Status and future scientific program of RAON

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Outline

1. Overview of the RAON construction project
2. Accelerator systems
   - Status of beam commissioning
3. RI & experimental systems
4. Summary
   - Ideas for early-time experiments with light stable-ion beams

Part 1.

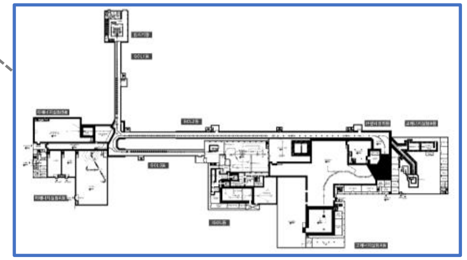
Overview of the RAON construction project

RAON 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 ~U$ 1.4 B for phase I
  - Accelerator & experimental facilities: ~U$ 500 M
  - Civil engineering & conventional facilities: ~U$ 900 M, including ~U$ 270 M for purchasing land
- Project period: 2011-2022 (1st phase), 2023-2025 (R&D for 2nd phase to develop 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 support 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)

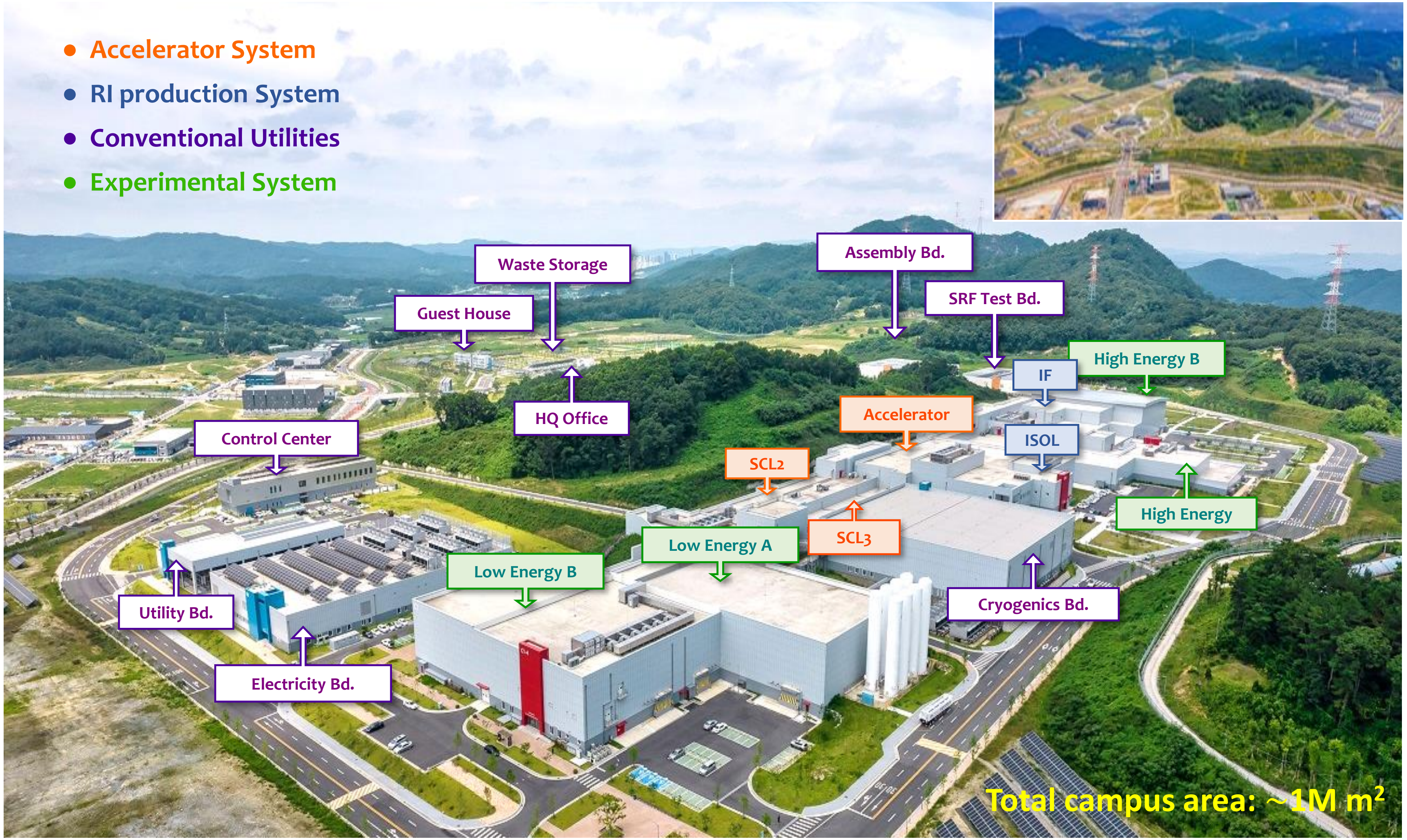
◐ **Providing high-intensity neutron-rich beams**

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

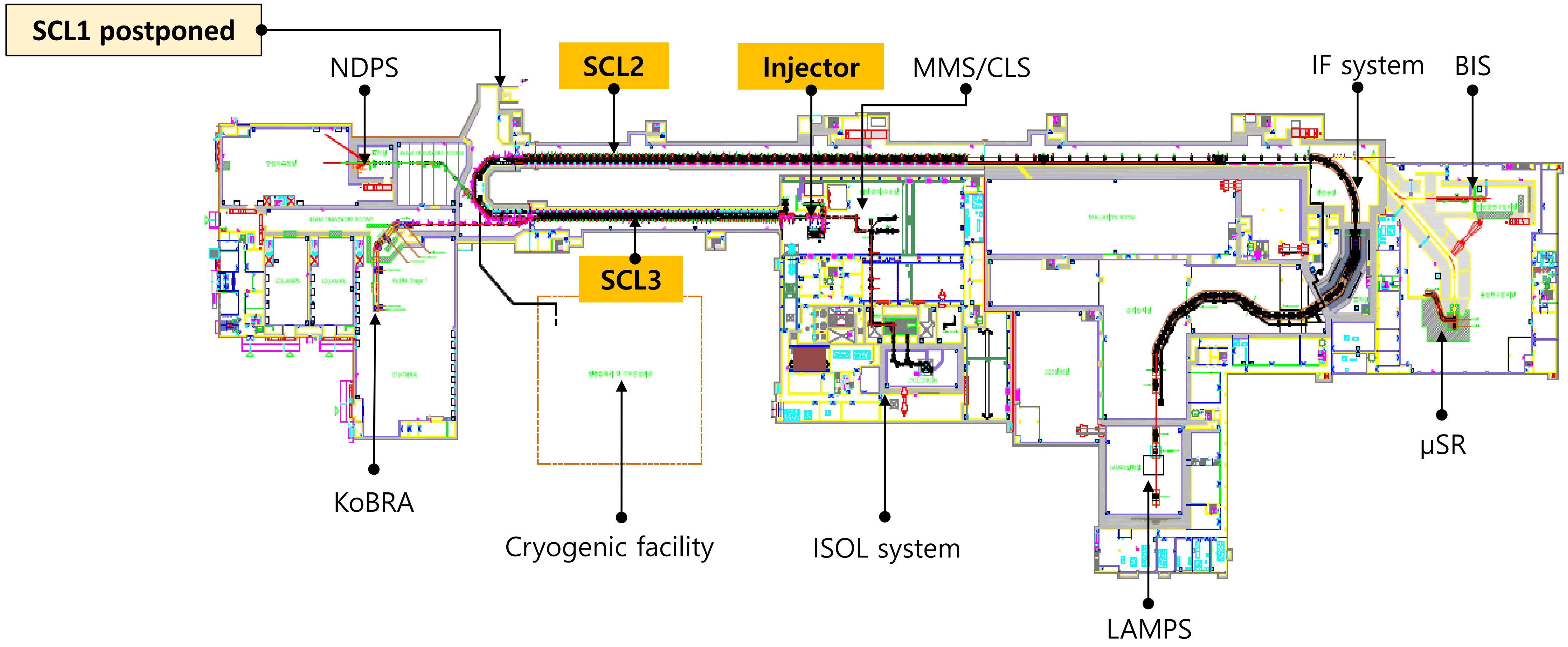
Layout



Accelerator System
RI production System
Conventional Utilities
Experimental System
Waste Storage
Assembly Bd.
SRF Test Bd.
Guest House
High Energy B
IF
HQ Office
Accelerator
Control Center
ISOL
SCL2
High Energy
SCL3
Low Energy A
Low Energy B
Cryogenics Bd.
Utility Bd.
Electricity Bd.
Total campus area: ~1M m²

