2022 CENuM Workshop

Inha University, Korea, 2-3 September 2022

Status of RAON ~~and LAMPS~~

Byungsik Hong

Center for Extreme Nuclear Matters (CENuM), Korea University

for IBS 중이온가속기연구소

기초과학연구원 Institute for Basic Science

중이온가속기건설구축사업단 Rare Isotope Science Project

Outline

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

Part 1.

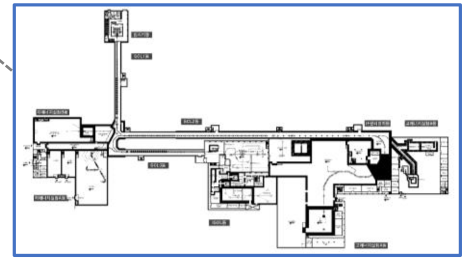
Overview

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 (1^{st} phase), 2023-2029 (2^{nd} 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 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

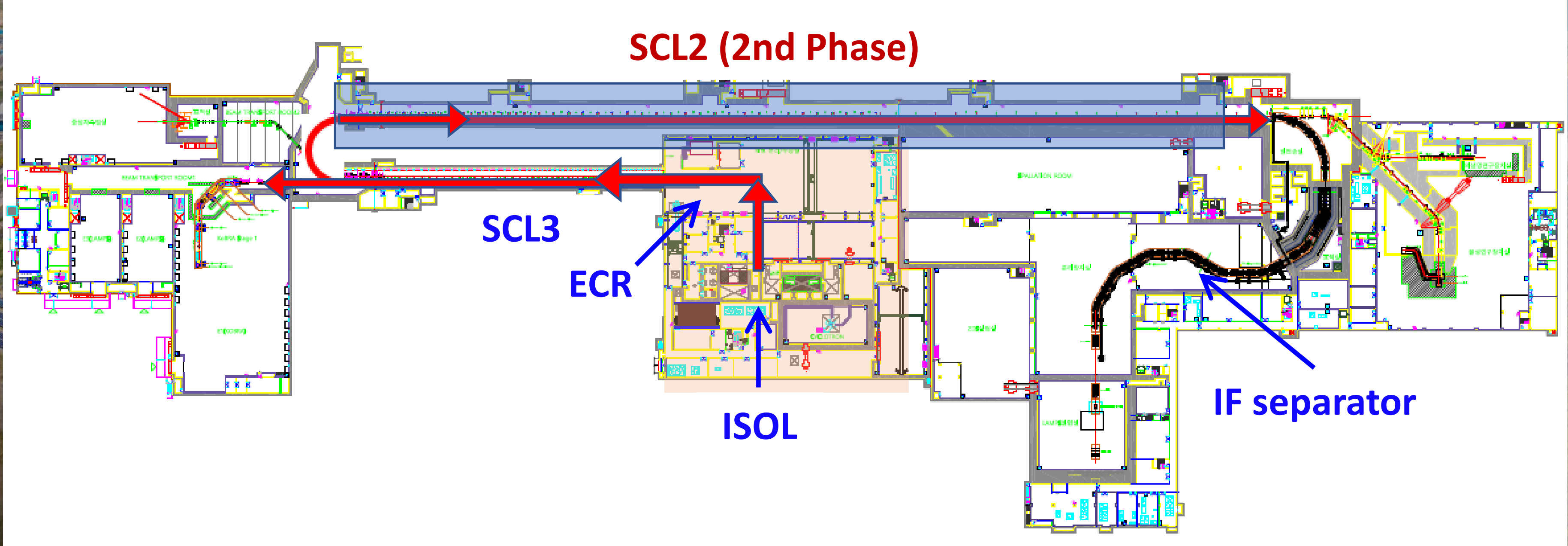
RAON Layout

- 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)

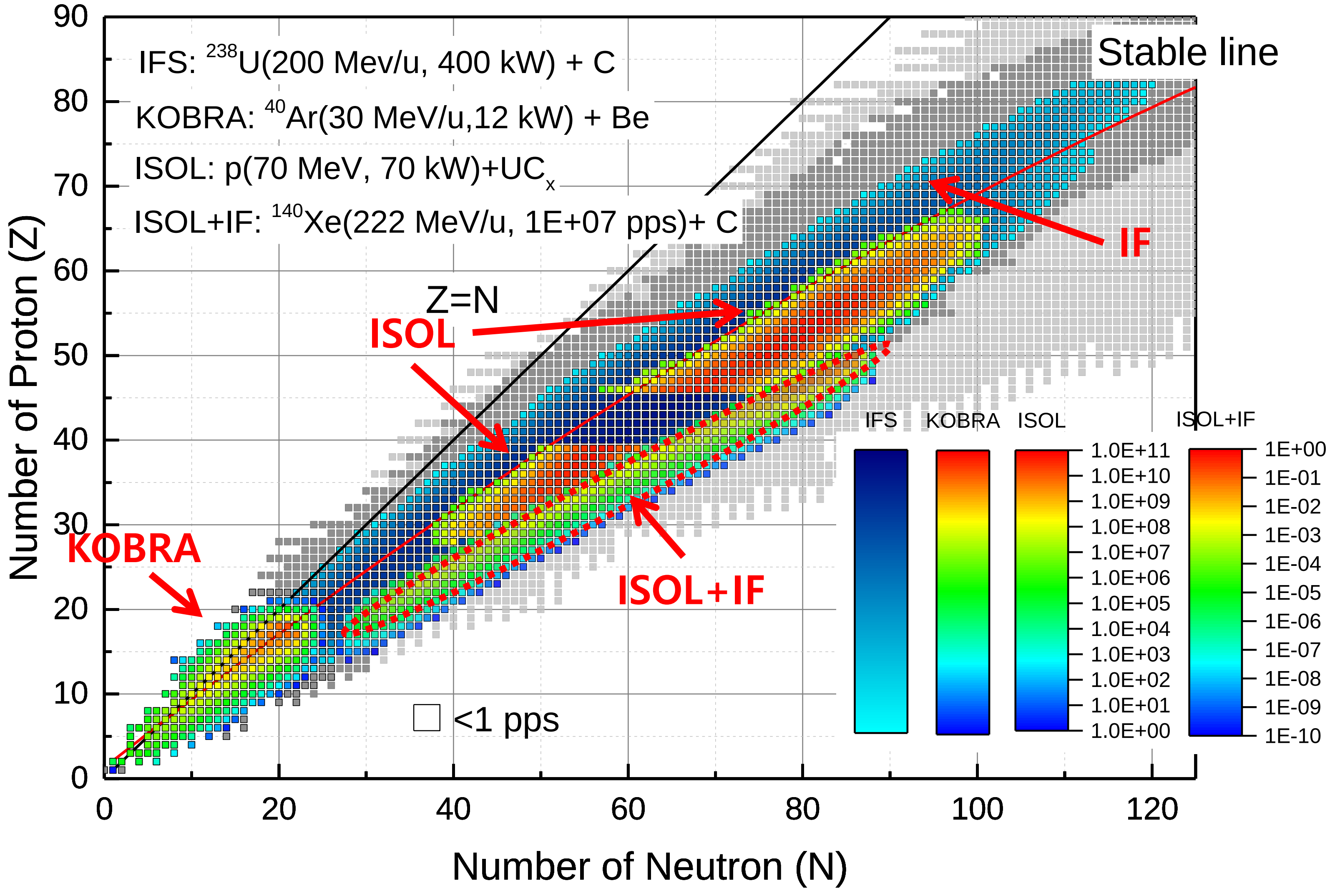
Scientific goals

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



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

RAON Accelerator system (Overview)

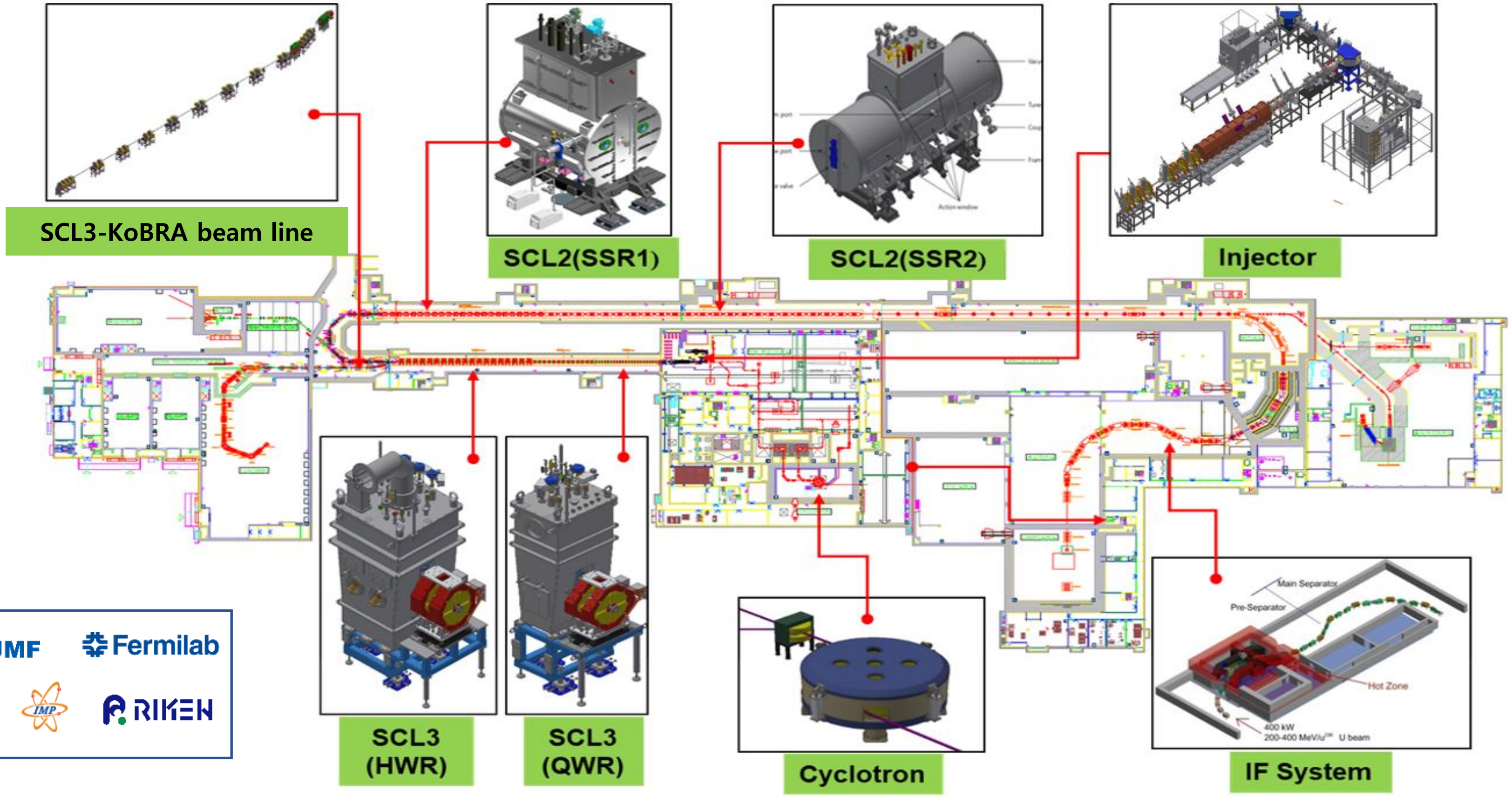
CENuM

← Injector → ← SC Linac → ← IF →

SCL1 / SCL3 (18 MeV/u) — SCL2 (200 MeV/u)

0.5 MeV/u

ISOL/ECR	LEBT	RFQ	MEBT	SCL31	SCL32	CSS	SCL21	SCL22	HEBT	IF
				β=0.047	β=0.12		β=0.3	β=0.51		



TRIUMF, Fermilab, IHEP, IMP, RIKEN

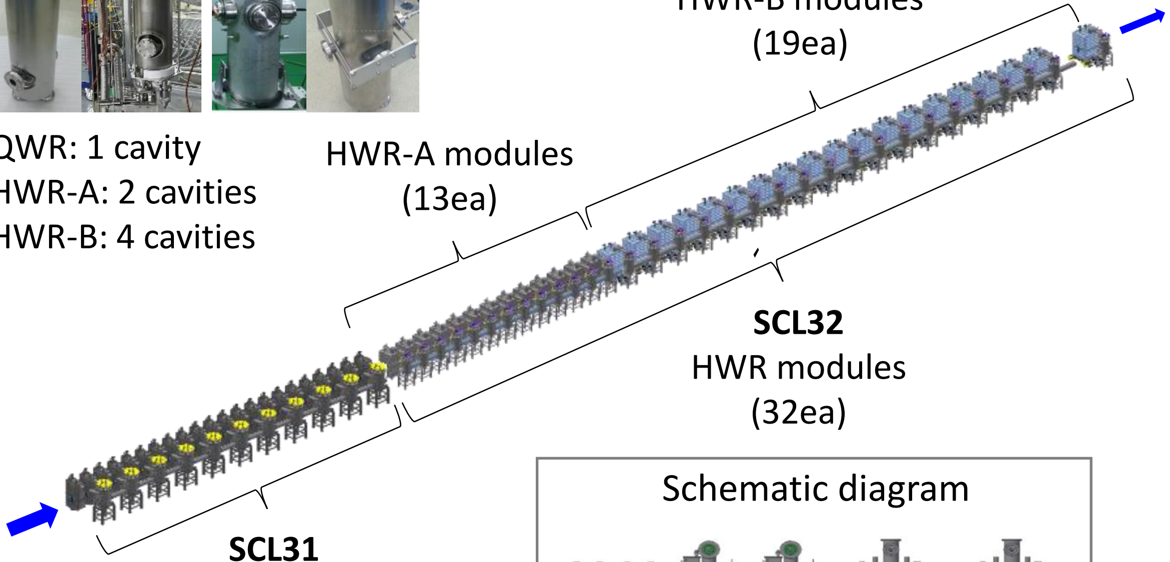
◐ **Phase I (~2022)**
- Installation and beam commissioning of the injector, SCL3 and ISOL
- Installation and machine commission of all experimental systems & IF separator

