RAON Rare isotope Accelerator complex for ON-line experiments

Status of RAON

Seung-Woo HONG
Institute for Rare Isotope Science (IRIS)

NUSYS-2023
August 7, 2023

Outline

I. Introduction to the RAON

II. Current Status of the Project
(Accelerator systems and Experimental systems)

III. Summary

RAON

라온 -> RAON -> Rare isotope Accelerator complex for ON-line experiments

What is it?

Rare Isotope accelerator:
- **Cyclotron for ISOL**
- **Superconducting Linac for In-Flight Fragmentation**

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

Status

1st Phase of the Construction: 2011.12 - 2022.12
R&D for the 2nd Phase: 2022.12 - 2025.12

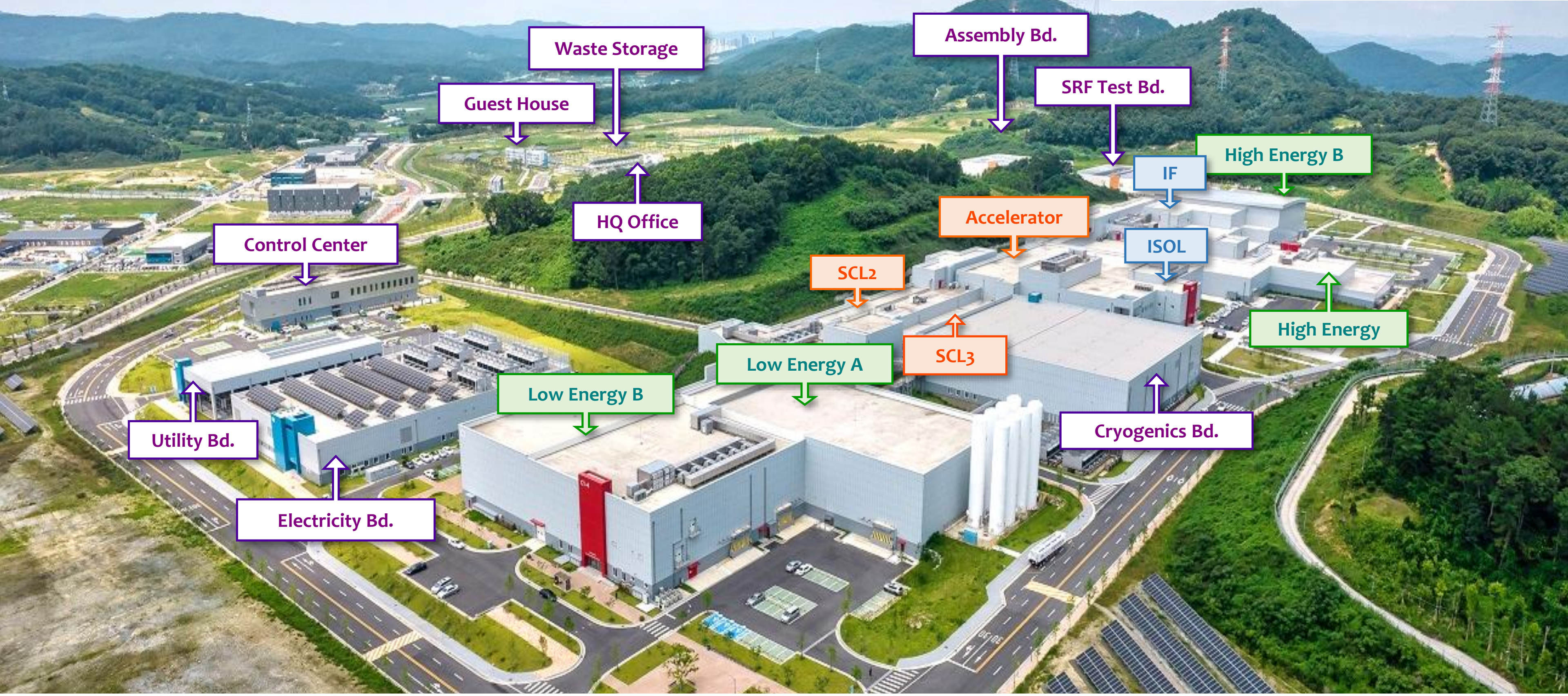
Budget

~$ 1.4 B (Facilities ~ $ 0.5 B, Land, Bldgs & Utilities ~ $ 0.9 B)
Facilities include experimental apparatus

Where is RAON?

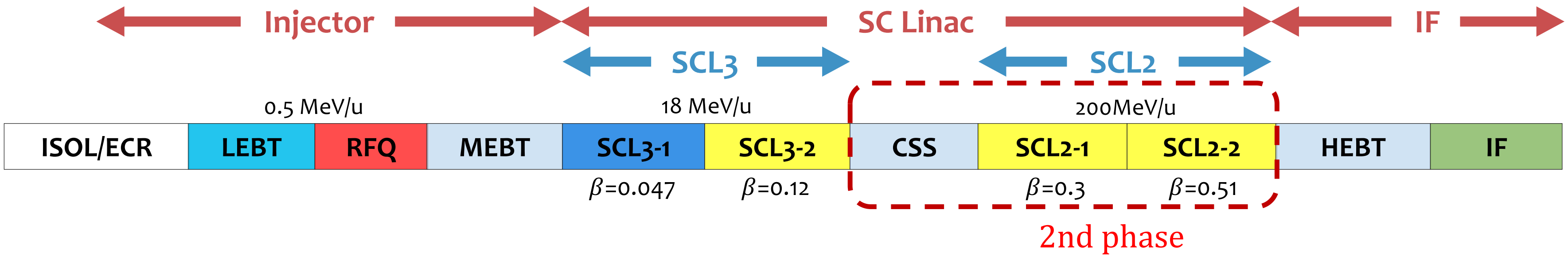
Bird's-eye-view of RAON

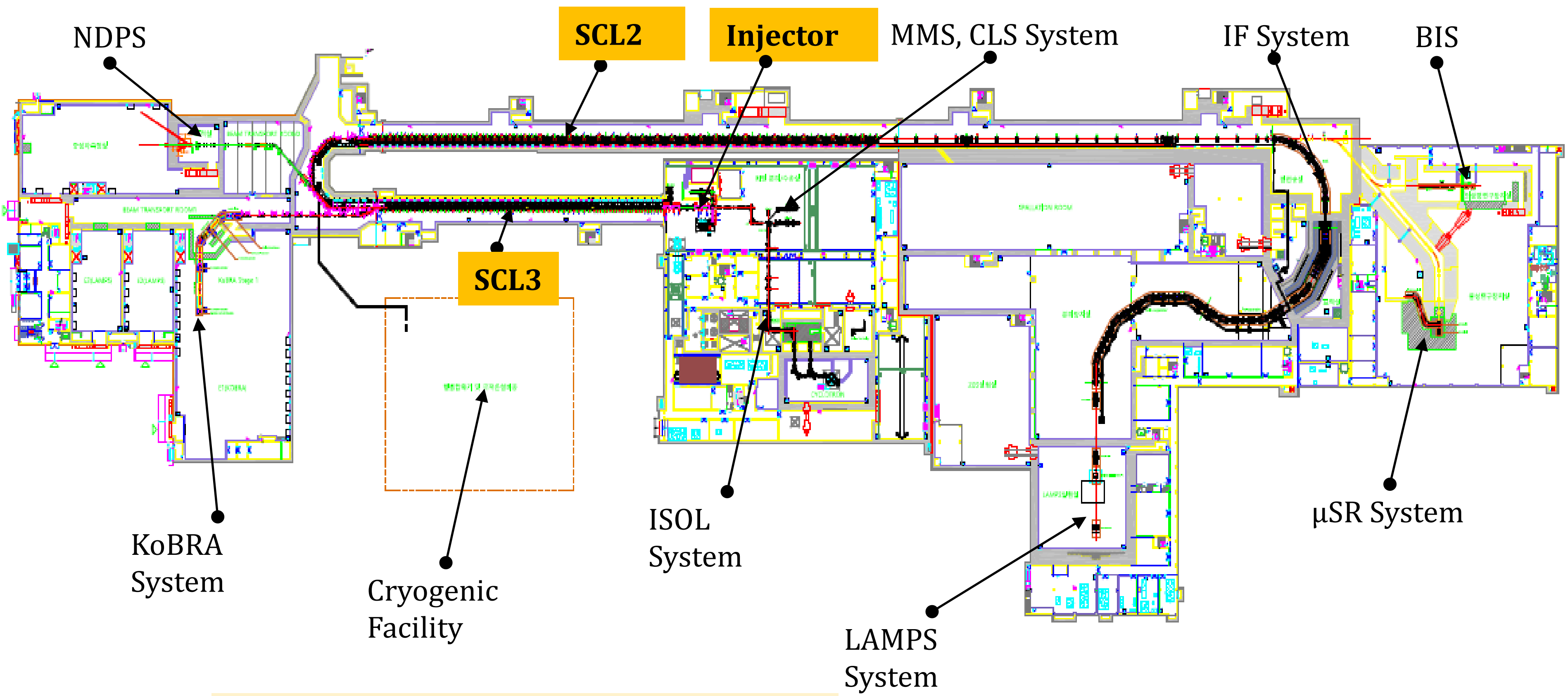
- Accelerator System
- RI production System
- Conventional Utilities
- Experimental System



Area of the land ~ 1 M m^2

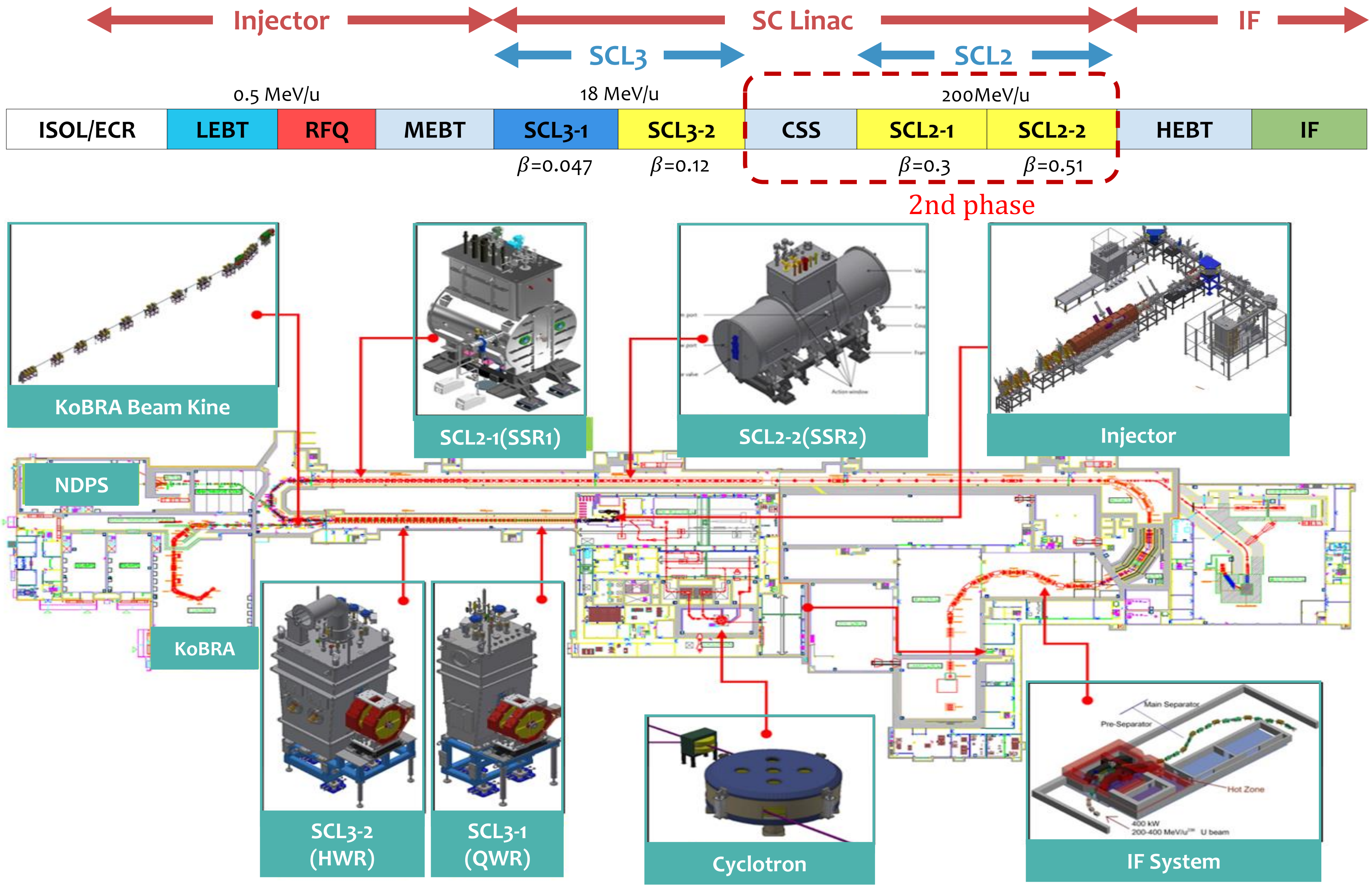
Accelerator System



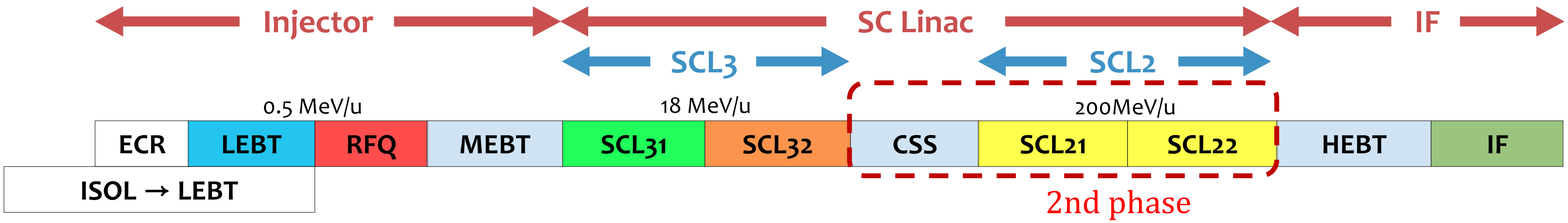


※ SCL1 is postponed and is not shown here.