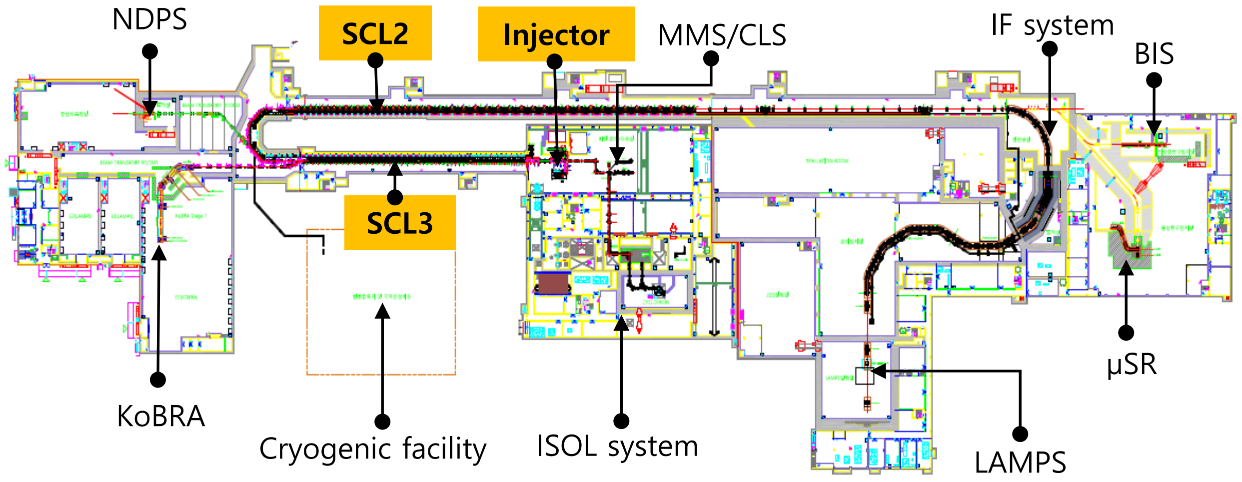
RAON Layout

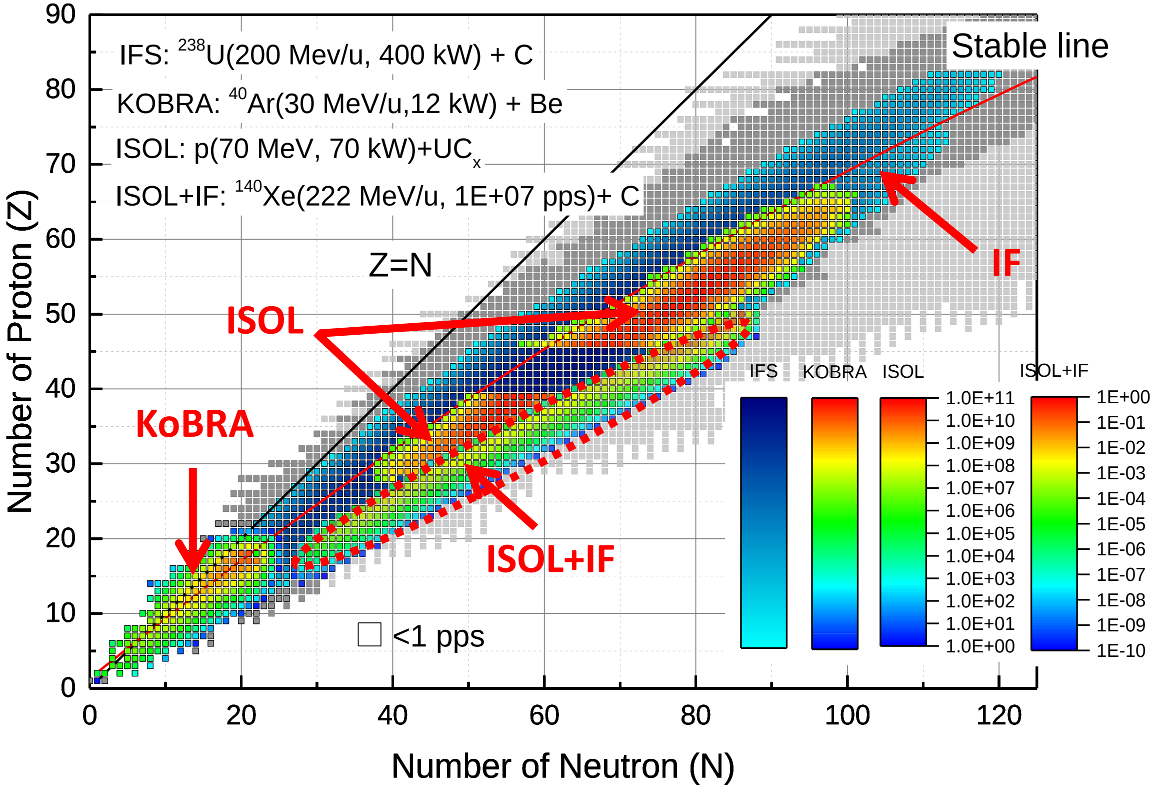
Injector				SC Linac					IF	
				SCL3			SCL2			
		0.5 MeV/u			18 MeV/u			200MeV/u		
ISOL/ECR	LEBT	RFQ	MEBT	SCL3-1	SCL3-2	CSS	SCL2-1	SCL2-2	HEBT	IF
				β=0.047	β=0.12		β=0.3	β=0.51		



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 & multi-nucleon transfer reactions	p induced U fission	PF, U fission
RIB energy	< a few tens of MeV/u	> a few keV/u	< a few hundreds of MeV/u





- RAON will eventually combine ISOL and IF to access more neutron-rich region of the nuclear chart.

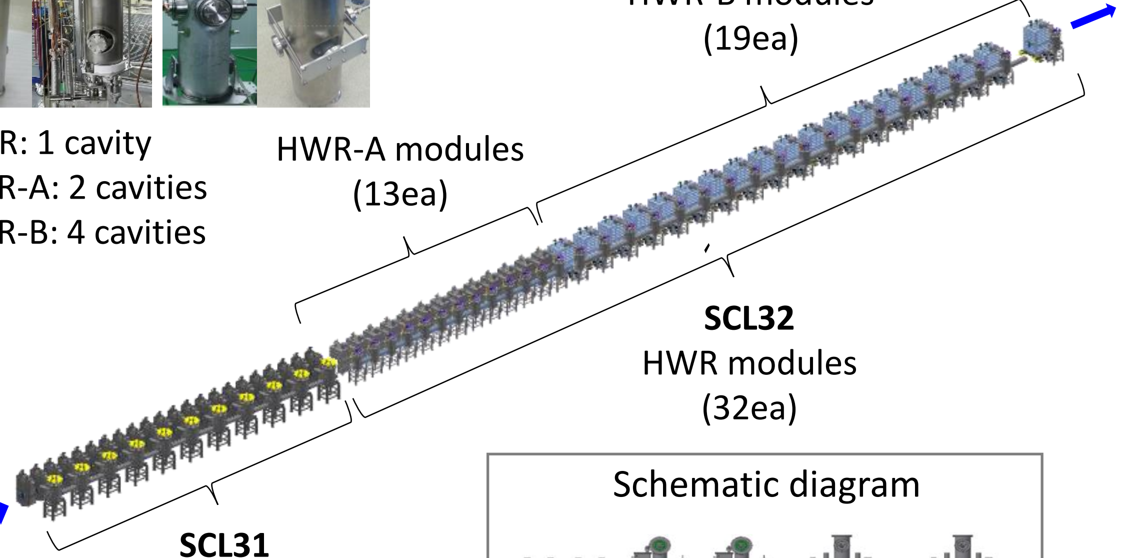
Part 2.

Accelerator systems

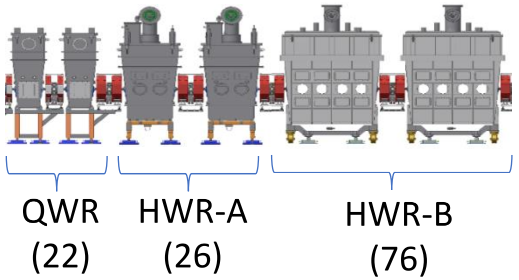
Accelerator system (Overview of SC Linacs)

SCL3 (Phase I)

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



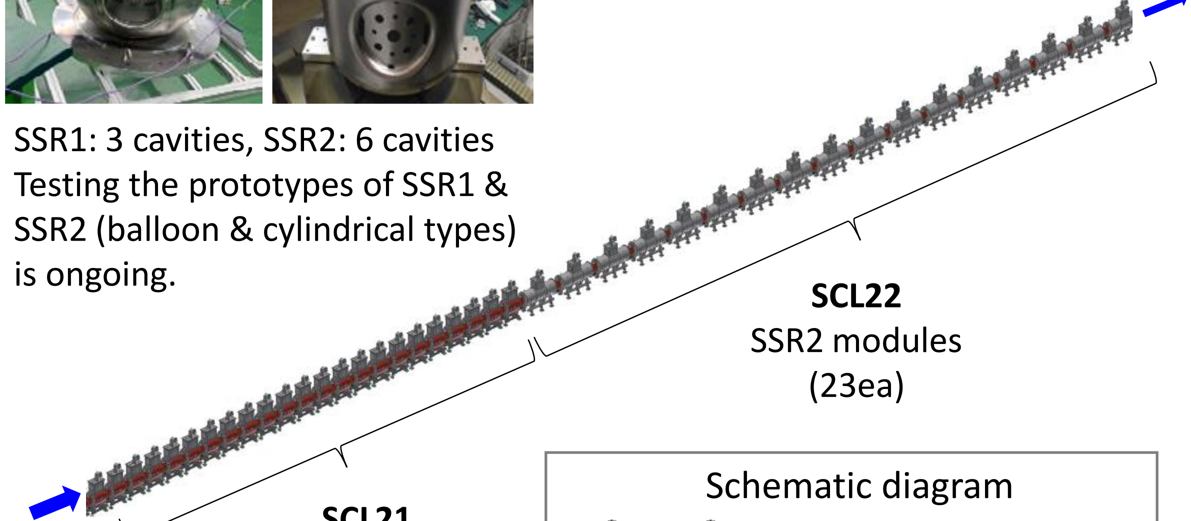
Schematic diagram



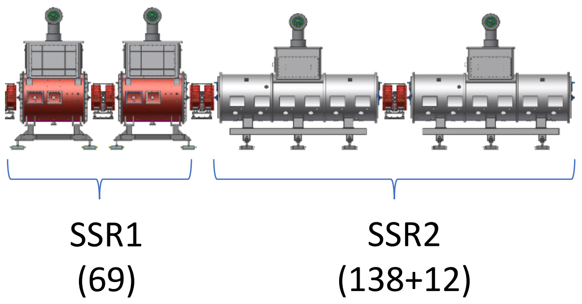
Total # of cavities (124)

SCL2 (Phase II)

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



Schematic diagram



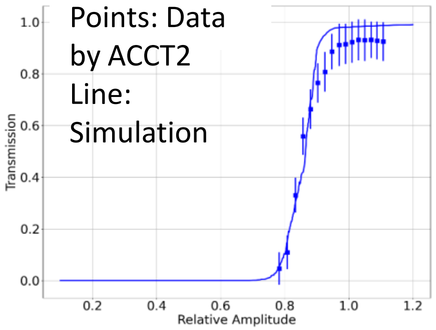
- *SSR2: 23 for acceleration and additional 2 for bunching*

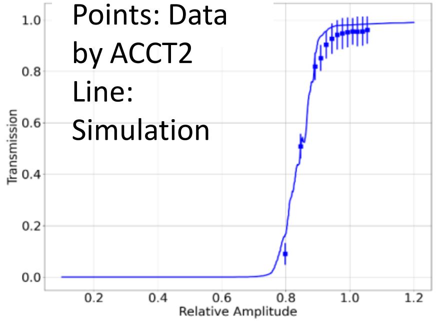
Total # of cavities (219)

