

Recent progress in RIKEN RI Beam Factory (RIBF)

- 1) Overview of RIBF
- 2) Recent R&D activities
- 3) Present status
- 4) Future plan

Osamu Kamigaito

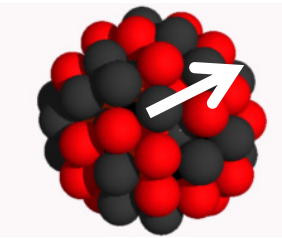
Accelerator Group

RIKEN Nishina Center for Accelerator-Based Science

1) Overview of RIBF

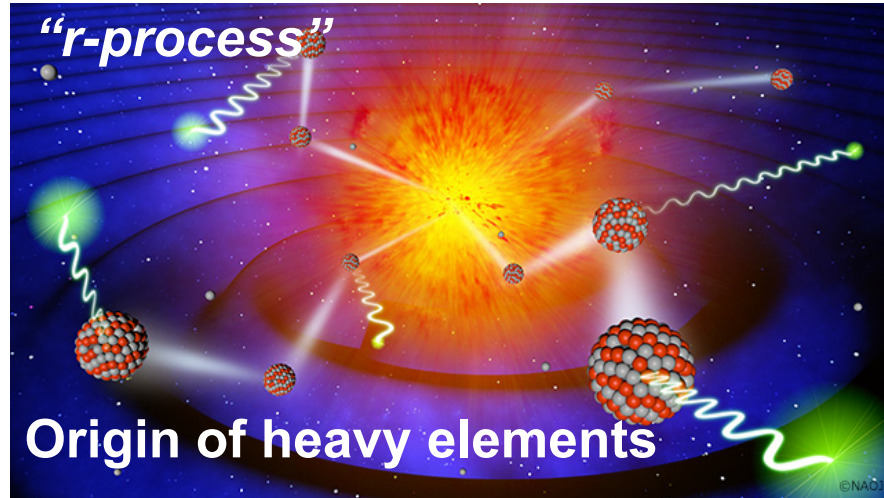
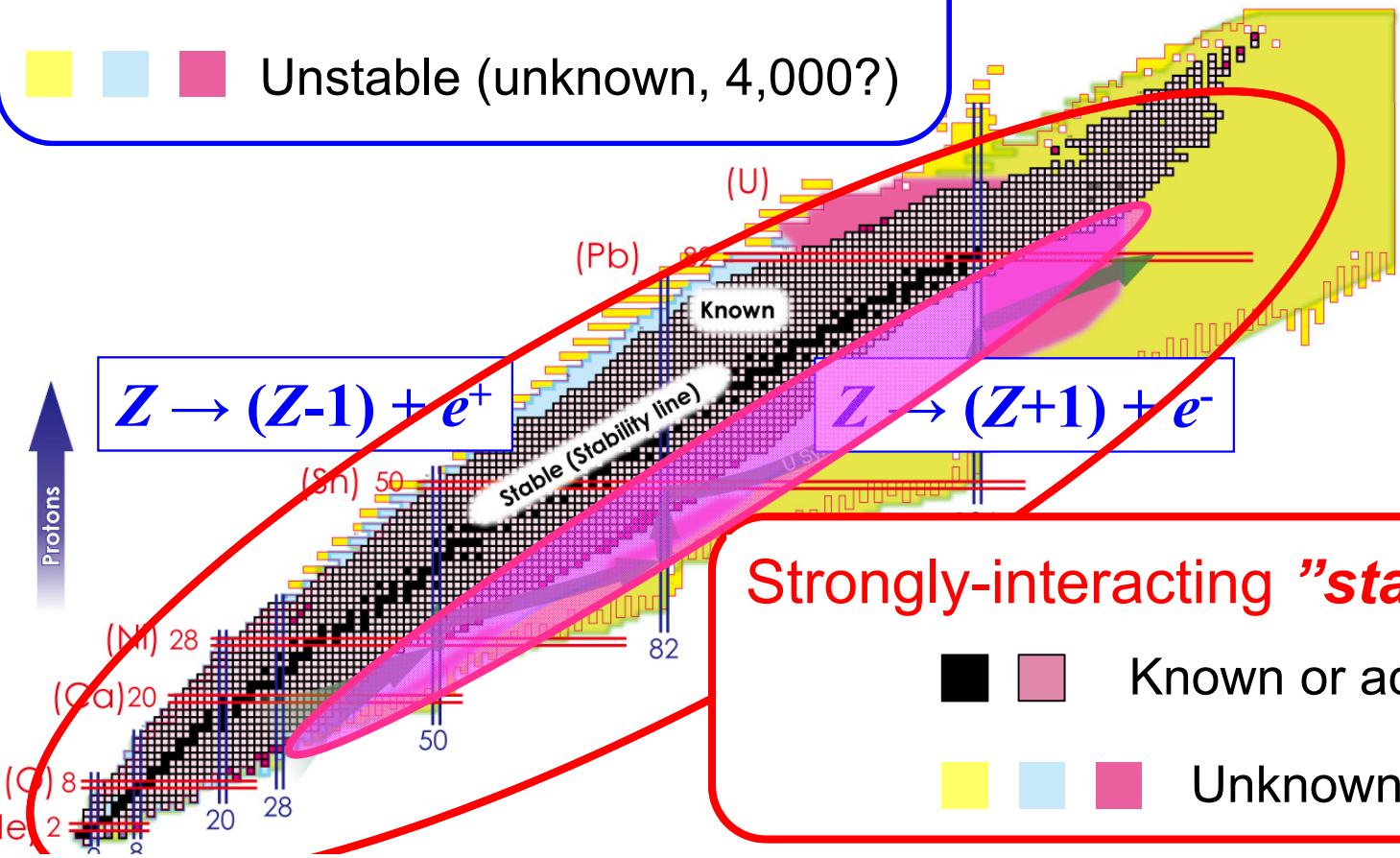
1. Toward comprehensive understanding of nuclear structure

2. Toward elucidation of elemental synthesis in the universe



Stable (256) against *beta-decay*
 Unstable (known, ~3,000)
 Unstable (unknown, 4,000?)