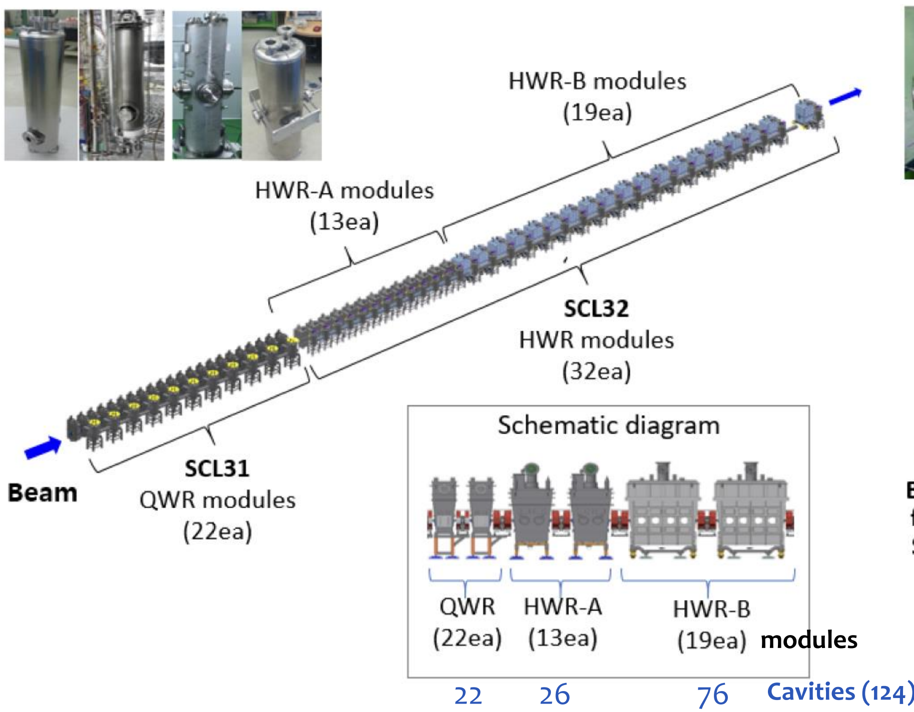
Accelerator System



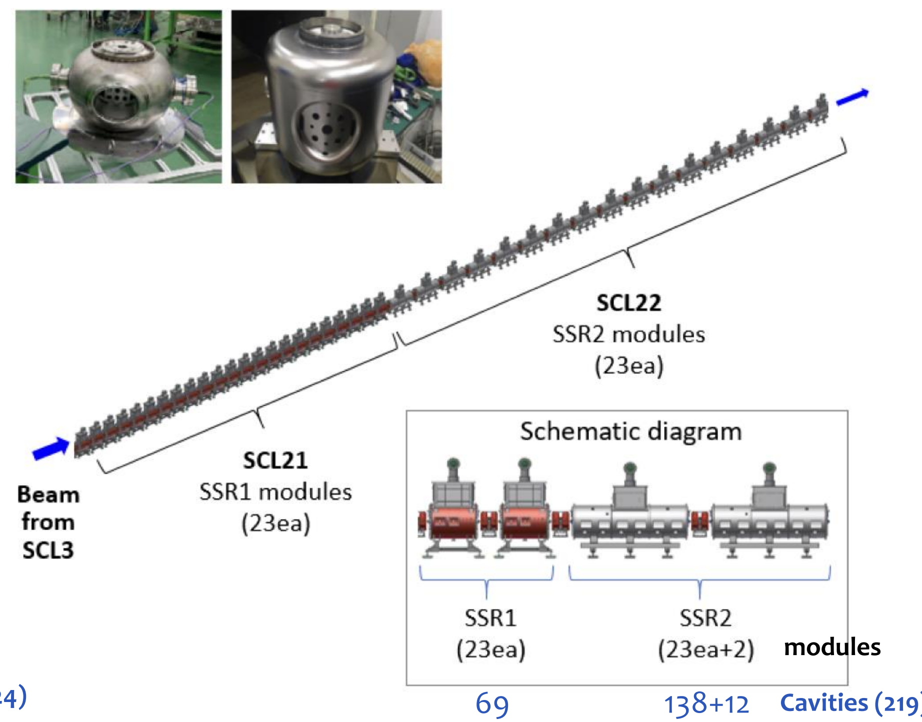
Accelerator System



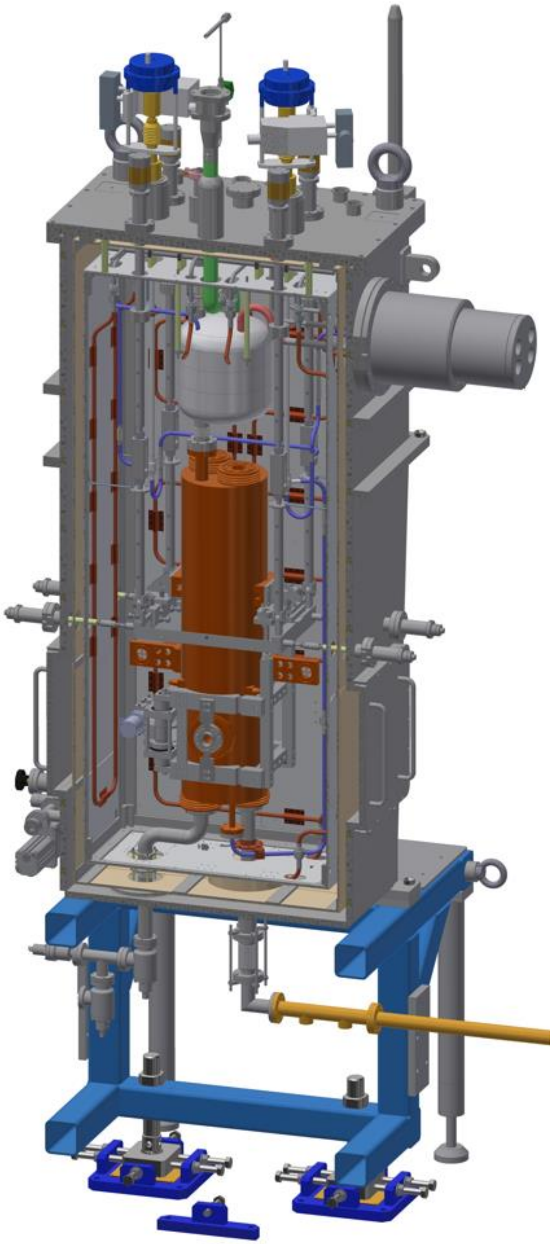
SCL3

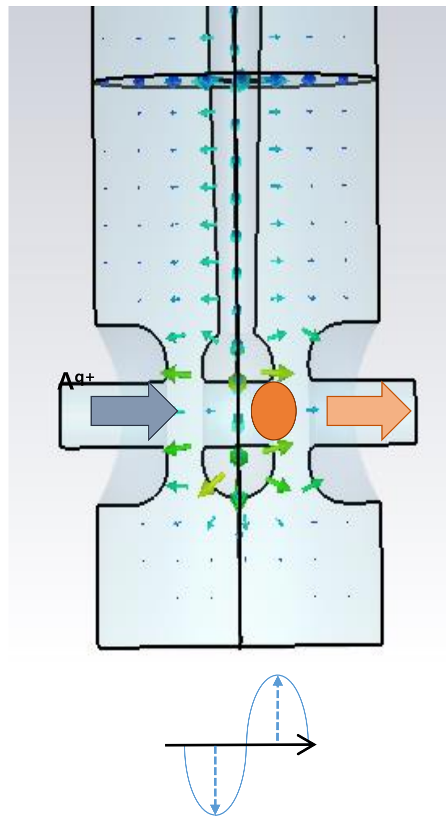


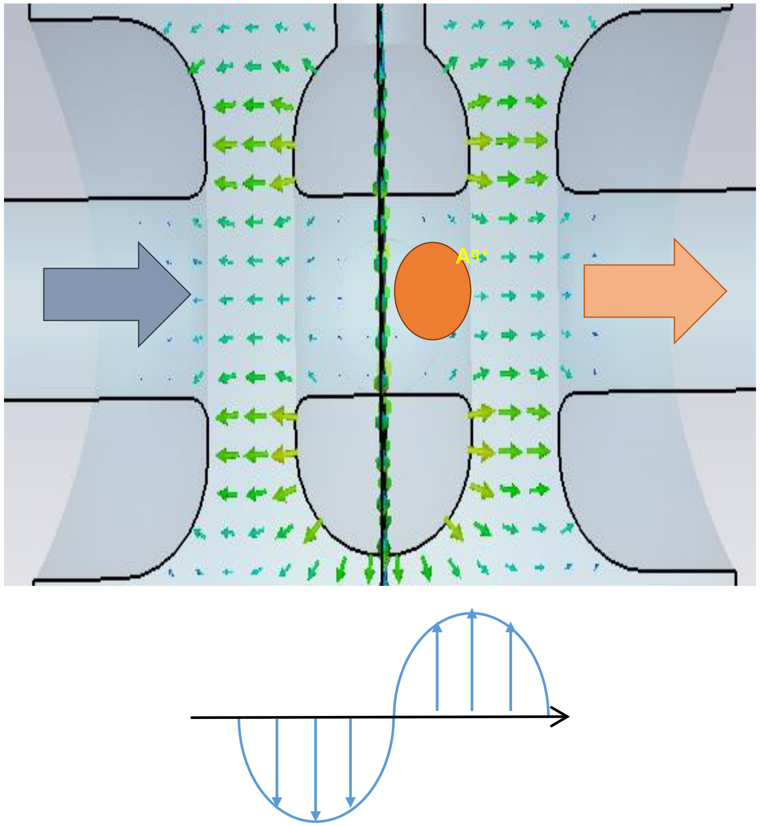
SCL2



QWR(Quarter Wave Resonator) cryomodule and cavity

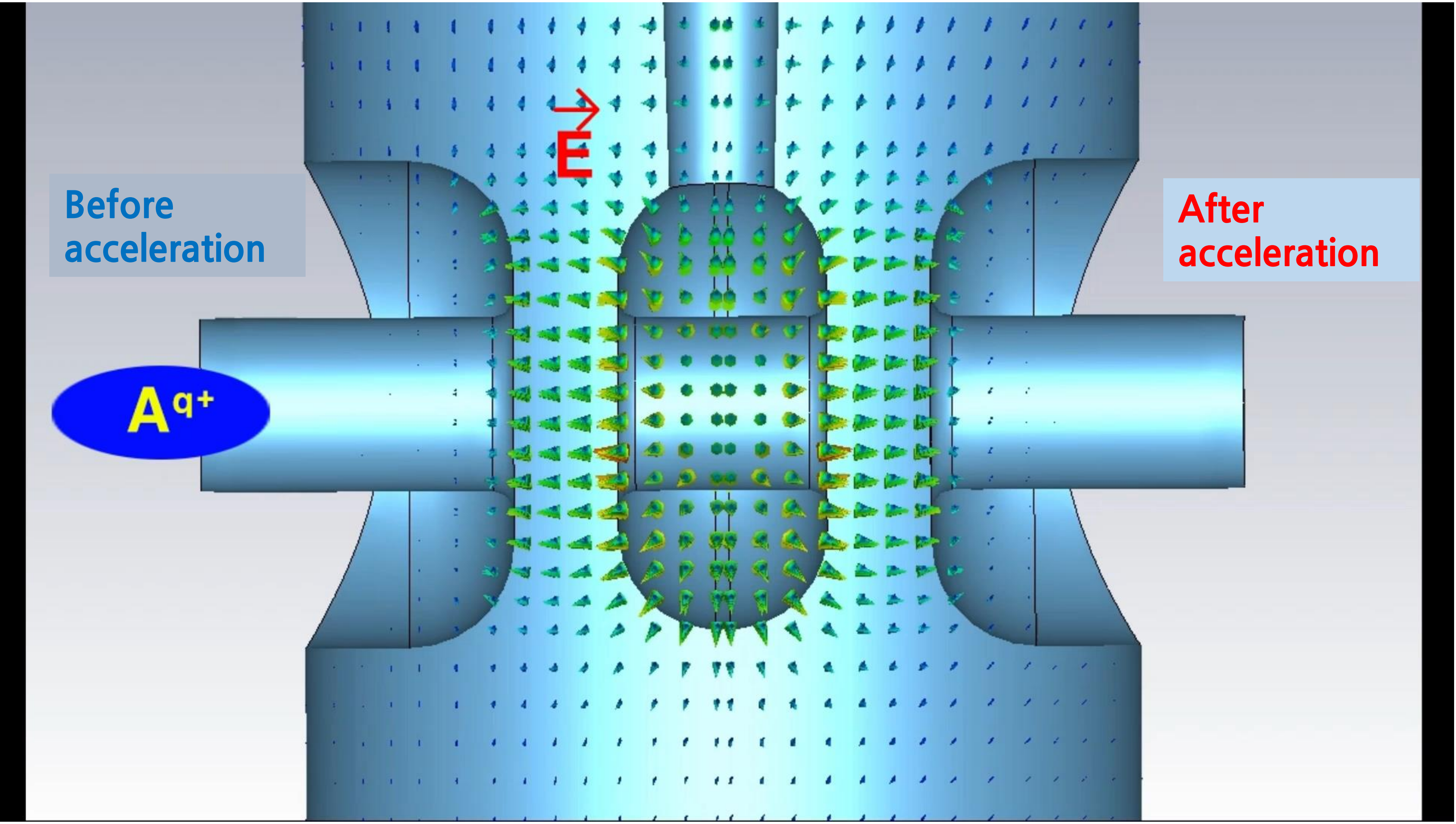






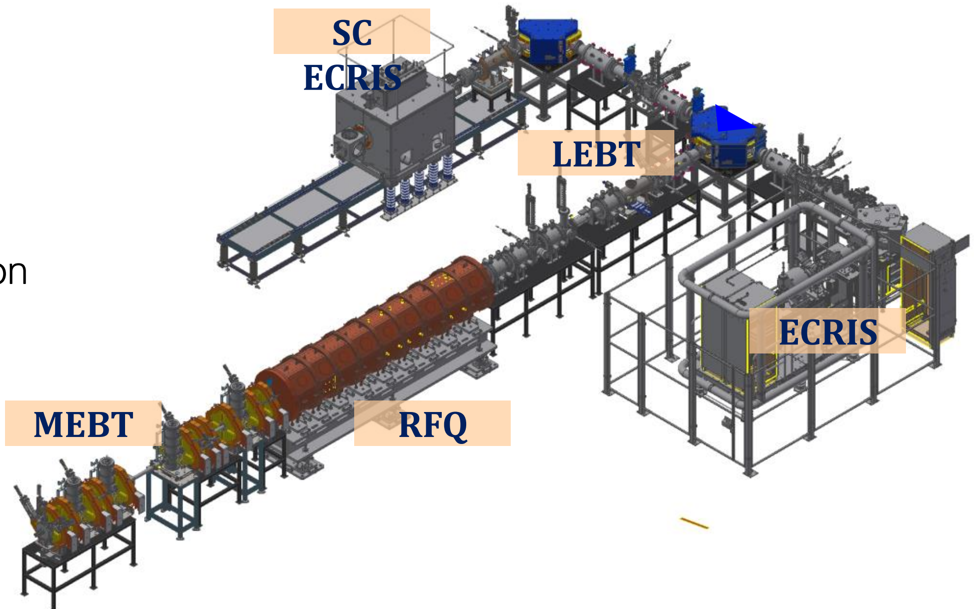
Acceleration of positive ions

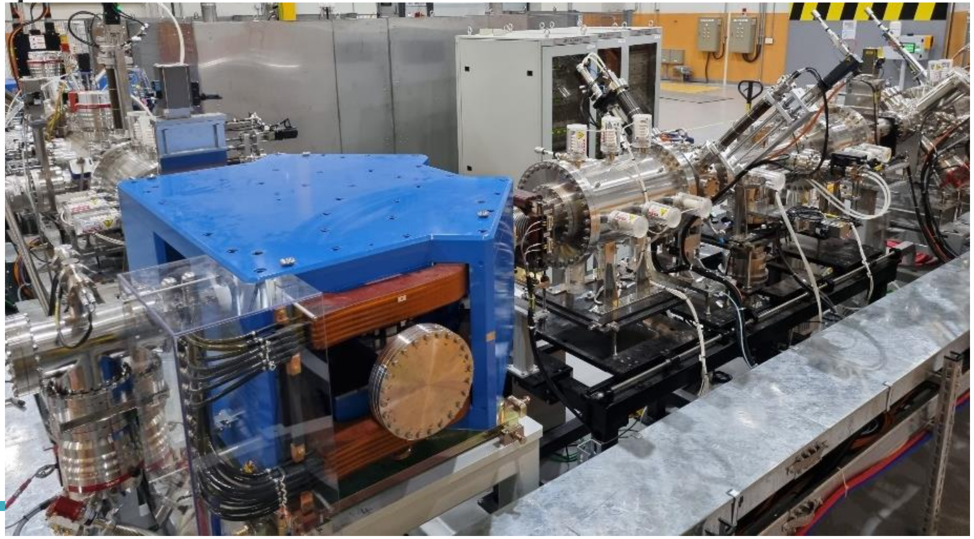
The electric field generated by the RF accelerates the ions



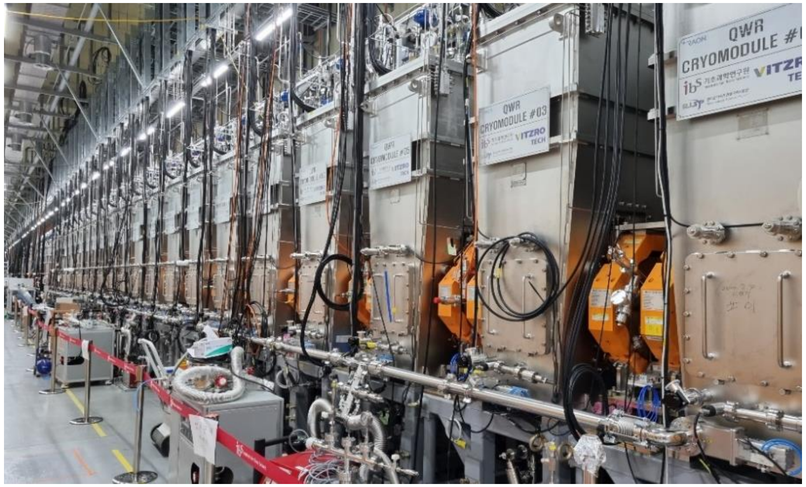
Injector System

- **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





Superconducting linac SCL3 (tunnel and gallery)



QWR & HWR Cryomodules

Cryogenic Distribution to Cryomodules

Clean beam line assembly

CM/Cryogenic Control Rack and SSPA

Installation completed in 2021

Cryogenic System

- 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)

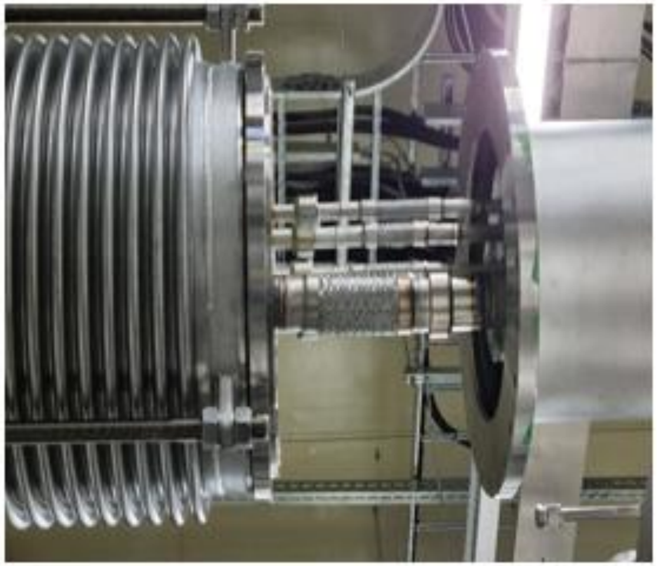
Compressors and Oil Removal System (WCS)

