MRTOF-MS at RAON:

Overview: RAON, ISOL

MRTOF-MS (Multi-reflection time-of-flight mass spectrograph): Physics, principle

Current status of MRTOF-MS at RAON, including on-line measurements

HIPPE project

Summary and plan (discussion)

July 11th 2025
Moon, Jun Young (IBS/IRIS)
(Collaboration meeting at POSTECH)

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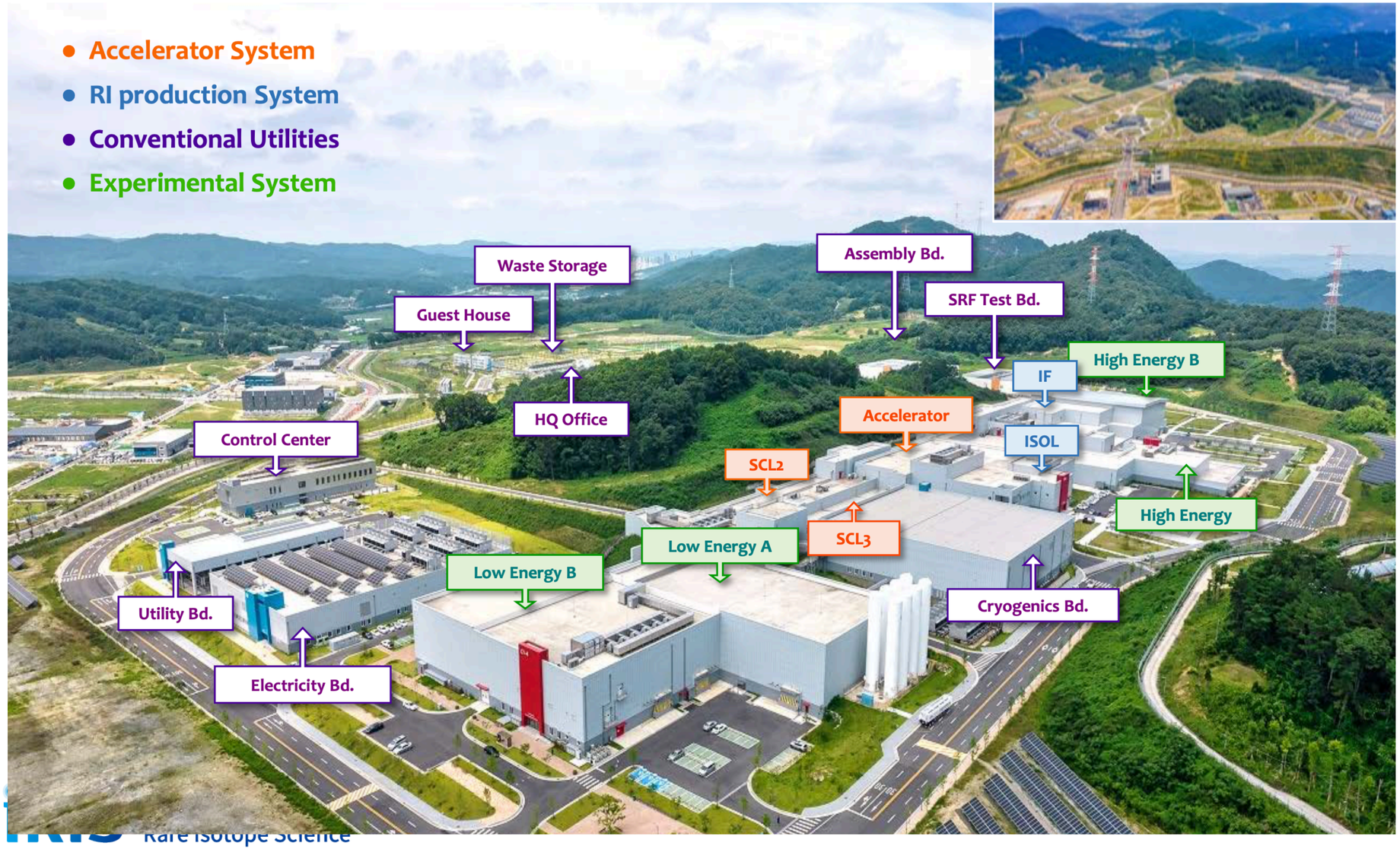
Overview : RAON

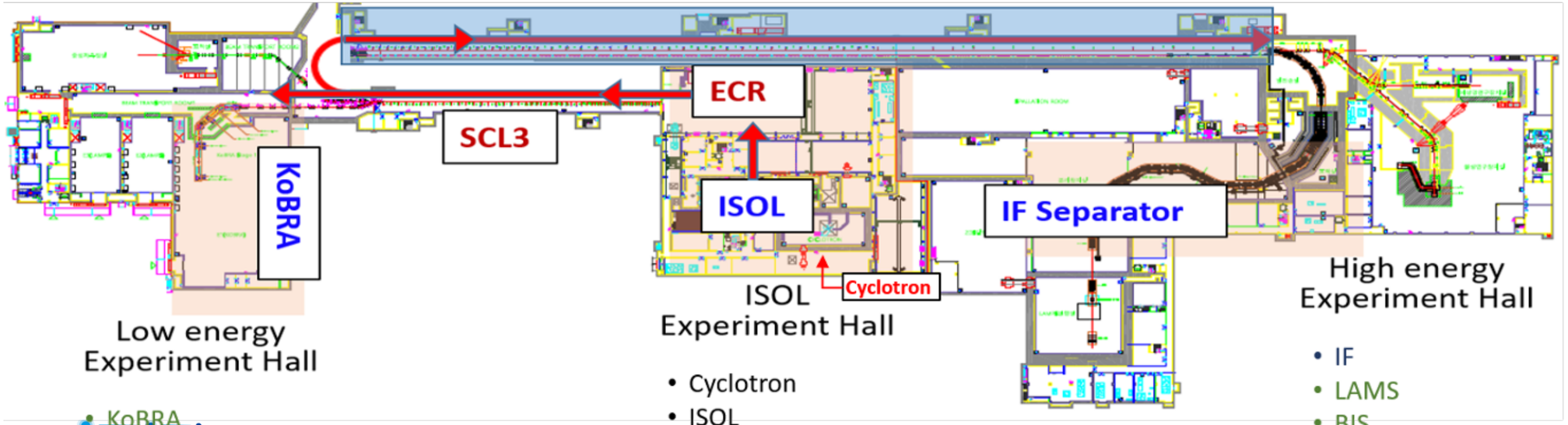
RAON (Rare isotope Accelerator complex for On-line experiments)



Overview: RAON

	KoBRA	ISOL	IF Separator
RIB production & acceleration mode	ECR (SIB) → SCL3 → KoBRA Prod. Target	Cyclotron (p) → ISOL (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

KoBRA : Korea Board acceptance Recoil spectrometer & Apparatus
IF : In-flight Fragmentation separator
SCL 3: (Low-energy) Super Conduction Linac 3
ISOL : Isotope-Separator Om-Line
SCL2 : (High-energy) Super Conduction Linac 2



