RAON Rare isotope Accelerator complex for ON-line experiments

apctp asia pacific center for theoretical physics

Status and Overview of RAON Heavy Ion Accelerator Facility

Taeksu Shin

Institute for Basic Science

Nov 3, 2022

APCTP Workshop on the Physics of Electron Hadron Collider(Nov 2-4)

ibs 기초과학연구원 Institute for Basic Science

RISP 중이온가속기건설구축사업단 Rare Isotope Science Project

Rare Isotope Science Project(RISP)

○ **Goal:** To build **a heavy ion accelerator complex RAON,**
for **rare isotope science** research in Korea.

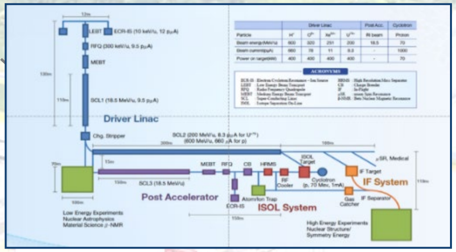
* RAON - Rare isotope Accelerator complex for ON-line experiments

○ **Budget: KRW 1,518 billion (US$ 1.32 billion, 1$=1,146krw)**
- accelerators and experimental apparatus : 522.8 billion won
- civil engineering & conventional facilities : 996 billion won (incl. site 357 billion won)

○ **Period: 2011.12 ~ 2022.12 (1st Phase)**
2023.1~2027.12(2nd Phase: Only for SCL2)

System Installation Project

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



Facility Construction Project

Construction of research and support facility to ensure the stable operation of the heavy-ion accelerator, experiment systems, and to establish a comfortable research environment

※ Accelerator and experiment buildings, support facility, administrative buildings, and guest house, etc.

◆ **Providing high intensity RI beams by ISOL and IF**
- ISOL: direct fission of ^{238}U by 70 MeV proton
- IF: 200 MeV/u ^{238}U (intensity: 8.3 pμA)

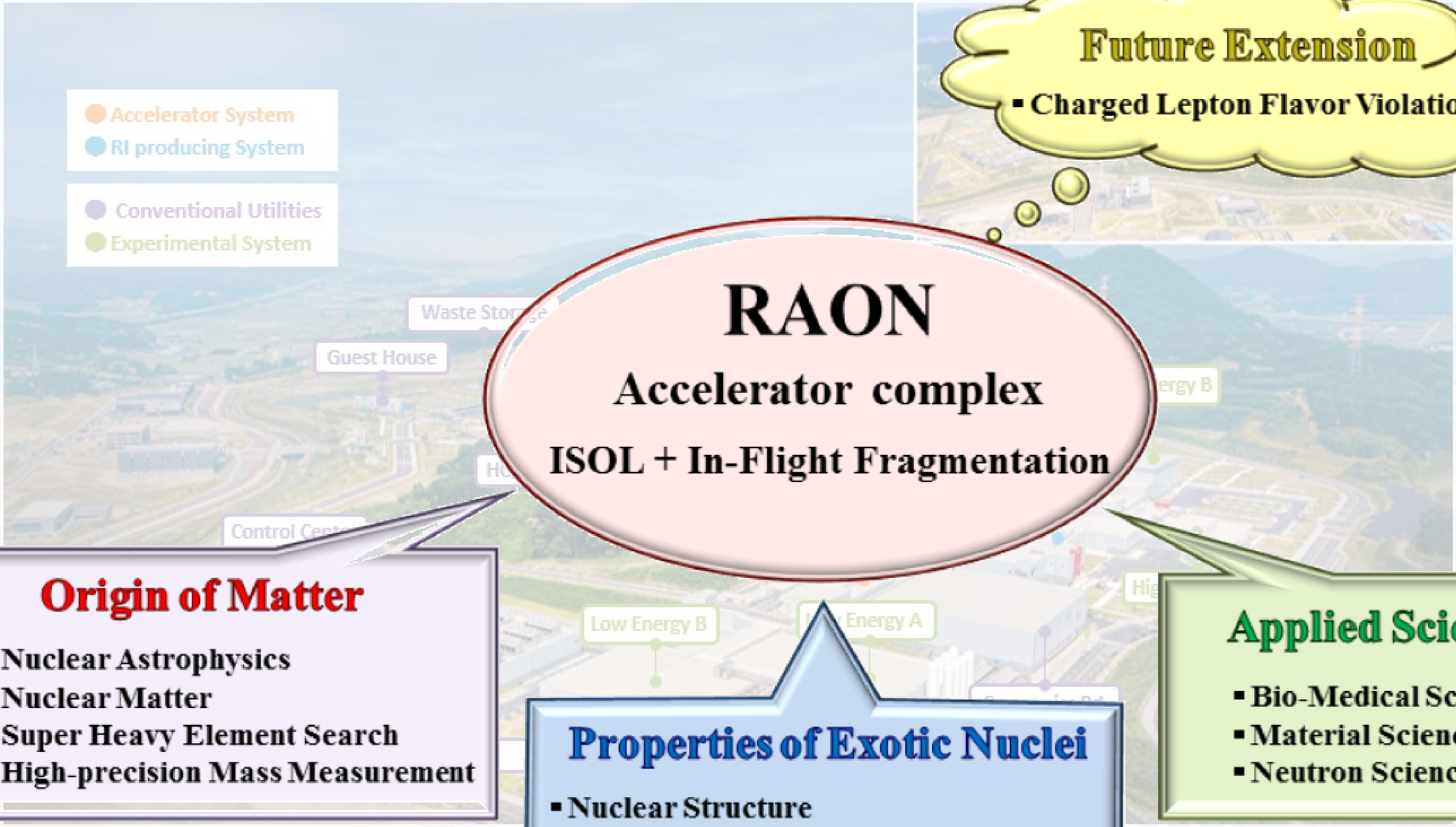
◆ **Providing high quality neutron-rich beams**
e.g., ^{132}Sn with up to 250 MeV/u,
up to 10^9 particles per second

◆ **Providing More exotic RI beam production by combination of ISOL and IF(ISOLIF)**

RAON Layout


● Accelerator System
● RI producing System
● Conventional Utilities
● Experimental System
Waste Storage
Guest House
Assembly Bd.
SRF Test Bd.
High Energy B
IF
HQ Office
Accelerator
ISOL
SCL2
SCL3
Control Center
High Energy A
Low Energy B
Low Energy A
Cryogenics Bd.
Utility Bd.
Electricity Bd.

Science Goals



Future Extension
- Charged Lepton Flavor Violation

RAON

Accelerator complex

ISOL + In-Flight Fragmentation

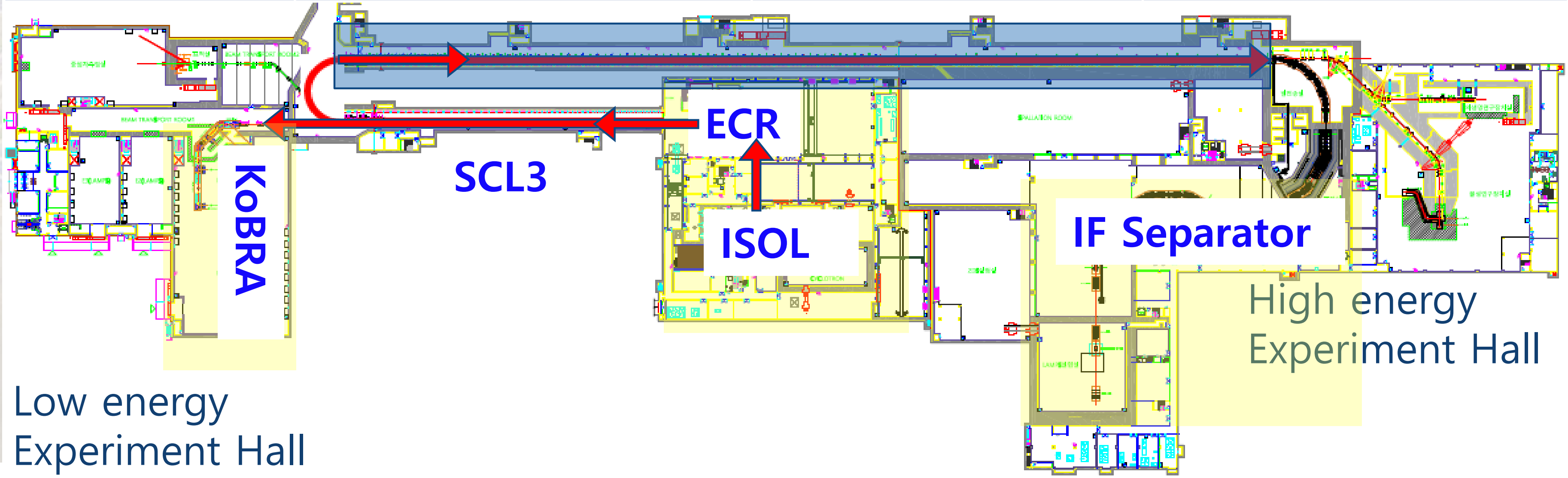
Origin of Matter
- Nuclear Astrophysics
- Nuclear Matter
- Super Heavy Element Search
- High-precision Mass Measurement

Properties of Exotic Nuclei
- Nuclear Structure
- Electric Dipole Moment and Symmetry
- Nuclear Theory
- Hyperfine Structure Study

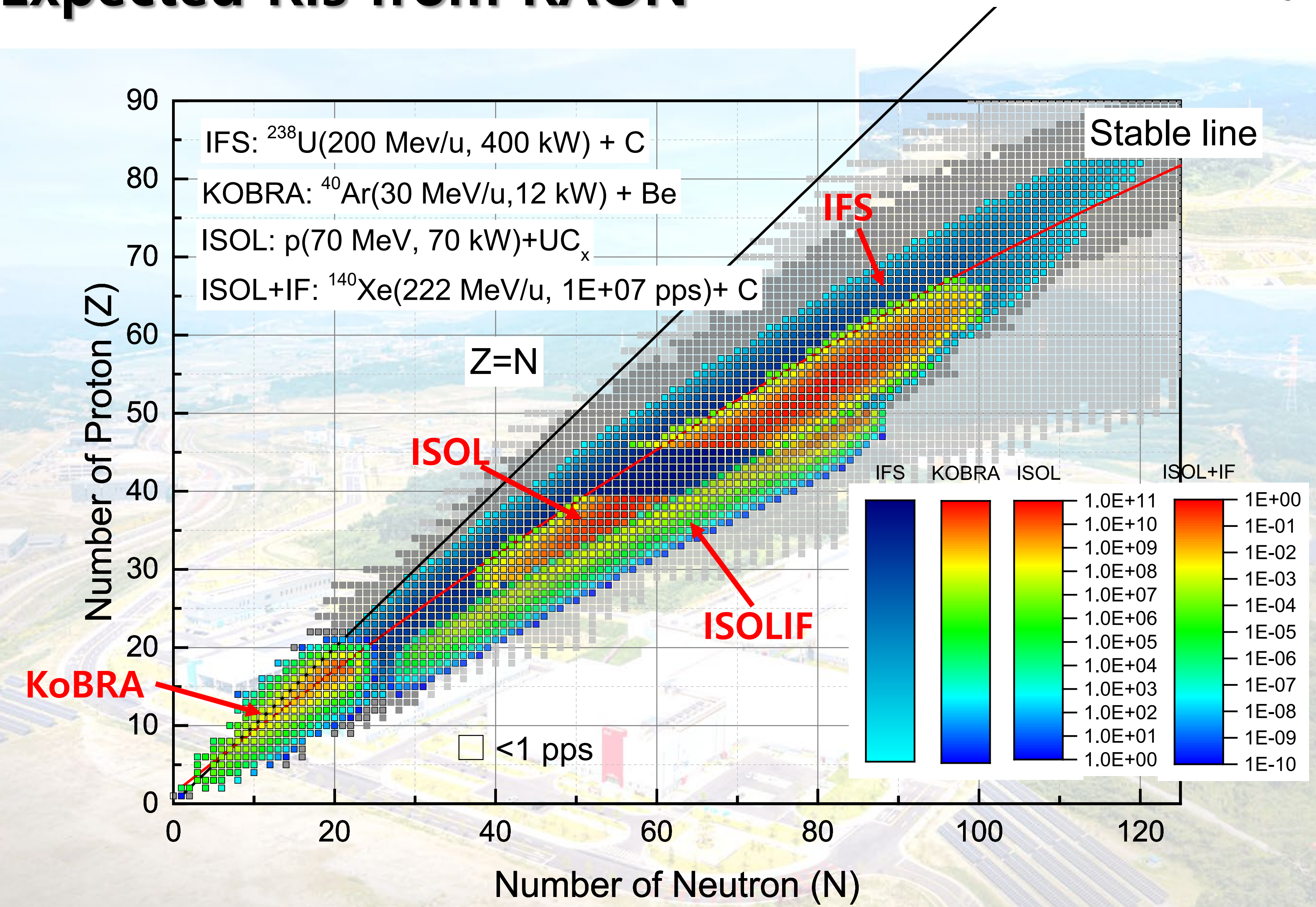
Applied Science
- Bio-Medical Science
- Material Science
- Neutron Science

RIB Production at RAON

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

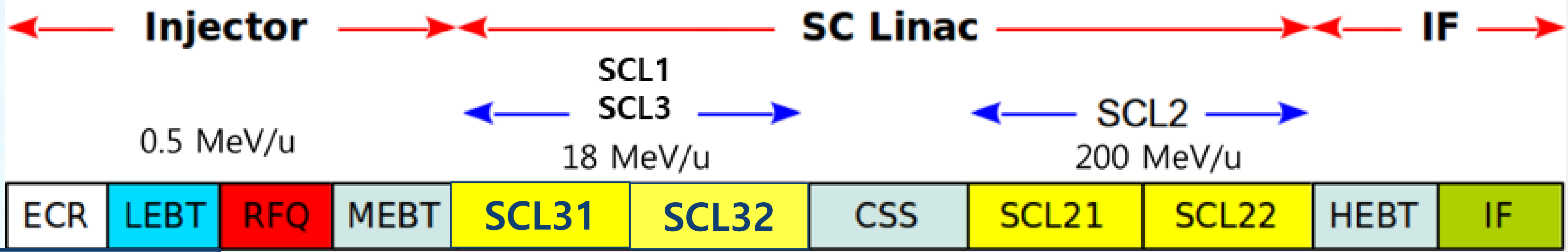


Expected RIs from RAON



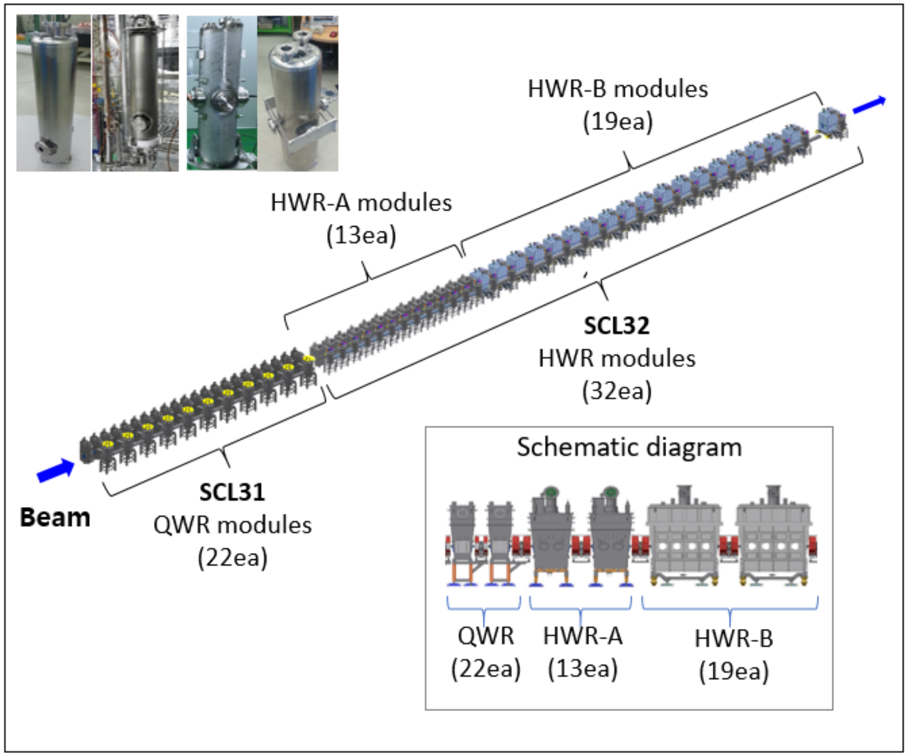
- RAON is expected to access to more neutron-rich regions of the nuclear chart