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

SCL3 Cryoplant was commissioned in Aug 2022

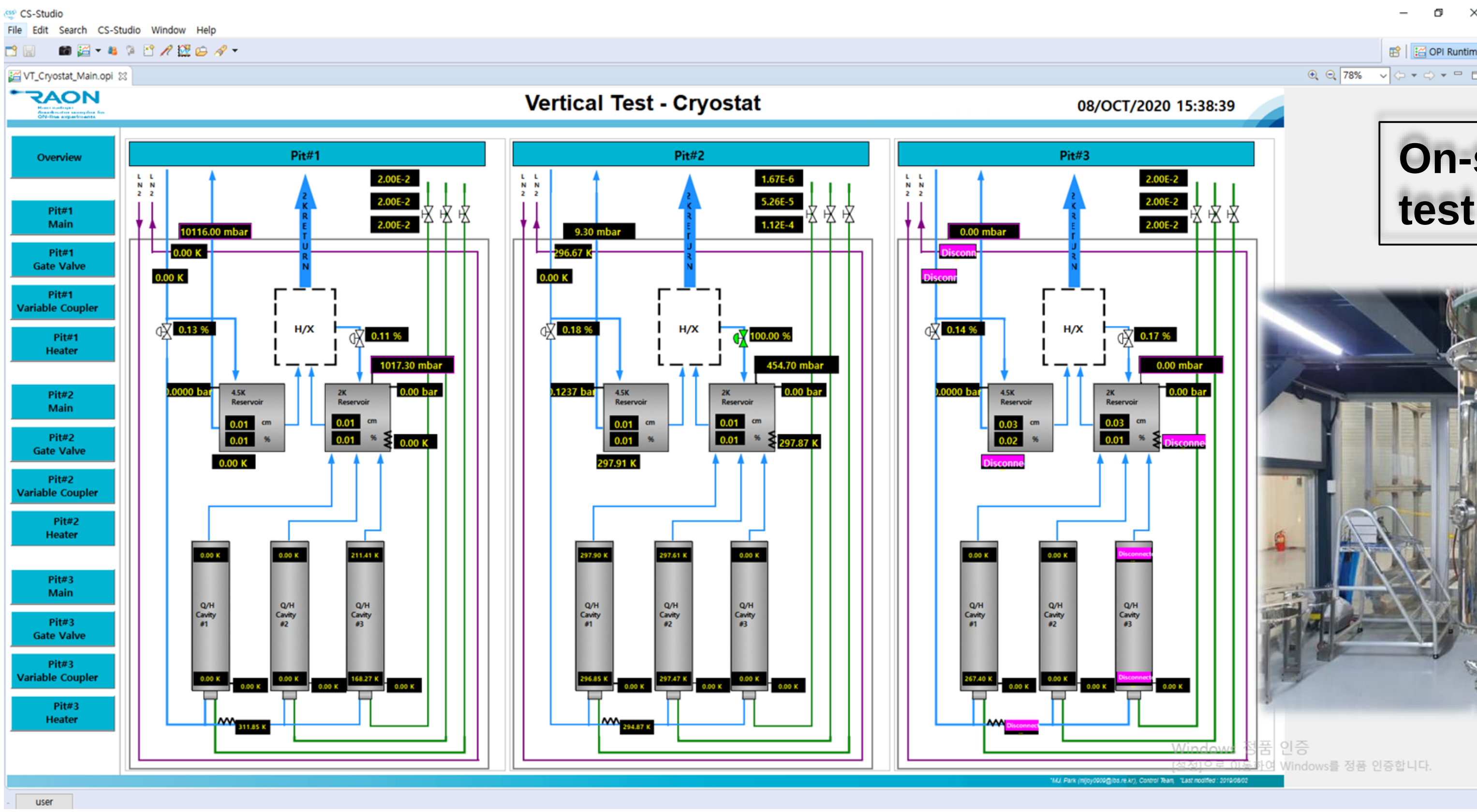
Cryogenic System

- Cryogenic Distribution System
  - All QWR VBx are installed and assembled (VBx-VBx, VBx-CM).
  - All HWR VBx are installed and assembled @ SCL3.
  - Cryogenic transfer Lines are installed
  - SSR1 VBx : 23 ea, SSR2 VBx : installed



SCL3 Cryoplant and CDS were commissioned in Aug 2022

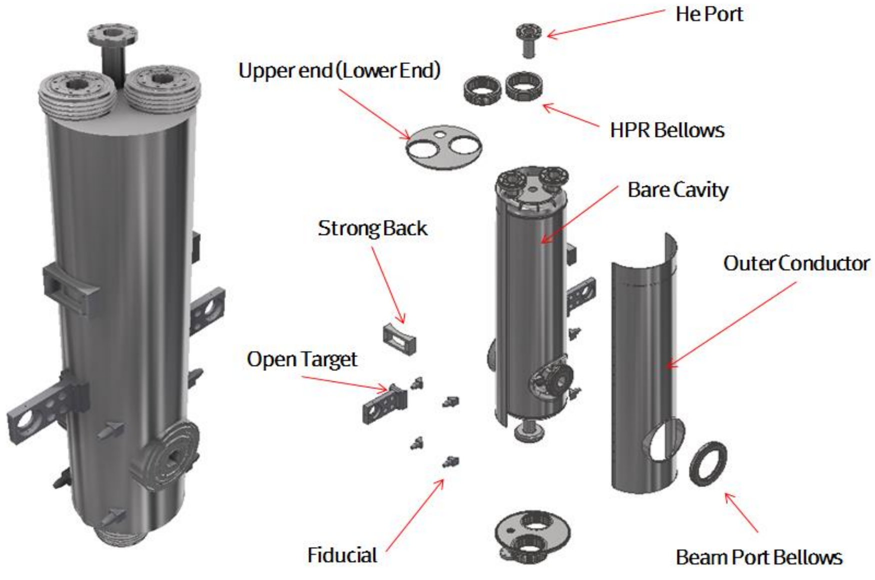
SRF test facility

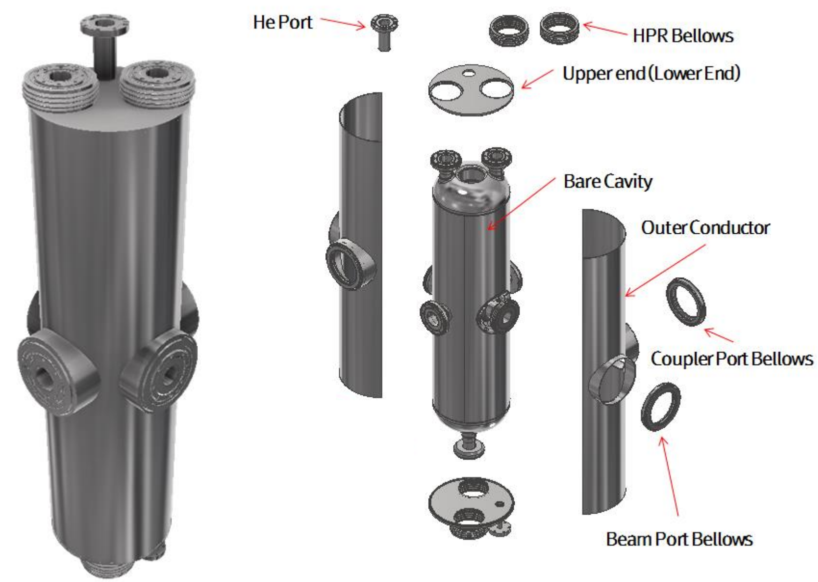


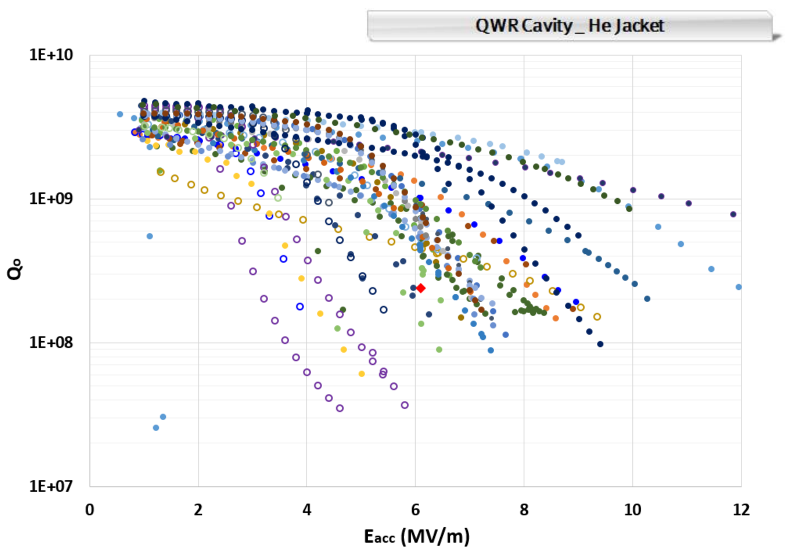
On-site SRF test facility

- 3 pits for VT; up to 3 cavities per pit
- 3 HT bunkers
- To cover all types of cavities - QWR (82.125 MHz), HWR (162.5 MHz) and SSR1 & 2 (325 MHz)

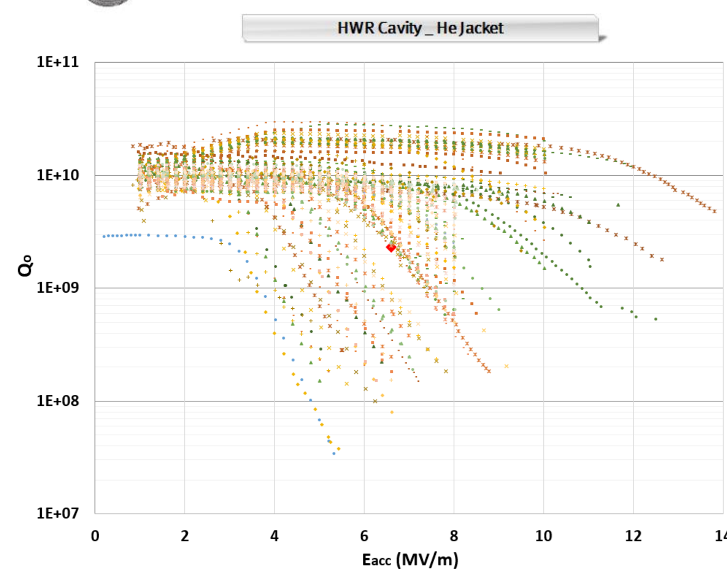
Vertical Test of Cavities







$[Q = 2.4\times10^{8}\, at\ E_{acc} = 6.1\, MV/m]$

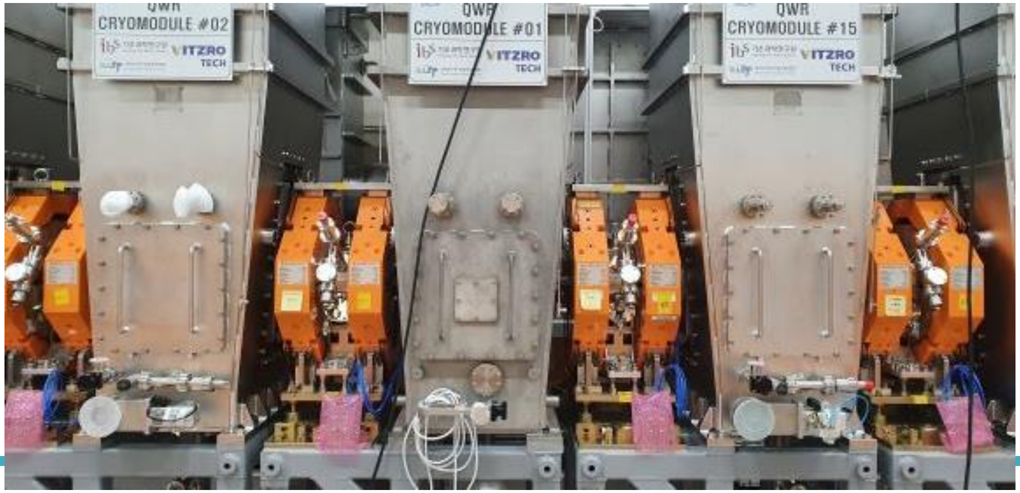


$[Q = 2.3\times10^{9}\, \text{at}\ E_{acc} = 6.6\, MV/m]$

Assembly of SCL3 linac in the tunnel

(Cryomodule + Warm section) + (Cryomodule + Warm section)

- Cryomodule & Warm section is clean-assembled in the clean booth in the tunnel
- Total particle counts(size=0.5um above/10 mins) were less than 30 counts

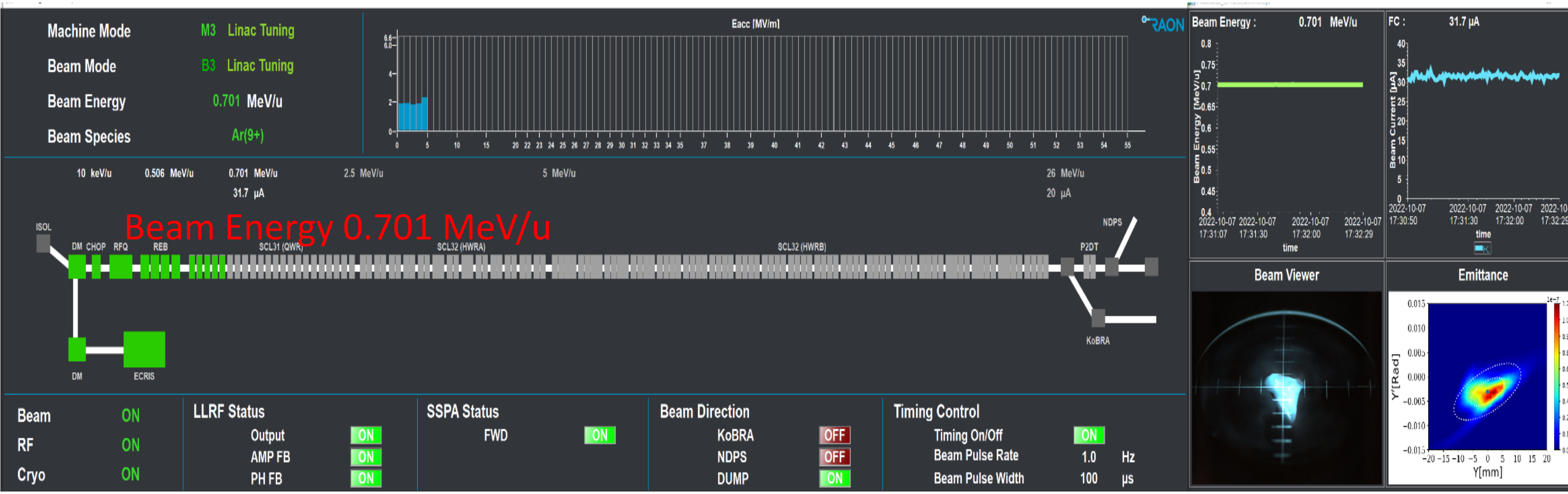


Empty tunnel before installing the linac

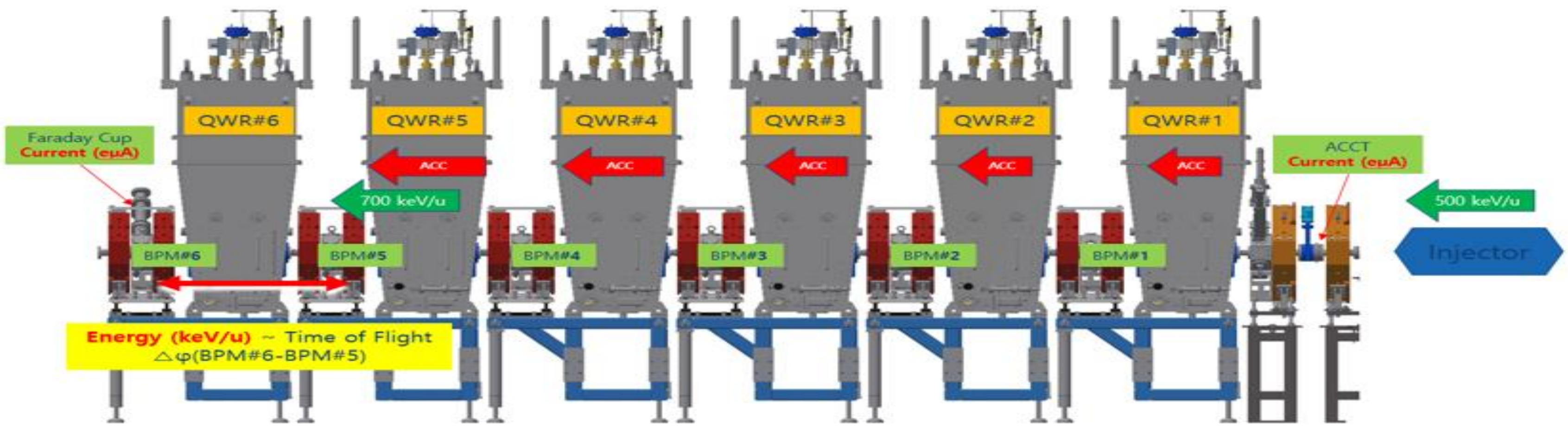
Assembed SCL3 linac in the tunnel

라온의 저에너지 가속구간은 올해 3월 말까지 빔 시운전을 완료한다. 빔 인출 시험의 총괄책임자인 정연세 IBS 중이온가속기연구소 시스템통합부장은 "압박감이 크다"면서도 과학동아 독자들에게 "시험 가동이 순조롭게 끝나기를 기원해달라"는 메시지를 전했다.