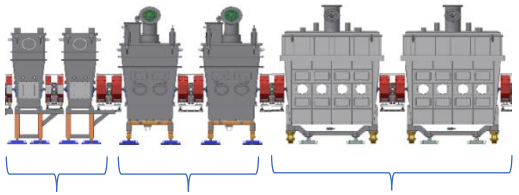
◐ **Phase II (~2029)**
- R&D, construction, installation and beam commissioning of SCL2

Accelerator system (Overview of SC Linacs)

SCL3 (Phase I)

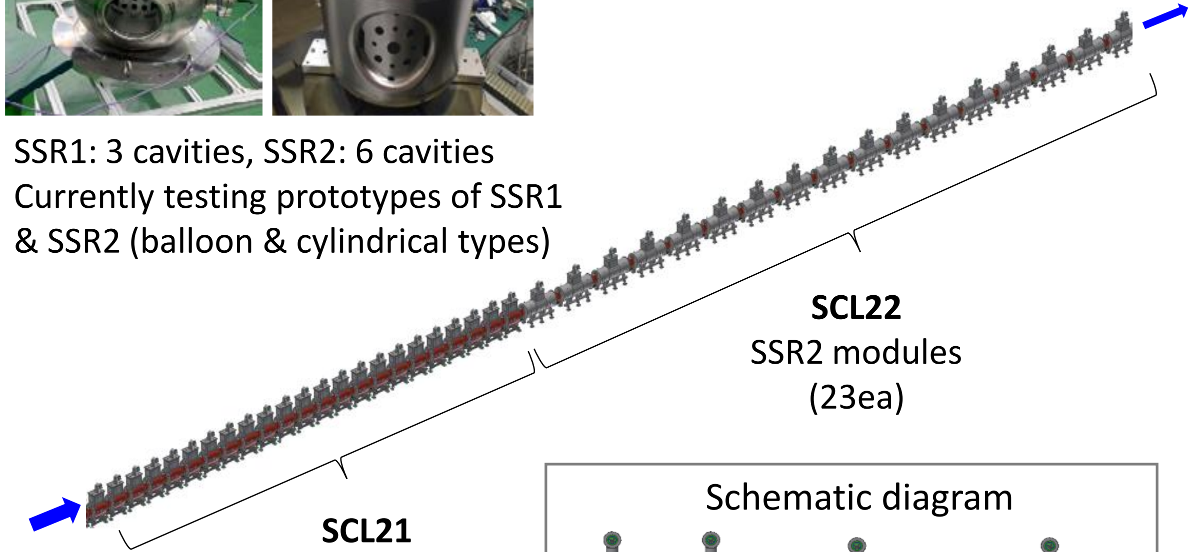
QWR: 1 cavity
HWR-A: 2 cavities
HWR-B: 4 cavities

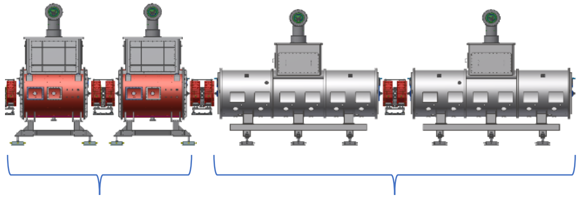




SCL2 (Phase II)

SSR1: 3 cavities, SSR2: 6 cavities
Currently testing prototypes of SSR1 & SSR2 (balloon & cylindrical types)

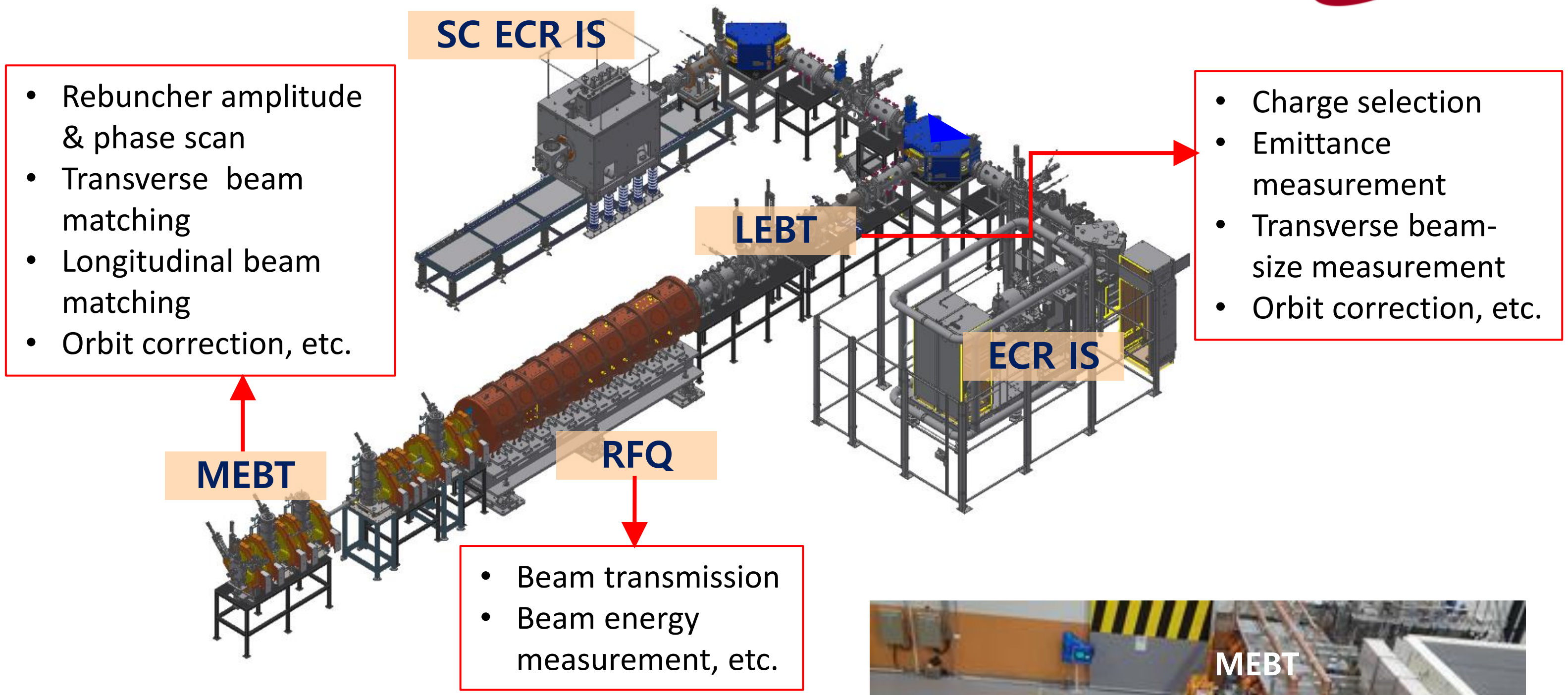




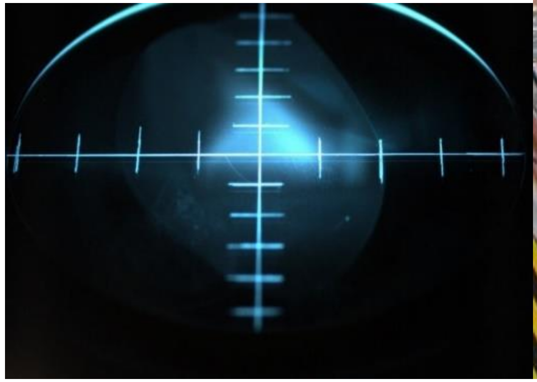
- *SSR2: 23 for acceleration and additional 2 for bunching*

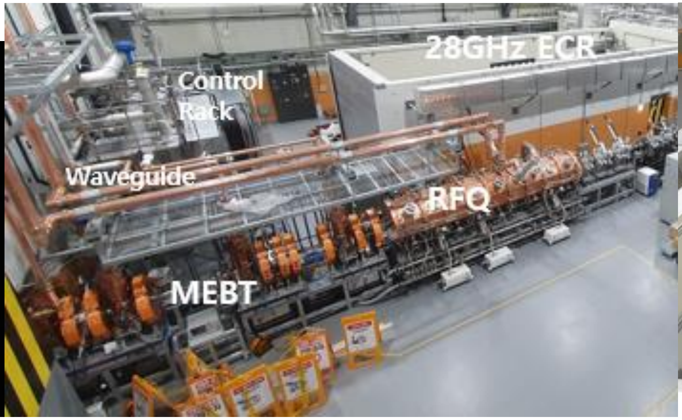
Injector system

- 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

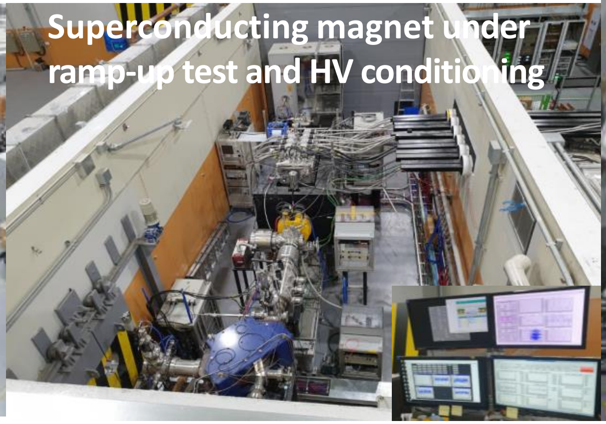


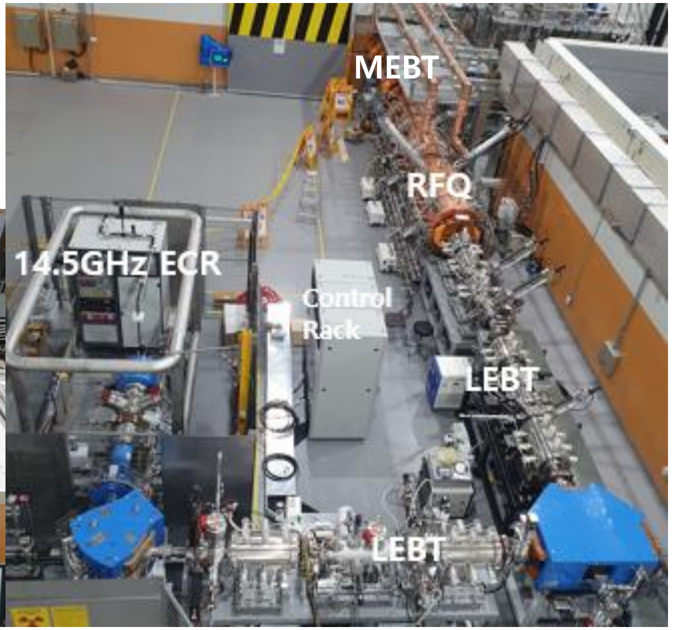
Ar^{8+} 10μA @ Beam Viewer('21)