Lifetime ~ ms >> Time scale of nucleon motion in nuclei ~ 10^{-22} s



*Graphics: NAOJ

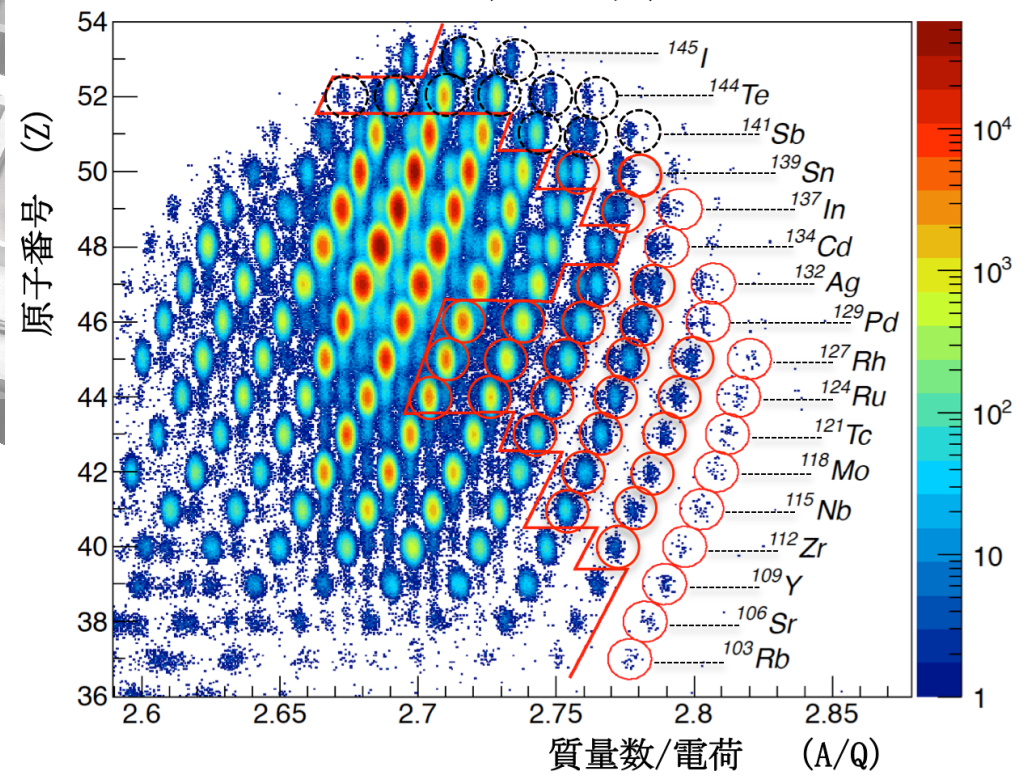
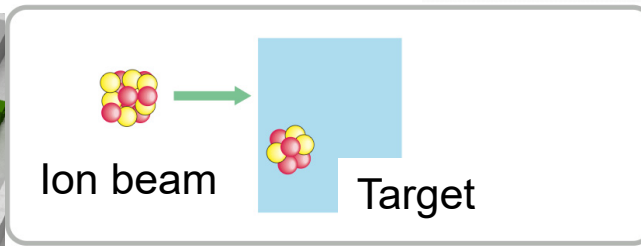
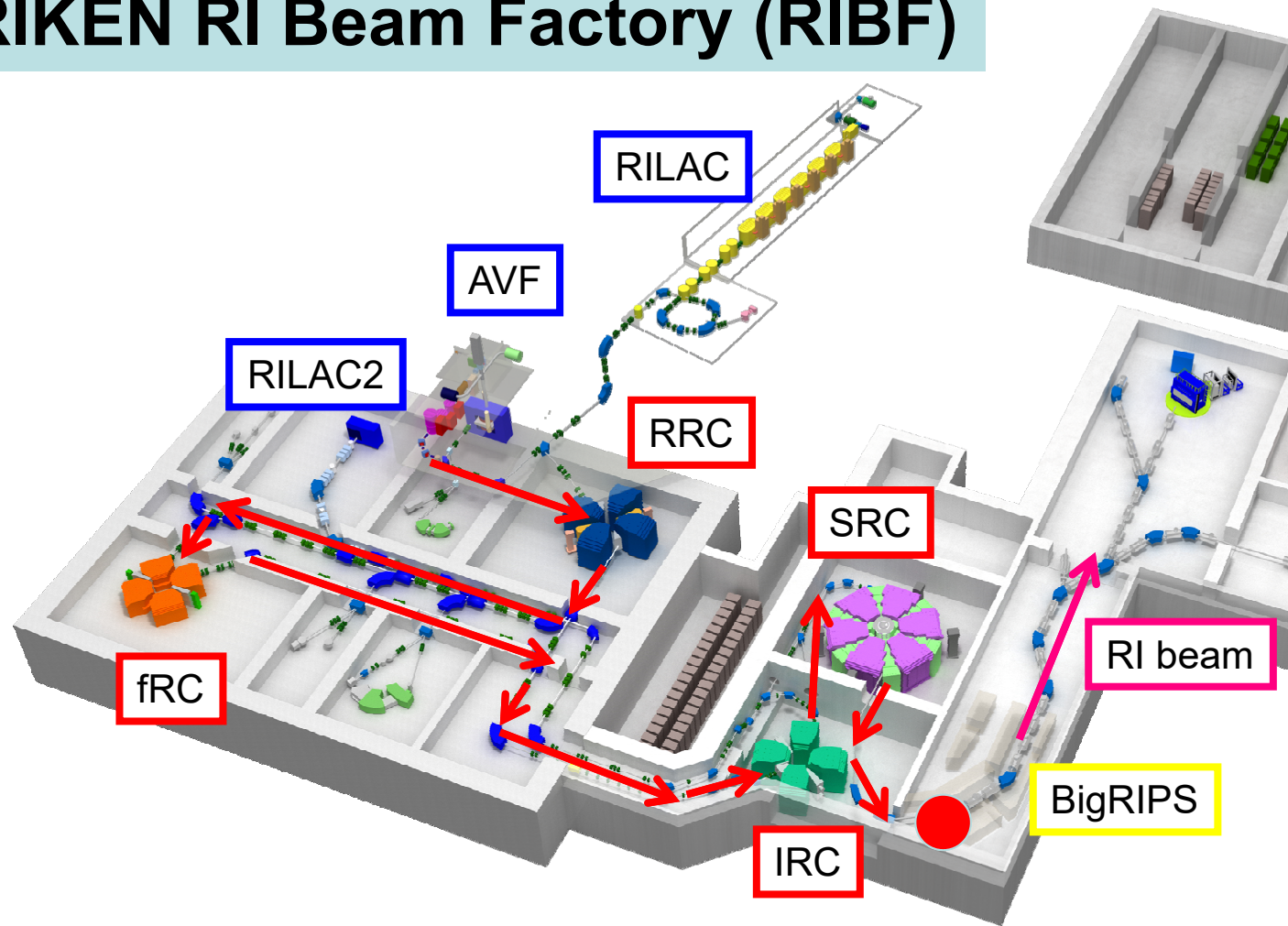
Strongly-interacting "*stable*" systems

Known or accessed
 Unknown

We need RI beams!

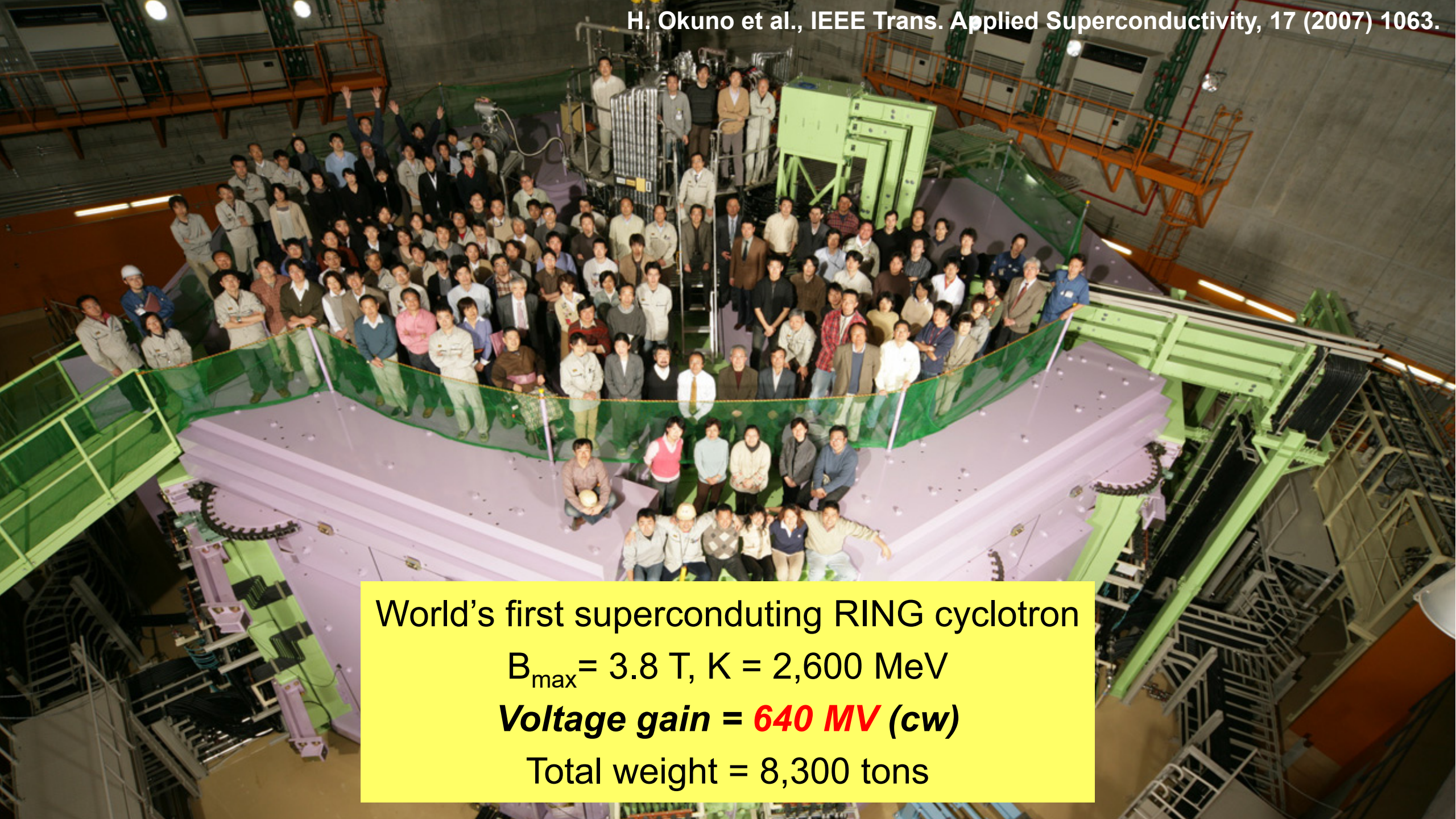
3. Promotion of application research with radioisotope beams

RIKEN RI Beam Factory (RIBF)



3 Injectors + 4 Booster cyclotrons + RI Beam separator capable of

- Acceleration of **ALL** ions up to 345 MeV/u (70% of **c**) in **CW** mode
- Production of RI beams in the **WHOLE** mass region



