RAON Rare isotope Accelerator complex for ON-line experiments

RAON USERS ASSOCIATION RARE ISOTOPE ACCELERATOR

RAON Beam Plan for Early Phase Experiment

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Institute for Basic Science

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Focused Workshop on Rare Isotope Physics At Yeosu

ibs 기초과학연구원 Institute for Basic Science

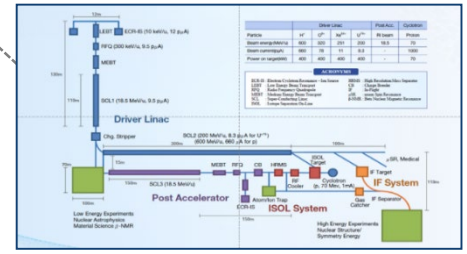
RISP 중이온가속기건설구축사업단 Rare Isotope Science Project

Rare Isotope Science Project(RISP)

- **Goal:** To build **a heavy ion accelerator complex RAON,** for **rare isotope science** research in Korea.
  * **RAON (라온)- 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: Just constructing 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.

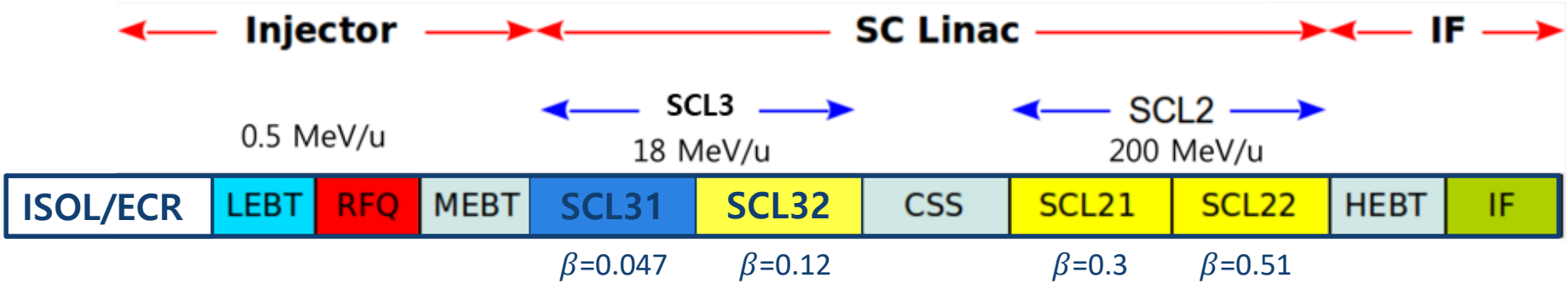
- **Providing high intensity RI beams by ISOL and IF**
  - ISOL: direct fission of ^{238}U by 70 MeV proton
  - IF: 200 MeV/u ^{238}U (intensity: 8.3 pμA)
- **Providing high quality neutron-rich beams**
  e.g., ^{132}Sn with up to 250 MeV/u, up to 10^9 particles per second
- **Providing More exotic RI beam production by combination of ISOL and IF(ISOLIF)**

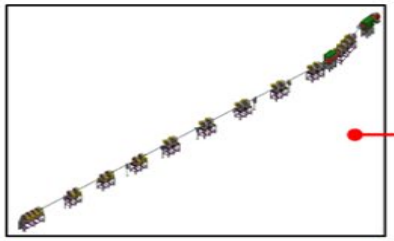
Bird's-eye-view of RAON

Science Goals of RAON

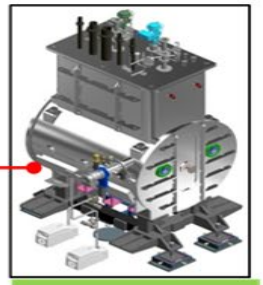
Accelerator System

RIKEN TRIUMF Fermilab IHEP IMP

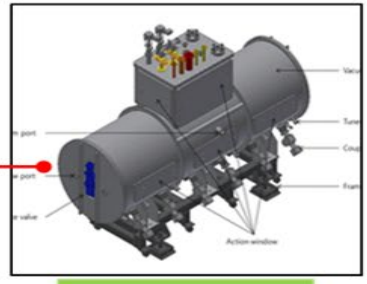




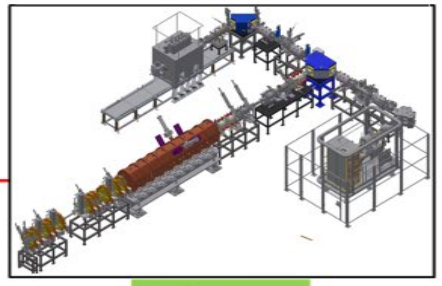
KoBRA Beam Line



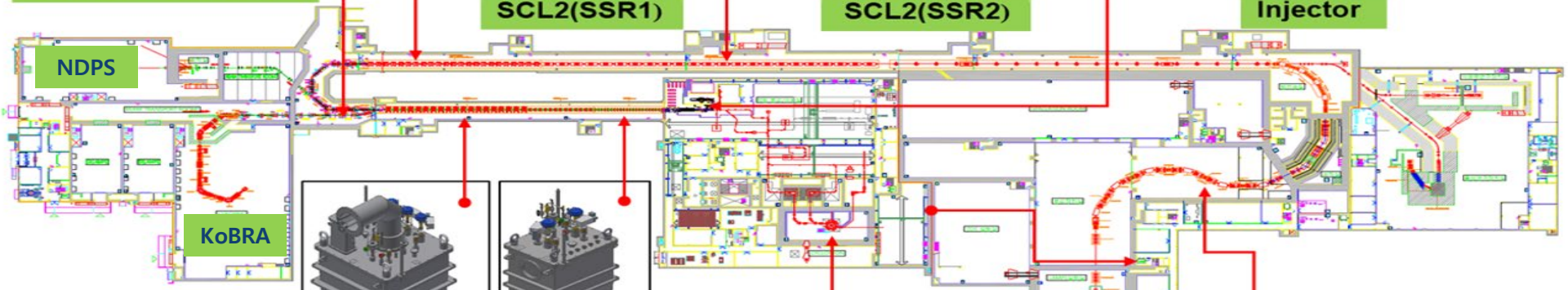
SCL2(SSR1)

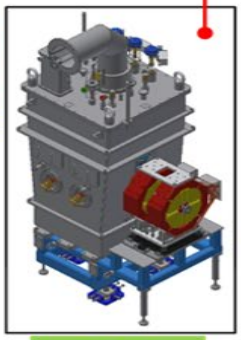


SCL2(SSR2)

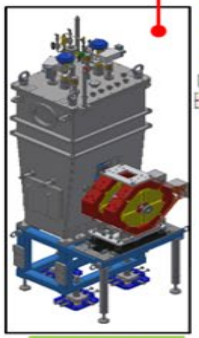


Injector

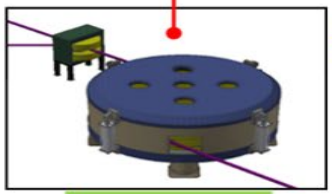




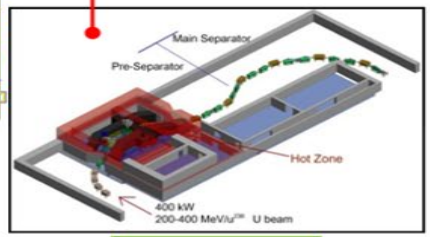
SCL3 (HWR)



SCL3 (QWR)

