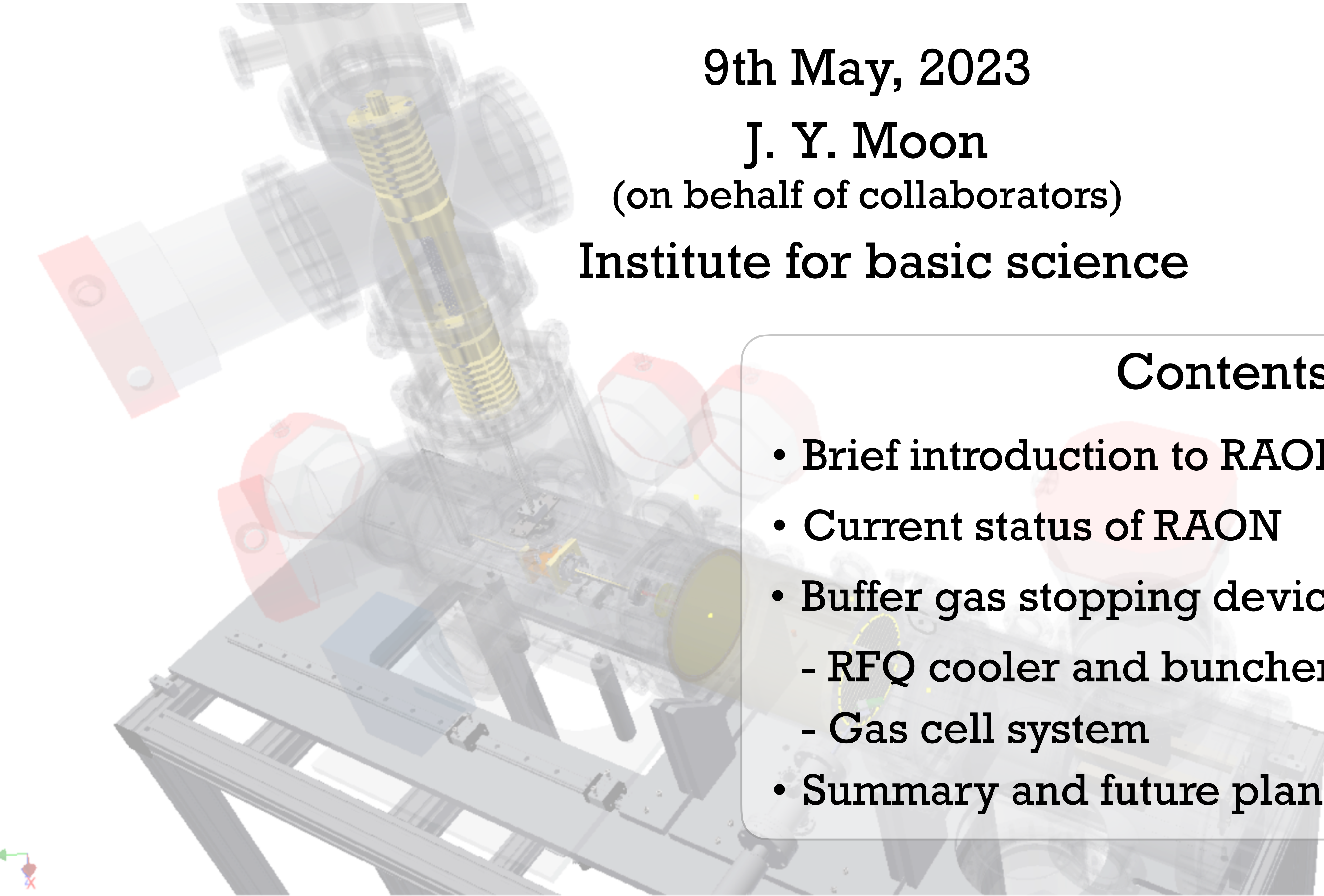
14th International Conference on Stopped and Manipulation of ions and Related topics
SMI-2023, 8th-11th of May 2023, Gießen, Germany
Burghotel Staufenberg

Current status of the gas stopping devices in RAON

9th May, 2023

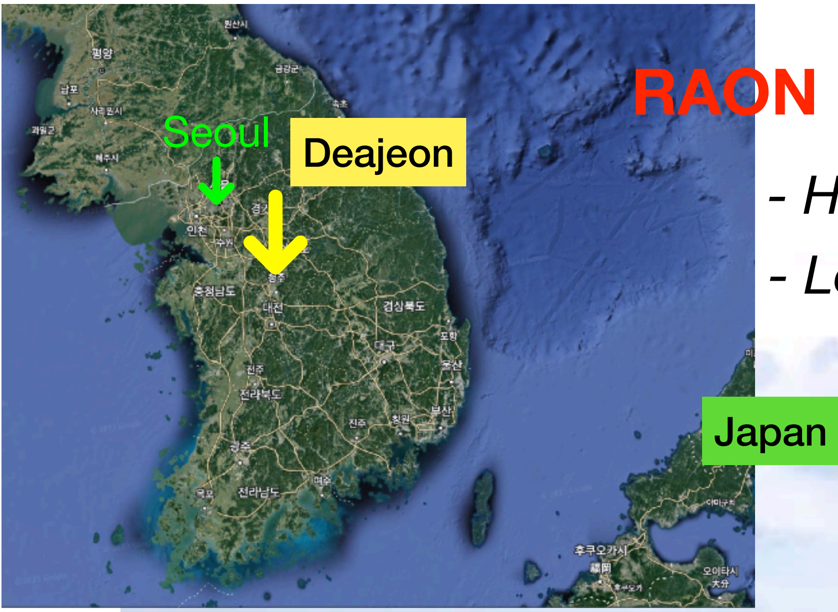
J. Y. Moon
(on behalf of collaborators)
Institute for basic science



Contents

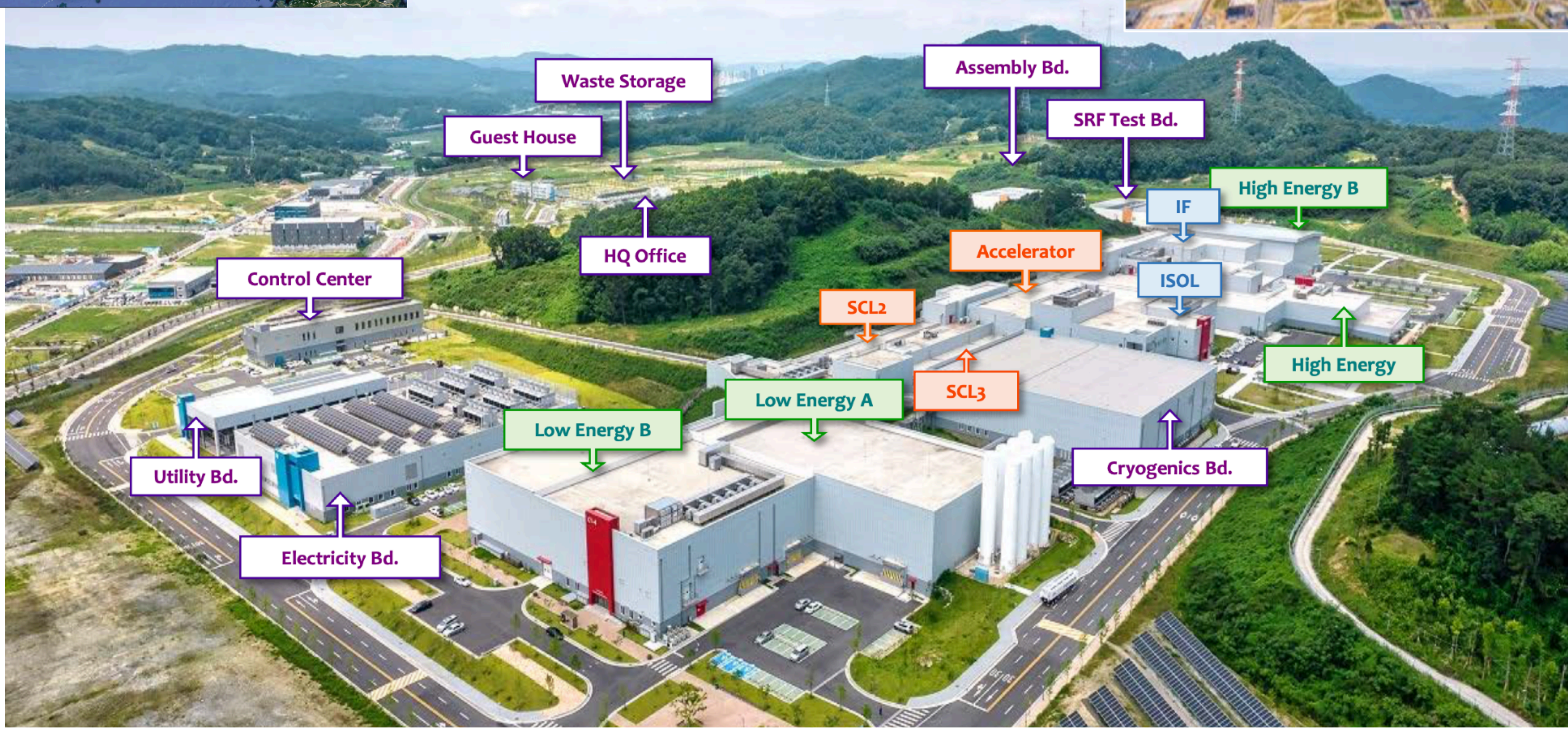
- Brief introduction to RAON
- Current status of RAON
- Buffer gas stopping devices in RAON
  - RFQ cooler and buncher
  - Gas cell system
- Summary and future plan

Introduction : RAON



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

- *Heavy ion accelerator complex, capable of RI beam production*
- *Located at "Daejeon", 2 hour-by-car away from the capital city of Korea (Seoul)*

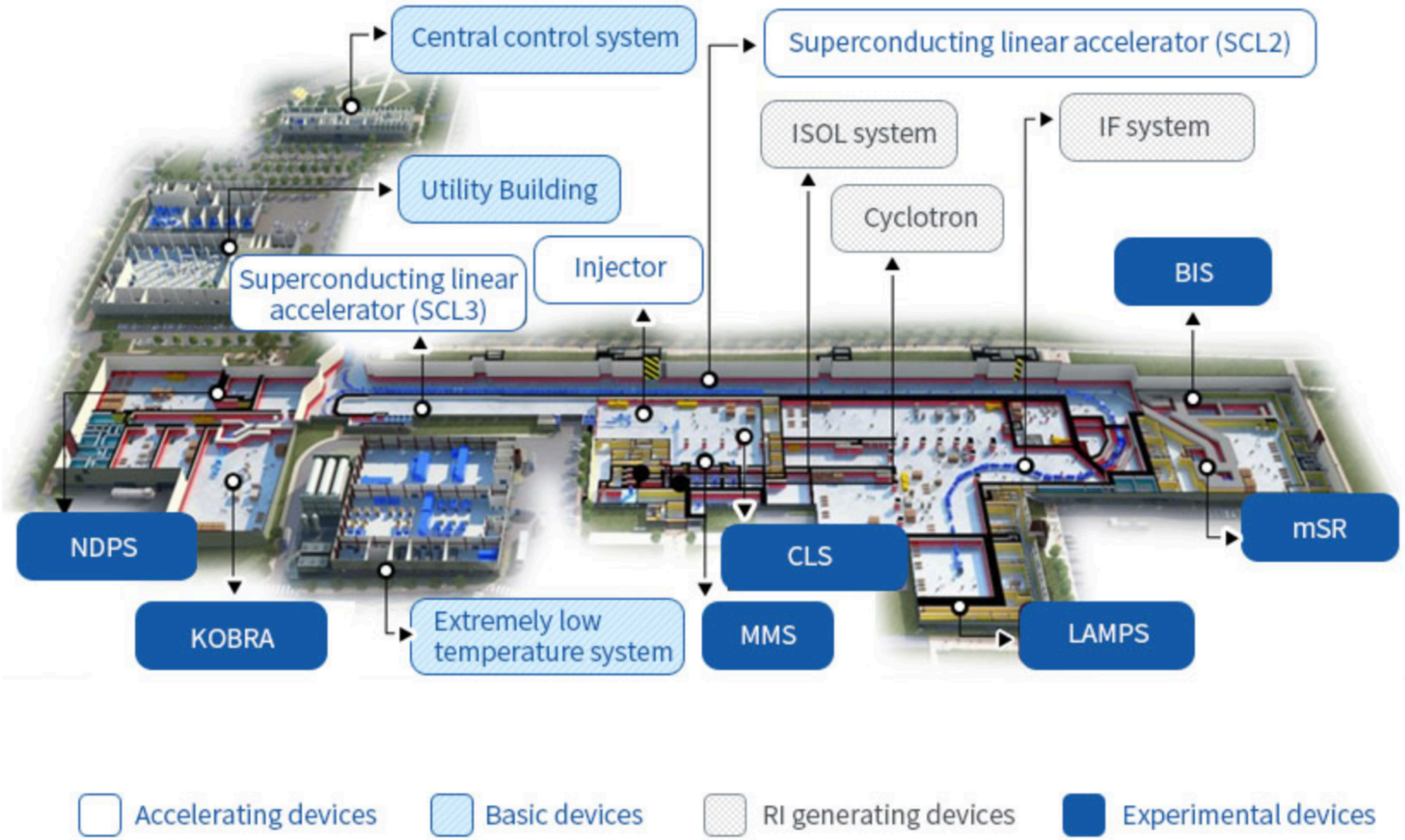


Introduction : RAON

- Two superconducting LINACs : < 18.5 MeV/u w/ SCL3, < 200 MeV/u w/ SCL3+*SCL2**
  - Low energy IF and High energy IF for RI beam production

(*: construction in Phase 2)

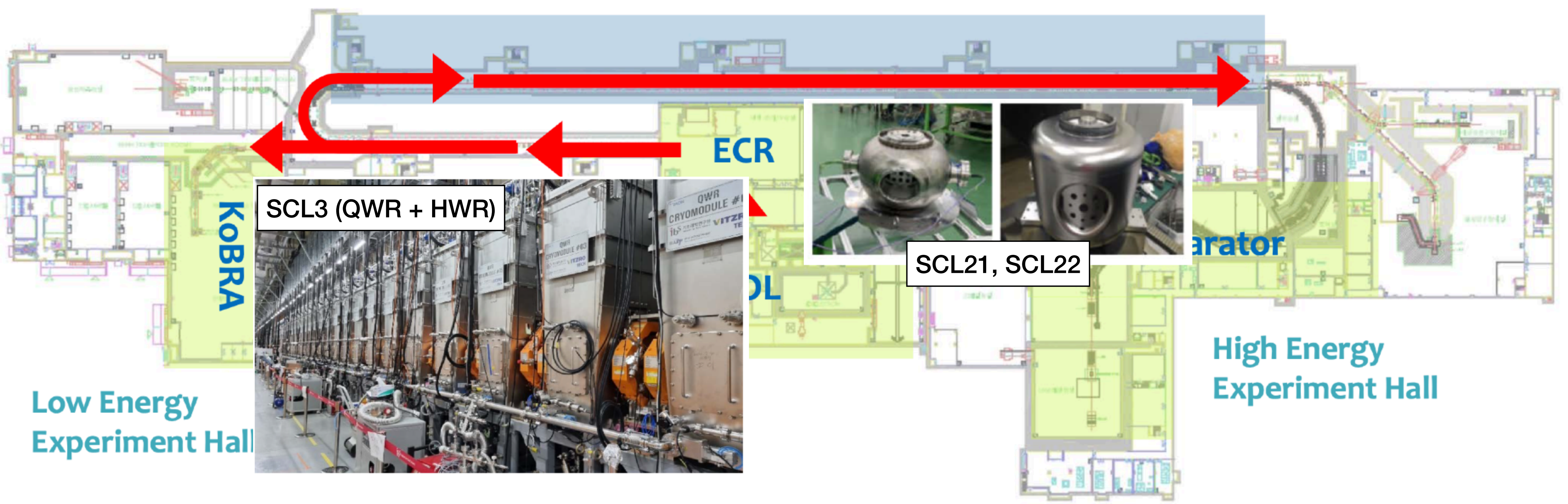
- Cyclotron (IBA, 70 MeV, 50 kW) : ISOL, recently started to send proton beam to TIS



Introduction : RAON

- Two superconducting LINACs : < 18.5 MeV/u w/ SCL3, < 200 MeV/u w/ SCL3+SCL2,
  Low energy IF and High energy IF for RI beam production
- Cyclotron (IBA, 70 MeV, 50 kW) : ISOL, recently started to send proton beam to TIS

	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 keV/u	< hundreds of MeV/u

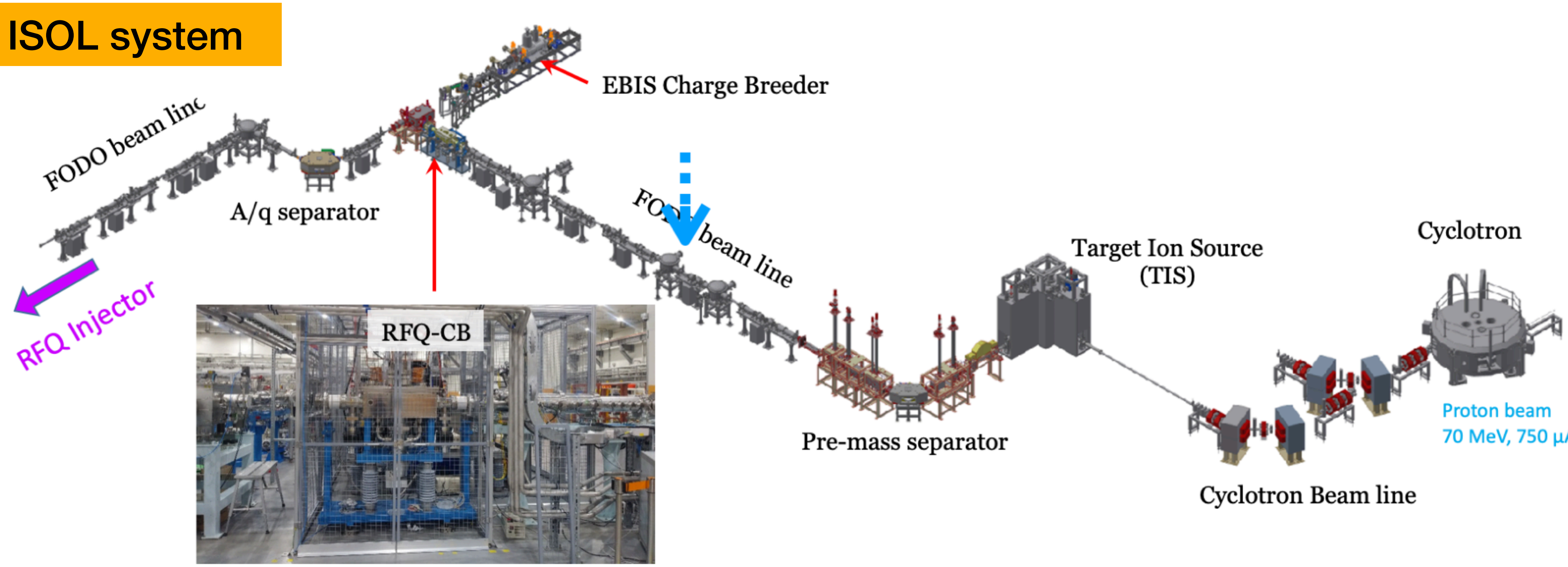


Introduction : RAON

- Two superconducting LINACs : < 18.5 MeV/u w/ SCL3, < 200 MeV/u w/ SCL3+SCL2, Low energy IF and High energy IF for RI beam production
- Cyclotron (IBA, 70 MeV, 50 kW) : ISOL, recently started to send proton beam to TIS

	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 keV/u	< hundreds of MeV/u

ISOL system



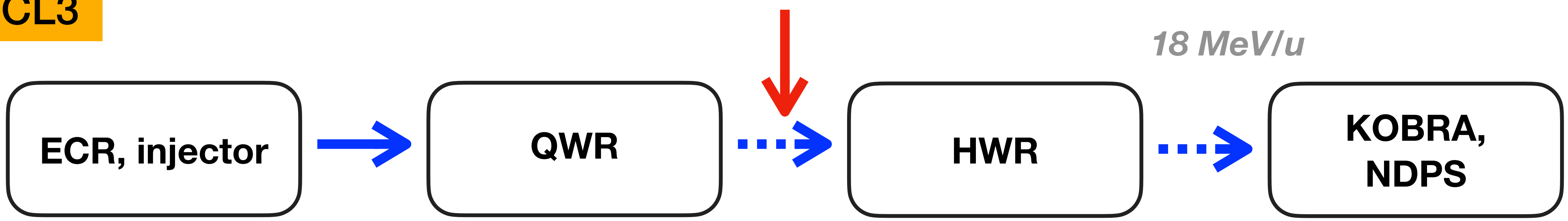
Introduction : RAON

We have recently achieved some successes.