World's first superconducting RING cyclotron

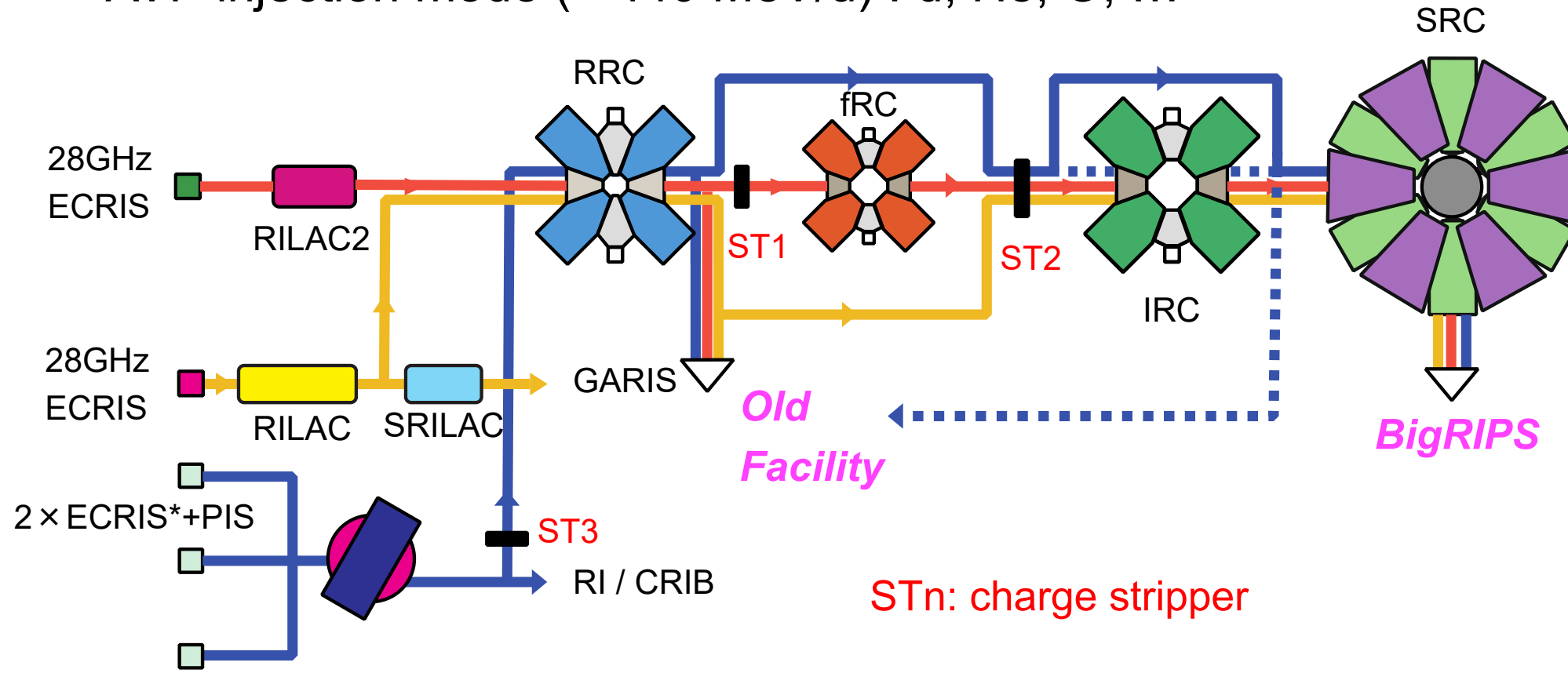
$B_{\max} = 3.8 \text{ T}$, $K = 2,600 \text{ MeV}$

Voltage gain = 640 MV (cw)

Total weight = 8,300 tons

Acceleration modes of RIBF accelerators

- Fixed-energy mode (345 MeV/u) : Zn, Kr, Xe, **U** ...
- Variable-energy mode (< 400 MeV/u) : Ar, Ca, ...
- AVF-injection mode (< 440 MeV/u) : d, He, O, ...



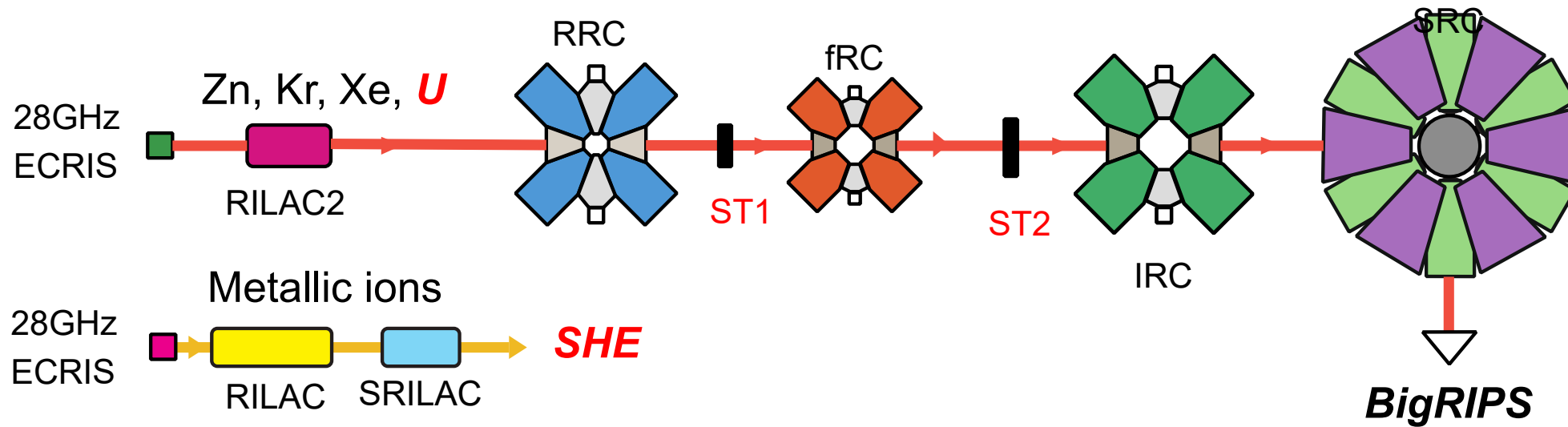
*one is operated by CNS, UTokyo

Independent operation

Fixed-energy mode (345 MeV/u) for Nuclear Physics

+ Super-Heavy Element research

+ Radioisotope production for various application



Radioisotope production

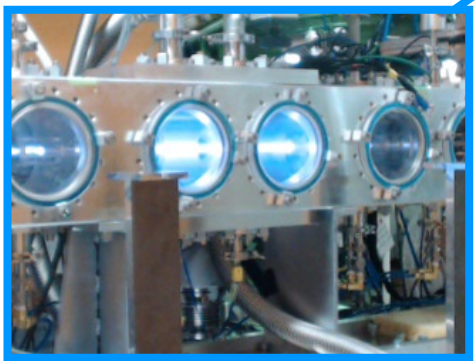
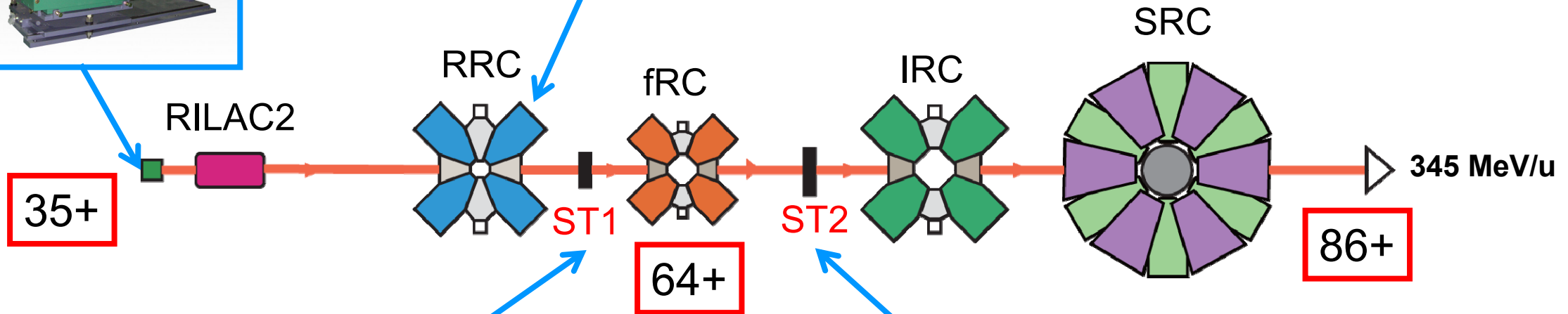
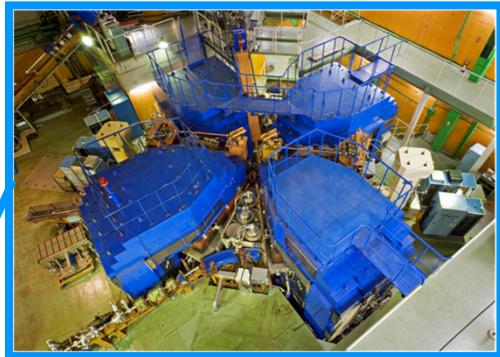
^{211}At delivered to universities etc. and to "Supply Platform of Short-lived RI"

2) Recent R&D activities

Uranium acceleration

RRC (RIKEN Ring Cyclotron)