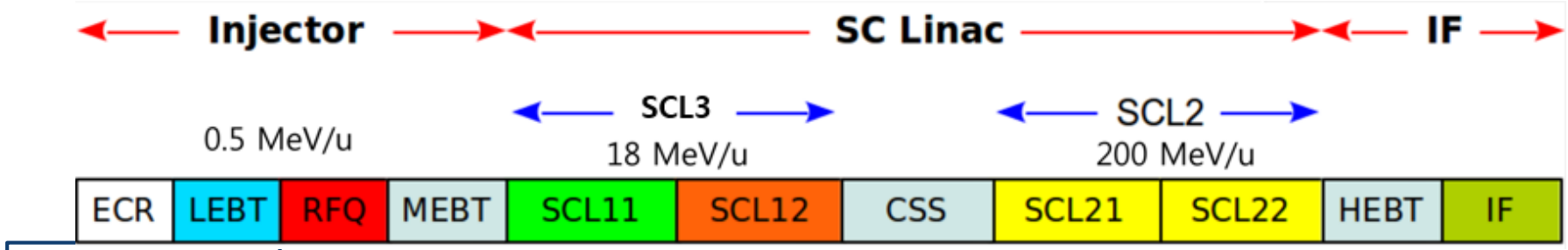


Cyclotron



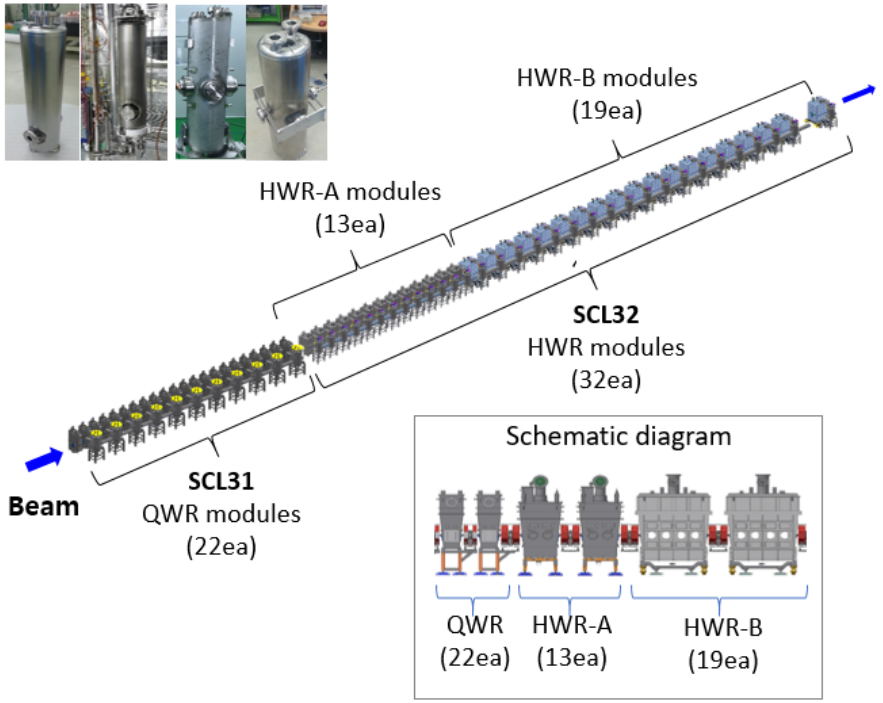
IF System

SCL3 and SCL2

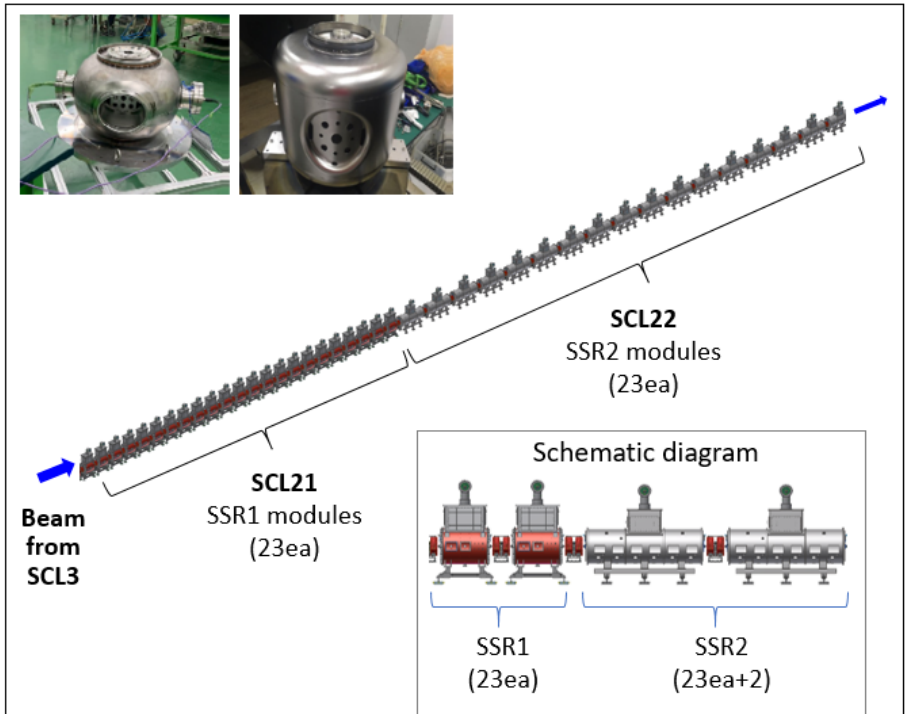


ISOL -> LEBT

SCL3

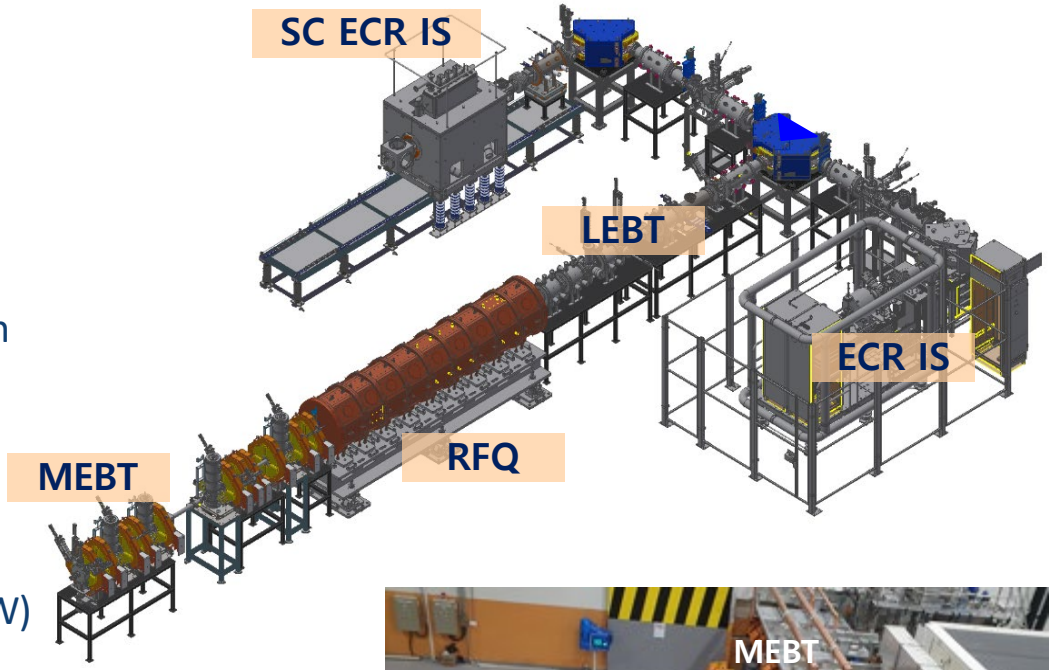


SCL2

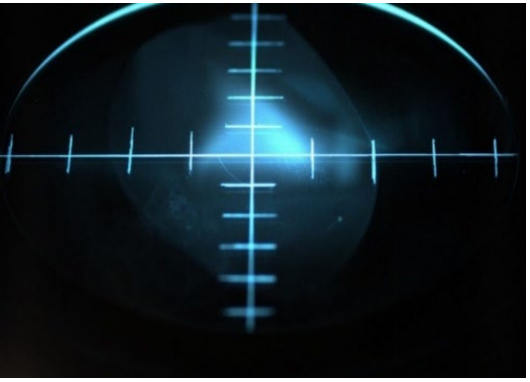


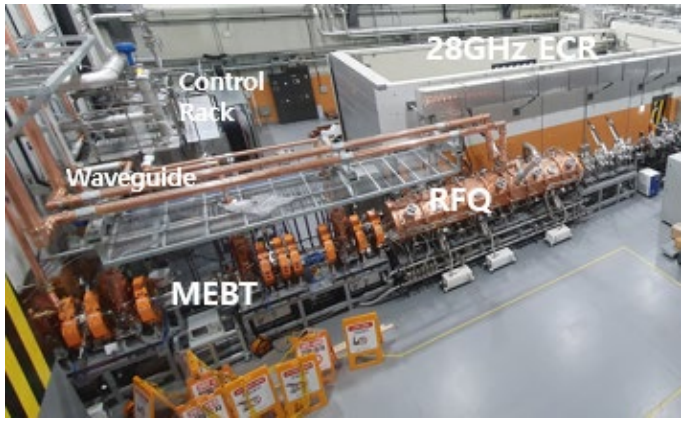
Injector System

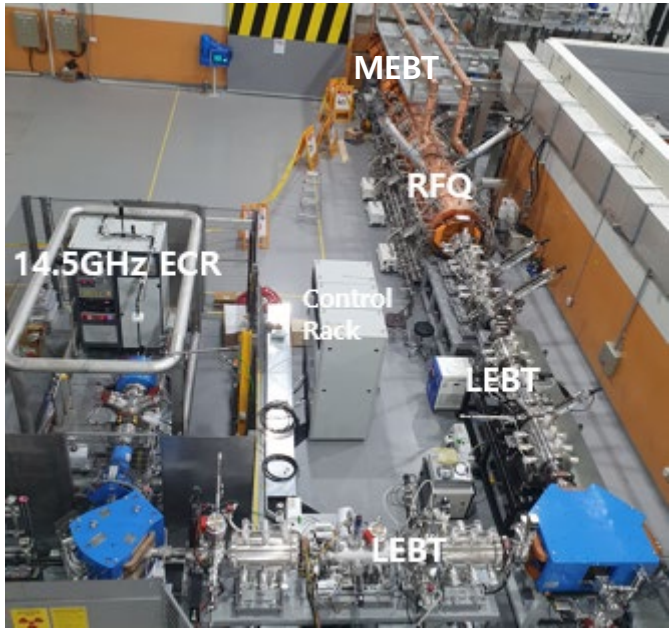
- Two ECR IS's
  - 14.5 GHz ECR ion source
  - 28 GHz superconducting ECR ion source
- LEBT (E = 10 keV/u)
  - 10 keV/u, Dual bending magnet
  - Chopper & Electrostatic quads, Instrumentation
- RFQ (E = 500 keV/u)
  - 81.25 MHz, Transmission efficiency ~98%
  - CW RF power 94 kW (SSPA: 150 kW)
- MEBT (E = 500 keV/u)
  - Four RF bunchers (SSPA: 20 kW, 15kW , 2 X 4 kW)
  - Simple quadrupole magnets, Instrumentation



Ar^{8+} 10μA @ Beam Viewer('21)

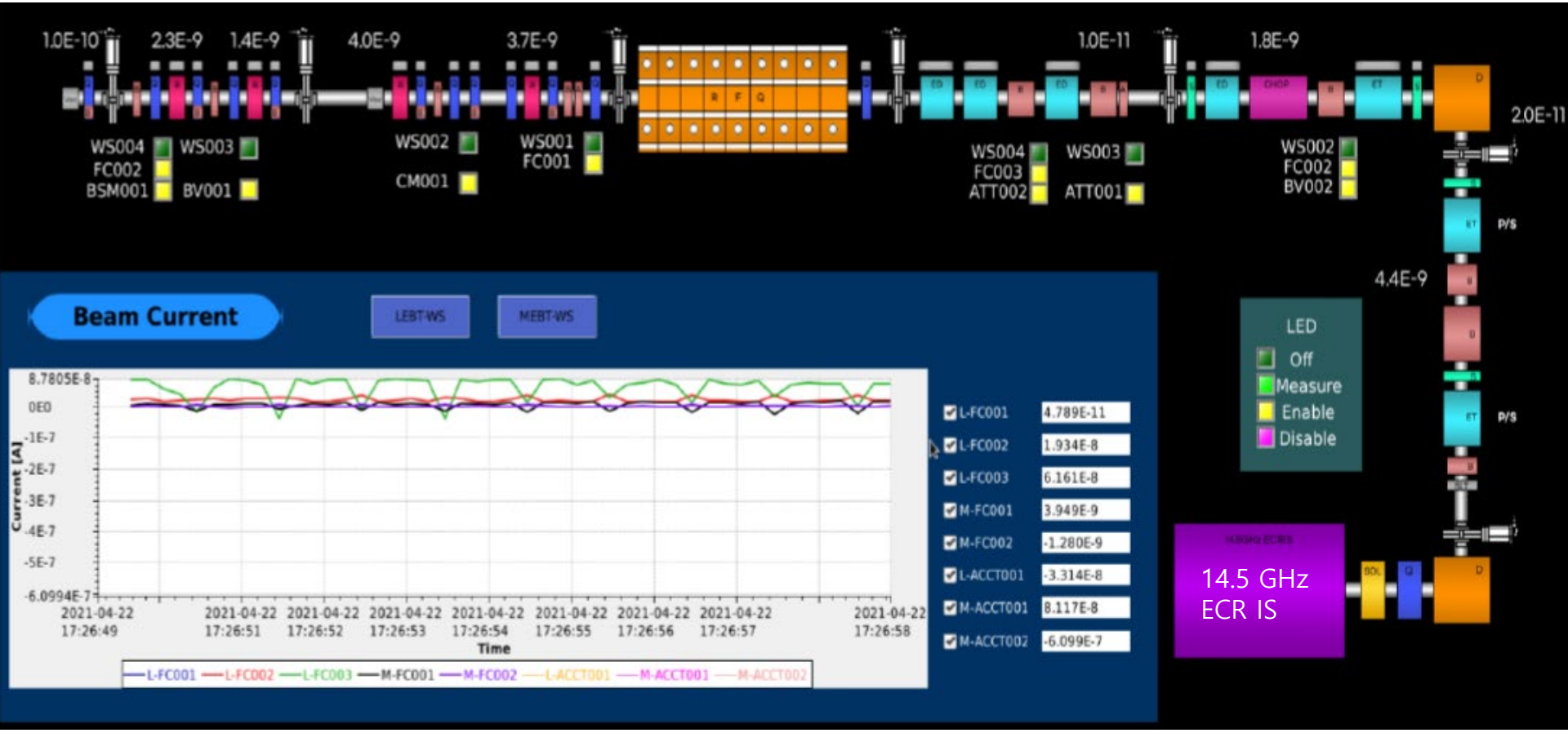






Beam Commissioning of Injector

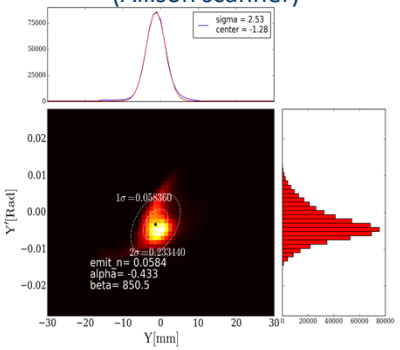
- Started in Aug 2021
- Ar $^{8+,9+}$ (1Hz, 10μs)
- ECR(14.5 GHz) → LEBT → RFQ → MEBT



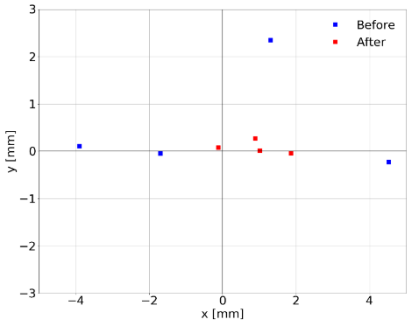
Injector beam commissioning

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

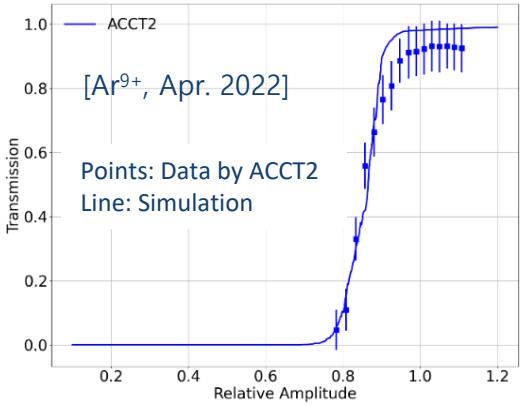
LEBT Beam emittance
(Allison scanner)

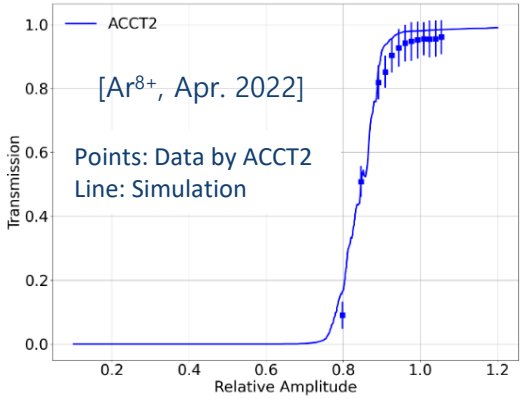


LEBT orbit correction



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

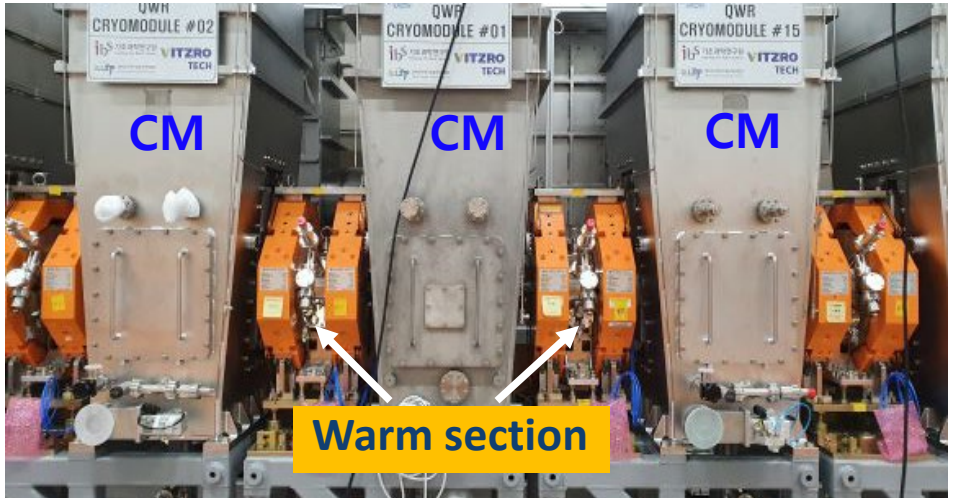




SCL3 Installation

SCL3 Installation finished in 2021

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



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)