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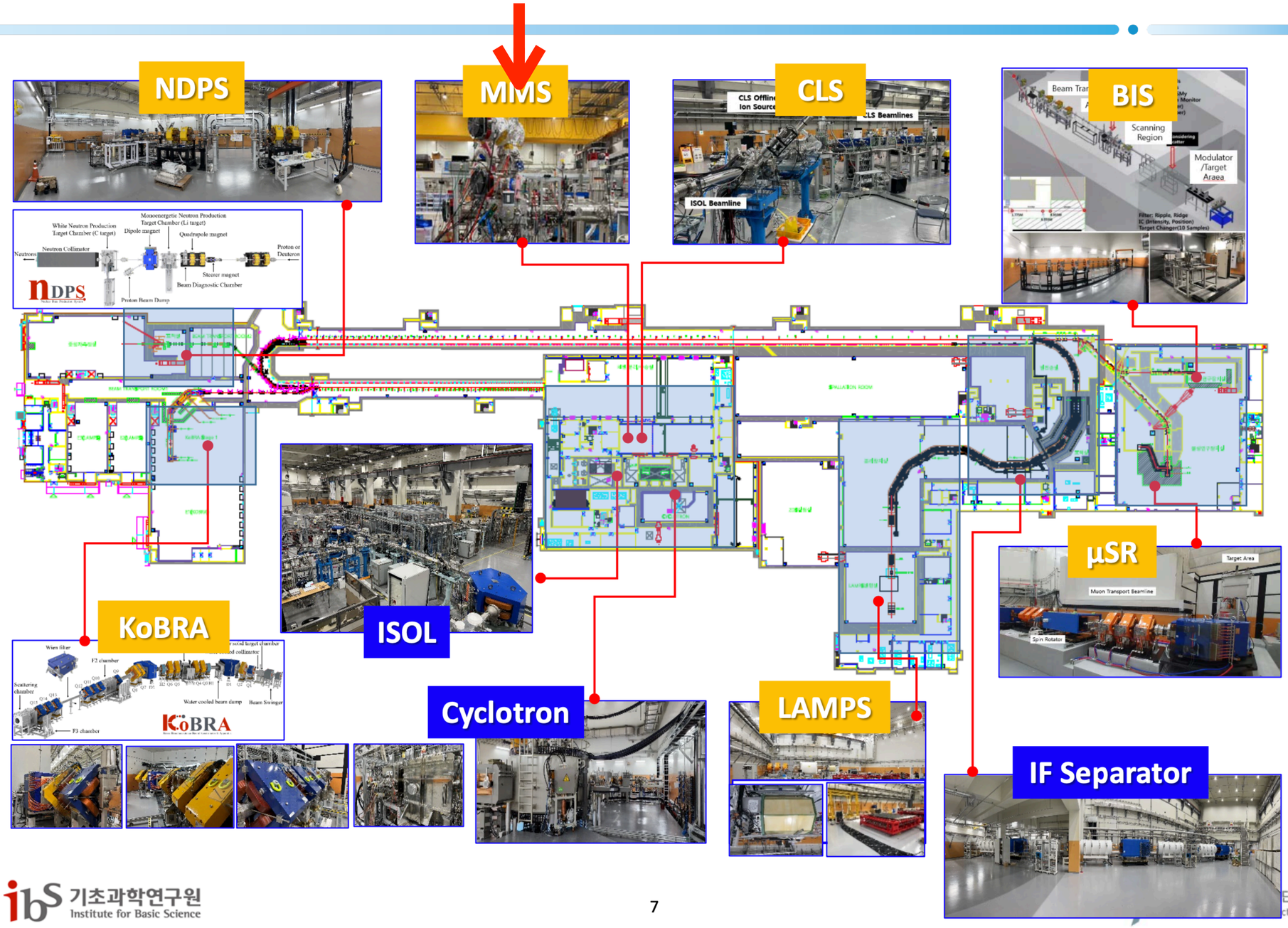
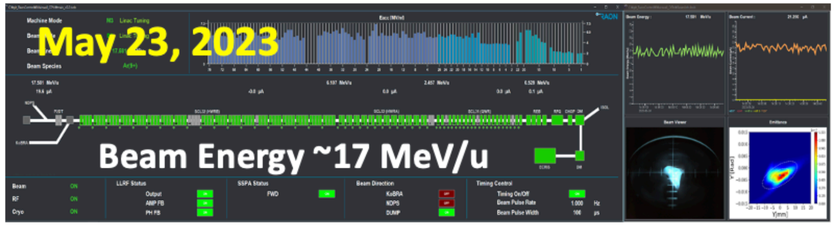
Overview: RAON



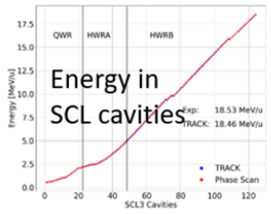
Overview: RAON

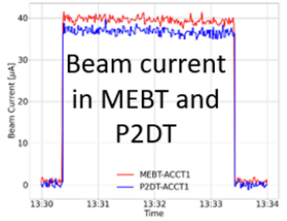
- **Commissioning of SCL3 with Ar beam**

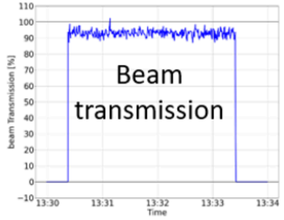


< The 1st commissioning with $^{40}Ar^{9+}$ beam >

- The first call for proposals was done in Dec. 2023 for domestic users (recommended by Science Advisory Committee)
- Three user experiments using SCL3 Ar beam and KoBRA were completed (July to August, 2024)



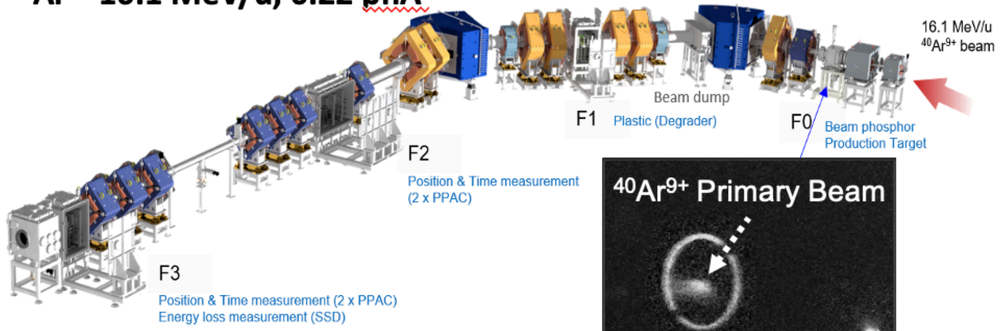




< The 2nd commissioning with $^{40}Ar^{8+}$ >

- **First Beam Commissioning of KoBRA (May 31 ~ June 2, 2023)**

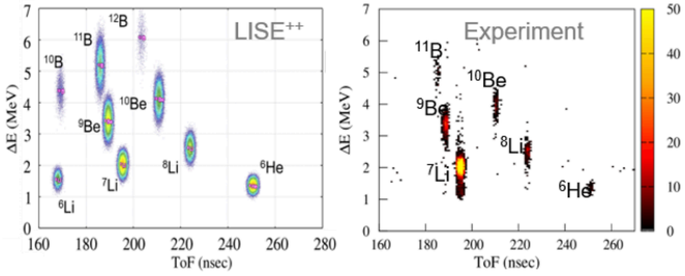
$^{40}Ar^{9+}$ 16.1 MeV/u, 0.22 pnA



< F0 Phosphor at KoBRA >

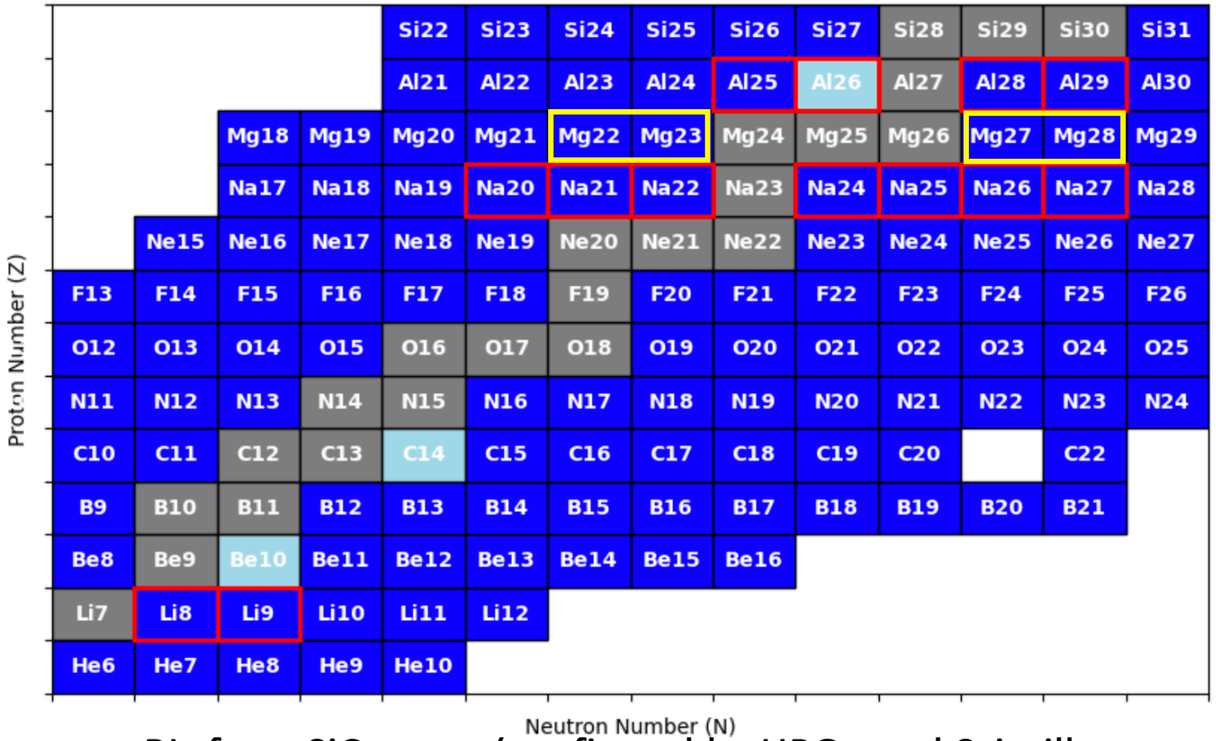
Particle identification with ΔE-ToF method