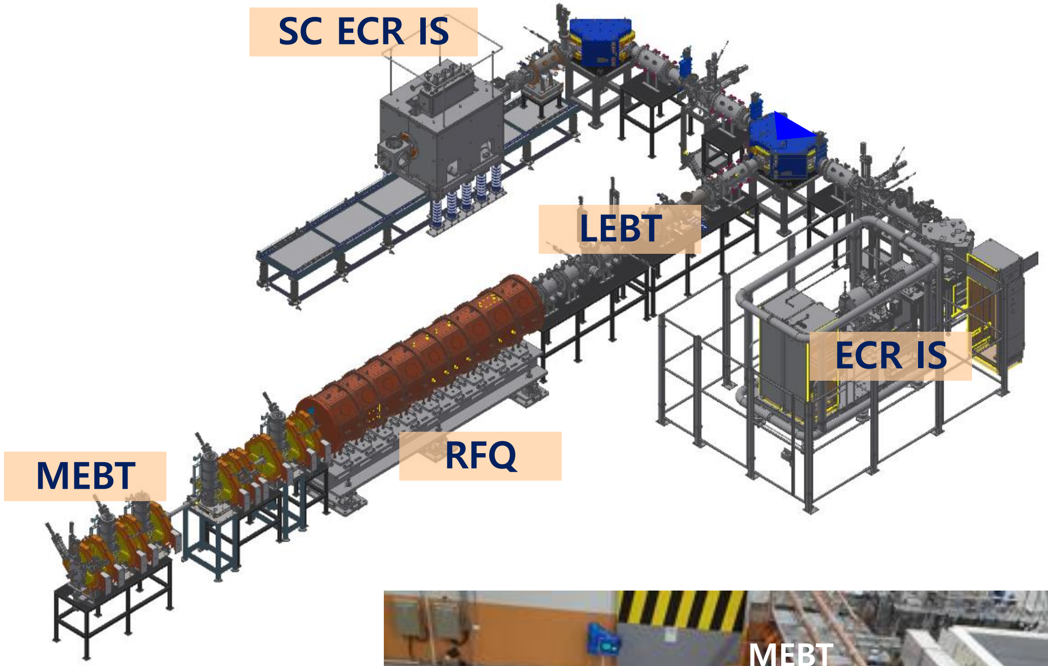
RAON Injector system

- 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 > 95%
  - 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 in Oct. 2020

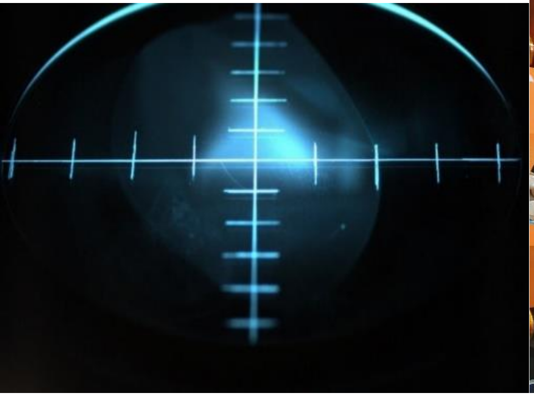
Transmission at RFQ



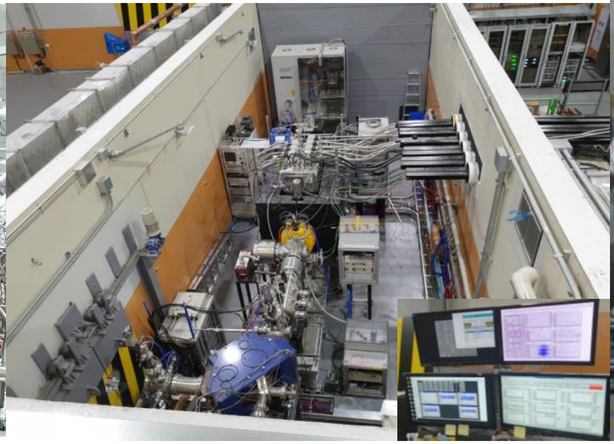


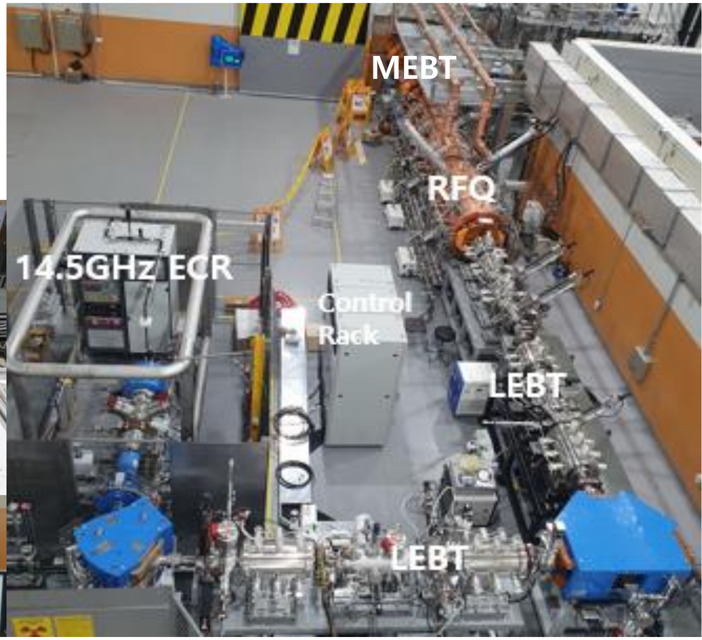


Ar^{8+} 10μA @ Beam Viewer('21)



28 GHz SC ECR IS





SRF test facility and cryoplants

- Performance test of SCL2 and SCL3 cavities and cryomodules at cryogenic temperature
- Onsite test facility: 3 VT pits with 3 cavities per pit + 3 HT bunkers
- RAON cavities: QWR (81.25 MHz), HWR (162.5 MHz) and SSR1/SSR2 (325 MHz)

- 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)

◐ SCL3 cryoplant and cryogenic distribution system were commissioned in August 2022.

Assembly of SCL3

- Cryomodules (CM) & warm sections were assembled in the clean booth in the tunnel.
- Total counts of particles for the size larger than 0.5 μm/10 minutes were less than 30.
- Installation was completed in 2021 and beam commissioning was finished in May 2023.

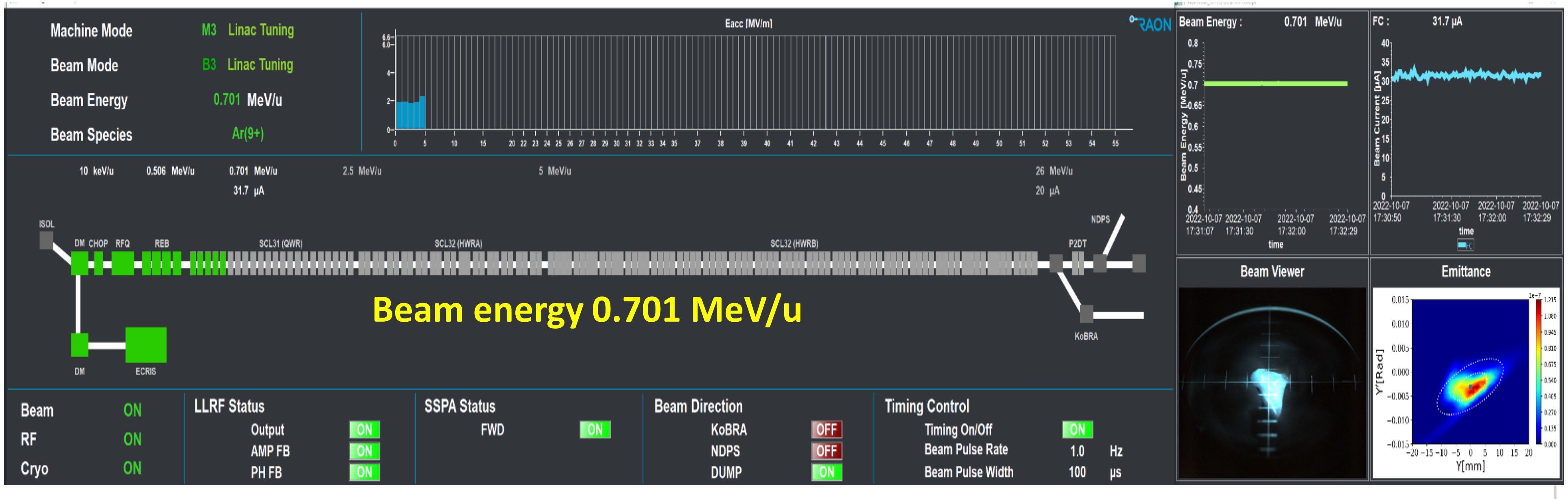
↓ **Cryogenic distribution to cryomodules**