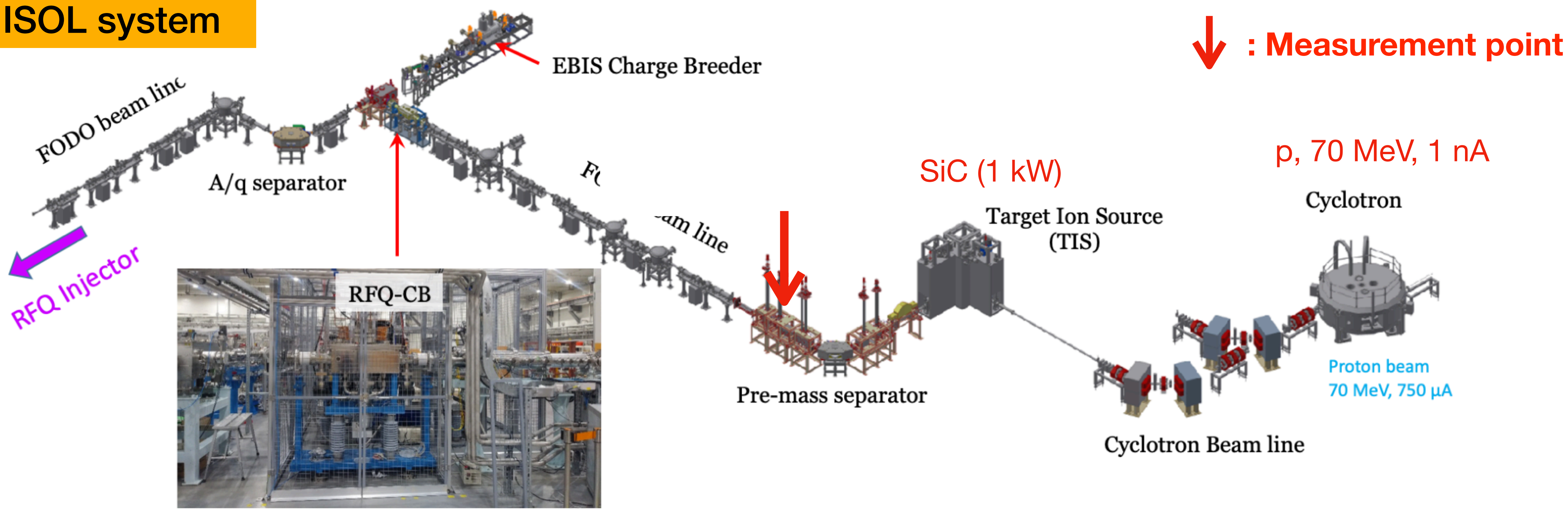
(Apr. 2023) Succeeded in acceleration of Ar^{9+} up to 2.3 MeV/u using QWR #1 ~ #22 in SCL3

(Mar. 2023) Identified radioactive ion beams from ISOL target, i.e. ^{21}Na ($T_{1/2}$=22.49 s), ^{24}Na ($T_{1/2}$=14.99 h), and ^{25}Na ($T_{1/2}$=59.1s)

SCL3

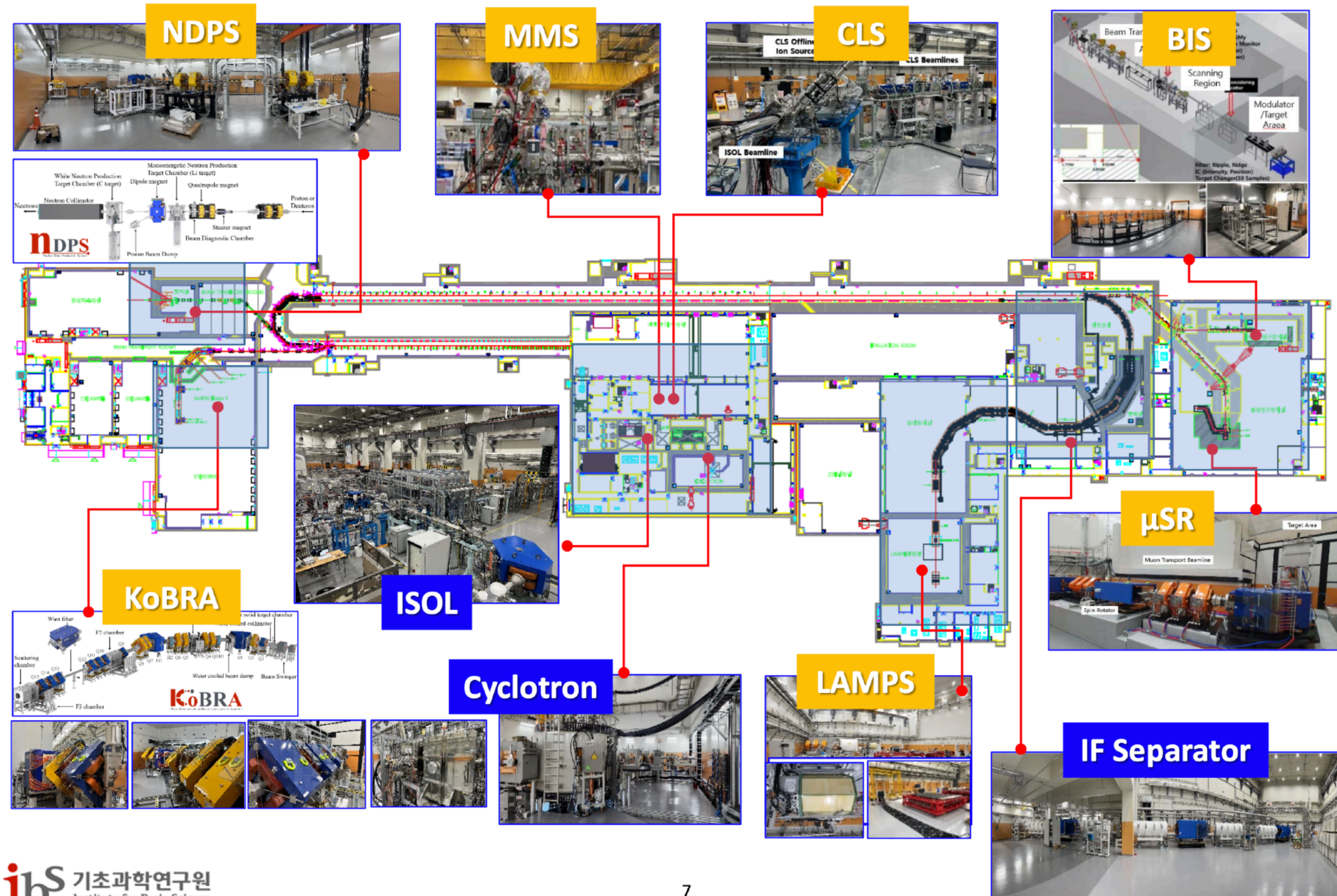


ISOL system



Introduction : RAON - User facilities

- Experimental devices for the nuclear science and its applications (material, bio, and etc.)



Buffer gas stopping devices @RAON

- Two buffer gas stopping devices, installed in ISOL beamline of RAON
  - RFQ cooler-buncher (RFQ-CB): cooling and bunching the ISOL beam for EBIS and *CLS*
  - Gas cell cooler-buncher (GCCB): thermalizing the ISOL beam for MRTOF-MS
- RFQ-CB is currently working only for the EBIS, but together with the GCCB can be applied for "*radioactive molecular beam formation in the trap*"

GCCB: beam diagnosis using CID technique
Collinear laser spectroscopy: Spectroscopy of MO beam

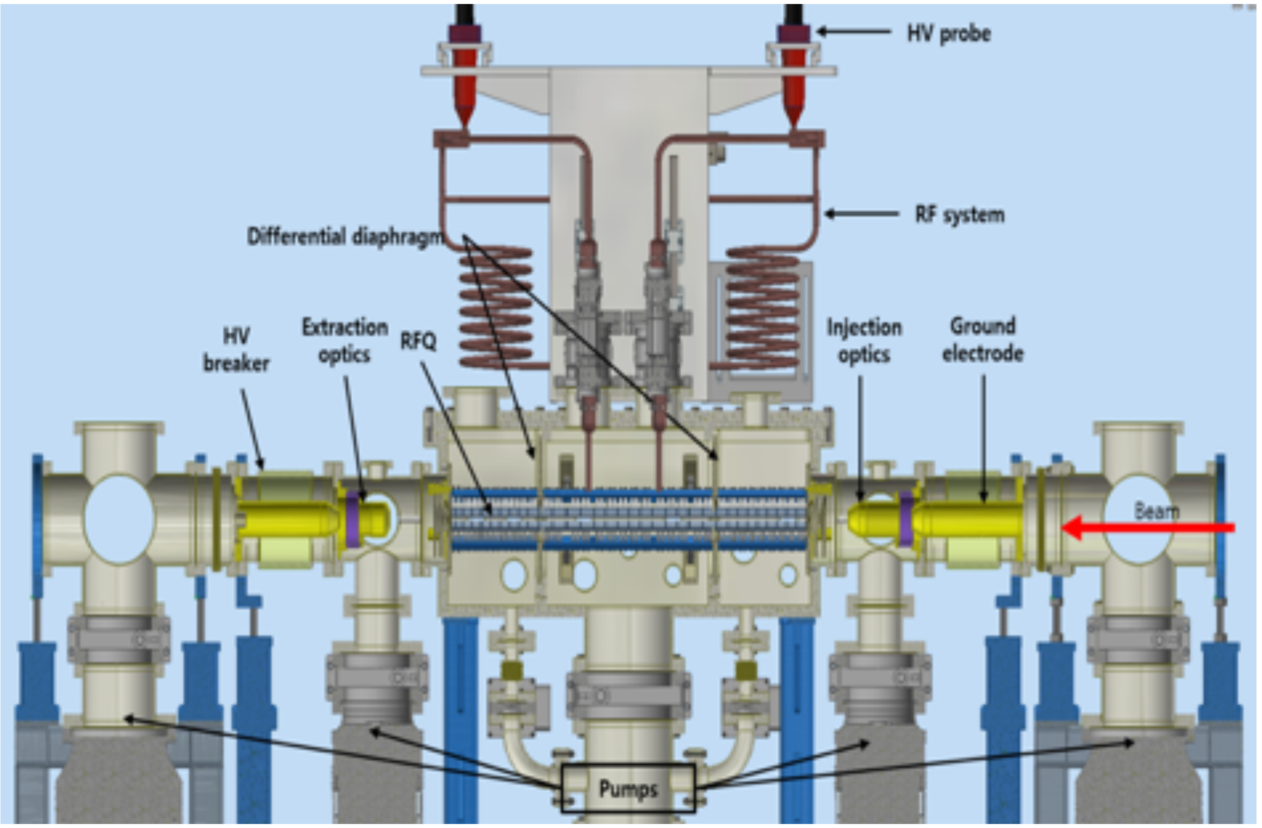
Under consideration!

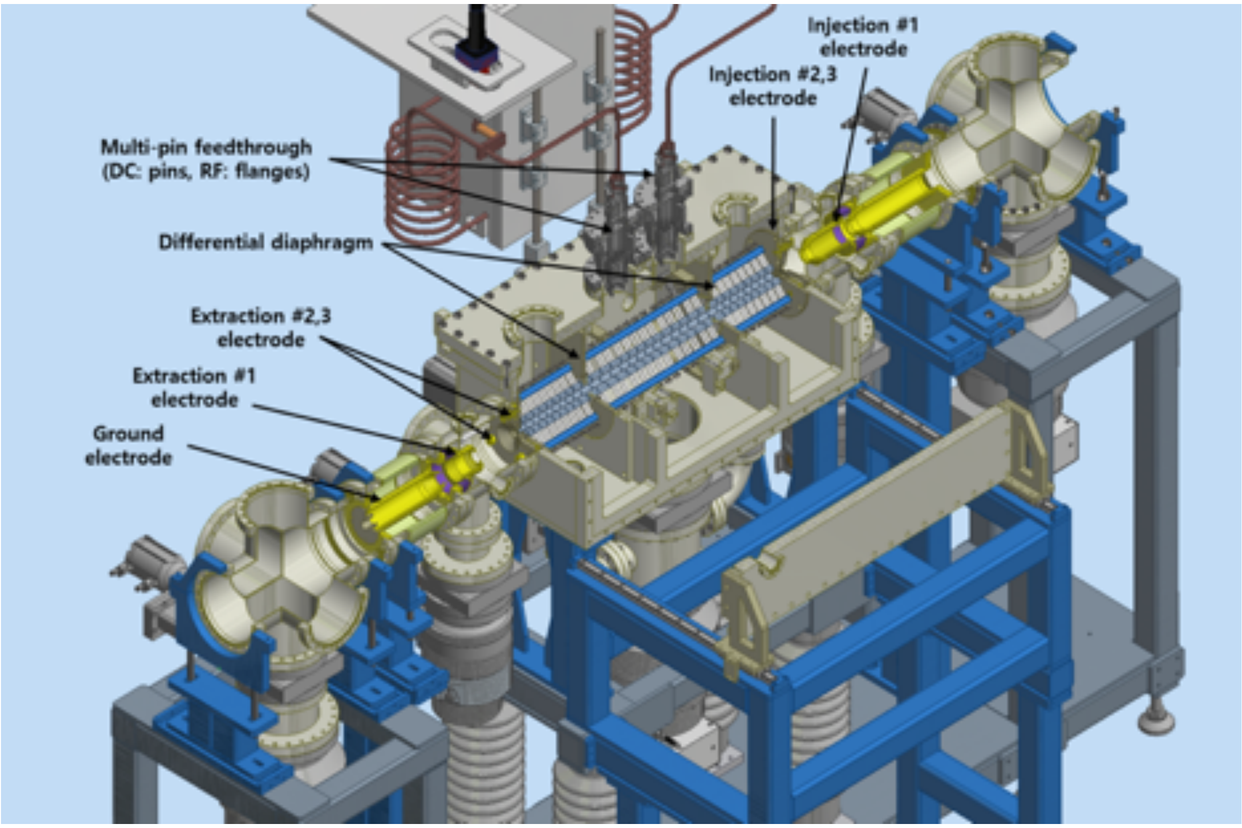
RFQ cooler and buncher

- The ISOL beam should be charge-bred via EBIS for re-acceleration.
- Cooled and bunched beam for the EBIS to have higher charge-breeding and transmission efficiencies, is indispensable.

Design parameters of RFQ-CB

Beam parameter	Performances for EBIS
Beam current	10^8 *ion per bunch*
Transverse Emittance	$< 10\ \pi\ mm\ mrad$
Energy Spread	< 10 eV
Bunch width	$< 100\ \mu s$
Cooling time	~ 100 ms
Transmission Efficiency	> 80 %

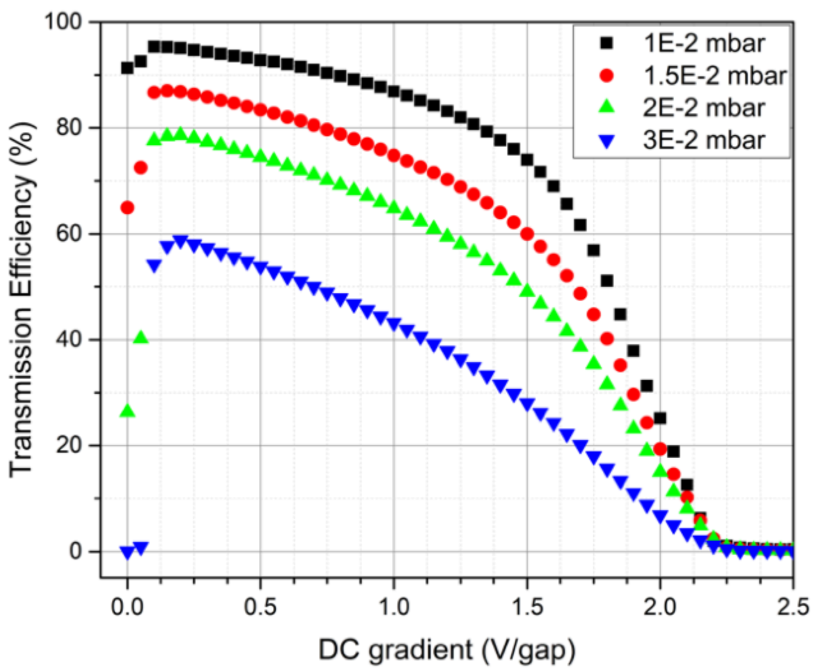


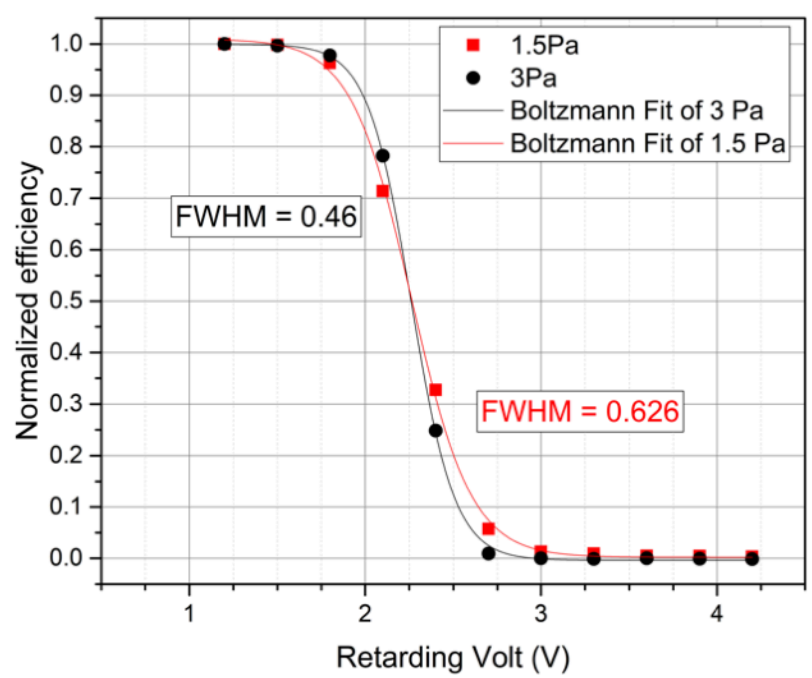


RFQ cooler and buncher

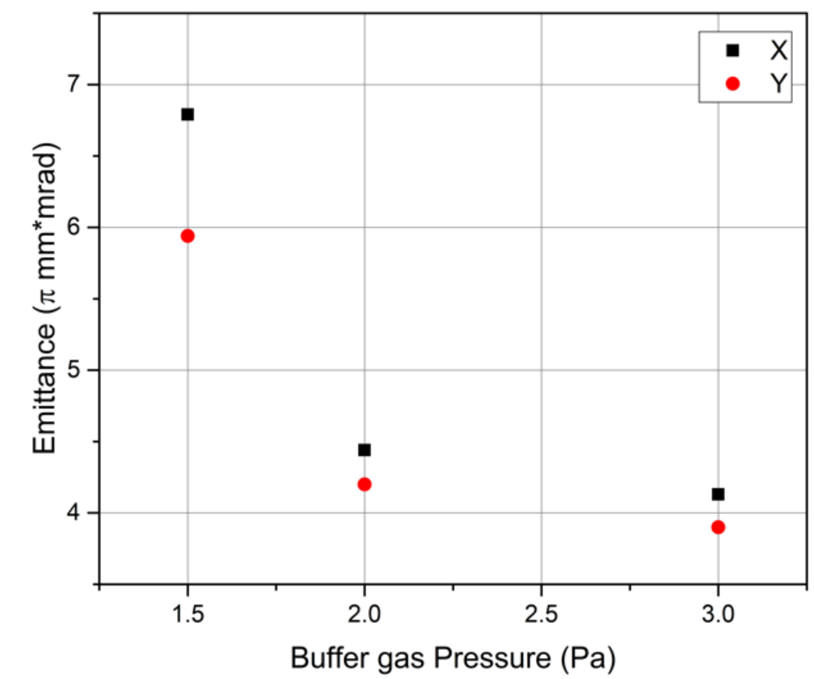
- Off-line commissioning: E_K = 5 keV, ^{133}Cs (Heatwave co.), DC/Bunch mode
- Beam diagnosis system: Faraday cup x 2 (current), Pepper pot x 2 (Profile, emittance)