- SSD: Energy loss measurement
- PPACs: Time-of-flight measurement

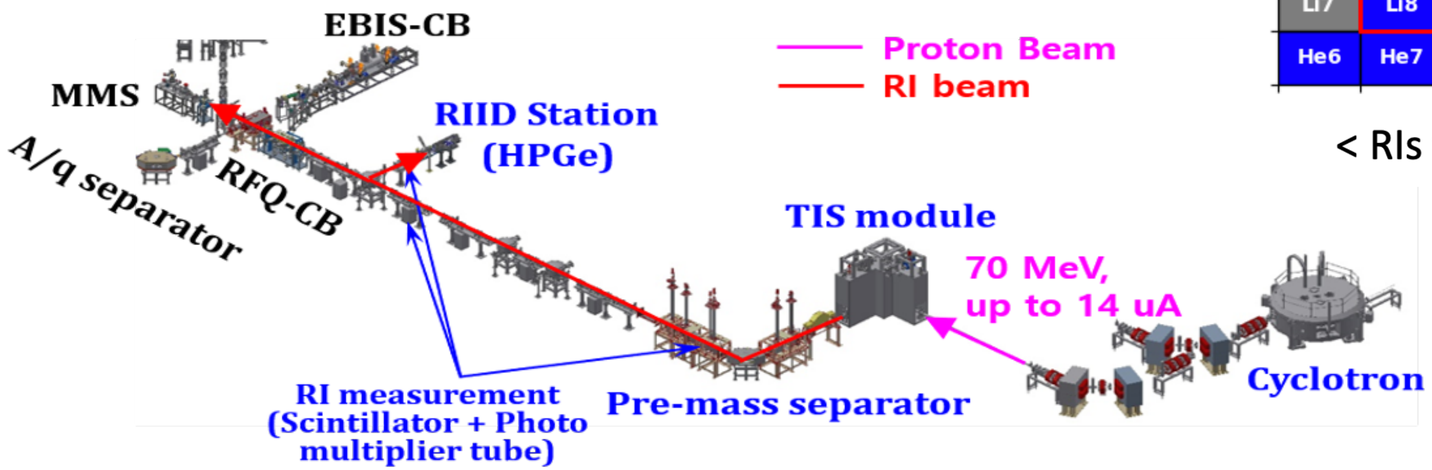


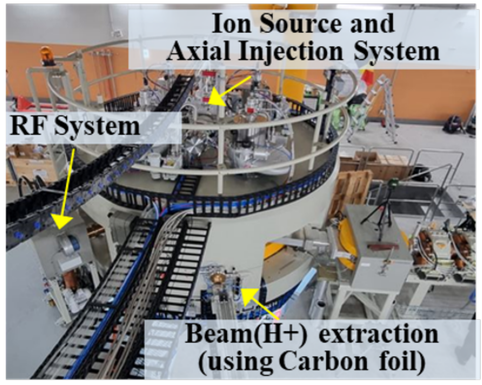
Overview: ISOL (Isotope Separation On-Line)

- Proton beam @E = 70 MeV, α Cyclotron
- Target: SiC, TiC, LaC_2, (UC_x)
- Ionization: Surface ionization, RILIS, (FEBIAD)
- RI's extracted and confirmed:
  - Na and Al isotopes (SiC, Surface)
  - Mg isotopes (SiC, RILIS)
  - Cs, Ba isotopes (LaC_2, Surface)
- RI re-acceleration of $^{25}Na^{6+}$ ($T_{1/2}$ = 59.4 s)



< RIs from SiC target (confirmed by HPGe and Scintillator >

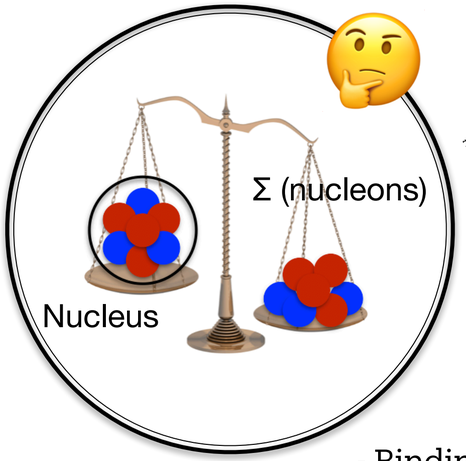




Cyclotron (IBA),

35~70 MeV, I < 0.75 mA

Mass: physics observable of MRTOF



M(Z,N) = Z×● + N×●

-Binding Energy (Z,N)

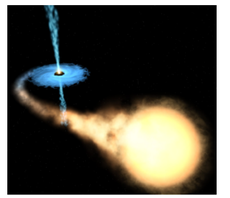
- Binding energy, attributed to the nuclear interaction
- Nuclear mass database, so helpful to understand
  a. nuclear interaction depending on isospin asymmetry
  b. nuclear synthesis path, in particular at the waiting points

Nuclear shell (structure) evolution, Origin of elements

Origin of elements: nuclear synthesis

r-process, *rp*-process, i-process, etc.,

occurring in various conditions



Binary system
(NS+Red Giant)

NSM

Mass: physics observable of MRTOF-MS

Neutron, proton separation Energy (S_n, S_p):

S_n (Z, N) = M(Z, N-1) + m_n - M(Z, N) = BE(Z, N) - BE(Z, N-1)

S_p (Z, N) = M(Z-1, N) + m_p - M(Z, N) = BE(Z, N) - BE(Z-1, N)

Resonance reaction rate:

resonance energy

$$N_A < \sigma v >= \frac{1.5399 \times 10^{11}}{(\mu T_9)^{3/2}} \Sigma(\omega\gamma)_i exp(-11.605 E_{Ri}/T_9)$$

Abundance ratio at the waiting point;

$$\frac{Y_{A+1}}{Y_A} = \rho_H \frac{G_{A+1}}{2G_A} \left(\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} exp(S_{p,A+1}/kT)$$

In r-process,

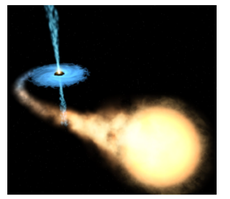
$$\frac{Y(Z, A+1)}{Y(Z, A)} = n_n \left(\frac{2\pi\hbar^2}{m_\mu kT}\right)^{3/2} \frac{G(Z, A+1)}{2G(Z, A)} \left(\frac{A+1}{A}\right)^{3/2} \times \exp\left[\frac{S_n(Z, A+1)}{kT}\right],$$

And $Q_{\beta\pm}$, important in the beta decays

Origin of elements: nuclear synthesis

r-process, *rp*-process, i-process, etc.,

occurring in various conditions



Binary system
(NS+Red Giant)

NSM

Principles of the MRTOF-MS

Basic principle: “Heavier and longer flight time”

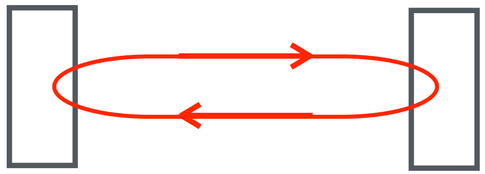
If KE = constant, $T \propto \sqrt{m} \longrightarrow m_1 = m_2 \left(\frac{t_1 - t_0}{t_2 - t_0}\right)^2 = m_2 \rho,$

1: unknown
2: Reference
m : ionic mass

$$R_m = \frac{m}{\delta m} = \frac{T}{2\delta T} \qquad Precision = \frac{\Delta m}{m} = \frac{1}{R_m \sqrt{N}}$$

N: number of ions

To achieve higher mass resolving power, *longer time-of-flight*, or *smaller width*, or both