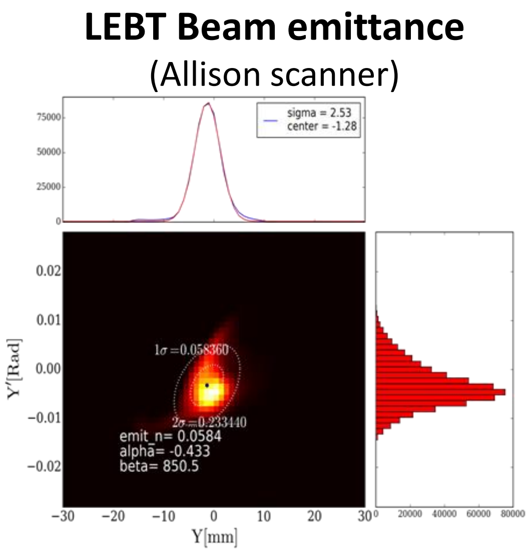
28 GHz SC ECR IS

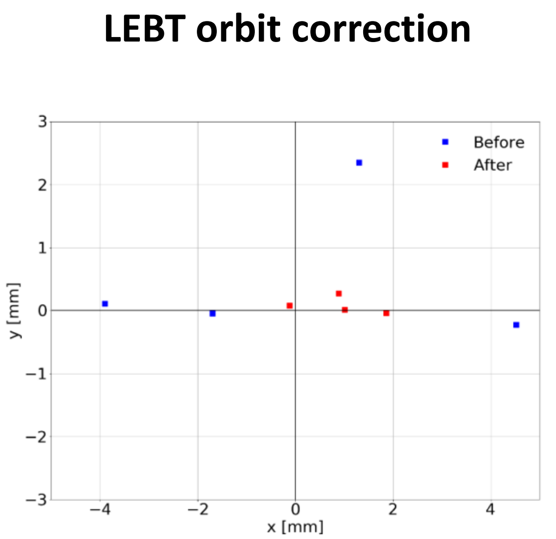




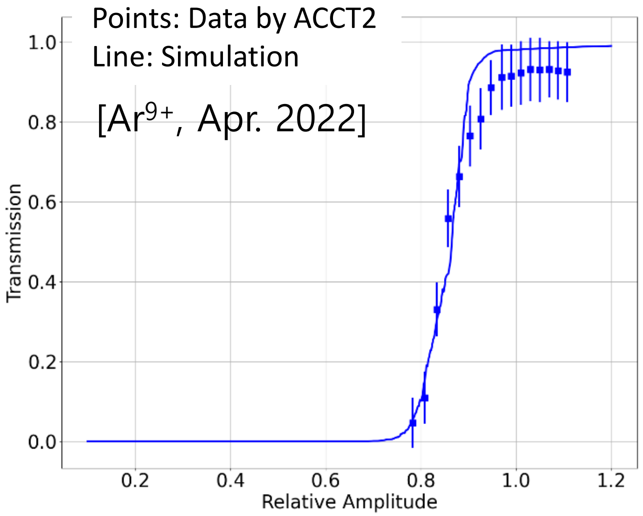
Injector beam commissioning

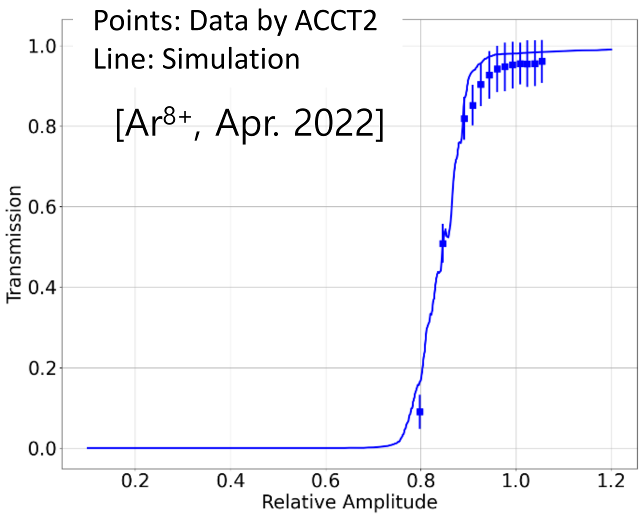
Parameter	Value
[Beam Properties]	
Frequency	81.25 MHz
Particle	H^{1+} to $^{238}U^{33+}$
Input energy	10 keV/u
Input current	0.4 mA
Input emittance	0.012 cm·mrad
Output energy	0.507 MeV/u
Output emittance	0.0125 cm·mrad
Transmission	~98% (simulation)
Duty factor	100%





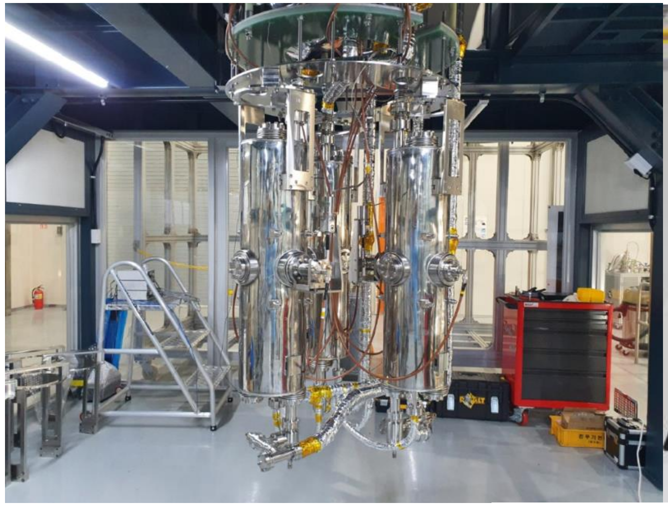
- Beams
  - Ar^{9+} (~30 μA) & Ar^{8+} (~47 μA): 100 μs long pulsed beam
  - Repetition rate: 1 Hz
- EPICS basis control system
- RFQ transmission
  - Measured by ACCTs in LEBT & MEBT (Error bar: 3σ)
  - Ar^{9+} (91.9% w/ σ=1.9%) & Ar^{8+} (95.4% w/ σ=1.3%)
- Energy
  - 507 keV/u by ToF using the two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

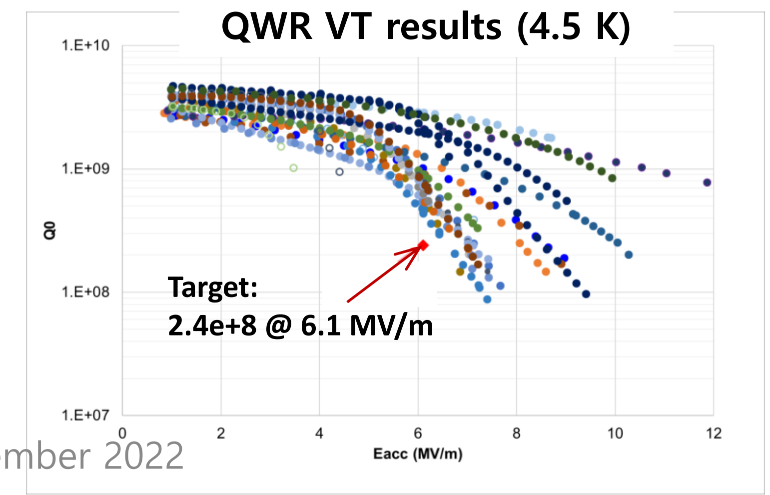


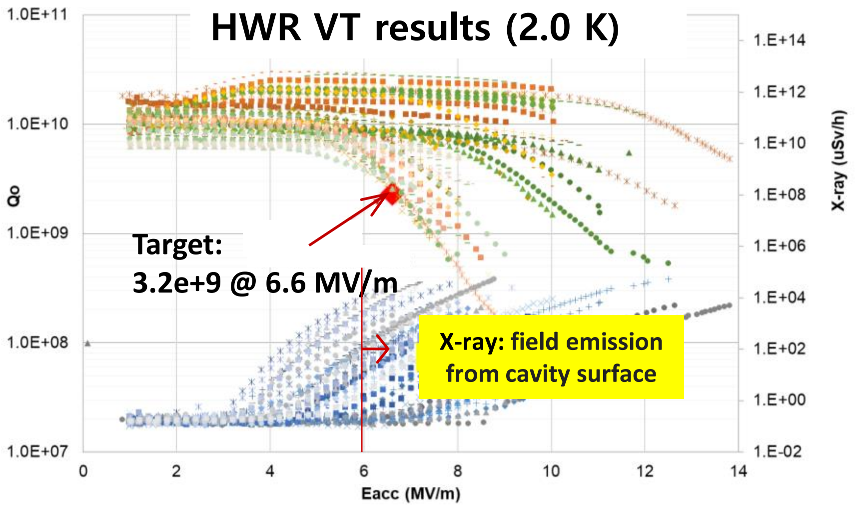


SRF test facility and QC

- Processing the performance tests of SCL2 and SCL3 cryo-modules at cryogenic temperature
- Onsite test facility: 3 VT pits and 3 cavities per pit + 3 HT bunkers
- Offsite (~15 km from the RAON campus) test facility: 2 VT pits and 2 cavities per pit
- They cover all RAON cavities: QWR (81.25 MHz), HWR (162.5 MHz) and SSR1/SSR2 (325 MHz)

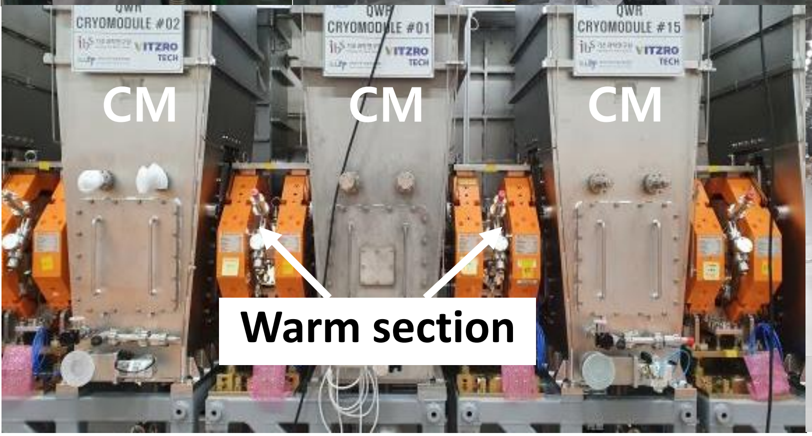






SCL3 and cryoplants

- Cryomodules (CM) & warm sections were assembled in the clean booth in the tunnel.
- Total particle counts for the size > 0.5 µm/10 minutes 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

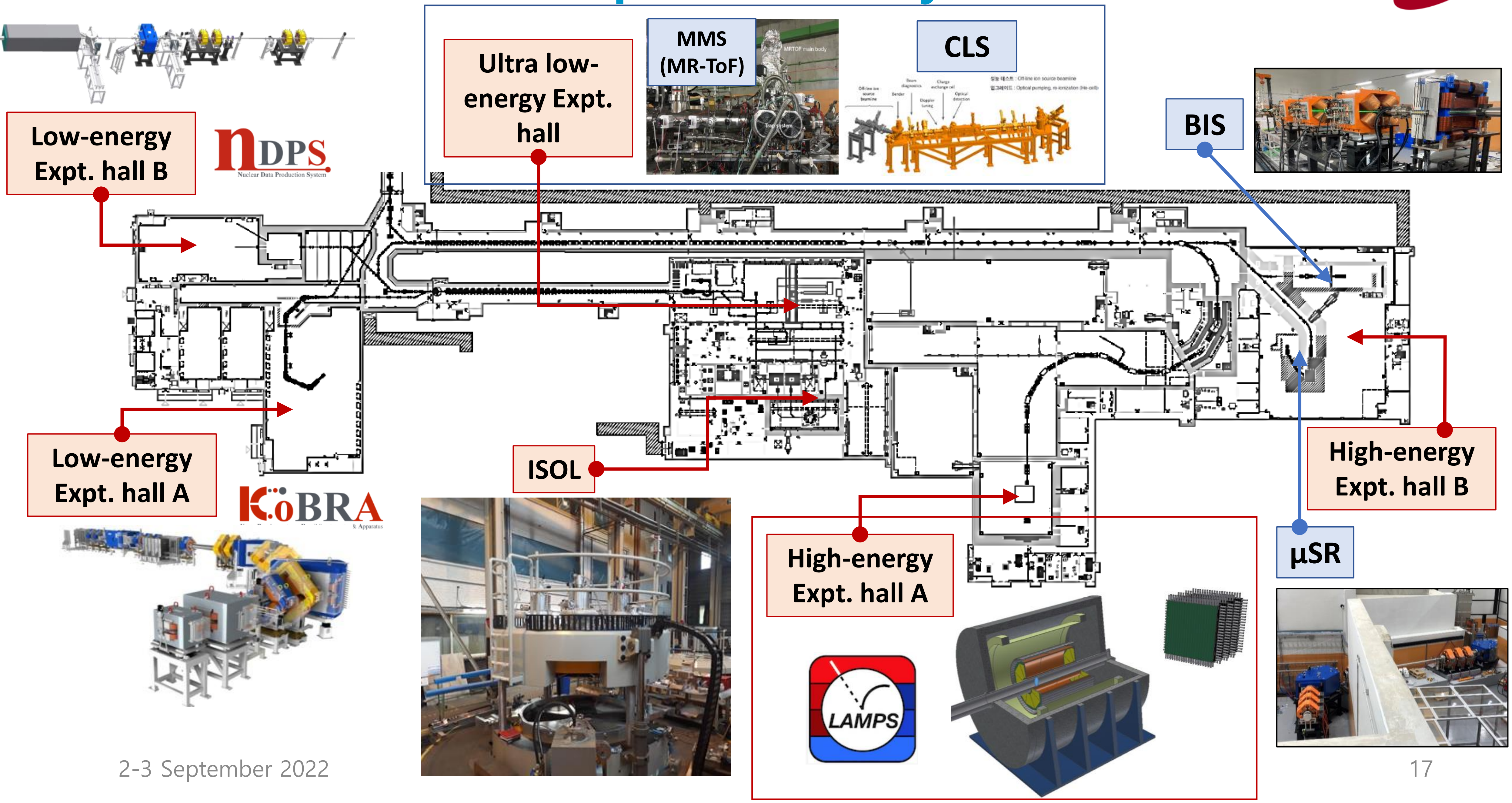
LHe Dist. box

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

Part 3.