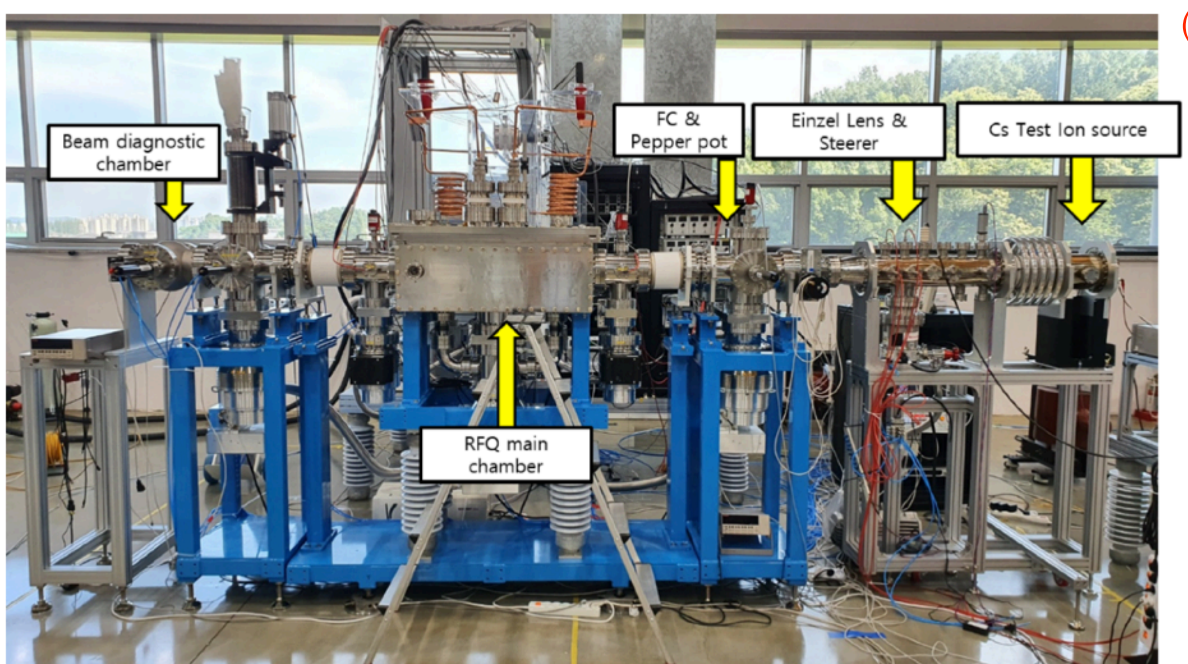
DC mode



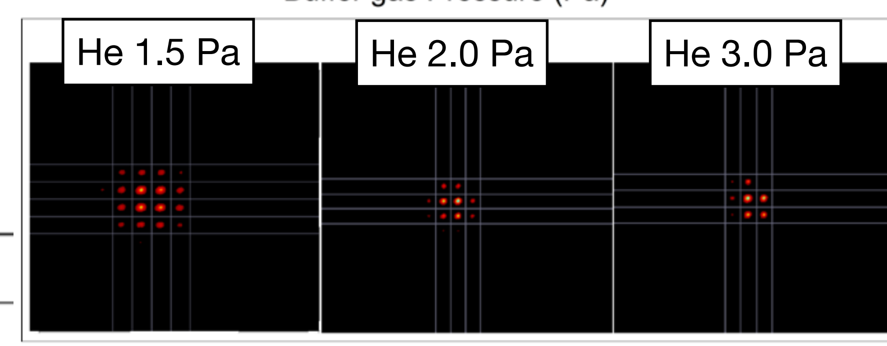


(Retarding voltage on the last elect.)





Parameter	Value	unit
Beam energy	5 k	eV
RF frequency	2	MHz
RF voltage	400∼4800	V_{p-p}
He pressure	0.5 ∼2	Pa
Beam current	1∼40	nA
DC gradient	0.1∼2	V/gap
DC gap	32	gap



Higher buffer gas pressure is beneficial for cooling ions, resulting in better emittance, but makes worse transmission.

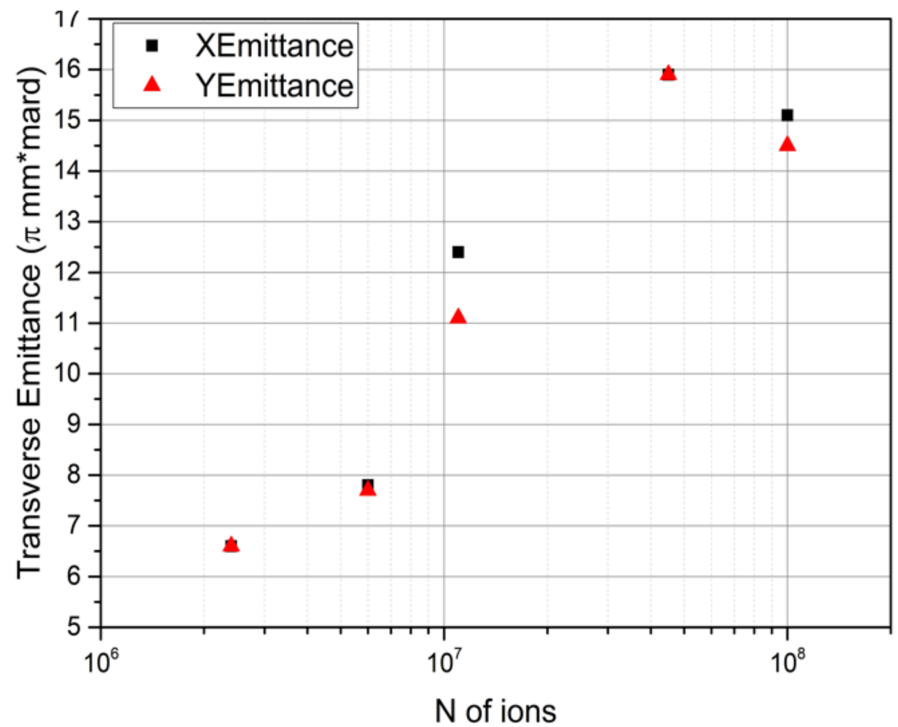
RFQ cooler and buncher

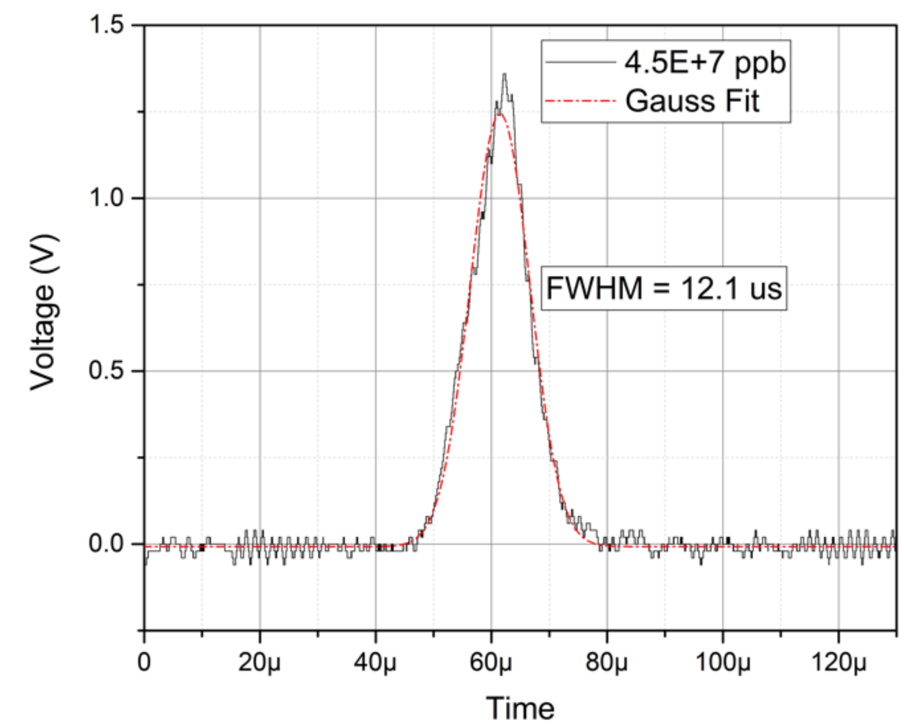
Bunch mode

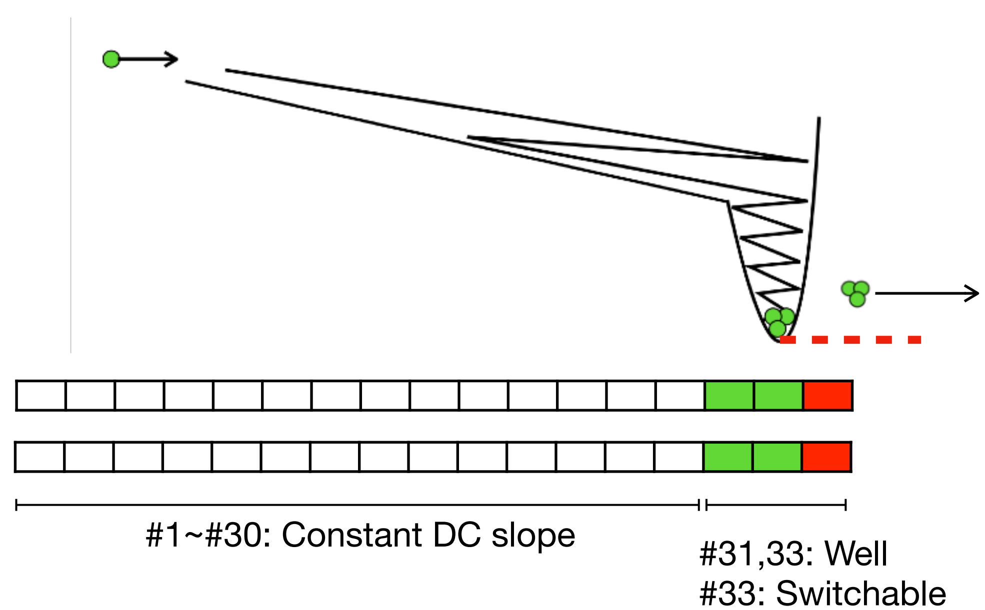
- Higher ions per bunch causes worse transverse emittance and wider bunch width due to space charge effect.

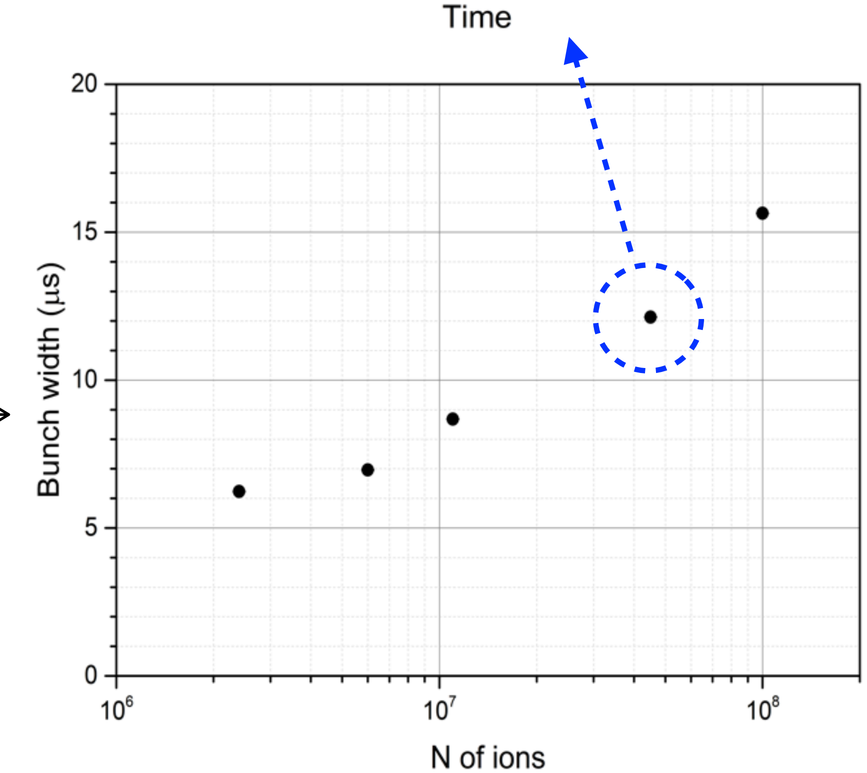
Parameters used

Parameter	Value	unit
High Voltage platform	4834	V
RFQ input energy	100	eV
RF frequency	2	MHz
RF voltage	1100	Vp-p
He pressure	2	Pa
Cooling time	99.95	ms
Repetition rate	10	Hz
Extraction time	46	us
DC electrode 1 Bias	66	V
DC electrode 30 Bias	56	V
Bunching electrode 31 Bias	55	V
Bunching electrode 32 Bias	20	V
Switching electrode 33 Bias	200	V
Extracting electrode 33 Bias	0	V
Bunch capacity	10^6 - 10^8	ppb
Injection electrode 1	3600	V
Injection electrode 2	4800	V
Injection electrode 3	3000	V
Extraction electrode 1	1500	V
Extraction electrode 2	4800	V
Extraction electrode 3	2000	V





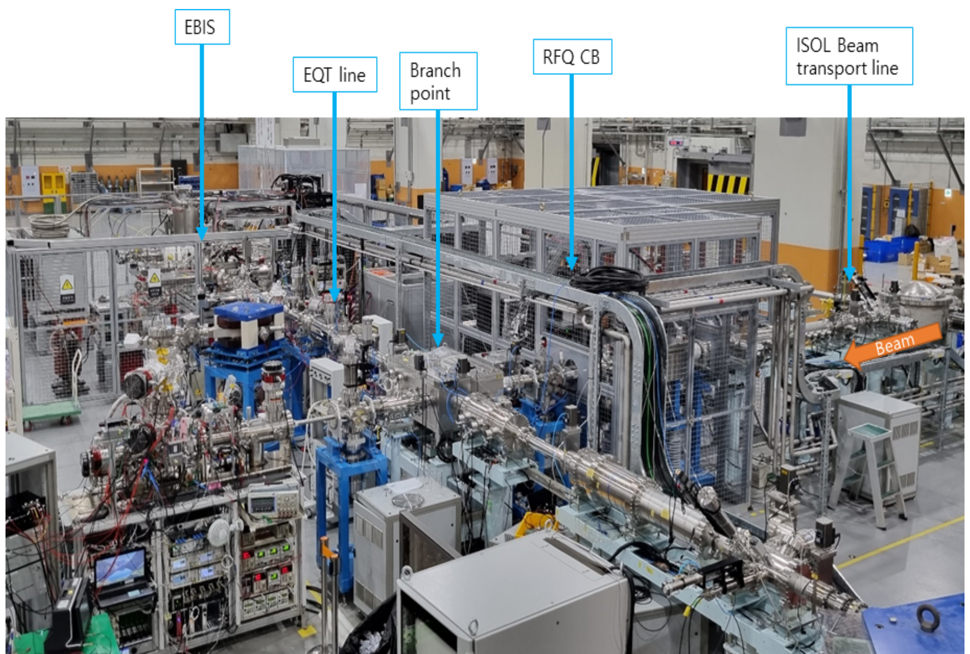


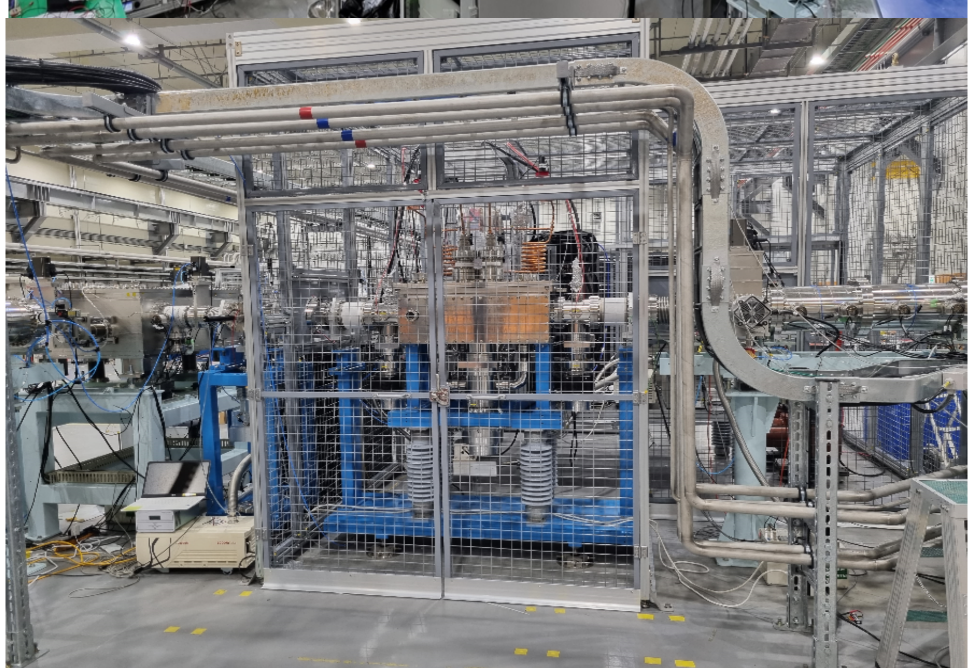


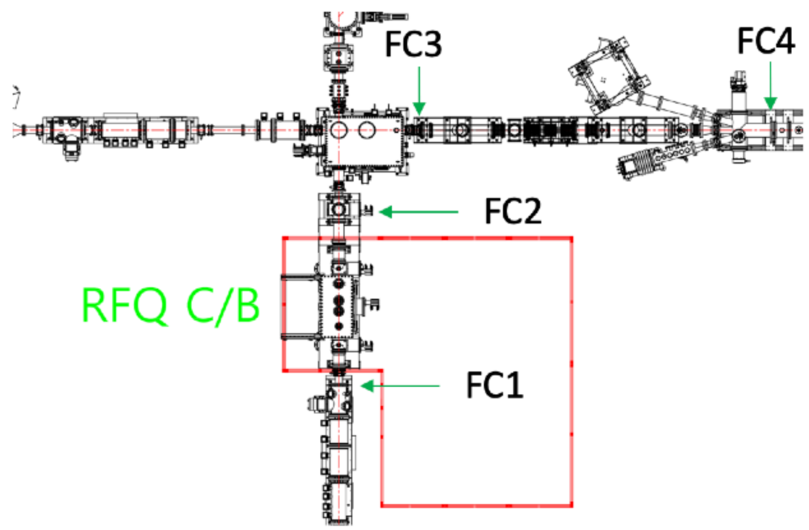
RFQ cooler and buncher

- On-line commissioning: Target ion source, ^{133}Cs, ^{120}Sn and ^{23}Na using surface ionization