28GHz SC-ECRIS

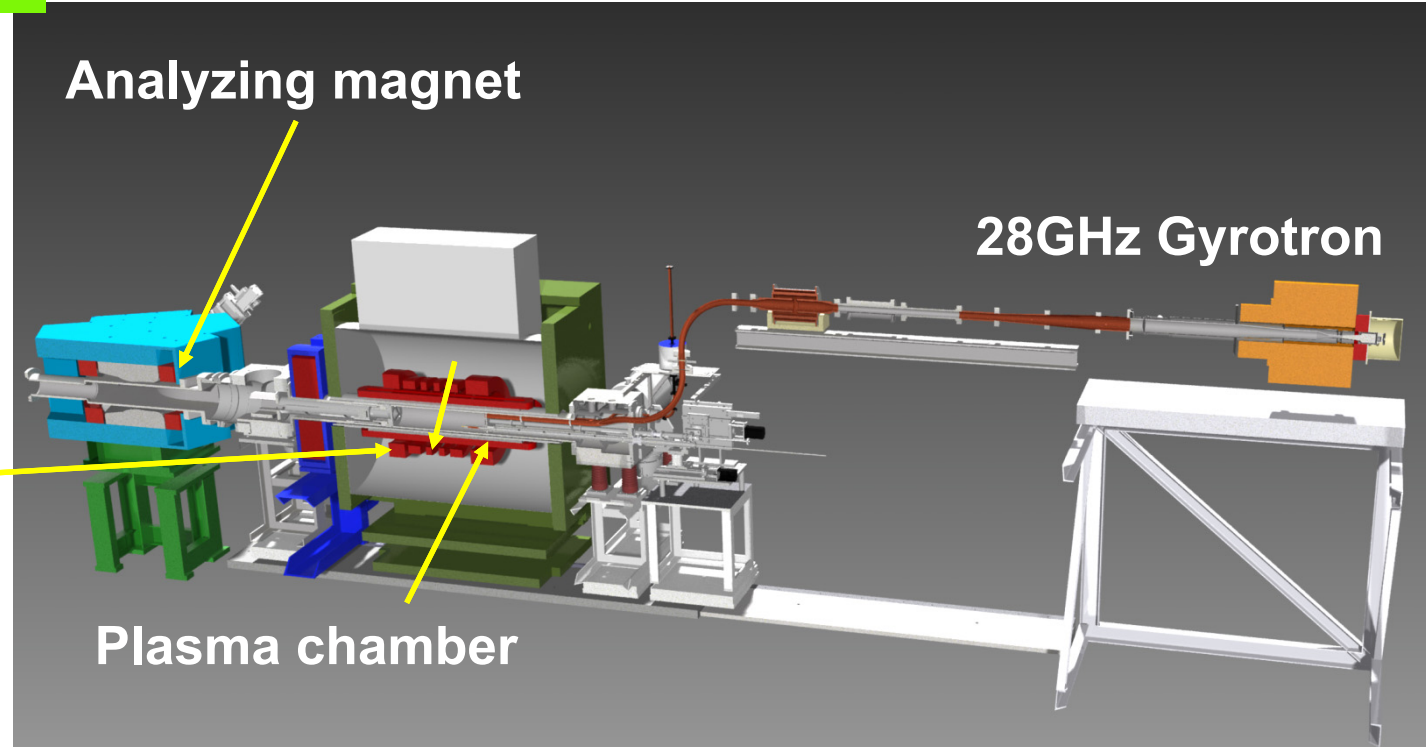
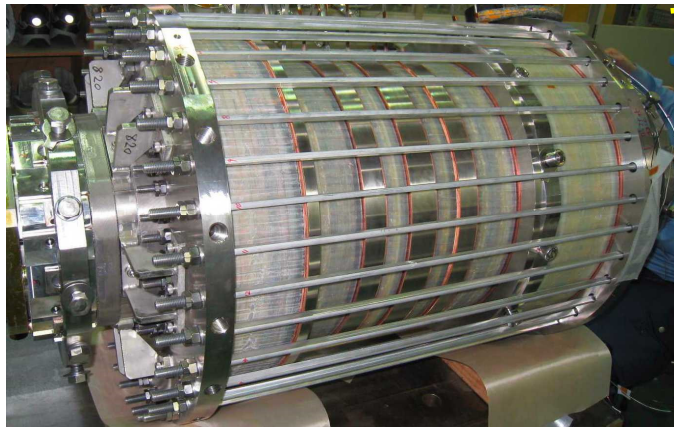