Electrostatic Mirror

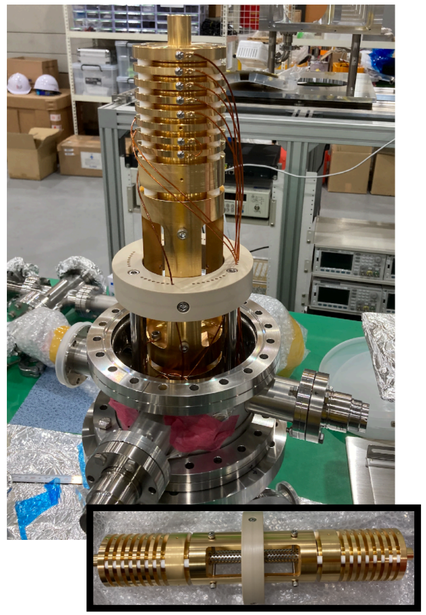
“Isochronous condition”, made to reduce the effect of initial energy spread of ions

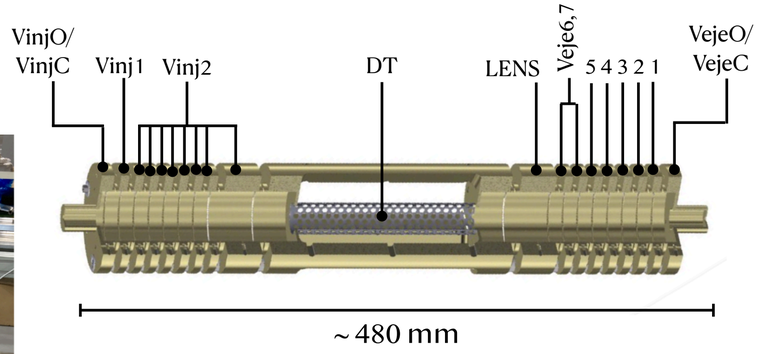
Large number of multiple reflections, equal to long flight length, e.g., a few hundreds meter or kilo-meter

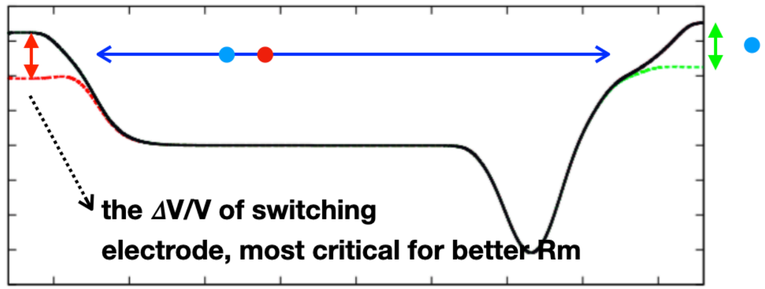
Principles of the MRTOF-MS

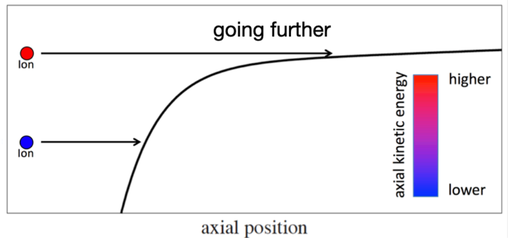
Multi-reflections in the well potential creating by mirror electrodes <—> A few 100s m flight

"Isochronous condition" creating a "Time focus" at a specific number of laps

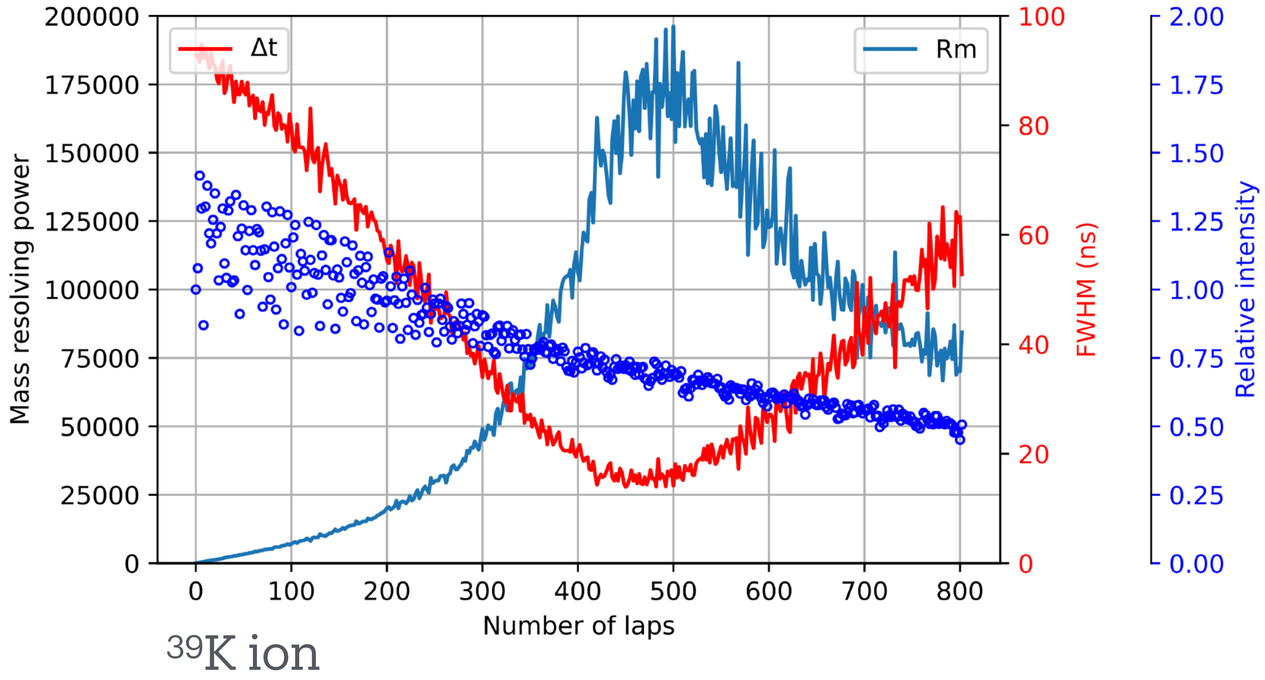








Internal transmission efficiency is around 60 ~ 70% for 500 laps (Time focus)