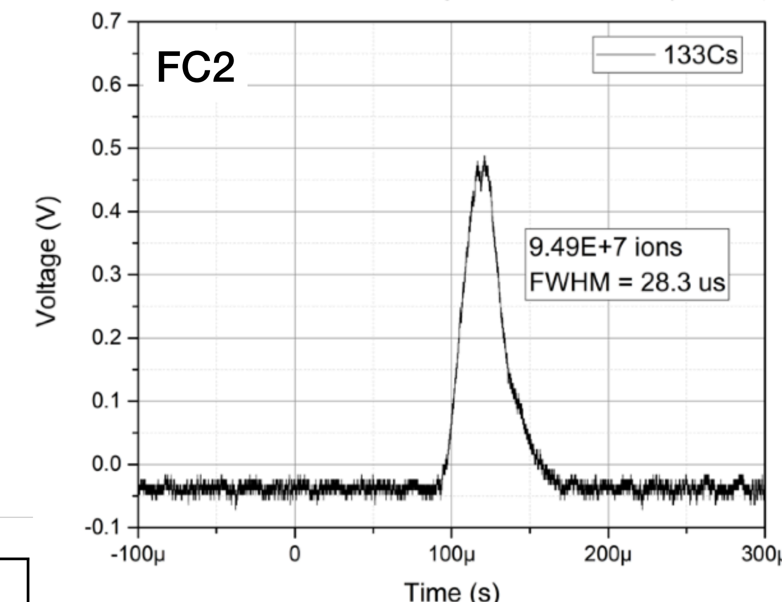
Beam species	I (ppb)@F2	I (ppb)@F4	Transmission (F4/F2)
^{133}Cs	9.49E+07	1.16E+08	82%
^{120}Sn	9.39E+07	9.06E+07	96.5%
^{23}Na	7.87E+07	6.75E+07	85%

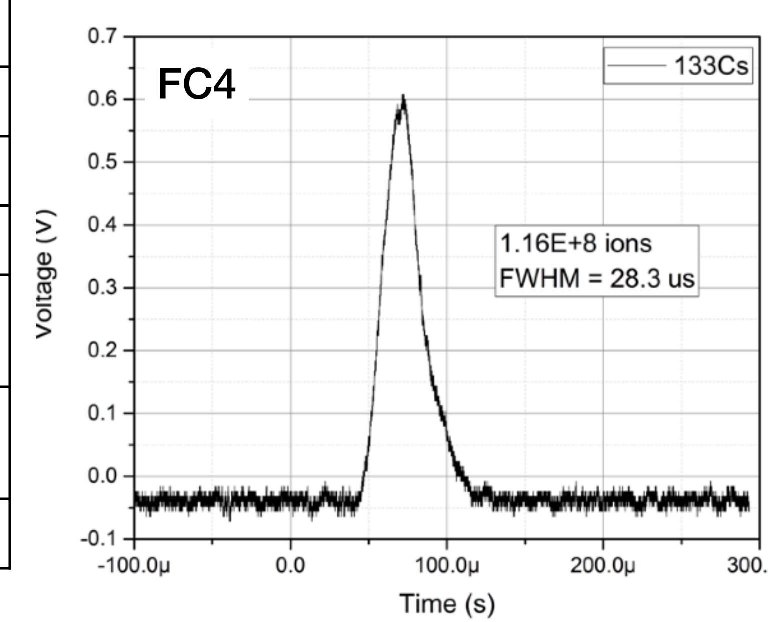






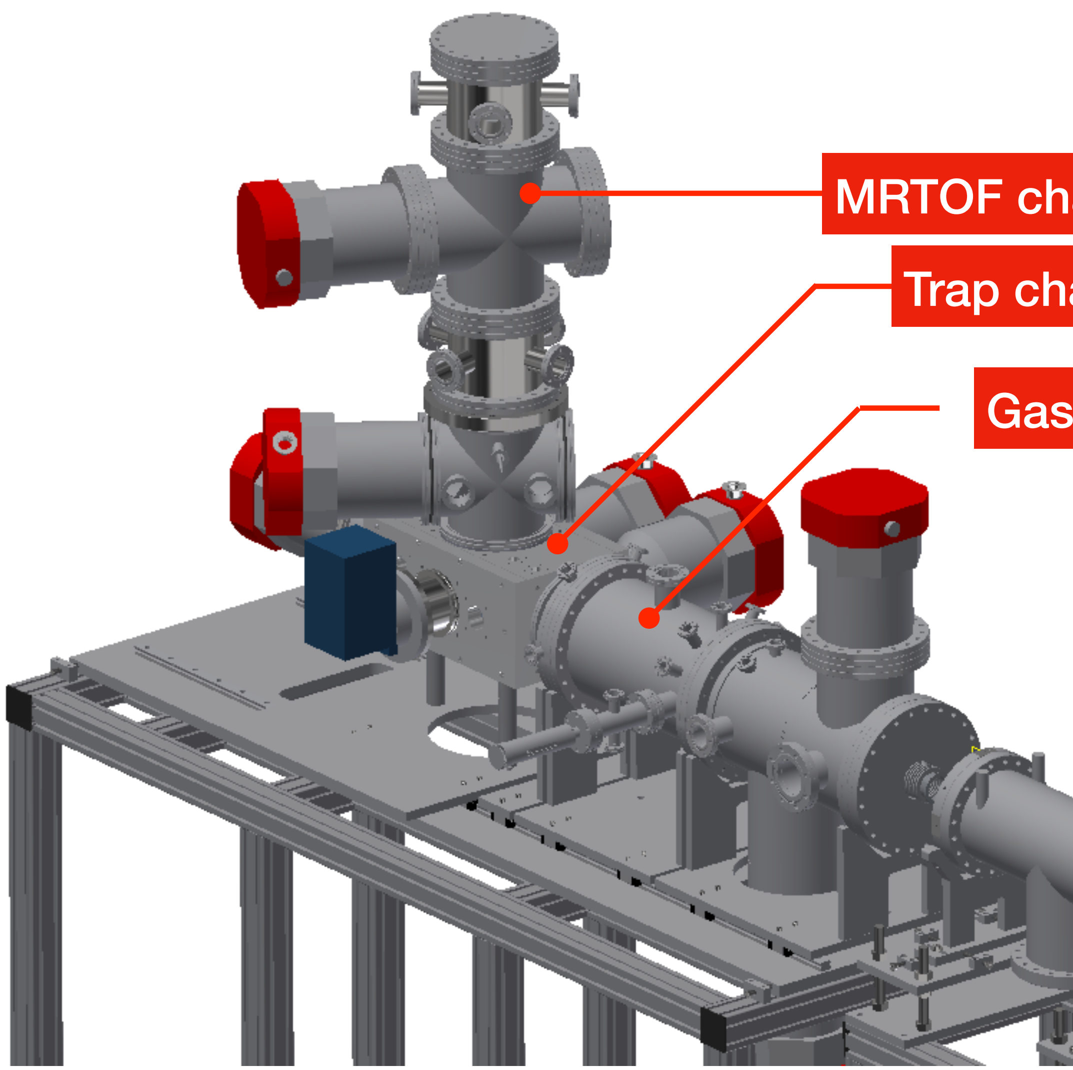
Parameter	Value	unit
Beam energy	19.8 k	eV
Repetition rate	6	Hz
Cooling time	99.94	ms
Extraction time	60	us
Input Beam current (FC1)	~ 200	pA
Bunch beam current (FC2)	~1E+8	particle/bunch
Bunch width	(FWHM) 28.3	us

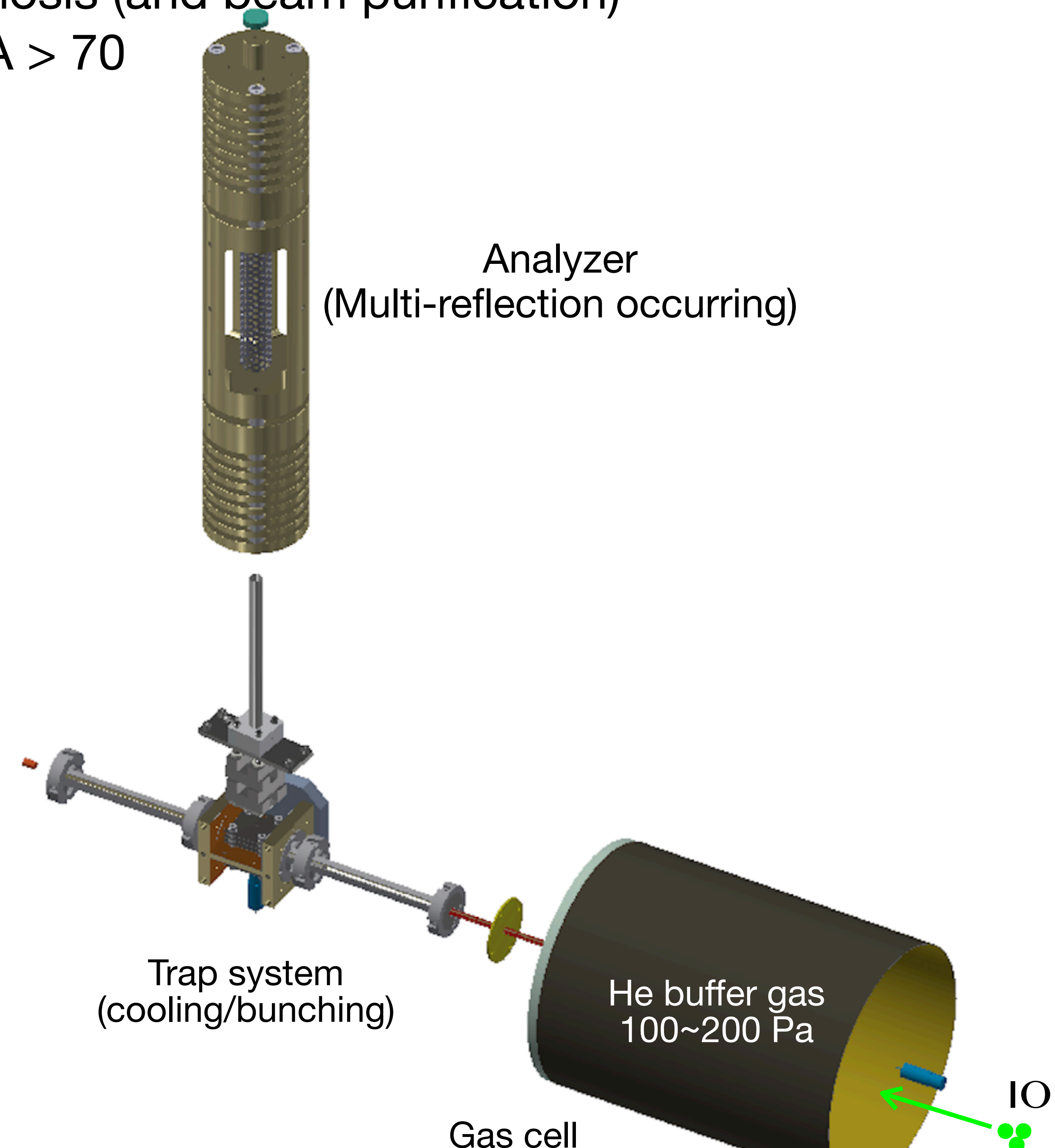




Gas cell system for MRTOF-MS

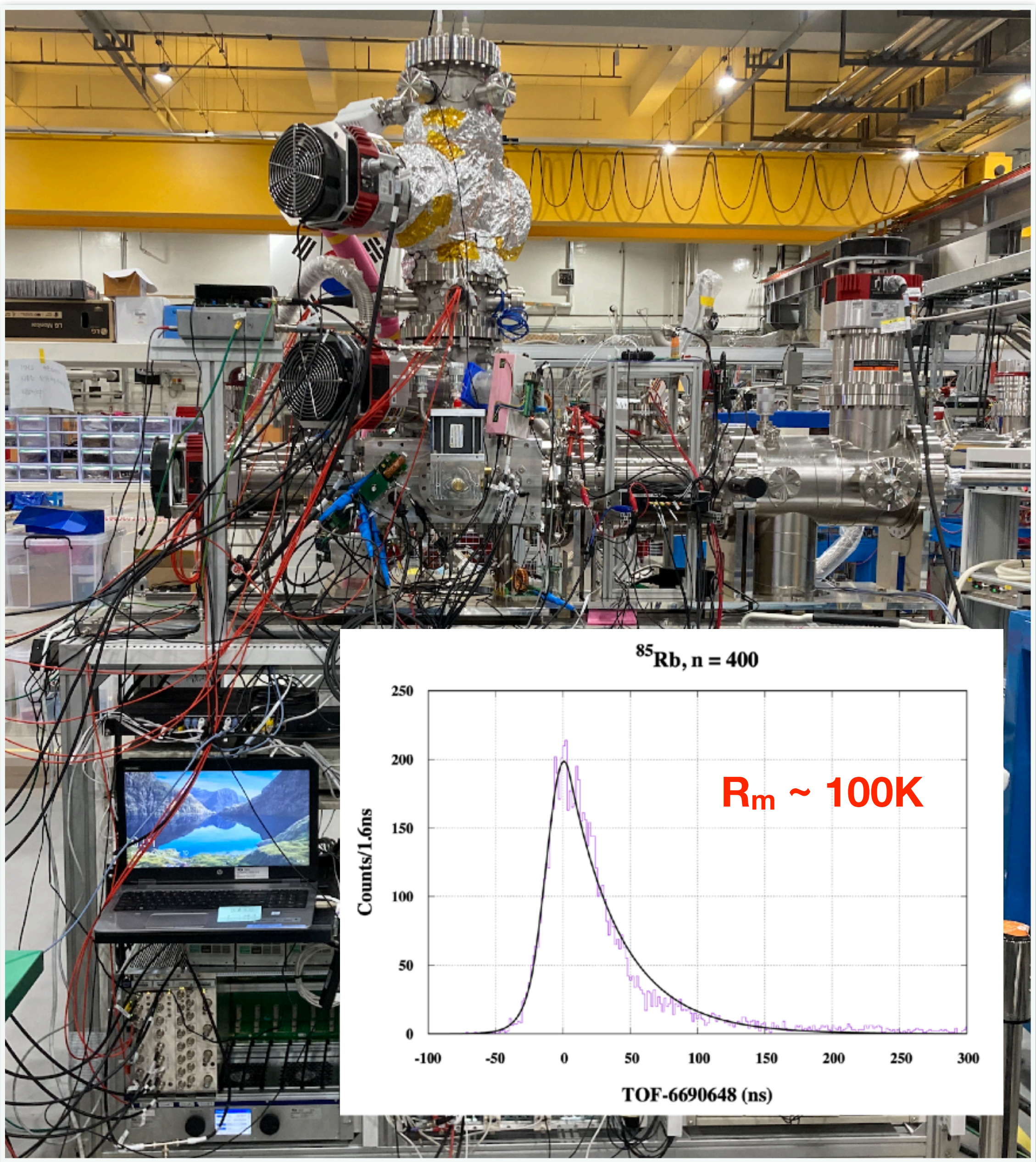
- MRTOF-MS system in RAON, a twin of that in KISS (KEK/WNSC), developed under the MOU between IBS and KEK (2016 ~ 2020)
  - MRTOF-MS: (room temperature) buffer gas cell, Trap system, and MRTOF analyzer
  - Application: mass measurement, beam diagnosis (and beam purification)
    diagnosis of ISOL beams of E < 60 keV and A > 70