Helium gas stripper @ 11 MeV/u



Graphite sheet stripper @ 50 MeV/u

RIKEN 28GHz ECR ion source

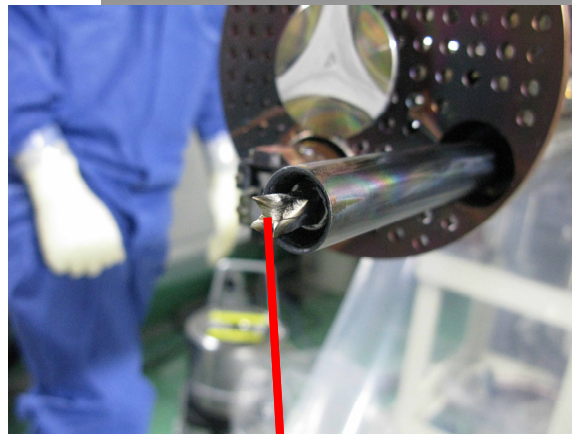


SC sextupole + SC solenoid

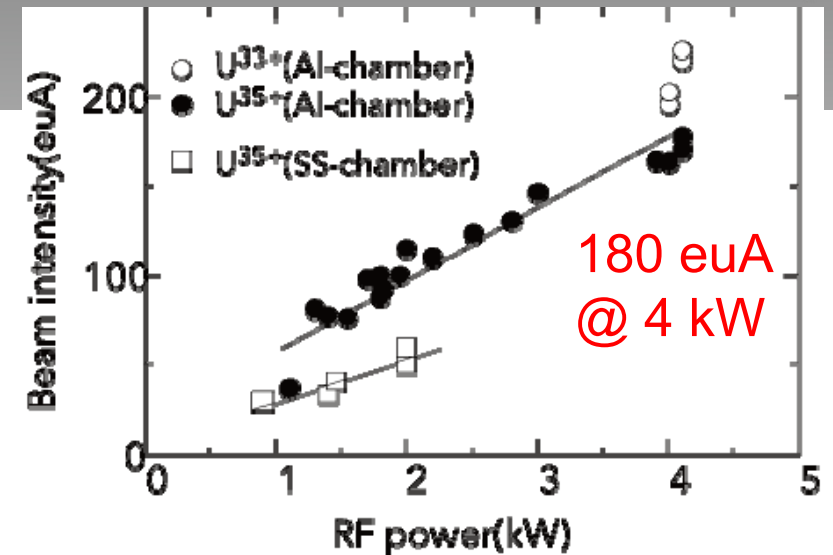
Stored Energy: 0.8MJ

NbTi-copper conductor

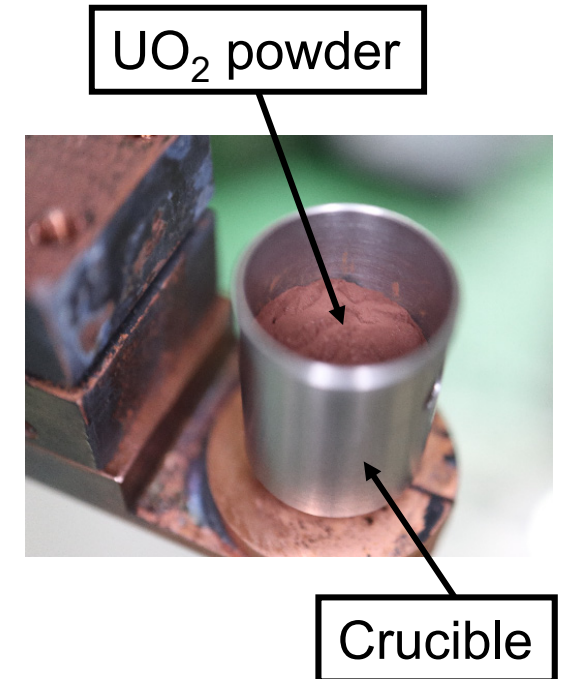
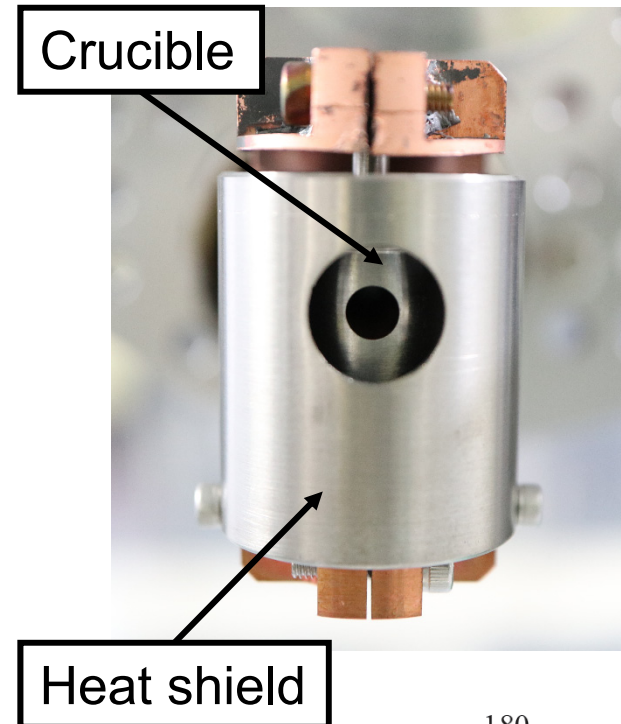
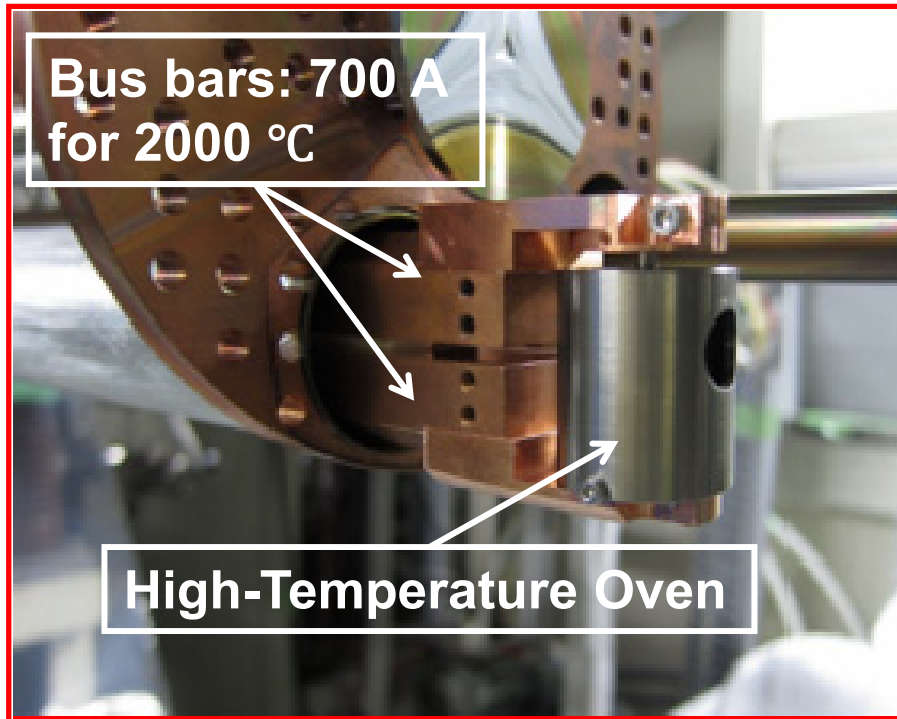
Bath-cooled in liquid helium



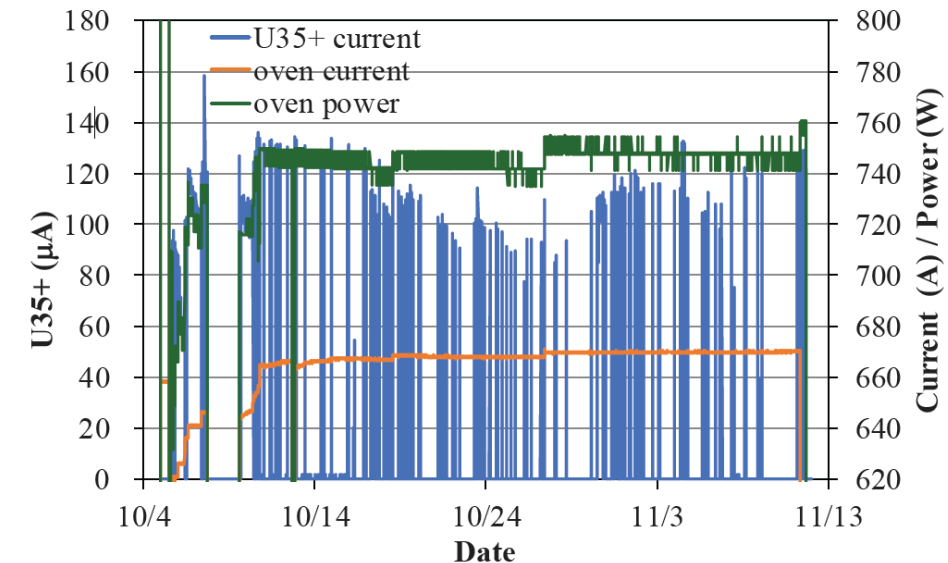
Uranium rod (until 2016)



High temperature oven for 28GHz ECRIS

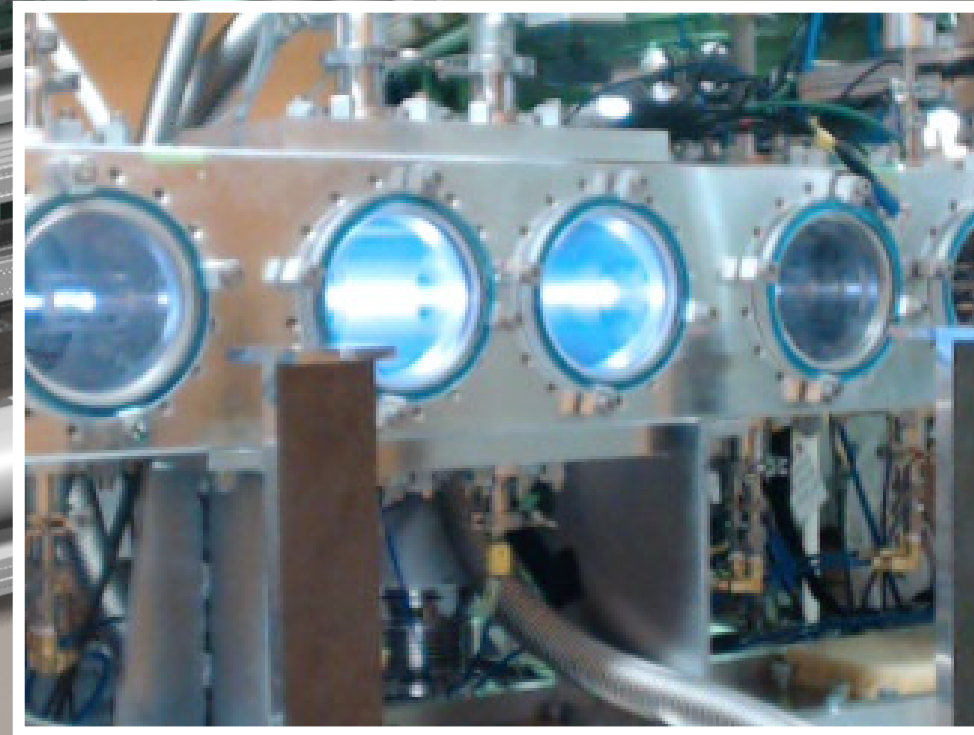
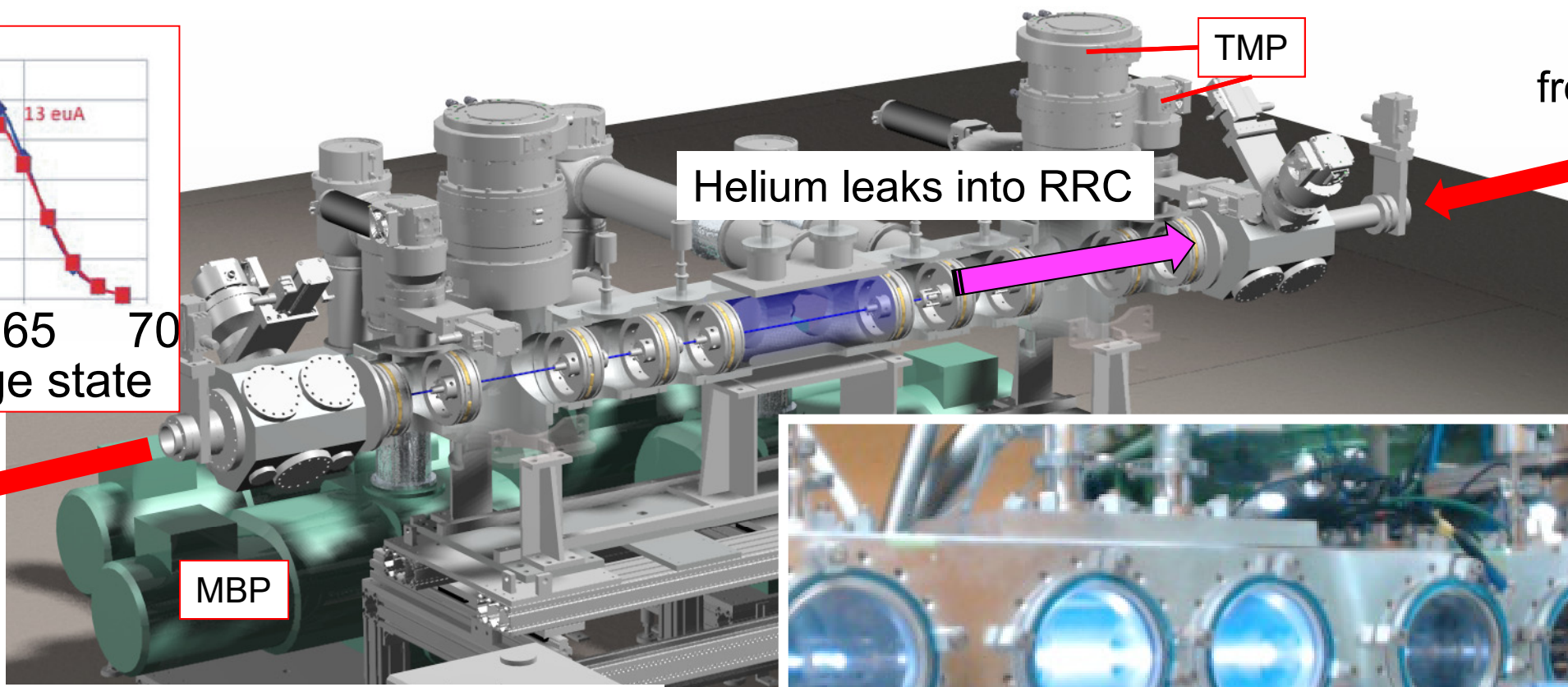
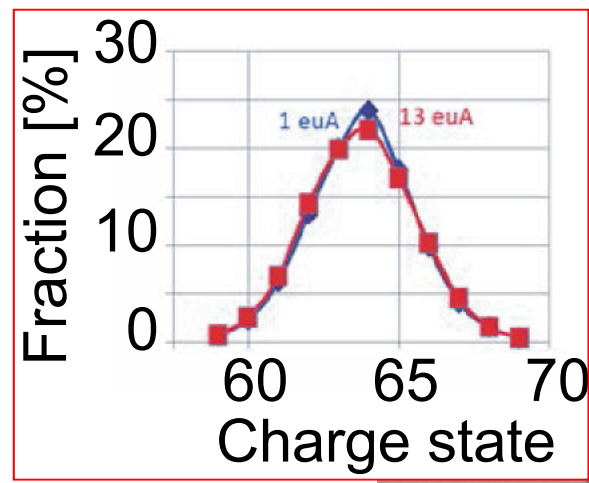