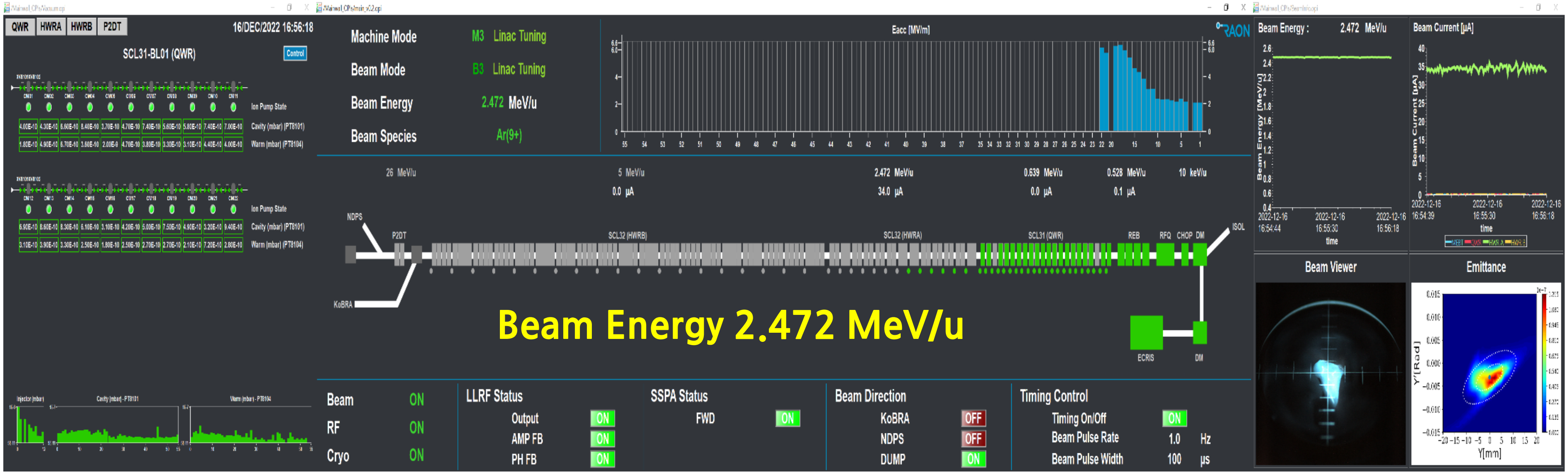
The 1st SCL3 Beam Commissioning (Oct. 7, 2022)



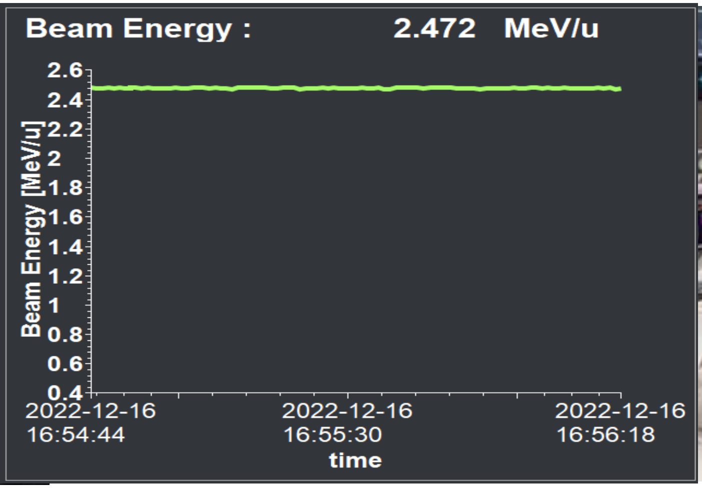
Ar^{9+} beams accelerated by QWR #1~#5 on Oct 7, 2022



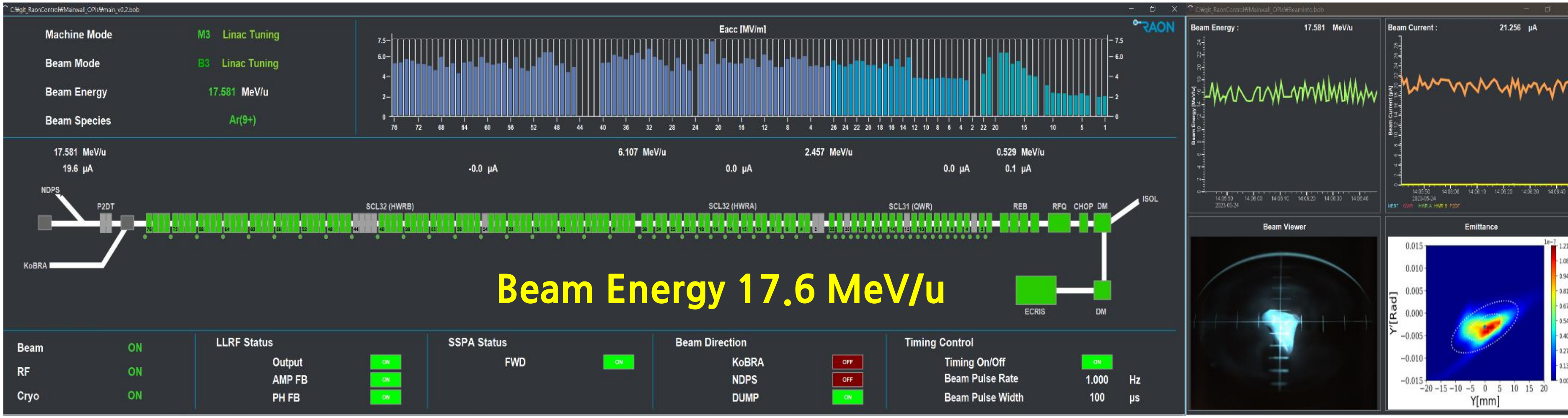
The 2nd SCL3 Beam Commissioning (Dec. 16, 2022)



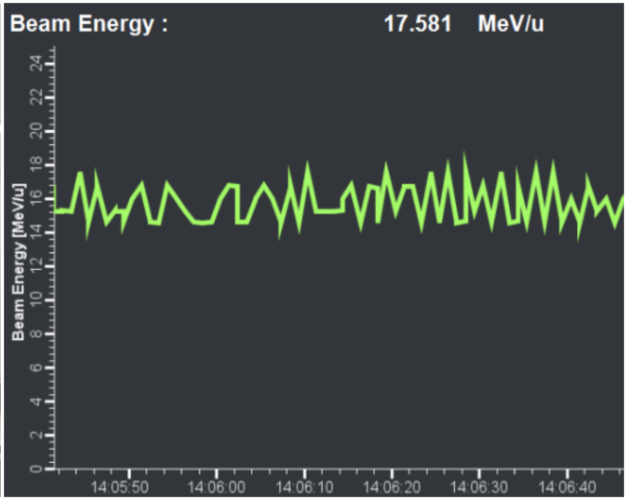
Ar^{9+} beams accelerated by QWR #1~#22 on Dec 16, 2022



The 3rd SCL3 Beam Commissioning (May 23, 2022)

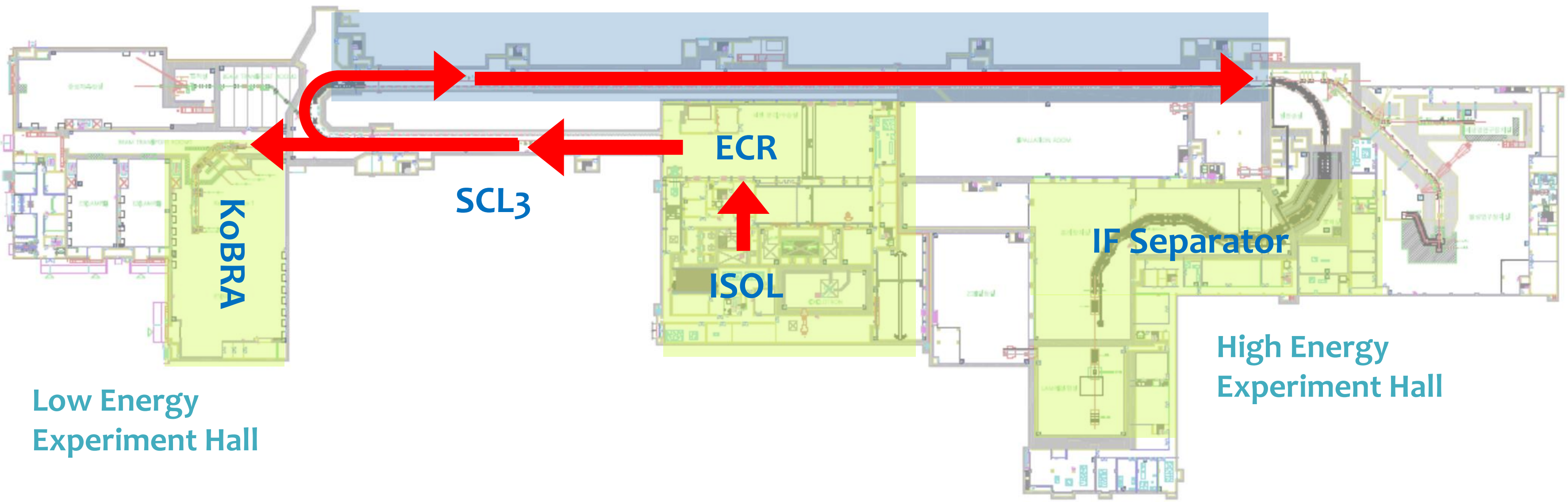


Ar^{9+} beams accelerated by entire SCL3(QWR/HWR) on May 23, 2022

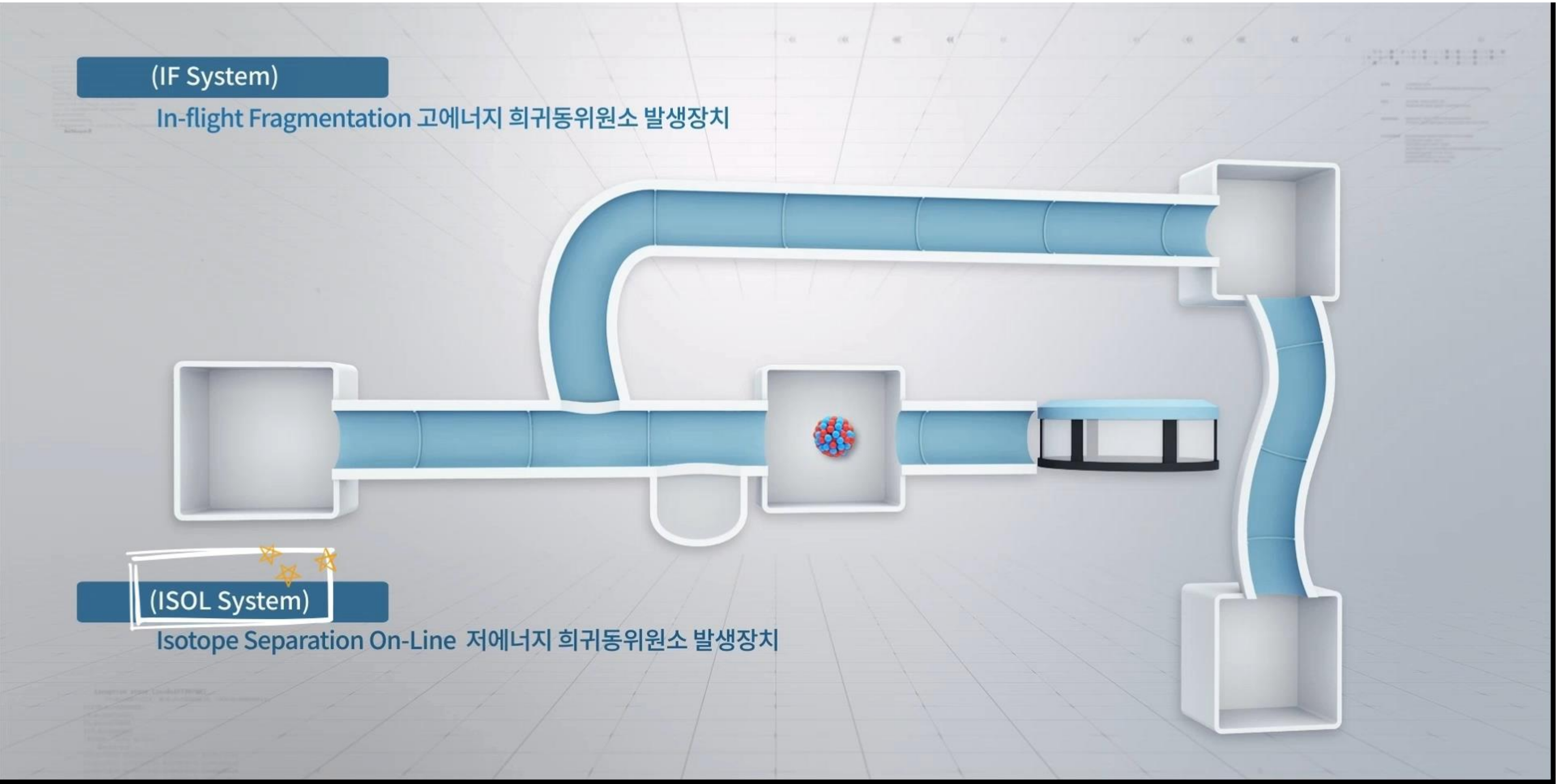


Uniqueness of RAON : RIB Production

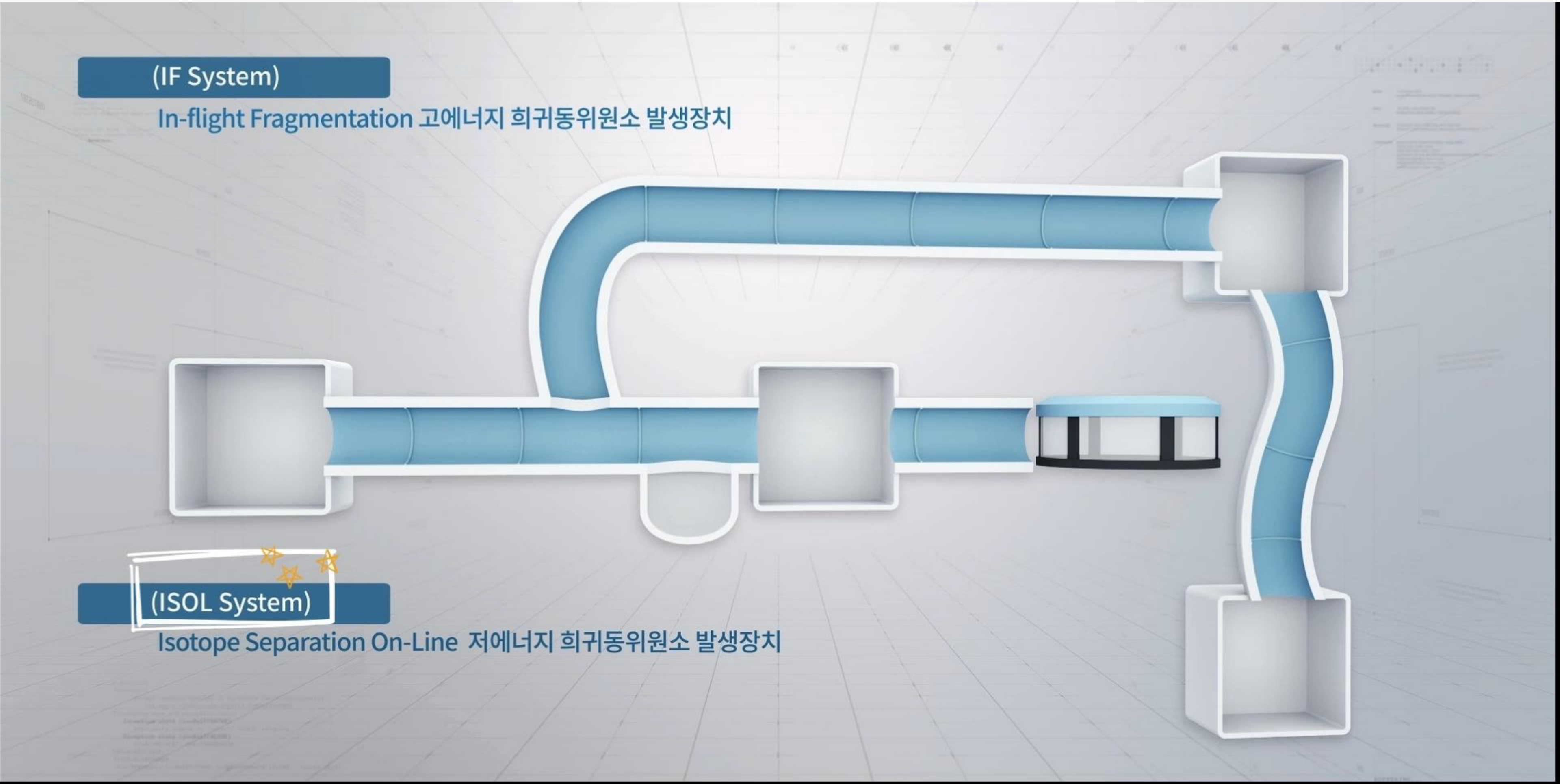
	KoBRA	ISOL	IF Separator
RIB Production & Acceleration Mode	ECR (SIB) → SCL3 → KoBRA production target	Cyclotron (p) → TIS (RIB) → SCL3	ECR (SIB) or ISOL (RIB) → SCL3 → SCL2 → IF (RIB)
Production Mechanism	Direct reactions & Multi Nucleon Transfer	p induced fission of U	Projectile Fragmentation (U fission)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



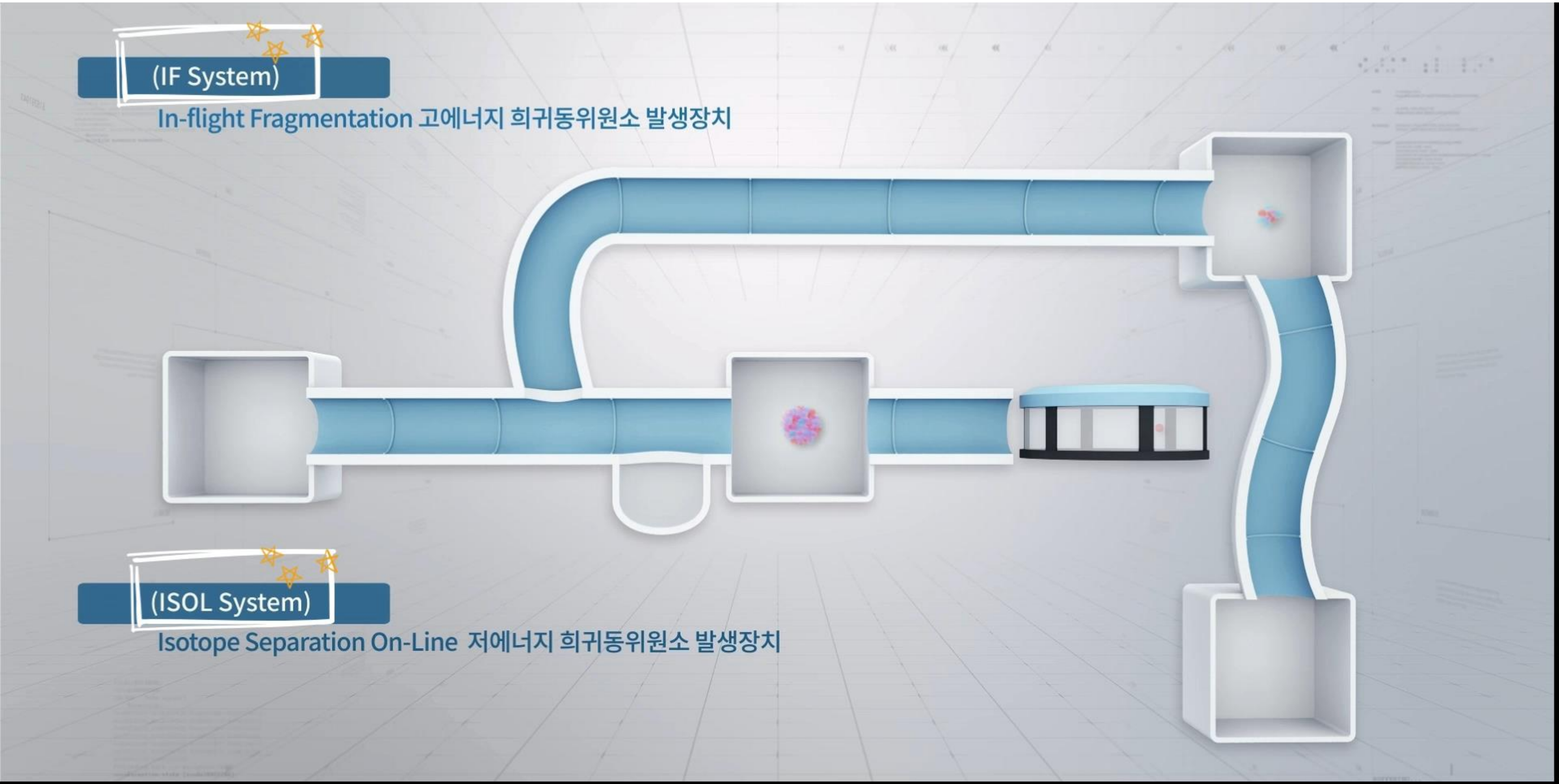
ISOL (Isotope Seperation On-Line)