SCL3 and SCL2

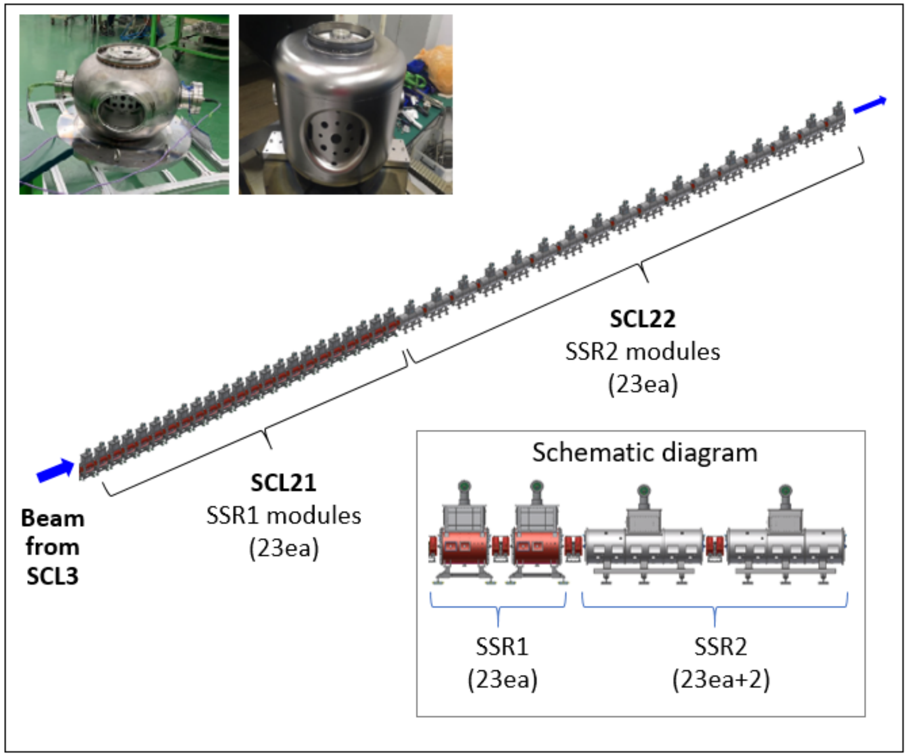


ISOL -> LEBT

SCL3

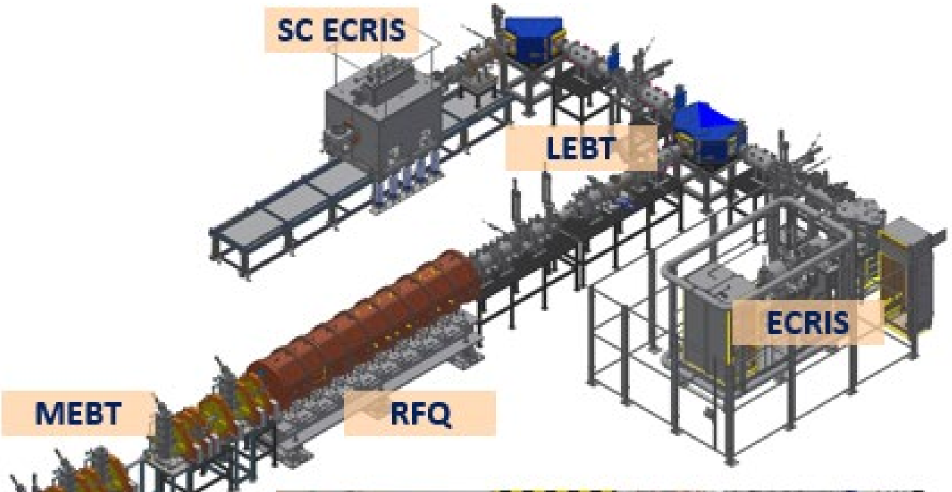


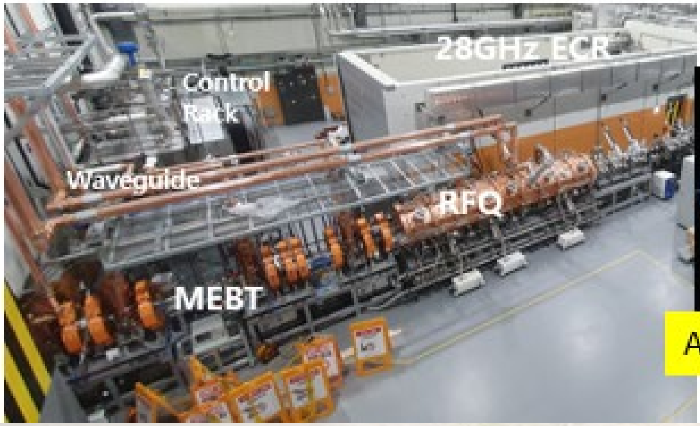
SCL2



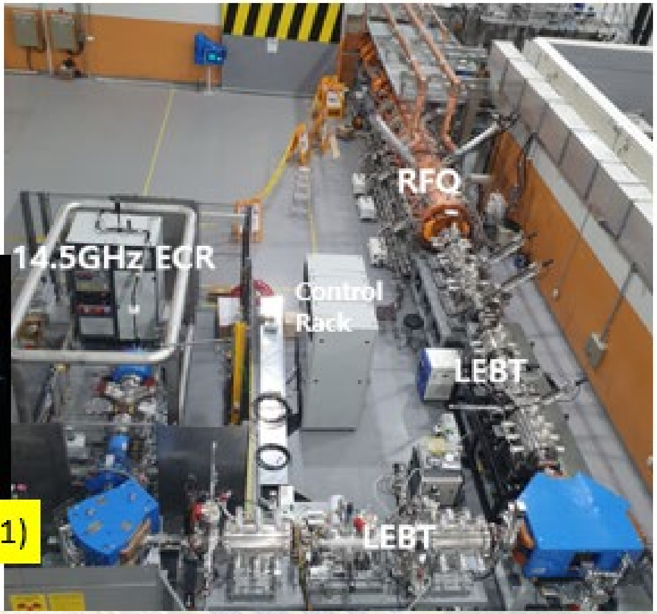
Injector System

- **Two ECR-IS on high-voltage platforms**
  - 14.5 GHz ECR ion source
  - 28 GHz superconducting ECR ion source
- **LEBT (E = 10 /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, 4×2 kW)
  - Simple quadrupole magnets, Instrumentation



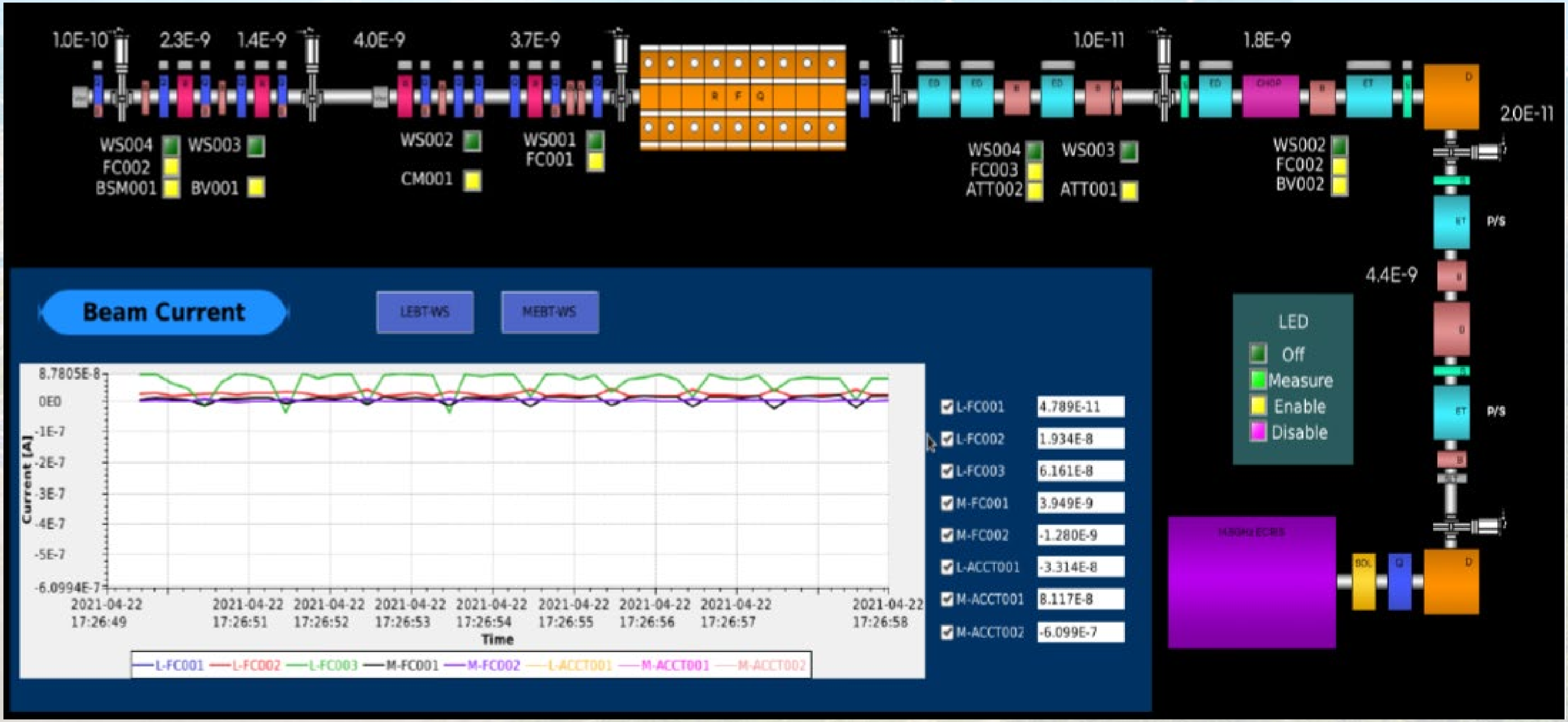


Ar^{8+} 10uA @ Beam Viewer('21)



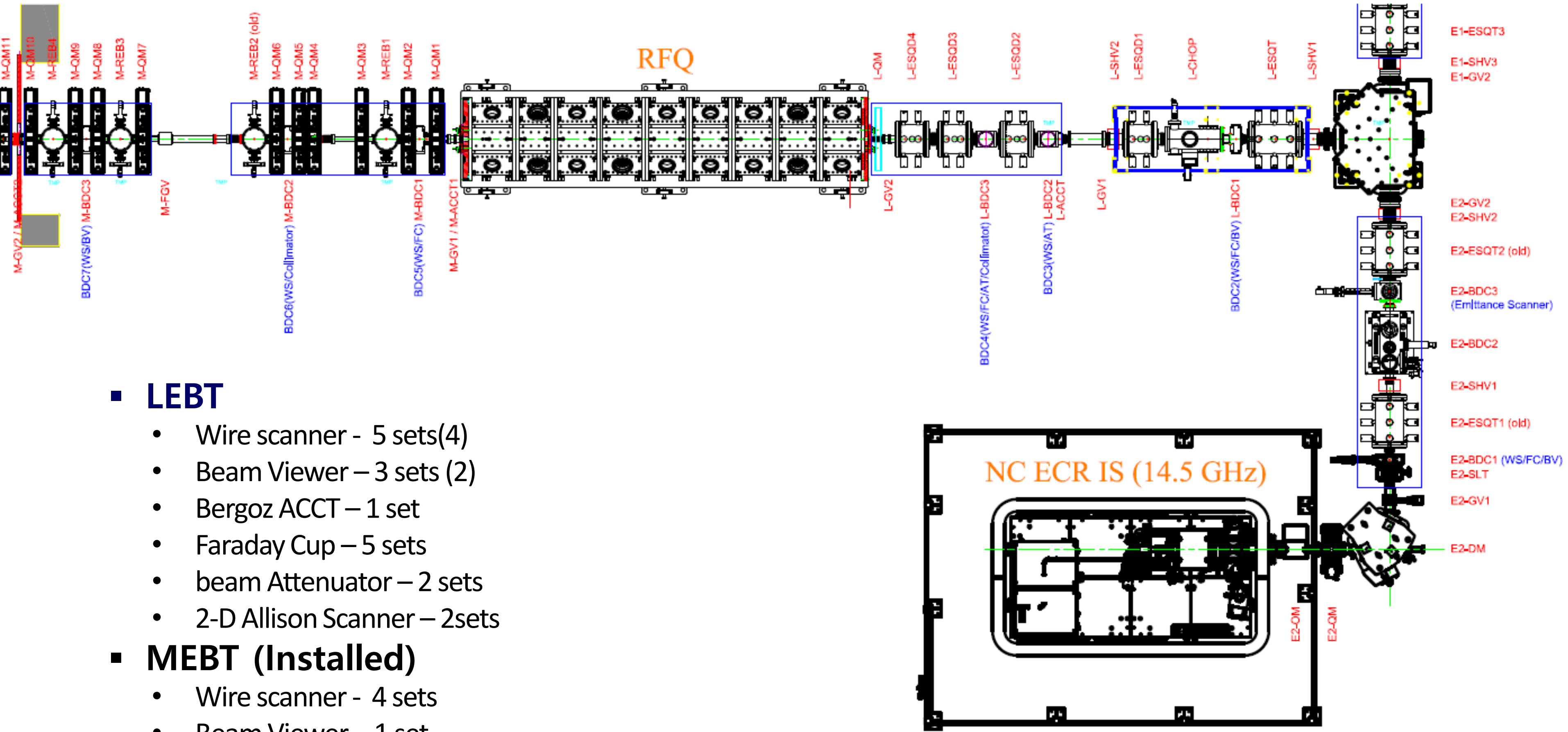
Beam Commissioning of Injector

- Started in Aug 2021
- Ar $^{8+,9+}$ Aug 2021(1Hz, 01μs)
- ECR(14.5 GHz) → LEBT → RFQ → MEBT



