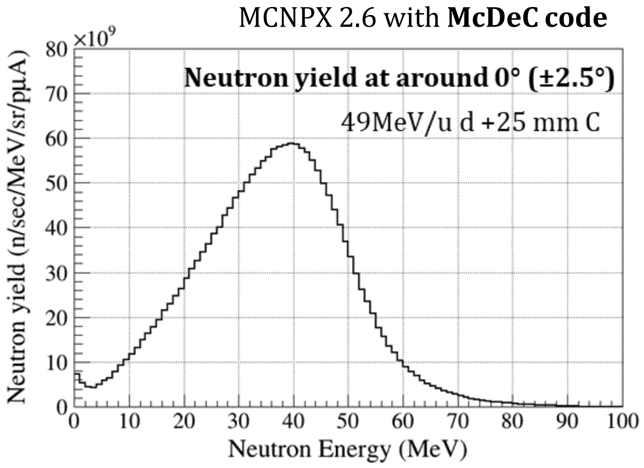


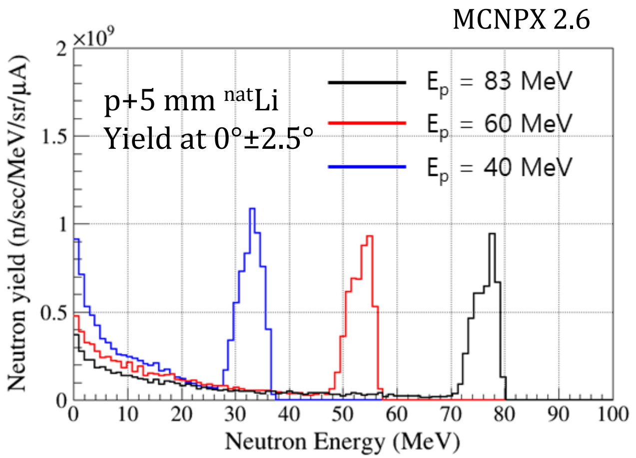
The momentum dispersion and resolving power at F1/F2/F3 agree with the expectation!

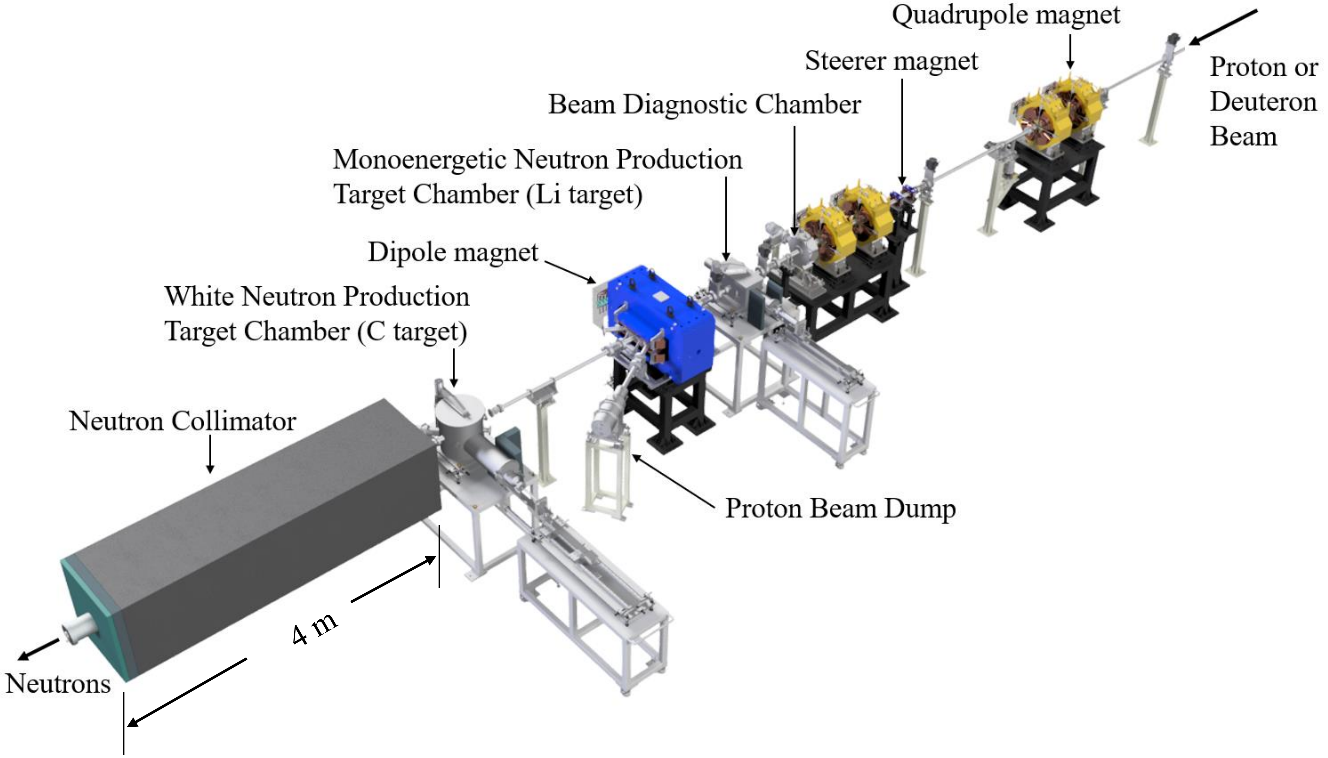
NDPS

- **N**uclear **D**ata **P**roduction **S**ystem
  - d+C for white neutrons
    - n intensity at the end of the collimator $\simeq \mathbf{10^8}$ **neutrons/cm^2/sec for 10 pμA**
  - p+Li for monoenergetic neutrons
    - n intensity at the end of the collimator $\simeq \mathbf{10^5}$ **neutrons/cm^2/sec for 10 pμA**

Beam species	proton, deuteron
Maximum Beam energy	49 MeV/u for deuteron 83 MeV for proton
Maximum Beam current	~10 μA
Target	C for white neutron Li for monoenergetic neutron
Bunch length	~1 ns (FWHM)
Repetition rate	1 – 200 kHz
Flight length	5 – 40 m
Neutron flux	~10^8 cm^{-2} sec^{-1} at 5 m