IF (In-Flight Fragmentation)



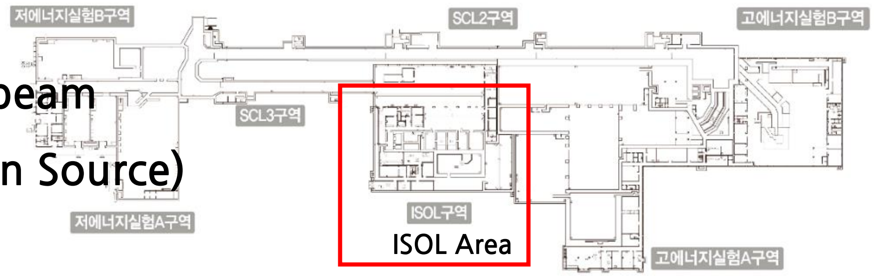
ISOL + IF


(IF System)
In-flight Fragmentation 고에너지 희귀동위원소 발생장치
(ISOL System)
Isotope Separation On-Line 저에너지 희귀동위원소 발생장치

Cyclotron

- Specs

  : 35~70 MeV proton, 0.75mA max with two beam lines connecting to ISOL TIS bunker(Target Ion Source)



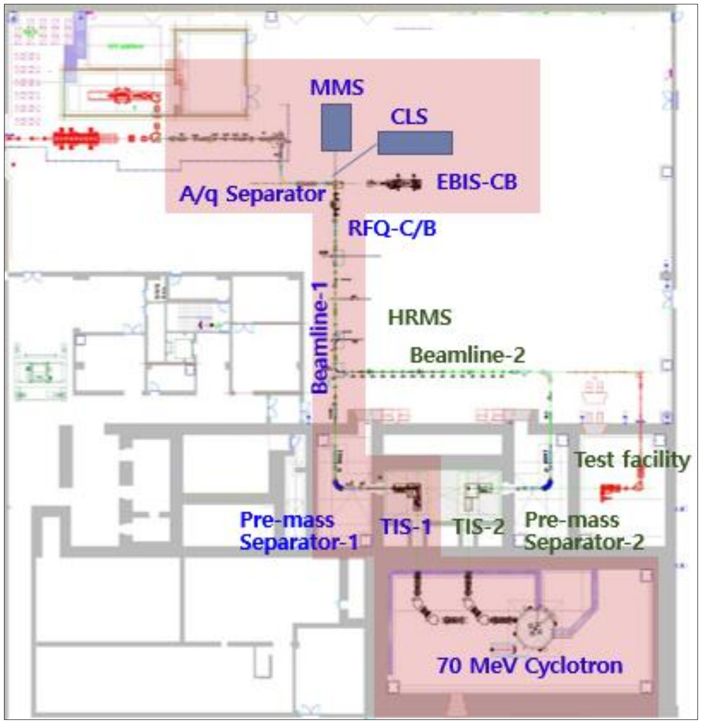
- Schedule

  : Contract('19.6), pre-survey('19.11) , Design finalized('20.4) , FAT ('21.6) , Shipping('21.8), Installation('21.11.11~22.4.28)

SAT on July of 2022

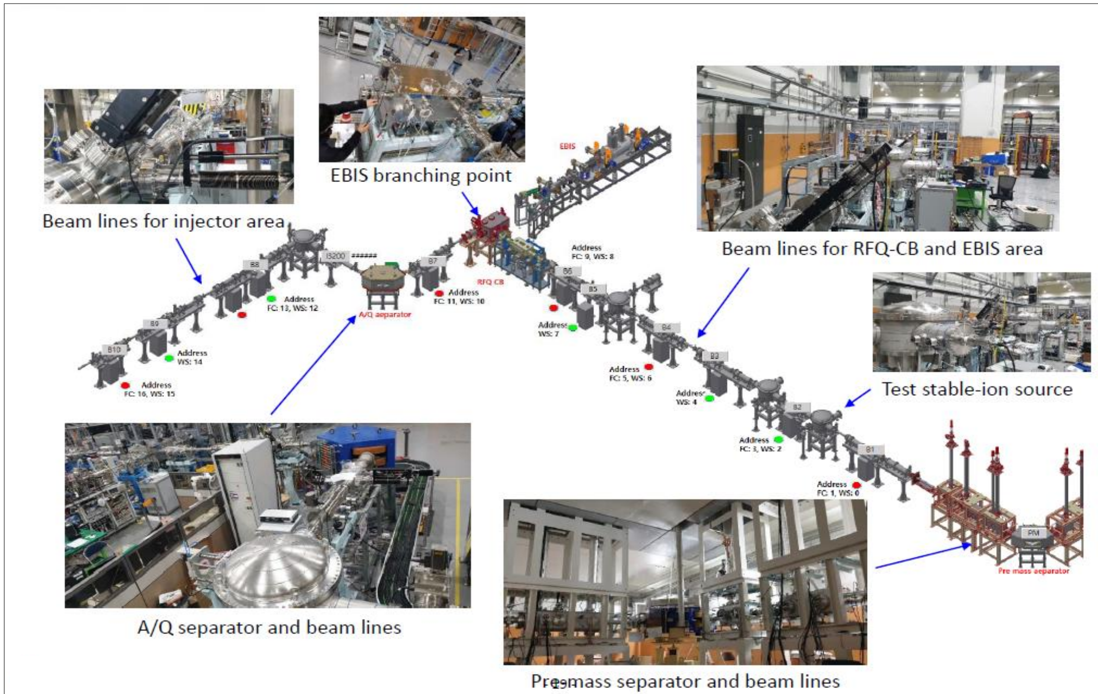
ISOL System

Target ion Source	Pre - Separator	RFQ Cooler	EBIS	Post linac
20 keV, $^{132}Sn^{1+}$	m/δm = 400	3πmm mrad, < 5ev	10 keV, $^{132}Sn^{33+}$	Charge state n+



- **Driver beam :** proton 35<K<70 MeV, up to 70 kW
- **Target :** UCx, MgO, BN, CaO, BeO, SiC, etc
- **Ion Source :** Surface, RILIS, Plasma
- **RIB :** 6< A < 250, 10<K< 80 keV, 10^8 pps(Sn), >90% purity @Exp.

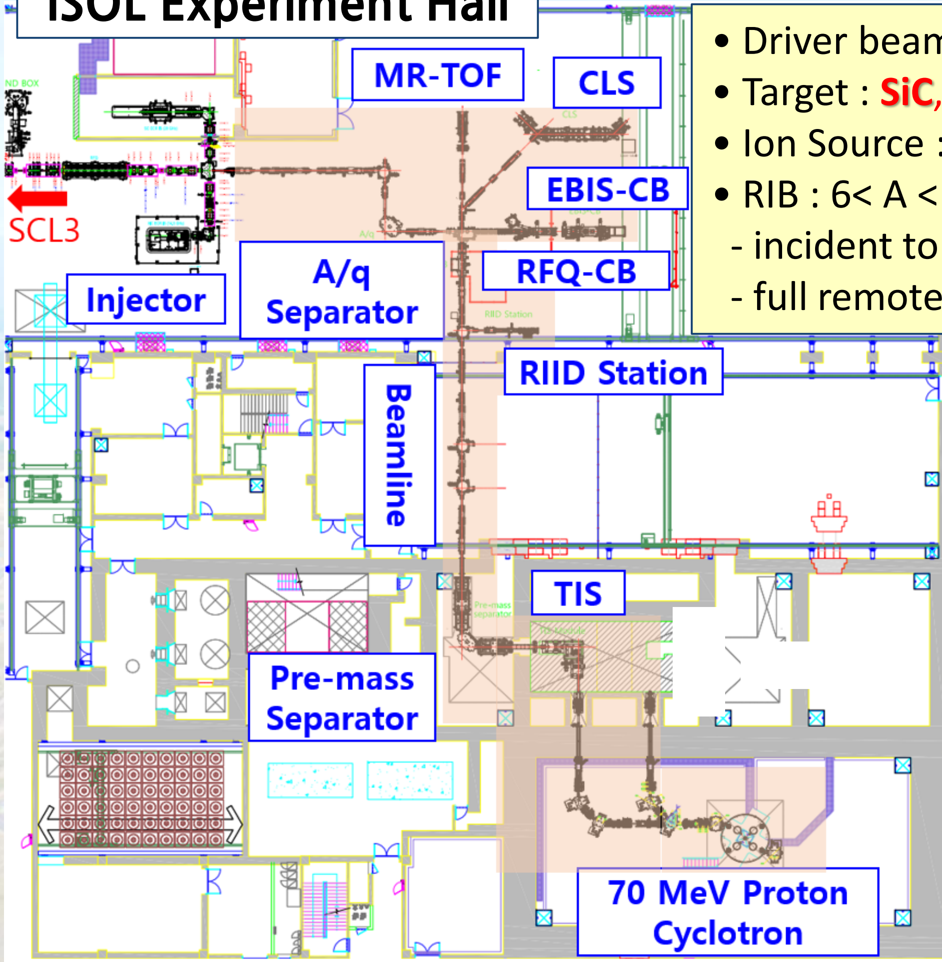
- incident to RFQ with 10 keV/u for post acceleration
- fully remote handling maintenance system with TIS modularization



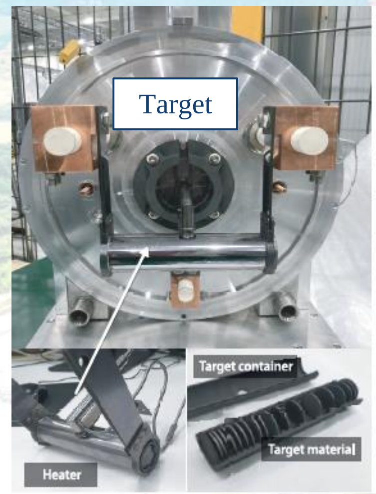
- In 2021, ISOL beam lines were commissioned with a Cs souce
- In 2023, ISOL system was commissioned with SiC target

ISOL System

ISOL Experiment Hall

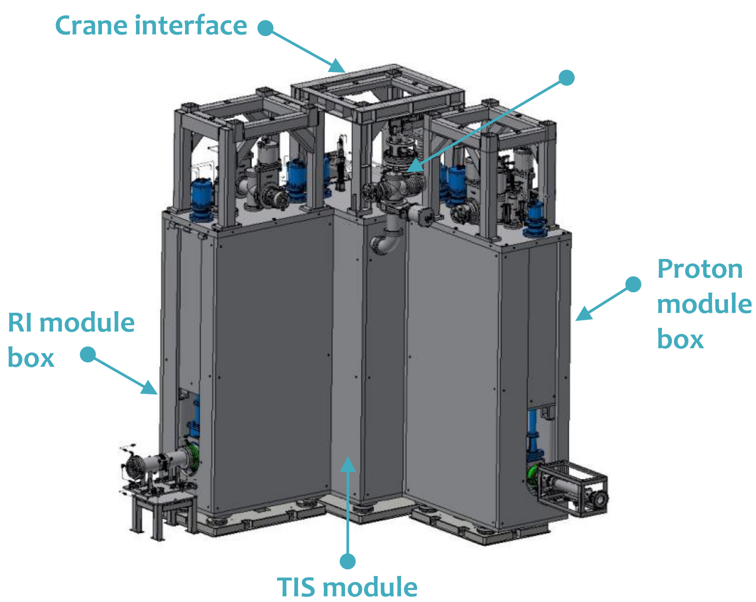


- Driver beam : proton 35 ~ 70 MeV, up to 70 kW
- Target : **SiC**, BN, MgO, LaC_2, UCx, CaO, BeO, etc
- Ion Source : **Surface, RILIS**, Plasma
- RIB : 6< A < 160, 10<K< 80 keV, 10^8 pps(Sn), >90% purity @Exp.
  - incident to RFQ of post accelerator 10 keV/u
  - full remote maintenance system with TIS modularization

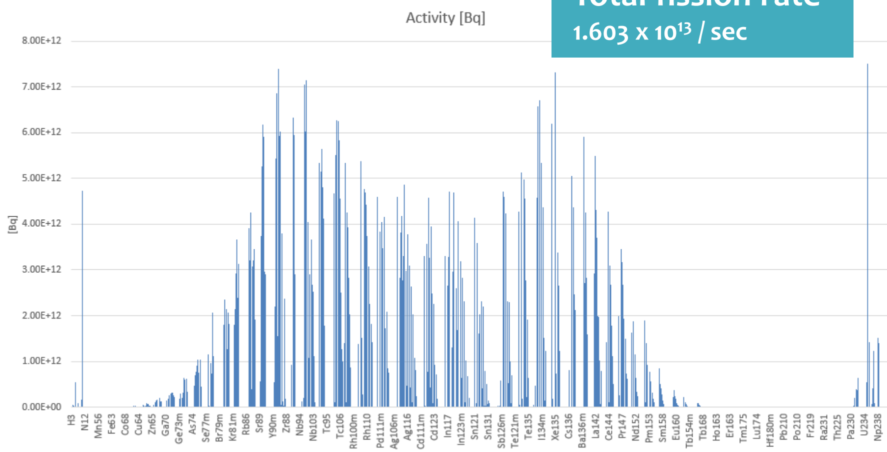


- ISOL beam lines including sub-systems were commissioned with a Cs ion source in Dec 2021
- **RI beam commissioning using SiC target (March 2023)**

ISOL System

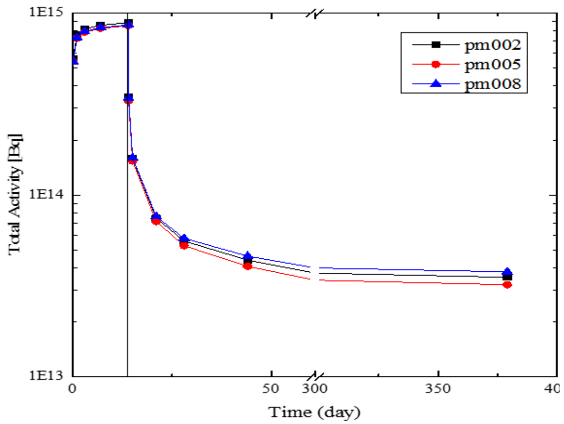


Total fission rate
1.603×10^{13} / sec



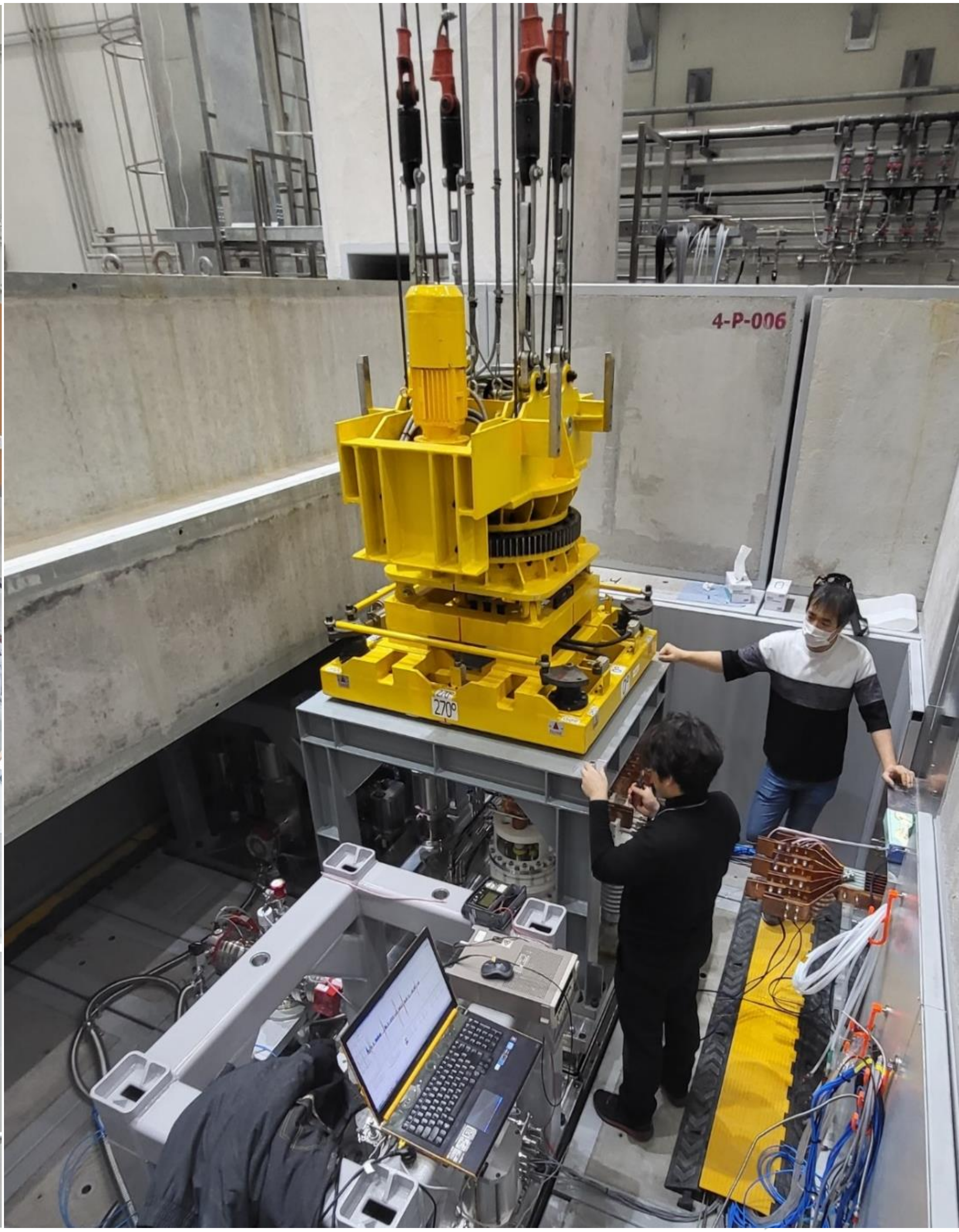
Fission Products : ~ 1000 Radioactive Nuclides
(~300 nuclides half-life > 3 days)