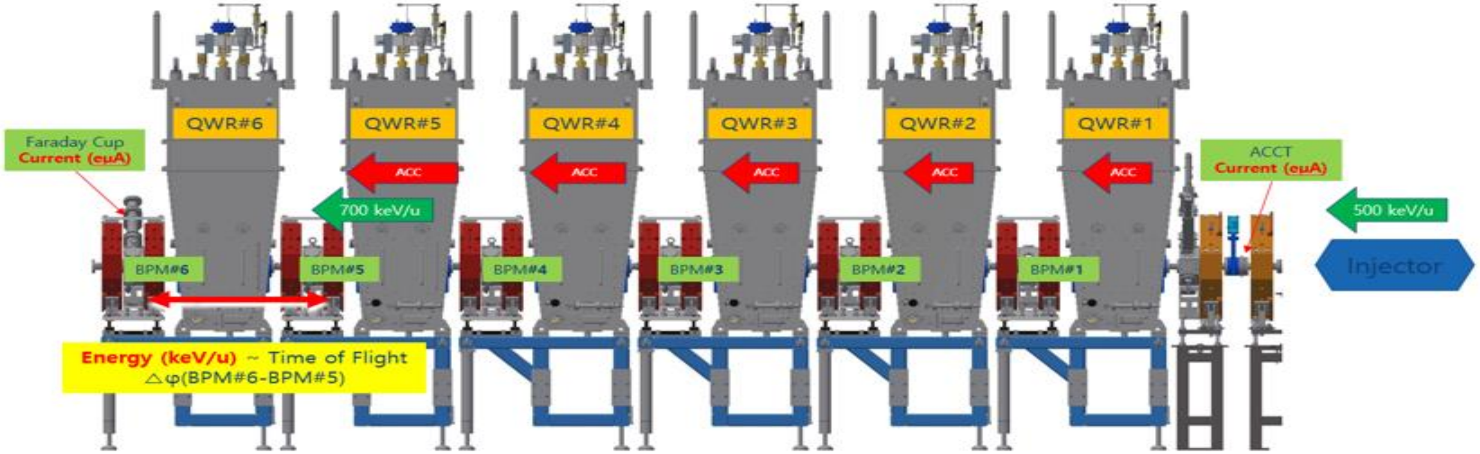
↓ **QWR+HWR (2021)**

← **CM/cryogenic control rack and SSPA**

RIB Accelerator Facility

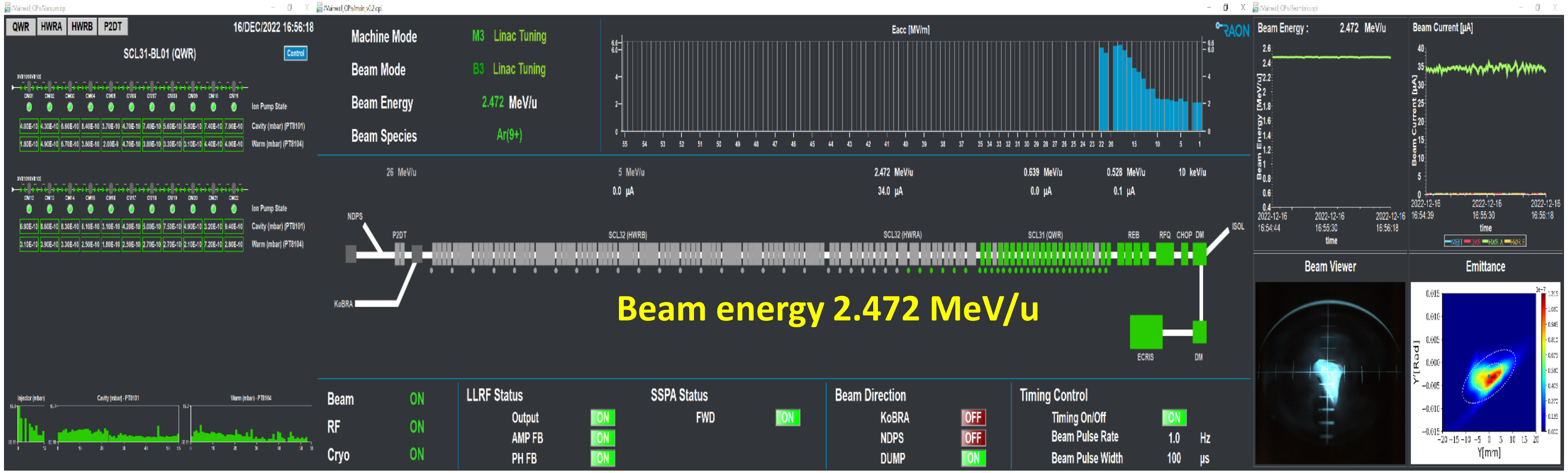
The 1st SCL3 beam commissioning (Oct. 7, 2022)

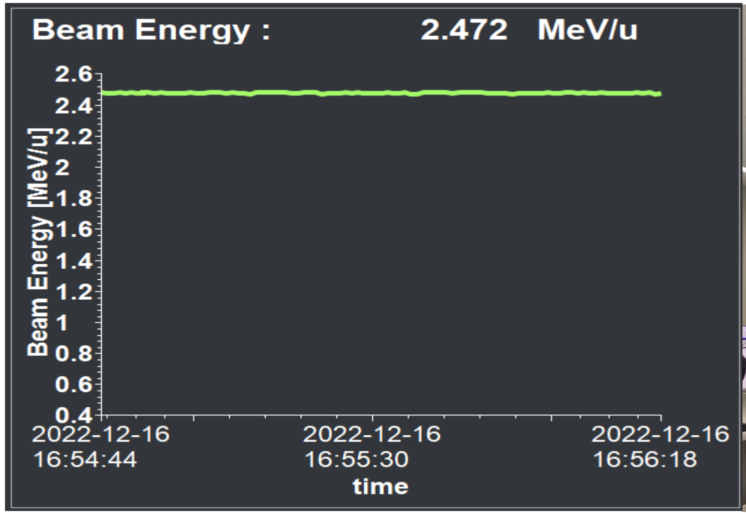




- Ar^{9+} beams were accelerated by QWR #1~#5.

The 2nd SCL3 beam commissioning (Dec. 16, 2022)

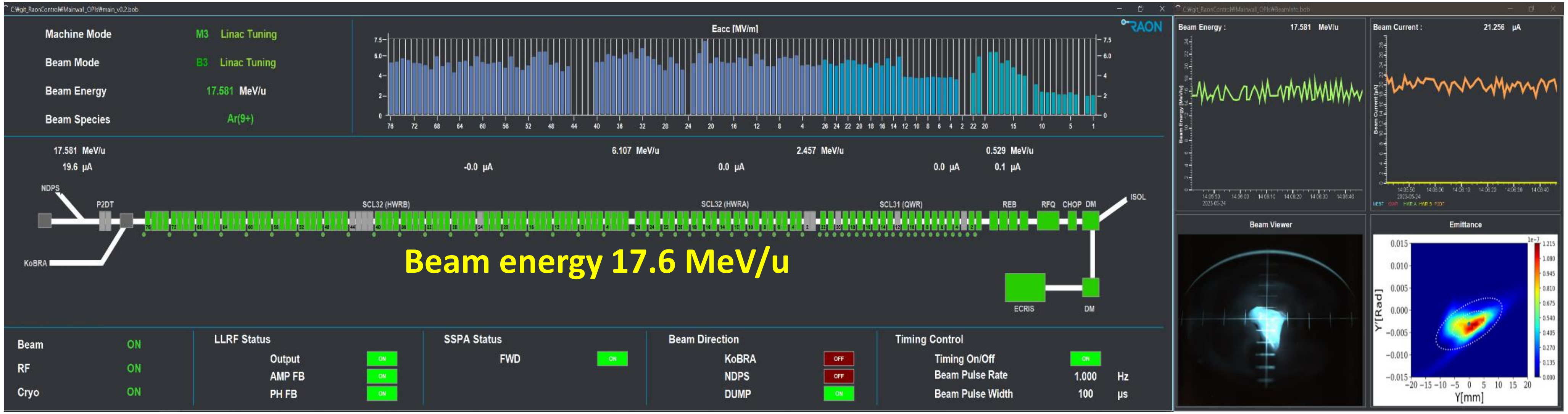




- Ar^{9+} beams were accelerated by entire QWR #1~#22.

RIB Accelerator Facility

The 3rd SCL3 beam commissioning (May 23, 2023)

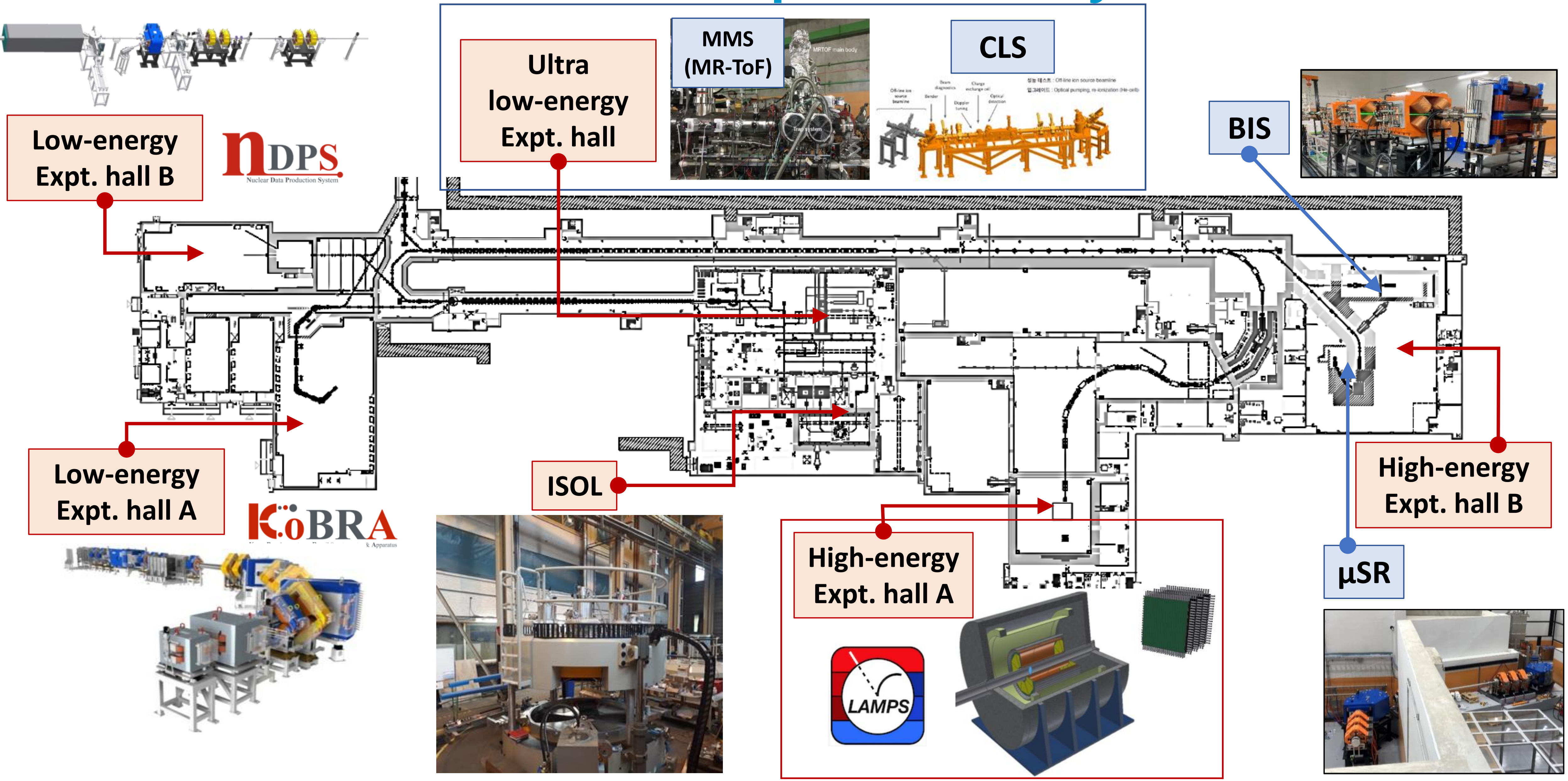


- Ar^{9+} beams accelerated by entire SCL3(QWR+HWR) on May 23.
- Ar^{9+} beams delivered to the KoBRA target on May 31.
  → **First RIBs were produced by Ar + C & transportated to F3 of KoBRA.**
- SCL3 warm up and maintenance started from June.
- Plan to deliver Ar beams to KoBRA for experiments for a short period in early 2024.

Part 3.