October 2020


ToF room


Target room

July 2022

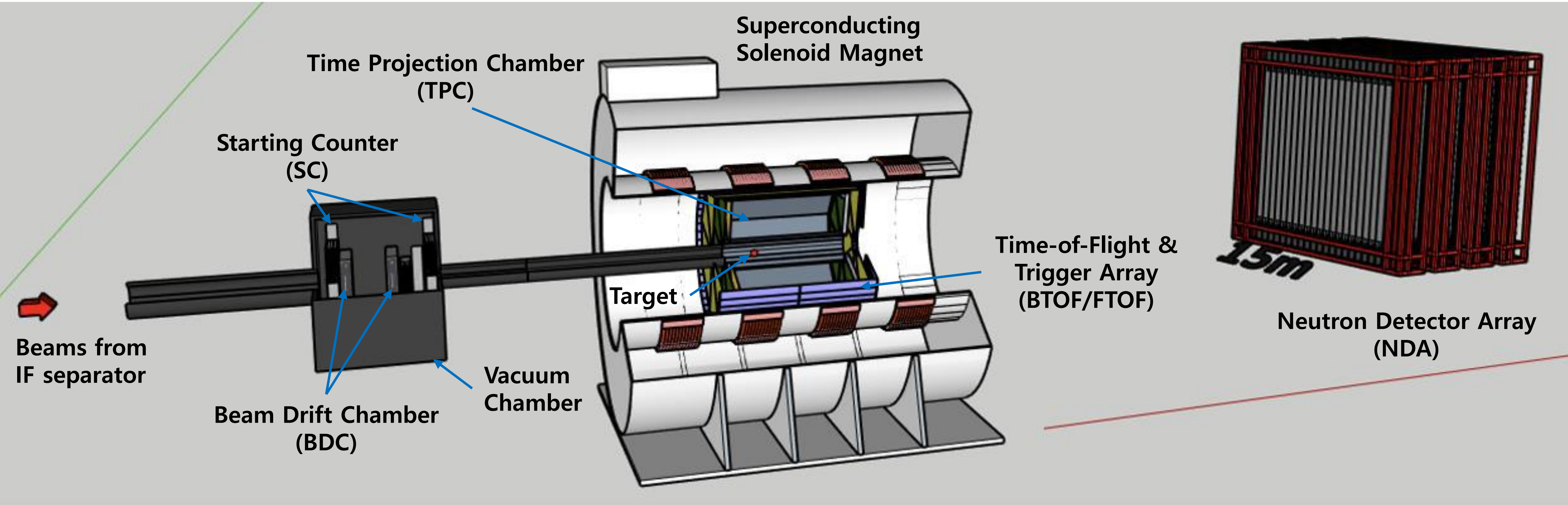
Neutron beam dump

Neutron Collimator

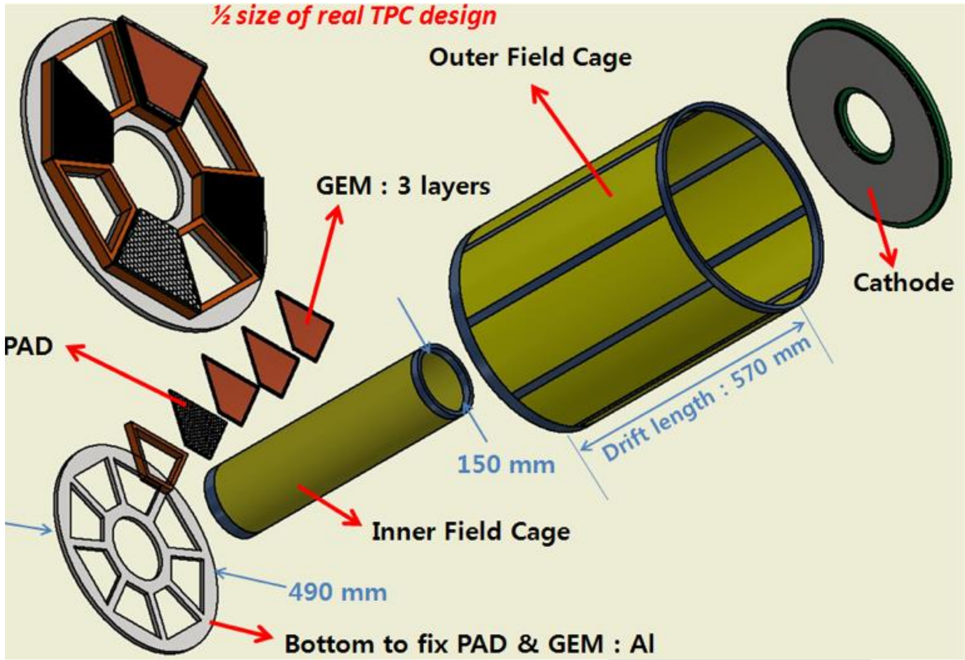

Target room

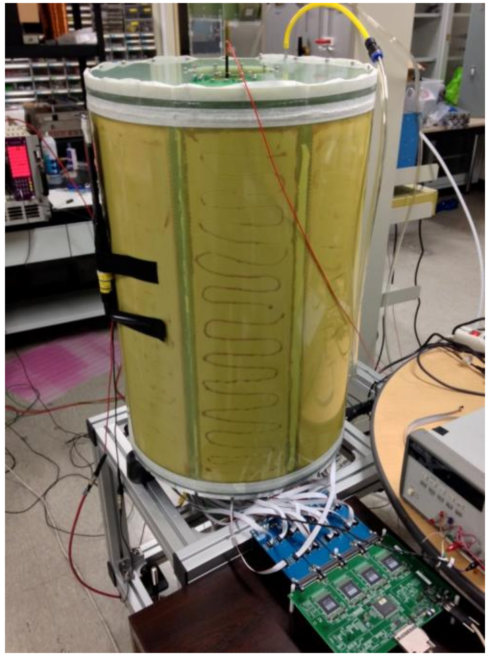
LAMPS

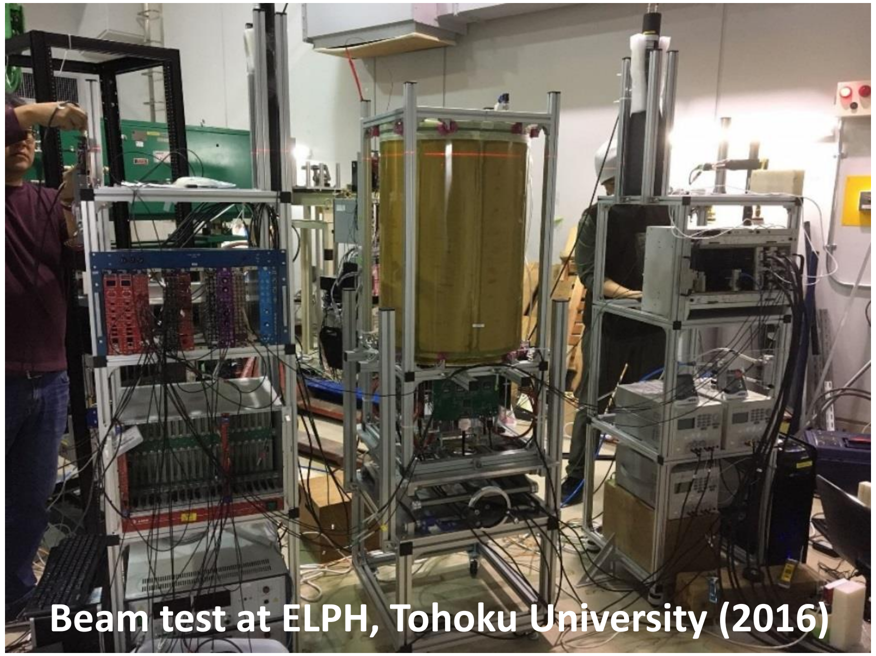
- **L**arge **A**cceptance **M**ulti-**P**urpose **S**pectrometer
  - Beam energies up to 250 MeV/u for ^{132}Sn with an intensity as large as 10^8 pps
  - Comprehensive detector system to investigate the nuclear equation of state (EoS) and symmetry energy
  - All detector components and magnet were already developed, manufactured, and assembled.
  - Integration and commissioning of the whole LAMPS system is being planned at the end of 2022.