☑ L-FC001 4.789E-11
☑ L-FC002 1.934E-8
☑ L-FC003 6.161E-8
☑ M-FC001 3.949E-9
☑ M-FC002 -1.280E-9
☑ L-ACCT001 -3.314E-8
☑ M-ACCT001 8.117E-8
☑ M-ACCT002 -6.099E-7

Beam Diagnostic System



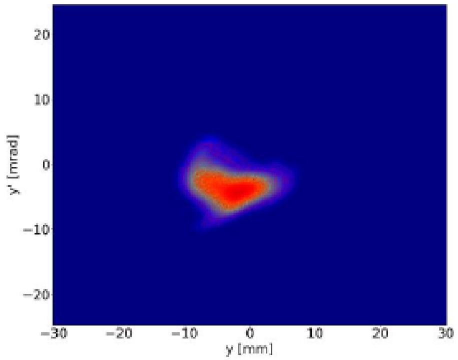
- **LEBT**
  - Wire scanner - 5 sets(4)
  - Beam Viewer – 3 sets (2)
  - Bergoz ACCT – 1 set
  - Faraday Cup – 5 sets
  - beam Attenuator – 2 sets
  - 2-D Allison Scanner – 2sets
- **MEBT (Installed)**
  - Wire scanner - 4 sets
  - Beam Viewer – 1 set
  - Bergoz ACCT – 2 sets
  - Faraday Cup – 2 sets
  - Stripline FFC – 1 set
  - BPM – 6 sets

Beam Test on LEBT

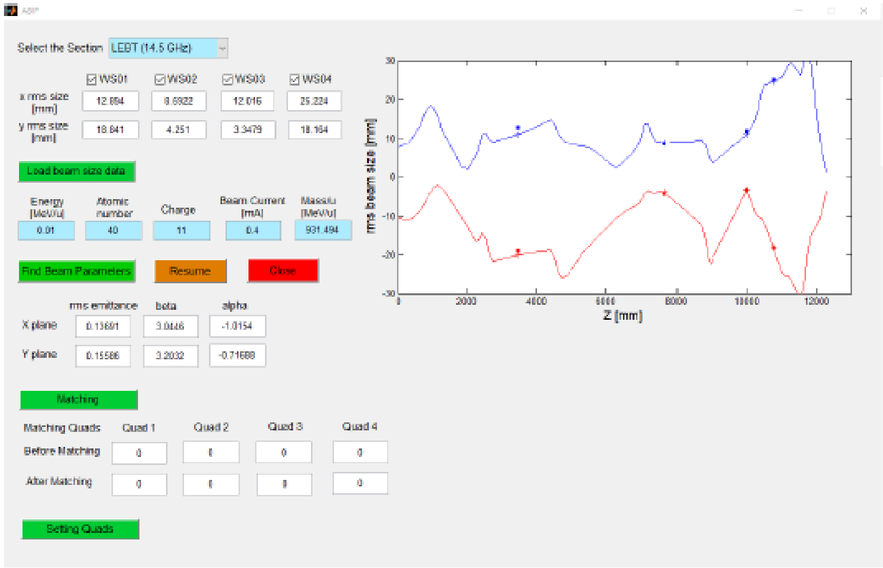
LEBT

- Beam matching to RFQ
- Transverse orbit correction

y-y′ with Allison scanner



Physics application tools developed



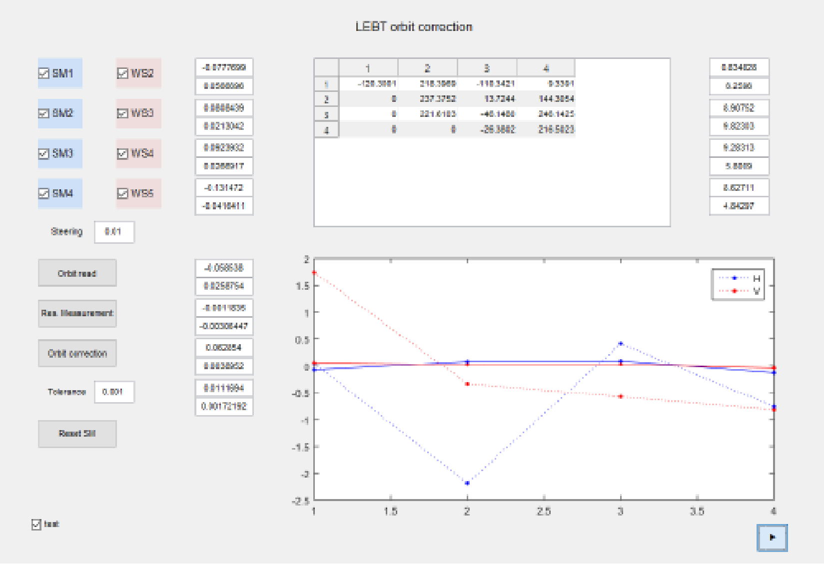
Select the Section: LEBT (14.5 GHz)

	☑ WS01	☑ WS02	☑ WS03	☑ WS04
x rms size [mm]	12.894	8.6922	12.016	25.224
y rms size [mm]	18.841	4.251	3.3479	18.164

Energy [MeV/u]	Atomic number	Charge	Beam Current [mA]	Mass/u [MeV/u]
0.01	40	11	0.4	931.494

	rms emittance	beta	alpha
X plane	0.13691	3.0446	-1.0154
Y plane	0.15586	3.2032	-0.71688

Matching Quads	Quad 1	Quad 2	Quad 3	Quad 4
Before Matching	0	0	0	0
After Matching	0	0	0	0



LEBT orbit correction

	1	2	3	4
1	-128.3981	218.3969	-118.3421	9.3391
2	0	237.3752	13.7244	144.3854
3	0	221.6183	-40.1488	246.1425
4	0	0	-26.3882	216.5823

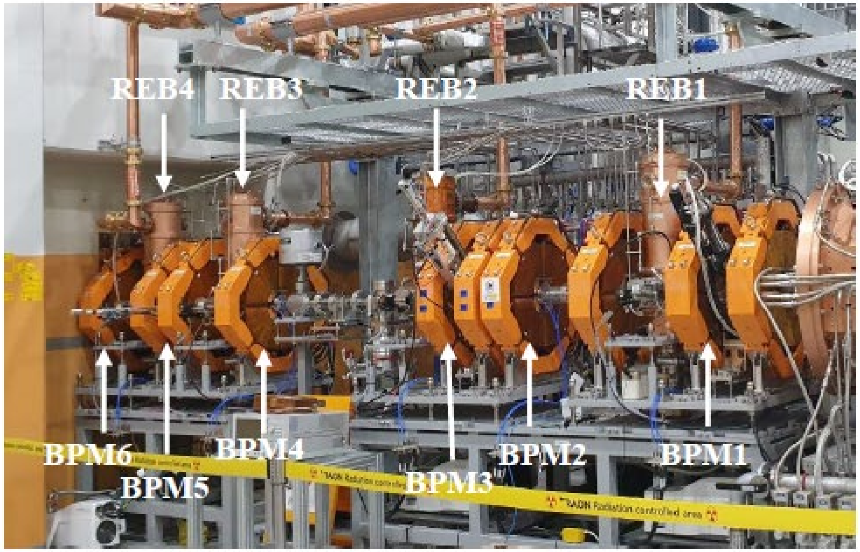
Steering 0.01

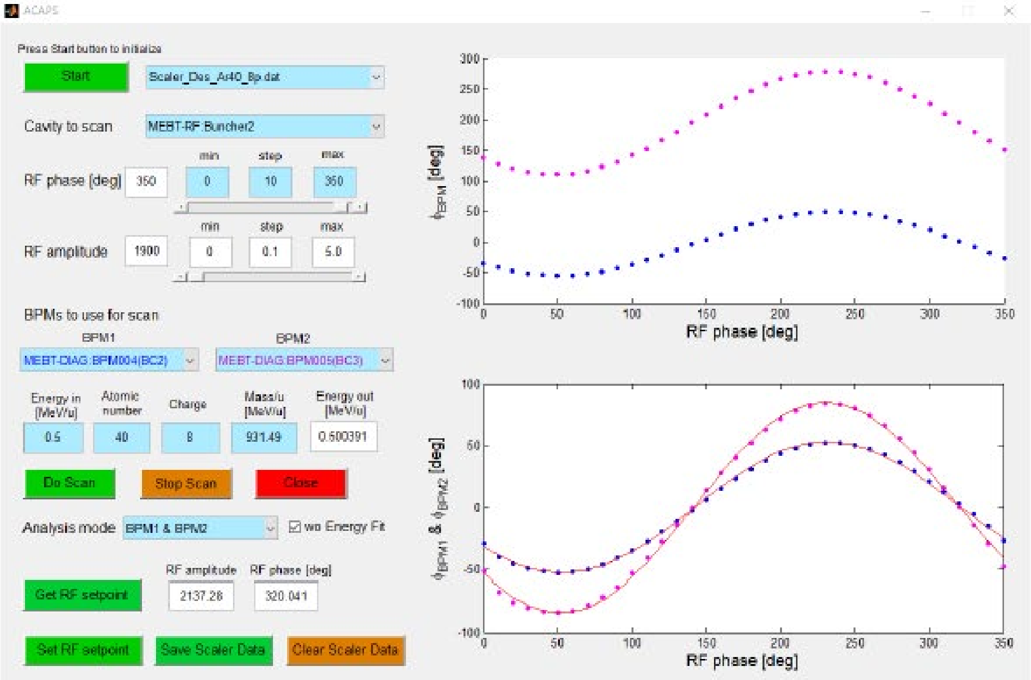
Tolerance 0.001

Beam Test on MEBT

Phase scan using BPM

- **Set phase and amplitude of four re-bunchers** in MEBT
- Phase scan with BPMs (Time of Flight measurement)




ACAPS

Press Start button to initialize

Scaler_Das_Ar40_8p.dat

Cavity to scan: MEBT-RF:Buncher2

RF phase [deg]: 350 min 0 step 10 max 360

RF amplitude: 1900 min 0 step 0.1 max 5.0

BPMs to use for scan

BPM1: MEBT-DIAG:BPM004(BC2)

BPM2: MEBT-DIAG:BPM005(BC3)

Energy in [MeV/u]	Atomic number	Charge	Mass/u [MeV/u]	Energy out [MeV/u]
0.5	40	8	931.49	0.500391

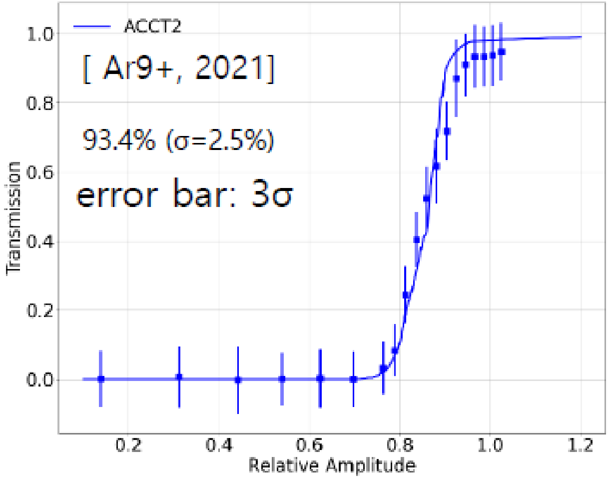
Analysis mode: BPM1 & BPM2 ☑ wo Energy Fit

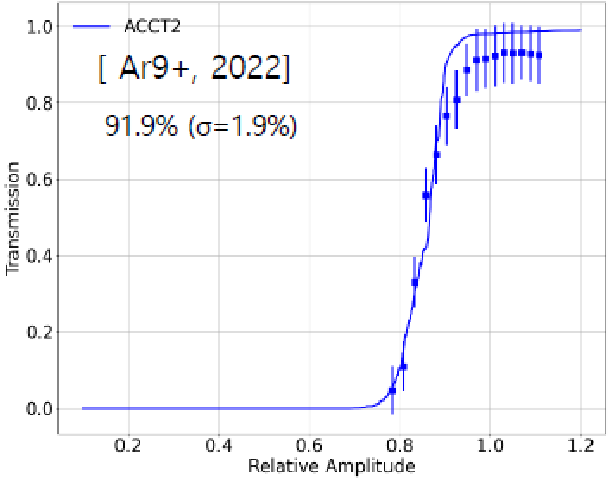
RF amplitude: 2137.28 RF phase [deg]: 320.041

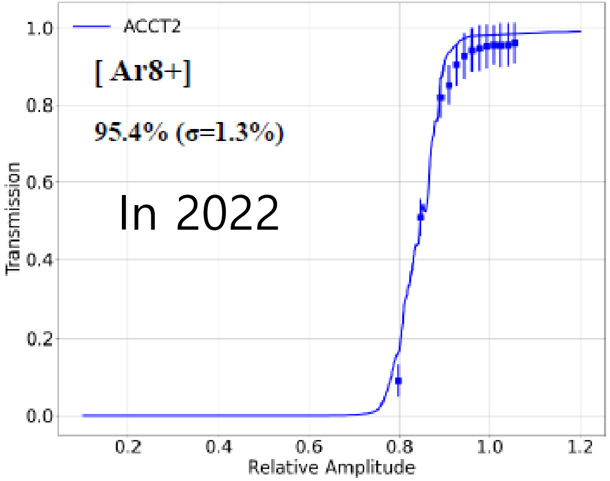
Beam Test on RFQ

Transmission measurement: ACCT's in LEBT and MEBT

I : Ar^{9+} ~30μA, Ar^{8+} ~47μA







Energy measurement: TOF, 1st and 2nd BPMs in MEBT

E: ~ 507 keV/u

SCL3 Installation

SCL3 Installation in 2021

- Cryomodule(CM) & Warm section is assembled in the clean booth in SCL3 tunnel
- Total particle counts (size=0.5μm above/10 mins) < 30 counts

Cryogenic System(I)

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

Cryogenic System(II)

- 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)