RI & experimental systems

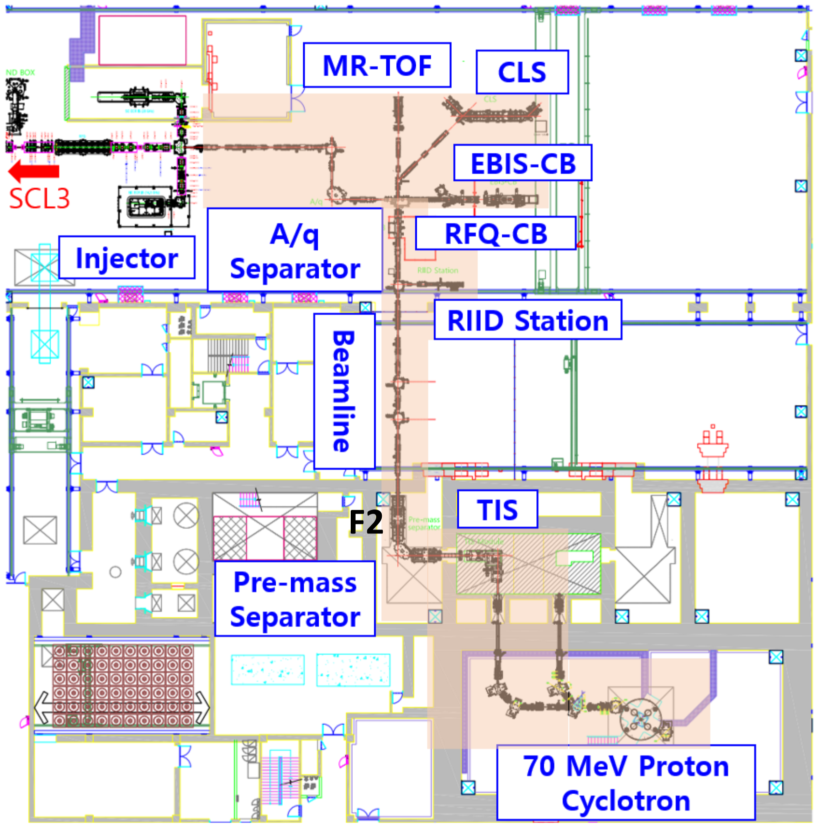
Overview of RI & experimental systems

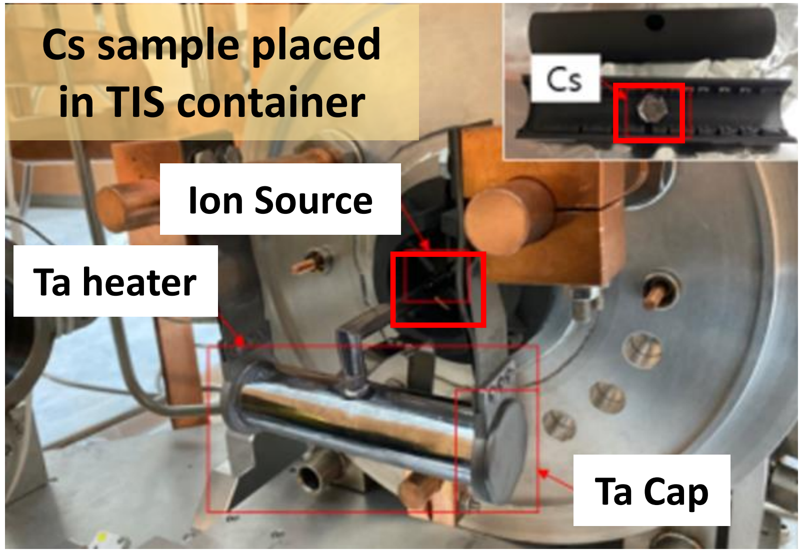


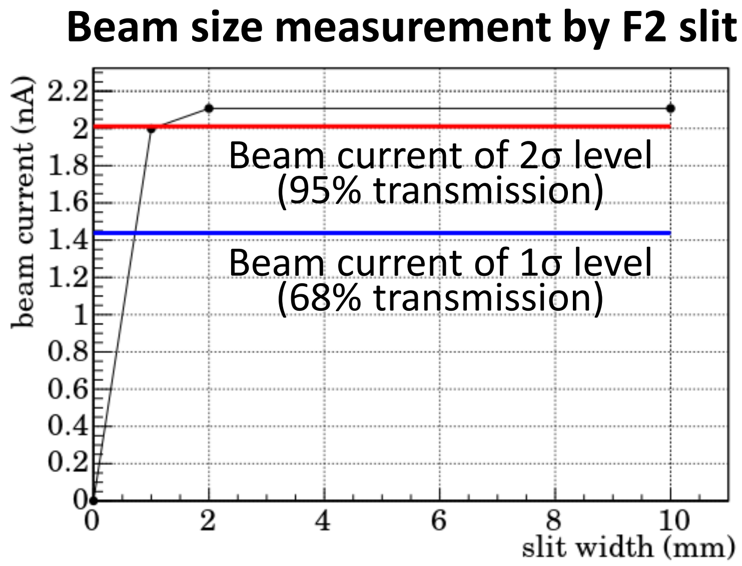
ISOL system

Target Ion Source ($^{132}Sn^{1+}$, 20 keV) → Pre-Separator ($m/\delta m \simeq 400$) → RFQ Cooler (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 up to 70 kW
- Target: SiC, BN, MgO, LaC_2, UC_X, CaO, BeO etc.
- 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 of post accelerator with 10 keV/u
- Full remote maintenance system with TIS modularization



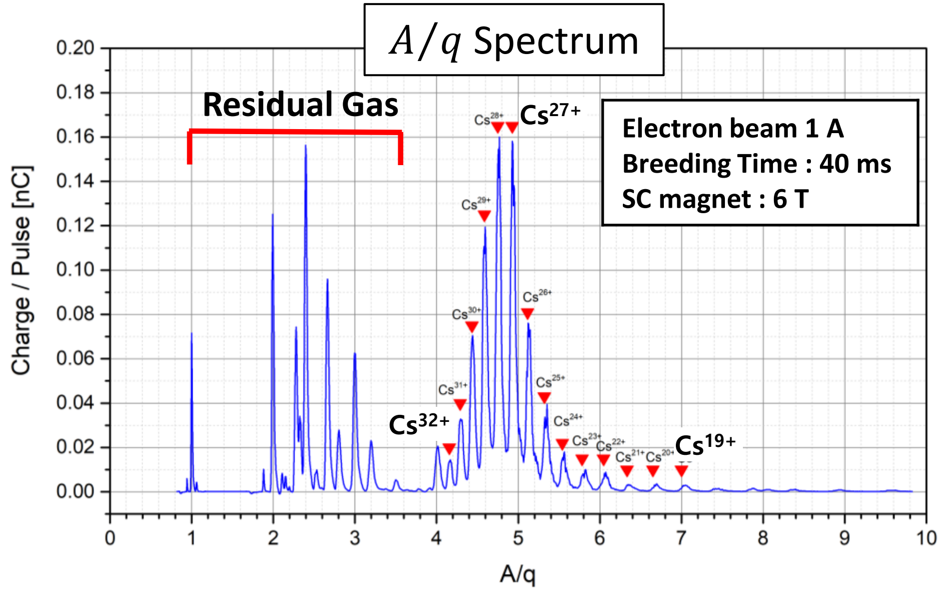


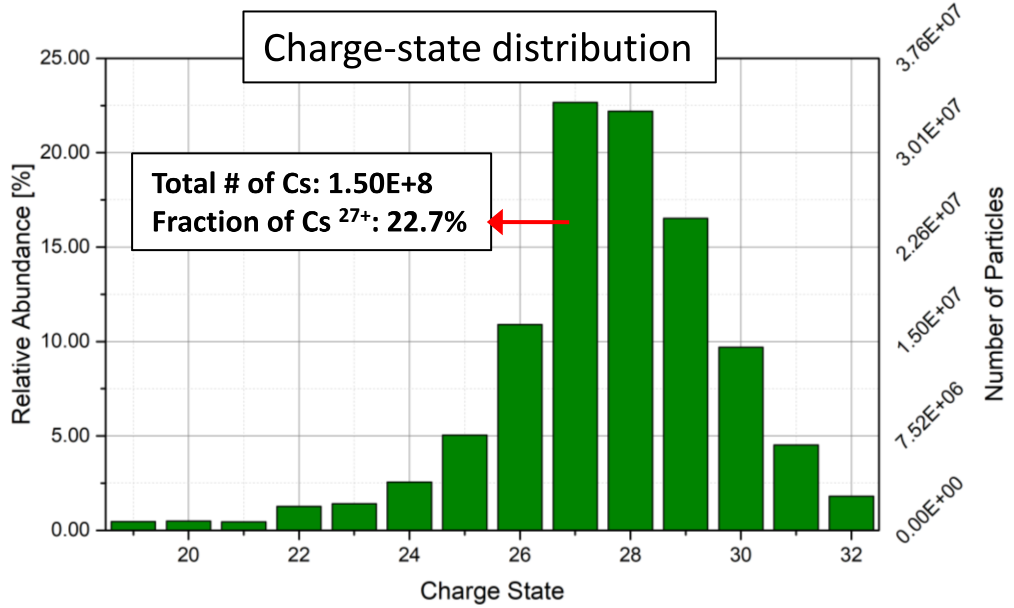


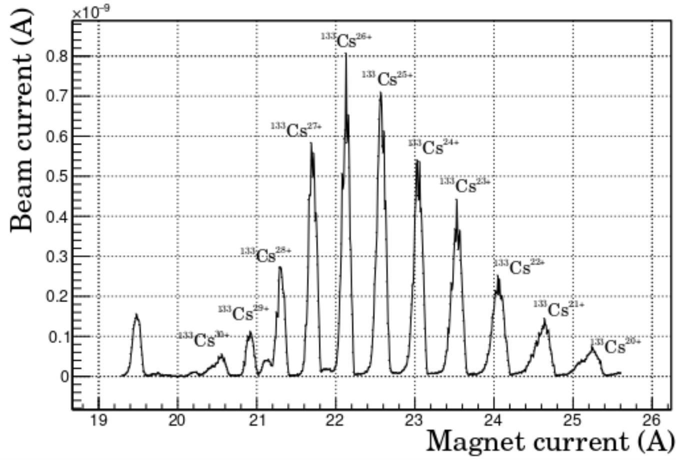
◐ In Dec. 2021, ISOL beamlines were commissioned with a Cs source.
- Horizontal beam size ~2 mm (2σ) at F2
- Mass resolving power of pre-mass separator ~1,000 (2σ)

ISOL system

Target Ion Source ($^{133}Cs^{1+}$, 20 keV) → Pre-Separator ($m/\delta m \simeq$1,000) → RFQ Cooler (>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 slit width dependence of beam current → Resolving power ~250 (2σ)
- With much more careful tuning, higher resolving power ~400 in 2σ can be achieved.