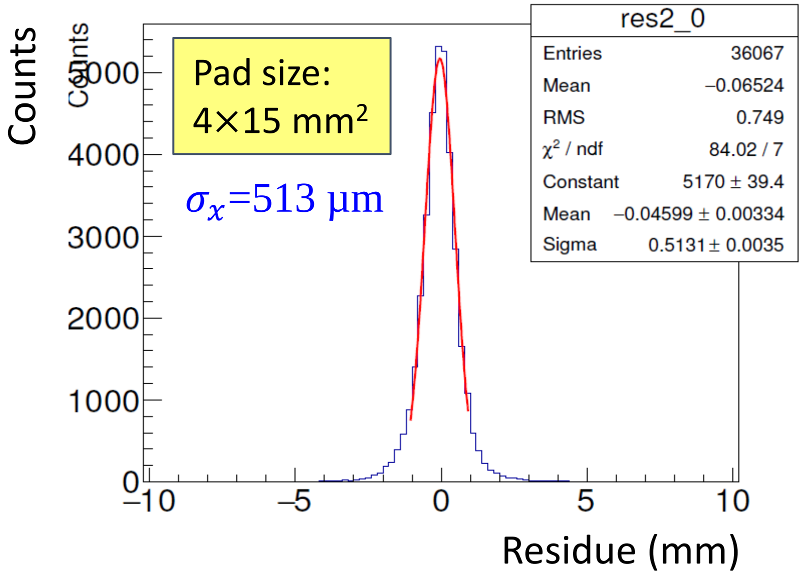


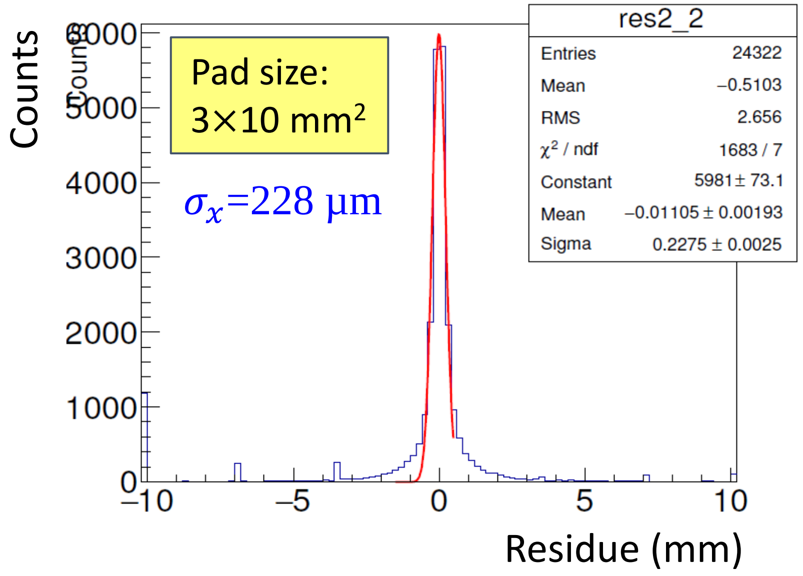
TPC: Performance test with prototype

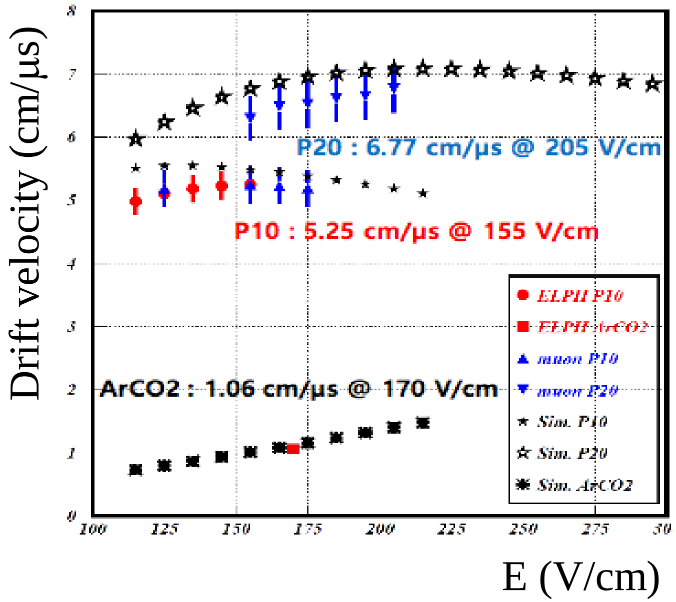




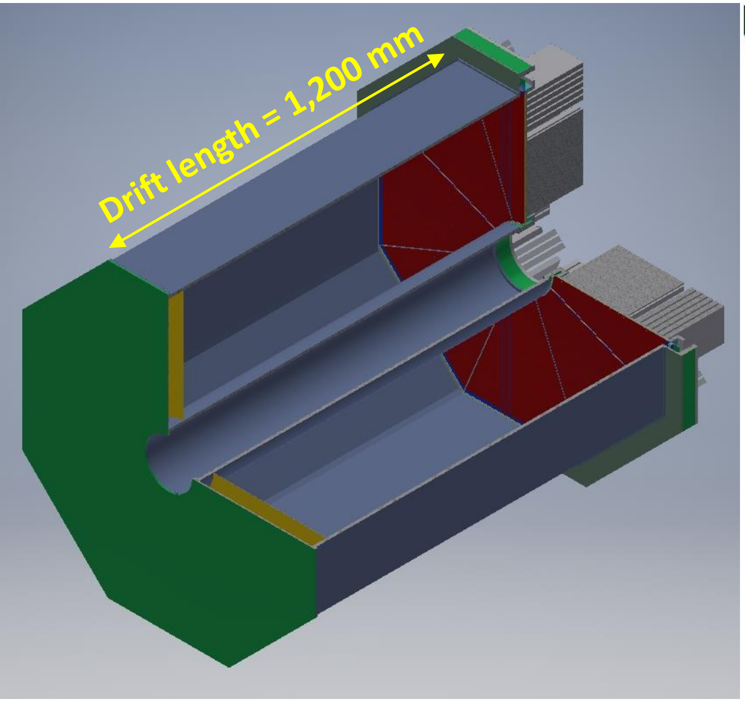


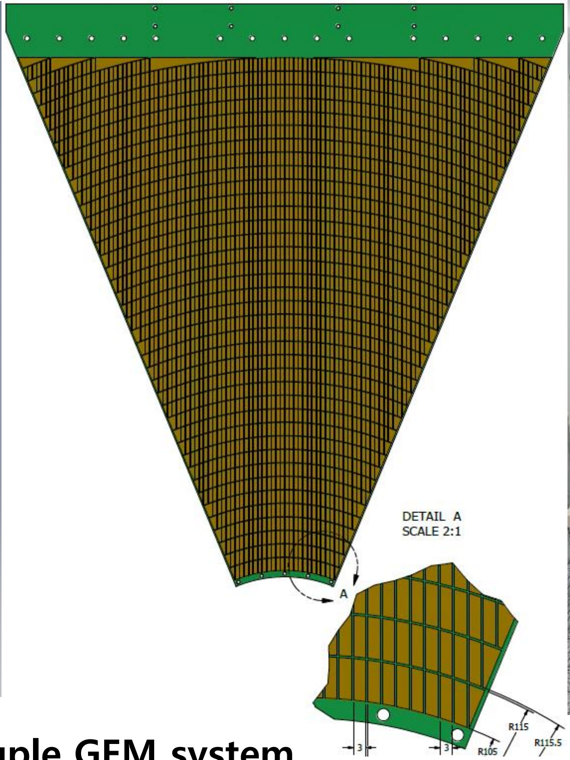


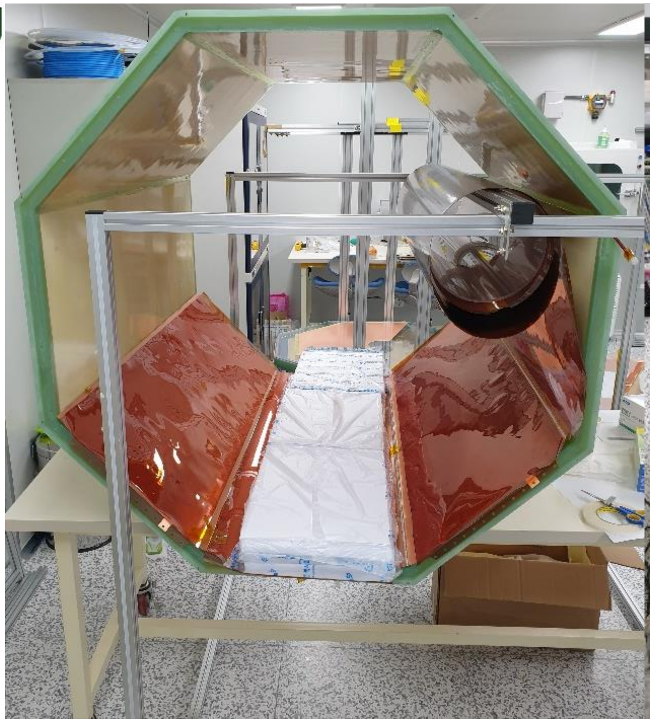




TPC: Construction of real detector

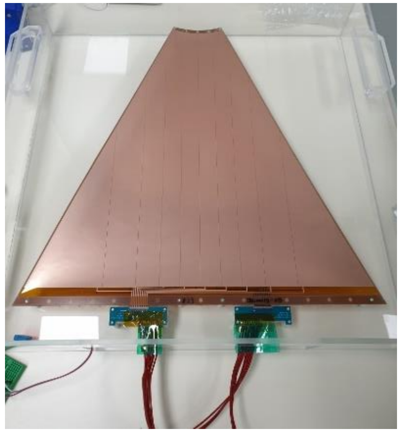


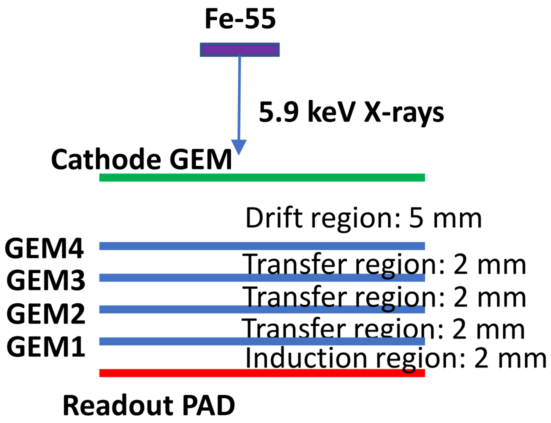


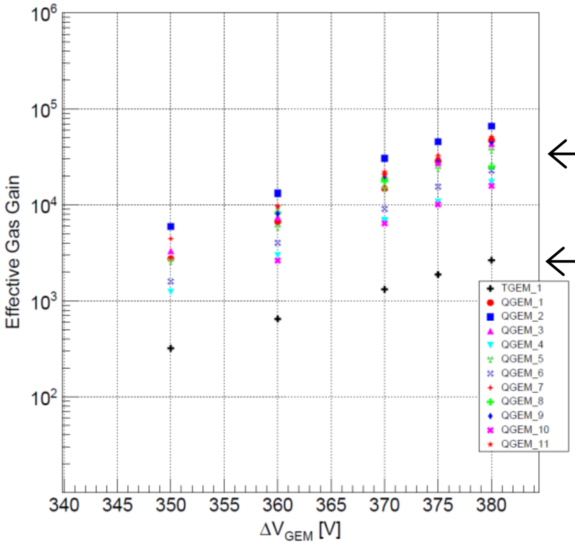


- Pad Dim.: 3×10 mm^2
- Ch. #: 2,618/sector $\times$ 8 sectors = 20,944
- FEE (GET electronics): 11 AsAD/sector $\times$ 8 sectors = 88 AsAD