RI & experimental systems

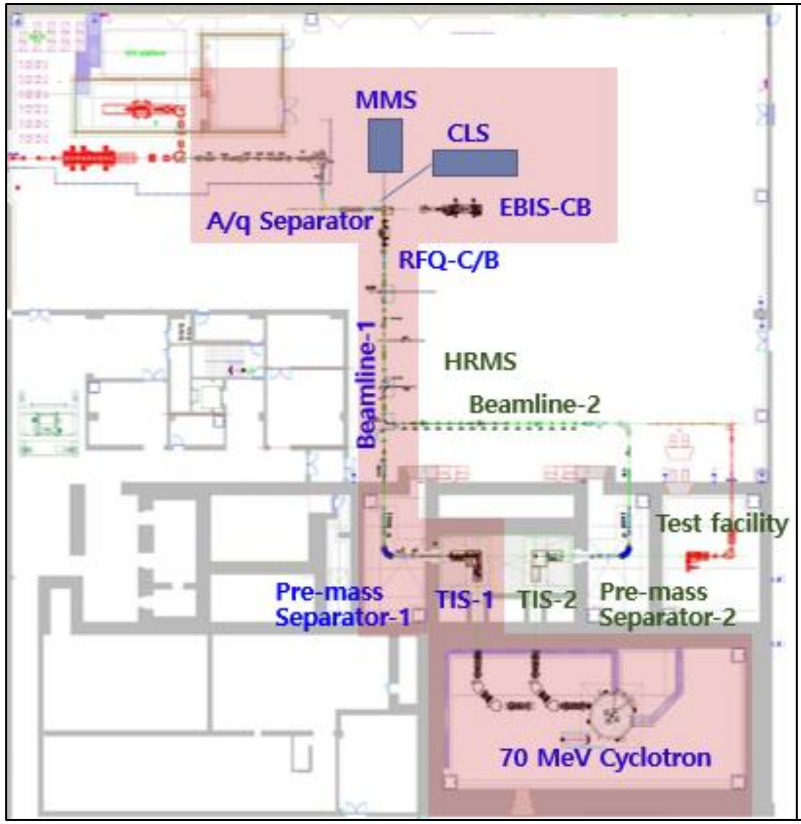
Overview of experimental systems

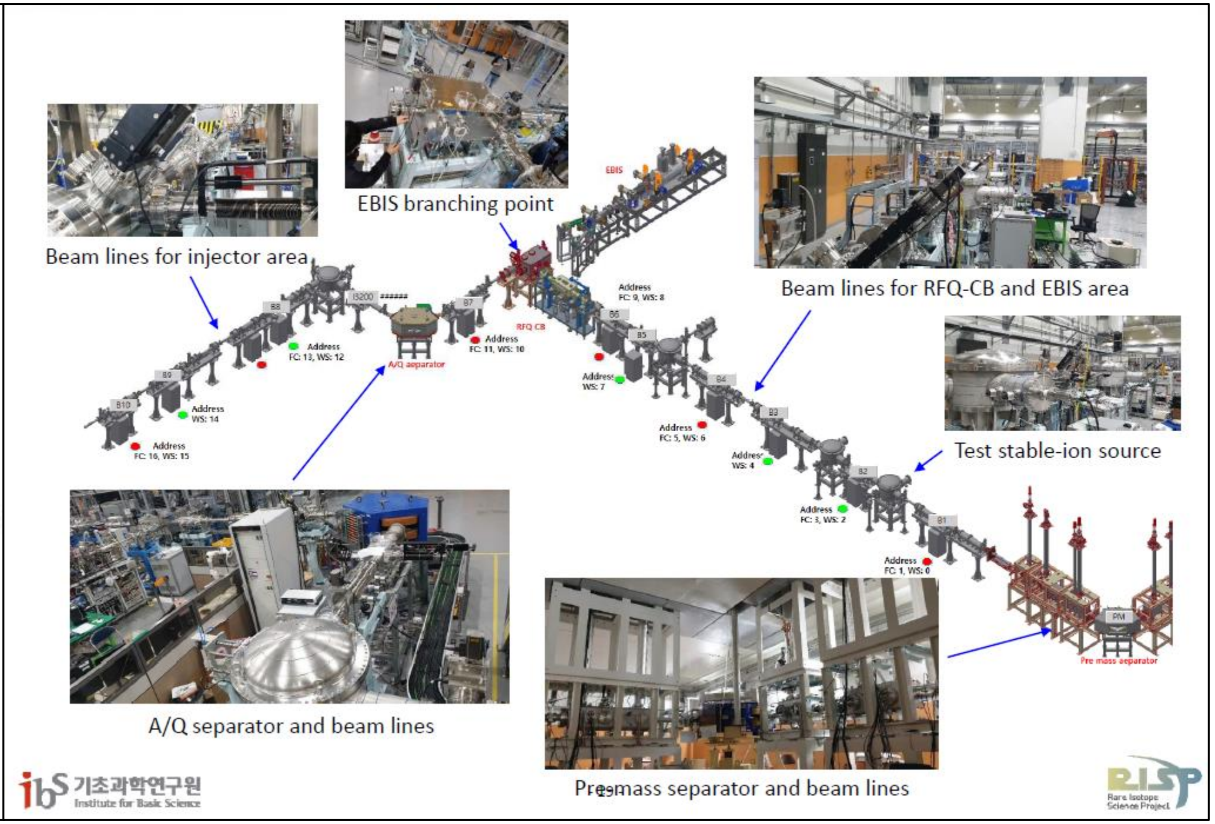


ISOL system

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 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 of post accelerator with 10 keV/u
- Full remote maintenance system with TIS modularization



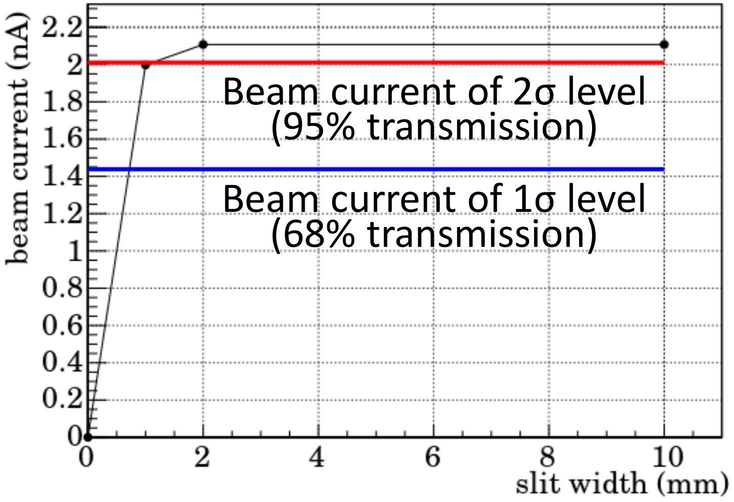


◐ ISOL beam lines including sub-systems were commissioned with Cs ions in 2021 (next slide).

ISOL SIB commissioning

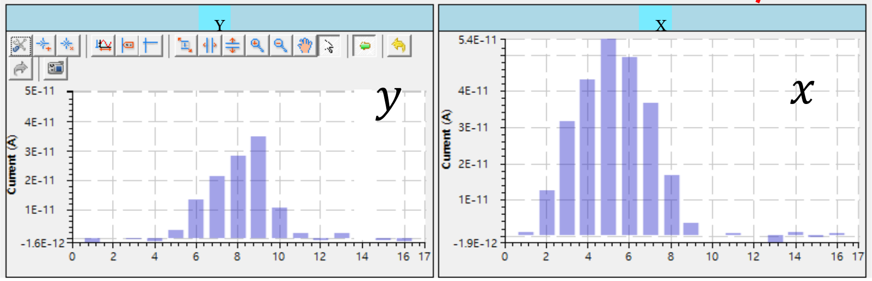
Target Ion Source ($^{133}Cs^{1+}$, 20 keV) → Pre-Separator ($m/\delta m \simeq$1,000) → RFQ Cooler (>10^8 ions/bunch) → EBIS (>15% $^{133}Cs^{27+}$, A/q<6) → A/q Separator ($m/\delta m \simeq$ 250) → Post Linac ($^{133}Cs^{27+}$, 10 keV/u)

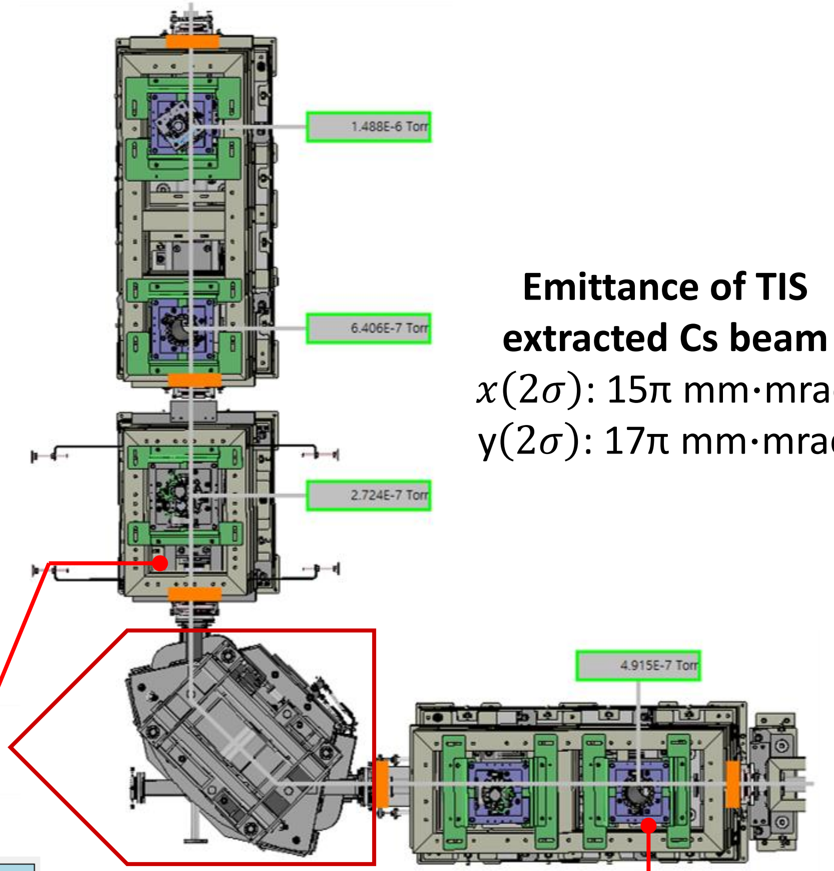
Beam size measurement by F2 slit

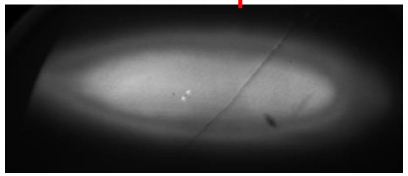


- Horizontal beam size~2 mm (2σ)
- Mass resolving power of Pre-mass Separator~1,000 (2σ)

Cs⁺ Beam profile (Wire Grid)

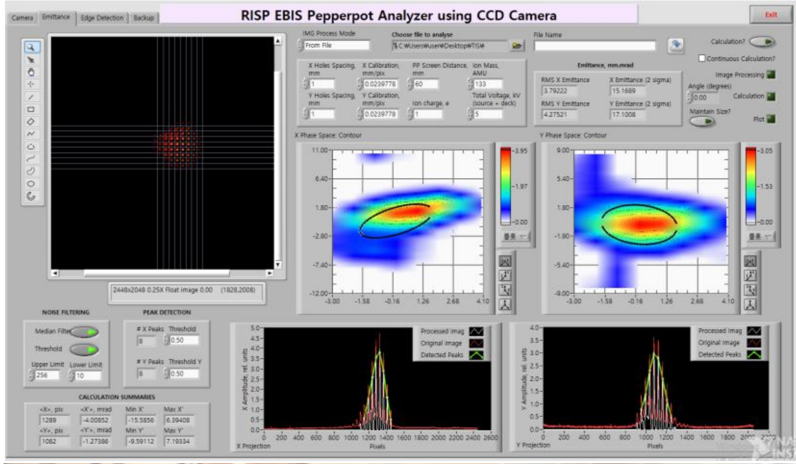


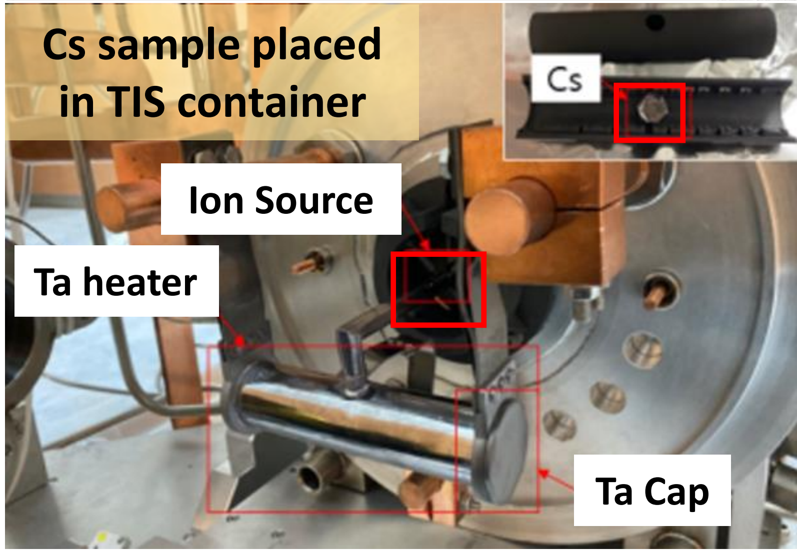




Beam viewer
x ~40 mm, y ~ 15 mm

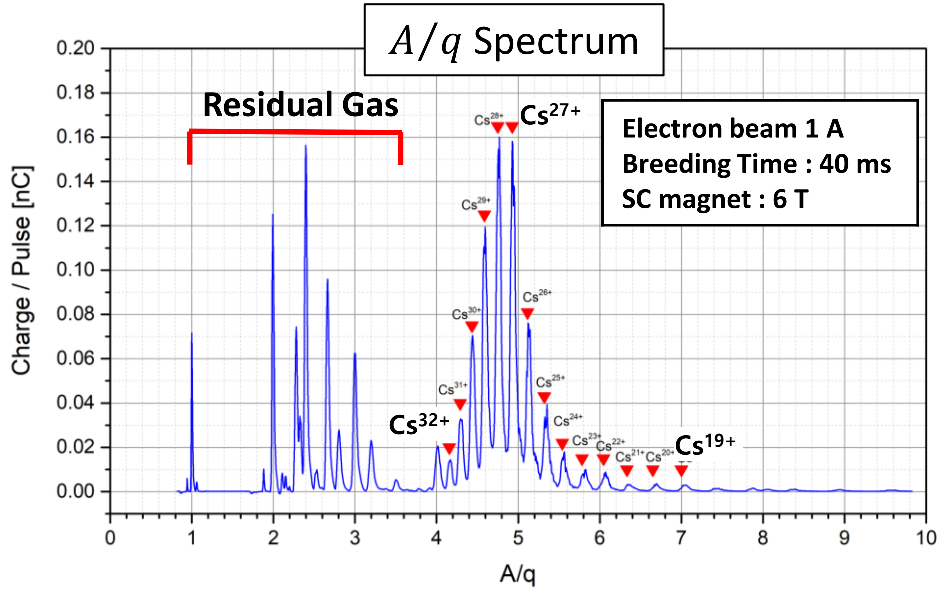
Emittance of TIS extracted Cs beam
$x(2\sigma)$: 15π mm·mrad
$y(2\sigma)$: 17π mm·mrad