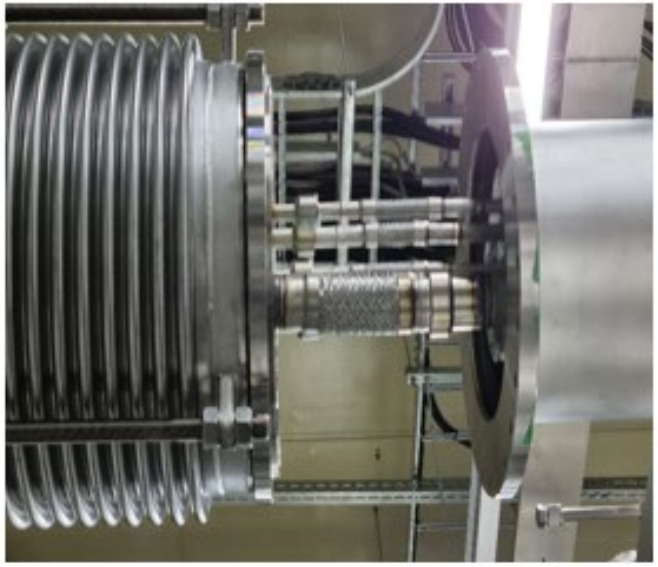

Compressors and Oil Removal System (WCS)


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

SCL3 Cryoplant was commissioned in Aug 2022

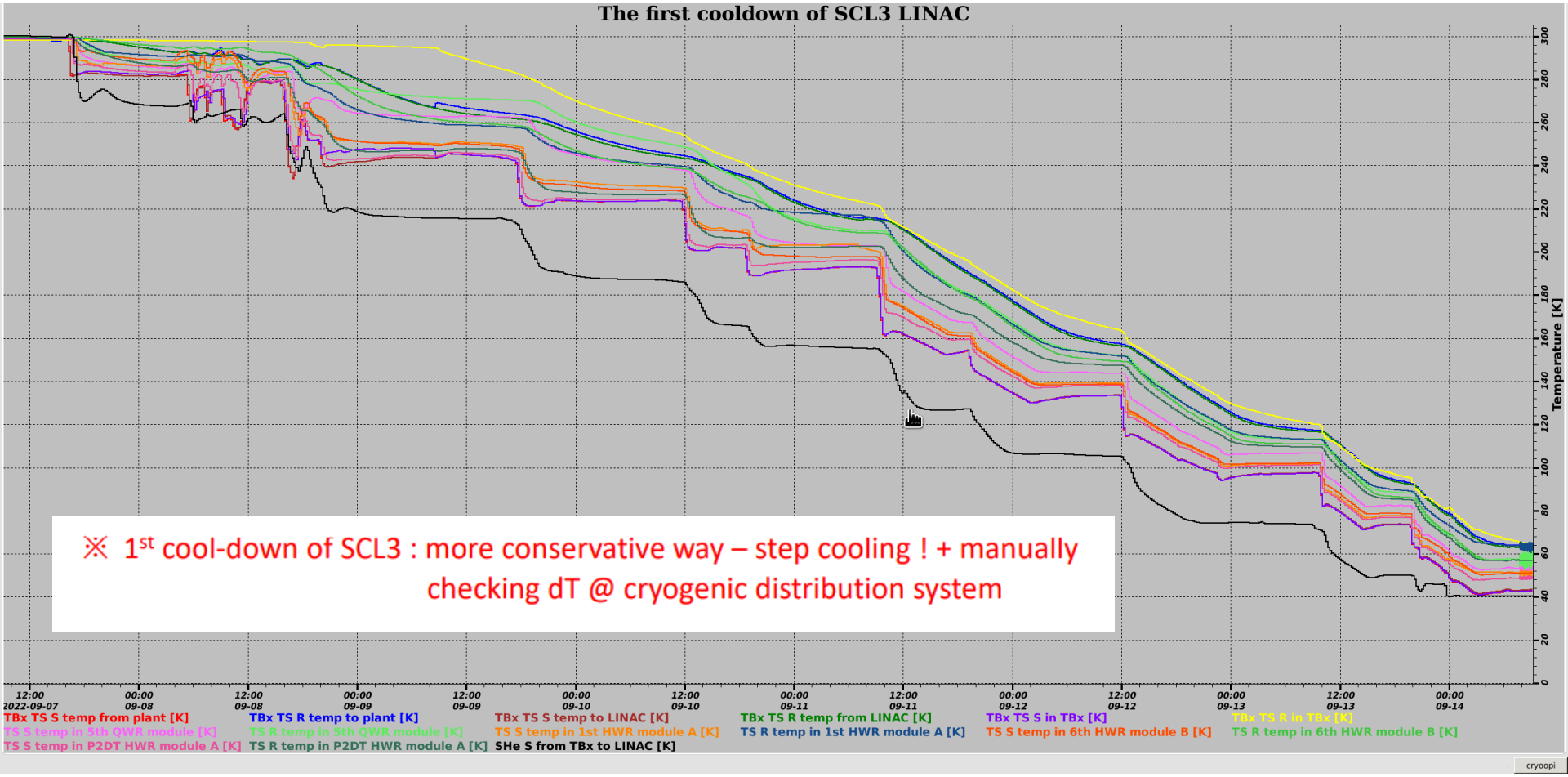
Cryogenic System

- 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



The First Cool-Down of SCL3

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

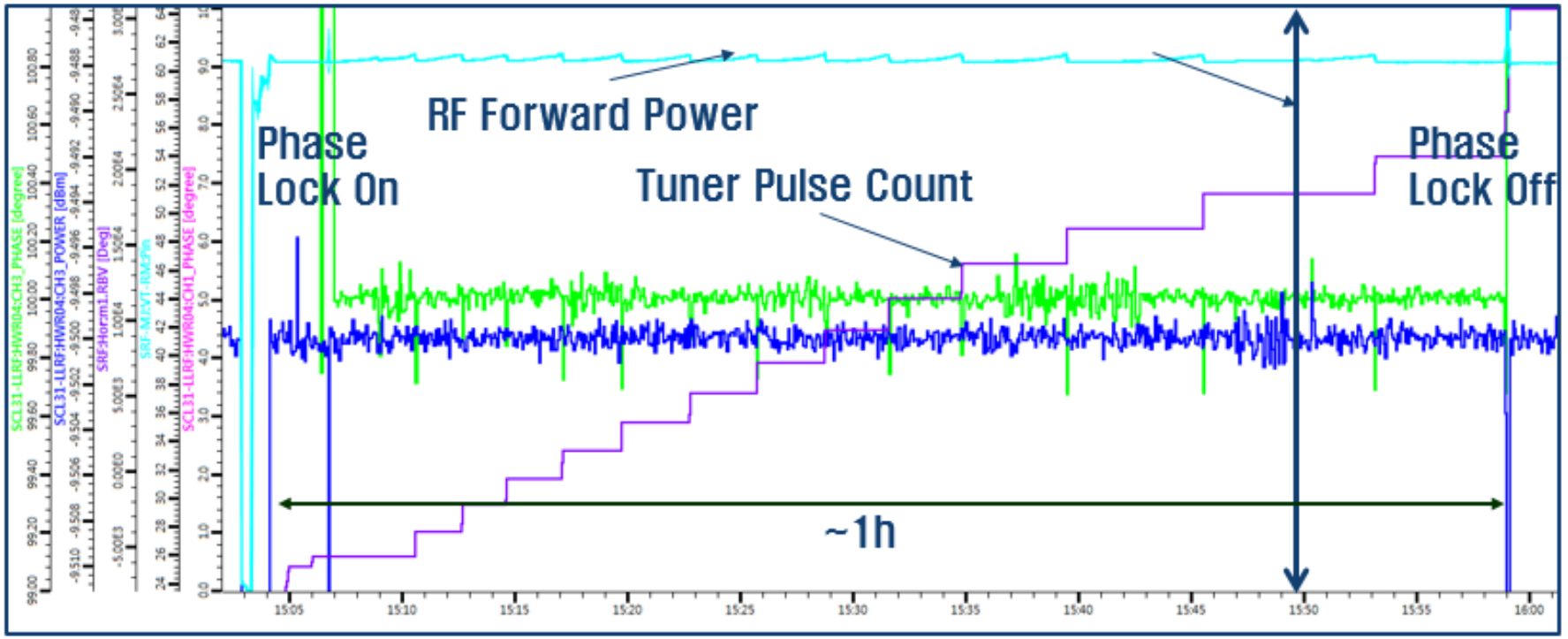


The first cool-down started on Sep. 7, 2022 (15:30)

RF Control Test of SCL3

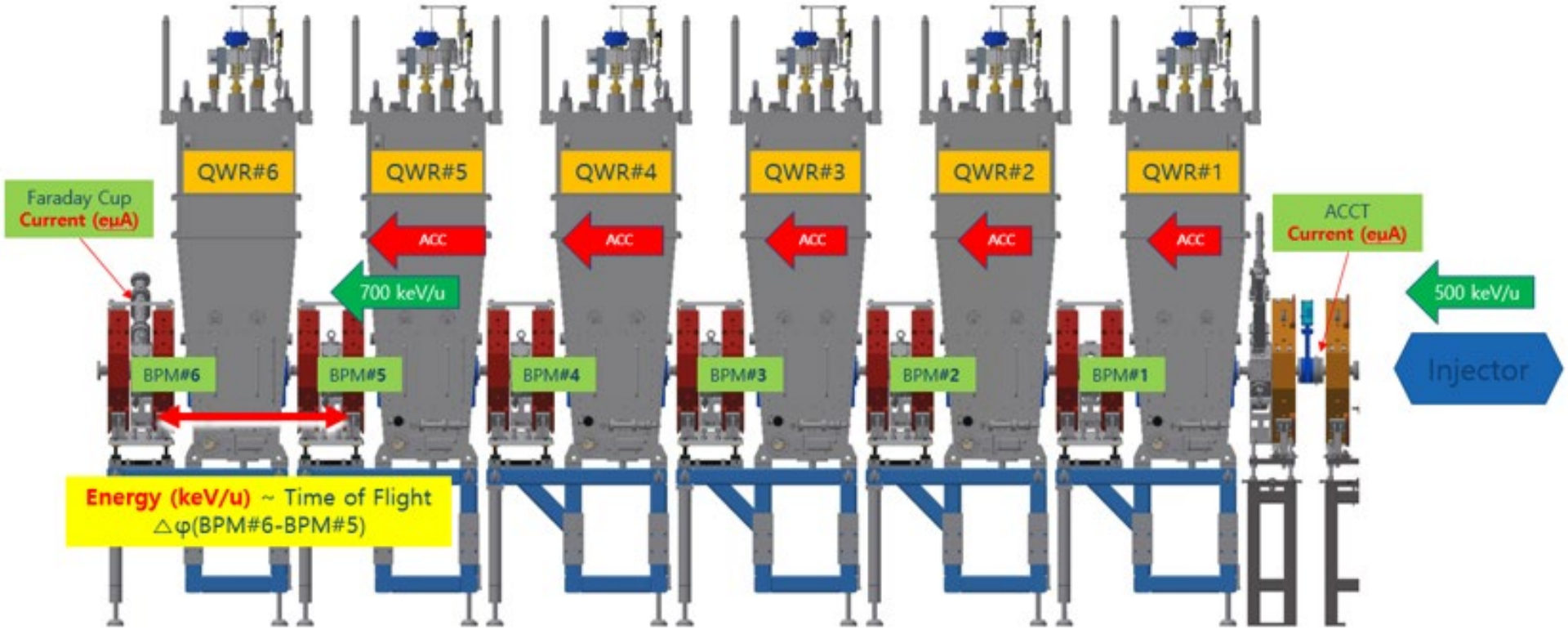
RF Control Test(Amplitude/Phase feedback with Tuner control)