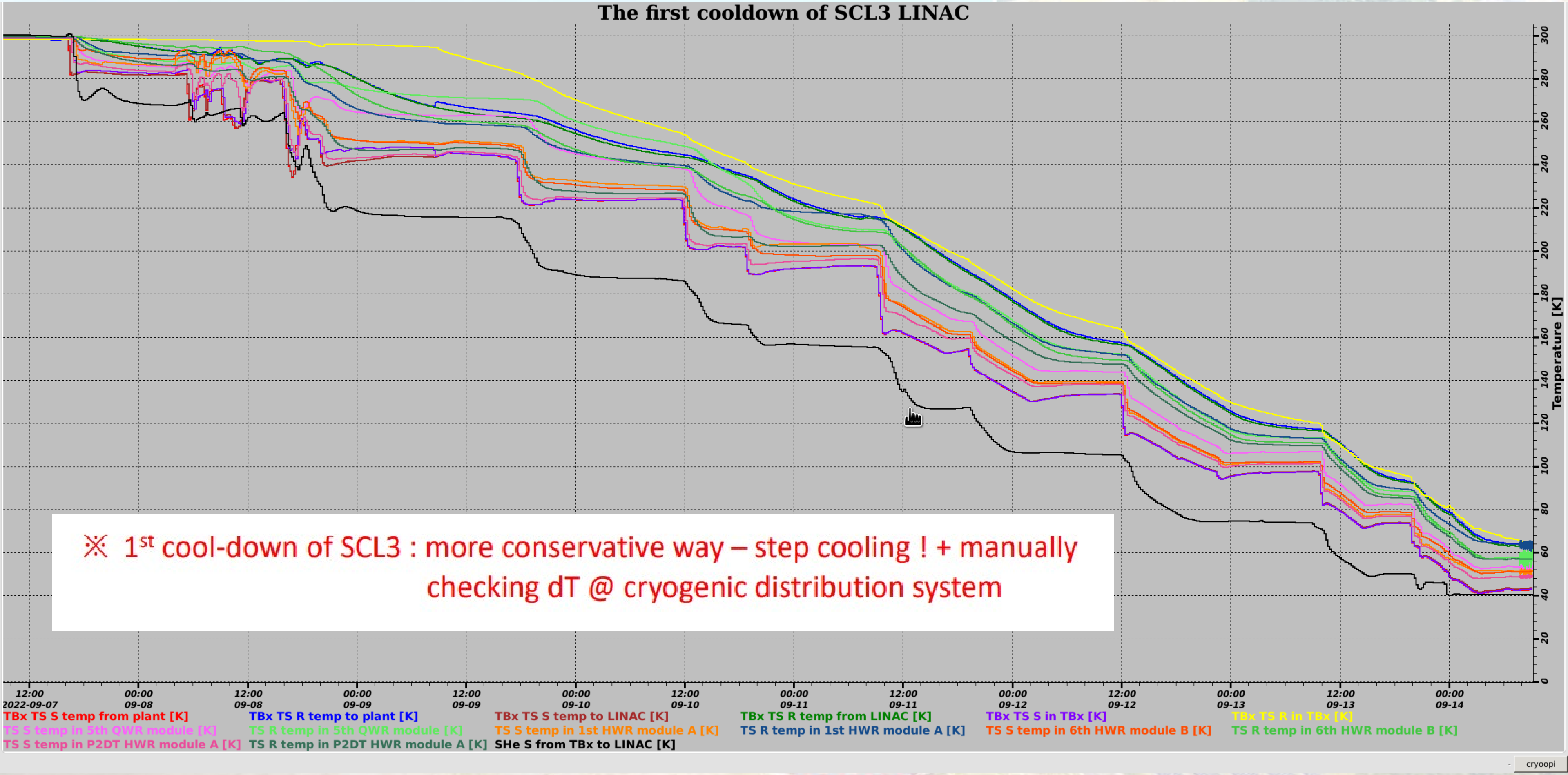
Compressors and Oil Removal System (WCS)

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

Commissioned in Aug 2022

The First Cool-Down of SCL3

Cooling down cryogenic distribution system, thermal shields of all cryomodules with SCL3 cryoplant, simultaneously.



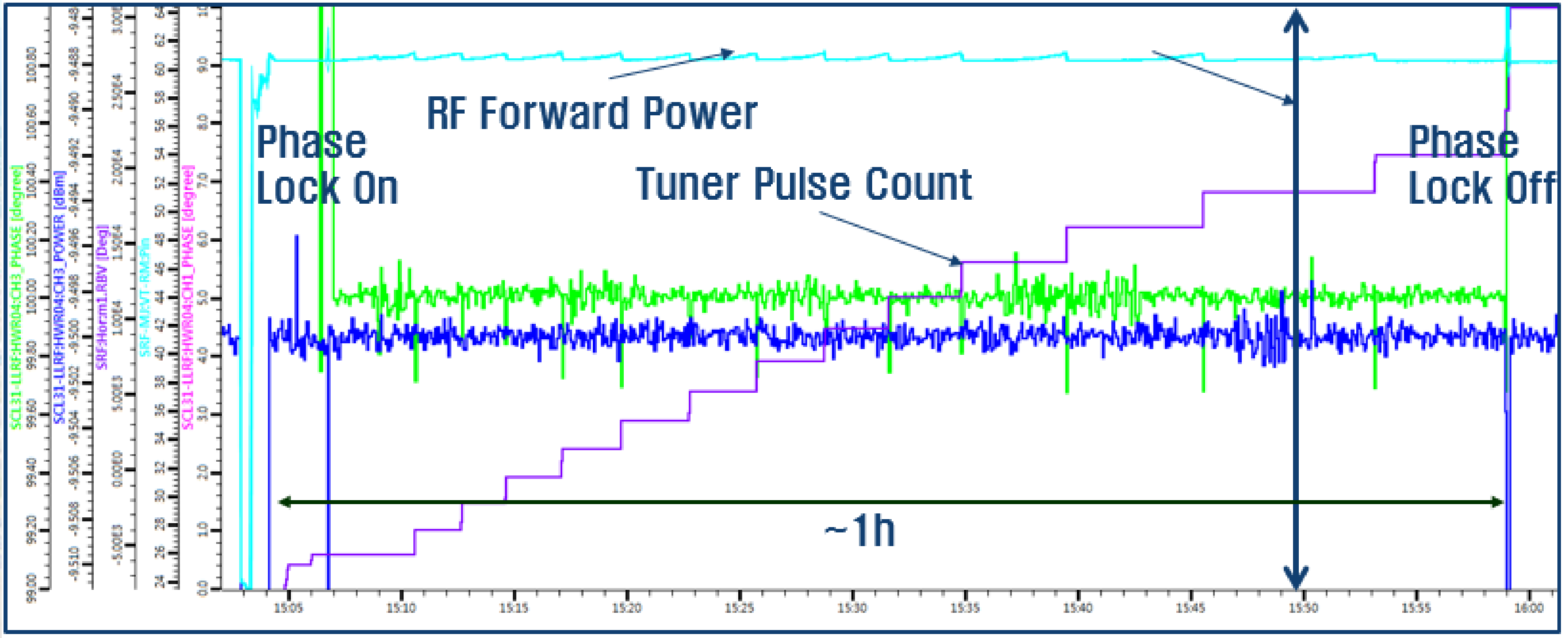
※ 1st cool-down of SCL3 : more conservative way – step cooling ! + manually checking dT @ cryogenic distribution system

The first cool-down : started on the 7th of Sep. 15:30

RF Control Test of SCL3

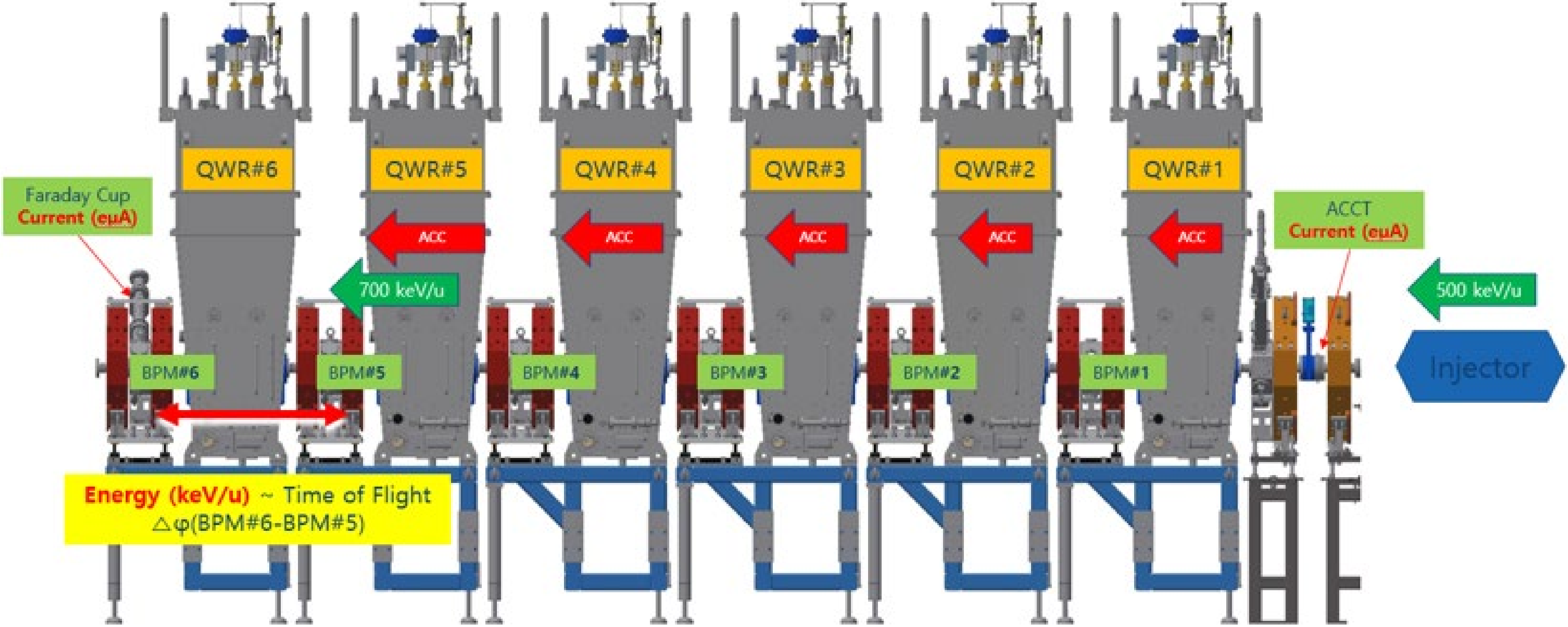
RF Control Test(Amplitude/Phase feedback with Tuner control)

RF Amplitude, Phase Control



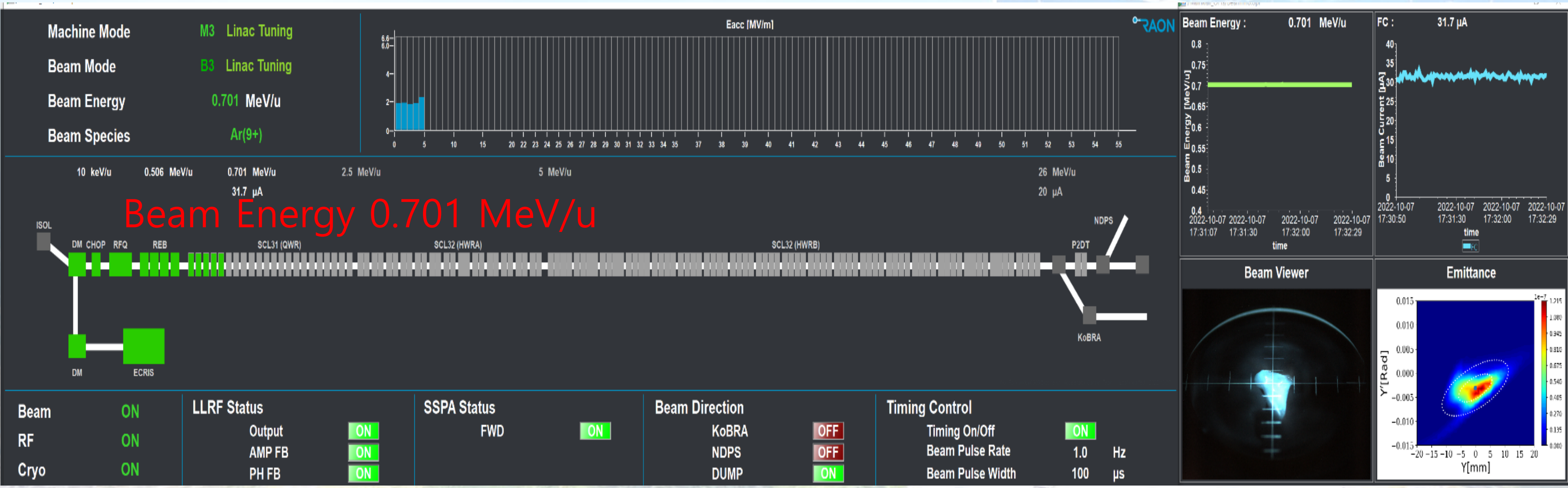
- Target RF amplitude error < 1%, phase error < 1deg
- Tuner operation threshold : +/- 5deg
- Control bandwidth: 90~160 Hz

SCL3 Beam Commissioning Exp



SCL3 Beam Commissioning-1st Phase

SCL3 Beam Commissioning Exp-1st Phase: Result



Machine Mode M3 Linac Tuning

Beam Mode B3 Linac Tuning

Beam Energy 0.701 MeV/u

Beam Species Ar(9+)