Quadruple GEM system





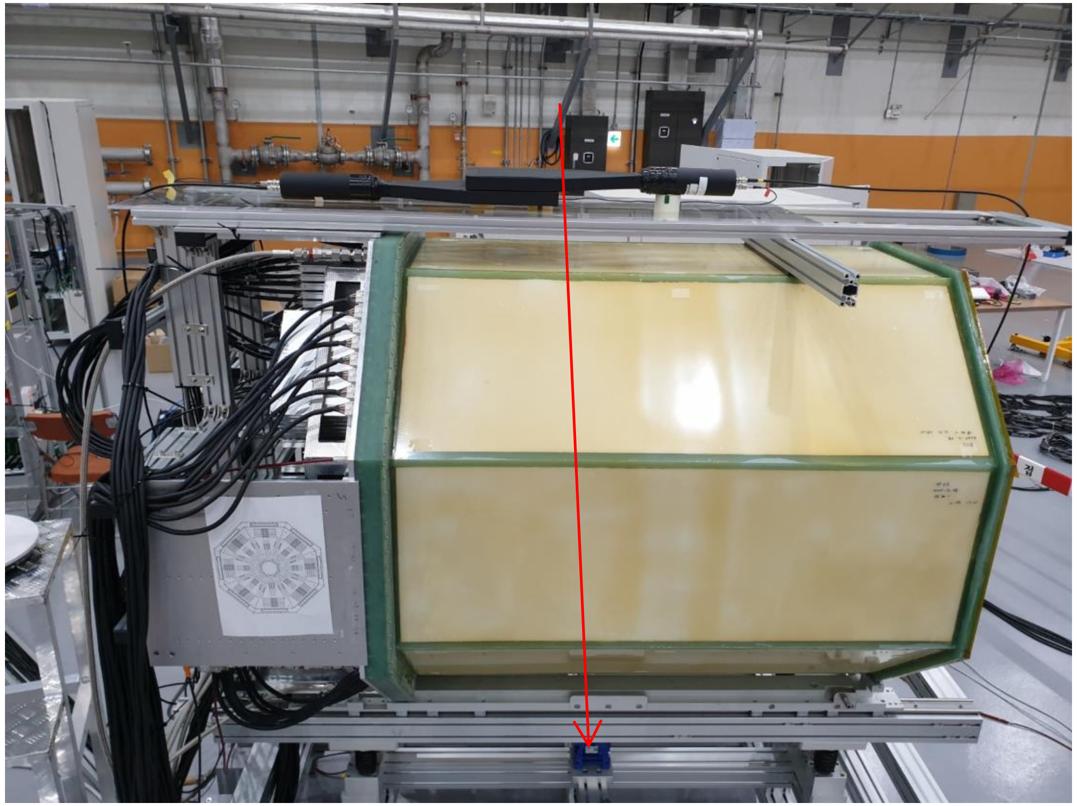


← Quadruple GEM

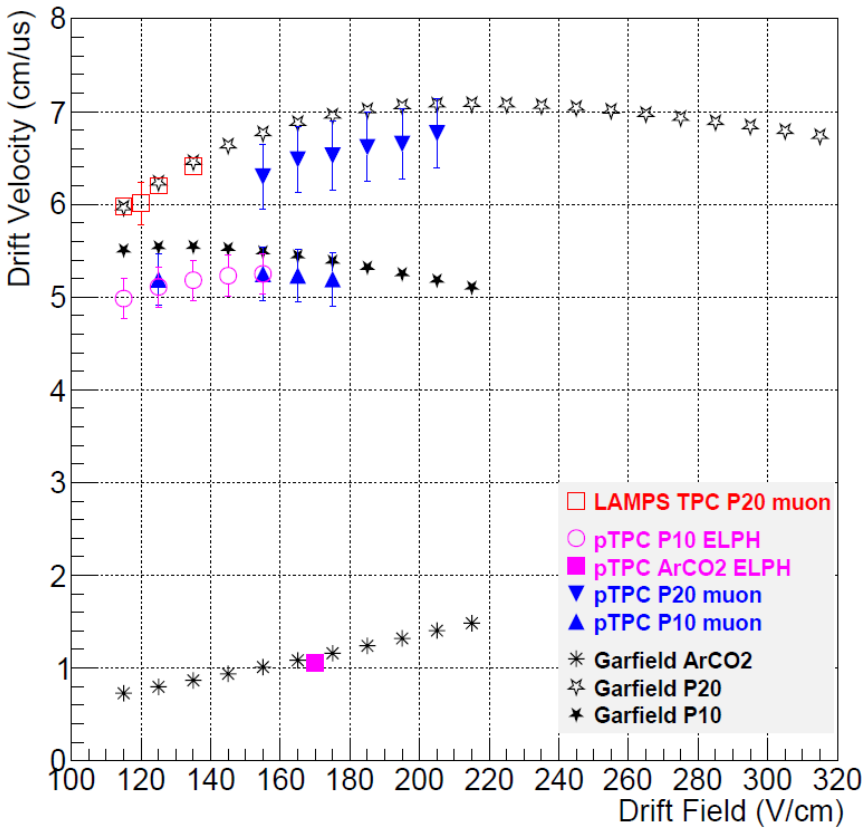
← Triple GEM

TPC: Drift velocity measurement by cosmic ray

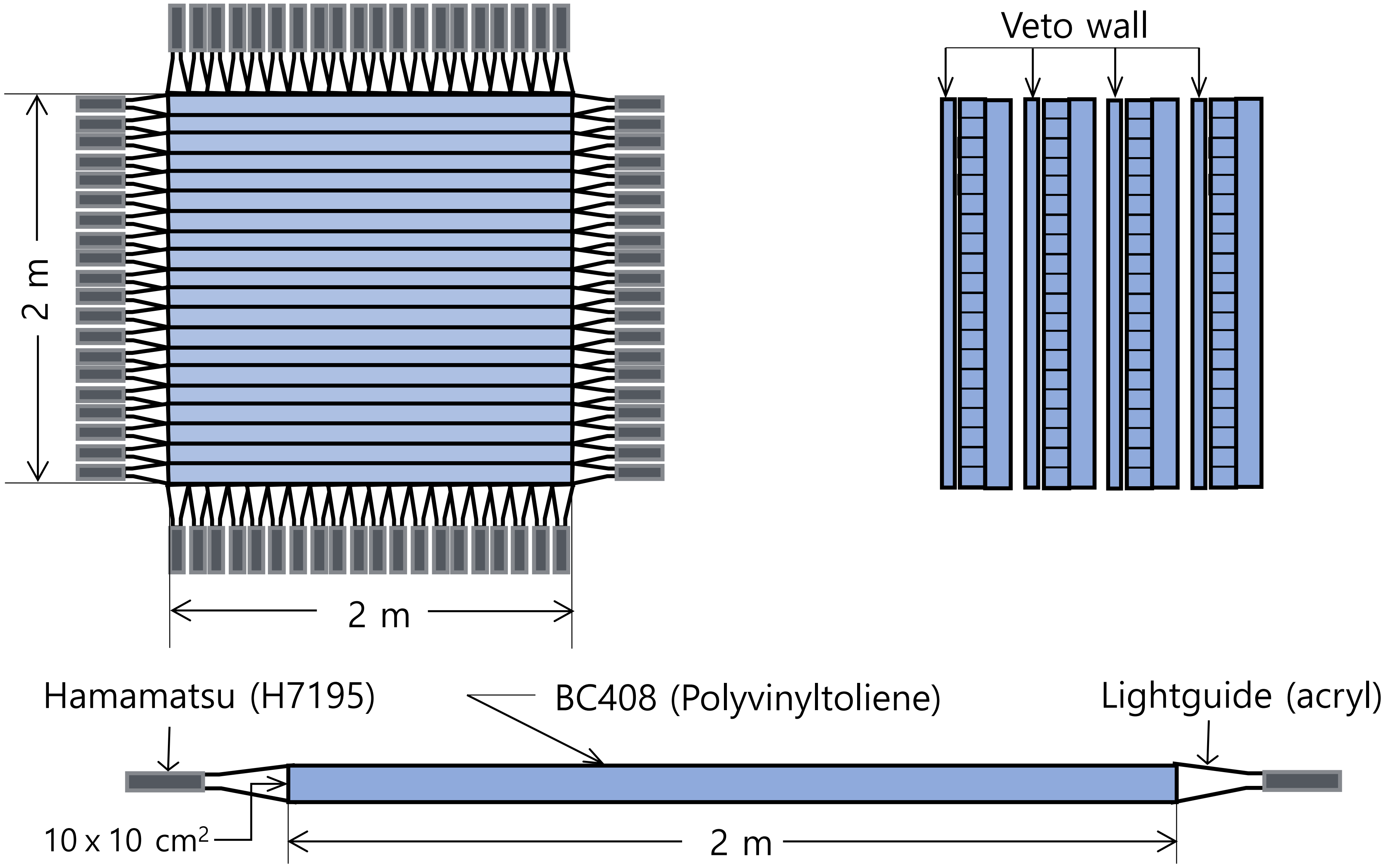
- Cosmic muon trigger
  - Coincidence of two scintillators (scintillator size: 20 x 20 cm^2 each)
  - Trigger position : 30, 60 and 90 cm
  - Measured drift field points: 115, 125 and 135 V/cm