RF Amplitude, Phase Control

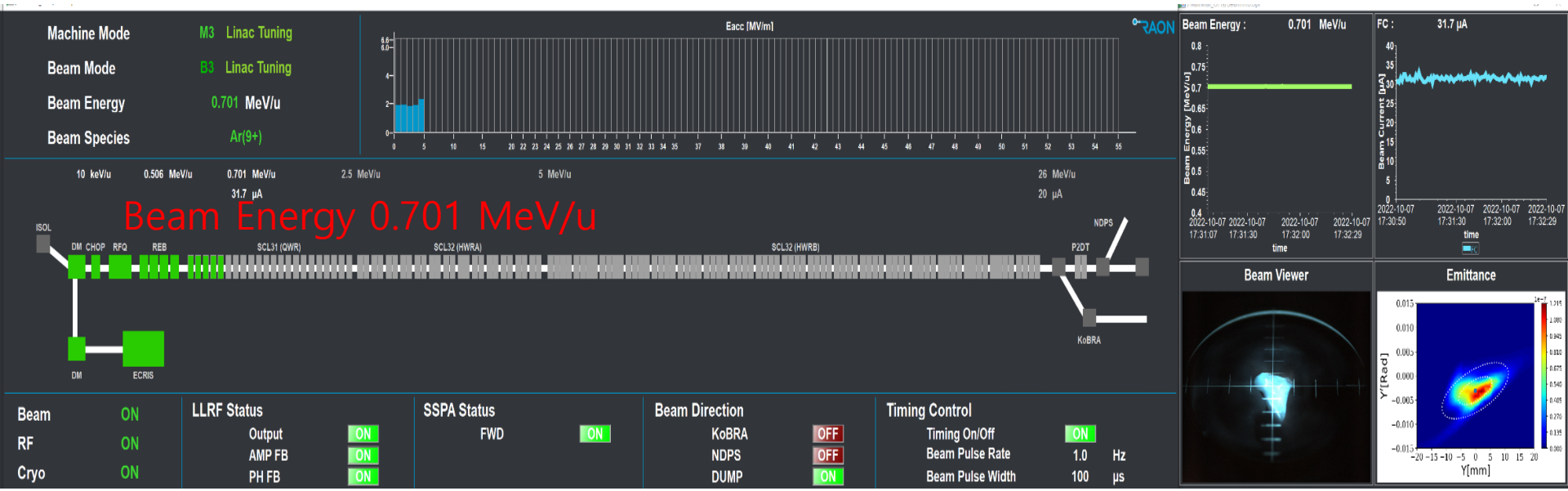


- Target RF amplitude error < 1%, phase error < 1deg
- Tuner operation threshold : +/- 5deg
- Control bandwidth: 90~160 Hz

The First Success of SCL3 Beam Commissioning Exp (Oct. 7, 2022)



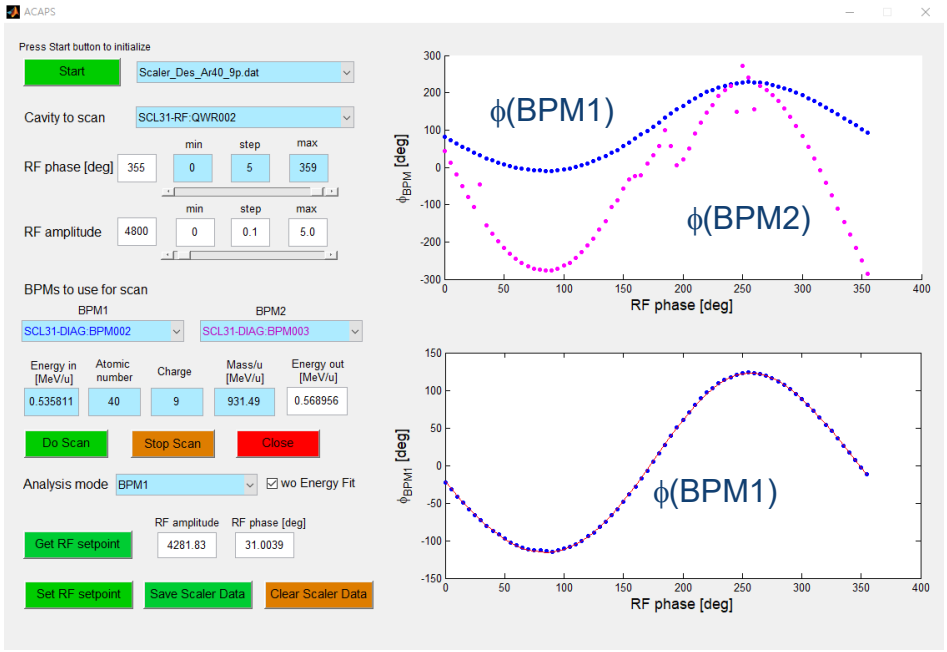
Result of the 1st SCL3 Beam Commissioning Exp



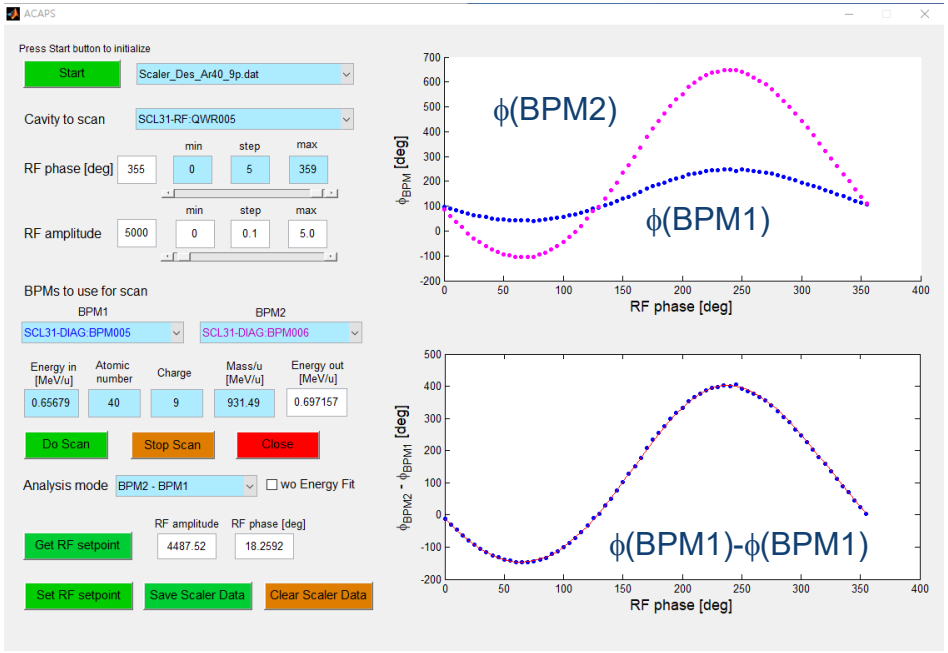
Ar^{9+} beams accelerated by QWR #1~#5 on the 7th of Oct, 2022 at 15:03

RF set-point for QWR cavities

- RF set-point of 5 QWR cavities by phase scan method:
  - Beam phase was measured by BPM (phase difference between 2 BPMs)
  - QWR2: problems in the 2nd BPM data ⇒ using single BPM
- QWR2: multipacting at RF amplitude set value ⇒ Increase RF amp by 12%
  ⇒ Adjust synchronous phase
- QWR3/QWR4: RF control is maintained for only 20 or 30 minutes in phase scan.



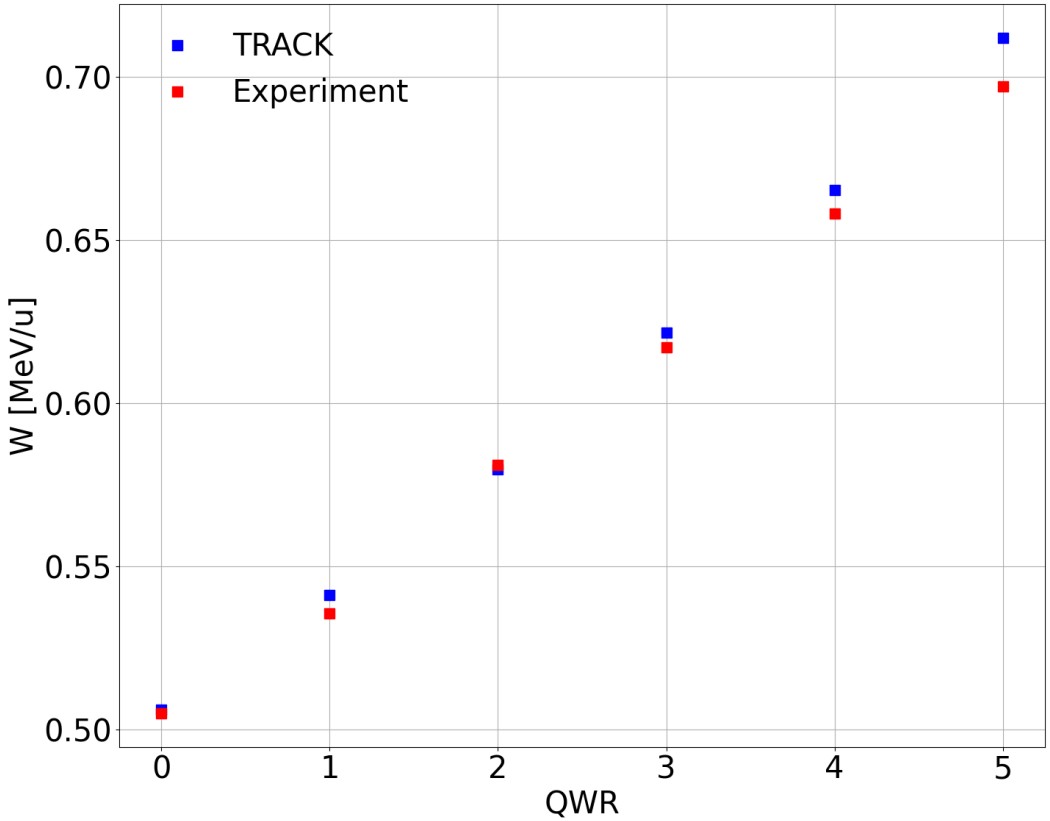
[Phase scan of QWR2]



[Phase scan of QWR5]

Beam Energy in 5 QWRs

- The energy at the exit of each QWR was determined in phase scan process:
  - Energies are slightly lower than TRACK estimation
  - Energy after QWR5 = 697 keV/u (TRACK: 712 keV/u)
  - In order to get energy > 700 keV/u, we increase RF amplitude of QWR5.