Beam Energy 0.701 MeV/u

Beam ON

RF ON

Cryo ON

LLRF Status

Output ON

AMP FB ON

PH FB ON

SSPA Status

FWD ON

Beam Direction

KoBRA OFF

NDPS OFF

DUMP ON

Timing Control

Timing On/Off ON

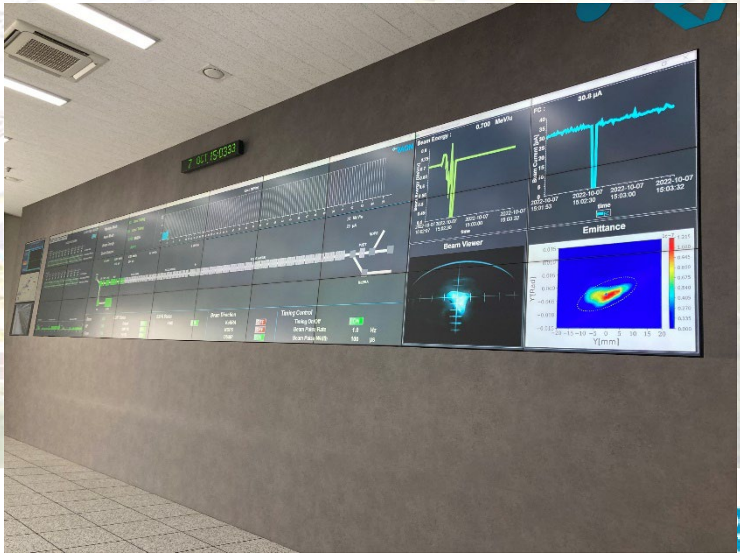
Beam Pulse Rate 1.0 Hz

Beam Pulse Width 100 μs

Beam Energy : 0.701 MeV/u

FC : 31.7 μA

Ar^{9+} beams accelerated through QWR #1~#5 on the 7th of October 15:03

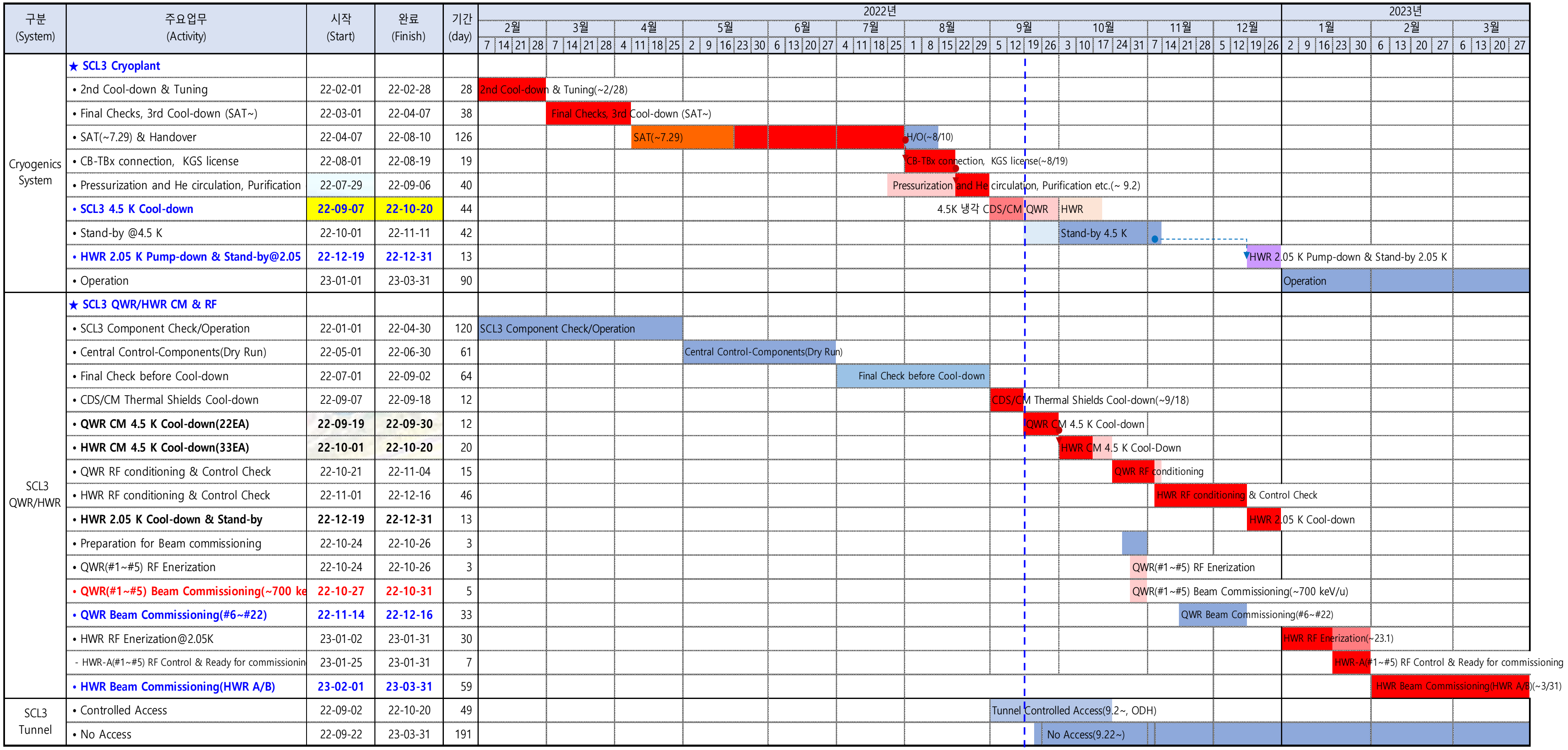


SCL3 Beam Commissioning Plan

SCL3 Beam Commissioning Master Schedule

● 작성일 : 2022. 09.13

● 작성자 : 중이온가속기연구소



구분 (System)	주요업무 (Activity)	시작 (Start)	완료 (Finish)	기간 (day)
Cryogenics System	**★ SCL3 Cryoplant**			
	• 2nd Cool-down & Tuning	22-02-01	22-02-28	28
	• Final Checks, 3rd Cool-down (SAT~)	22-03-01	22-04-07	38
	• SAT(~7.29) & Handover	22-04-07	22-08-10	126
	• CB-TBx connection, KGS license	22-08-01	22-08-19	19
	• Pressurization and He circulation, Purification	22-07-29	22-09-06	40
	• SCL3 4.5 K Cool-down	**22-09-07**	**22-10-20**	44
	• Stand-by @4.5 K	22-10-01	22-11-11	42
	• HWR 2.05 K Pump-down & Stand-by@2.05	**22-12-19**	**22-12-31**	13
	• Operation	23-01-01	23-03-31	90
SCL3 QWR/HWR	**★ SCL3 QWR/HWR CM & RF**			
	• SCL3 Component Check/Operation	22-01-01	22-04-30	120
	• Central Control-Components(Dry Run)	22-05-01	22-06-30	61
	• Final Check before Cool-down	22-07-01	22-09-02	64
	• CDS/CM Thermal Shields Cool-down	22-09-07	22-09-18	12
	• QWR CM 4.5 K Cool-down(22EA)	**22-09-19**	**22-09-30**	12
	• HWR CM 4.5 K Cool-down(33EA)	**22-10-01**	**22-10-20**	20
	• QWR RF conditioning & Control Check	22-10-21	22-11-04	15
	• HWR RF conditioning & Control Check	22-11-01	22-12-16	46
	• HWR 2.05 K Cool-down & Stand-by	**22-12-19**	**22-12-31**	13
	• Preparation for Beam commissioning	22-10-24	22-10-26	3
	• QWR(#1~#5) RF Enerization	22-10-24	22-10-26	3
	• QWR(#1~#5) Beam Commissioning(~700 ke	**22-10-27**	**22-10-31**	5
	• QWR Beam Commissioning(#6~#22)	**22-11-14**	**22-12-16**	33
	• HWR RF Enerization@2.05K	23-01-02	23-01-31	30
	- HWR-A(#1~#5) RF Control & Ready for commissionin	23-01-25	23-01-31	7
	• HWR Beam Commissioning(HWR A/B)	**23-02-01**	**23-03-31**	59
SCL3 Tunnel	• Controlled Access	22-09-02	22-10-20	49
	• No Access	22-09-22	23-03-31	191

- All the activities until March 2023
- From March 2023, SCL3 Beam on KoBRA spectrometer

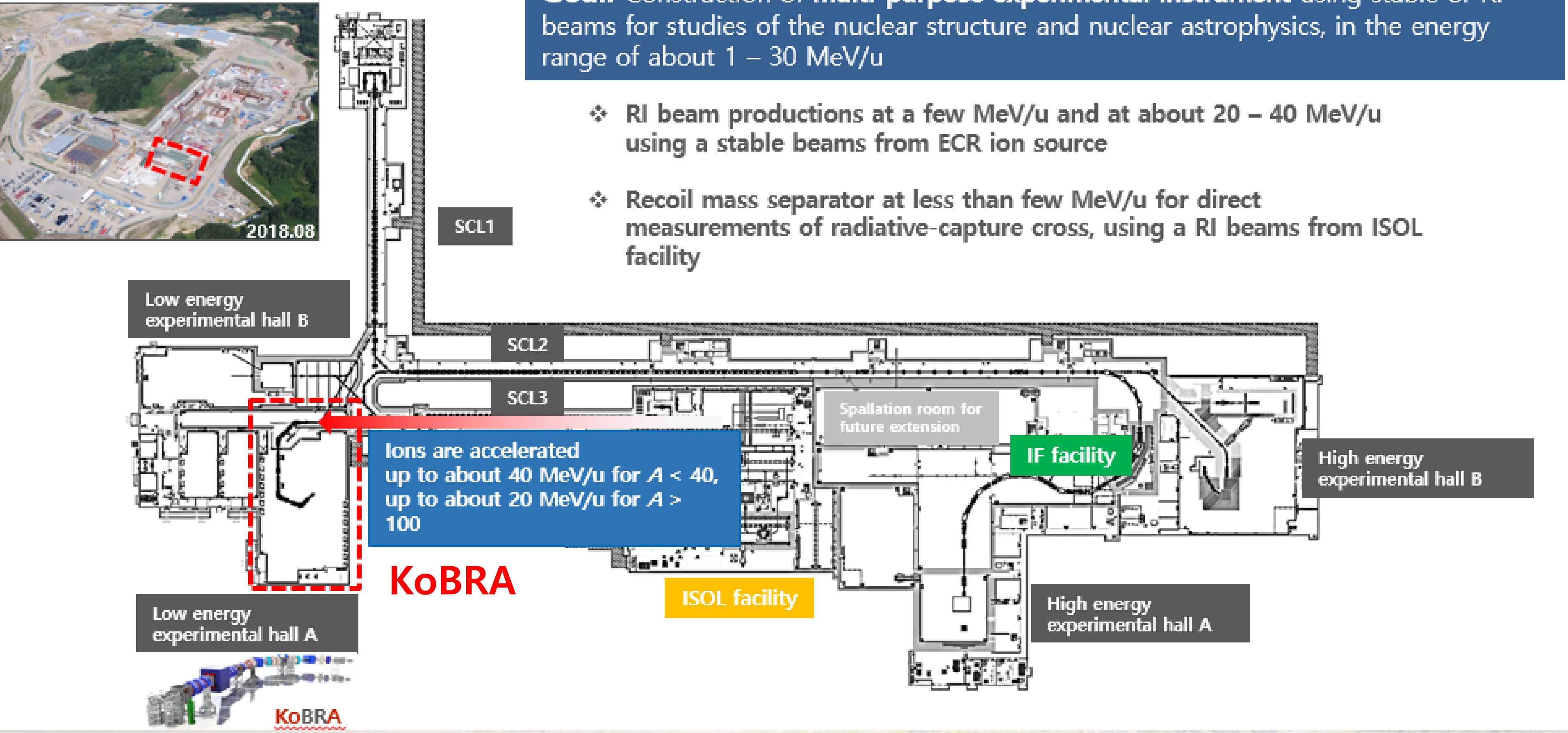
Finished SCL3 Cool down On Oct 26

KoBRA Spectrometer(I)

Korea **B**road acceptance **R**ecoil spectrometer and **A**pparatus

Goal: Construction of **multi-purpose experimental instrument** using stable or RI beams for studies of the nuclear structure and nuclear astrophysics, in the energy range of about 1 – 30 MeV/u

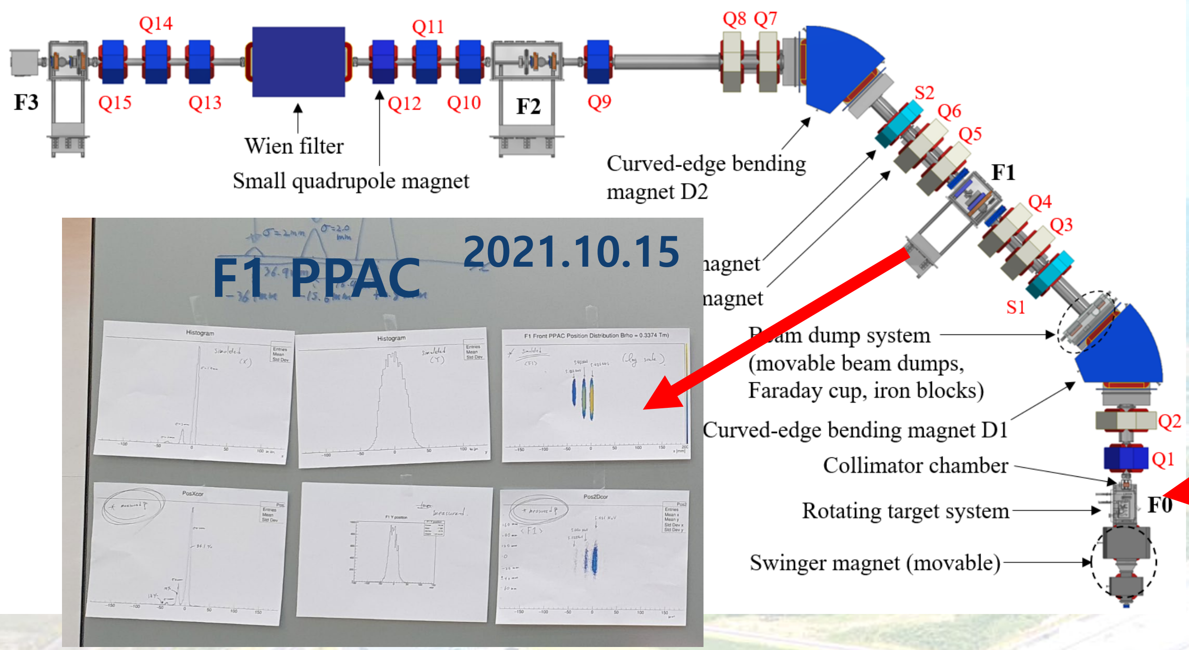
- RI beam productions at a few MeV/u and at about 20 – 40 MeV/u using a stable beams from ECR ion source
- Recoil mass separator at less than few MeV/u for direct measurements of radiative-capture cross, using a RI beams from ISOL facility



Ions are accelerated up to about 40 MeV/u for $A < 40$, up to about 20 MeV/u for $A > 100$

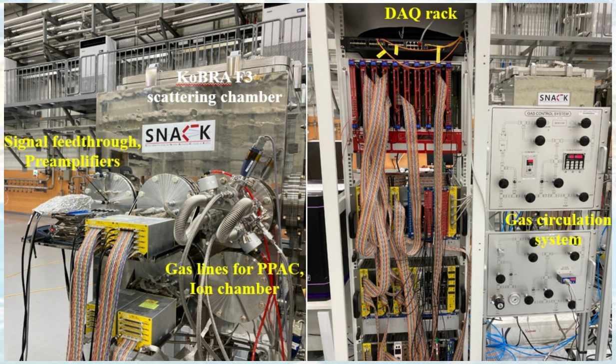
KoBRA Spectromter(II)

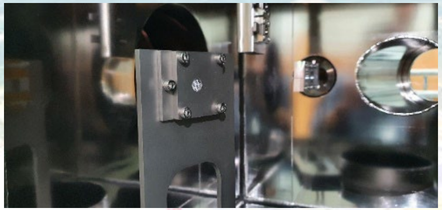
KoBRA machine commissioning completed on 2021.10