- The High-Temperature Oven method has been used during a long beam time of more than one month since 2016.
- Average beam current of U35+ → 100 – 120 micro-A @ ion source.



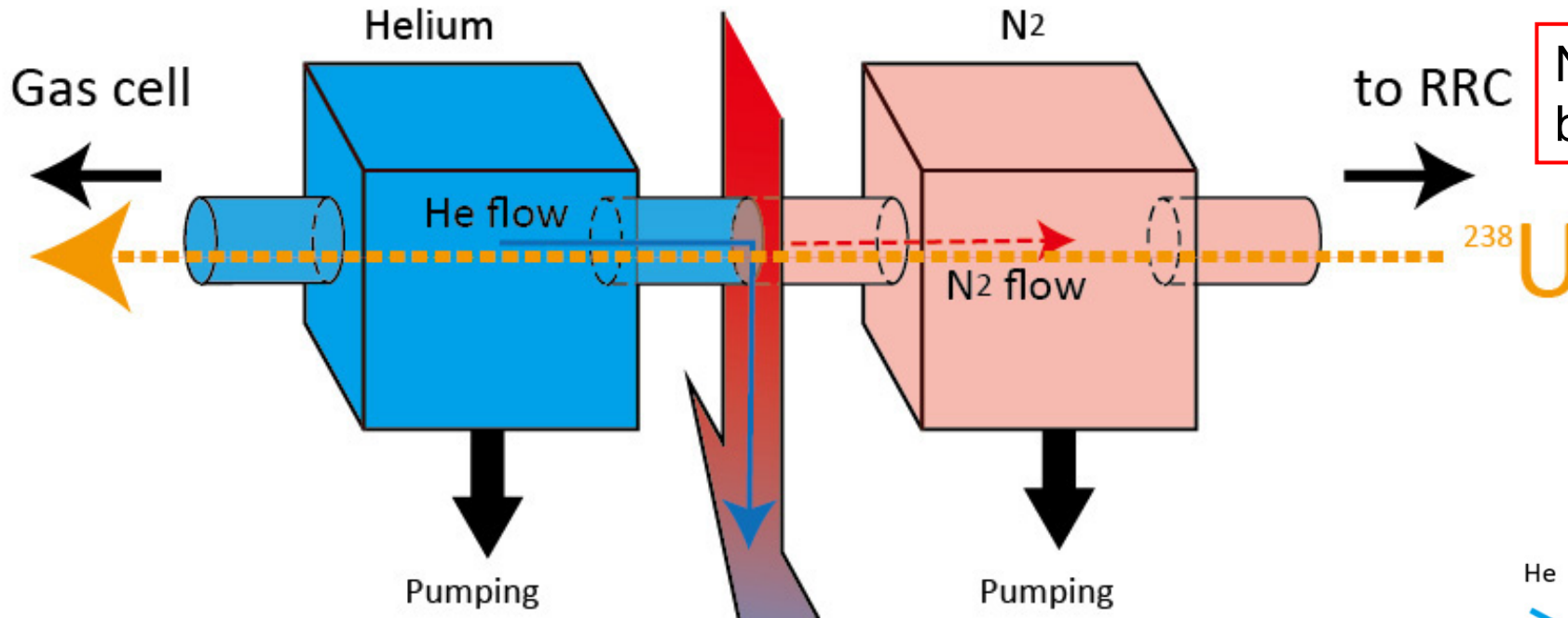
Window-less helium gas stripper @ 11 MeV/u

H. Imao, ACFA Accelerator Prize (2013)



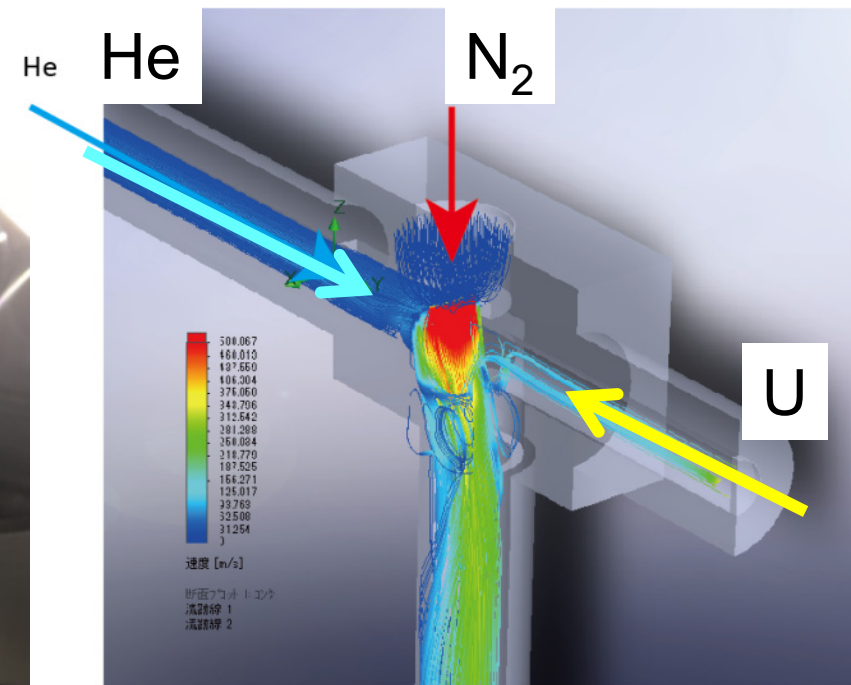
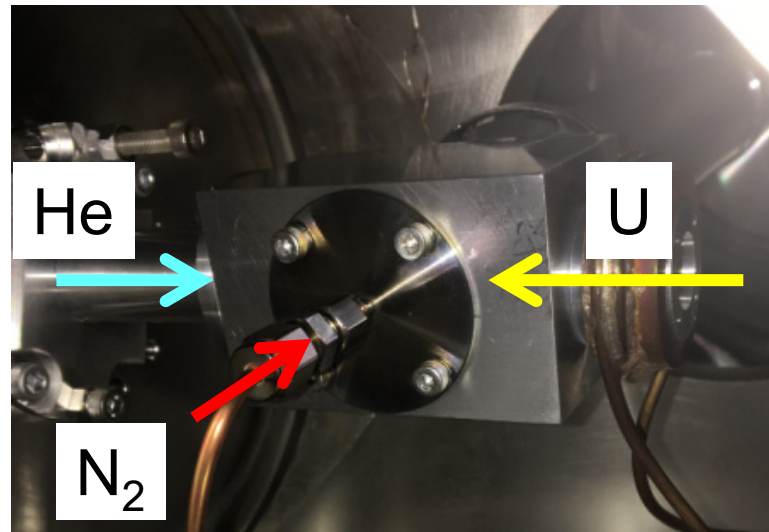
Large beam aperture: $> \phi 10 \text{ mm}$
8 order pressure reduction: $7,000 \text{ Pa} \Rightarrow 10^{-5} \text{ Pa}$
5 stage differential pumping: 21 pumps
He circulating volume: $300 \text{ m}^3/\text{day}$
(unique recycling system)