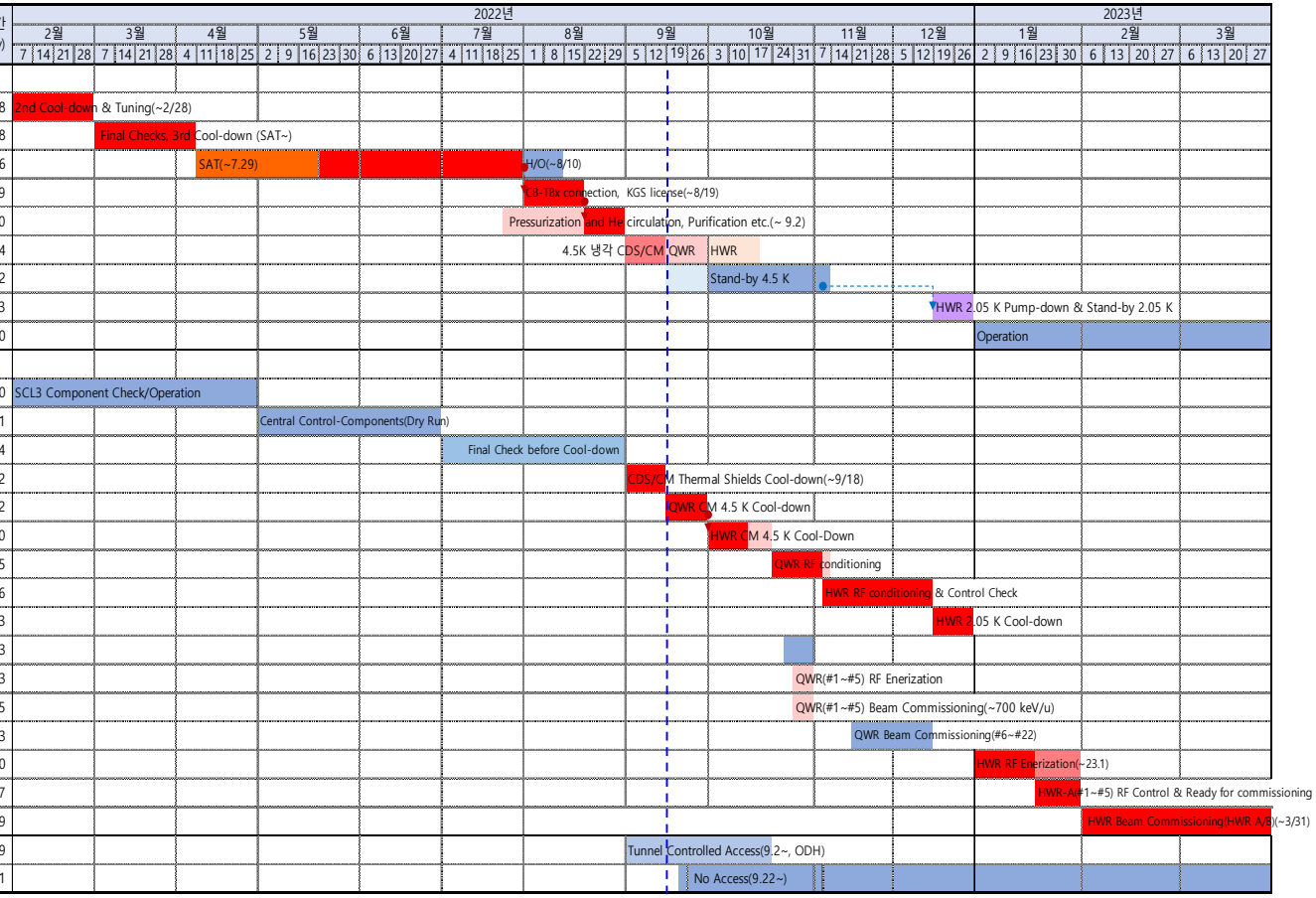


SCL3 Beam Commissioning Plan

SCL3 Beam Commissioning Master Schedule

● 작성일 : 2022. 09.13
● 작성자 : 중이온가속기연구소

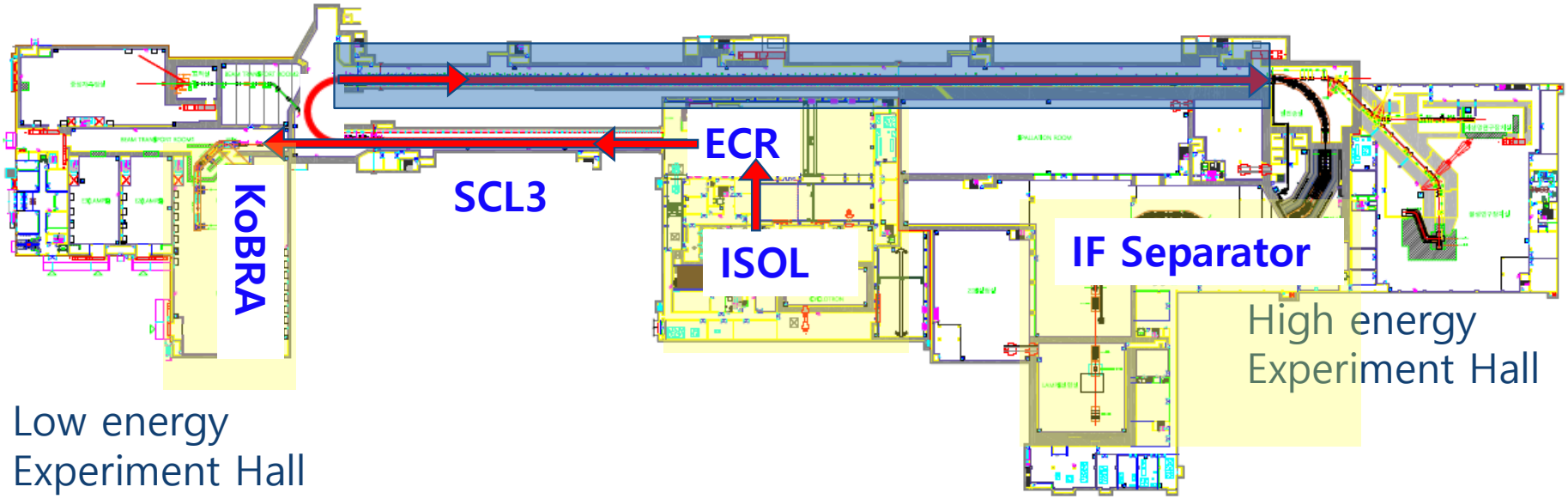
구분 (System)	주요업무 (Activity)	시작 (Start)	완료 (Finish)	기간 (day)
Cryogenics System	★ SCL3 Cryoplant			
	• 2nd Cool-down & Tuning	22-02-01	22-02-28	28
	• Final Checks, 3rd Cool-down (SAT~)	22-03-01	22-04-07	38
	• SAT(~7.29) & Handover	22-04-07	22-08-10	126
	• CB-TBx connection, KGS license	22-08-01	22-08-19	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



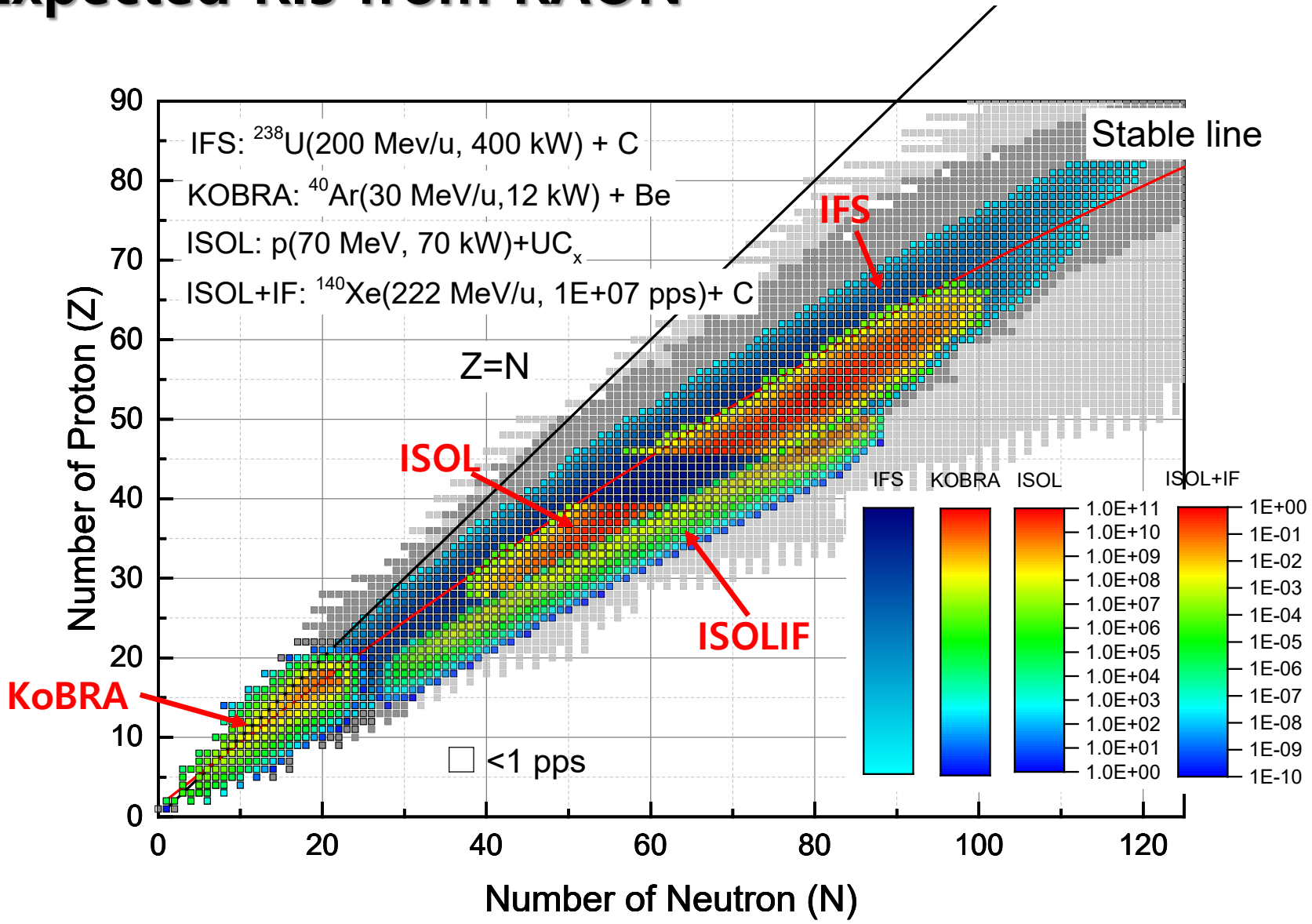
- Finished cooling-down of SCL3 on Oct. 26, 2022.
- Commissioning of SCL3 to be finished until March 2023
- From March 2023, beams on KoBRA spectrometer

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 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 more neutron-rich regions of the nuclear chart**

KoBRA Spectrometer

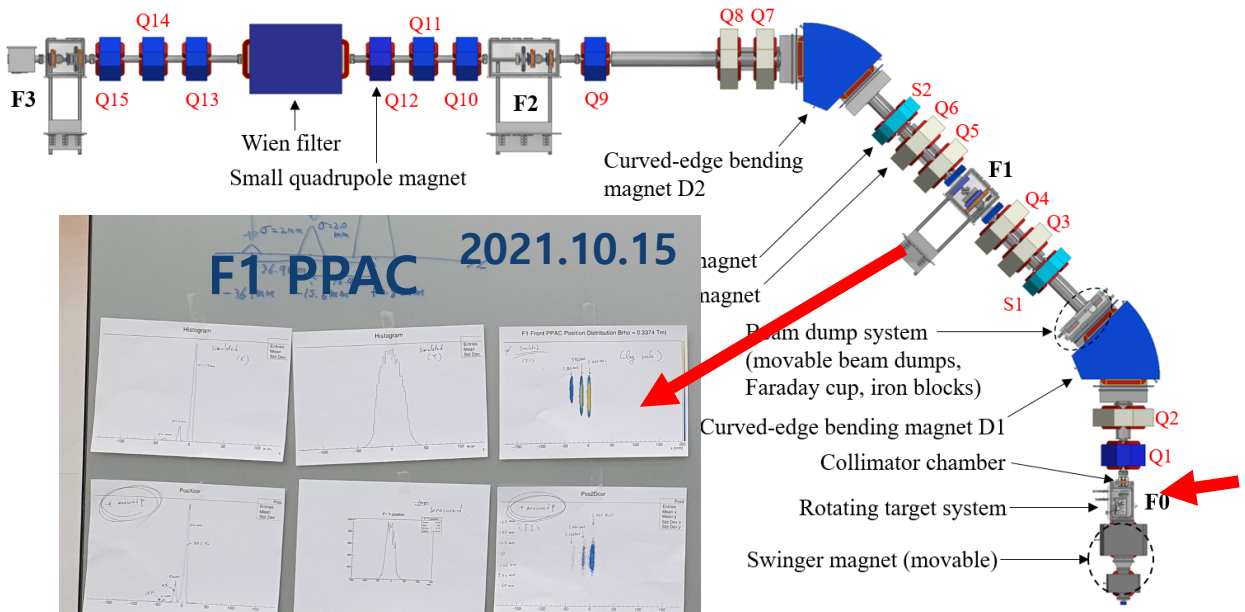
Korea Broad acceptance Recoil spectrometer and Apparatus

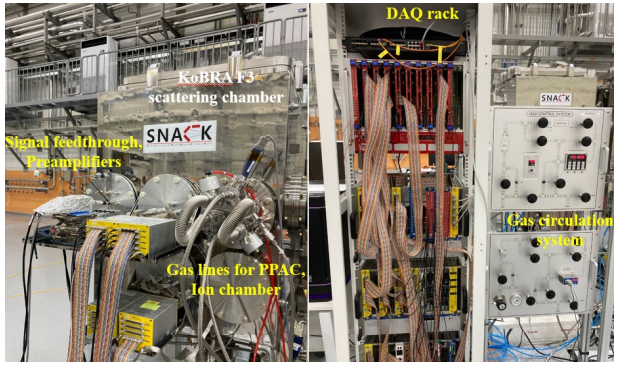
Goal: Construction of **multi-purpose experimental instrument** using stable or RI beams for studies of the nuclear structure and nuclear astrophysics, in the energy range of about 1 – 30 MeV/u

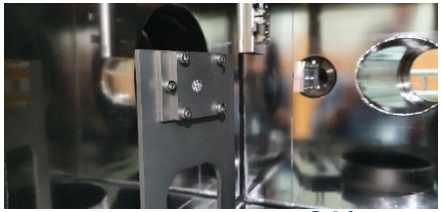
- RI beam productions at a few MeV/u and at about 20 – 40 MeV/u using a stable beams from ECR ion source
- Recoil mass separator at less than few MeV/u for direct measurements of radiative-capture cross, using a RI beams from ISOL facility

KoBRA Spectromter

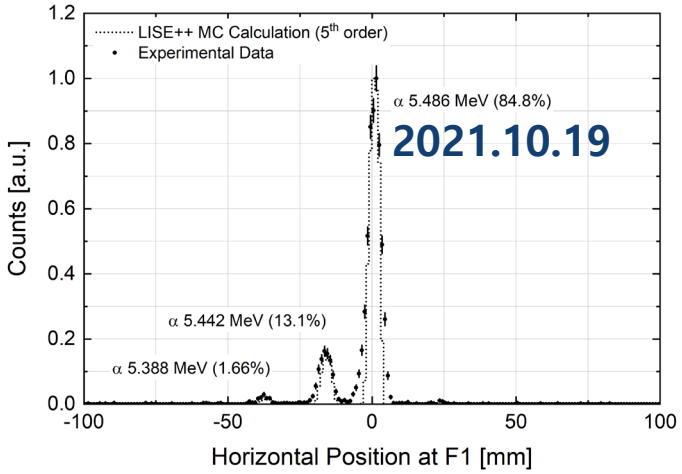
KoBRA machine commissioning completed on 2021.10