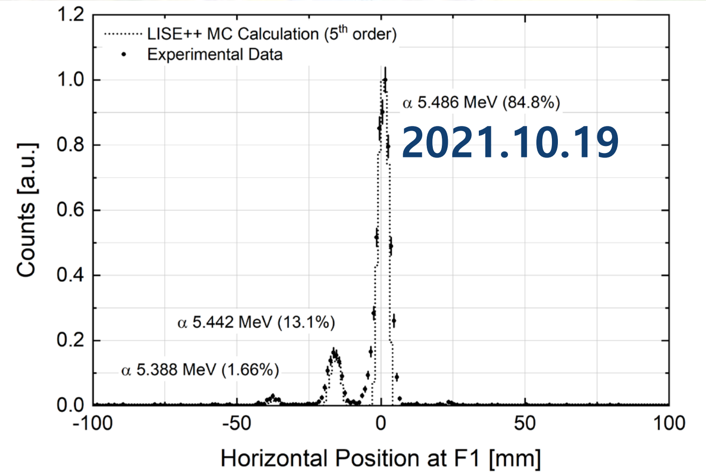
F1 PPAC

2021.10.15





Alpha source (^{241}Am)



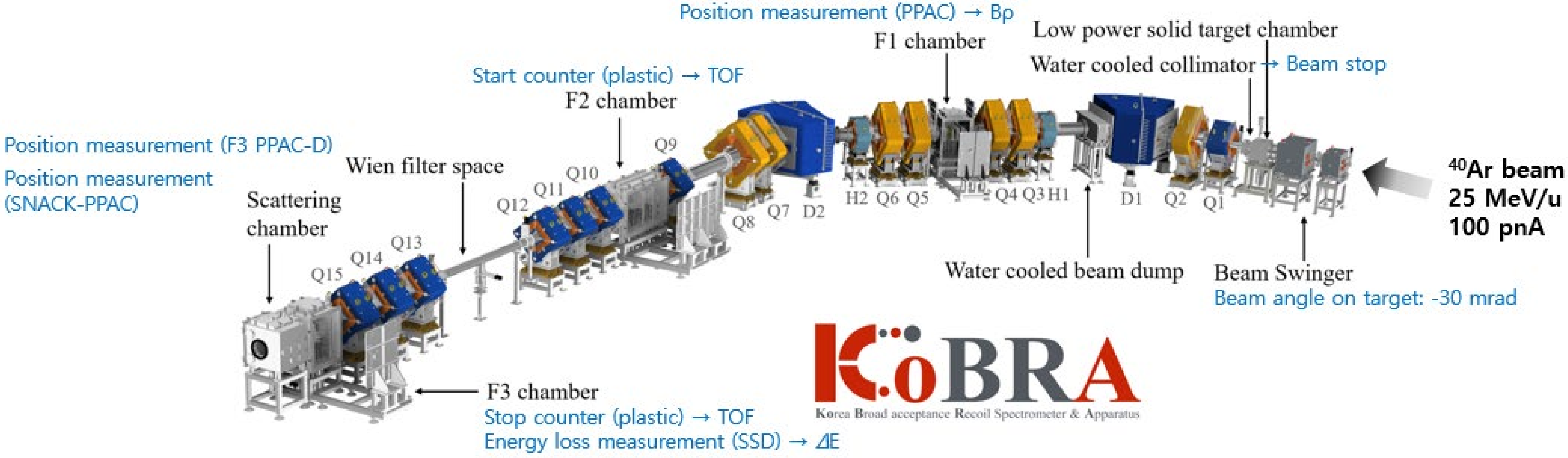
2021.10.19

2021.10.18

KoBRA Beam Experiment(I) : Plan

- Primary beam : 25 MeV/u ^{40}Ar with intensity of 100 pnA ($\sigma_{x,y}$=1 mm, $\sigma_{\theta,\varphi}$=2 mrad)
- Production target : 0.1 mm-thick graphite (or materials Be, … with thickness 0.1-0.2 mm)
- Swing angle on production target : -30 mrad (or adjustable 0-200 mrad)
- Completely Rejected: ^{40}Ar^{18+}, ^{40}Ar^{17+}, ^{40}Ar^{16+} (^{40}Ar^{15+} can be transport to F2)
- Detectors:

  F1 chamber : Large area PPAC (resolution of 0.4 mm in σ)
  F2 chamber : PPAC and Plastic scintillator (resolutions: 0.4 mm and 0.1 nsec in σ)
  F3 chamber : PPAC, Plastic scintillator, and SSD (resolutions: 0.4 mm, 0.1 nsec, and 0.75% in σ)

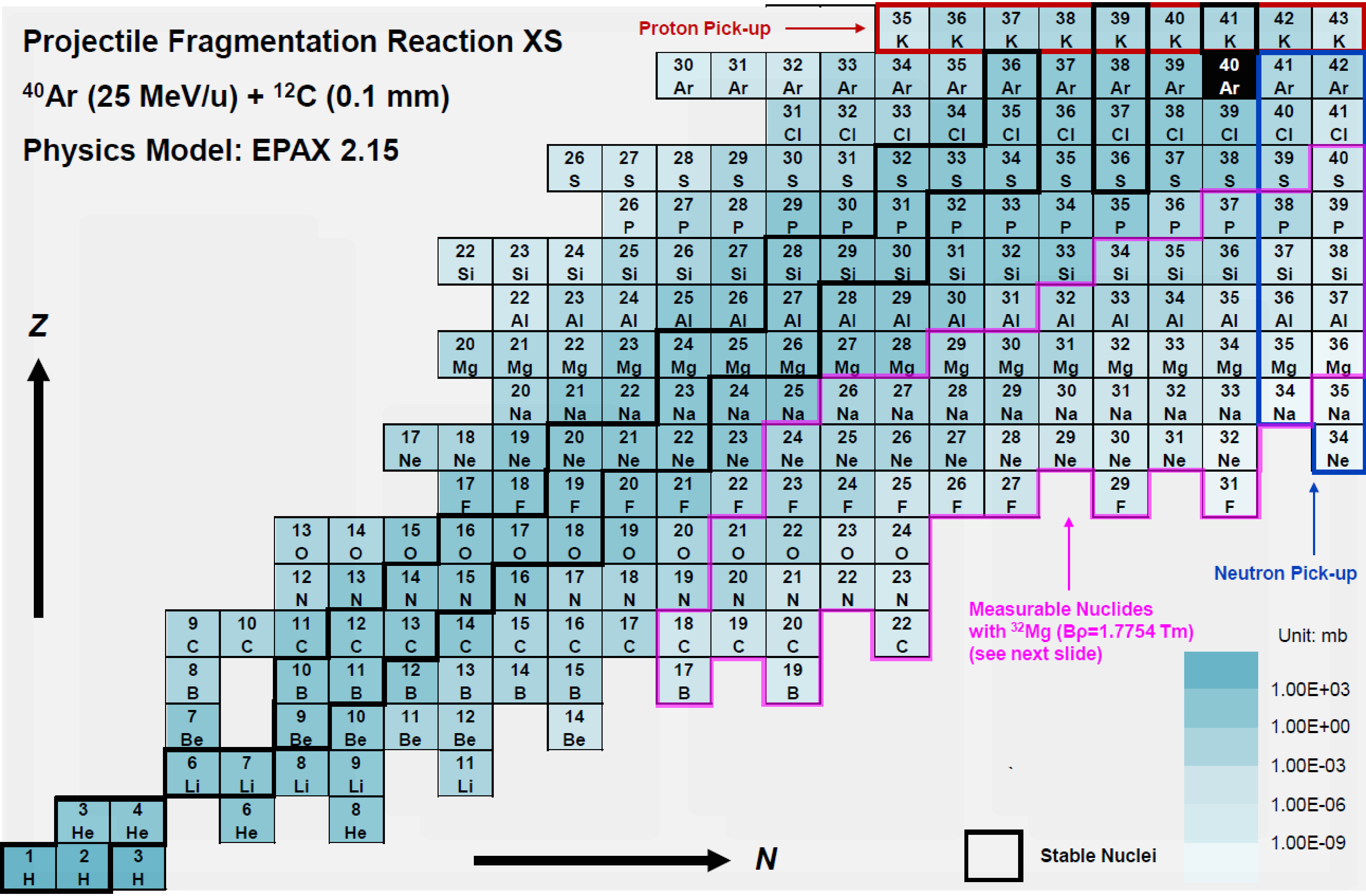


KoBRA Beam Experiment(II) : Plan

Projectile Fragmentation Reaction XS

^{40}Ar (25 MeV/u) + ^{12}C (0.1 mm)

Physics Model: EPAX 2.15



Measurable Nuclides with ^{32}Mg (Bρ=1.7754 Tm) (see next slide)

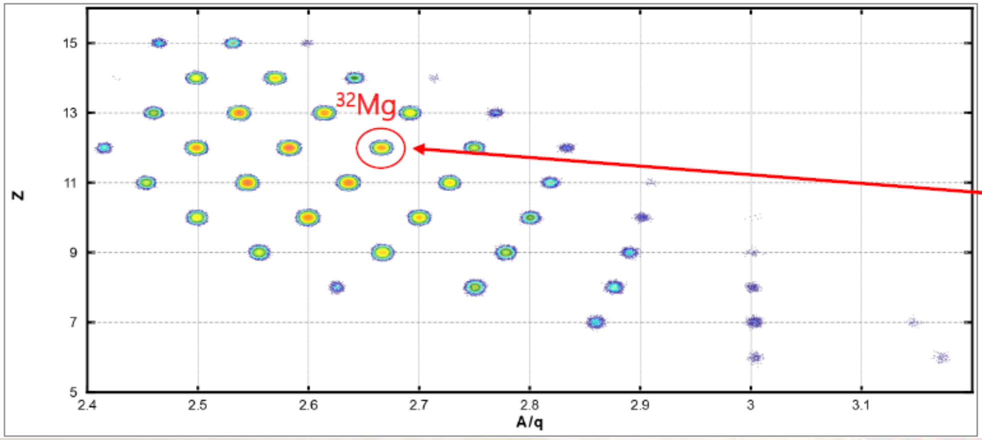
KoBRA Beam Experiment(III) : Plan

^{32}Mg Yield Calculation

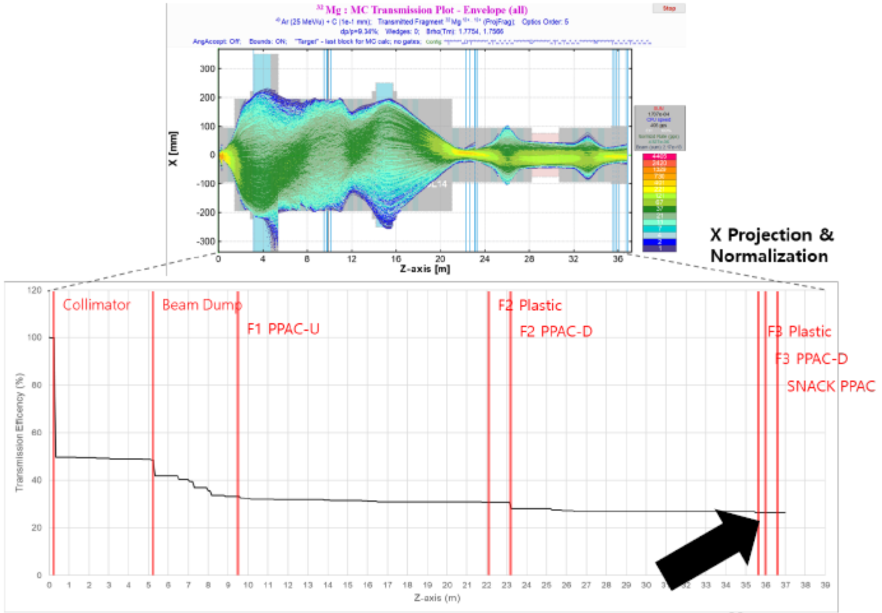
$$I = I_p \times \sigma_{Mg} \times \frac{\rho_A}{M} \times A_V \times \varepsilon_t \times \Omega_c$$

I_p = Intensity of primary beam ^{40}Ar = 100 pnA
σ_{Mg} = ^{32}Mg XS calculated with EPAX 2.15 = 6.96E-04 mbarns
ρ_A = Area density of C target = 0.02253 g/cm^2
M = Atomic mass of C target = 12.01 g/mol
A_v = Avogadro number = 6.022E+23 atoms/mol
ε_t = Transmission efficiency of ^{32}Mg to KoBRA F3
= 27.6% (1st order, MC cal.), 26.3% (5th order, MC cal.)
Ω_c = Correction factor for solid angle

Z vs A/q Distribution



^{32}Mg Transmission Efficiency (5th order MC)



Transmission Efficiency 26.3% at F3 target

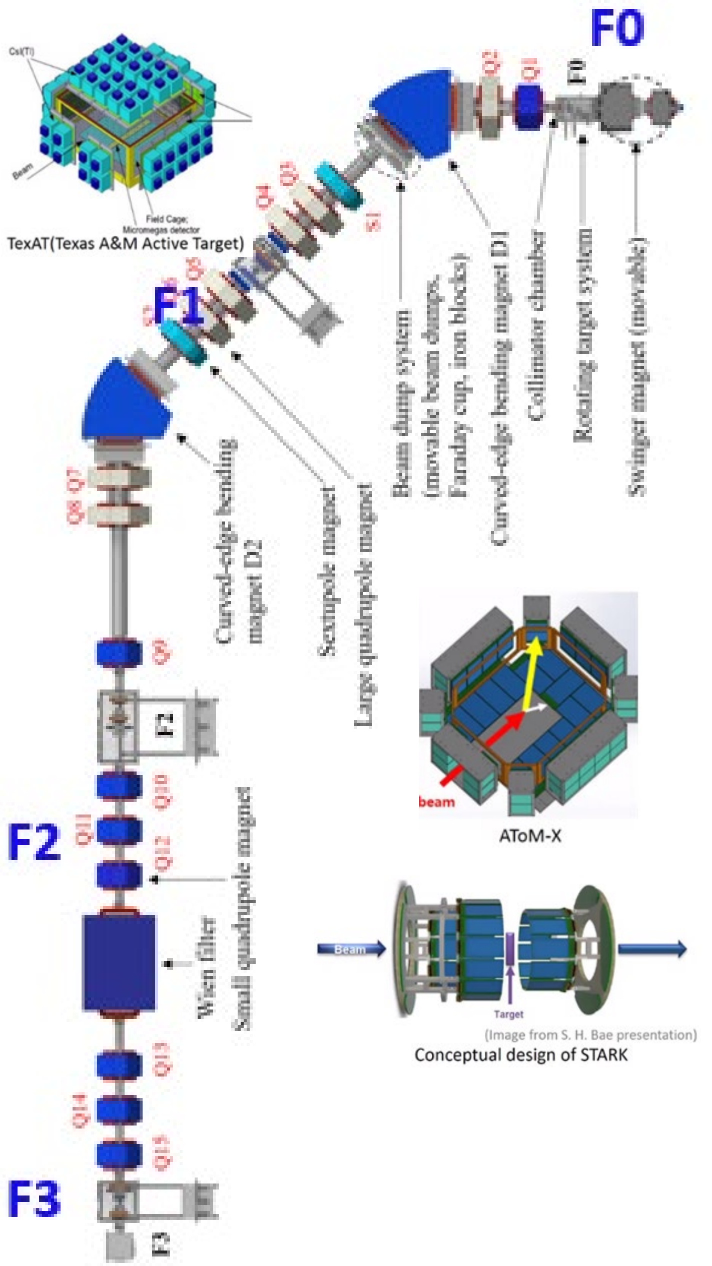
^{32}Mg (transported to F3)