Cyclotron

- Specifications
  - Proton beams at 35~70 MeV
  - Maximum beam current: 1 mA (currently at 0.75 mA)
  - Two beam lines to the ISOL TIS bunker

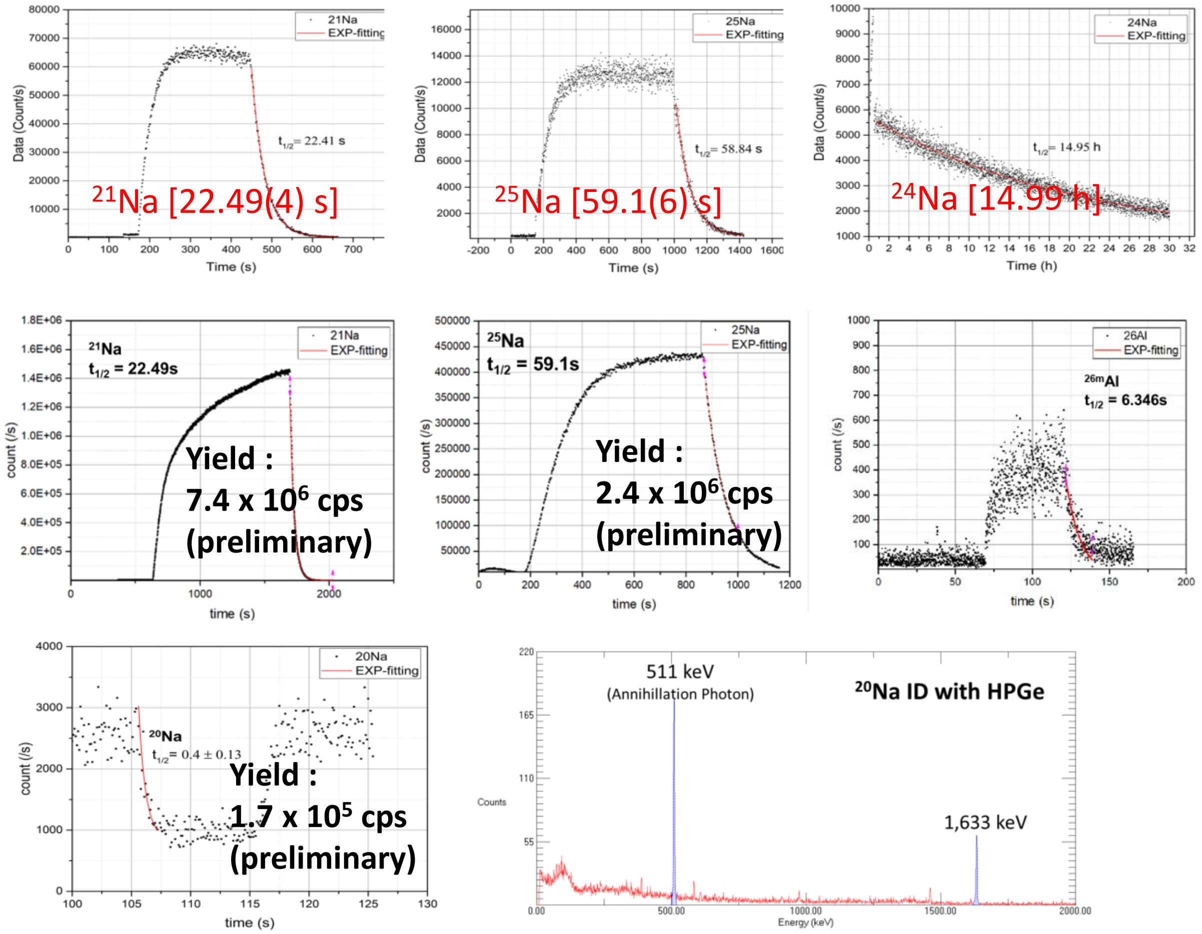
- History
  - Jun. 2019: Contract
  - Apr. 2020: Design finalized
  - Jun. 2021: Factory Acceptance Test (FAT)
  - Aug. 2021: Shipping
  - Nov. 2021~Apr. 2022: Installation
  - Oct. 2022: Site Acceptance Test (SAT)

Cyclotron

Cyclotron beam line installation

ISOL system

- First RI production and transportation by the ISOL system was demonstrated using SiC.
  - Production and measurement of half-lives of Na isotopes (^{21,22,24,25}Na) on March 3, 2023
  - Second RI production test produced ^{26m}Al in addition to Na isotopes on May 23, 2023.



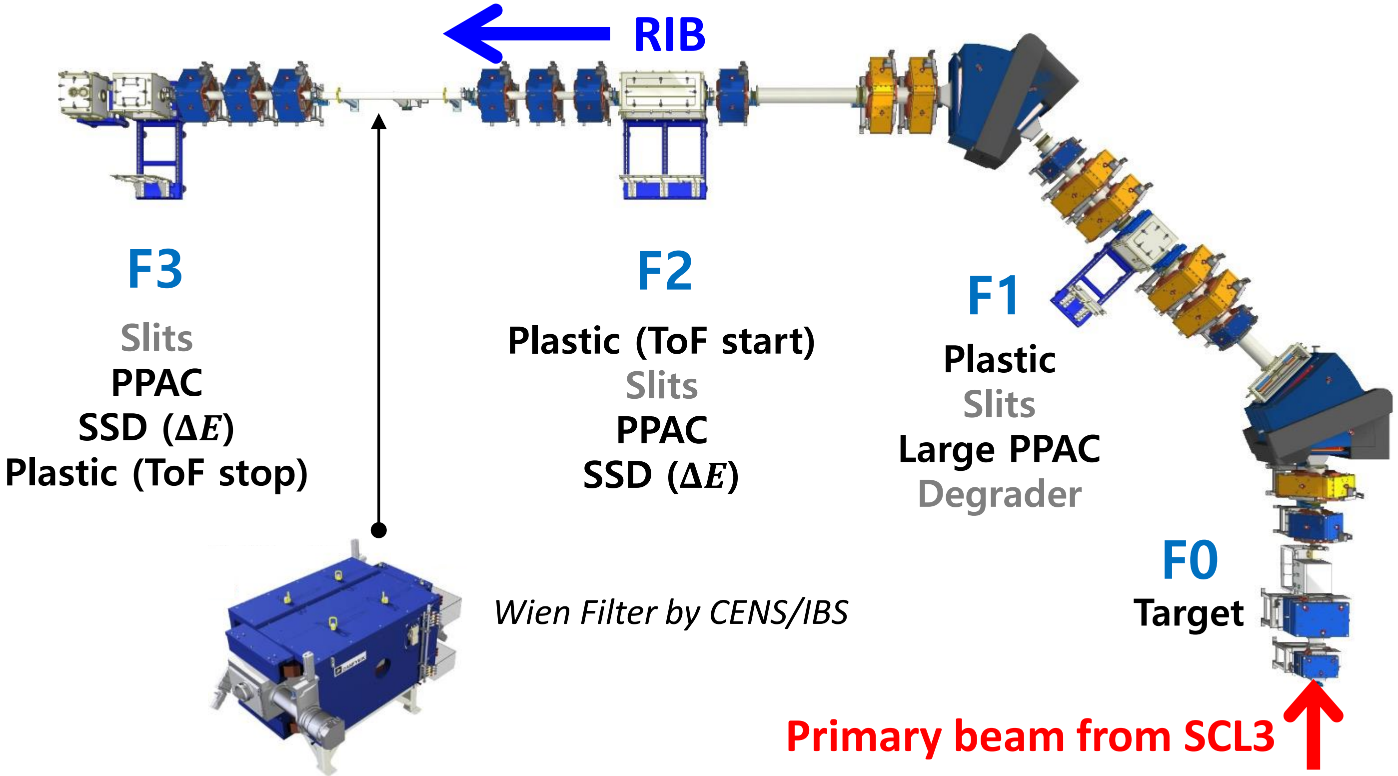
- Experimental conditions
  - Proton beam: 70 MeV, 1.2 μA
  - SiC target temperature
  - ~1,400°C (Ta heater ohmic heating 1.8 kW)

↓ Measured RIs until June 1

		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- 19 4.0ps	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- 18 1.3E-21s	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
6 s	Ne- 17 109.2ms	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

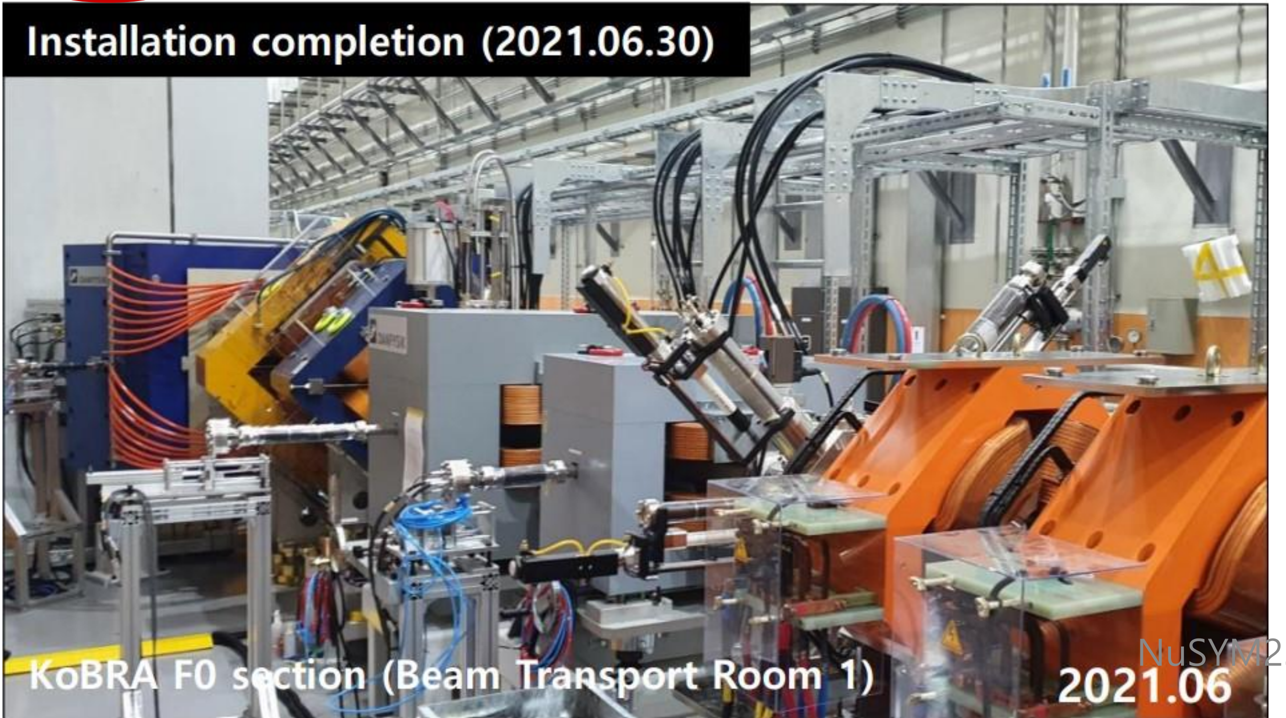
KoBRA

- **Ko**rea **B**road acceptance **R**ecoil spectrometer & **A**pparatus
- Spectrometer 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 ($\leq$ 40 MeV/u for $A \leq 40$ and $\leq$ 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