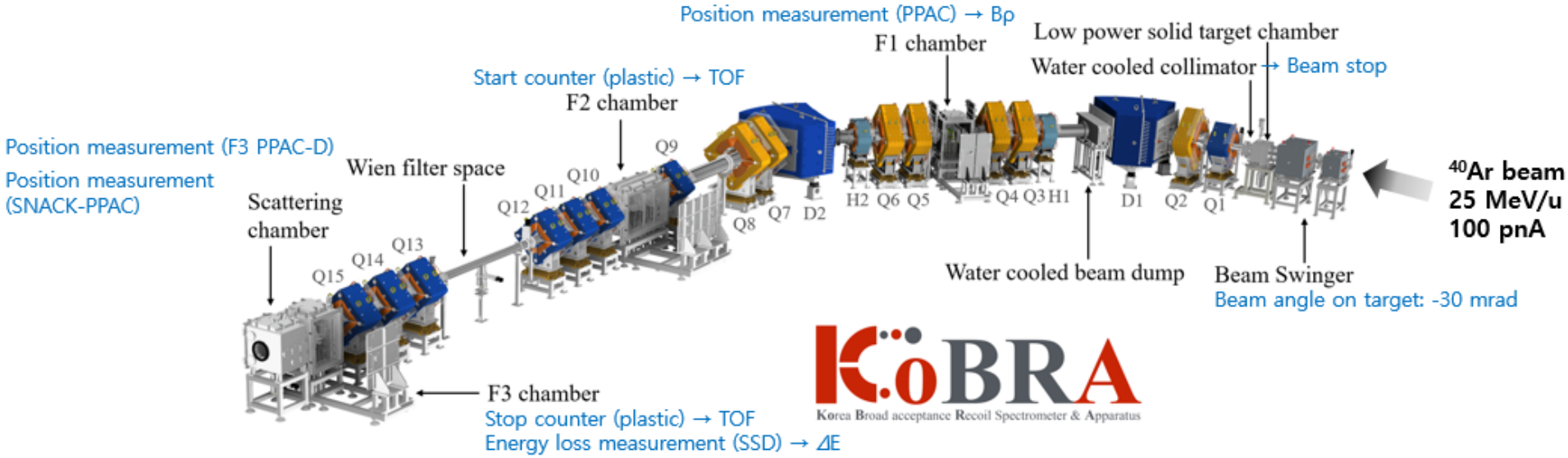


Alpha source (^{241}Am)

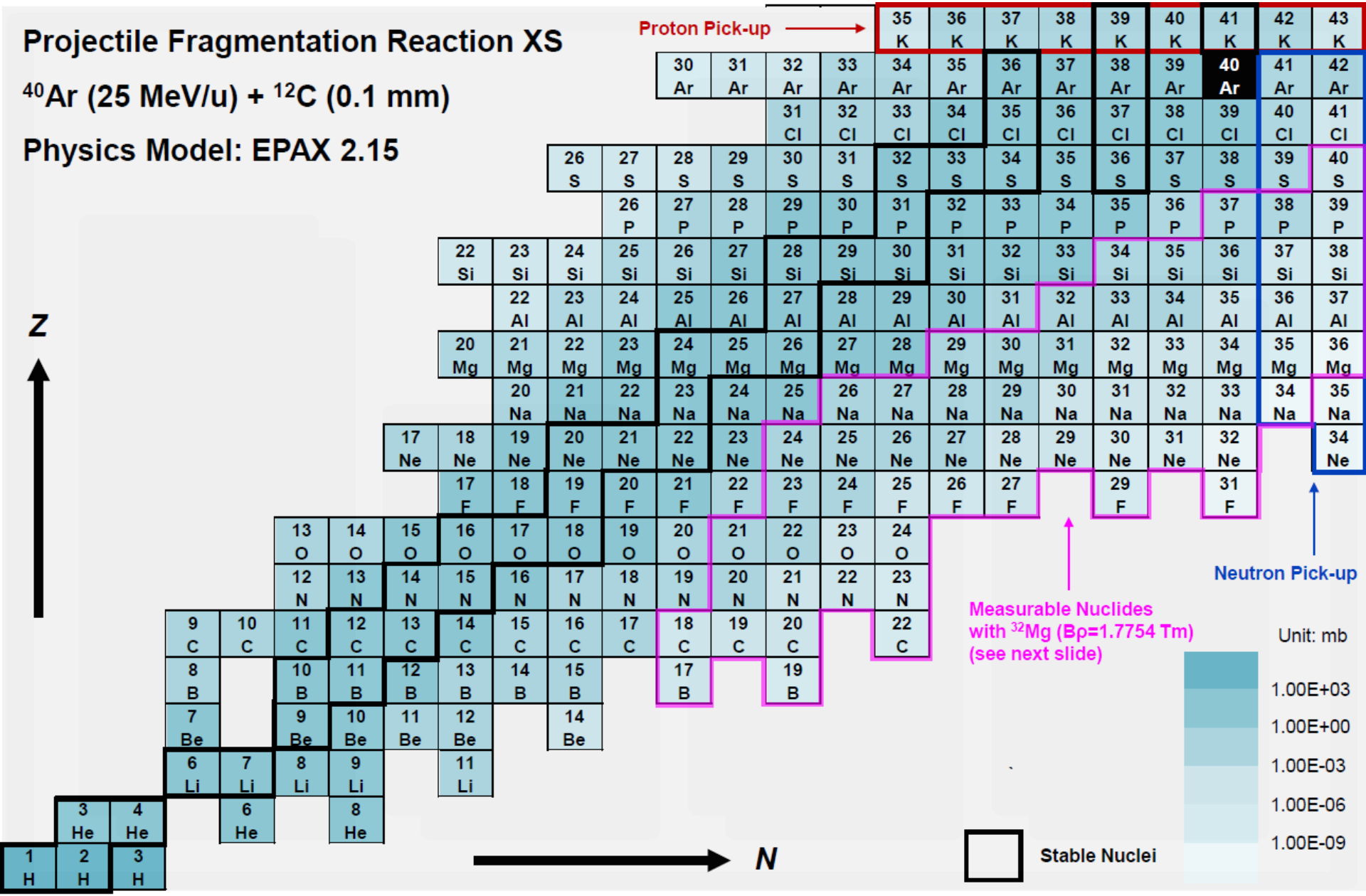


KoBRA Beam Experiment : Plan

- **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 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 : Plan



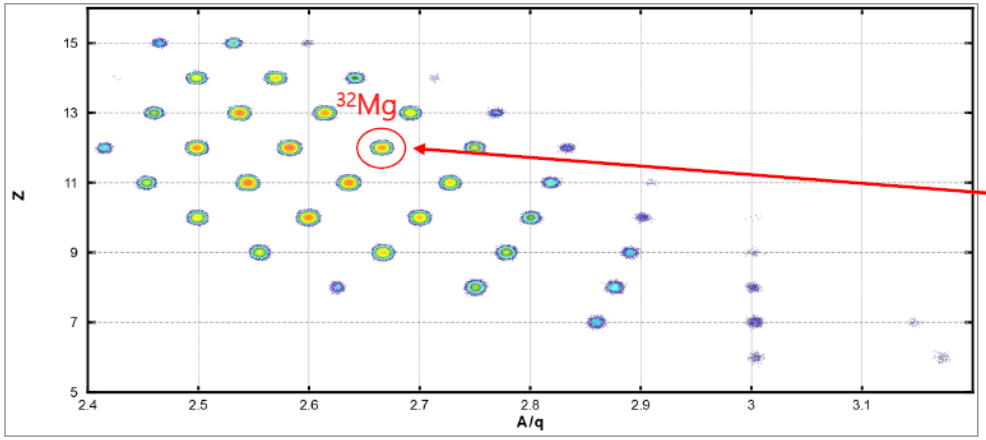
KoBRA Beam Experiment : Plan

^{32}Mg Yield Calculation

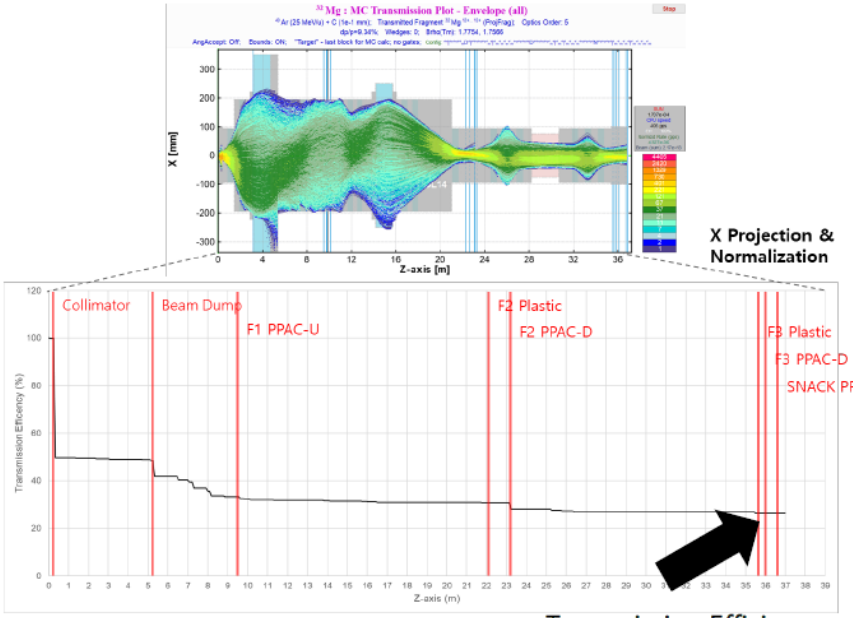
$$I = I_p \times \sigma_{Mg} \times \frac{\rho_A}{M} \times A_V \times \varepsilon_t \times \Omega_c$$

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% (5^{th} order, MC cal.)
Ω_c = Correction factor for solid angle

Z vs A/q Distribution



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



Transmission Efficiency
26.3% at F3 target

DGKIM from KoBRA team

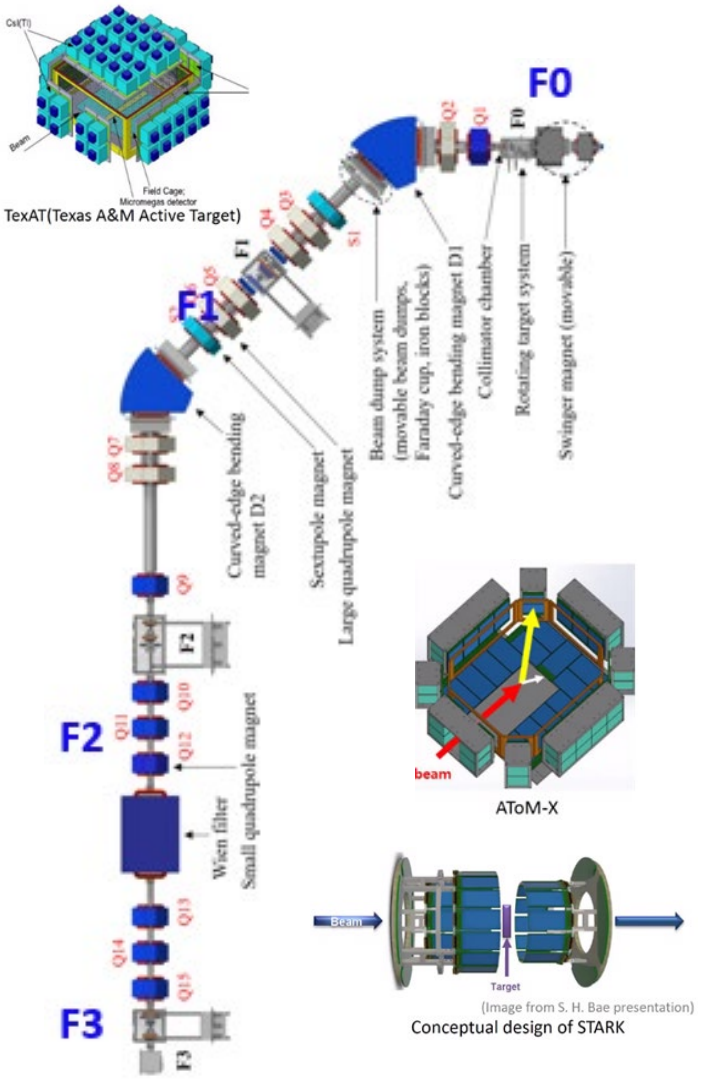
^{32}Mg (transported to F3)