Drift velocity data (preliminary)

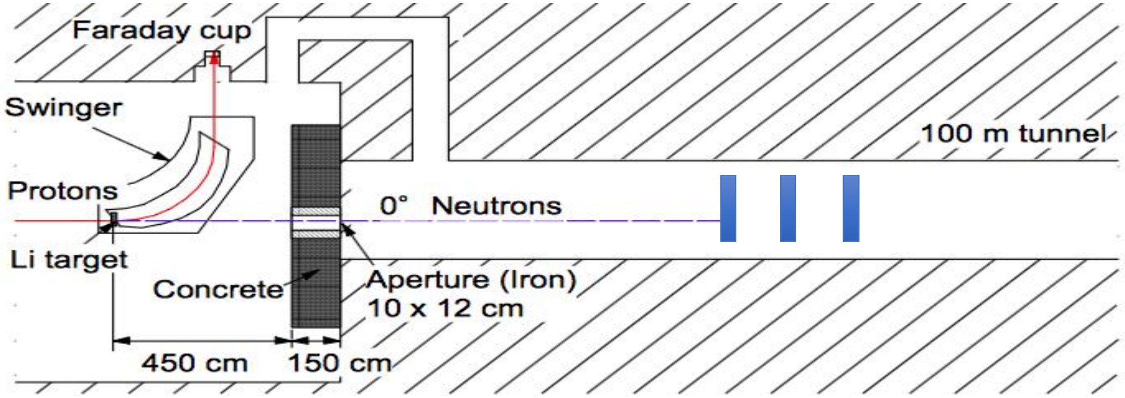


Neutron Detector Array (NDA): Structure

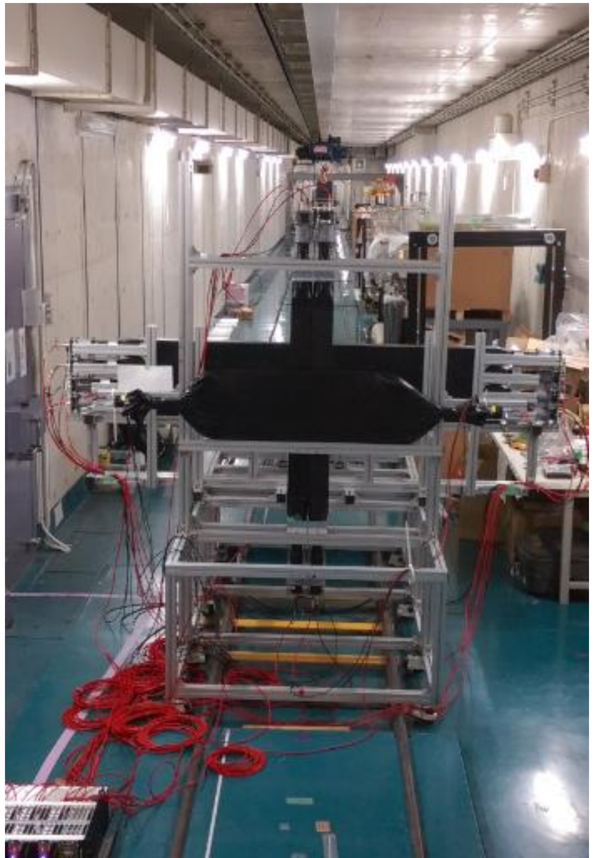


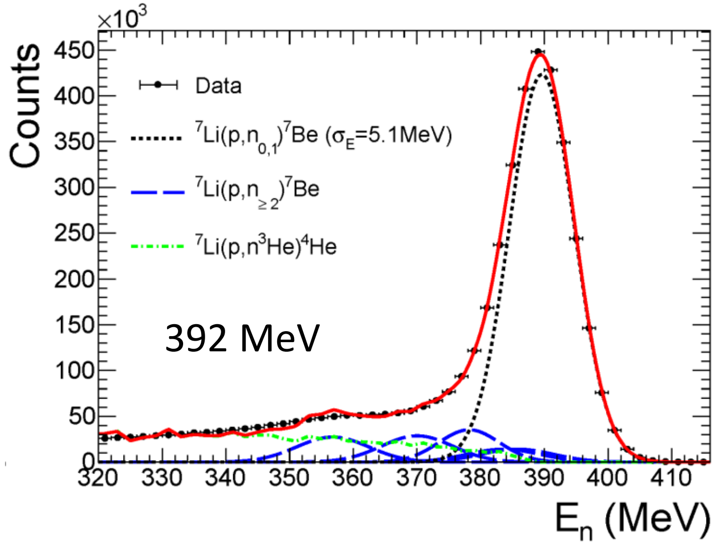
NDA: Performance test with prototype

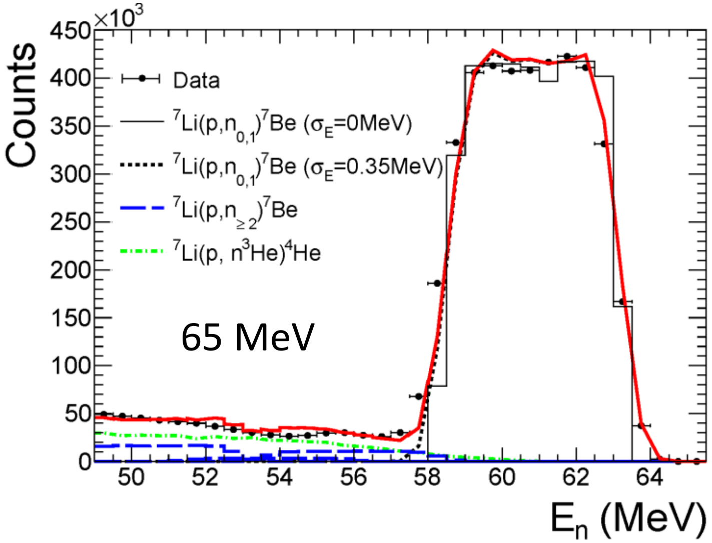
Beam test at RCNP (2016)



- Beam specifications
  - Production reaction: p+^{7}Li → n + ^{7}Be
  - Neutron beam flux: 1×10^{10} n/sr/μC
  - Neutron energy: 65 and 392 MeV
  - Background neutrons above 3 MeV is < 1% [NIMA 629, 43 (2011)]

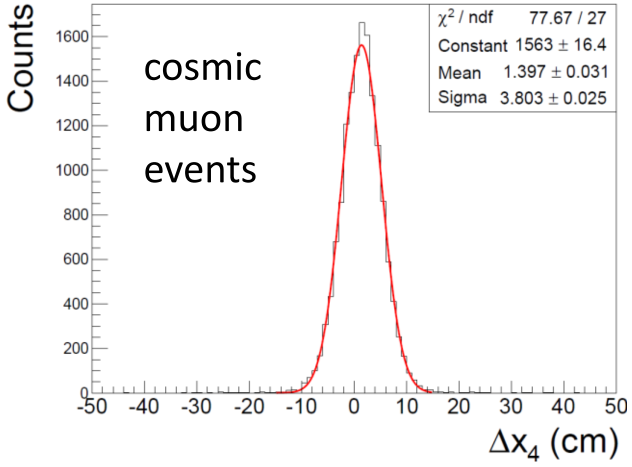






- Significant energy-loss effect in the Li target at 65 MeV
- Low-energy background dominated by the 3-body decays $^7\text{Li}(p,n\ ^3\text{He})\ ^4\text{He}$
- Energy resolution (FWHM): 3.1% @ 392 MeV, 1.3% @ 65 MeV

NDA: Performance with prototype



← Position difference between the projected hit position and the detected hit position for cosmic muons: $\Delta x_4 \equiv x_{D4,proj} - x_{D4,hit}$