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 4th order
Degrader at F1	Homogeneous

RAON KoBRA

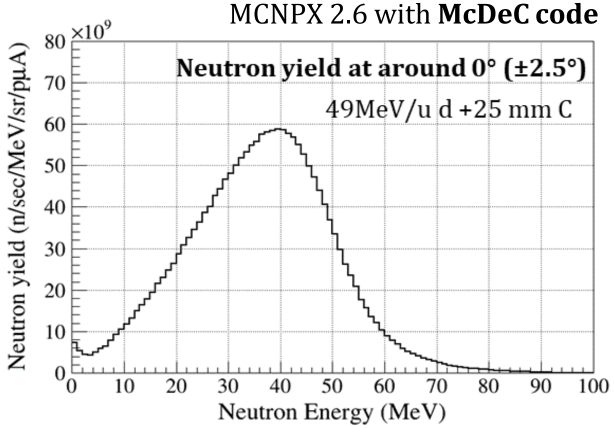


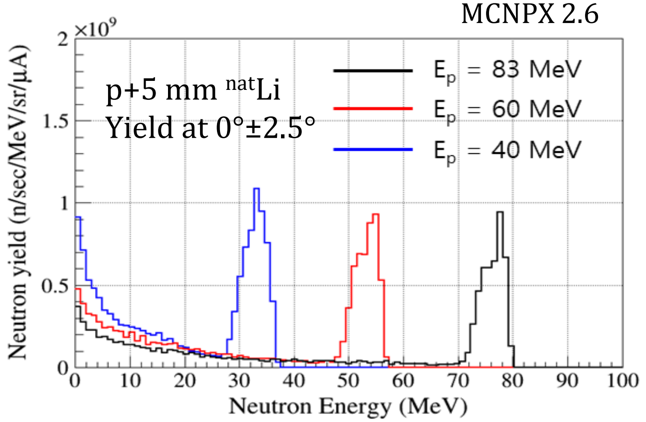
SNACK: **S**ilicon detector array for **N**uclear **A**strophysi**C**s study at **K**oBRA

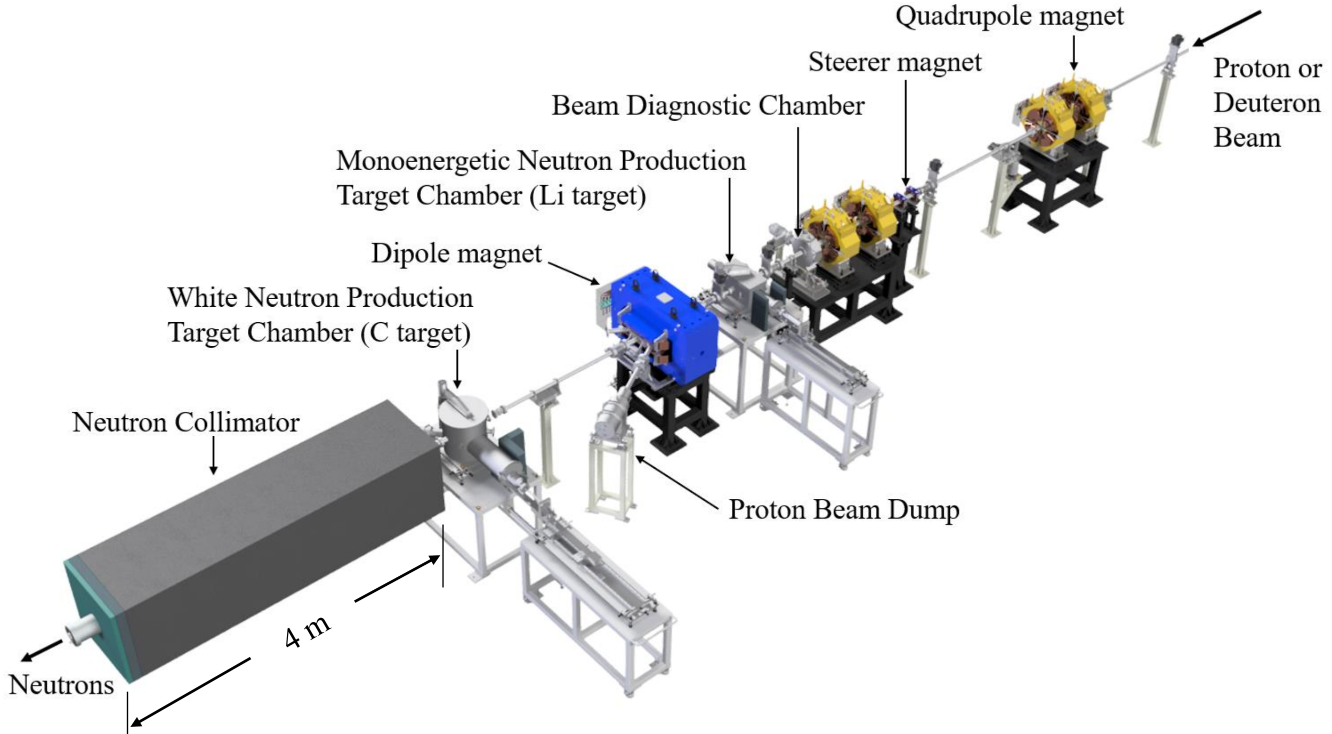
Nuclear Data Production System

- d+C for white neutrons
  - n intensity at the end of the collimator $\simeq$ **10^8 neutrons/cm^2/sec for 10 pμA**
- p+Li for monoenergetic neutrons
  - n intensity at the end of the collimator $\simeq$ **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







RAON NDPS

October 2020


ToF room


Target room

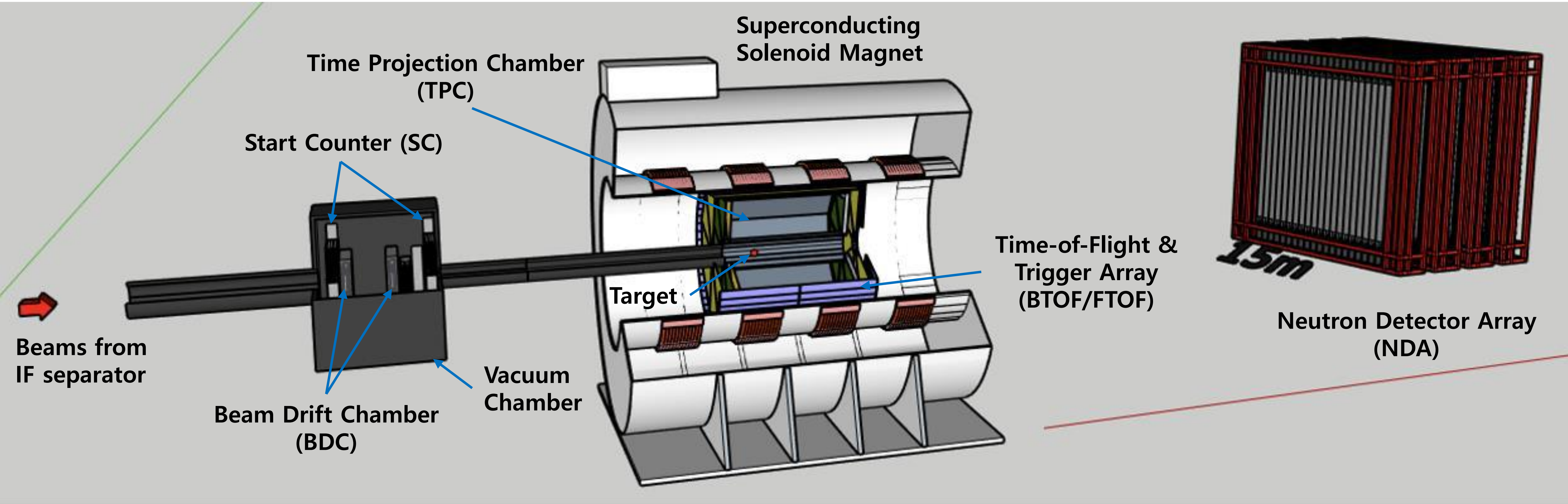
July 2022

Neutron beam dump

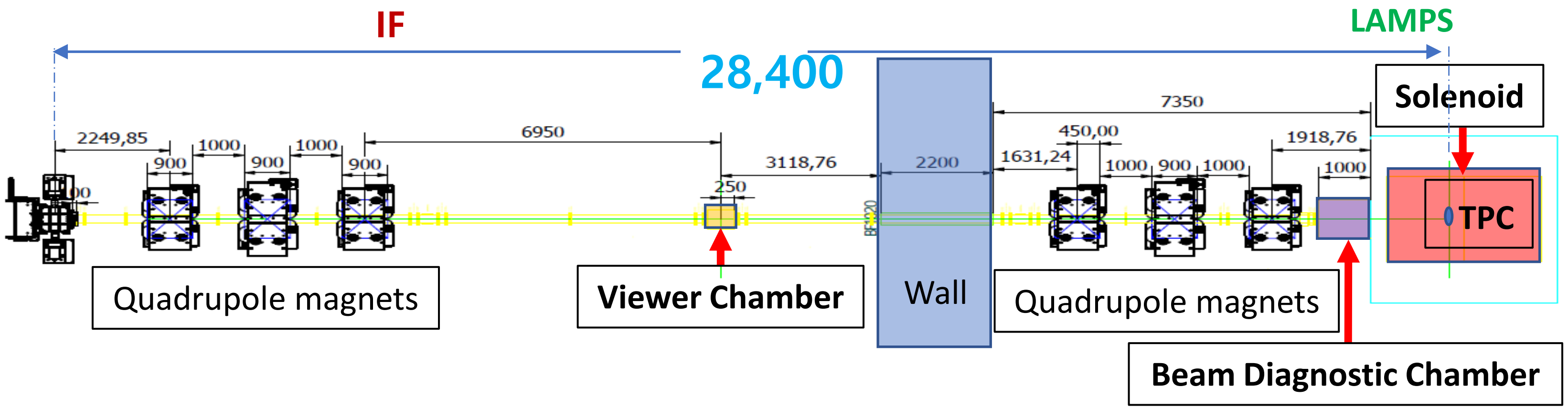
Neutron Collimator


Target room

- **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 2023.