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

※ pps: particles per second

Proposed experiments with stable beams

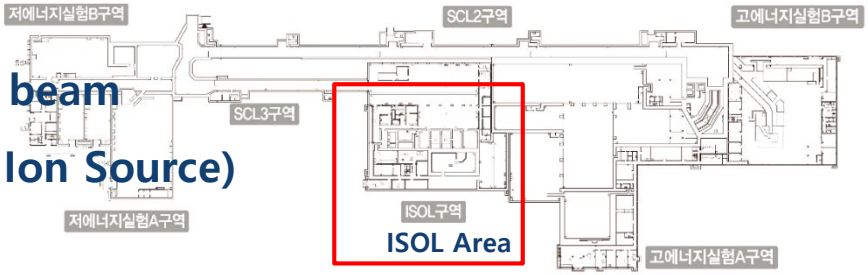
- Study on neutron-deficient nuclei using proton-induced fusion-evaporation
- 3n fusion-evaporation reactions to study MEDs in Tz=-3/2 nuclei
- Fusion Reaction Studies related to Stellar Evolution
- The study of lifetime of isotopes near doubly magic N=Z nuclei ^{40}Ca
- Optical model potential studies 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



Proposed by CENS/IBS

Cyclotron

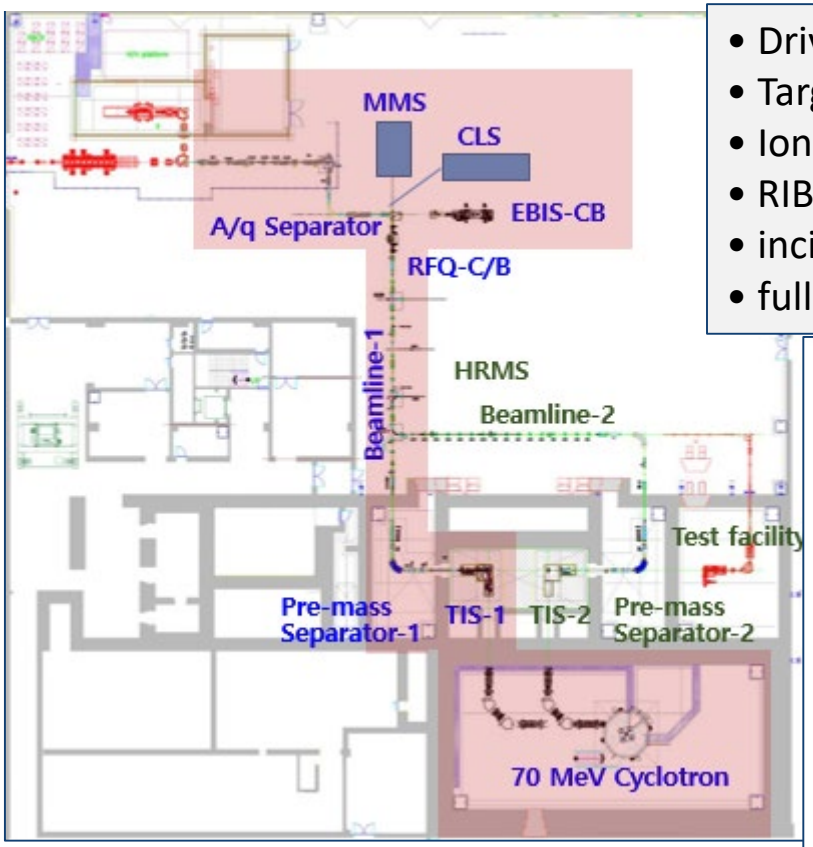
- **Specs**
  : 35~70 MeV proton, 0.75mA max with two beam lines connected to ISOL TIS bunker(Target Ion Source)
- **Schedule**
  : Contract('19.6), pre-survey('19.11), Design finalized('20.4) , FAT ('21.6), Shipping('21.8), Installation('21.11.11~22.4.28)



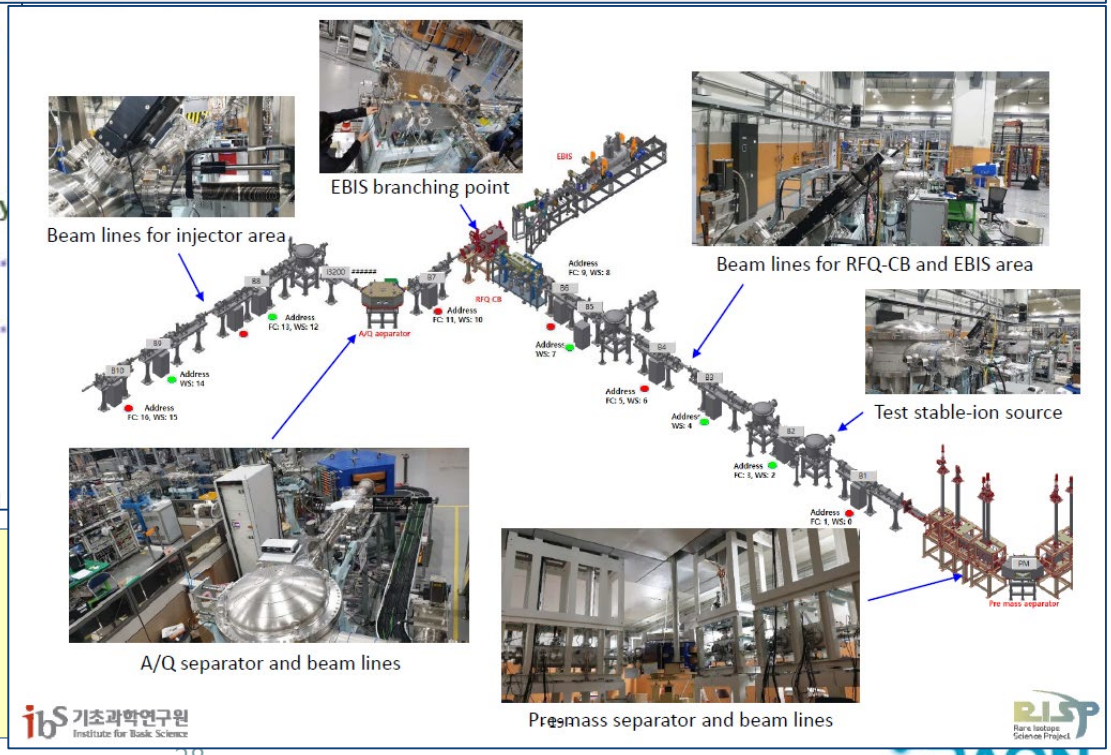
SAT on Oct 2022

ISOL System

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

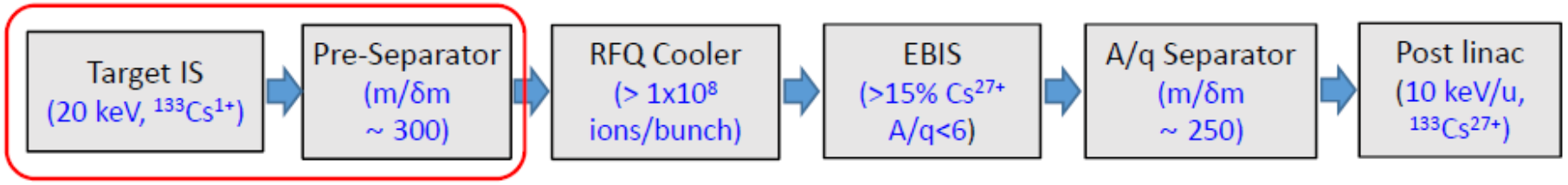


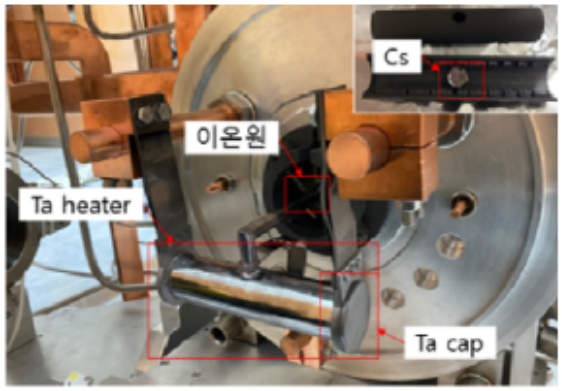
- Driver beam : proton 35<K<70 MeV, up to 70 kW
- Target : UCx, MgO, BN, CaO, BeO, SiC, etc
- Ion Source : Surface, RILIS, Plasma
- RIB : 6< A < 250, 10<K< 80 keV, 10^8 pps(Sn), >90% purity @Exp.
- incident to RFQ of Post accelerator 10 keV/u
- full remote maintenance system with TIS modularization



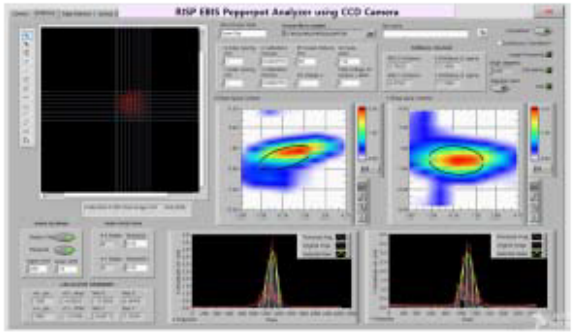
- ISOL beam lines including sub-systems are commissioned with Cs beam in 2021
- RI beam commissioning using SiC target (Dec 2022)

ISOL Beam Test in 2021

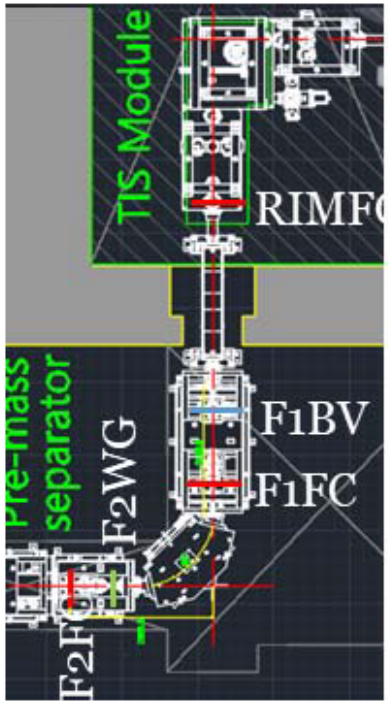


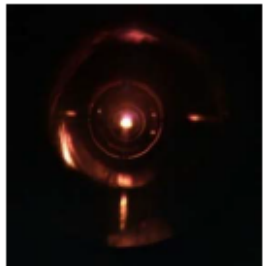


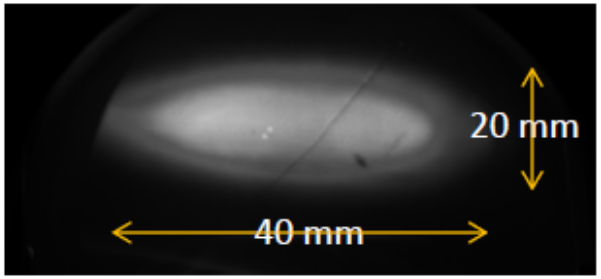
Cs sample preparation in TIS chamber



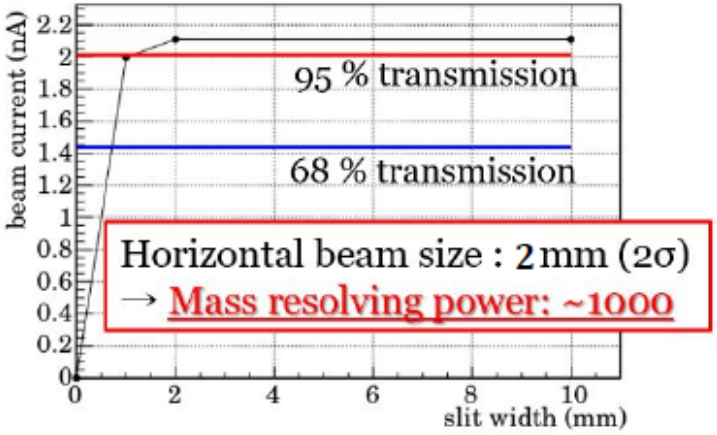
Beam emittance of TIS extracted Cs beam
X(2σ) : 15 pi mm mrad
Y(2σ) : 17 pi mm mrad