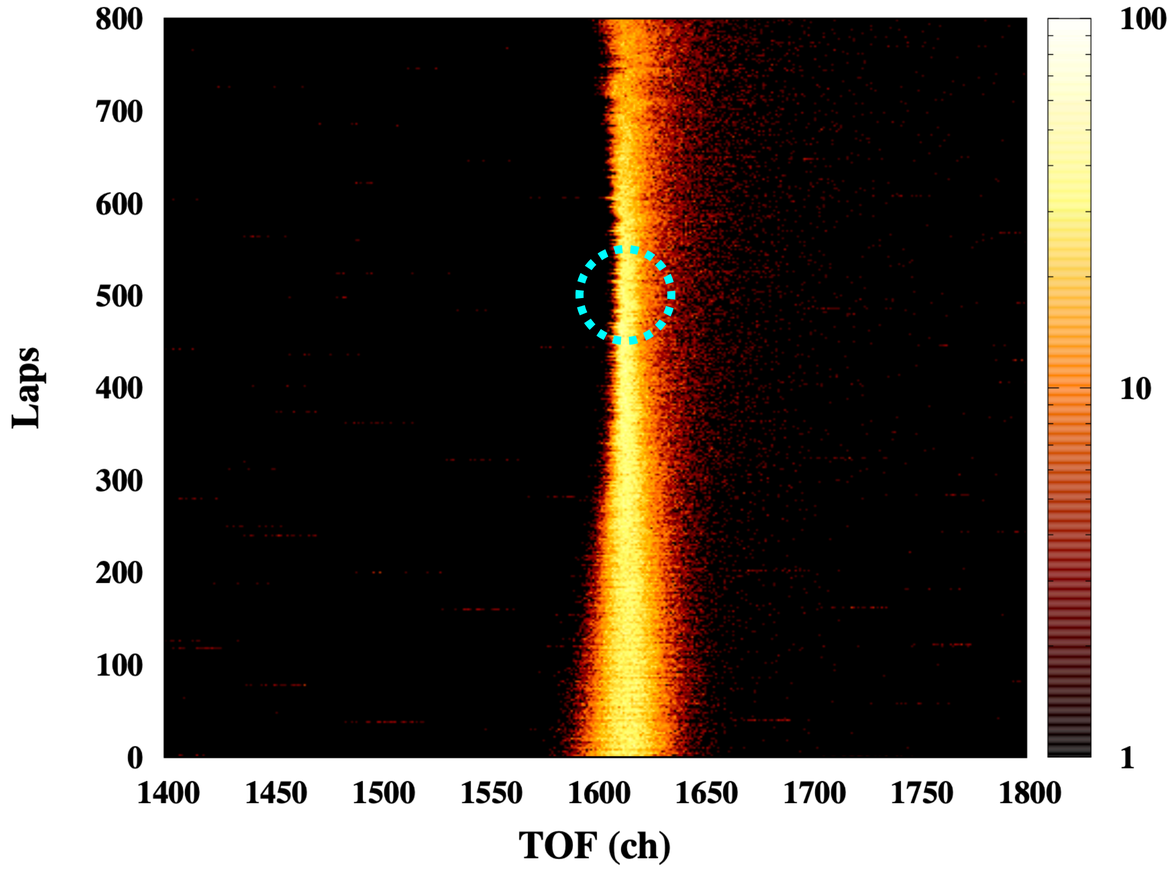


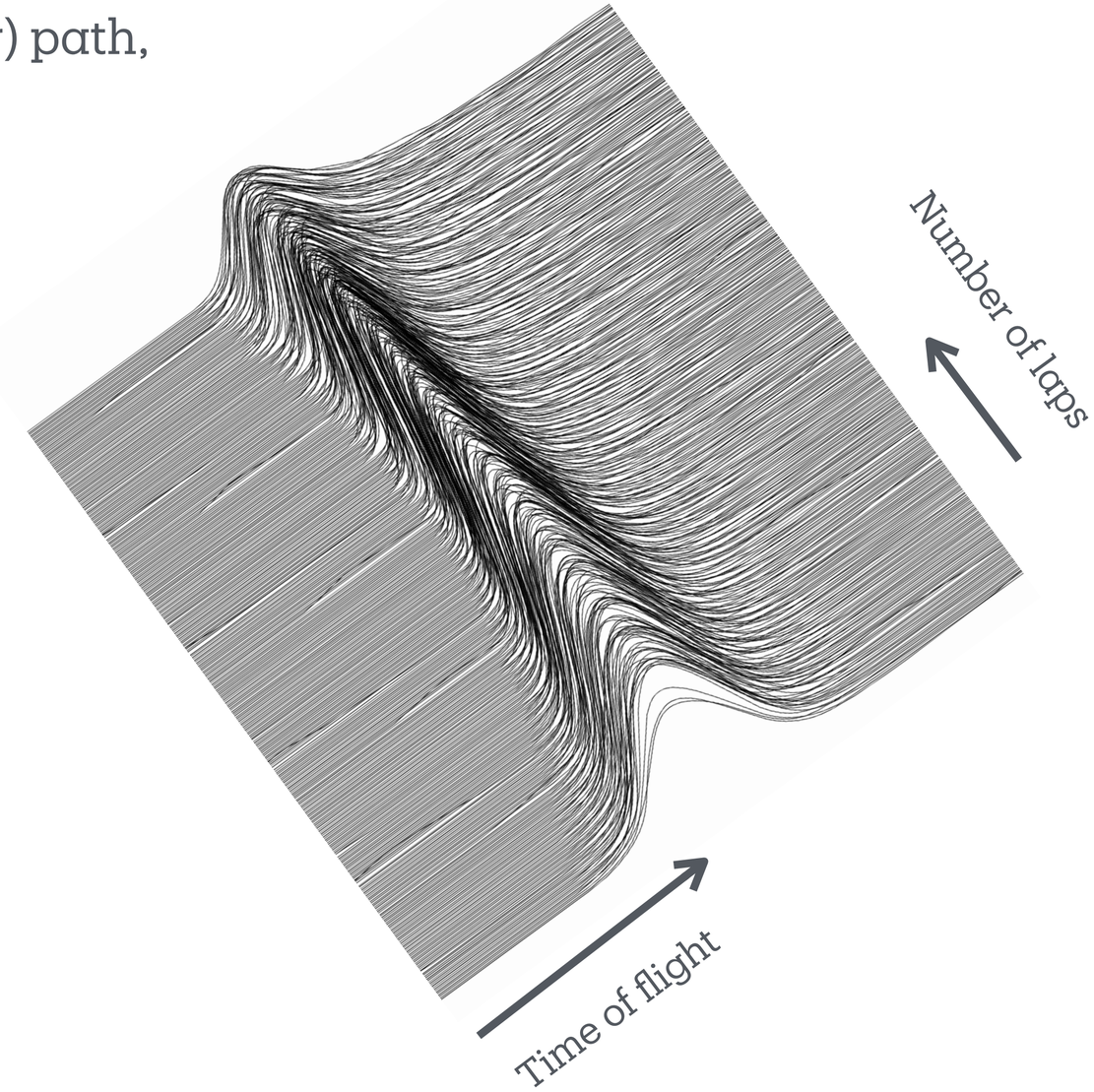
^{39}K ion

Principles of the MRTOF-MS

At the lap of time-focus, the width of TOF peak is at the minimum.

Ions in the faster (slower) region travel longer (shorter) path, making the TOF peak more narrow.

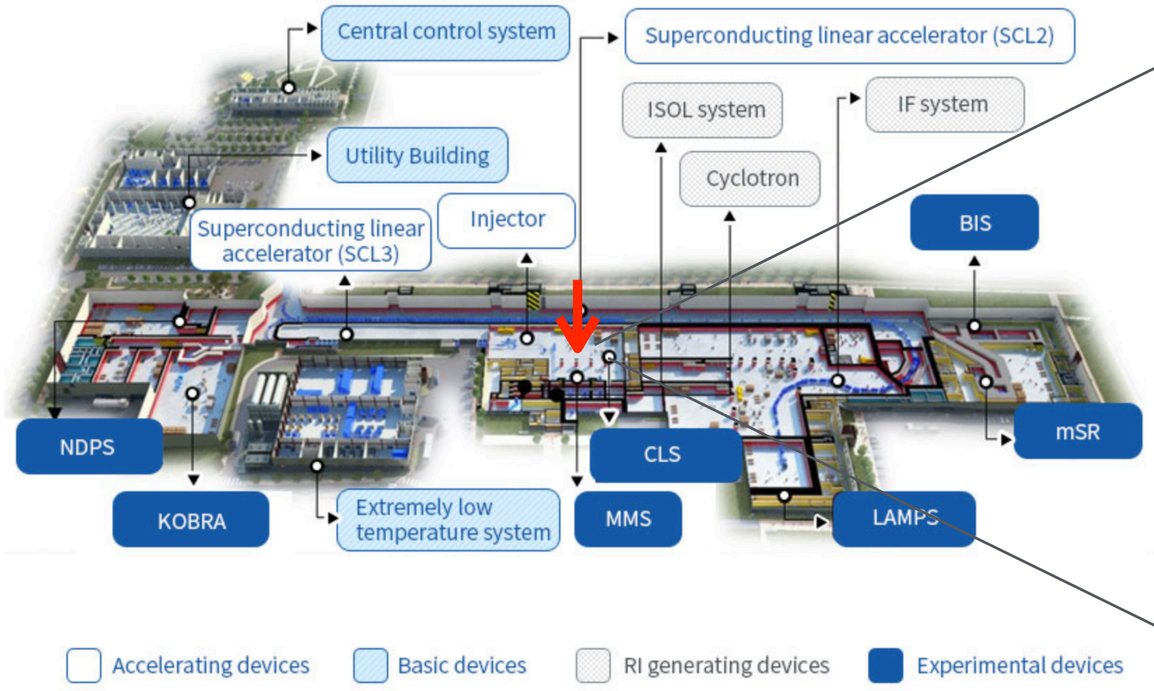




MRTOF-MS at RAON

RAON (Rare isotope Accelerator for ON-line experiments): A large scaled accelerator complex in Daejeon

- RI production: In-flight (IF), ISOL (Isotope Separation On Line) and combination of both
- MRTOF-MS, one of seven User experimental devices, installed at the ISOL hall.