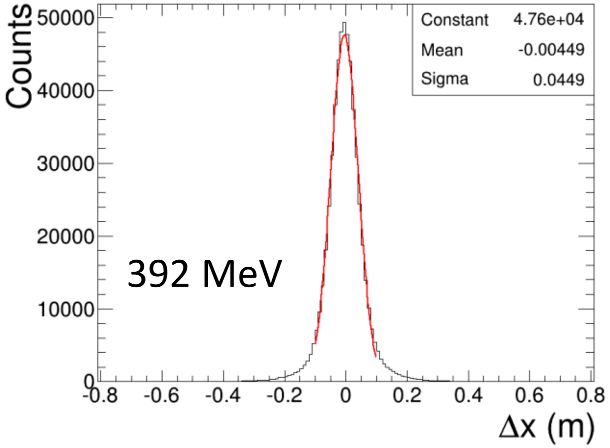
← Relative position resolution for cosmic muons for one bar:

$$\sigma_x = \frac{\sigma(\Delta x_4)}{1.87} = 2.0\ \text{cm}: R_x(\mu) = 4.8\ \text{cm (FWHM)}$$

→ Hit position difference between neighboring scintillators for neutrons with simultaneous hits: $\Delta x_{S1} \equiv x_{D1} - x_{D2}$ for 10 MeV threshold and $\delta t < 3$ ns

→ Relative position resolution for neutrons for one bar:

$$\sigma_n = \frac{\sigma(\Delta x_{S1})}{\sqrt{2}} = 4.5\ \text{cm}: R_x(n) = 7.5\ \text{cm (FWHM)}$$



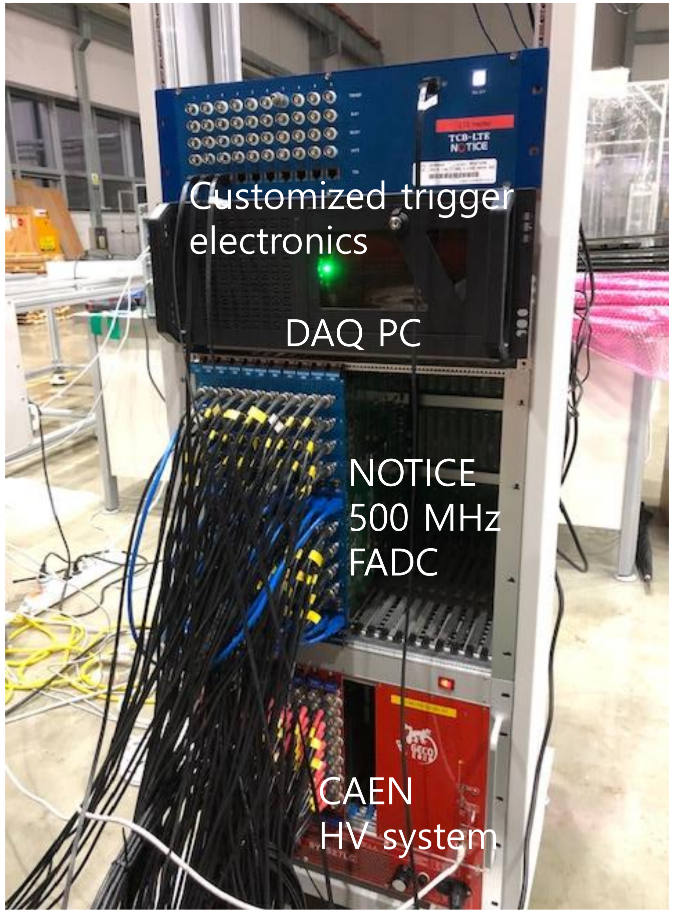
Comparison of performances by cosmic rays for similar configuration of neutron detectors [NIMA 927, 280 (2019)]

	LAMPS (this work)	MoNA [13]	NEBULAR [14]	LAND [15]
Dimensions (cm^3)	10 × 10 × 200	10 × 10 × 200	12 × 12 × 180	10 × 10 × 200
Time resolution (ps)	309	423	376	588
Position resolution (cm)	4.8	5.2	6.1	7.1

NDA: Construction

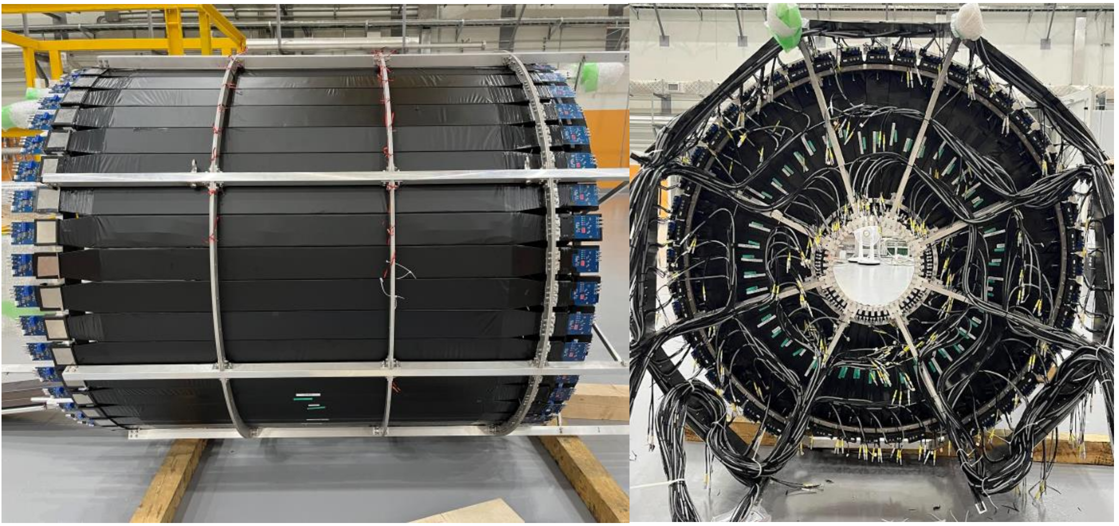
- Installation of all modules in the frame was completed at the Sejong campus of Korea University in Dec. 2018 to test the performance.
- The whole system was dissembled and transported to the RAON site in Sindong in March and assembled again with the three additional veto walls in September in 2022.
- The fully assembled system will take the cosmic muon data at the RAON site very soon.


Assembled detector system at the Sejong Campus of Korea Univ.