Concept of N₂-gas jet curtain

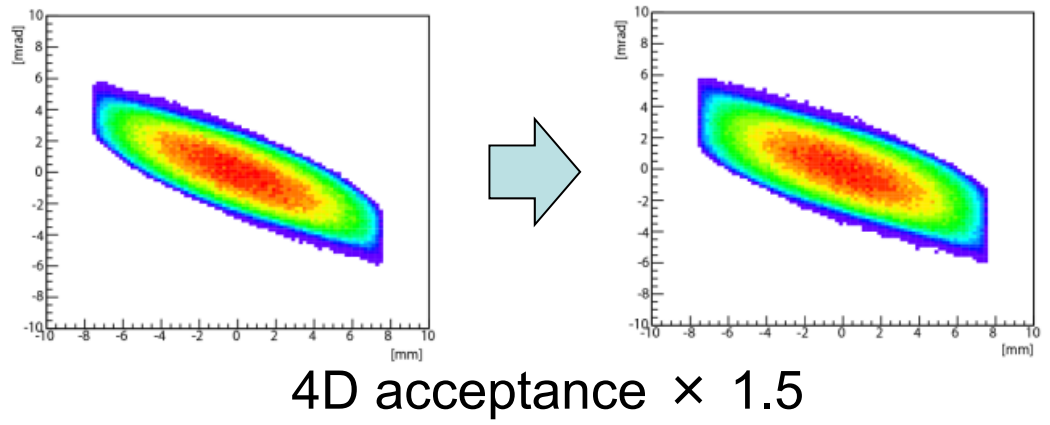
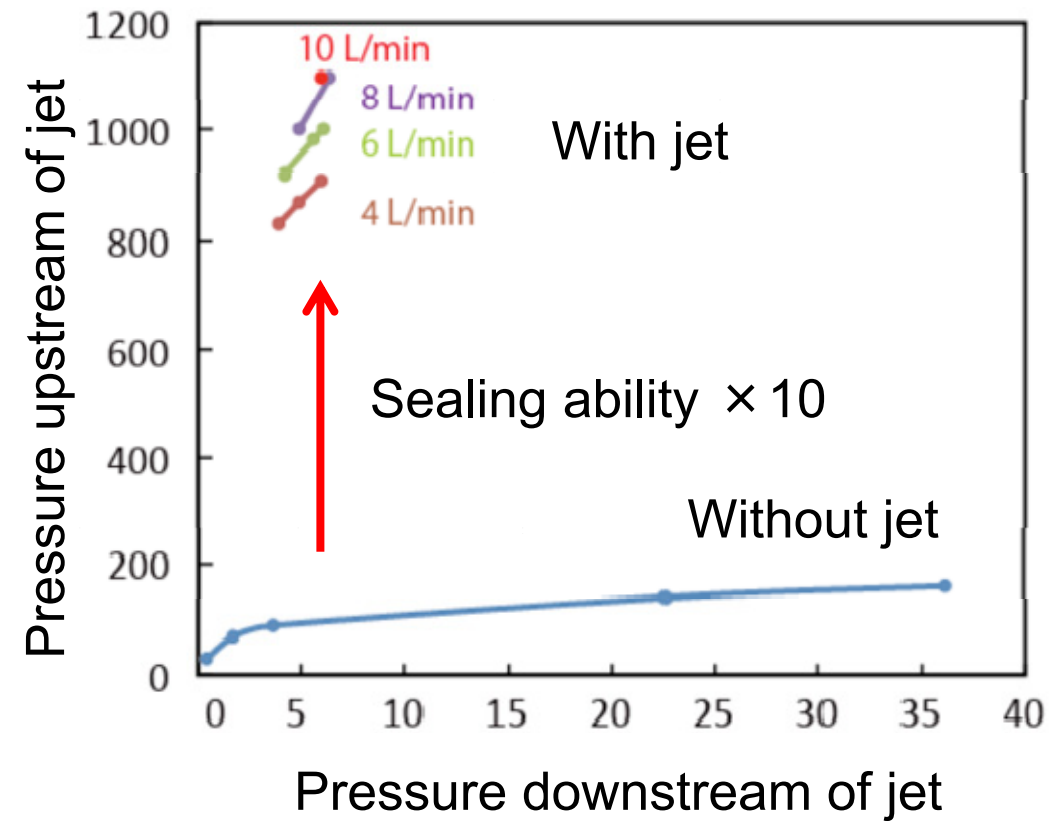
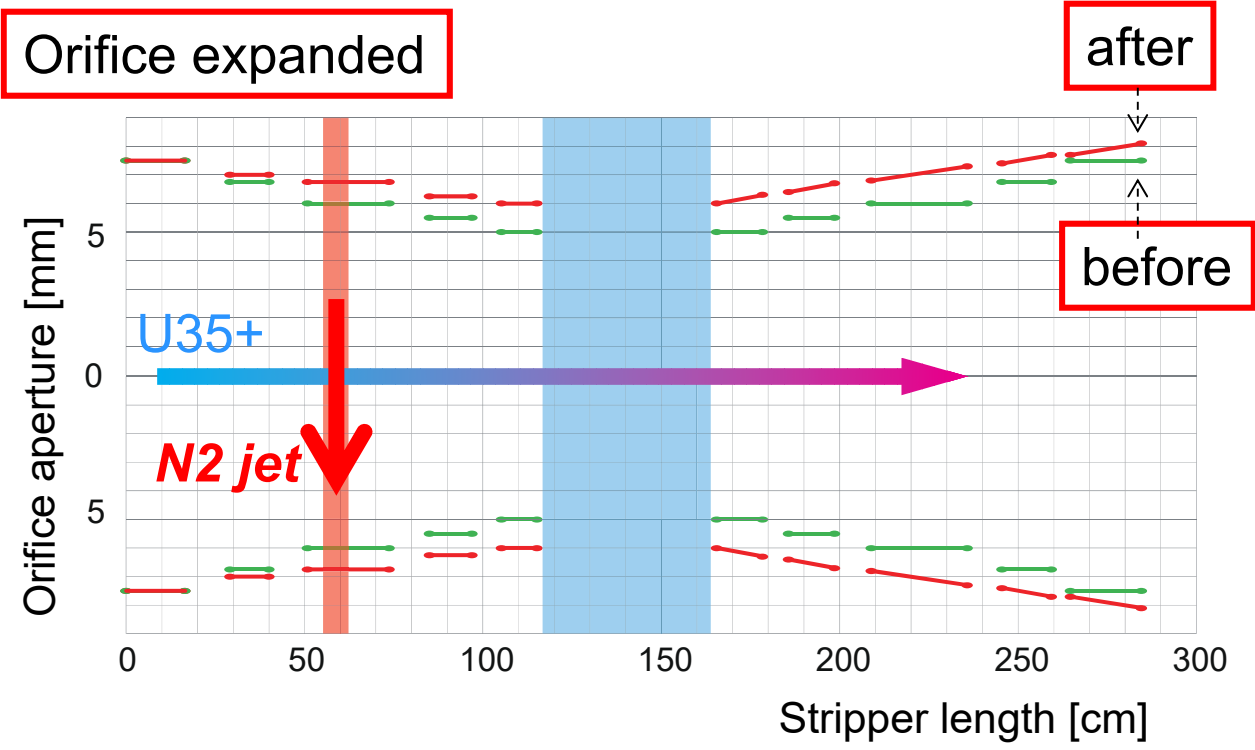


N₂ gas can be evacuated by cryopumps in RRC (120 m³/s)