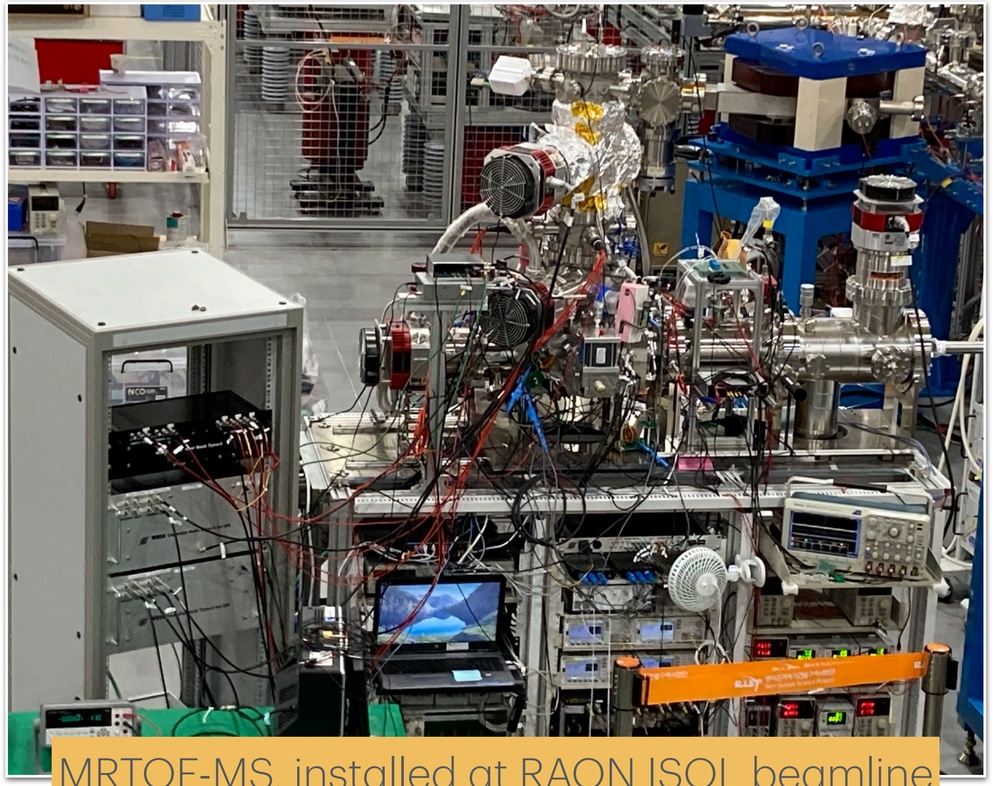


MRTOF-MS, installed at RAON ISOL beamline

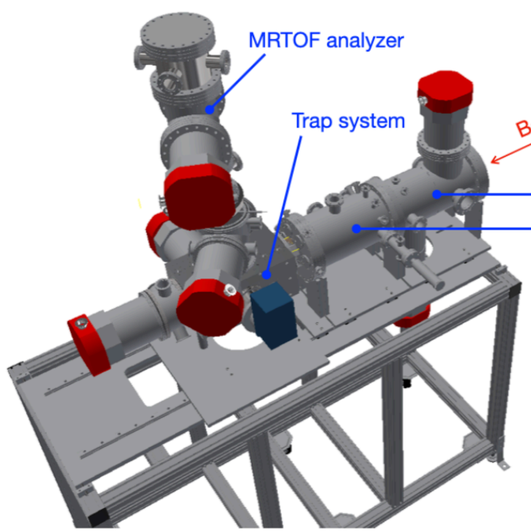
MRTOF-MS at RAON

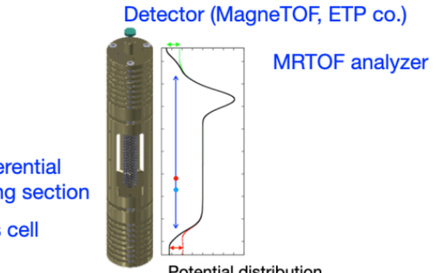
Gas cell (stopping incident ion beam of E < 10 keV), Trap system (cooling, bunching), and MRTOF analyzer (multi-reflections of ions)

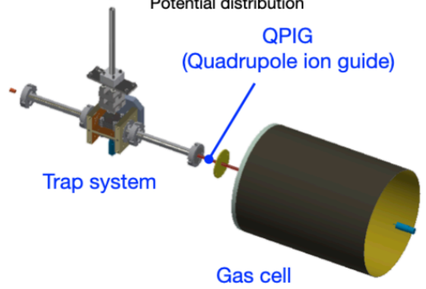
- Compact, quick and precise : Measurement time of < 10 ms, sub-ppm level relative precision
- Mass measurement, (*Isobar separation*)

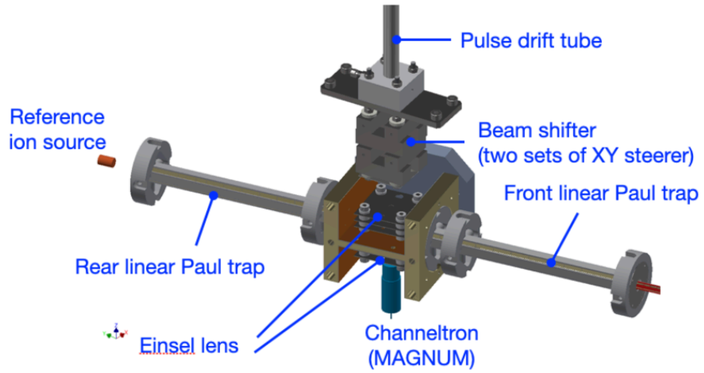


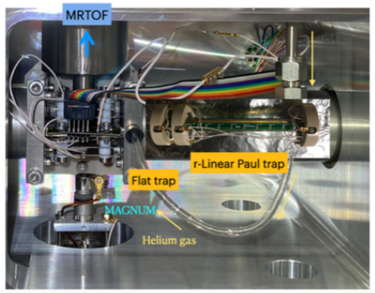
MRTOF-MS, installed at RAON ISOL beamline