Items	Yield	Solid angle correction
5th order, LISE++	130 pps	150 pps

※ pps: particles per second

Stable Beam experiments : '23~

- Study on neutron-deficient nuclei using proton-induced fusion-evaporation
- 3n fusion-evaporation reactions to study MEDs in Tz=-3/2 nuclei
- Fusion Reaction Studies related to Stellar Evolution
- The study of 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 section



TexAT(Texas A&M Active Target)

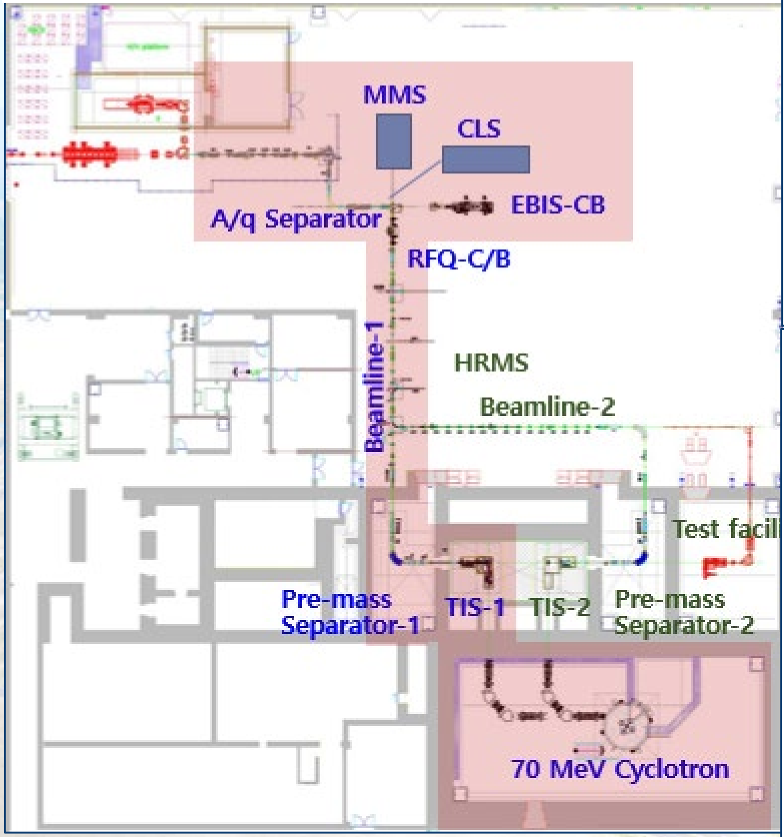
AToM-X

(Image from S. H. Bae presentation)

Conceptual design of STARK

ISOL System

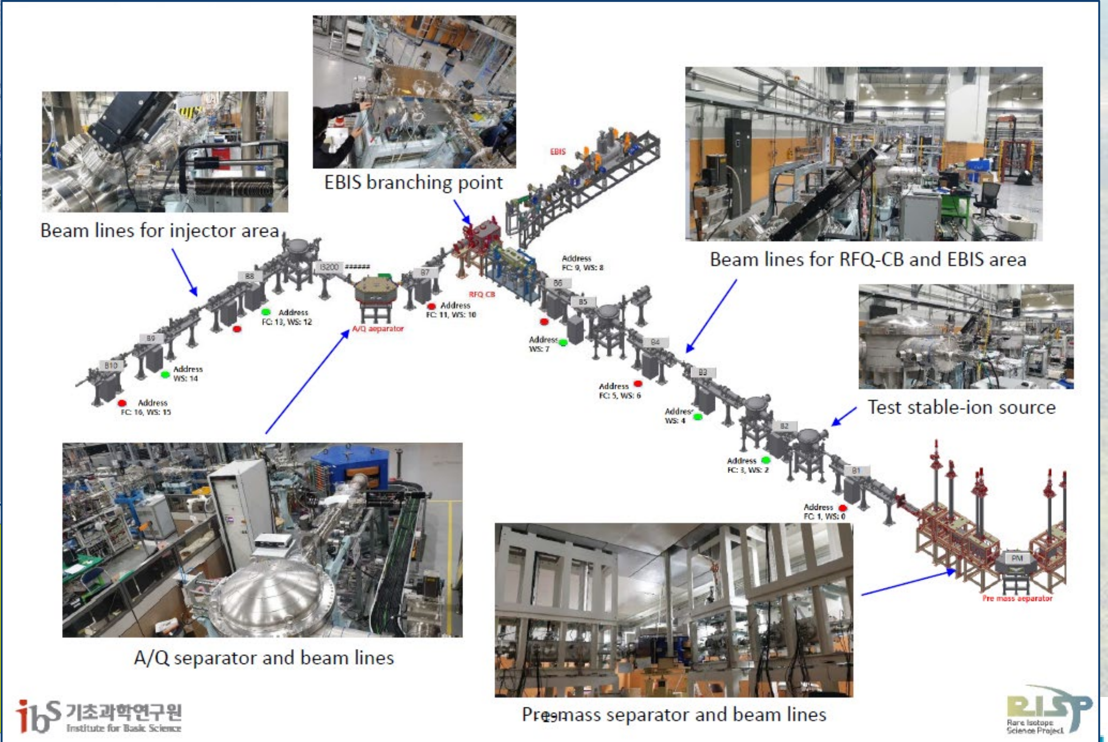
Target ion Source (20 keV, $^{132}Sn^{1+}$) → Pre-Separator ($m/\delta m = 400$) → RFQ Cooler (3πmm mrad, < 5ev) → EBIS (10 keV/u, $^{132}Sn^{33+}$) → Post linac (Charge state n+)



- 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 of Post accelerator 10 keV/u

- full remote maintenance system with TIS modularization



Beam lines for injector area

EBIS branching point

Beam lines for RFQ-CB and EBIS area

Test stable-ion source

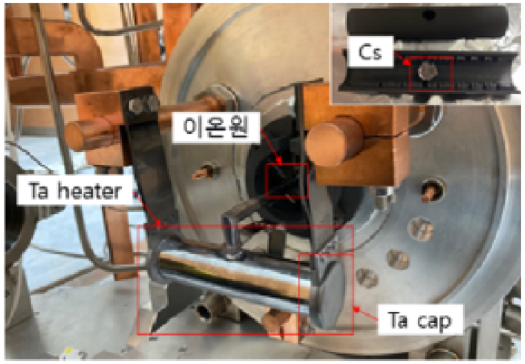
A/Q separator and beam lines

Pre-mass separator and beam lines

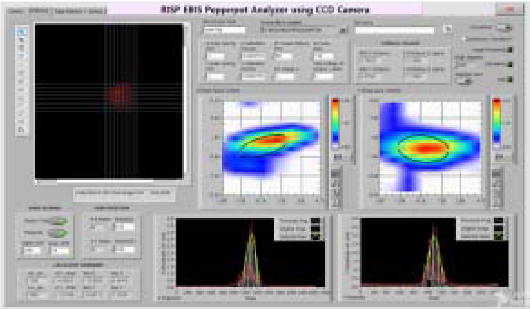
- ISOL beam lines including sub-systems are commissioned with Cs beam in 2021
- RI beam commissioning using SiC target (Dec 2022)

ISOL Beam Test in 2021 (I)

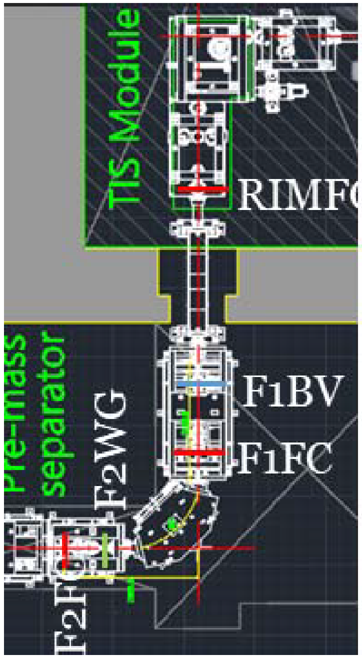
- Target IS (20 keV, $^{133}Cs^{1+}$)
- Pre-Separator (m/δm ~ 300)
- RFQ Cooler (> 1x10^{8} ions/bunch)
- EBIS (>15% Cs^{27+} A/q<6)
- A/q Separator (m/δm ~ 250)
- Post linac (10 keV/u, $^{133}Cs^{27+}$)

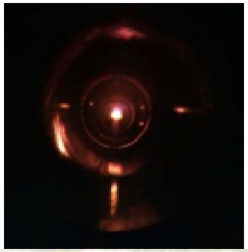


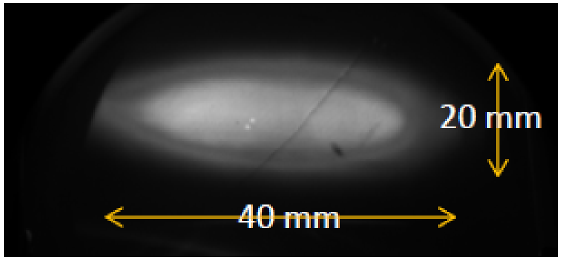
Cs sample preparation in TIS chamber



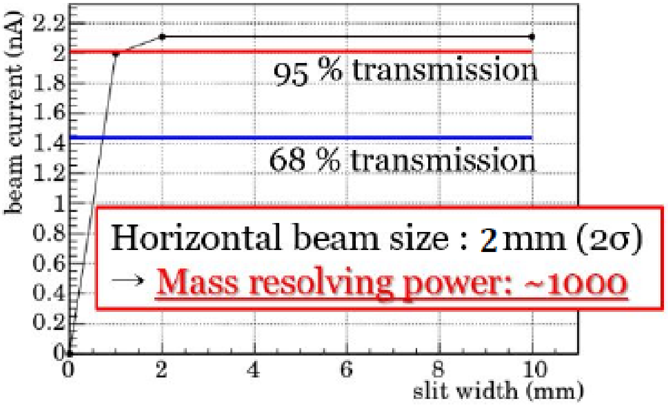
Beam emittance of TIS extracted Cs beam
X(2σ) : 15 pi mm mrad
Y(2σ) : 17 pi mm mrad







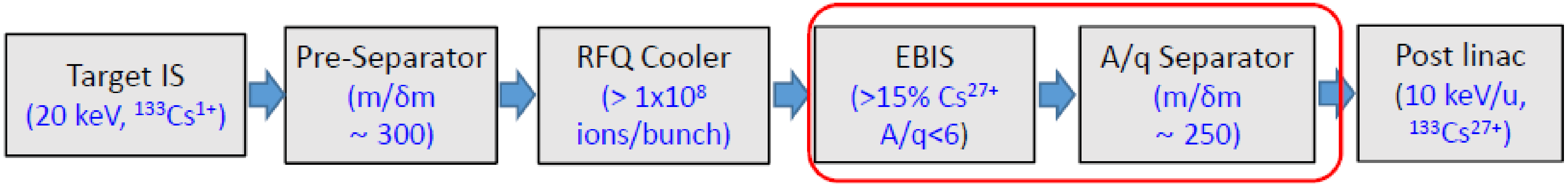
F1 beam viewer



Horizontal beam size : 2mm (2σ)
→ Mass resolving power: ~1000

Beam size measurement by using F2 slit

ISOL Beam Test in 2021 (II)



Target IS (20 keV, $^{133}Cs^{1+}$)

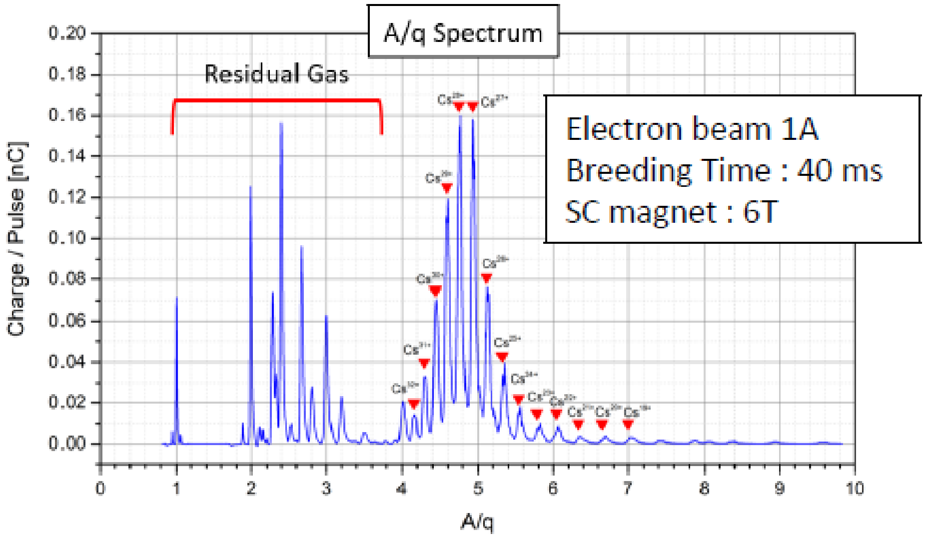
Pre-Separator ($m/\delta m$ ~ 300)

RFQ Cooler (> $1x10^8$ ions/bunch)

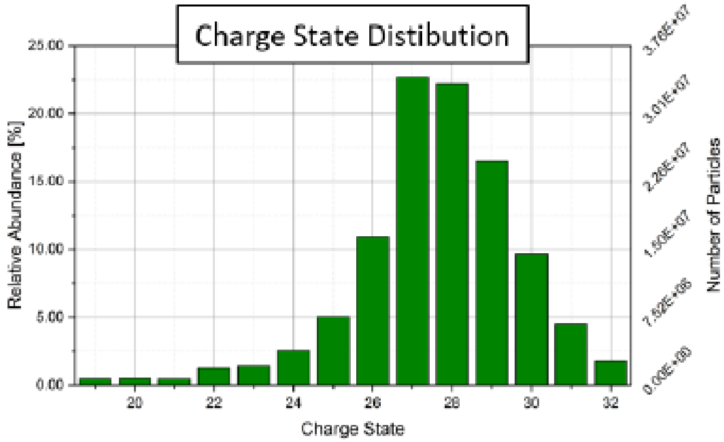
EBIS (>15% Cs^{27+} A/q<6)

A/q Separator ($m/\delta m$ ~ 250)

Post linac (10 keV/u, $^{133}Cs^{27+}$)

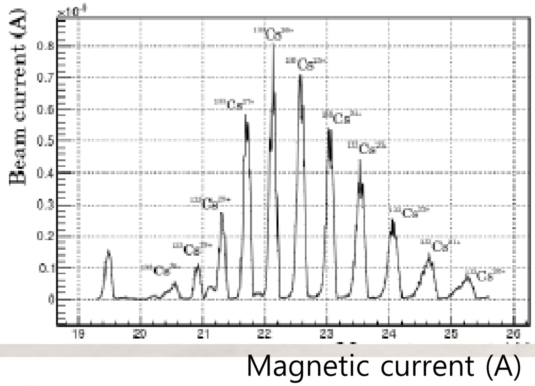


Electron beam 1A
Breeding Time : 40 ms
SC magnet : 6T



Cs Total Number	Cs^{27+} Number (A/q=4.92)
1.50E+8	3.41E+7 (22.67%)

A/q spectrum and the present resolving power(preliminary)



Momentum dispersion of the A/q magnet: 1.244 m

Beam size in 2σ ~ ±5 mm (from the slit width dependence of beam current)

→ Resolving power ~ 250 (2σ)

Our tuning is not finalized.
We may be able to obtain much higher resolving power (~400 in (2σ)) with careful tuning.