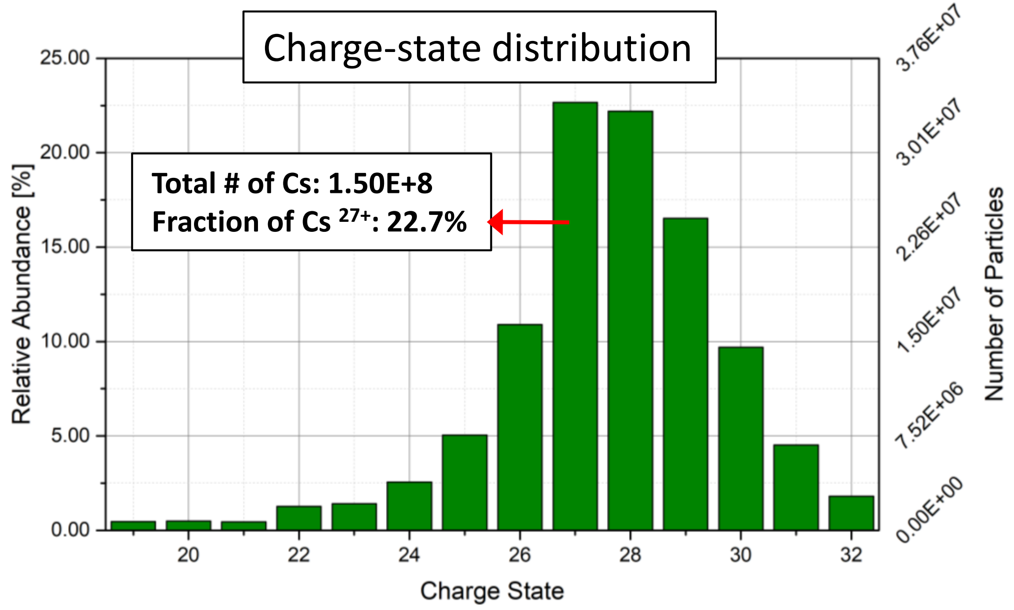


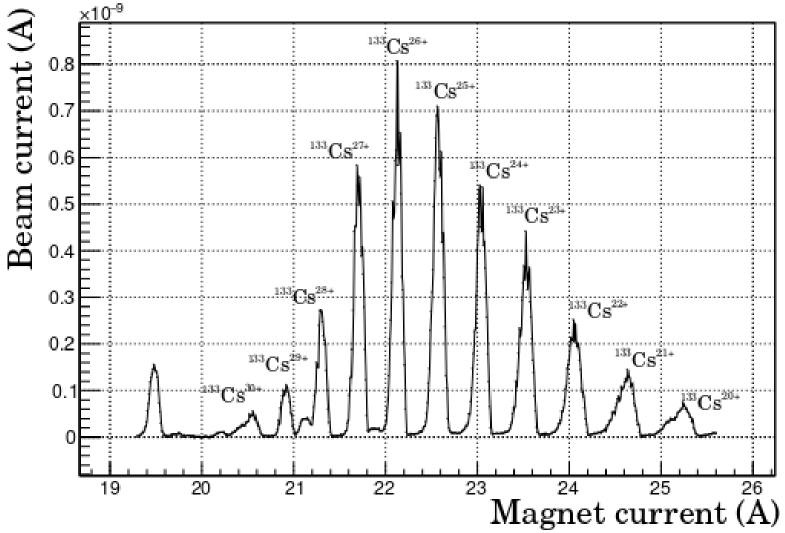


ISOL SIB commissioning

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 current: 0.75 mA
  - Two beam lines to the ISOL TIS bunker

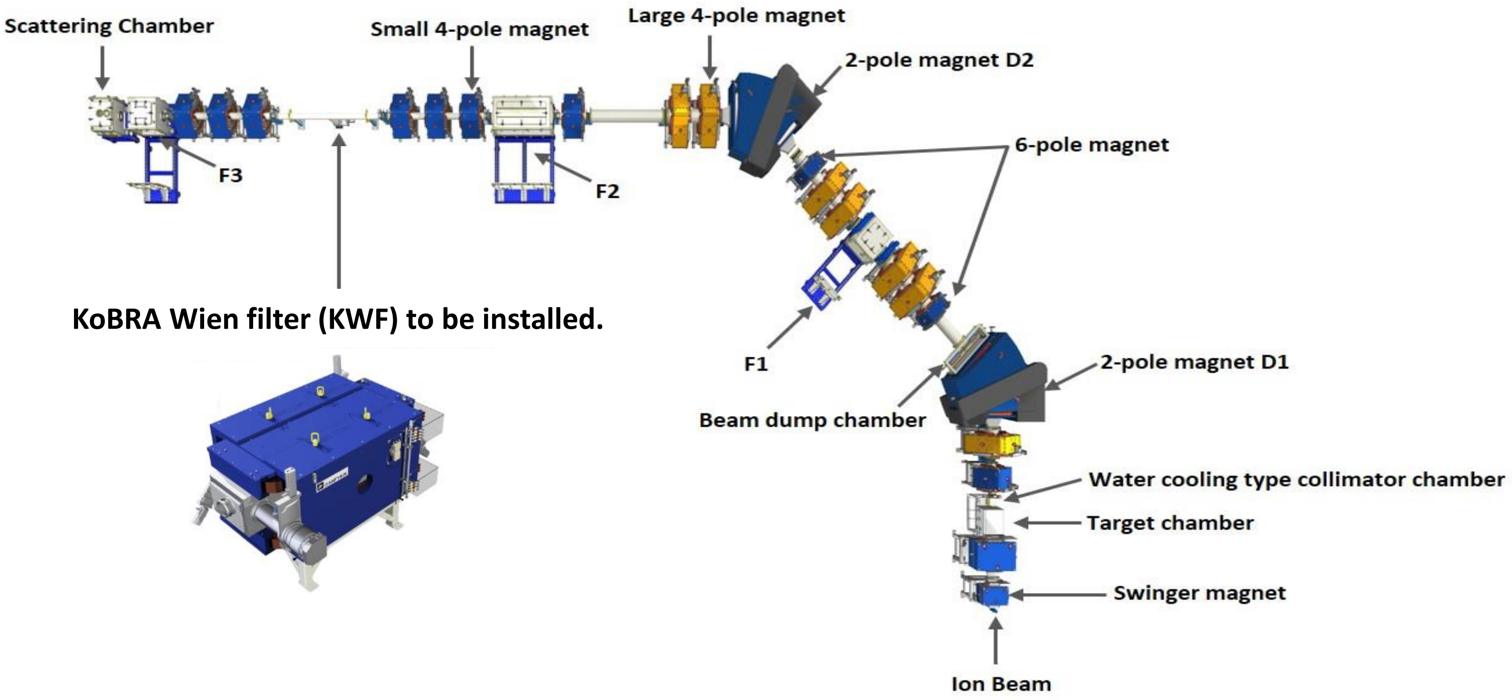
- History
  - Jun. 2019: Contract
  - Apr. 2020: Design finalized
  - Jun. 2021: Factory Acceptance Test (FAT)
  - Aug. 2021: Shipping
  - Nov. 2021~Apr. 2022: Installation
  - Oct. 2022: Site Acceptance Test (SAT) (plan)
  - Still need to finalized the interface between cyclotron and ISOL

Cyclotron

Cyclotron beam line 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
  - Roll of recoil mass separator for RIBs from ISOL at beam energies less than a few MeV/u

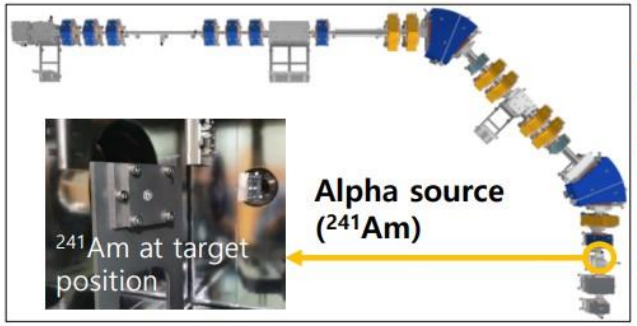


Magnetic rigidity	0.25 – 3.0 Tm
Angular acceptance	80 mrad (H) 200 mrad (V)
Momentum acceptance	8%
Momentum resolving power at F1	2100 at 2 mm beam size
Mass resolving power (with Wien filter)	750 at 2 mm beam size
Beam swinger	up to 12 degree for 3 Tm
High order correction	up to 4th order
Degrader at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

RAON KoBRA

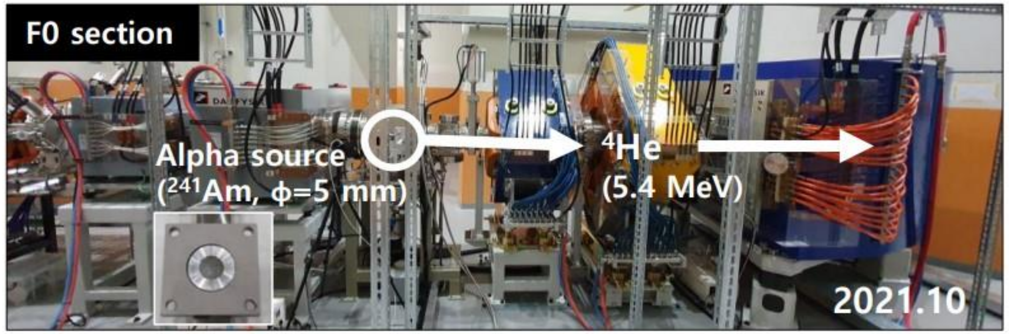
SNACK: **S**ilicon detector array for **N**uclear **A**strophysi**C**s study at **K**oBRA

RAON KoBRA

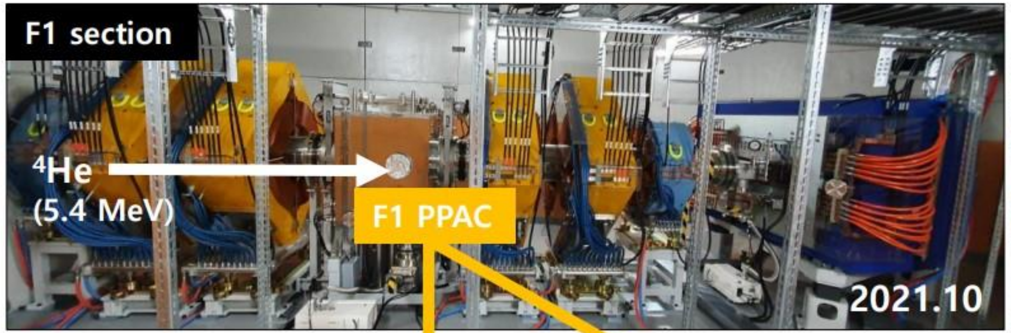


Alpha source
(^{241}Am)
^{241}Am at target position

Detector DAQ PC
DAQ PC
2021.10



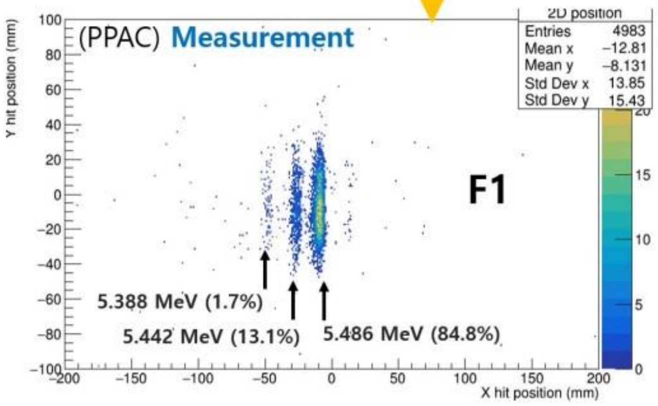
F0 section
Alpha source
(^{241}Am, ϕ=5 mm)
^{4}He
(5.4 MeV)
2021.10