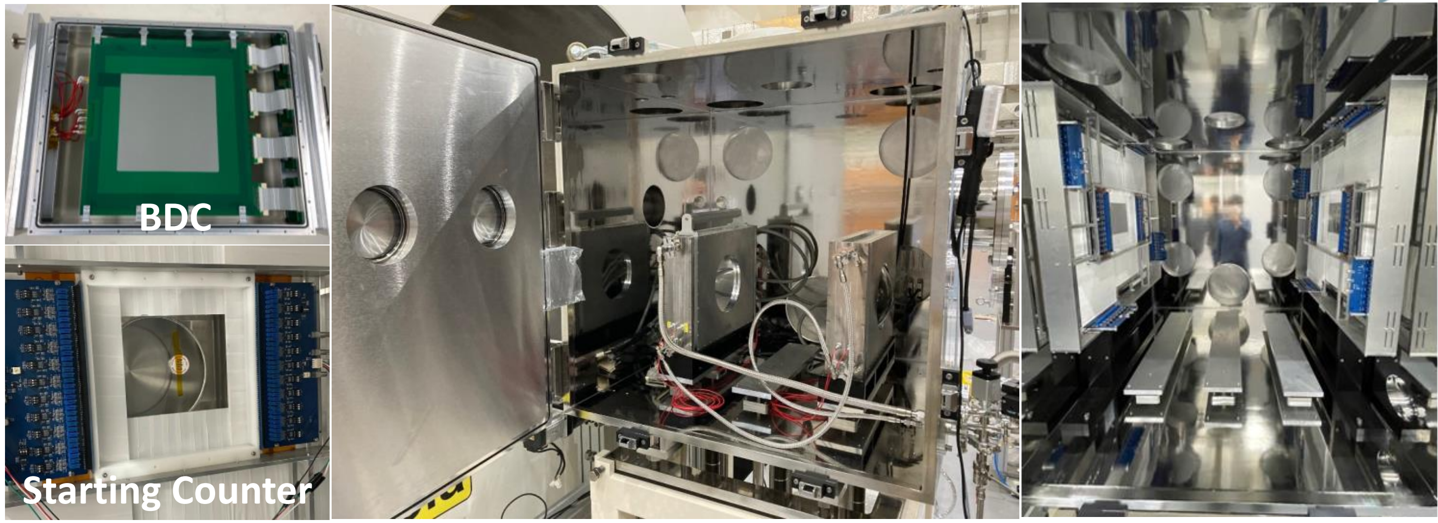



First station assembled at the high-energy experimental hall of the RAON site

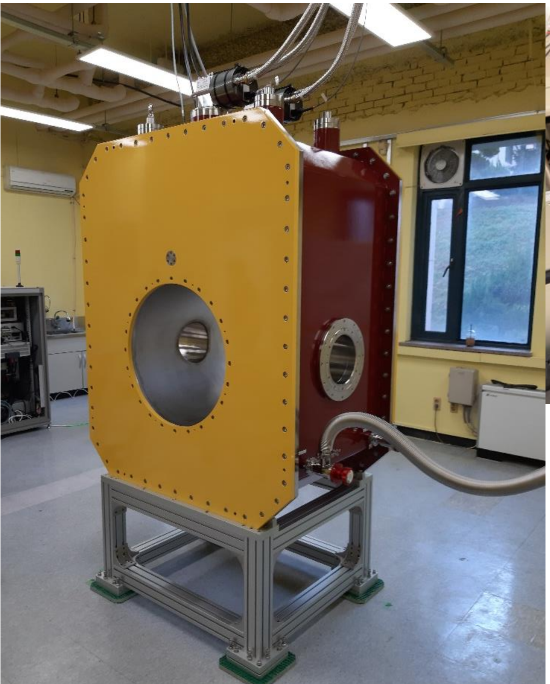
RAON LAMPS

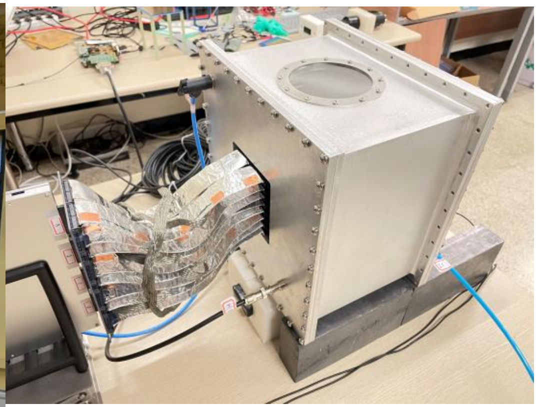


ToF & Trigger array (BTOF/FTOF)

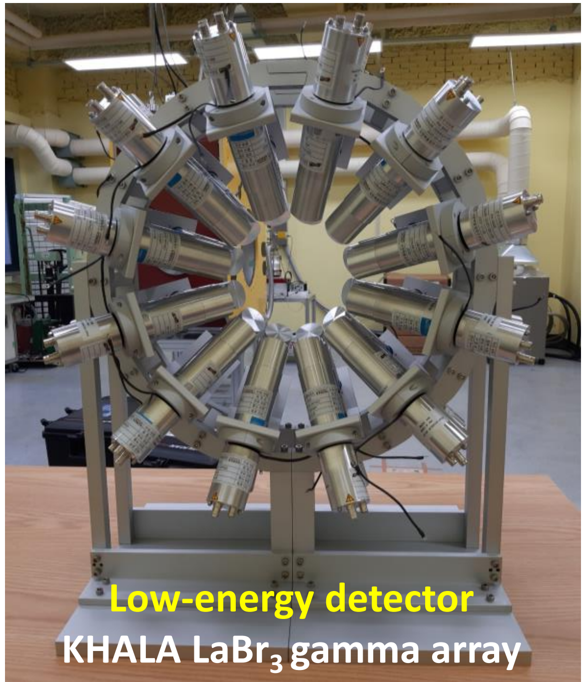


BDC (left) & SC (right) in beam diagnostic vacuum chamber





Low-energy detectors
(Left) SC magnet with
B_{max} = 1.5 T
(Above) AT-TPC (prototype)



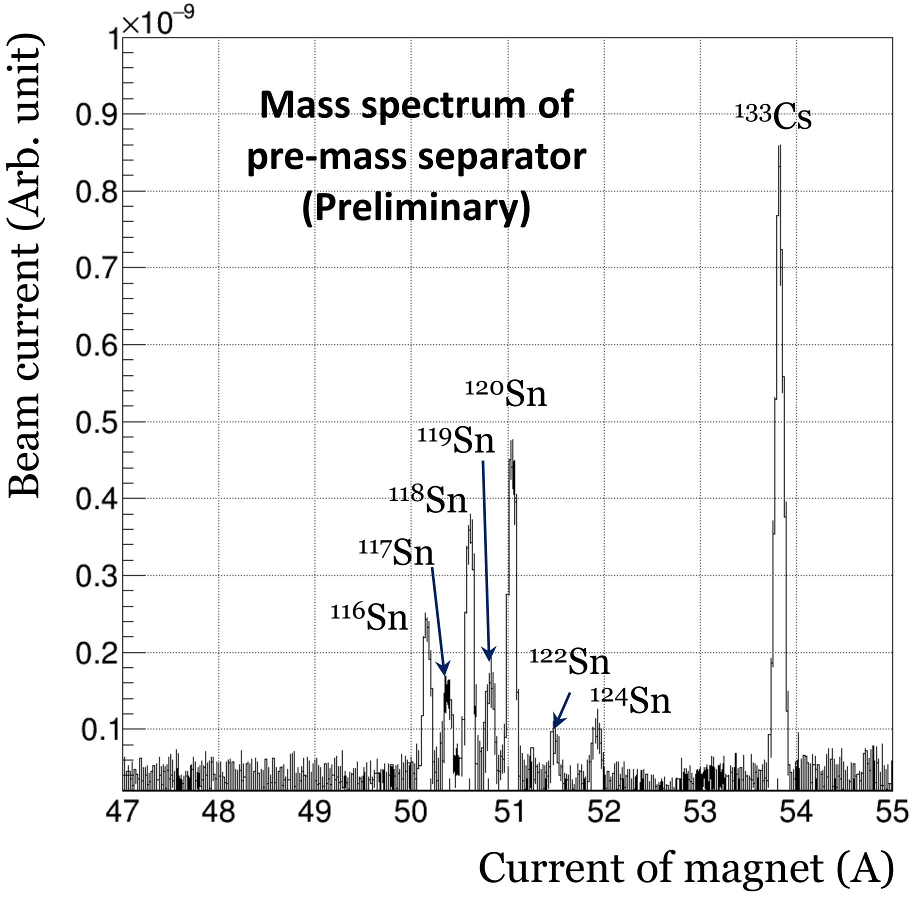
Low-energy detectors
(left) Si-CsI telescope
(Above) Prototype FAZIA FEE board produced in Korea

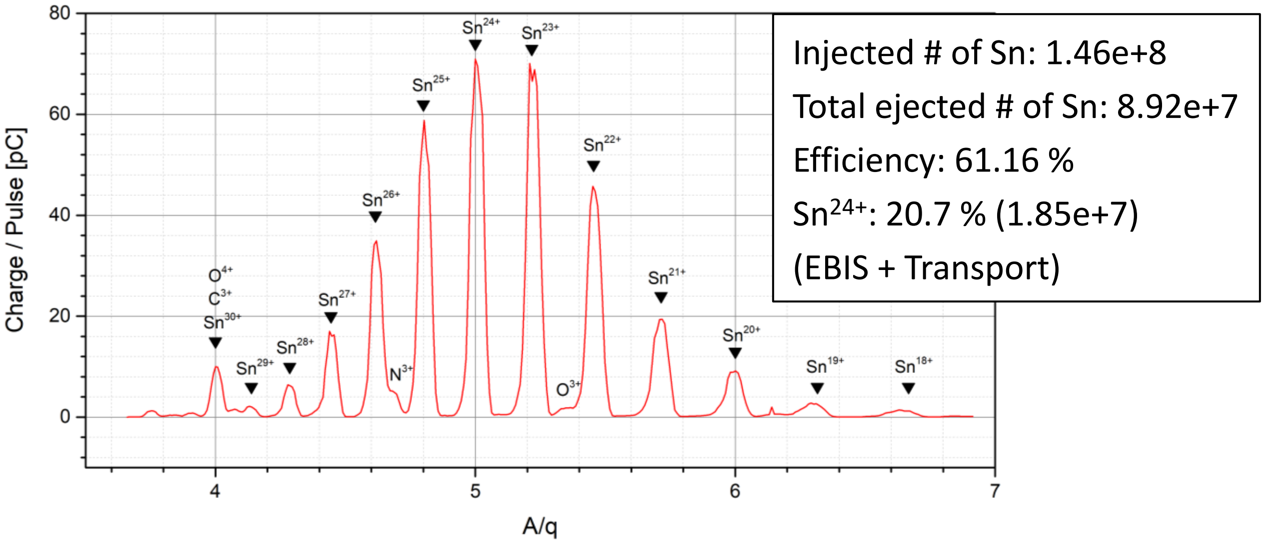
Part 4.