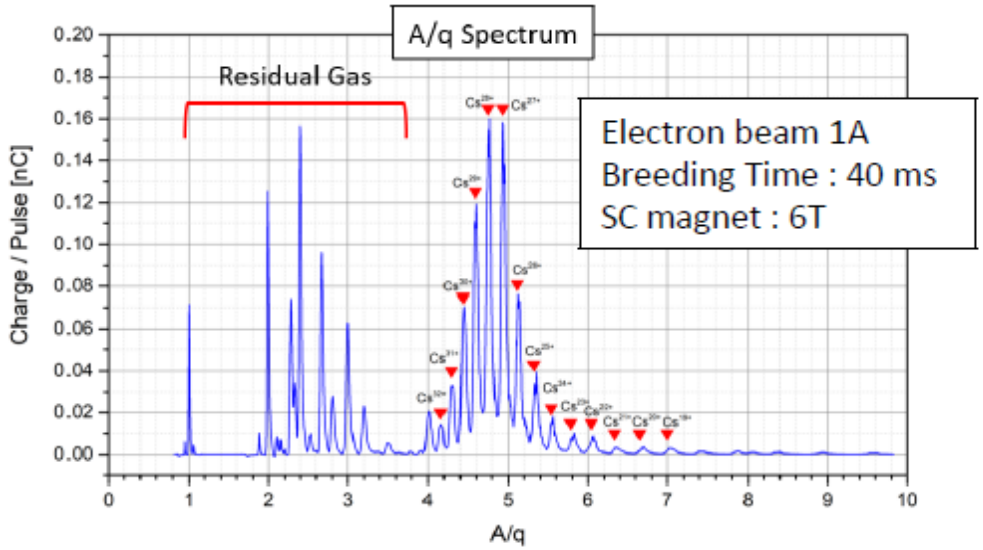
F1 beam viewer

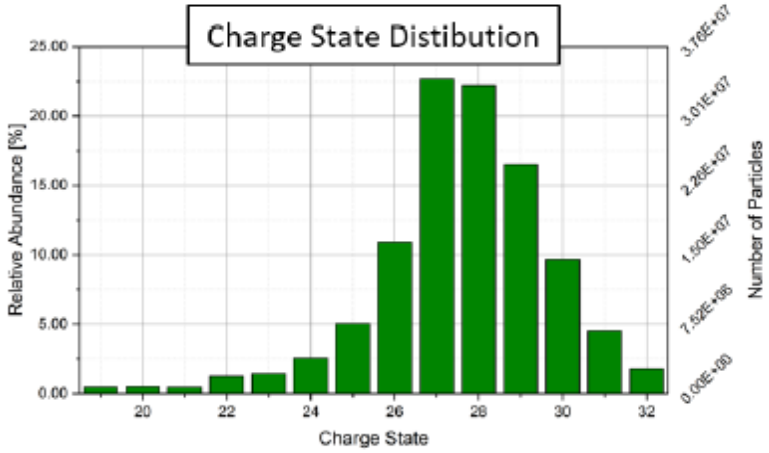


Beam size measurement by using F2 slit

ISOL Beam Test in 2021 (II)

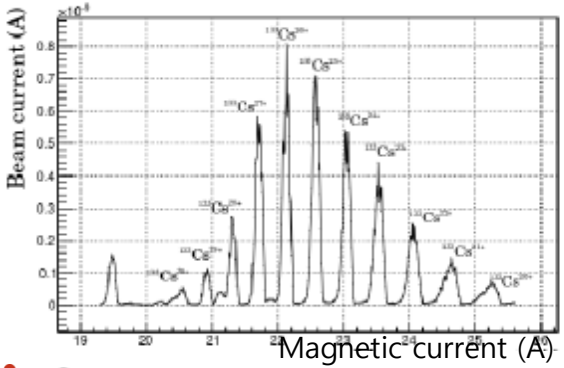
Target IS (20 keV, $^{133}Cs^{1+}$) → Pre-Separator (m/δm ~ 300) → RFQ Cooler (> 1x10^8 ions/bunch) → EBIS (>15% Cs^{27+} A/q<6) → A/q Separator (m/δm ~ 250) → Post linac (10 keV/u, $^{133}Cs^{27+}$)





Cs 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.

ISOL RI Beam Plan

❖ RI commissioning

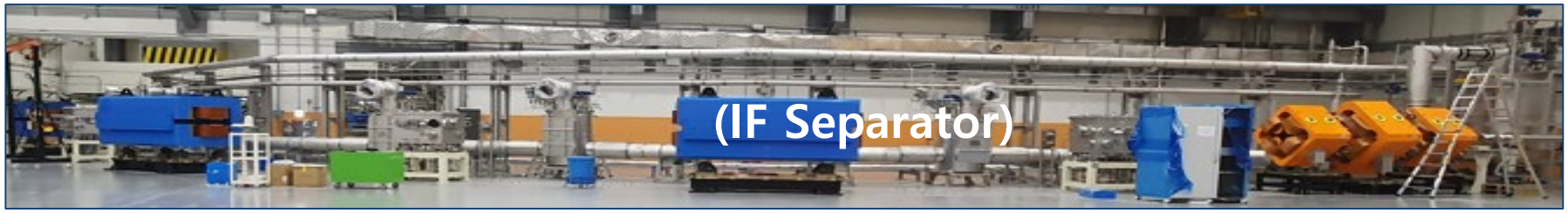
- '22. 10 : Cyclotron SAT
- '22. 11 : RI Commissioning with SiC target & TIS module ISOL relocation/ operational parameter check with SI beam/proton beam
- '22.12~ : proton beam on SiC inside TIS module and $Na^{20\sim25}$ extraction experiment
- ~'23.12 : Na & Al beam operation and experiments in ISOL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

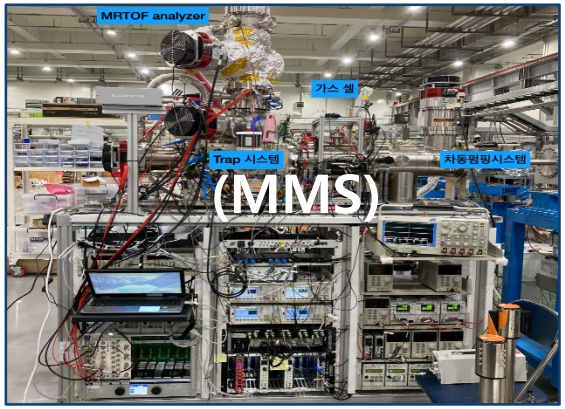
❖ RI Beam Schedule(~'24)

- 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

Other Experimental Systems

TRIUMF RIKEN





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

SCL3 to KoBRA Beam Commissioning

❖ SCL3 → KoBRA SIB Commissioning (’22.10~’23.4)

- Ar(9+), A/q = 4.44, 100 μsec, 1 Hz, 30euA
- SCL3 Linac SIB commissioning(~23.03)
- SCL3-KoBRA beam transportation line(~23.4)
- SCL3→KoBRA Secondary RI beam production experiment(23.4~) :

Note>Ar beam specification/requirements on KoBRA target needs to discuss

SCL3 A/q Machine Study

❖ SCL3 A/q Machine Study using SIB('23.4~'23.6)

- Ar6+(6.67)/Ar7+(5.71)/Ar8+(4.0), ~70 euA('23.4)
- O5+(3.20)/O6+(2.67) with 30euA('23.5)
- Other gas beams(e.x. Ne)(23.6)
- ECR-IS extraction study : Ne6+, Kr14+, C4+, p & d, metal beam(Mg, Ca, Mo, Ag, Sn, Sm, Au)(~'24)

Note> Post acceleration of ISOL RI Beam: expect low beam current and need the same A/q of SIB for beam parameters such as pulse duration and repetition, timing

ISOL Beam Commissioning

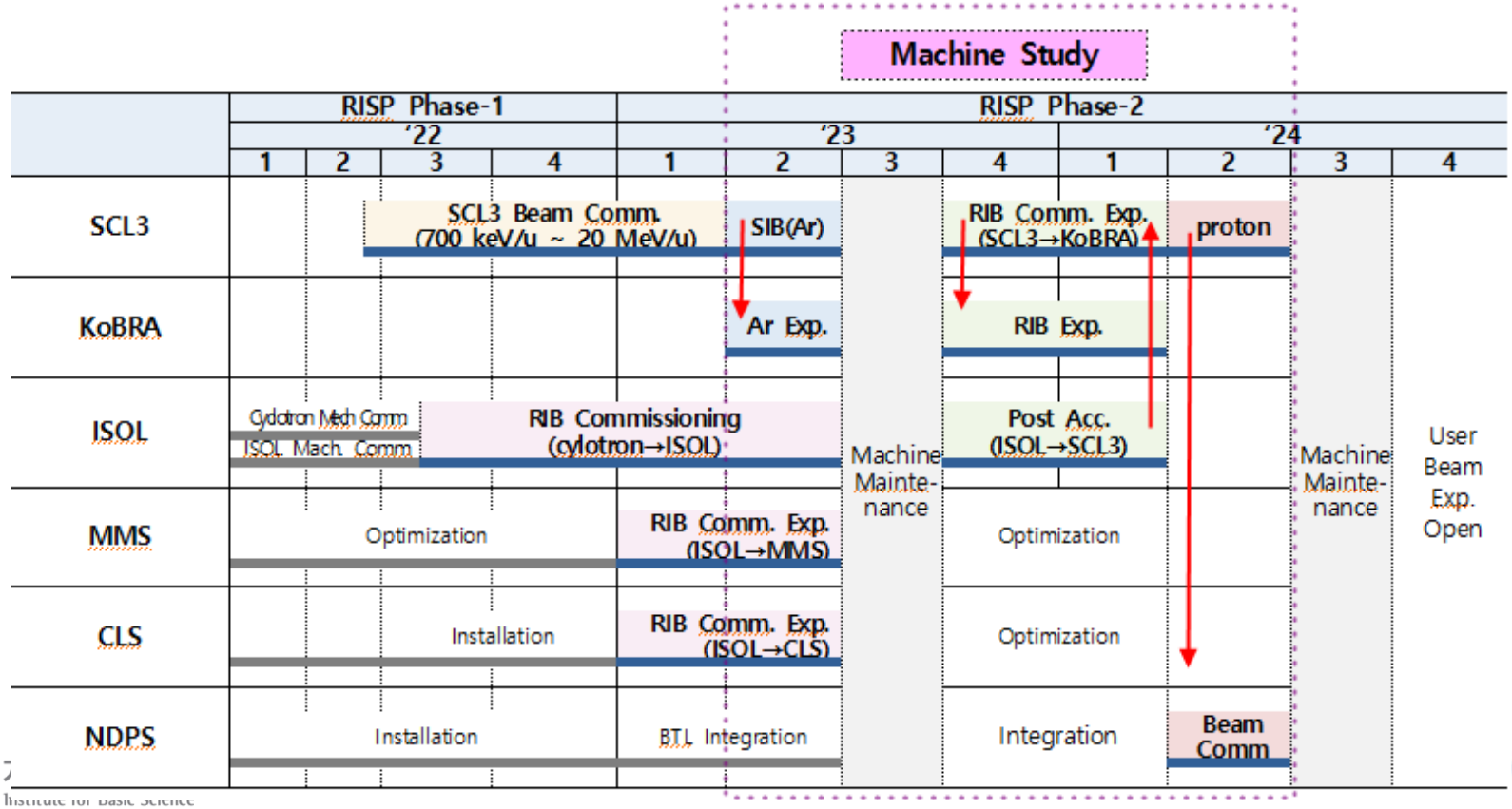
❖ ISOL RIB Beam Commissioning

- Na-21 RIB commissioning using SiC target(22.12~23.3)
- Na-21/Al-26m using SiC to MMS/CLS(~23.12)
- LaC2 target for UC2 target preparation(~24)
- Low power(<1kW) UCx (~25)

Plan for ’22~’24

❖ User beam experiments will open in ’24. Q4

- RIBs from ISOL to be injected into SCL3 on 2023
- SIB experiments(ECR→SCL3 → KoBRA/NDPS) will be carried out in Q4 of 2023
- RIB experiments in ISOL beamline using Al isotope beams in 2023
- Call for the proposal in ‘23



Summary

❖ RAON is preparing for beam commissioning

- 1st beam extraction using 5 QWR CMs in SCL3 is successfully done.
- ECR → SCL3 → KoBRA using Ar-40(8+/9+) on Q2 of 2023
- Cyclotron → ISOL for RI beam extraction will be on Dec 2022

❖ Plan for ISOL → SCL3

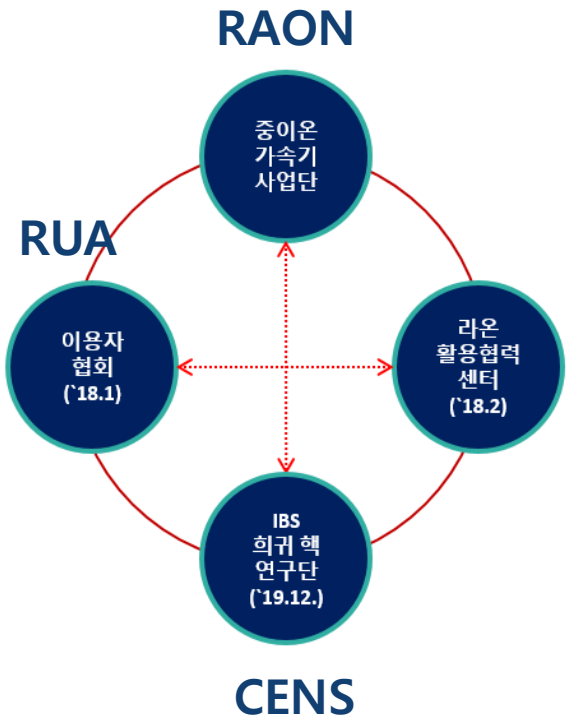
- RIBs from ISOL to be injected into SCL3 on 2023

❖ 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 "Call for Proposals in 2023"

Domestic Collaboration



User Groups and Collaborating Institution