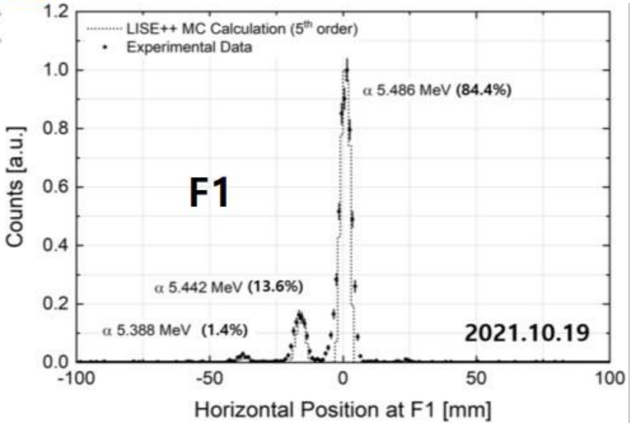
F1 section
^{4}He
(5.4 MeV)
F1 PPAC
2021.10

F2 section
^{4}He
(5.4 MeV)
F2 PPAC
2021.10

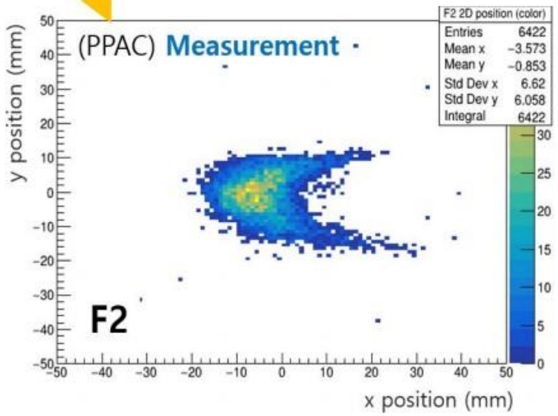
F3 section
^{4}He
(5.4 MeV)
F3 PPAC
2021.10



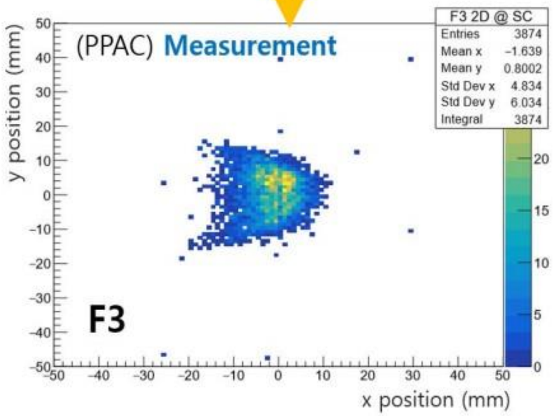
(PPAC) Measurement
2D position
Entries 4983
Mean x −12.81
Mean y −8.131
Std Dev x 13.85
Std Dev y 15.43
F1
5.388 MeV (1.7%)
5.442 MeV (13.1%)
5.486 MeV (84.8%)
Y hit position (mm)
X hit position (mm)



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%)
F1
2021.10.19
Counts [a.u.]
Horizontal Position at F1 [mm]

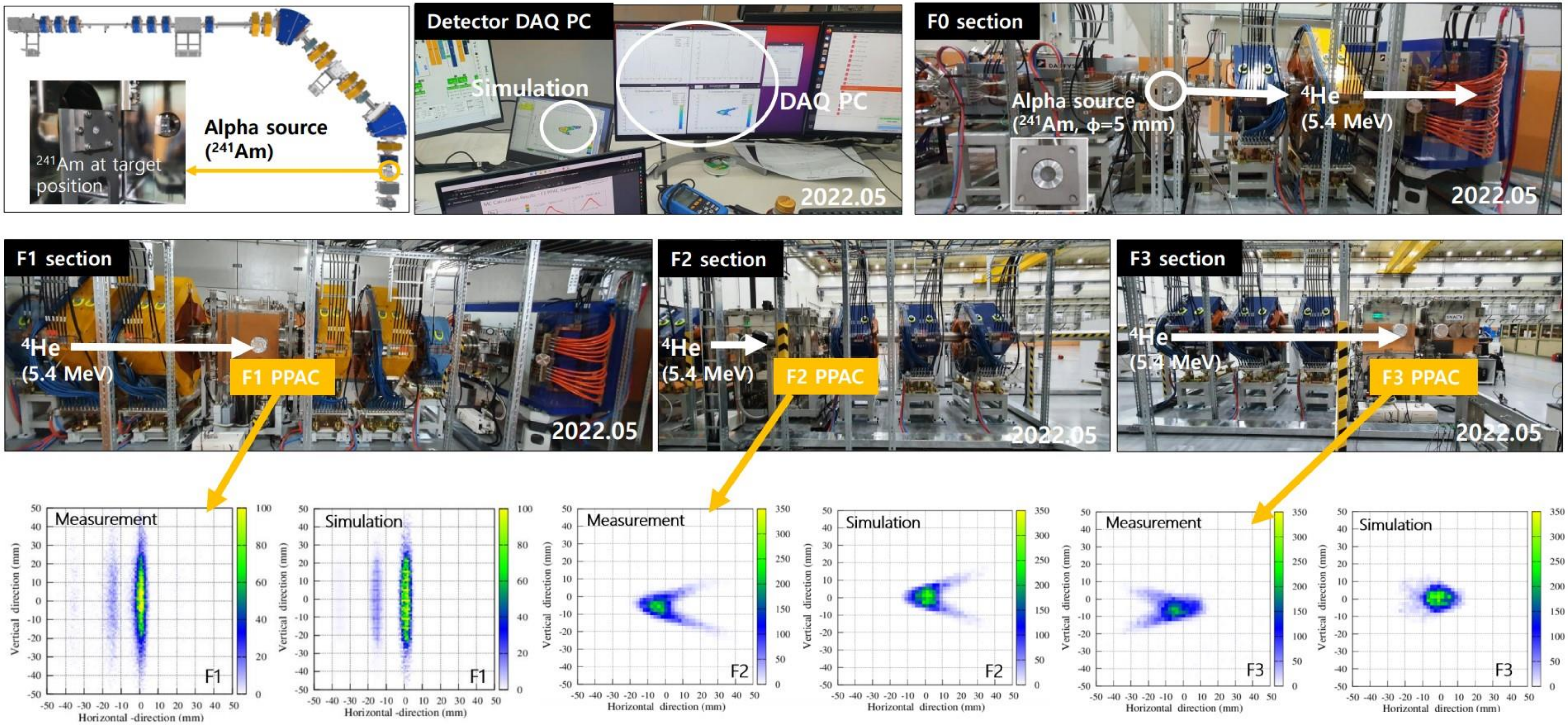


(PPAC) Measurement
F2 2D position (color)
Entries 6422
Mean x −3.573
Mean y −0.853
Std Dev x 6.62
Std Dev y 6.058
Integral 6422
F2
y position (mm)
x position (mm)



(PPAC) Measurement
F3 2D @ SC
Entries 3874
Mean x −1.639
Mean y 0.8002
Std Dev x 4.834
Std Dev y 6.034
Integral 3874
F3
y position (mm)
x position (mm)

RAON KoBRA

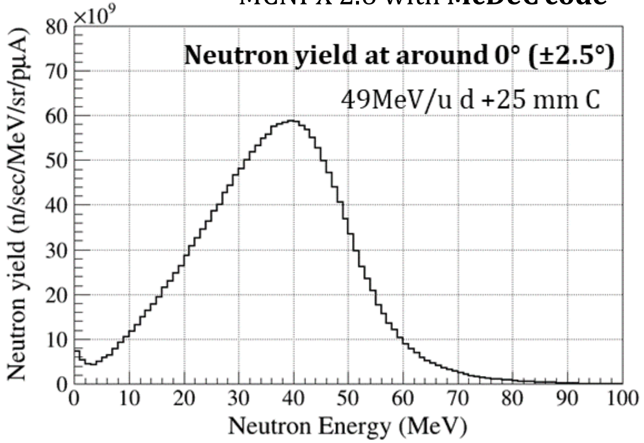


The momentum dispersion and resolving power at F1/F2/F3 agree with the expectation!

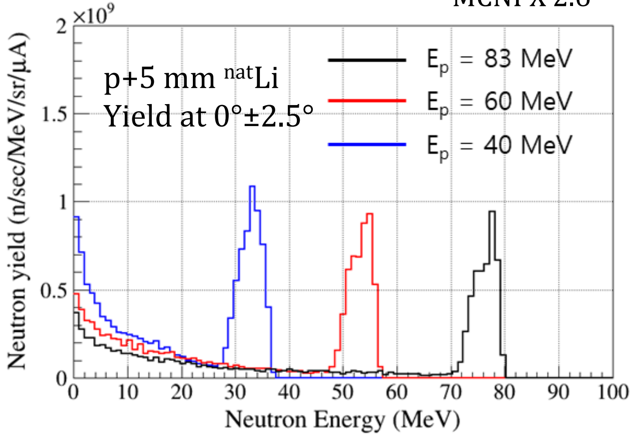
- Nuclear Data Production System
  - d+C for white neutrons
    - n intensity at the end of the collimator $\simeq$ **10^8 neutrons/cm^2/sec for 10 pμA**
  - p+Li for monoenergetic neutrons
    - n intensity at the end of the collimator $\simeq$ **10^5 neutrons/cm^2/sec for 10 pμA**

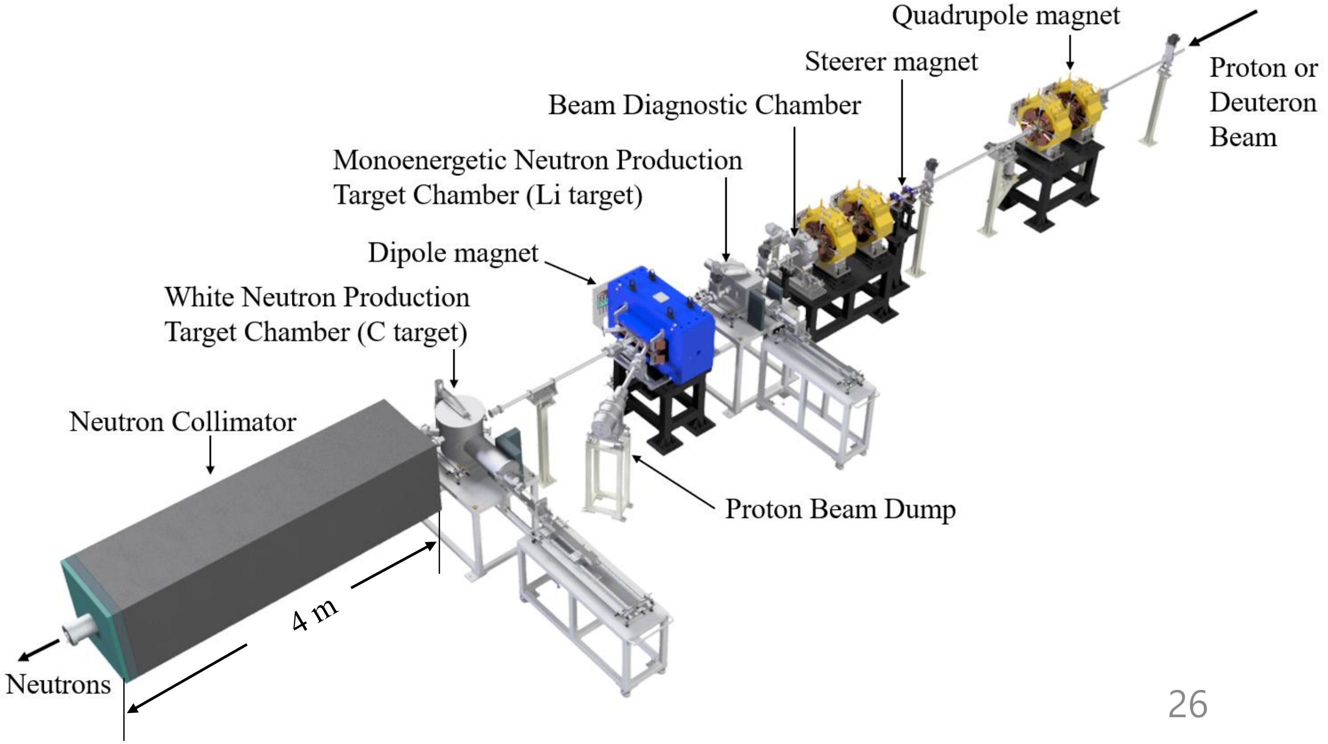
Beam species	proton, deuteron
Maximum Beam energy	49 MeV/u for deuteron 83 MeV for proton
Maximum Beam current	~10 μA
Target	C for white neutron Li for monoenergetic neutron
Bunch length	~1 ns (FWHM)
Repetition rate	1 – 200 kHz
Flight length	5 – 40 m
Neutron flux	~10^8 cm^{-2} sec^{-1} at 5 m