10 kW ISOL target & chamber



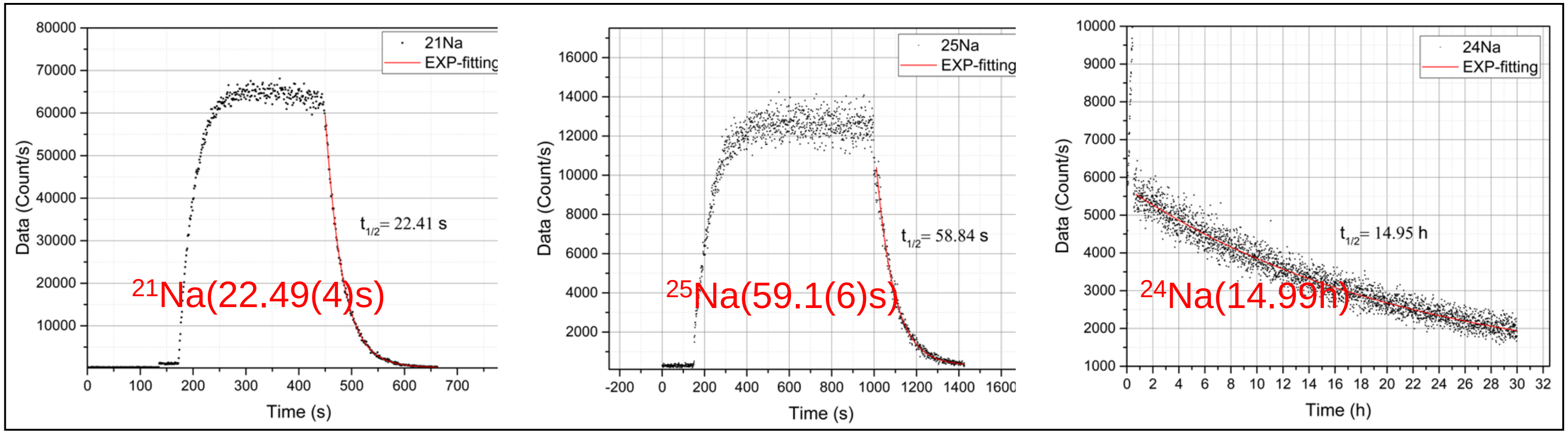
Decay of Total Activity of 70 KW UCx Target after two weeks operation

ISOL bunker

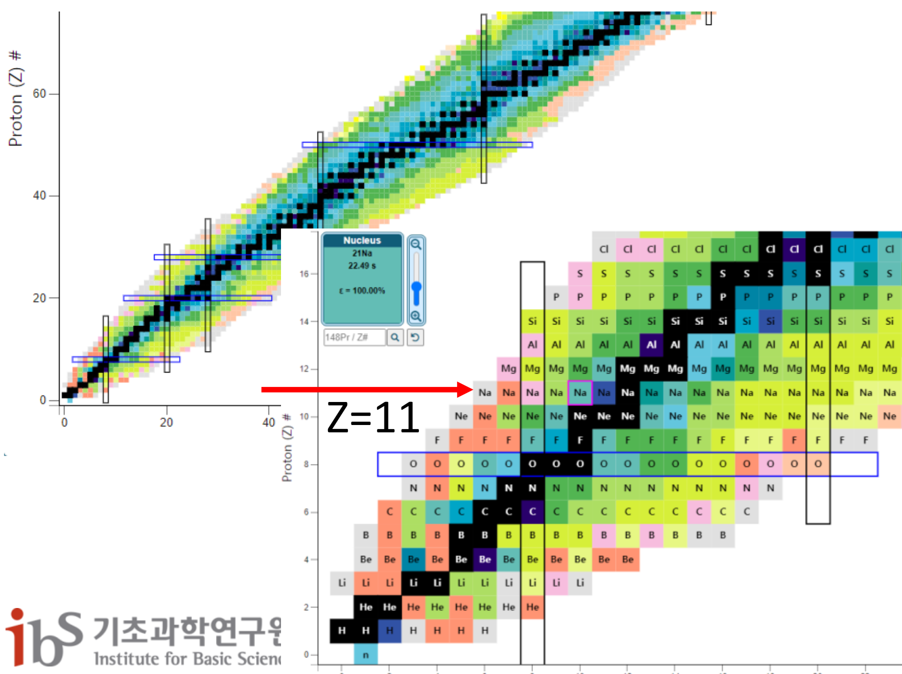


First ISOL Beam Commissioning with RIB ($^{21, 22, 24, 25}$Na)

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



The measured half-lives of Na isotopes by using PMT & Scintillators



	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
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
F - 16 1.1E-19s	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 - 15 2.037m	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 - 14 99.636	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

Second ISOL Beam Commissioning with RIB (^{26m}Al)

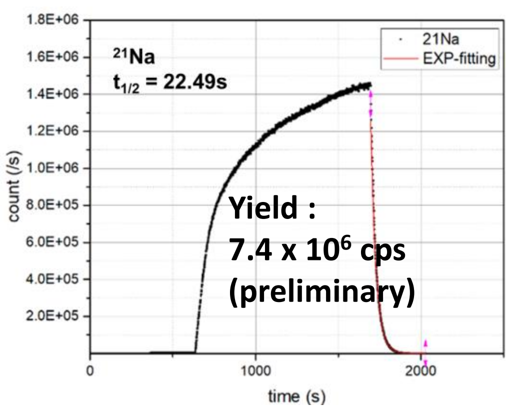
- **Experimental results**

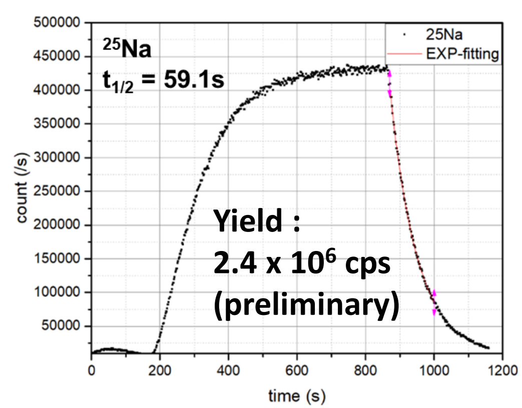
The second RI Production on May 23, 2023

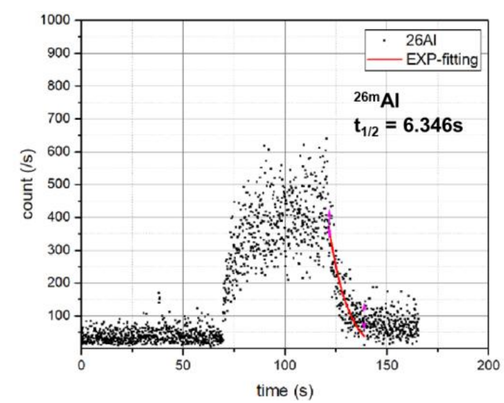
  - Proton beam 70 MeV, 1.2 μ A
  - SiC target temperature ~1,400℃ (Ta heater ohmic heating 1.8 kW)
  - Measured RIs (so far June 1)

		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

^{26m}Al







< Measurement results using scintillator + PMT >

Commissioning of ISOL system

- **2022. 10 : Cyclotron SAT**
- **2022. 11 : RI Commissioning with SiC target & TIS module operation parameter check**
- **2023.03 : proton beam on SiC inside TIS module and $Na^{21\sim25}$ extraction experiment**
- **2023.12 : Na & Al beam operation and experiments in ISOL hall**

RI Beam Schedule (~'24)

- **Non-fissile targets :** SiC, BN, LaC_2, MgO
- **Expected RI beams with 1 kW proton**

  - ^{22}Na(SIS) : $10^{6\sim7}$ pps / ^{26}Al(SIS+RILIS) : $10^{4\sim5}$ pps / ^{8}Li(SIS) : $10^{6\sim7}$ pps

  - $^{131\sim132}$Cs, ^{131}Ba, ^{135}Ce

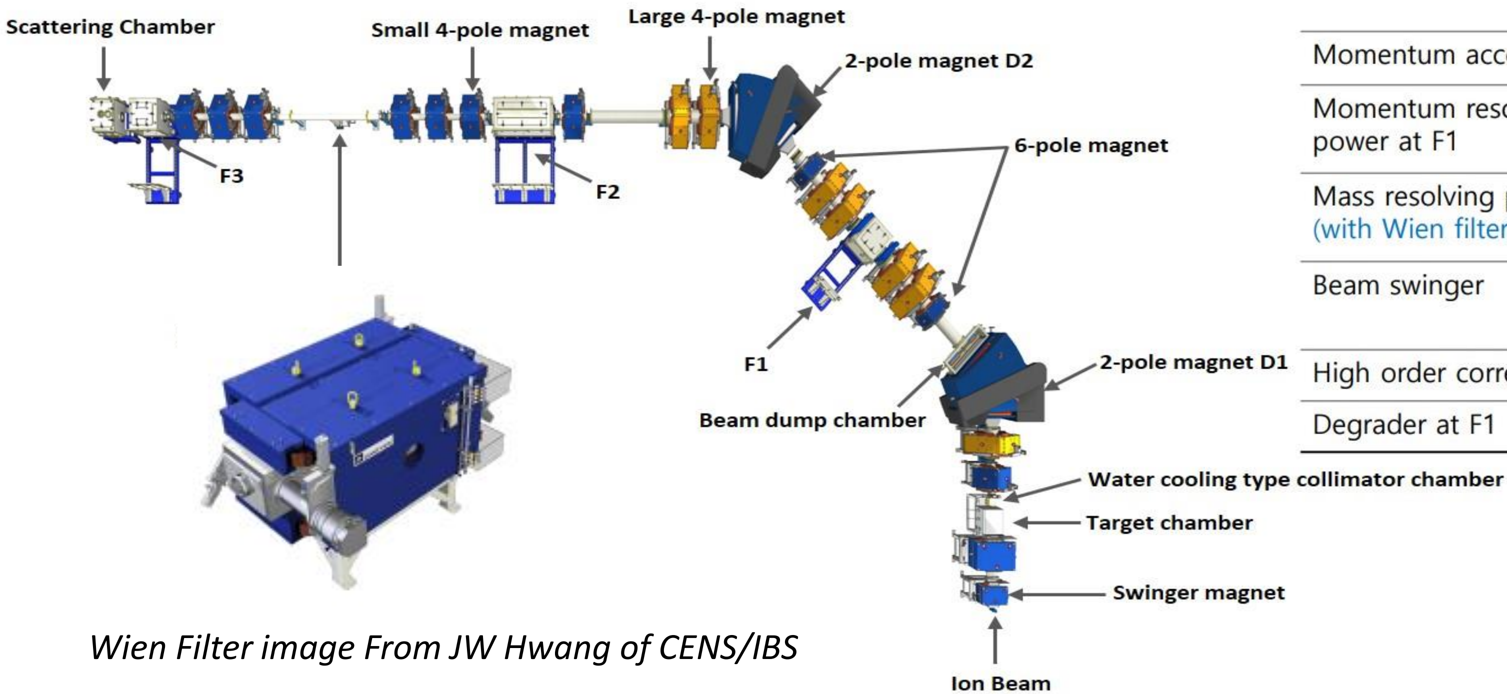
KoBRA spectrometer

KoBRA(**Ko**rea **B**road acceptance **R**ecoil spectrometer and **A**pparatus)

Multipurpose spectrometer for nuclear structure and nuclear astrophysics using stable or RI beams in the energy range of 1~40 MeV/u

- RI production at a few MeV/u and 20 ~ 40 MeV/u using a stable beam from ECR-IS
- Recoil mass spectrometer (<a few MeV/u) for direct measurement of the radiative capture process, using RI beams from ISOL

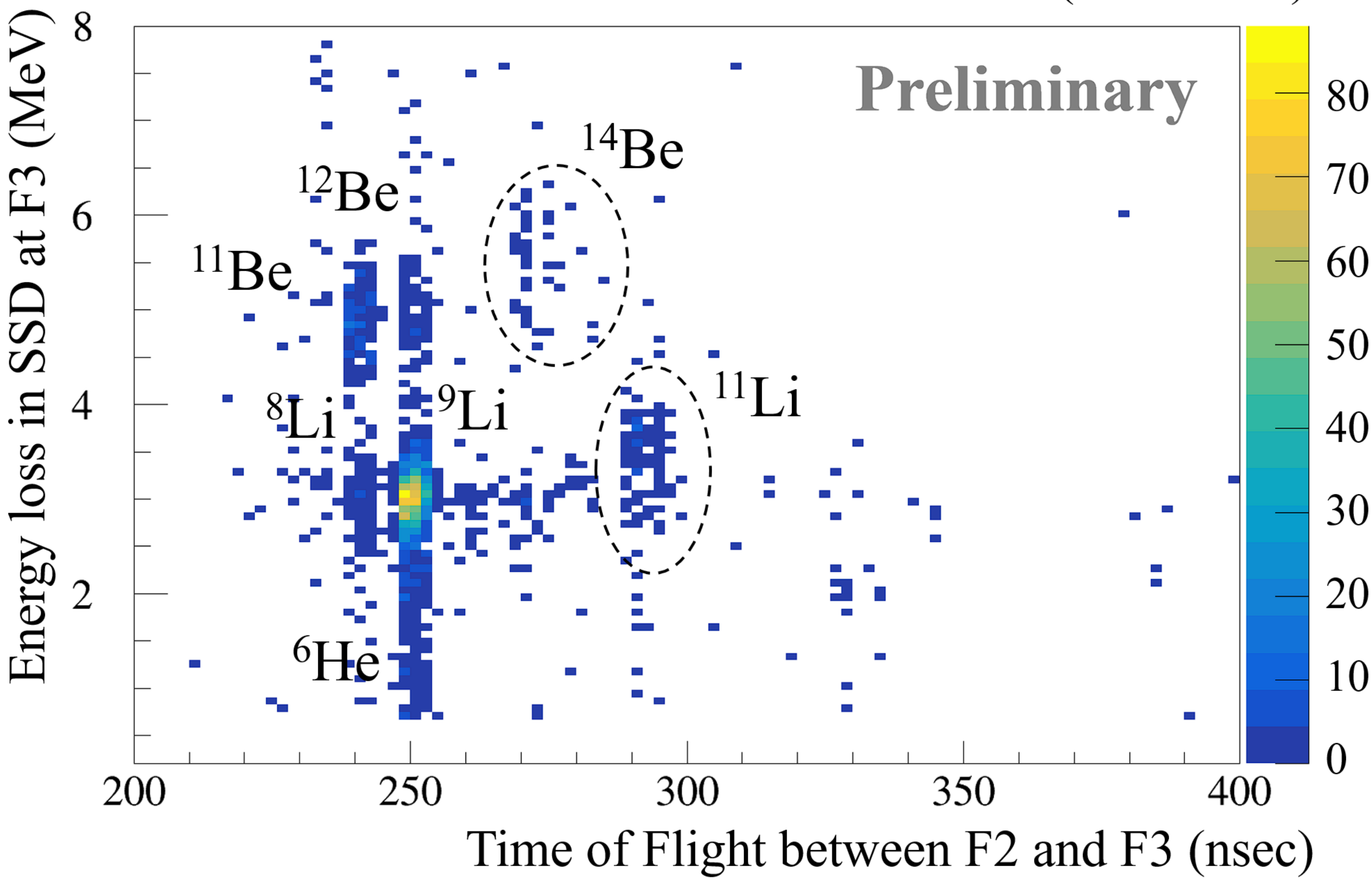
Magnetic rigidity	0.25 – 3.0 Tm
Angular acceptance	80 mrad (H) 200 mrad (V)
Momentum acceptance	8%
Momentum resolving power at F1	2100 at 2 mm beam size
Mass resolving power (with Wien filter)	750 at 2 mm beam size
Beam swinger	up to 12 degree for 3 Tm
High order correction	up to 4th order
Degrader at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