Cyclotron

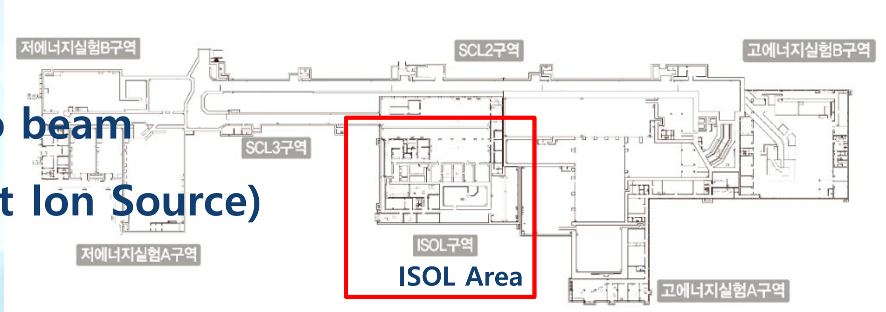
- **Specs**

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

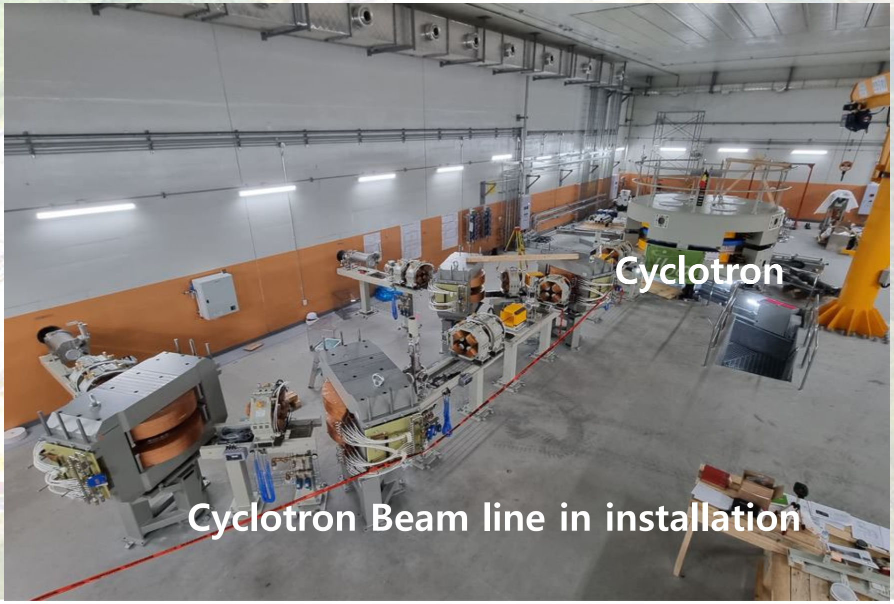
- **Schedule**

  : Contract('19.6), pre-survey('19.11) , Design finalized('20.4) ,

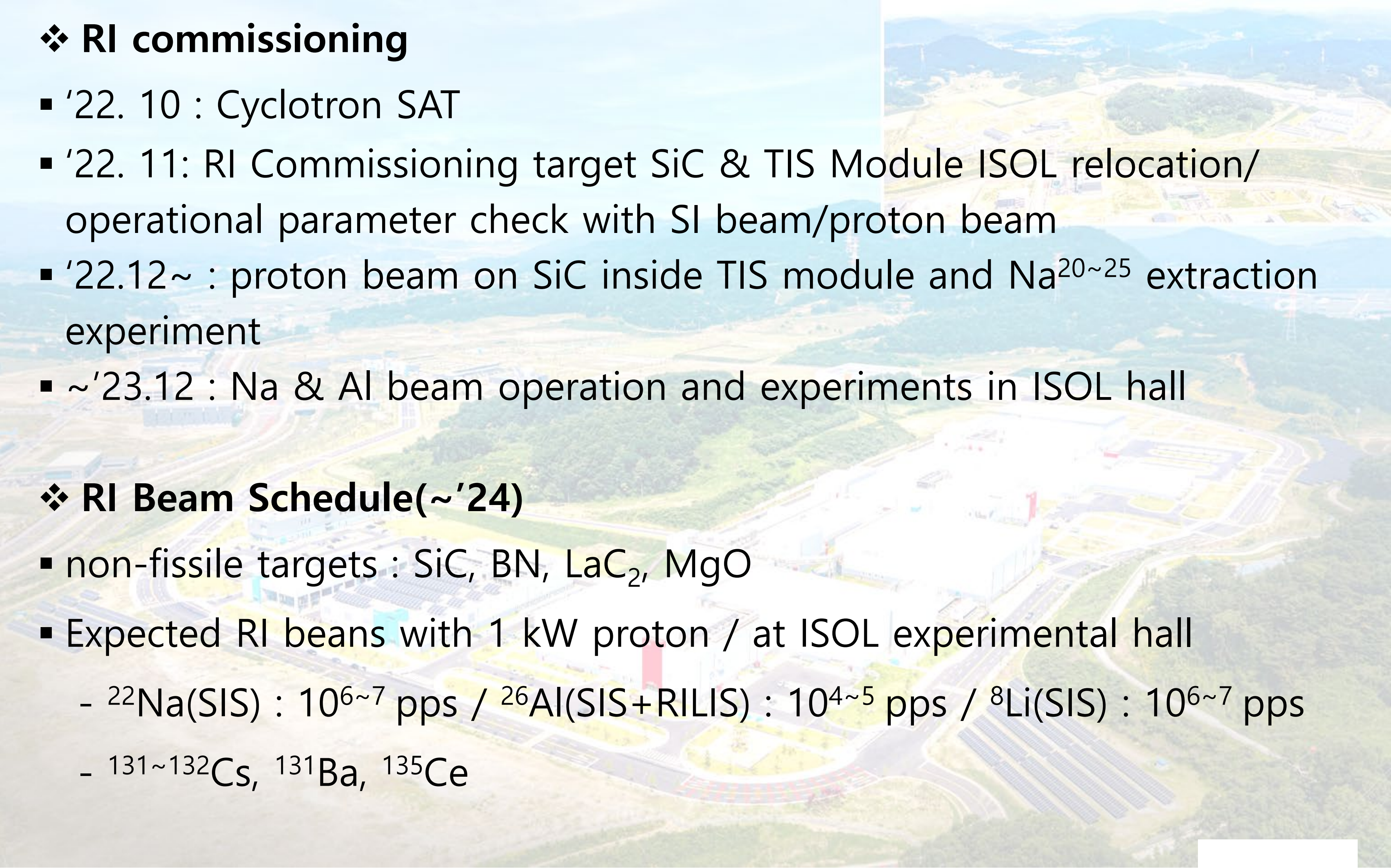
  FAT ('21.6) , Shipping('21.8), Installation('21.11.11~22.4.28)



SAT on Oct 2022



ISOL RI Beam Plan



❖ RI commissioning

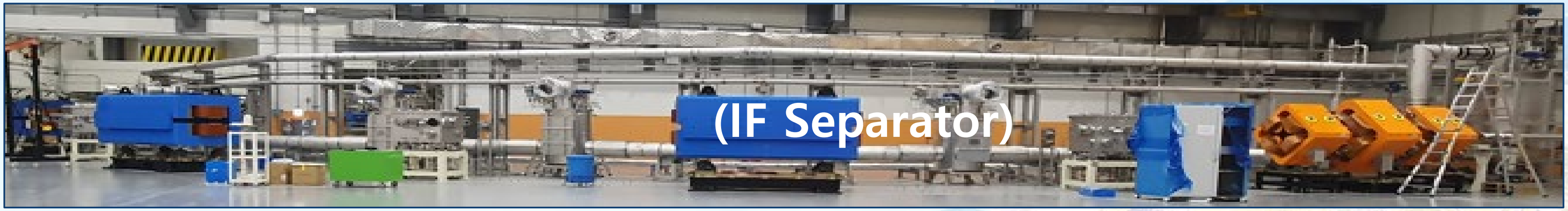
- '22. 10 : Cyclotron SAT
- '22. 11: RI Commissioning target SiC & TIS Module ISOL relocation/ operational parameter check with SI beam/proton beam
- '22.12~ : proton beam on SiC inside TIS module and Na$^{20\sim25}$ extraction experiment
- ~'23.12 : Na & Al beam operation and experiments in ISOL hall

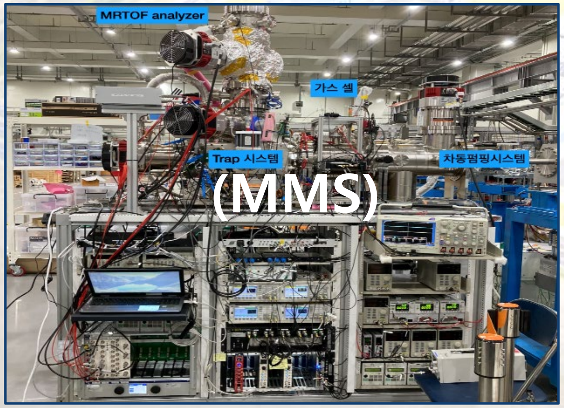
❖ RI Beam Schedule(~'24)

- non-fissile targets : SiC, BN, LaC$_2$, MgO
- Expected RI beans with 1 kW proton / at ISOL experimental hall
  - ^{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

Exp. Systems

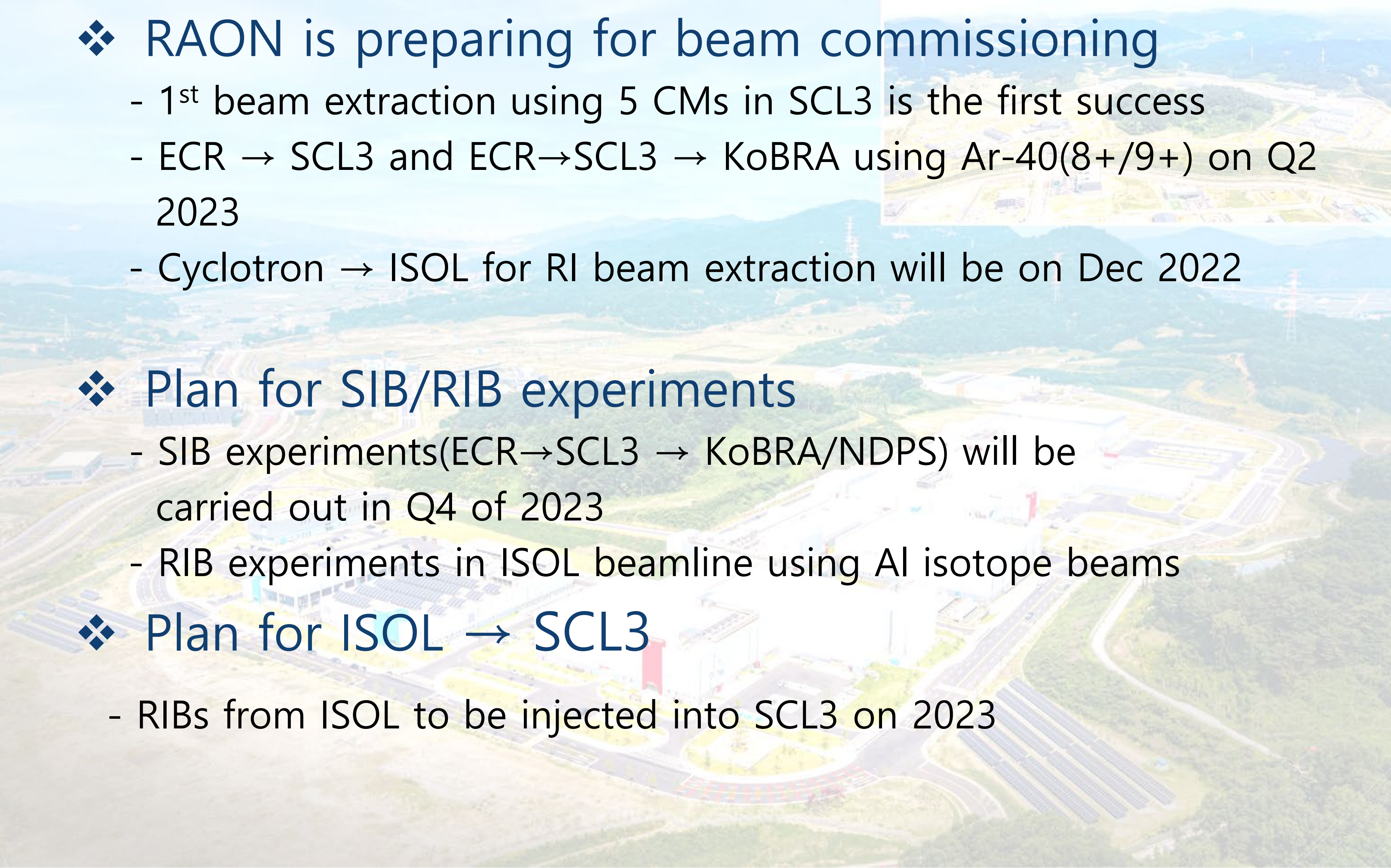
TRIUMF RIKEN





All Exp. Systems are to be installed and machine commissioned by 2022

Summary



❖ RAON is preparing for beam commissioning

- 1st beam extraction using 5 CMs in SCL3 is the first success
- ECR → SCL3 and ECR→SCL3 → KoBRA using Ar-40(8+/9+) on Q2 2023
- Cyclotron → ISOL for RI beam extraction will be on Dec 2022

❖ Plan for SIB/RIB experiments

- SIB experiments(ECR→SCL3 → KoBRA/NDPS) will be carried out in Q4 of 2023
- RIB experiments in ISOL beamline using Al isotope beams

❖ Plan for ISOL → SCL3

- RIBs from ISOL to be injected into SCL3 on 2023