MCNPX 2.6 with **McDeC code**



MCNPX 2.6

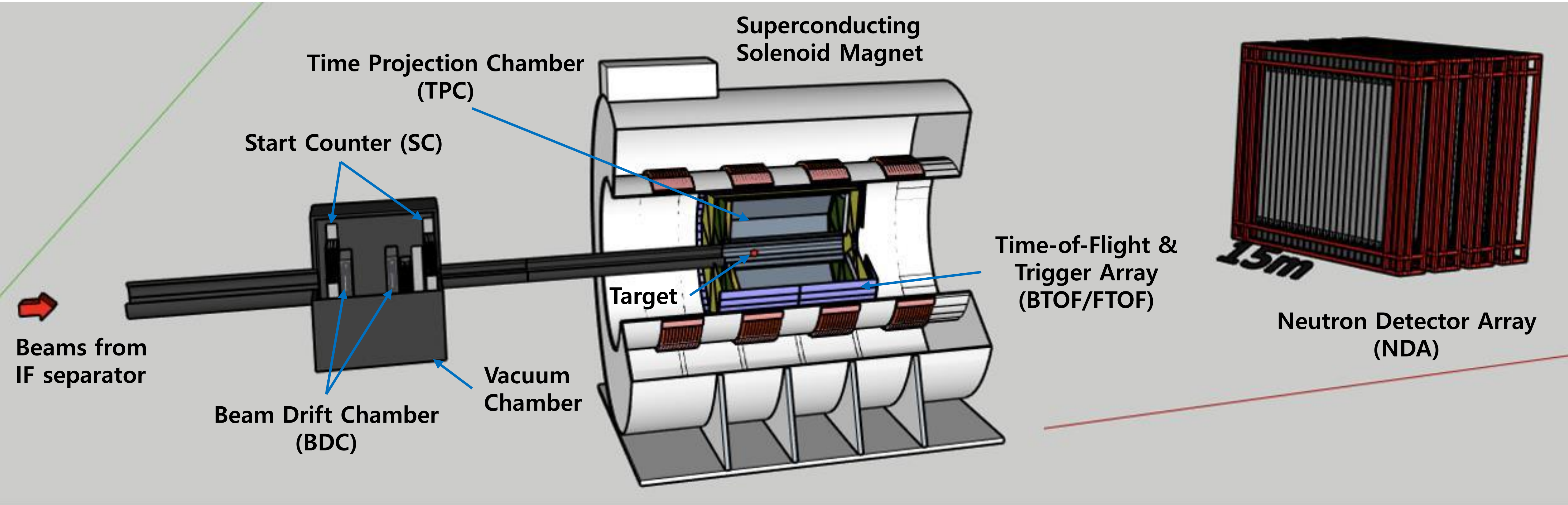




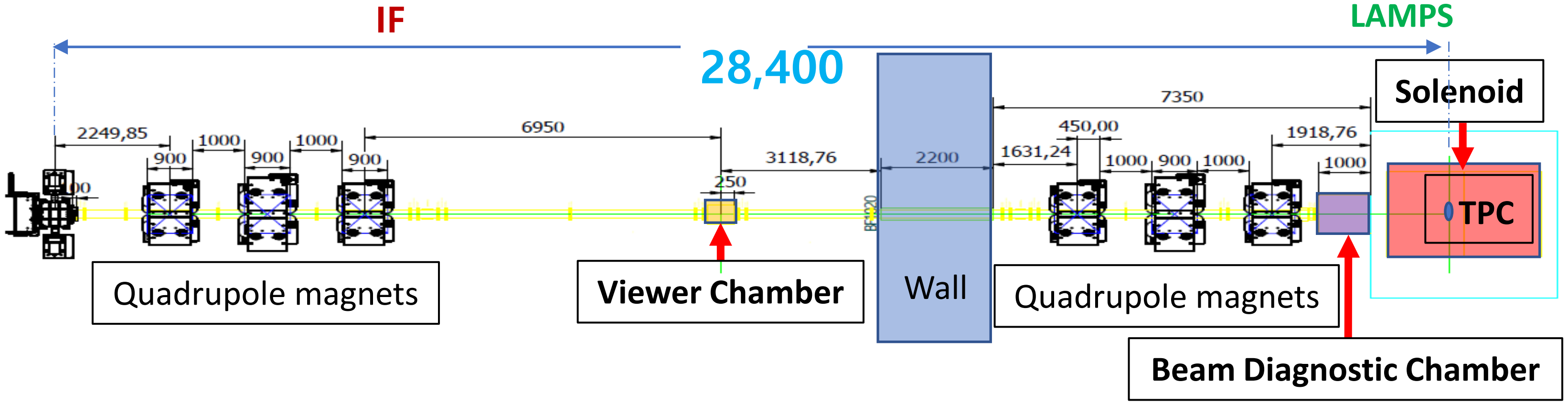
October 2020

July 2022

- **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.

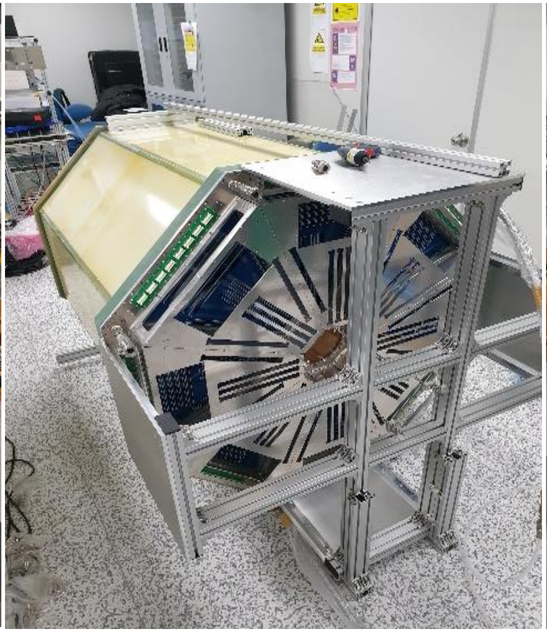


RAON LAMPS

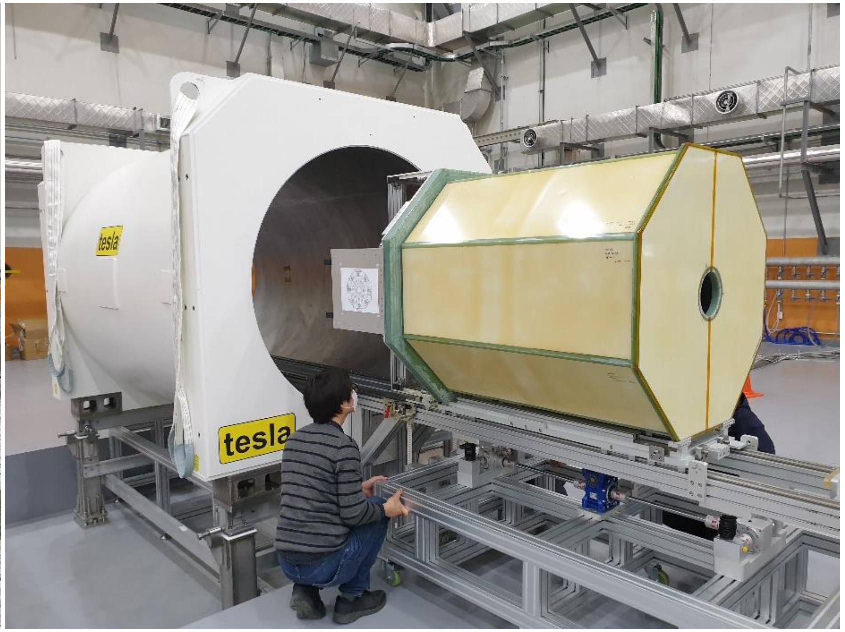


Beamline (Left: IF side, Right: LAMPS side)

SC magnet (B_{max} = 1 T)



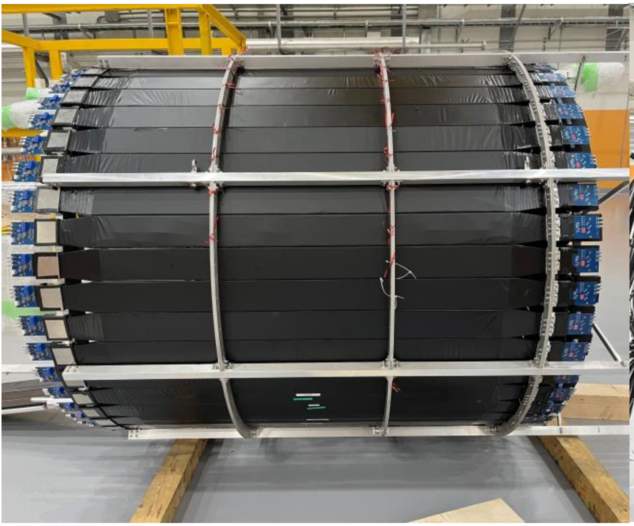
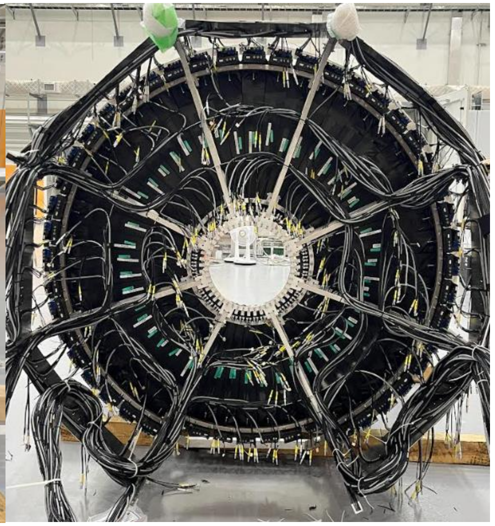
TPC



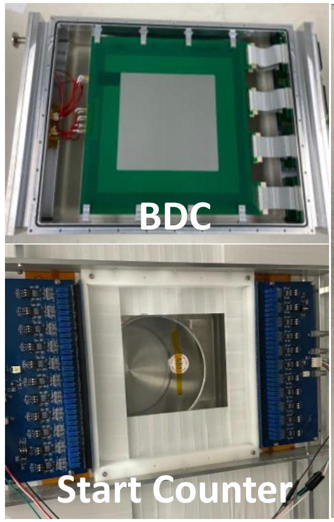
Installation of TPC inside the magnet

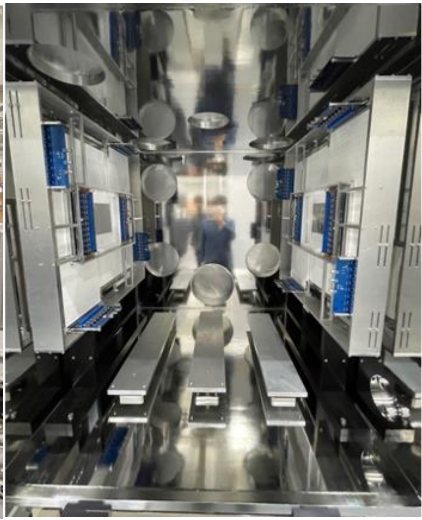
Neutron detector array

RAON LAMPS

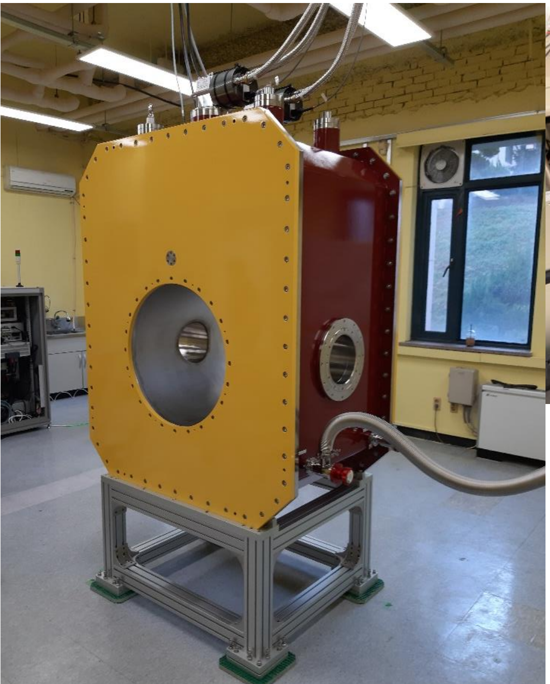
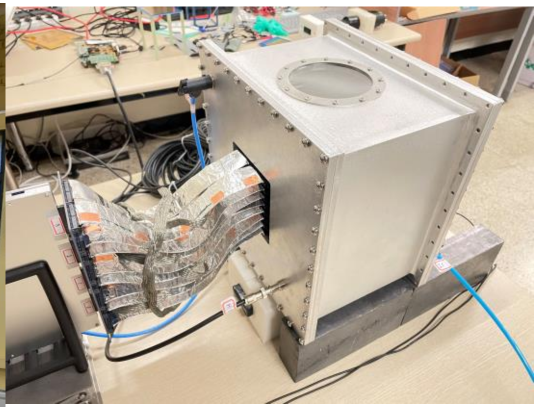



ToF & Trigger array (BTOF/FTOF)