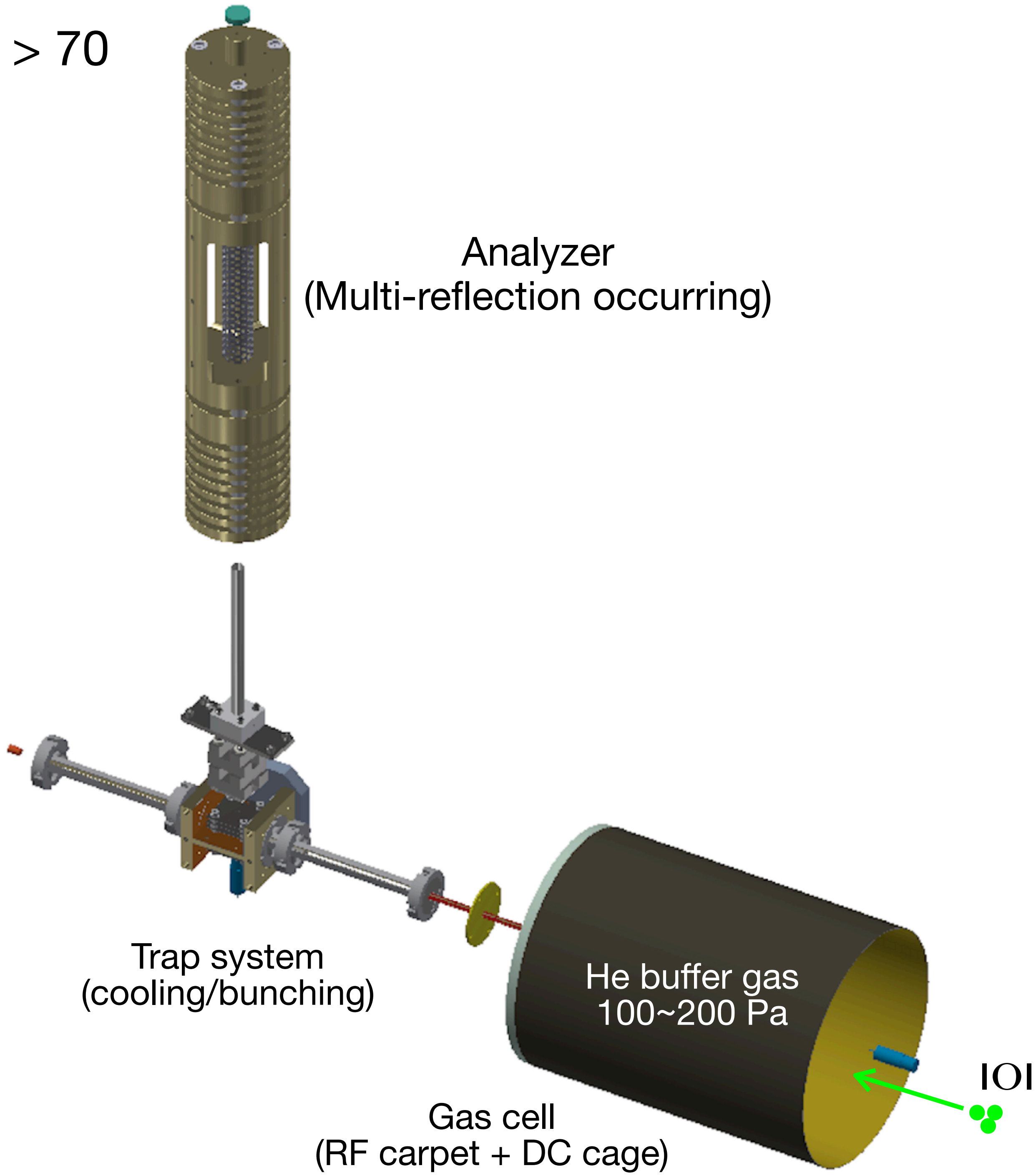




Gas cell system for MRTOF-MS

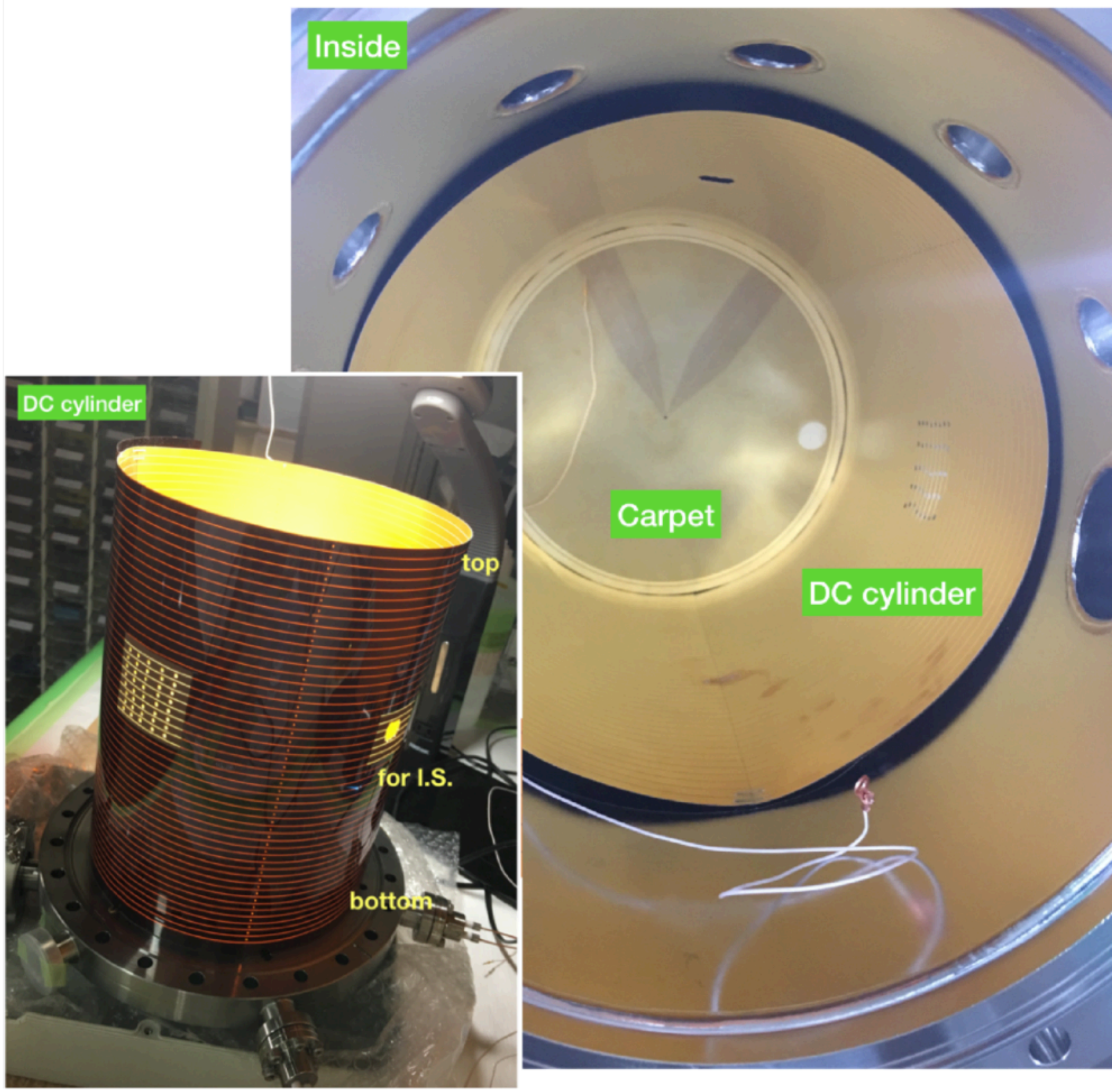
- MRTOF-MS system in RAON, a twin of that in KISS (KEK/WNSC), developed under the MOU between IBS and KEK (2016 ~ 2020)
  - MRTOF-MS: (room temperature) buffer gas cell, Trap system, and MRTOF analyzer
  - Application: mass measurement and diagnosis of ISOL beams of E < 60 keV and A > 70

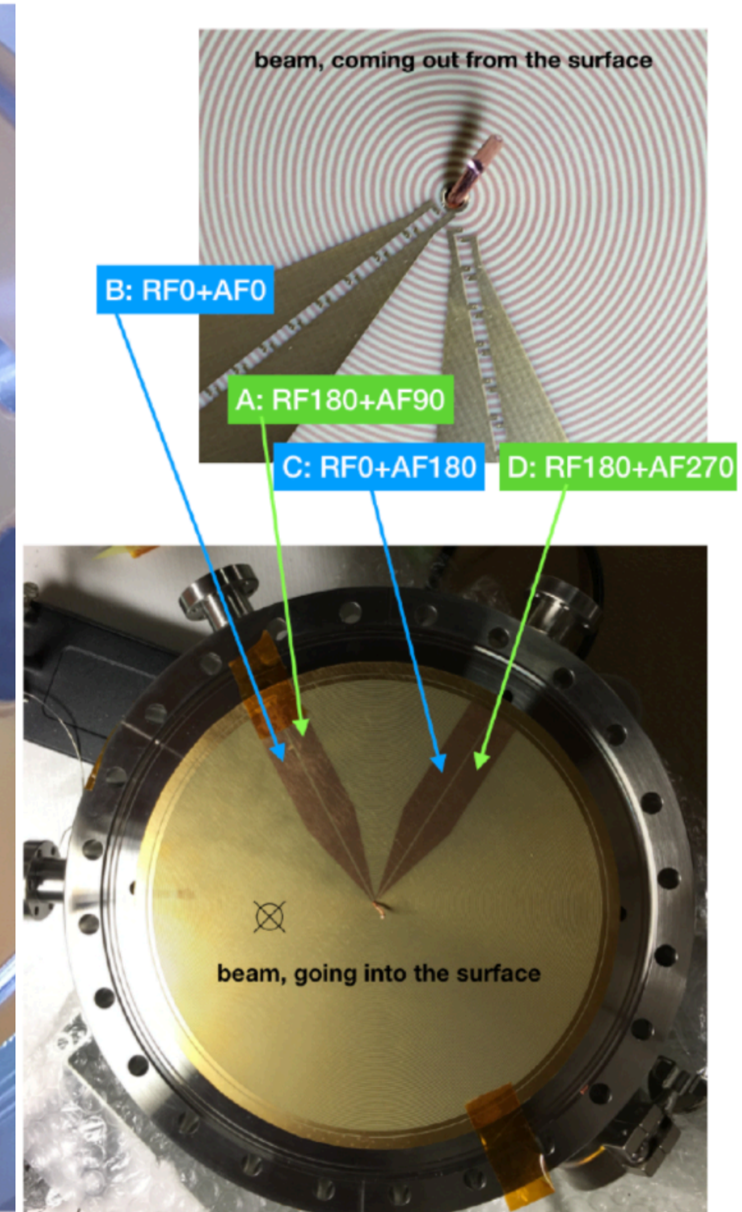




Gas cell system for MRTOF-MS

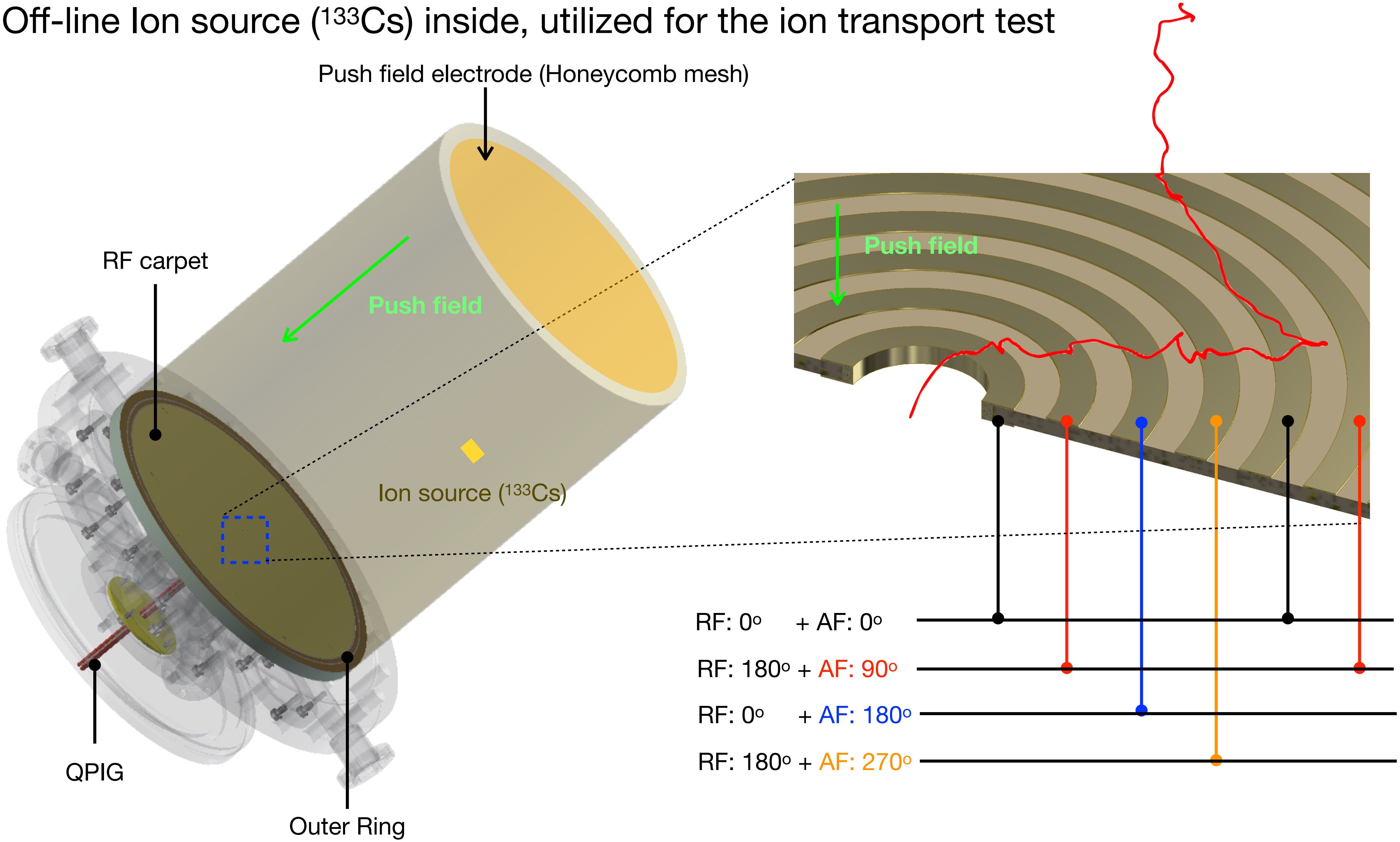
- Gas cell system: room-temperatured He gas, RF carpet and DC cage.
- RF carpet, generating effective repelling force
  - Circular disk with ϕ190 mm in diameter and ϕ1.28 mm hole in the center
  - Concentric electrodes, Au-plated Cu, 0.64-mm pitch and 0.32-mm width, FR4 substrate.
- DC cage, generating push field toward the carpet
  - Cylindrical shape with L ~ 242 mm and ϕ190 mm, voltage dividing by 10 kΩ (total : 250 kΩ)





Gas cell system for MRTOF-MS

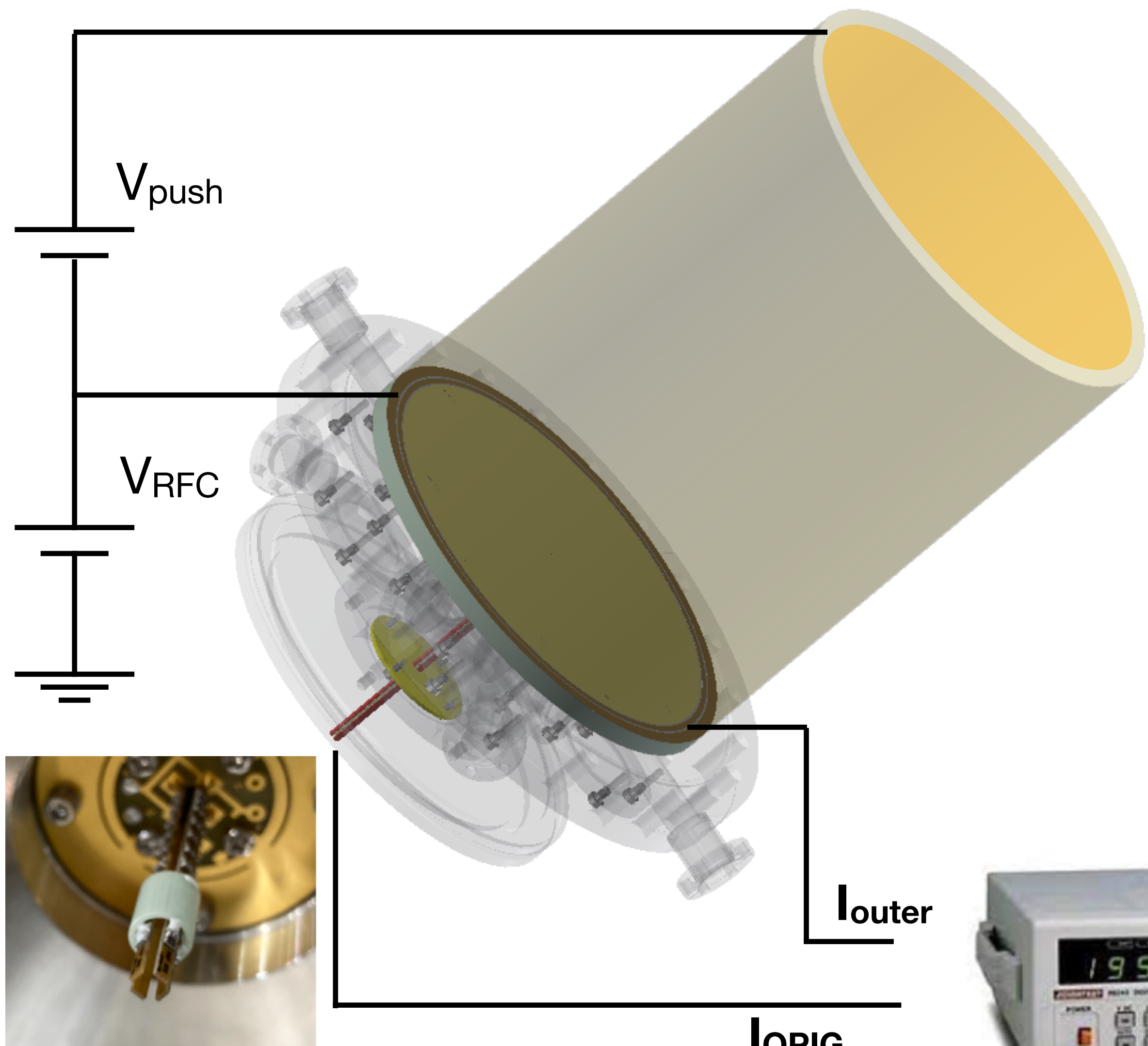
- DC push field + RF carpet (effective) repulsive field, levitating the ions over the carpet
- Four phase low frequency RF creates "traveling wave" to guide them to the exit hole.
- Off-line Ion source (^{133}Cs) inside, utilized for the ion transport test



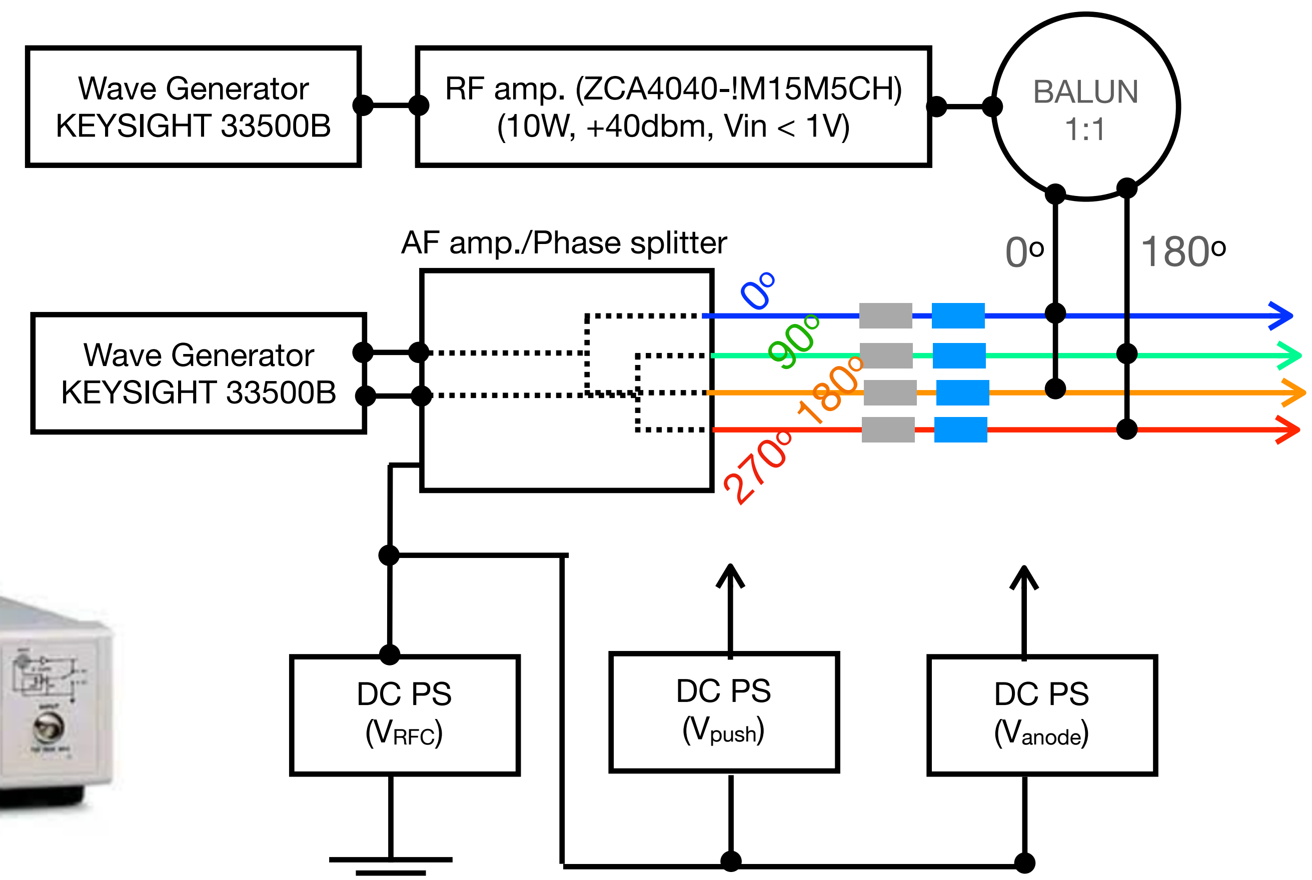
Gas cell system for MRTOF-MS

- Off-line commissioning w/ IS (^{133}Cs, Heatwave co.): 1.6 A, 2.96 V (4.74 W) --> 40 pA
- He buffer gas, 1 mbar
- Ion current measurement
  - Faraday cups : QPIG for extracted ions, Outer-ring electrode for normalization
  - Current meter : Digital electrometer 8240 (ADCMT co.)

f_{RF} = 7.5 MHz, V_{in} = 700 mV_{pp} (V_{out} ~ 100 V_{pp}),
f_{AF} = 44.5 kHz, V_{in} = 400 mV_{pp} (V_{out} ~ 3 V_{pp})
V_{push} = 40 V, V_{RFC} = 25 V (offset), V_{outer} = 0 V



QPIG



Gas cell system for MRTOF-MS

- Off-line Ion source (^{133}Cs, Heatwave co.) : 1.6 A, 2.96 V (4.74 W) --> 40 pA (fig. 2)
- He buffer gas, 1 mbar
- Ion current measurement
  - Faraday cups : QPIG for extracted ions, Outer-ring electrode for normalization
  - Current meter : Digital electrometer 8240 (ADCMT co.)
- Results (fig. 1): extraction efficiency ~ 1 and found that "ion surfing" mode worked!