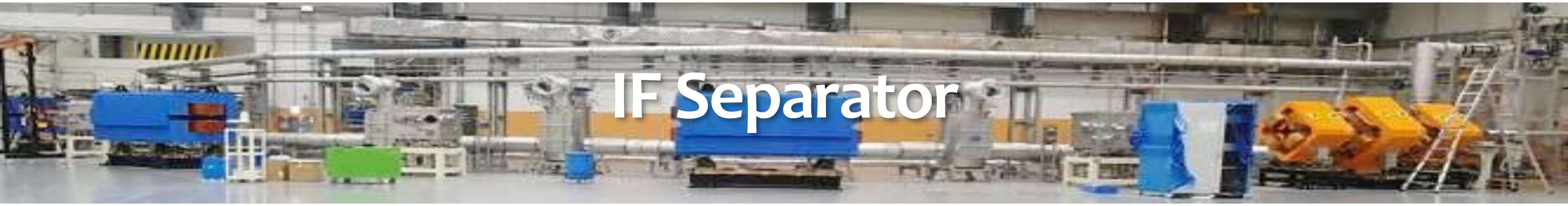
Wien Filter image From JW Hwang of CENS/IBS

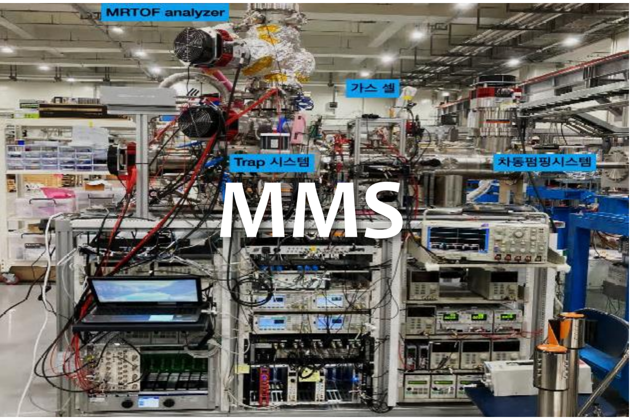
First production of RIs at F3 of KoBRA spectrometer (Ar + C)

Particle identification with the first KoBRA beam commissioning (2023.06.01)



Other Experimental Systems





All exp. systems are installed and machine-commissioned by 2022

NDPS (Nuclear Data Production System)

- Basic Science
  - Origin of chemical elements (slow and rapid neutron capture processes)
  - Nuclear structure and reaction mechanism
  - Nuclear fission dynamics
  - etc
- Technology and Engineering
  - Nuclear reactors and safety
  - Neutron imaging
  - Medical isotopes (diagnosis and therapy)
  - Semiconductor soft errors
  - etc

NDPS (Neutron TOF facility)

The surprisingly large neutron capture cross-section of ^{88}Zr

Jennifer A. Shusterman[1,2,3*], Nicholas D. Scielzo[1], Keenan J. Thomas[1], Eric B. Norman[4], Suzanne E. Lapi[5], C. Shaun Loveless[5], Nickie J. Peters[6], J. David Robertson[6], Dawn A. Shaughnessy[1] & Anton P. Tonchev[1]

Nature v.565 p.328 (2019)

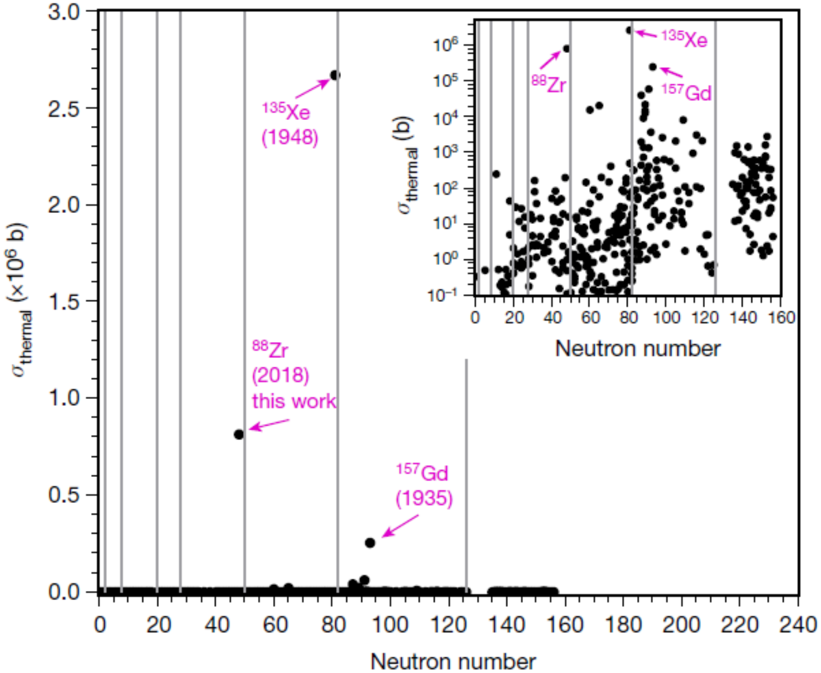
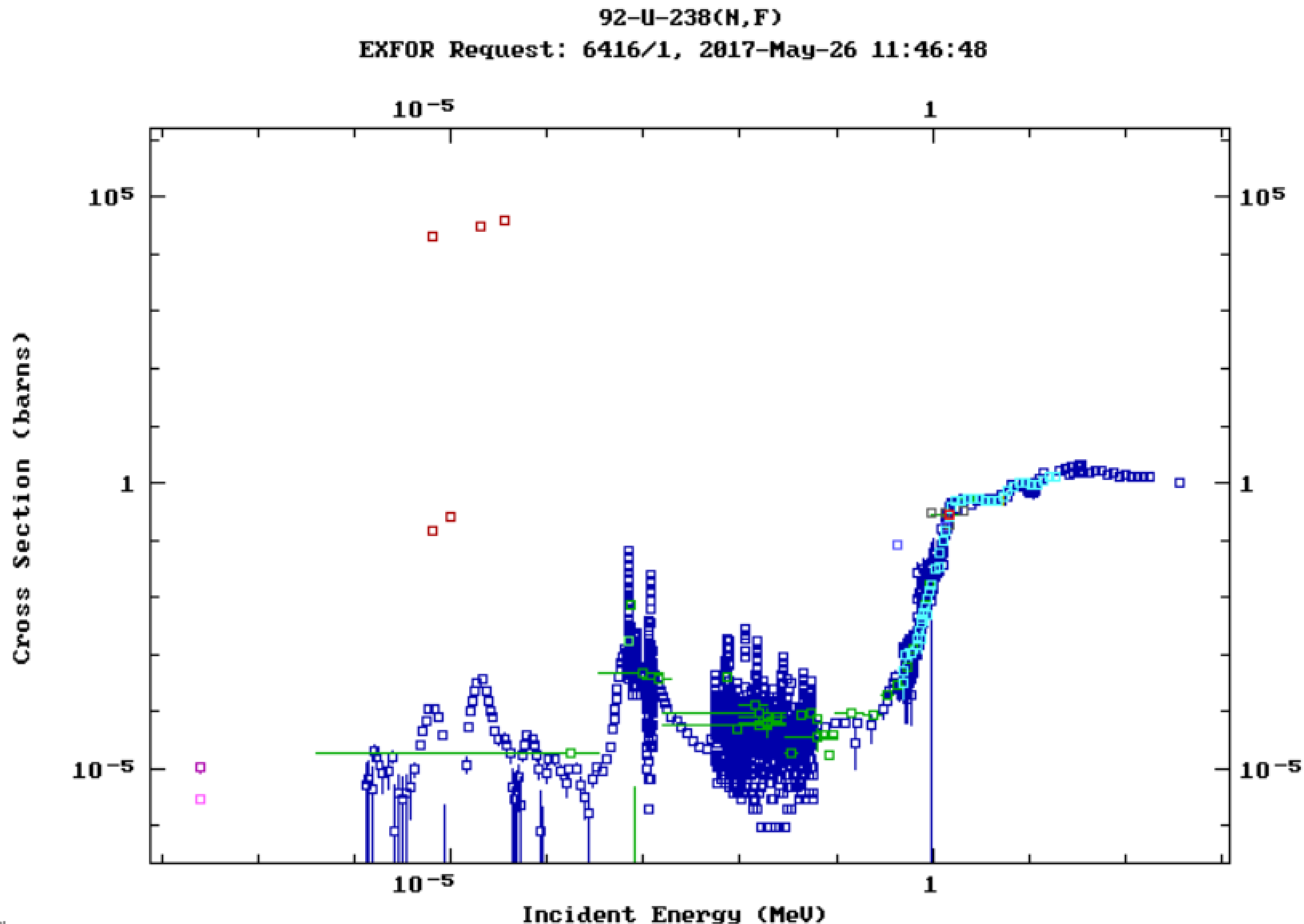


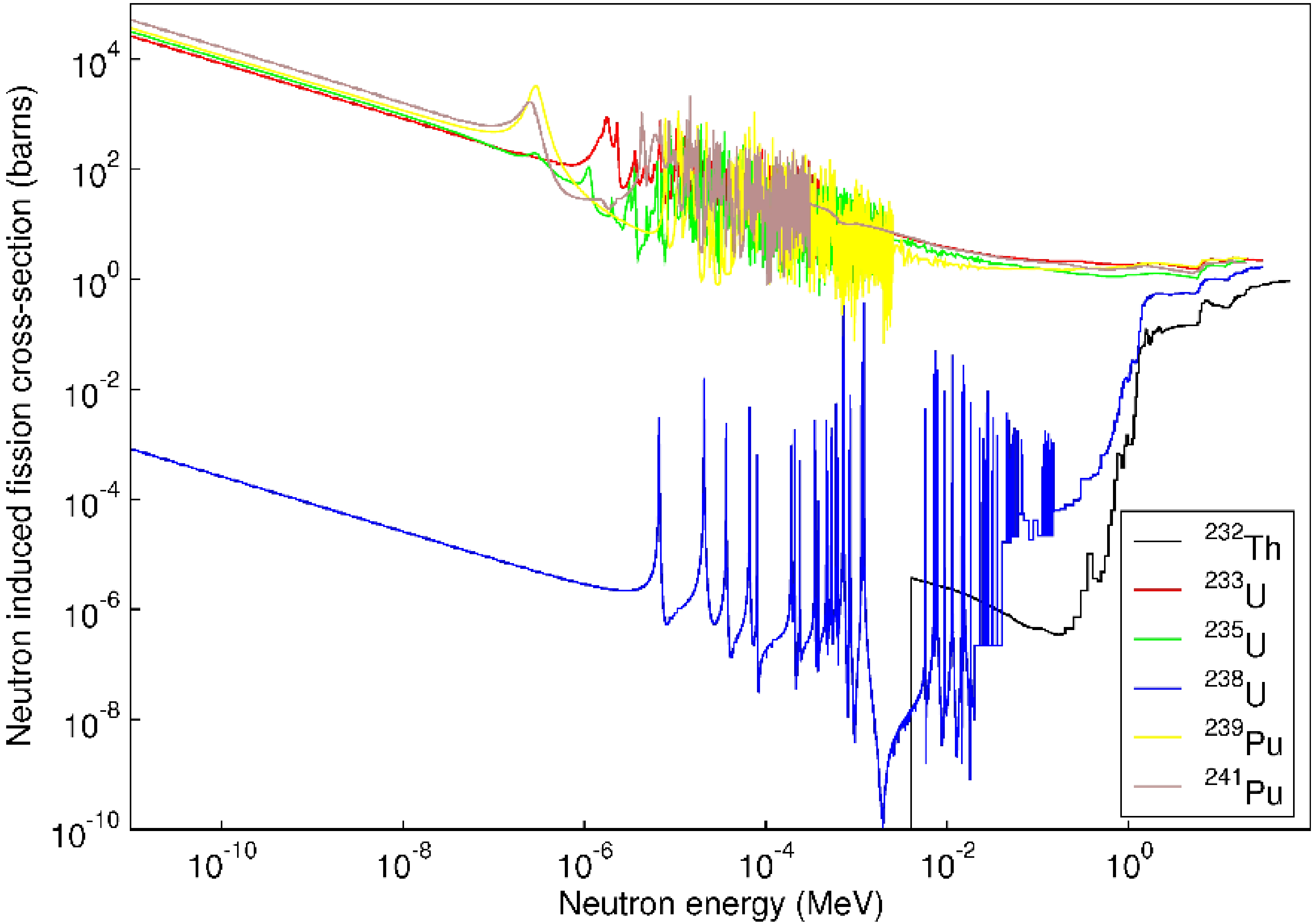
Fig. 3 | Measured thermal neutron capture cross-sections as a function of neutron number of the target. The main plot shows all the existing data on a linear scale, and the inset displays the same data on a logarithmic scale. The vertical lines indicate the neutron-shell closures, which occur for nuclei with 2, 8, 20, 28, 50, 82 and 126 neutrons. The three isotopes with cross-sections of more than 10^5 b are labelled along with the year of the measurement.

Tacoma Narrows Bridge

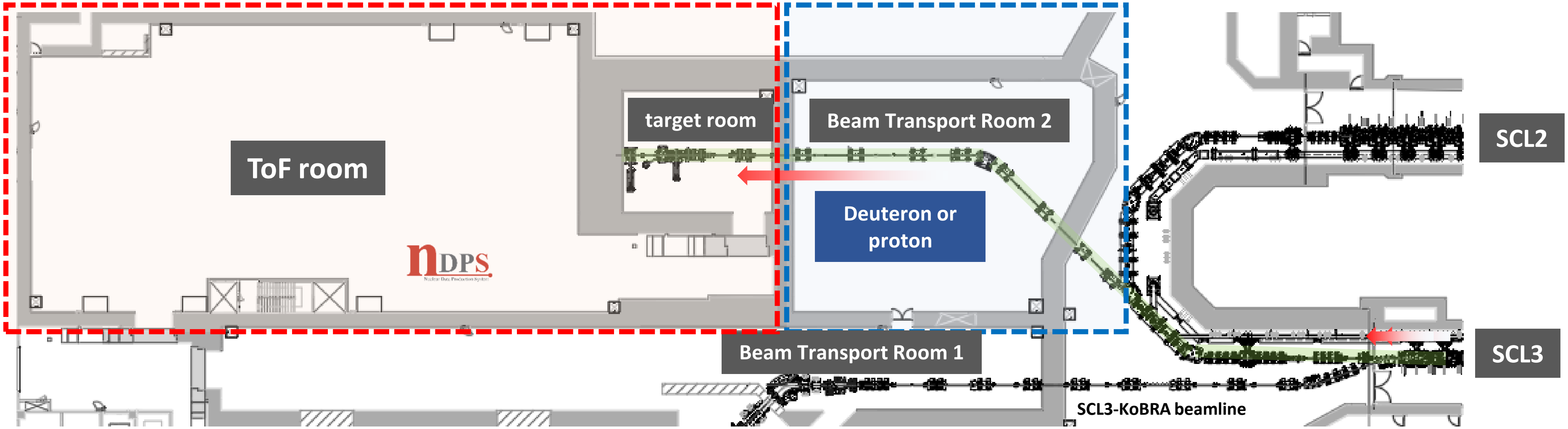
Resonances in ^{238}U (n, fission)



Resonances in (n, fission) reactions

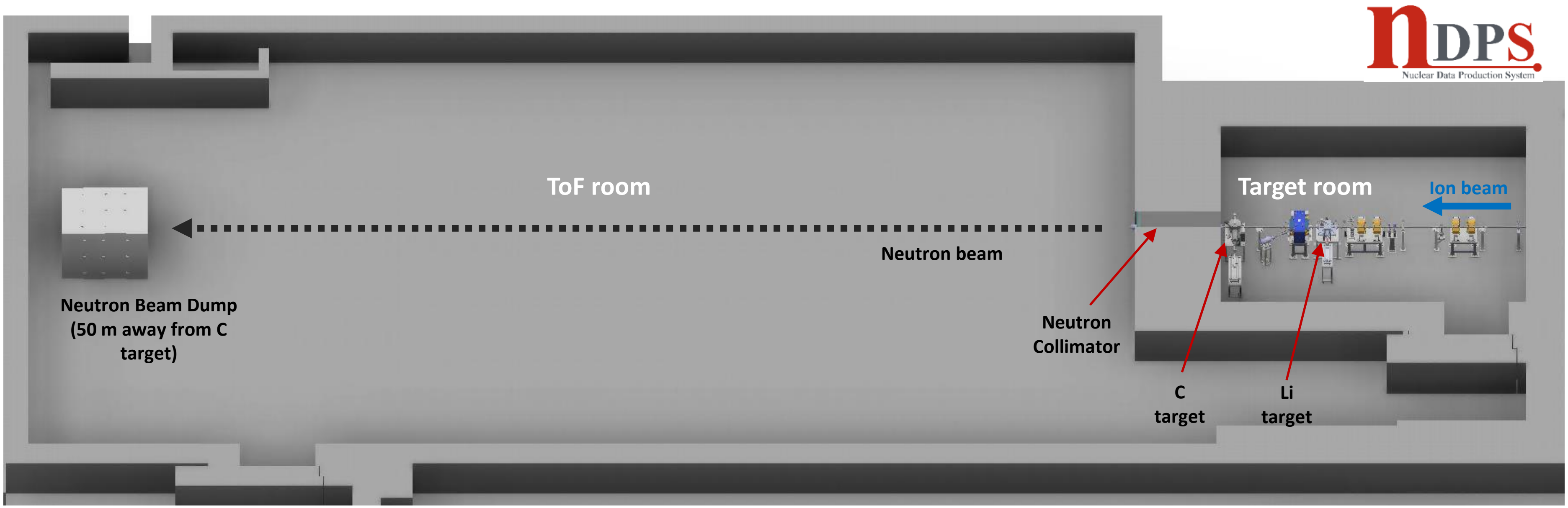


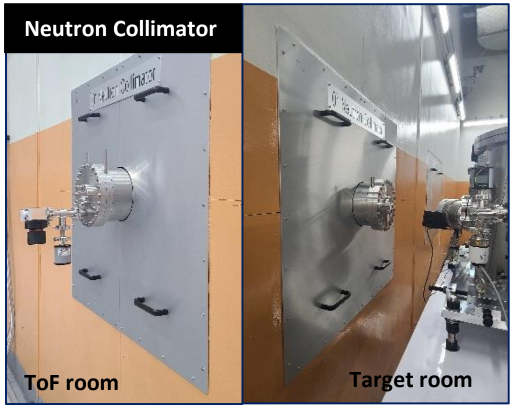
NDPS (Nuclear Data Production System)