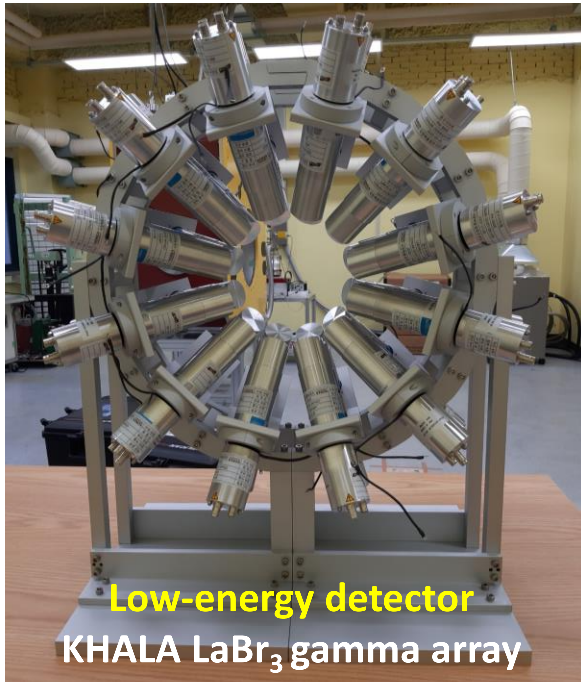


BDC (left) & SC (right) in beam diagnostic vacuum chamber

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



Low-energy detector
KHALA $LaBr_3$ gamma array

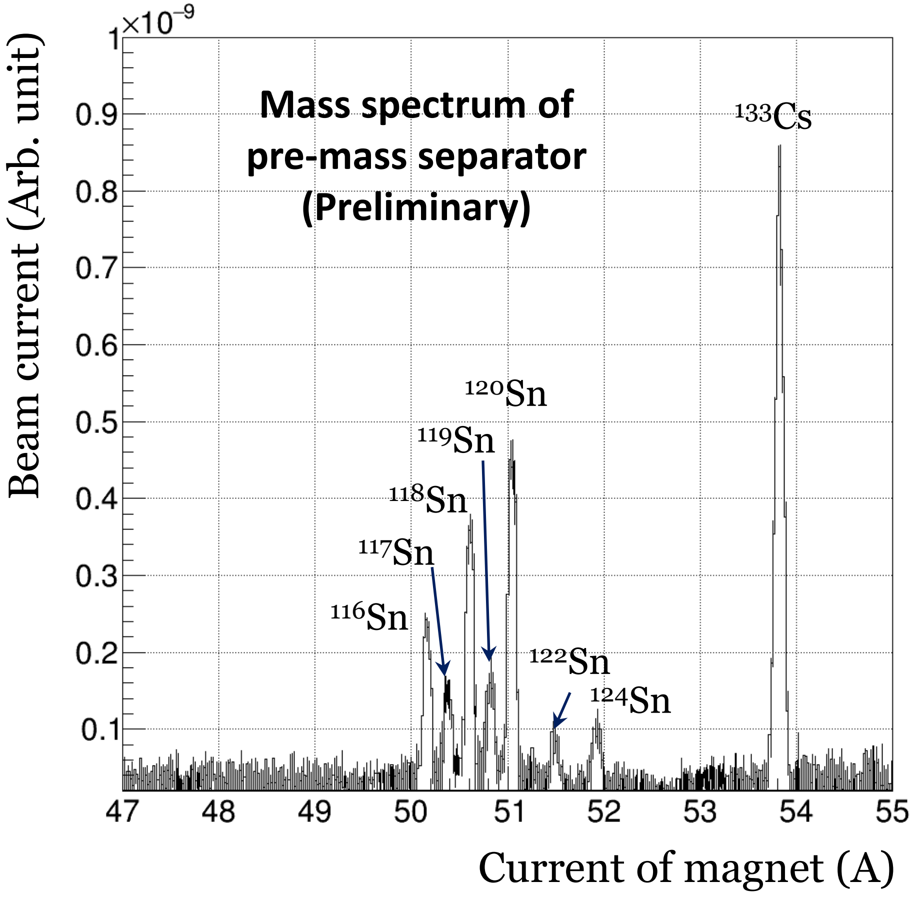

Low-energy detectors
(left) Si-CsI telescope
(Top) New FEE board
for Si-CsI

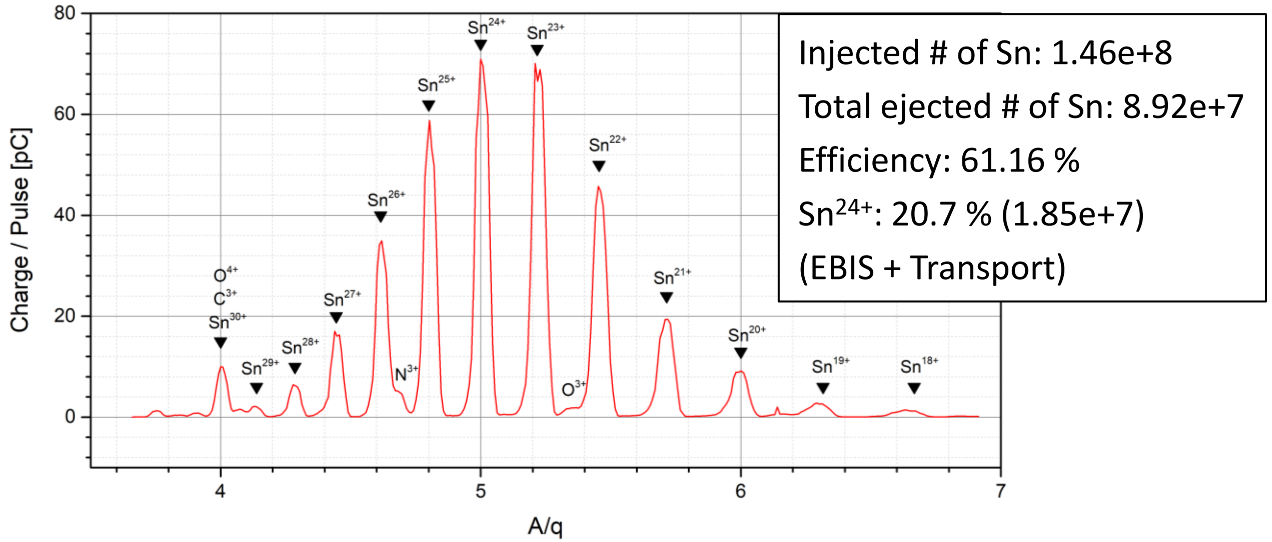
Part 4.

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)





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.

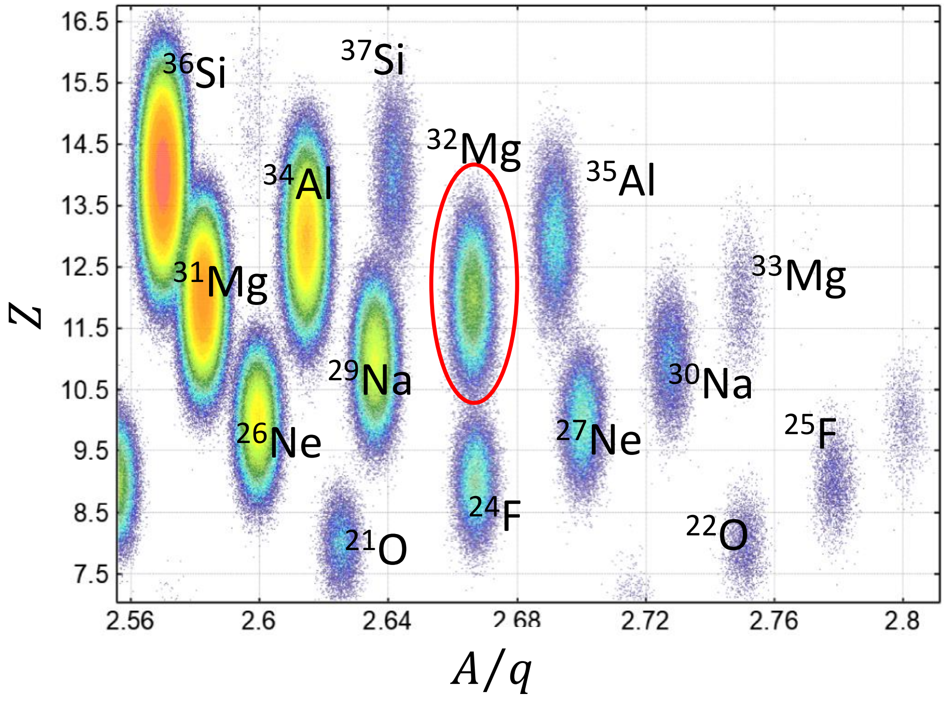
- RI beam commissioning plan for ISOL with SiC target
  - ^{24}Na beams with an intensity of ~$10^{6\text{-}8}$ pps (1 kW@70 MeV) in Oct.~Dec. 2022
  - $^{24\text{-}26m}$Al beams will be transported to MMS & CLS in 2023
  - Plan to provide $^{20\text{-}24}$Na, $^{22\text{-}23}$Mg, $^{24\text{-}26}$Al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

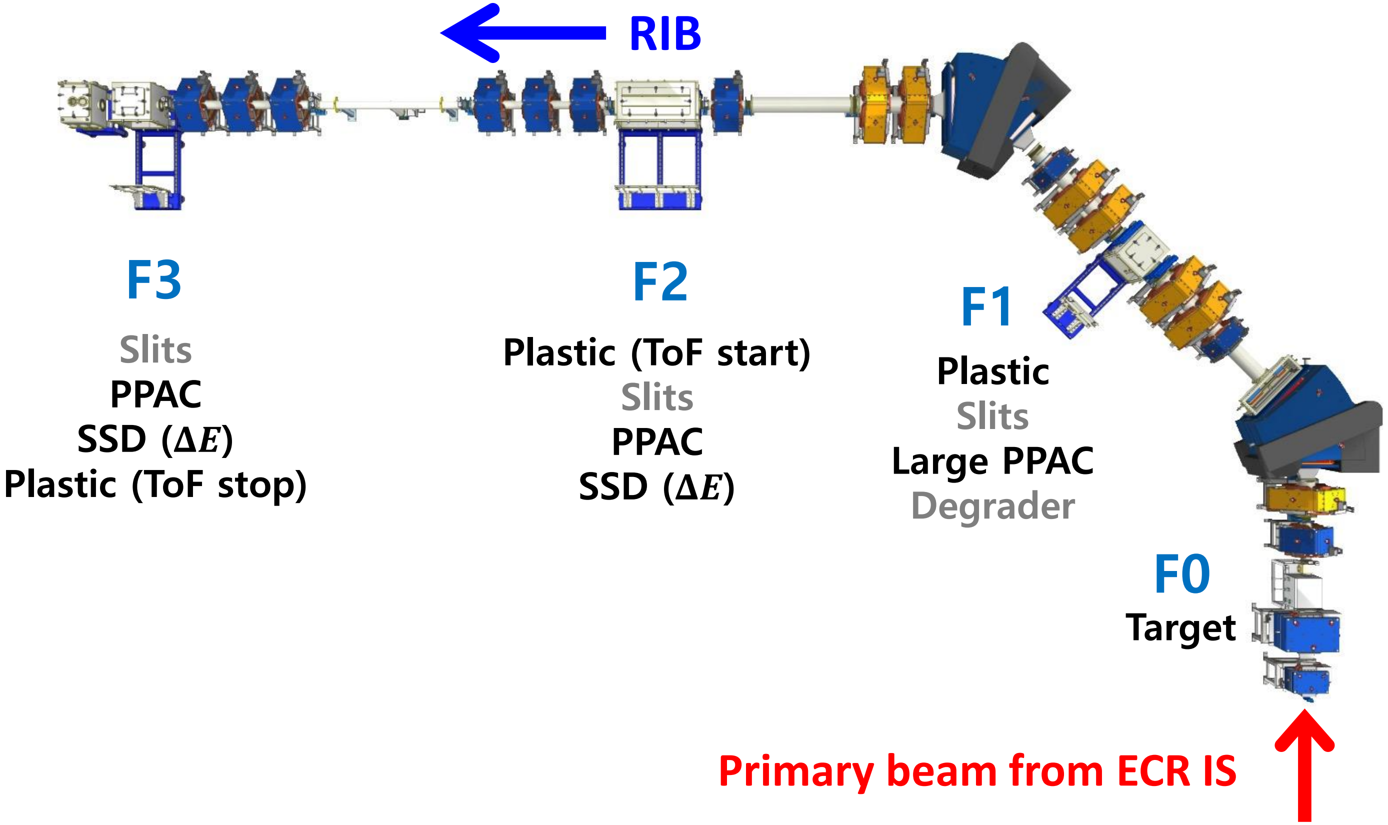
KoBRA beam commissioning

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 2022
  - RI production near Fermi energy using quasi projectile-like fragmentation/multinucleon transfer reactions
  - $B\rho$-ToF-ΔE method for PID with detectors at F0~F3

MC tuned for ^{32}Mg





Summary

- Major achievement on the accelerator, RI & experimental systems
  - SCL3 low-energy superconducting Linac: Installation completed in 2021
  - Cryogenic plants: Cool-down, RF conditioning, and beam commission from Sep. 2022
  - ISOL SIB transportation for all sub systems and beam lines in Dec. 2021
  - Machine commissioning for KoBRA: Done in Oct. 2021
- Near-term plan (for the next ~2 years)
  - Delivery of stable ^{16}O & ^{40}Ar beams: ECR IS → SCL3 (2022), SCL3 → KoBRA (2023)
  - Extraction and delivery of RIB: ISOL → Ultra-low-energy Expt. hall (2022), ISOL → SCL3 (2023)
  - KoBRA beam commissioning experiment: RIBs for $A \lesssim 50$ and beam energy $\lesssim$ 20 MeV/u (2023)
  - Preparation of the 2nd stage for the construction of SCL2 (2024)
  - Installation and independent commissioning of IF, LAMPS, neutron beams, BIS and μSR
- Long-term plan
  - Operation of ISOL with UC_X target (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 programs with ISOL and IF
  - Beam commissioning for ISOL → SCL3 → SCL2 → IF