From fig.1, the ion current at each side shows response to the relative phase change.

Fig 1. : Ion current

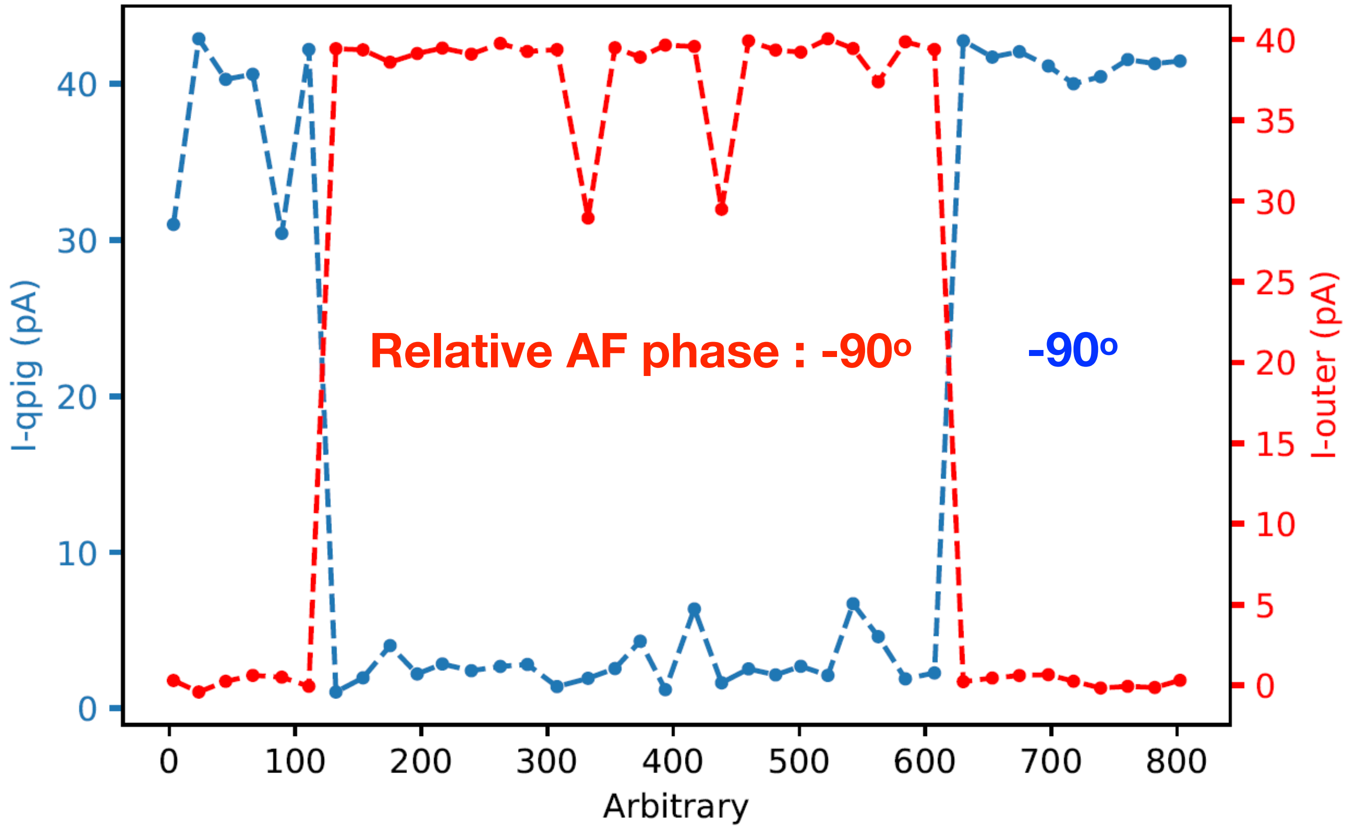
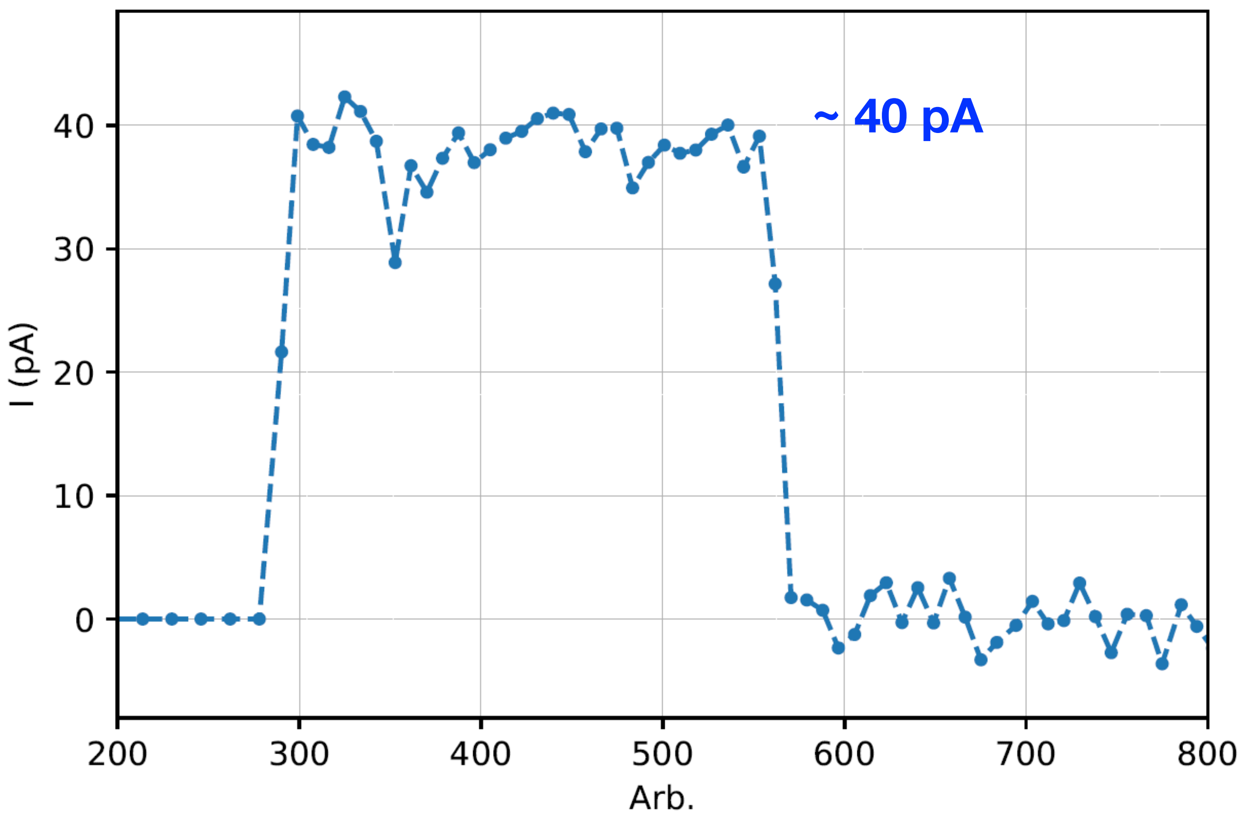


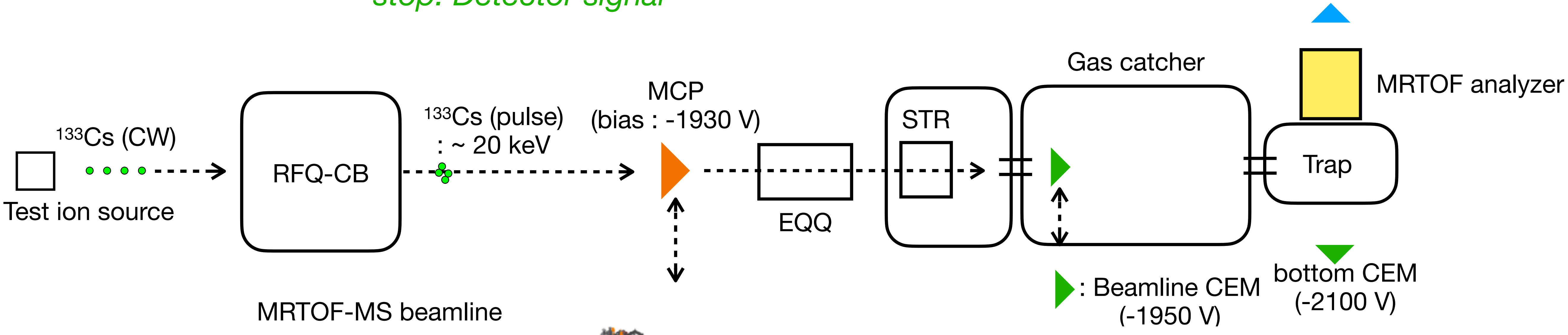
Fig 2. : Ion current @Carpet surface

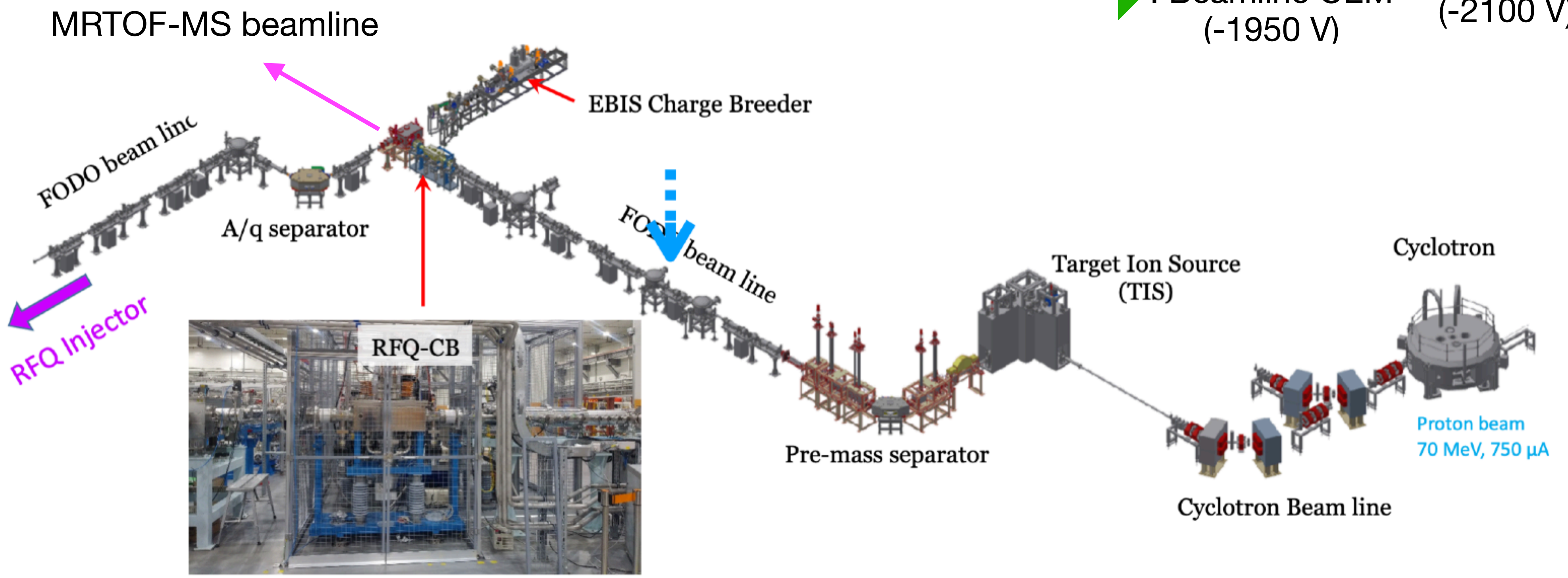


Gas cell system for MRTOF-MS

- <u>On-line commissioning</u> with a test ion source (*blue arrow*)
  - ^{133}Cs beam, whose intensity can be measured by MCP and beamline CEM
  - Signals sent to a TDC (MCS6A, Fast ComTech co.), processed to make TOF spectra

start : RFQ-CB ejection TTL or Flat trap ejection NIM
stop: Detector signal

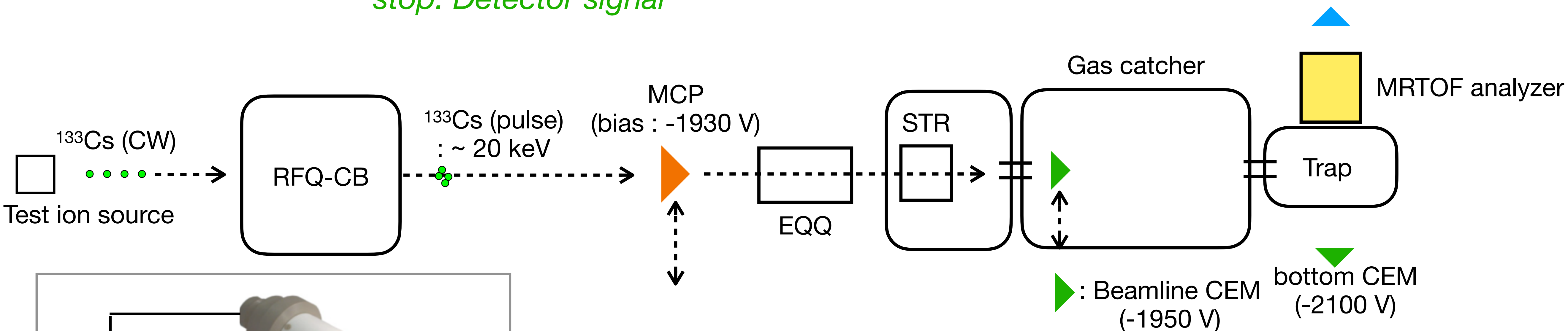


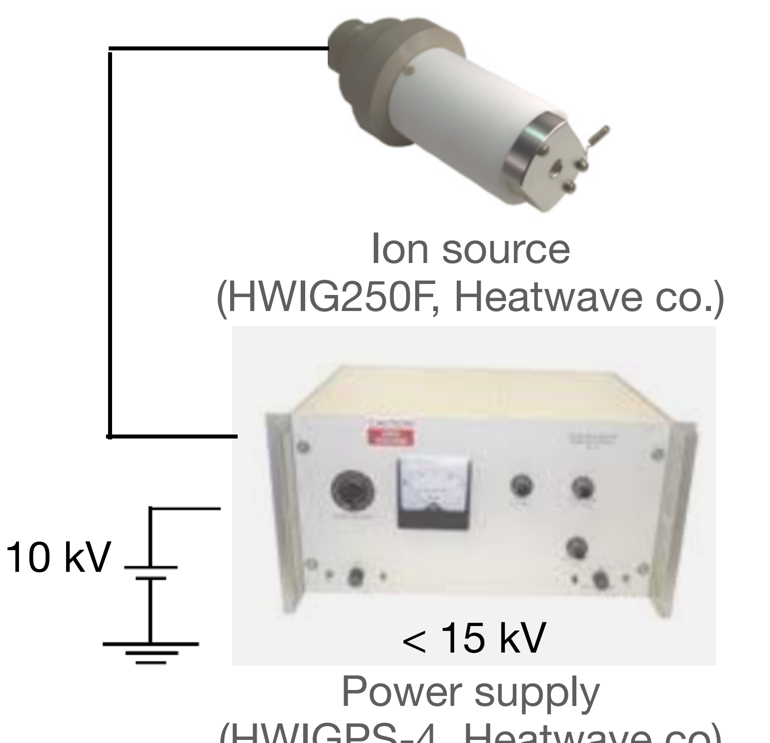


Gas cell system for MRTOF-MS

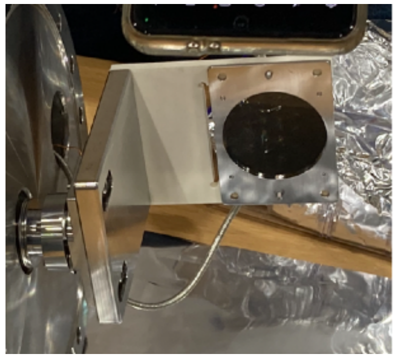
- On-line commissioning with a test ion source (*blue arrow*)
  - ^{133}Cs beam, whose intensity can be measured by MCP and beamline CEM
  - Signals sent to a TDC (MCS6A, Fast ComTech co.), processed to make TOF spectra

start : RFQ-CB ejection TTL or Flat trap ejection NIM
stop: Detector signal





Beamline Test ion source



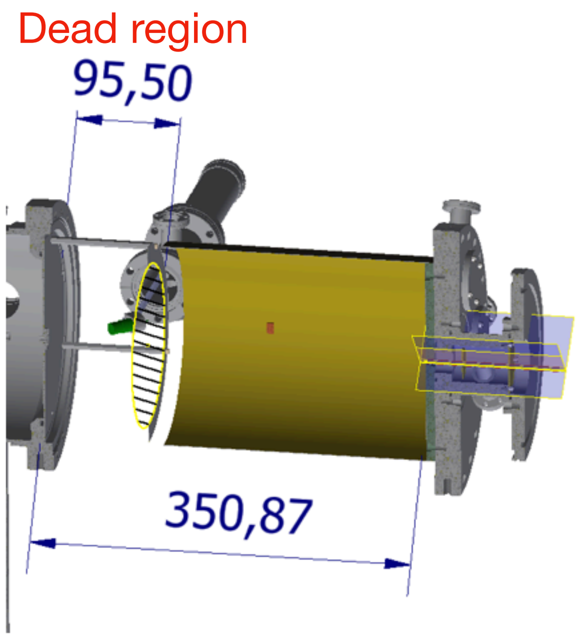
MCP
Model: F12334-11
FWHM : 1.5 ns
Effective area : ϕ20 mm
HAMAMATSU Photonics