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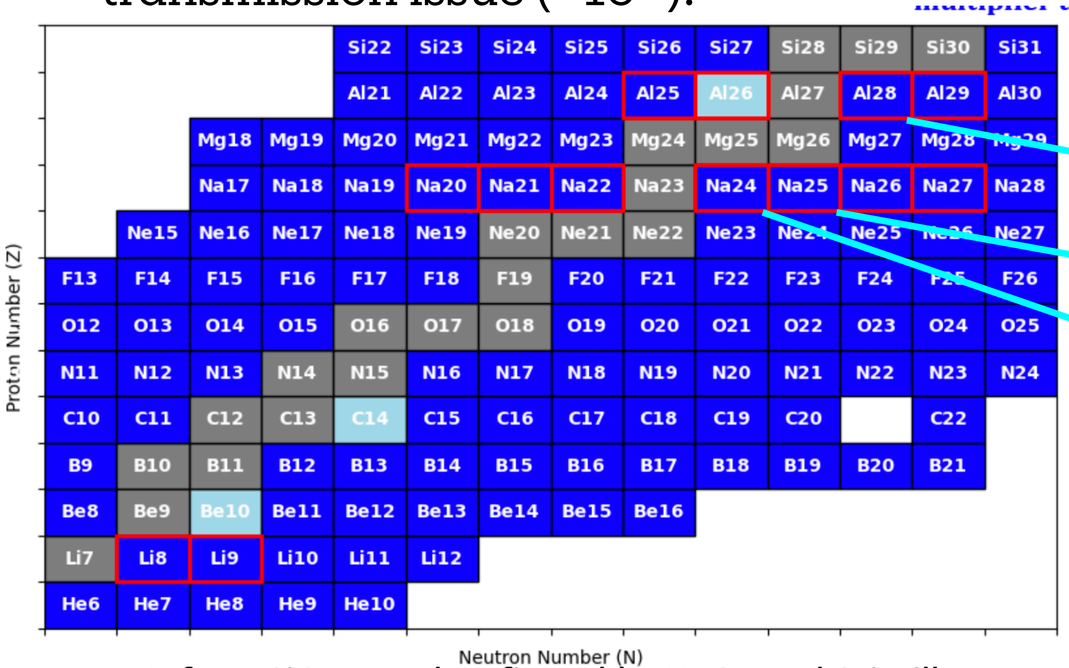
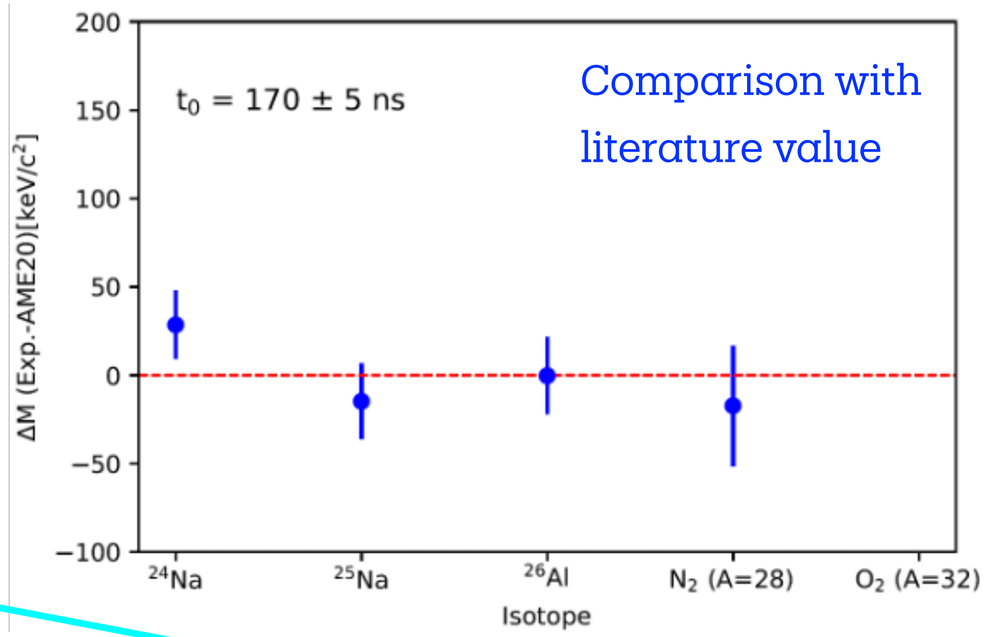
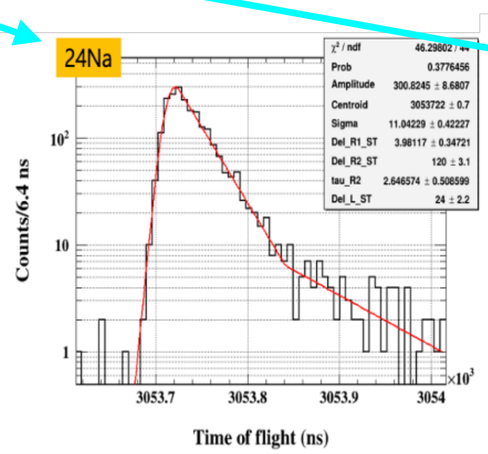
On-line Measurement of ISOL RI beams

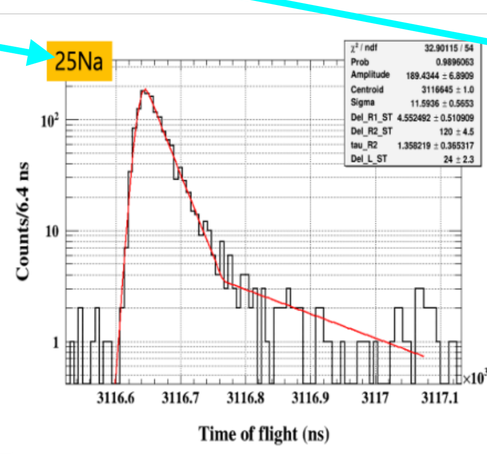
- Relatively intense rare isotopes produced at the ISOL TIS, have been measured at the MRTOF-MS.
- Observation is well agreed to the literature within the error.
- Lower yield isotopes will be accessed after resolving transmission issue (~ 10^{-4}).

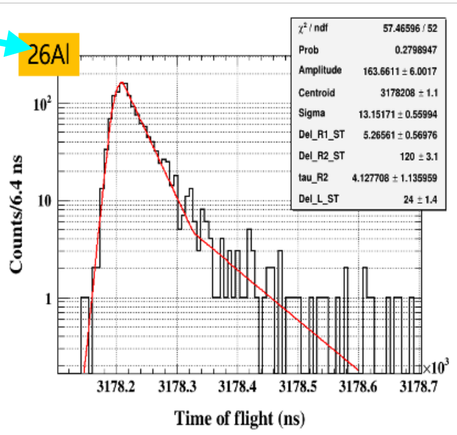


< RIs from SiC target (confirmed by HPGe and Scintillator >



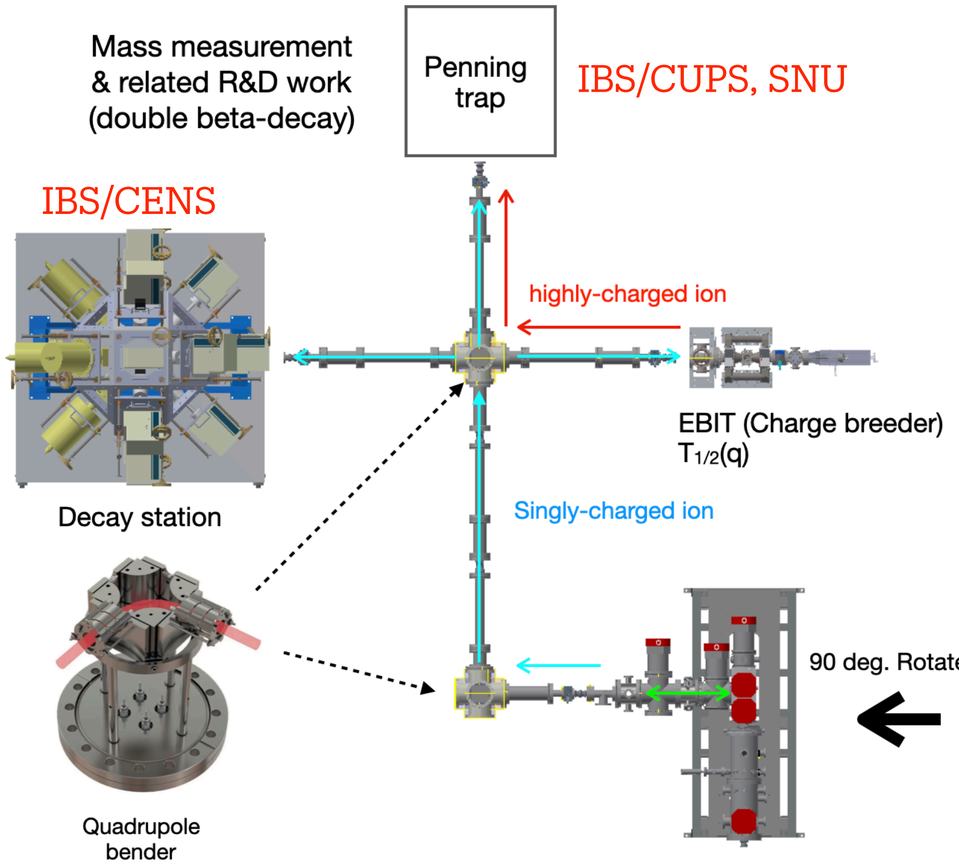




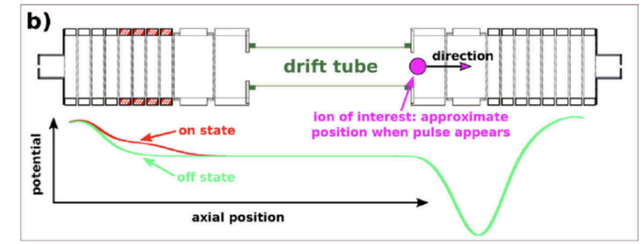


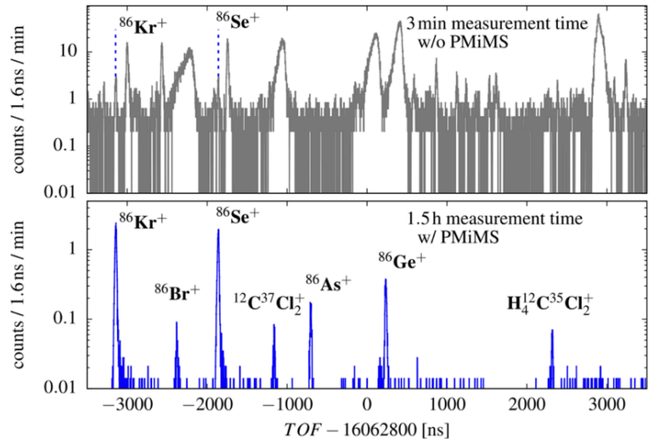
HIPPE beam line construction project

- Motivation: Diversification of the physics topics using ISOL beam
- Construction of the additional beamline for ISOL beam transport to the advanced facilities (“HIPPE”)