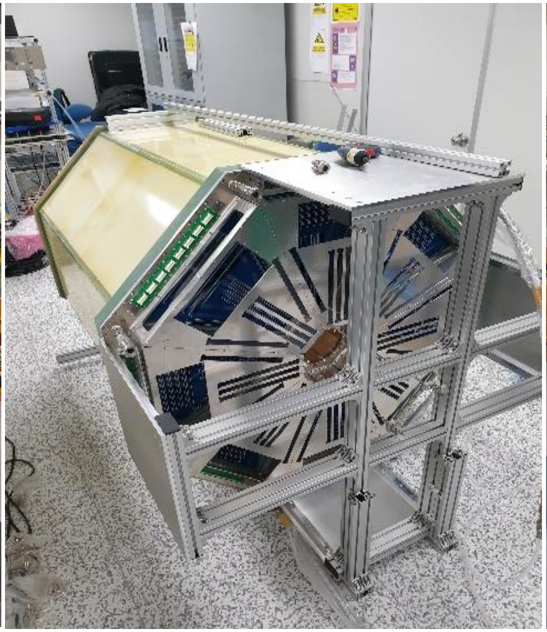


RAON LAMPS

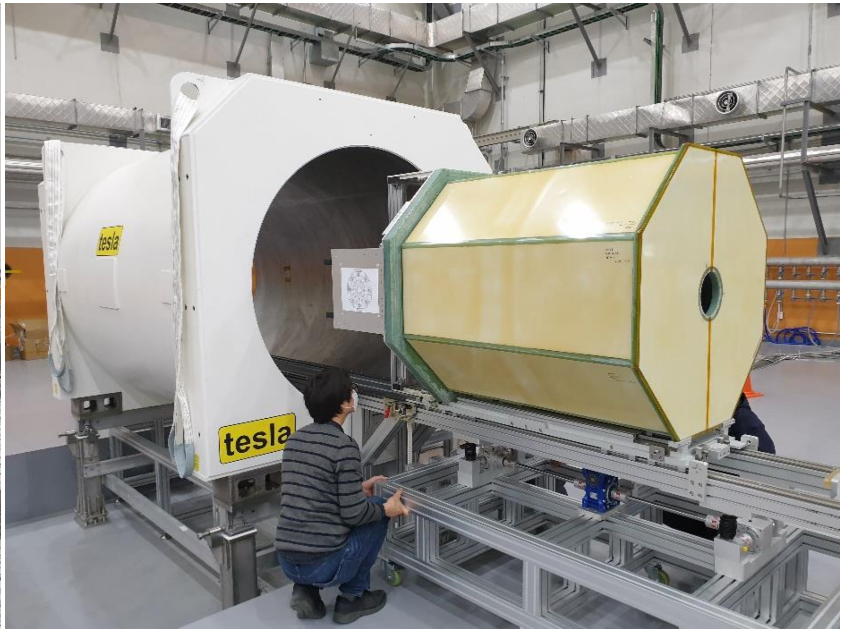


Beamline (Left: IF side, Right: LAMPS side)

SC solenoid magnet (B_{max} = 1 T)

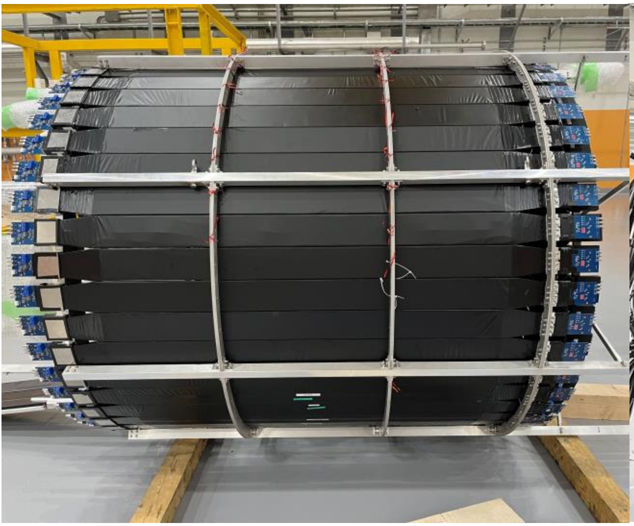
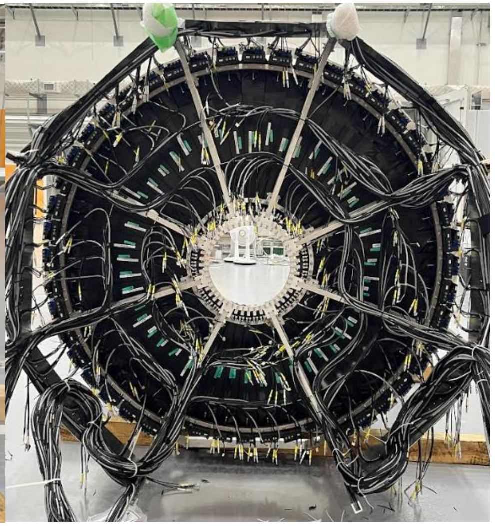


TPC

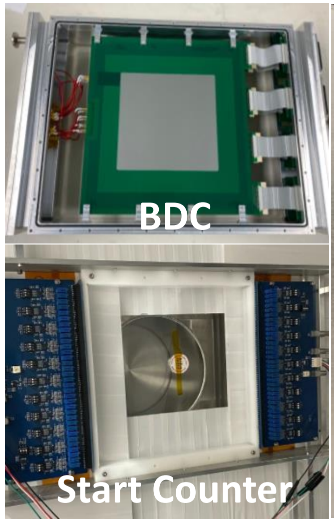


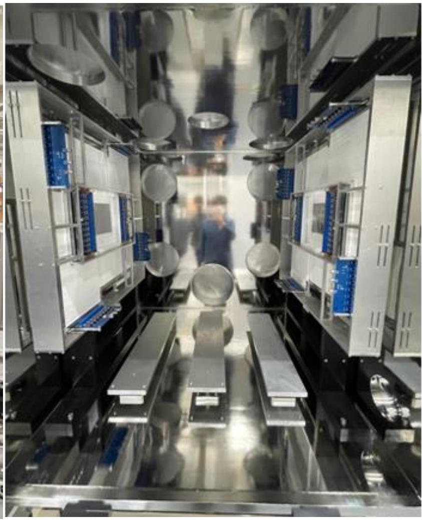
Installation of TPC inside the magnet

Neutron detector array

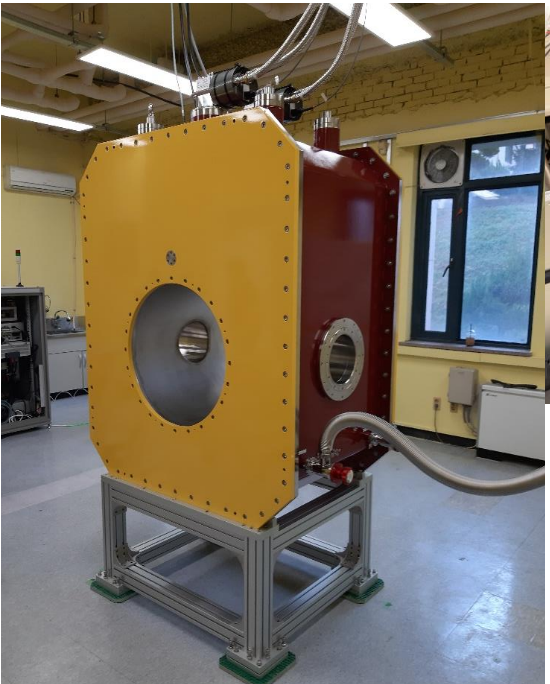
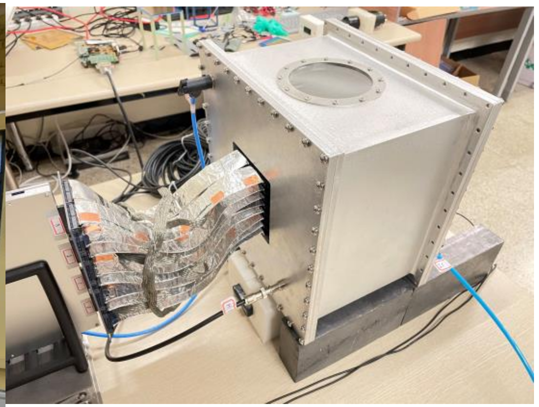



ToF & Trigger array (BTOF/FTOF)



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

Summary of status

- Injector beam commissioning
  - Measurement of the beam parameters (emittance and beam size, etc.)
  - Controlling LEBT and MEBT beam optics as needed
  - Achieved beam transmission of 95% max (routinely > 90%)
  - Machine verification including diagnostics devices
- Linac (SCL3) beam commissioning
  - Ar^{9+} beams were, for the first time, delivered to the KoBRA production target on May 31, 2023.
  - As soon as the cryoplants started operation, it took just a month to cool the linac and transmit the RF.
  - SCL3 warm-up and maintenance is planned from June 2023.
- Constraints from RAON
  - Very limited beam (Ar) delivery to KoBRA for experiments is expected in early 2024
  - Light RIB (e.g., Na or Al isotopes) from ISOL may be available in 2025.
  - The beam energy will be ~20 MeV/u until approximately 2030 when SCL2 is completed.
  - The first PAC is expected in the second half of 2024.
  - *The high-energy accelerator SCL2 will be available in 2030 or later.*

Proposed experiments at KoBRA with stable ion beams in early phase

- Study on neutron-deficient nuclei using proton-induced fusion-evaporation
- $3n$ fusion-evaporation reactions to study MEDs in T_z = -3/2 nuclei
- Fusion reaction studies related to stellar evolution
- Lifetime of isotopes near doubly magic $N = Z$ nuclei ^{40}Ca
- Optical model potential studies using stable beams at KoBRA
- Decay spectroscopy and fast-timing measurements by using KHALA at RAON
- High-resolution in-beam γ-ray experiments: Internal conversion electron spectroscopy
- Spectroscopy of proton, neutron and alpha emitters
- RI experiments probing isospin symmetry
- Measurement of RI production cross sections
- Symmetry energy at low densities using isospin mixing in fusion reactions
- Cluster structure of nuclei