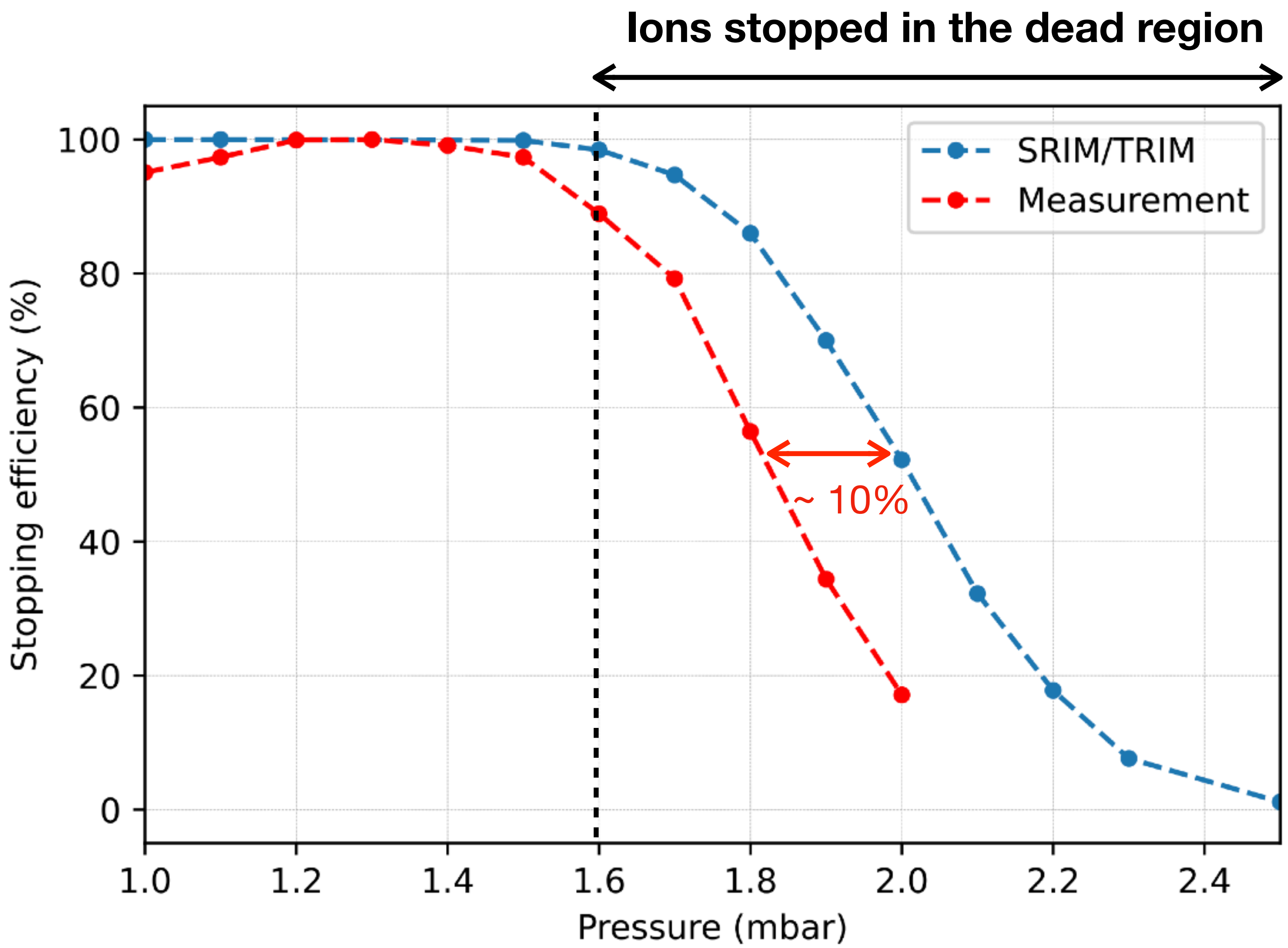
MCS6A : multiple-event time digitizer
Time resolution: 100 ps

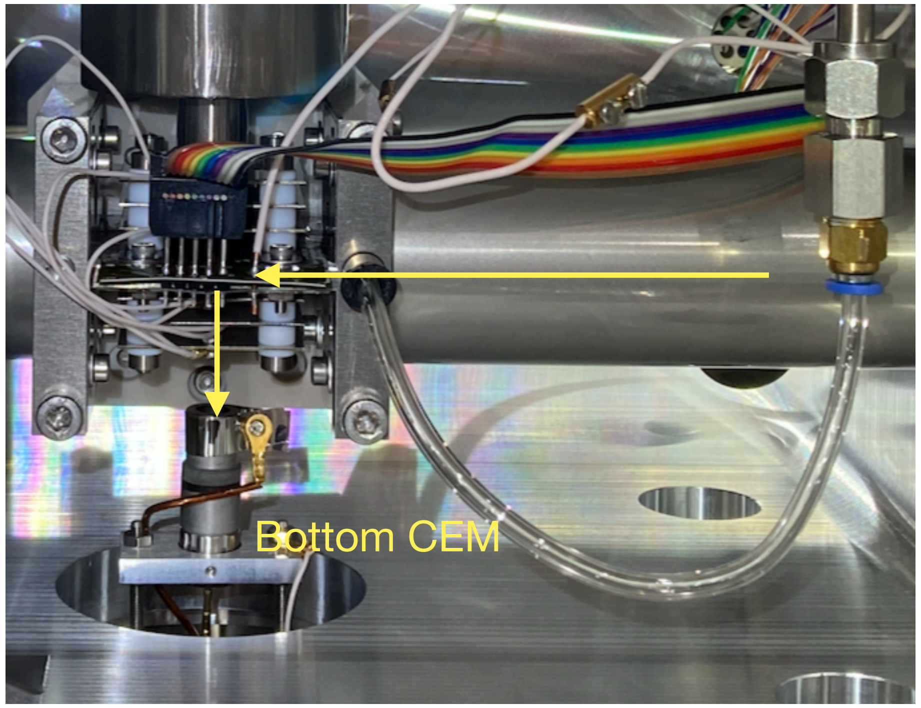
Gas cell system for MRTOF-MS

- Buffer gas pressure should be optimized for ^{133}Cs beam ions of E_K ~ 20 keV
  - ^{133}Cs ions counted as the buffer pressure changes
  - Bottom CEM (-2100 V), MCS6A (Threshold : -15 mV)

    START : Flat trap ejection NIM, STOP: Bottom CEM signal
  - Most of ions stopped in the gas cell at P_{He} = 1.0 ~ 1.5 mbar
  - From a recent data, SRIM showed 10 ~ 20% underestimation, measurement is consistent with SRIM prediction.



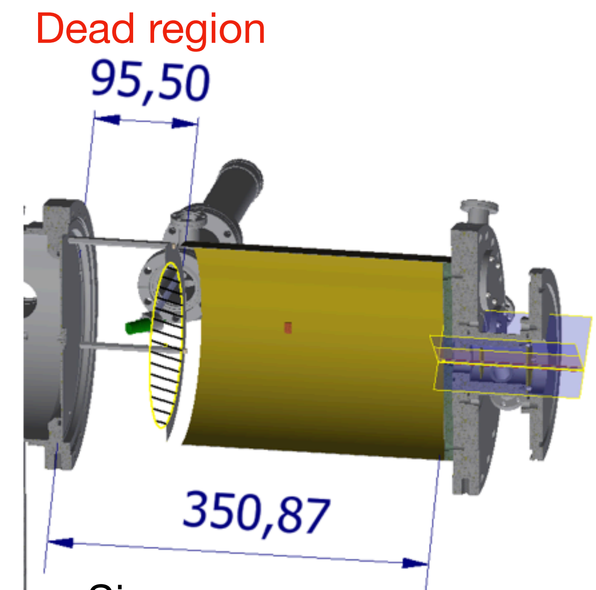


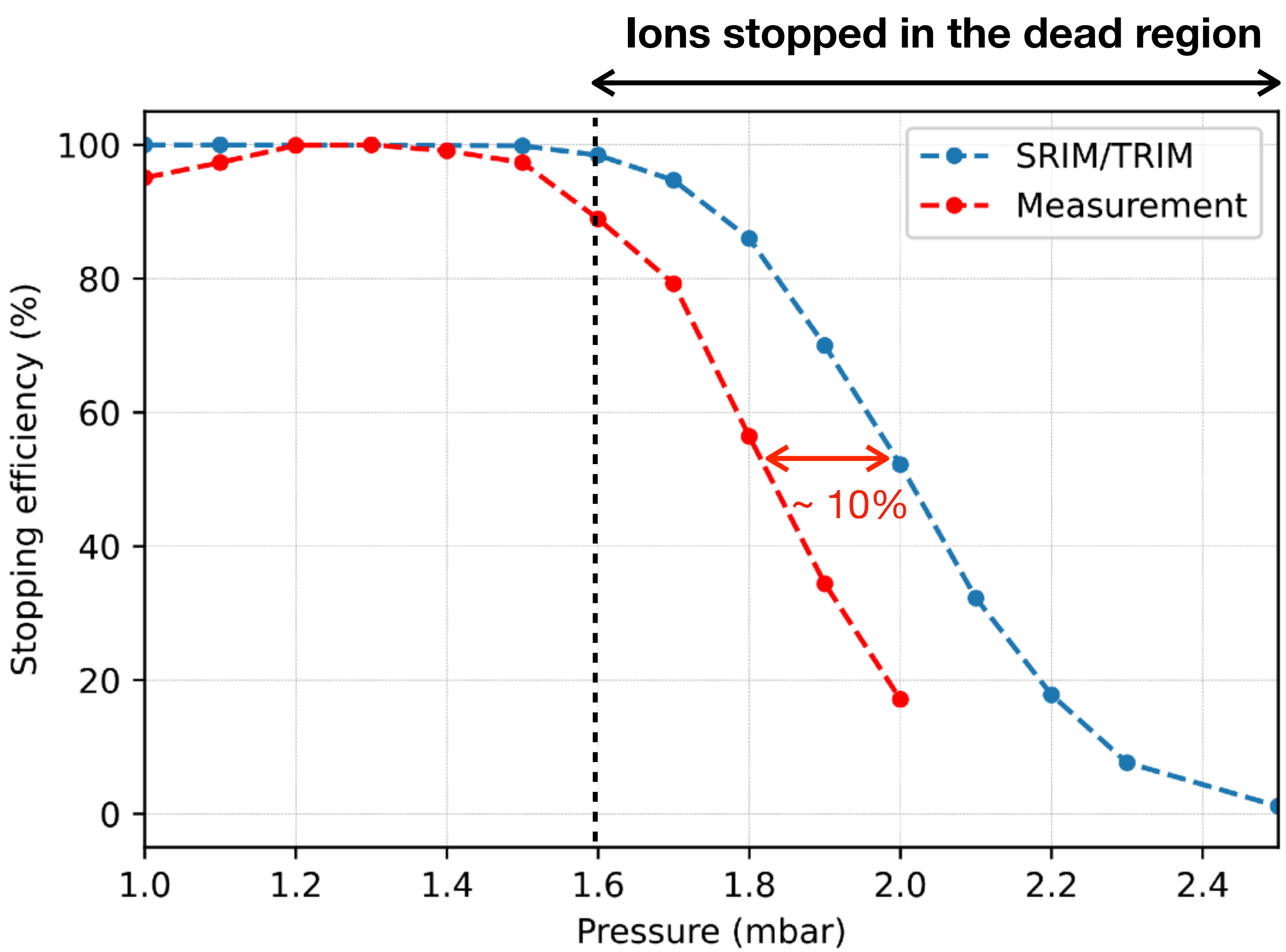


Gas cell system for MRTOF-MS

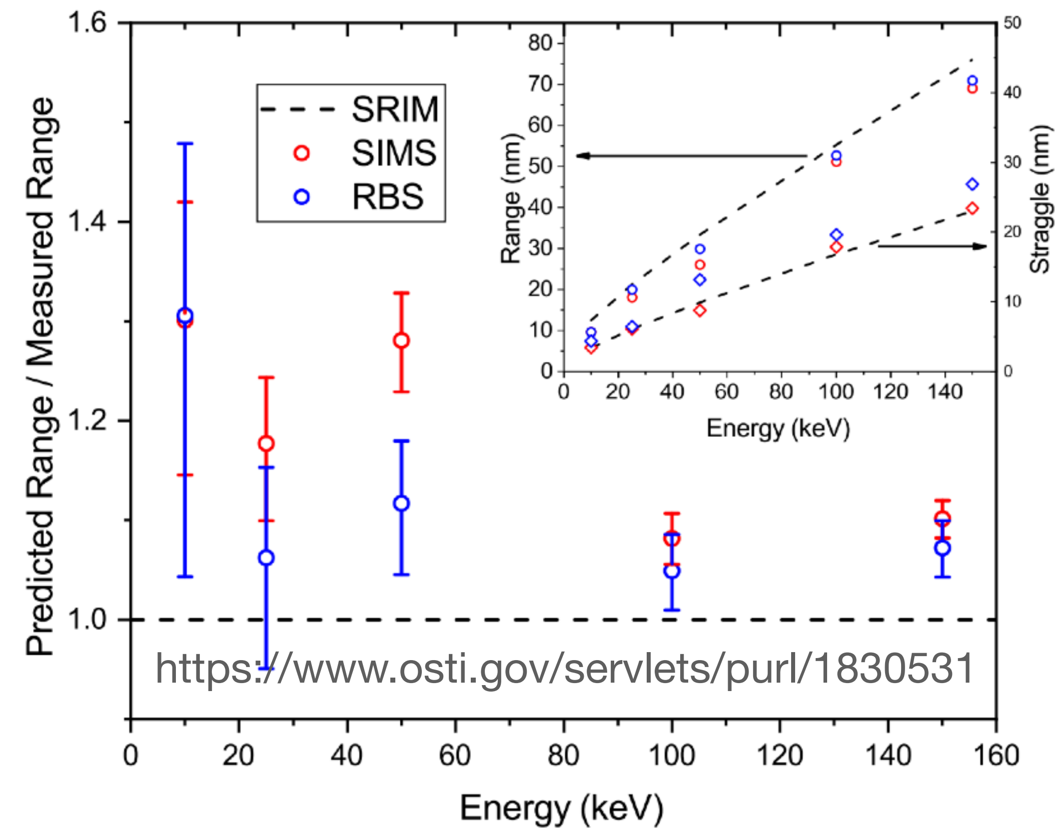
- Buffer gas pressure should be optimized for ^{133}Cs beam ions of E_K ~ 20 keV
  - ^{133}Cs ions counted as the buffer pressure changes
  - Bottom CEM (-2100 V), MCS6A (Threshold : -15 mV)

    START : Flat trap ejection NIM, STOP: Bottom CEM signal
  - Most of ions stopped in the gas cell at P_{He} = 1.0 ~ 1.5 mbar
  - From a recent data, SRIM showed 10 ~ 20% underestimation, measurement is consistent with SRIM prediction.





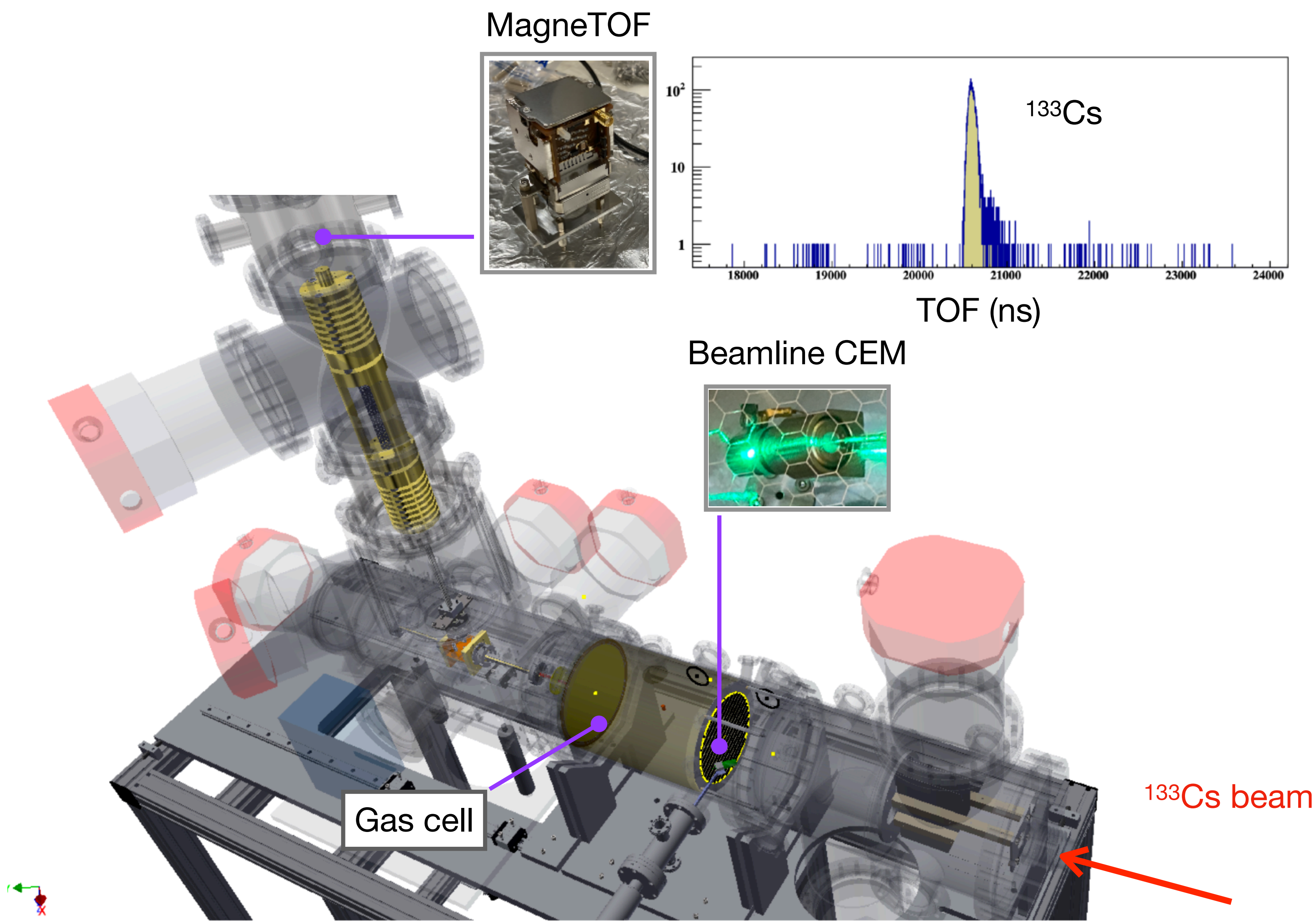
Sb ions beam on Si



Gas cell system for MRTOF-MS

- Overall efficiency of ion transport from the gas cell to the MagneTOF, measured
  - Incident ion intensity, measured by the beamline CEM (I_{inc})
  - Ion intensity, measured by the MagneTOF (I_{MTOF})
  - QPIG, fRFQ, and Flat trap in between, optimized with *the off-line ion source*