Status of beam commissioning and summary

Preparation of RIB production by ISOL

- Target Ion Source: Sn beam extraction using RILIS and transportation to A/q separator (Apr. 2022)





- RI beam commissioning plan for ISOL with SiC target
  - ^{24}Na beams with an intensity of ~$10^{6\text{-}8}$ pps (1 kW@70 MeV) in Oct.~Dec. 2022
  - $^{24\text{-}26m}$Al beams produced and transported to Ultra low-energy Expt. hall (MMS & CLS) in 2023
  - Plan to provide $^{20\text{-}24}$Na, $^{22\text{-}23}$Mg, $^{24\text{-}26}$Al and $^{8\text{-}9}$Li beams
- UC_x target from 2025

Nuclei	^{116}Sn	^{117}Sn	^{118}Sn	^{119}Sn	^{120}Sn	^{122}Sn	^{124}Sn
Measured Current (nA)	0.243	0.152	0.360	0.161	0.450	0.097	0.102
Current Ratio (%)	15.5	9.70	23.0	10.28	28.75	6.20	6.52
Natural abundance (%)	14.54	7.68	24.22	8.59	32.58	4.63	5.79
Abundance ratio	14.79	7.83	24.71	8.76	33.23	6.32	6.65

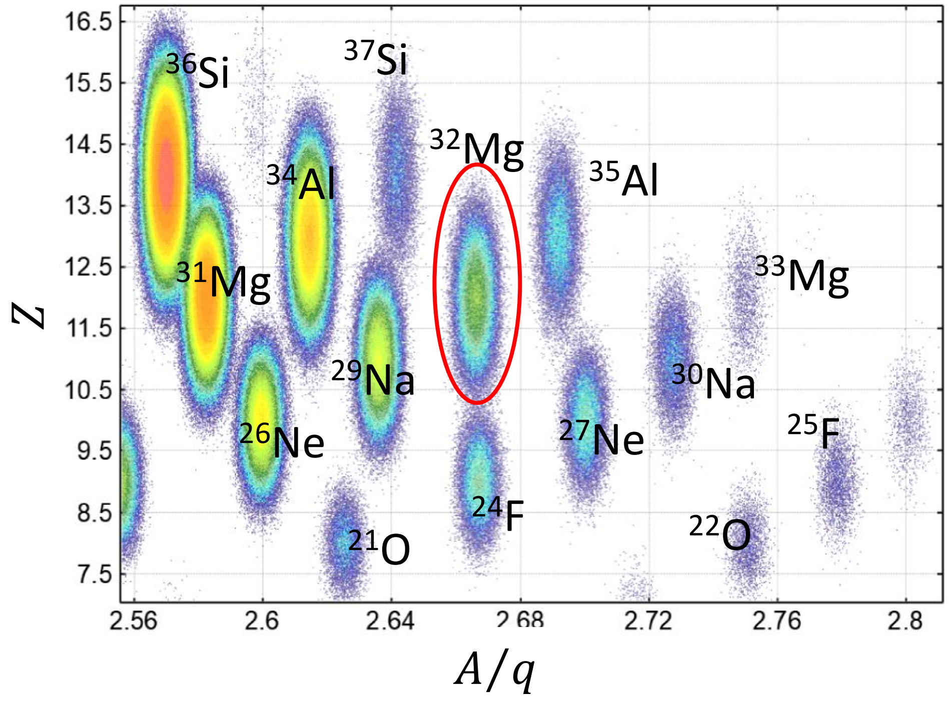
← Beam current ratio can be explained by the natural abundance of Sn.

KoBRA beam commissioning plan

Injector with 14.5 GHz ECR IS ($^{40}Ar^{8+}$, >30 eμA, 500 keV/u)	→	SCL3 ($^{40}Ar^{8+}$, >30 eμA, ~30 MeV/u)	→	KOBRA (Production target)

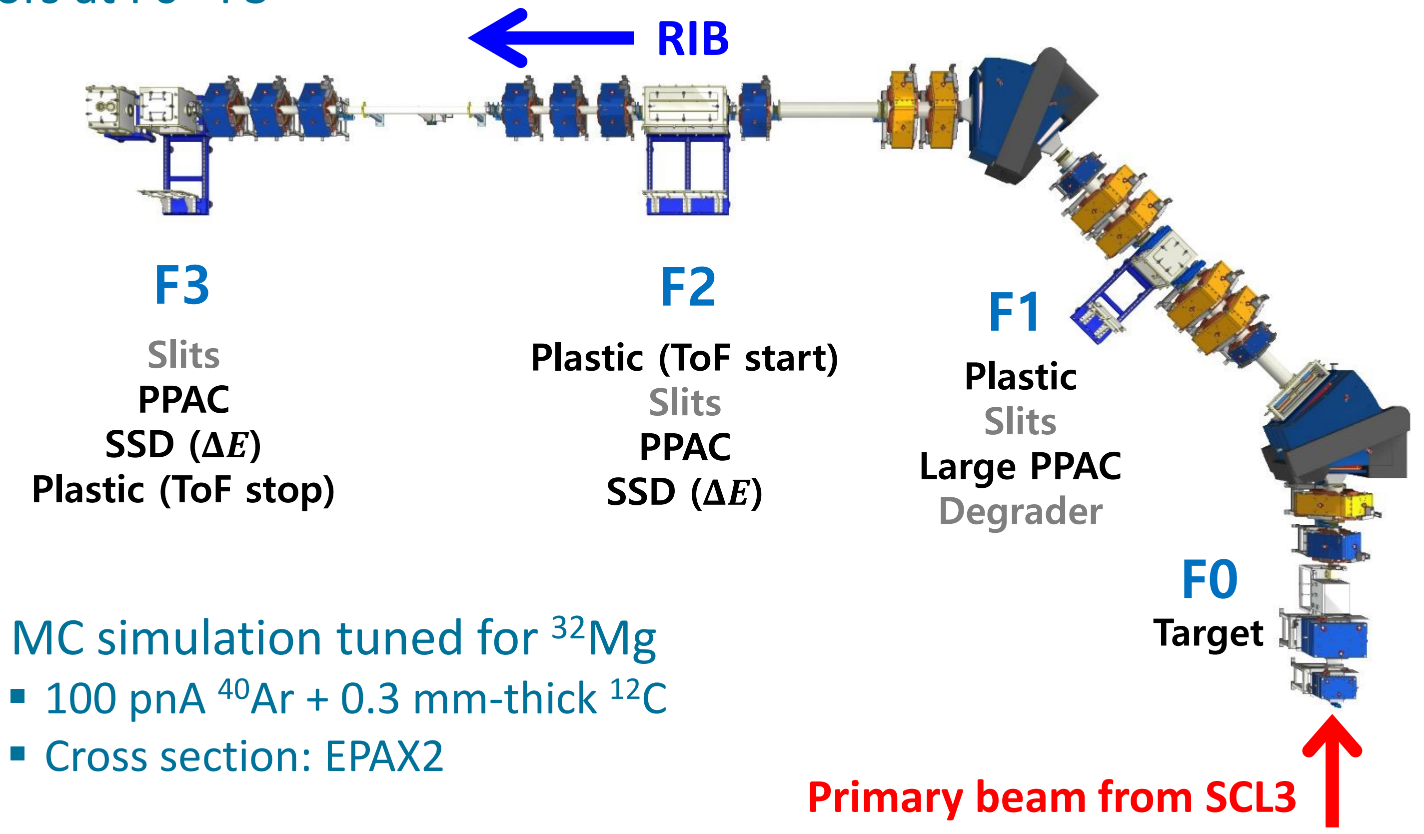
◐ KoBRA beam commissioning in Mar. – Jun. 2023

- RI production using quasi projectile-like fragmentation from ^{40}Ar in the energy range of 20~30 MeV/u
- $B\rho$-ToF-ΔE method for PID with detectors at F0~F3



← MC simulation tuned for ^{32}Mg

- 100 pnA ^{40}Ar + 0.3 mm-thick ^{12}C
- Cross section: EPAX2



Summary

- Major achievements
  - SCL3: Installation completed in 2021
  - Cryogenic plants: Cooldown and RF conditioning, beam commission started in Sep. 2022
  - ISOL: SIB transportation for all sub systems and beam lines tested in Dec. 2021
  - KoBRA: Machine commissioning done in Oct. 2021
- Near-term plan (for the next ~2 years)
  - Delivery of stable ^{16}O & ^{40}Ar beams to KoBRA in 2023
  - Extraction of RIB from ISOL and delivery to ultra low-energy experimental hall for MMS & CLS in 2023
  - KoBRA beam commissioning experiment with RIBs for $A \lesssim 50$ with beam energy $\lesssim$ 20 MeV/u in 2023
  - Installation and independent commissioning of IF, LAMPS, BIS and µSR in 2023
  - Preparation of the 2^{nd} phase for the construction of SCL2 by 2024
- Long-term plan
  - Operation of ISOL with UC_X target from 2025
  - Completion of SCL2 and stable operation of U beams at 200 MeV/u up to 80 kW (Goal: 400 kW)
  - Starting of the scientific program with ISOL and IF
  - Beam commissioning for ISOL → SCL3 → SCL2 → IF

Thank you very much for your attention!