Beam ion	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
Repetition rate	(1 – 200) kHz
Flight length	5 – 40 m
Neutron flux	~ 10^8 cm^{-2} sec^{-1} at 5 m

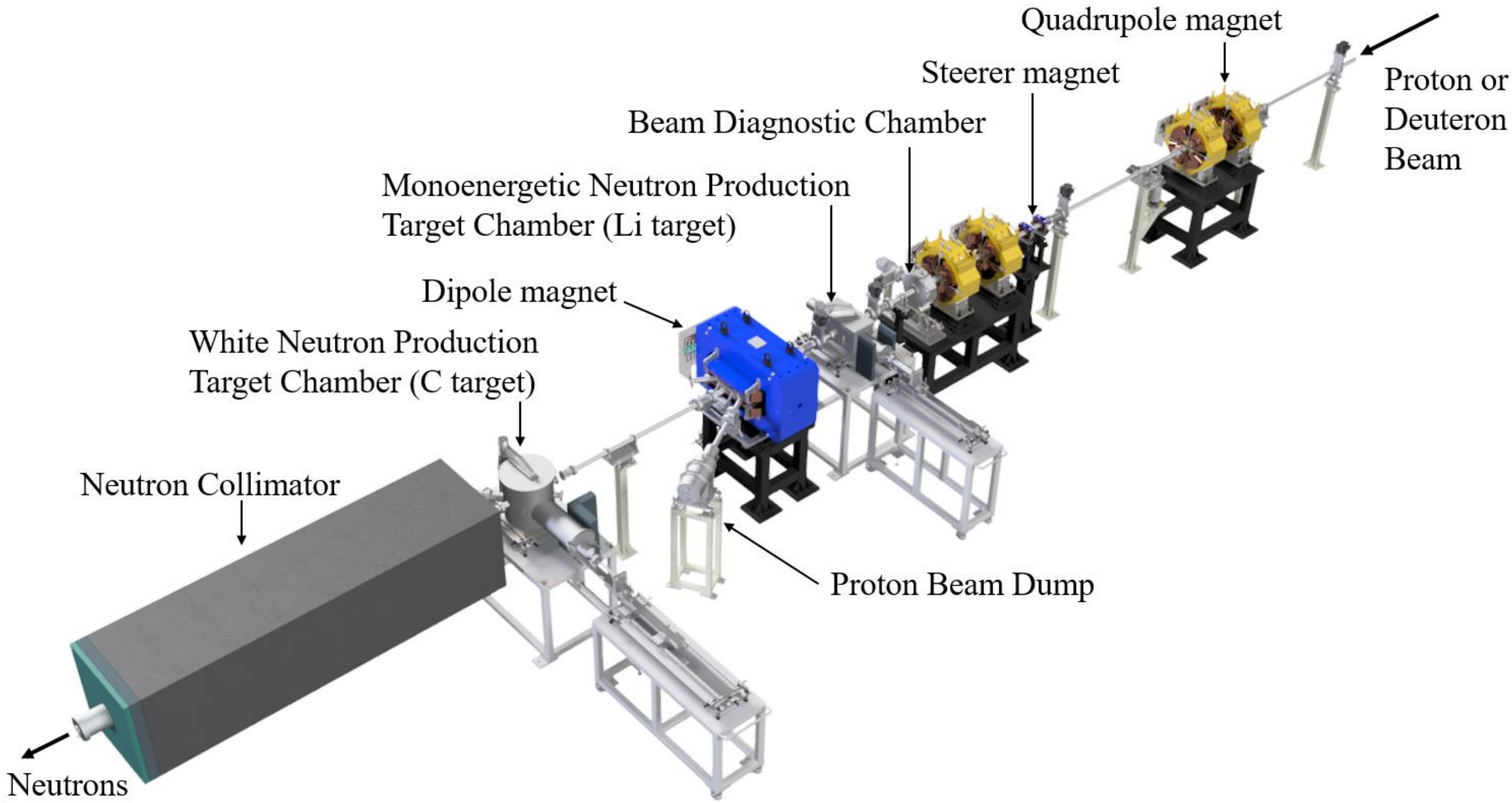
NDPS (Nuclear Data Production System)



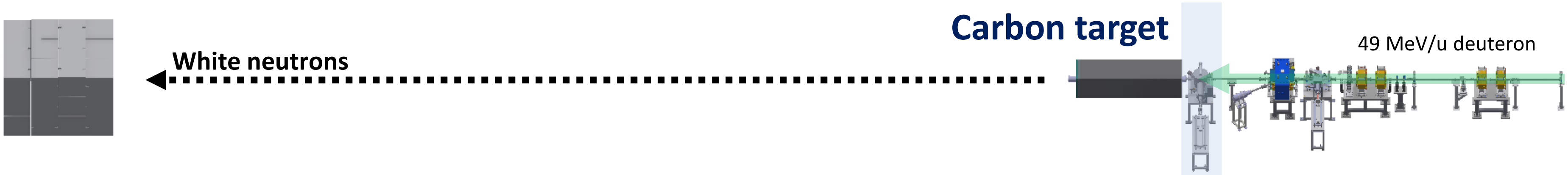


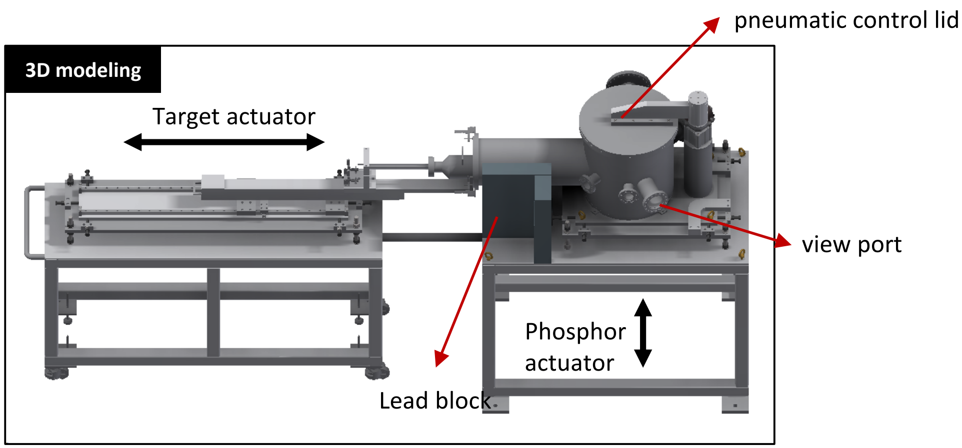
NDPS (Nuclear Data Production System)

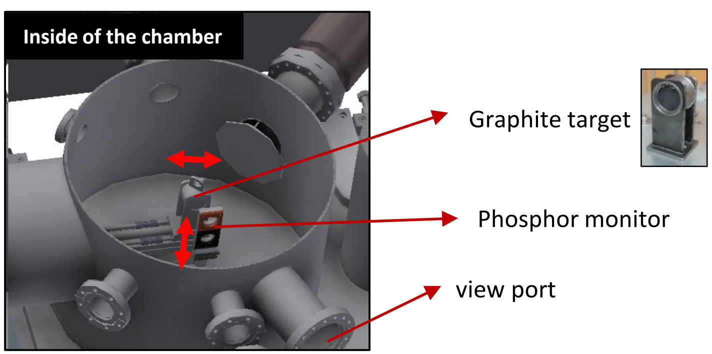
❖ **Neutron production target, beam line, collimator**

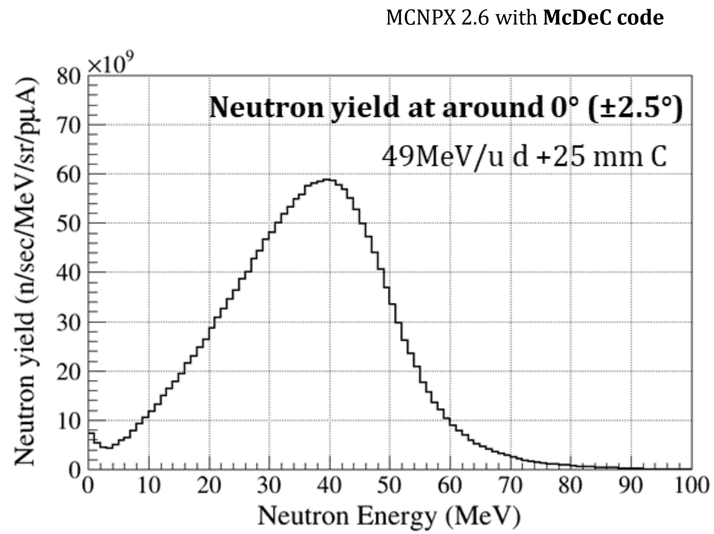


NDPS (Nuclear Data Production System)









Neutron intensity at the end of the collimator

$\simeq$ **10^8 neutrons/cm^2/sec for 10 pμA**

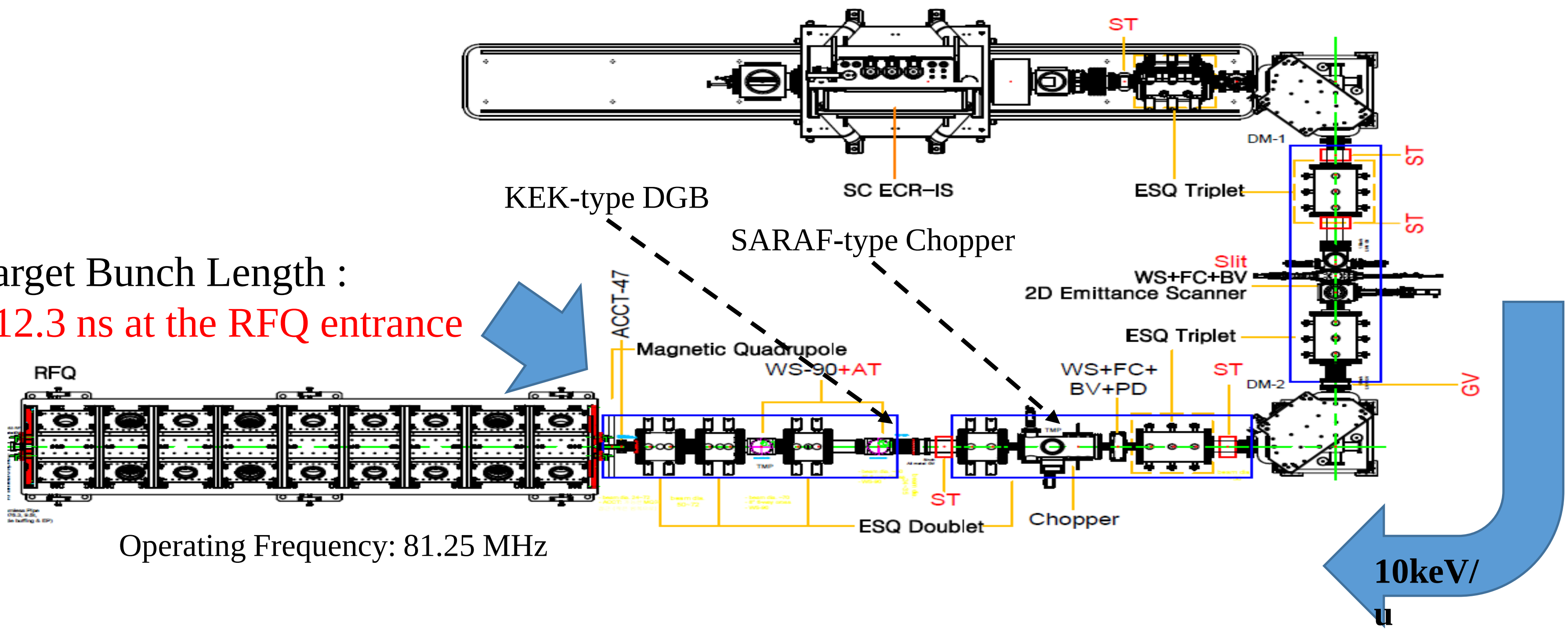
Single bunch selection for TOF

Single Bunch Selection Scheme

UNIST

Initial stage: SARAF-type fast chopper (≤200 kHz) + KEK-type DGB
→ Well-demonstrated and cost-effective approach
→ Not altering existing beamline configuration

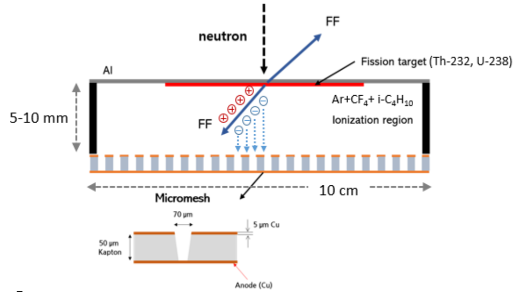
Target Bunch Length :
<12.3 ns at the RFQ entrance



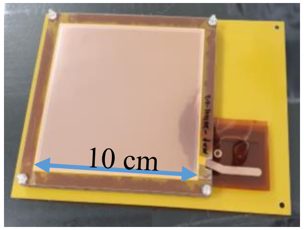
Operating Frequency: 81.25 MHz

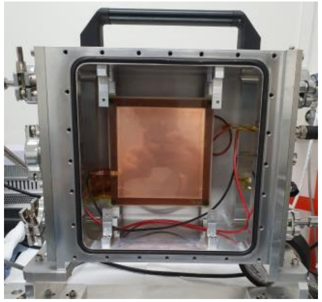
Neutron monitoring detectors for NDPS

1. MICROMEGAS (MICRO-MEsh GAseous Structure)



Micromesh



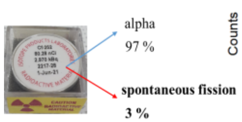


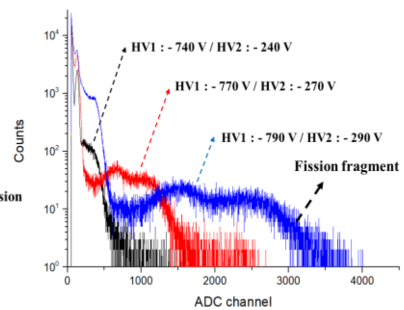
MGAS

Manufactured by Korea company

MECARO

^{252}Cf fission source

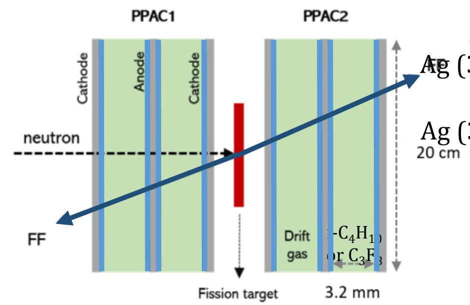




D. Y. Kim *et al.*, J. Korean Phys. Soc. 68, 1060 (2016)

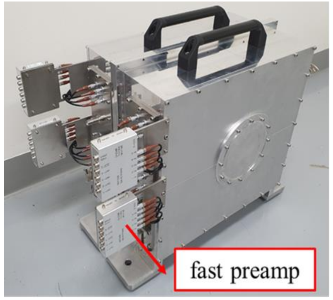
C. M. Ham *et al.*, J. Korean Phys. Soc. 75, 775 (2019)

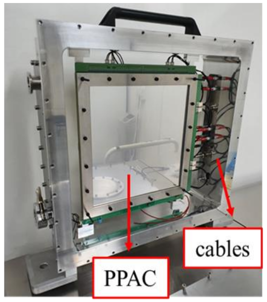
2. PPAC (Parallel Plate Avalanch Counter)



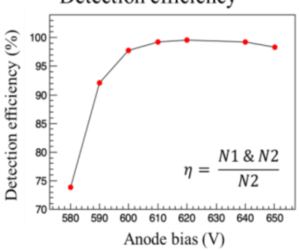
Anode
Ag (30nm) on Mylar(2.5um)
Cathode (strip pattern)
Ag (30nm) on Mylar(2.5um)

PPAC

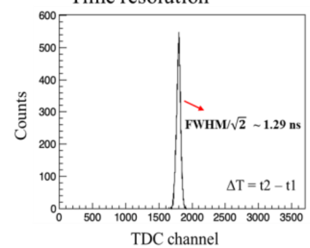




Detection efficiency



Time resolution



47

C. Akers *et al.*, Nucl. Instrum. Methods 910, 1 (2018)

Candidates of early experiments at NDPS

- Measurements of (n, xn) reactions with quasi mono-energy neutrons by activation technique
  - $^{59}Co(n,xn)$, $^{93}Nb(n,xn)$, $^{197}Au(n,xn)$, $^{209}Bi(n,xn)$
- Fission cross section measurements for heavy elements (Pb, Bi, Th, etc.) or actinides
- Activation experiments induced by light or heavy ions
- Surrogate reactions for (d, pɣ) and fission fragment measurement

R&D is underway for the high-energy section SCL2

MOUs with 17 International Institutes

Summary

- The beam commissioning of accelerator systems is done.
- Initial beam commissioning of the KoBRA spectrometer is done.
- NDPS is expected to be prepared for use in 2024
  Fission experiments are planned.
- Candidates of early stage experiments are under discussion with users.
- Beams will be provided to domestic users first in early 2024.
- The first PAC may be held in late 2024.
- RAON will provide new opportunities not only in nuclear physics, but also in nuclear data and other applications.
- Domestic and International collaboration has been essential.
- Beams will be provided to the international users soon.