Overall efficiency (single pass): $\frac{I_{MTOF}}{I_{inc}} = \frac{116}{1200} \sim 10\,\%$ *: ~ 90% of ions is missing somewhere*



Gas cell parameters

He buffer gas : 1.3 mbar

RF carpet : 7.5 MHz, 800 mV_{pp}

44.5 kHz, 400 mV_{pp}

DC push field : 0.23 V/mm (54V/232mm)

(* V_{push} = 54 V, V_{anode} = 33 V

V_{RFC} = 14 V, V_{outer} = 16 V)

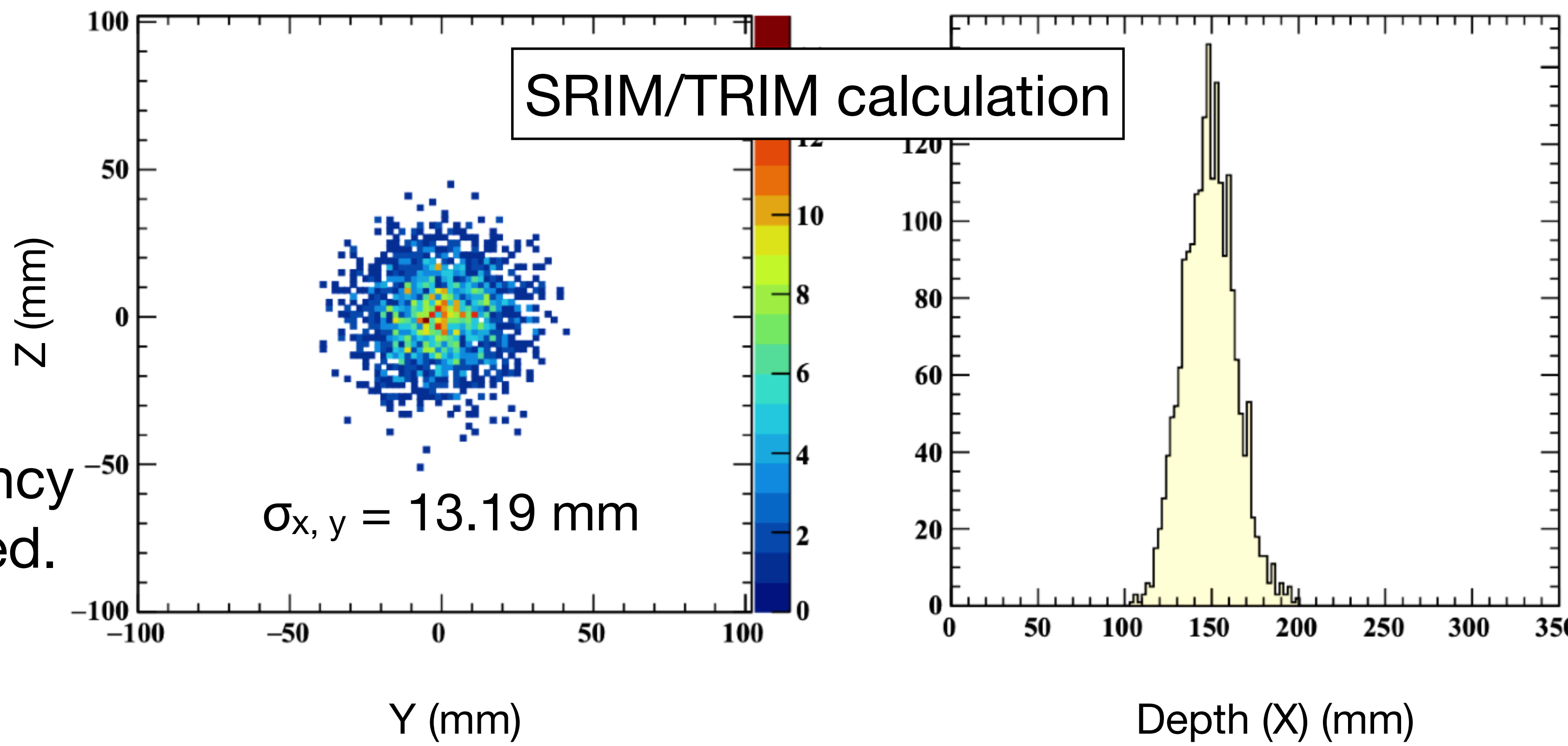
Gas cell system for MRTOF-MS

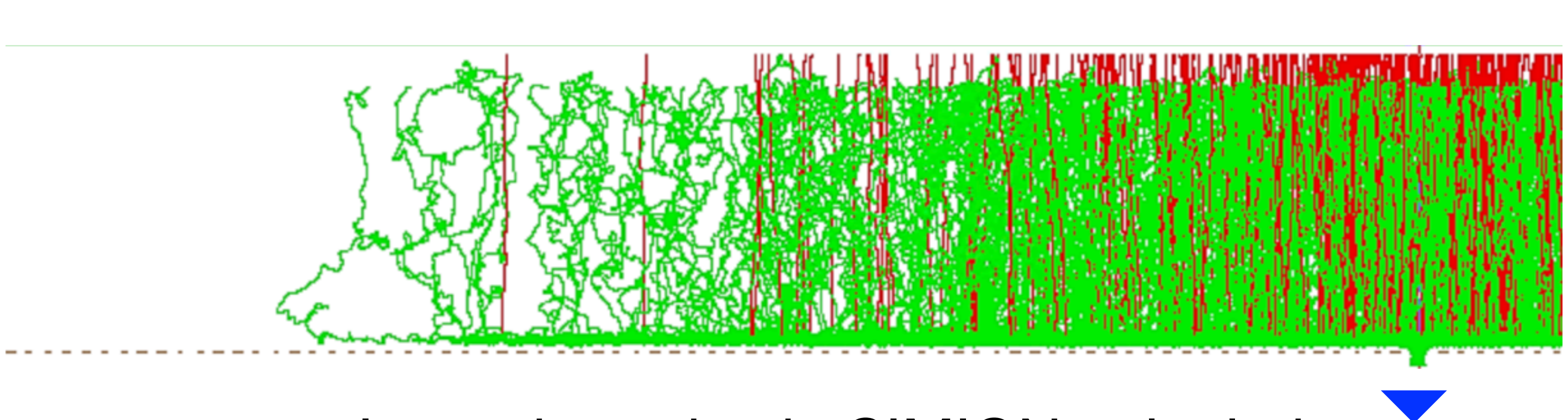
- SIMION calculation with the parameters used
  - Lateral distribution, obtained from SRIM calculation:

    ^{133}Cs, 20 keV

    He, 130 Pa, 293 K

  - Push field and VAF dependency investigated, while others fixed.





Ion trajectories in SIMION calculation

Gas cell parameters

He buffer gas : 1.3 mbar

RF carpet : 7.5 MHz, 800 mV_{pp}

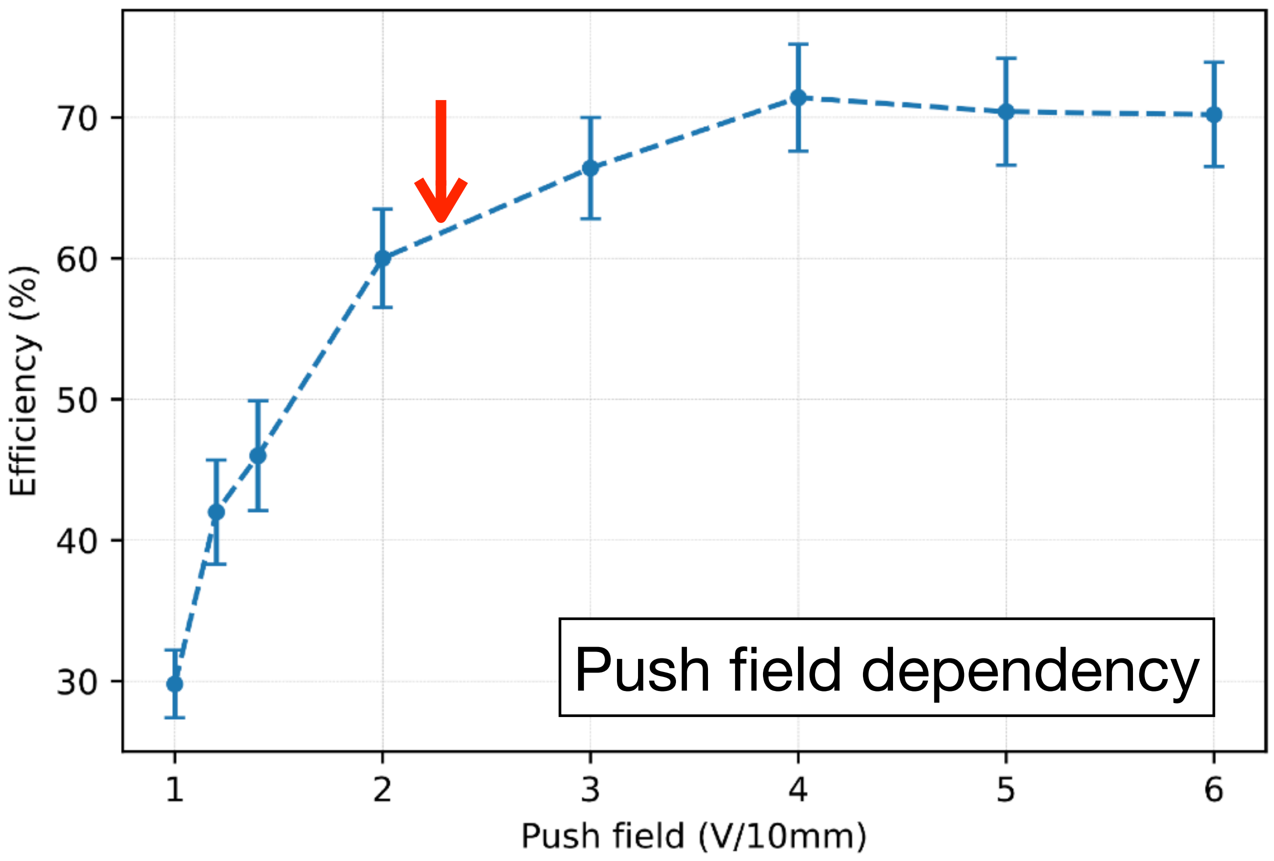
V_{out} = 106/106/100/80 V_{pp}

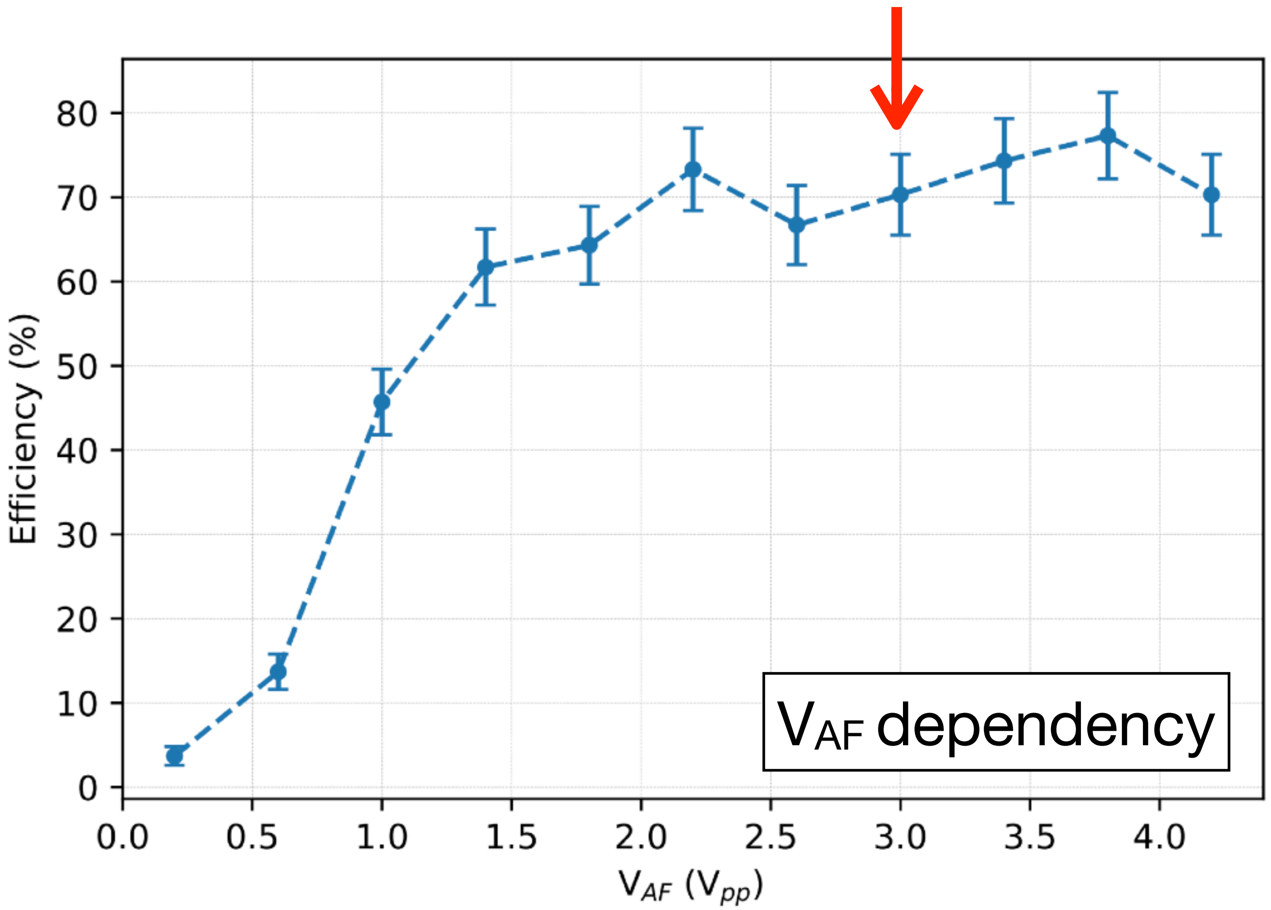
44.5 kHz, 400 mV_{pp} (V_{out} = 3 V_{pp})

DC push field : 2.3 V/cm (54V/232mm)

Gas cell system for MRTOF-MS

- SIMION calculation with the parameters used





For the parameter set used (red arrow), it was found that we were already near or in a saturated phase.

With a little increment of push field, sufficiently high extraction efficiency of ~ 70% can be achieved, so "missing points" are more likely somewhere in QPIG, fRFQ,...

"Inline devices should be optimized with much lower-intense current"
Radioactive ion beam needed to avoid the obscured detection efficiency is necessary

Summary and outlook

- New RI beam factory in Korea, RAON has completed the phase 1 (c.f., Phase 2: SCL2), and is working on beam acceleration at SCL3 and RI extraction from ISOL.
- Recently, we have achieved some successes in beam acceleration in SCL3 and RI extraction test in ISOL.

  - In SCL3, HWR cooling is done for further acceleration

  - RI extraction test with the same beam and target will be resumed from May

- The RFQ cooler-buncher, currently operational for charge breeding in the EBIS system, holds future application in experimental devices. i.e. CLS (*and MO beam formation*)
- Gas cell cooler-buncher is now examined with low-intense ion beam together with detailed simulation and *its efficiencies will be measured with ISOL RI beam (Na isotopes)*
- Utilization of the MRTOF-MS in ISOL should be expanded to other than simple "*Mass measurement*", if the RI production schedule of ISOL considered.

  Radioactive molecular beam production : Beam diagnosis

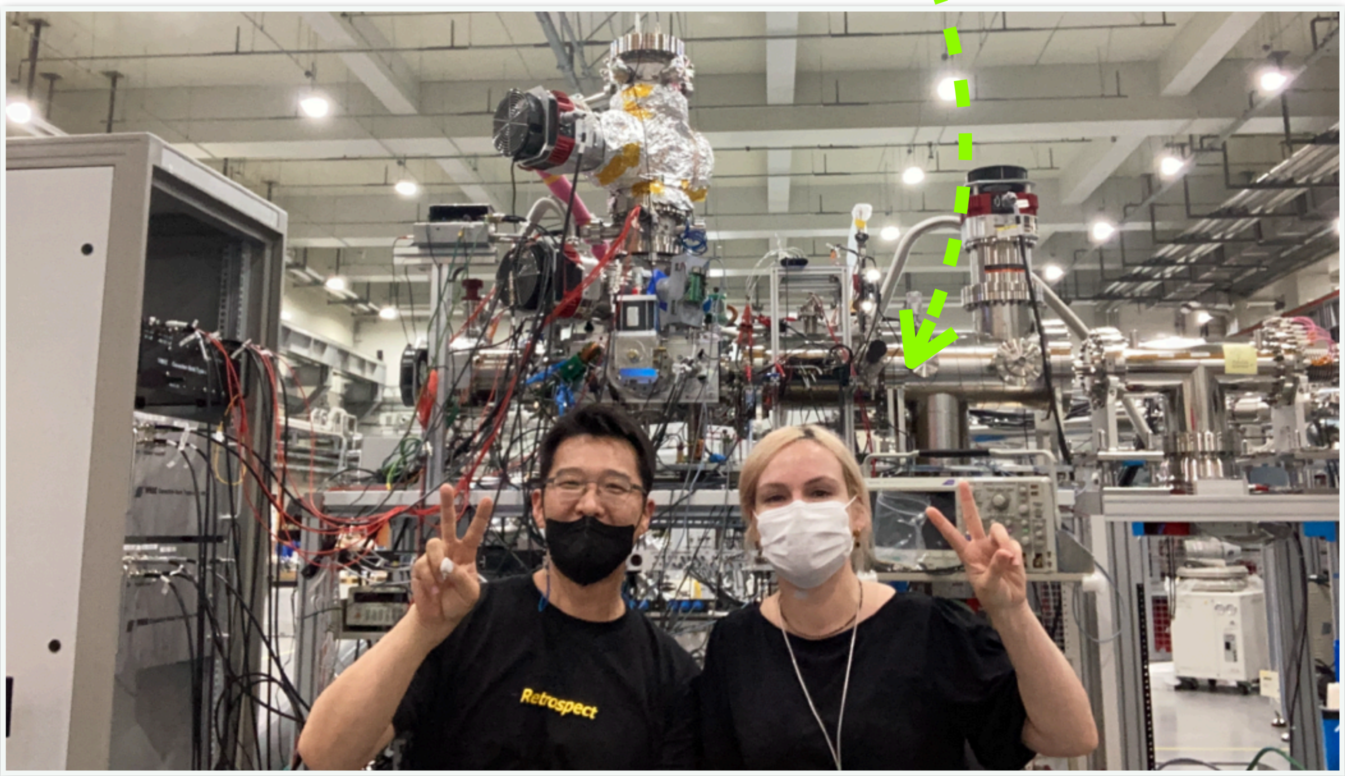
  Penning trap mass measurement : Beam purification

Under consideration!

Gas cell as a place of CID (collision induced dissociation),
to utilize the IDI (Isolation-dissociation-Isolation) method for diagnosis and purification

Collaborators

Dr. K. Zeren



Post doc. position is always open!

RIKEN, Japan
Dr. Aiko Takamine
Dr. M. Rosenbusch

KEK Wako Nuclear Science Center

KEK/WNSC, Japan

Prof. M. Wada
Prof. P. Schury
Prof. Y. X. Watanabe
Prof. Y. Hirayama

Dr. T. Niwase

JAEA, Japan
Dr. Y. Ito

Thank you for your attention.