- HIPPE : HIgh Precision and Purity Experimental beamline
- MRTOF: Isobar separation for better beam purity





Before

After

M. Rosenbusch et al. NIMA 1047, 167824 (2023)

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HIPPE beam line construction project (Current status)

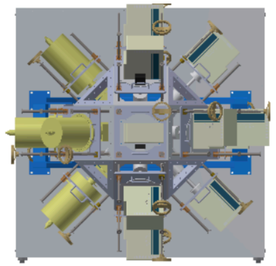
- Ion Optics carried out, with SIMION
- Q-bender and steerer, constructed

Mass measurement
& related R&D work
(double beta-decay)

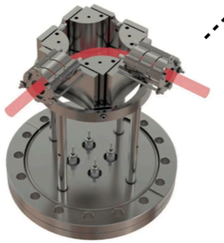
Penning trap

IBS/CUPS, SNU

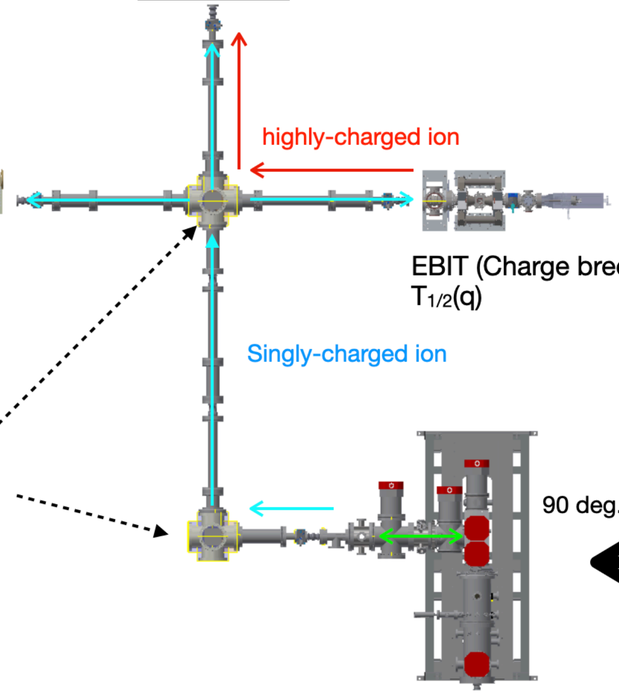
IBS/CENS



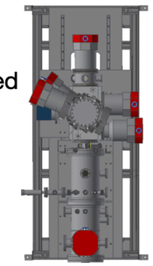
Decay station



Quadrupole bender



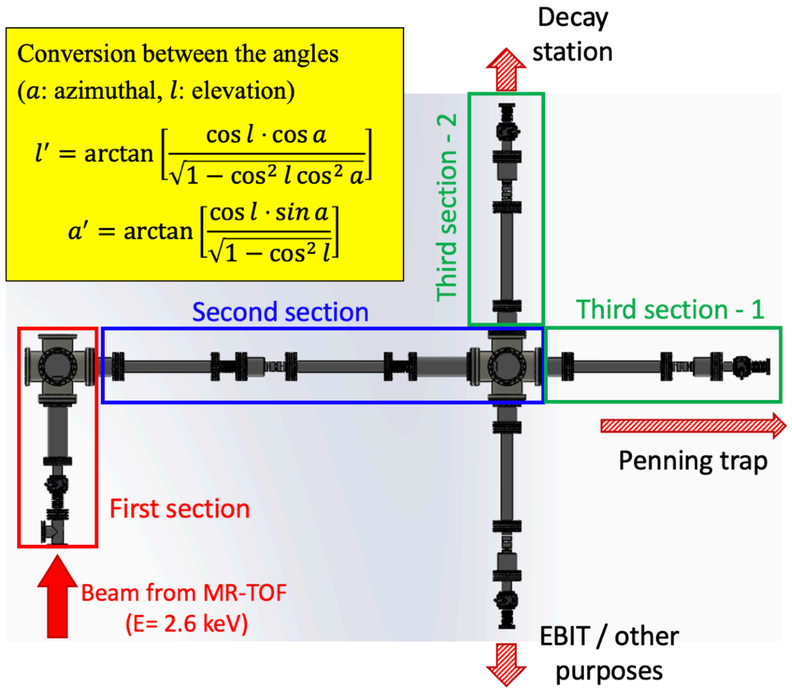
90 deg. Rotated



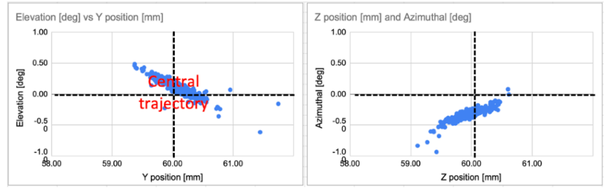
Conversion between the angles
(a: azimuthal, l: elevation)

$$l' = \arctan\left[\frac{\cos l \cdot \cos a}{\sqrt{1-\cos^2 l \cos^2 a}}\right]$$

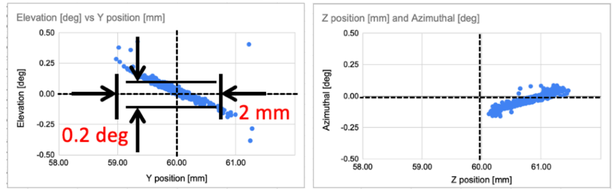
$$a' = \arctan\left[\frac{\cos l \cdot \sin a}{\sqrt{1-\cos^2 l}}\right]$$

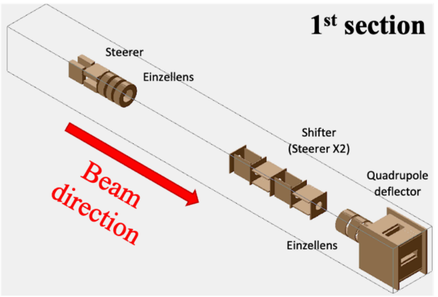


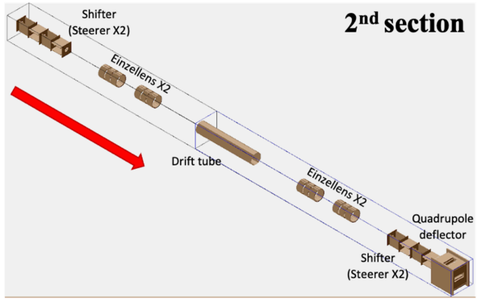
[Emittances - 90 deg]

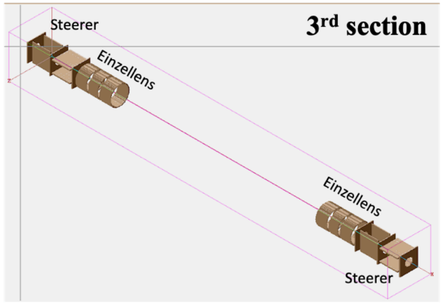


[Emittances - 0 deg]









Summary and plans

- RAON is Korea's largest accelerator research facility, aiming to achieve global competitiveness and address the needs of external users.
- The ISOL facility offers key advantages:
  - Intense and better emittance rare isotope or stable ion beams.
  - Particularly suitable for low-energy ion beam experiments, i.e., E < 20 keV.
- MRTOF (Multi-Reflection Time-of-Flight Mass Spectrometer):
  - Specialized in the short-lived, low-intensity rare isotopes.
  - Expected to contribute to optimization of beam production.
- Future plans (Construction of new beam line):
  - Installation of new experimental devices to expand the research fields in the ISOL
  - Decay Station (IBS/CENS), Penning Trap (IBS/CUP), EBIT (POSTECH), in consideration.
  - Promote research collaboration through this.

감사합니다.

Back-up

Indirect methods such as “reactions” and “decays (α, β, γ, p, etc)”

- Useful especially for the isotopes whose structures are well known

Direct measurement is more preferred, many devices currently in operation.