Blocks helium flow and exchange gas species

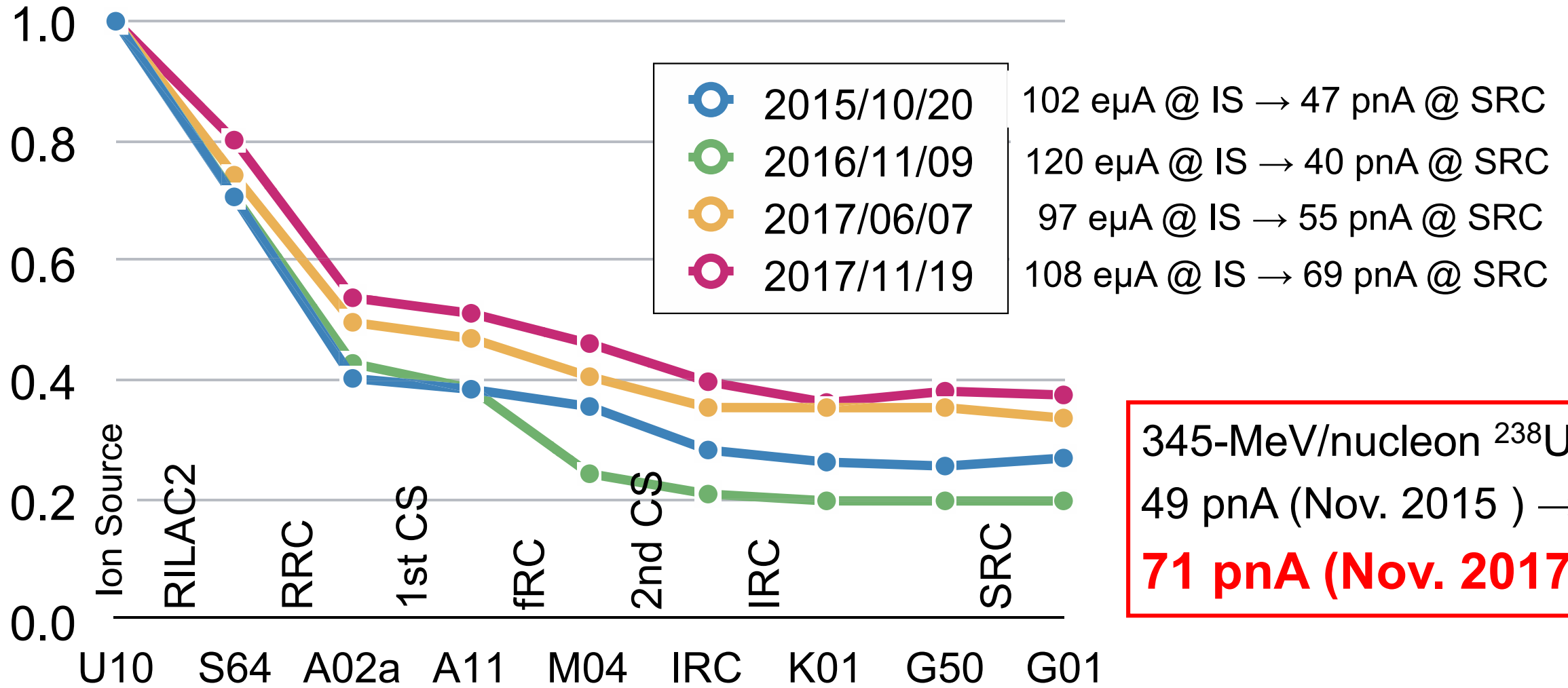


Improvement of helium gas stripper



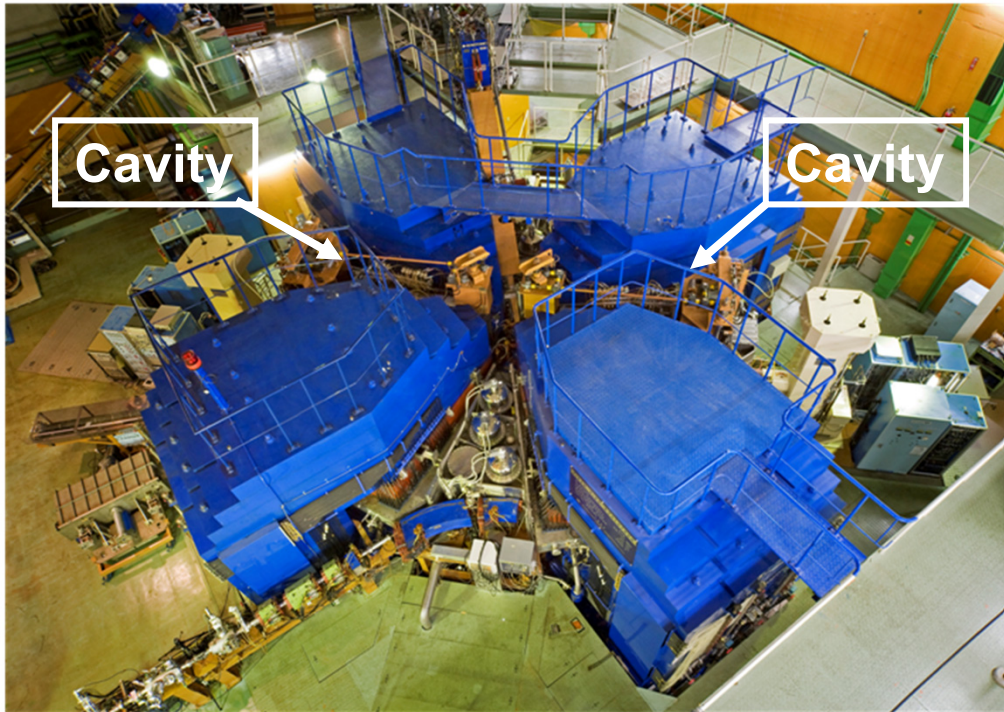
Transmission efficiency*

*Stripping efficiency is excluded.



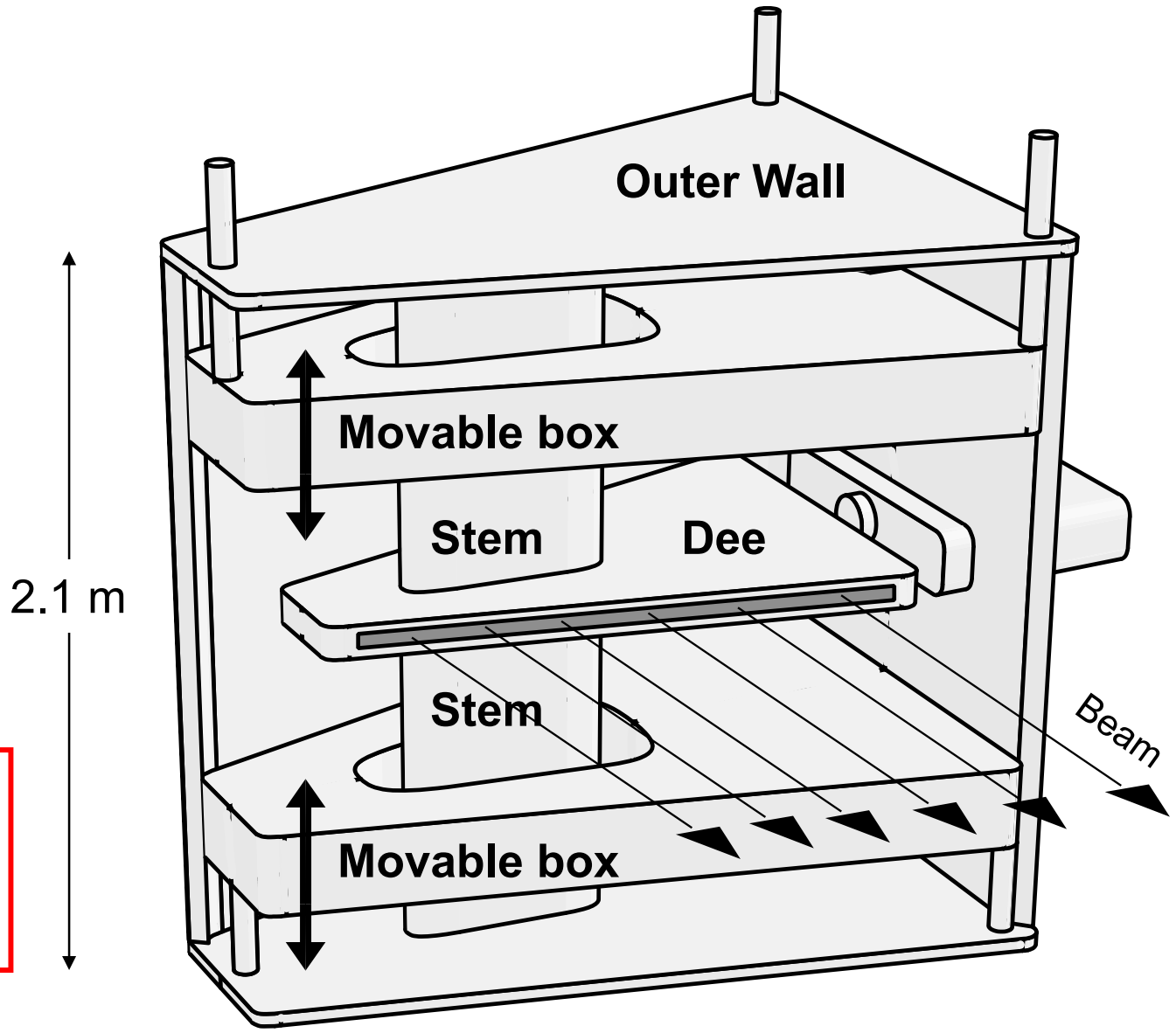
345-MeV/nucleon ^{238}U
 49 pnA (Nov. 2015) →
71 pnA (Nov. 2017)

RRC cavity



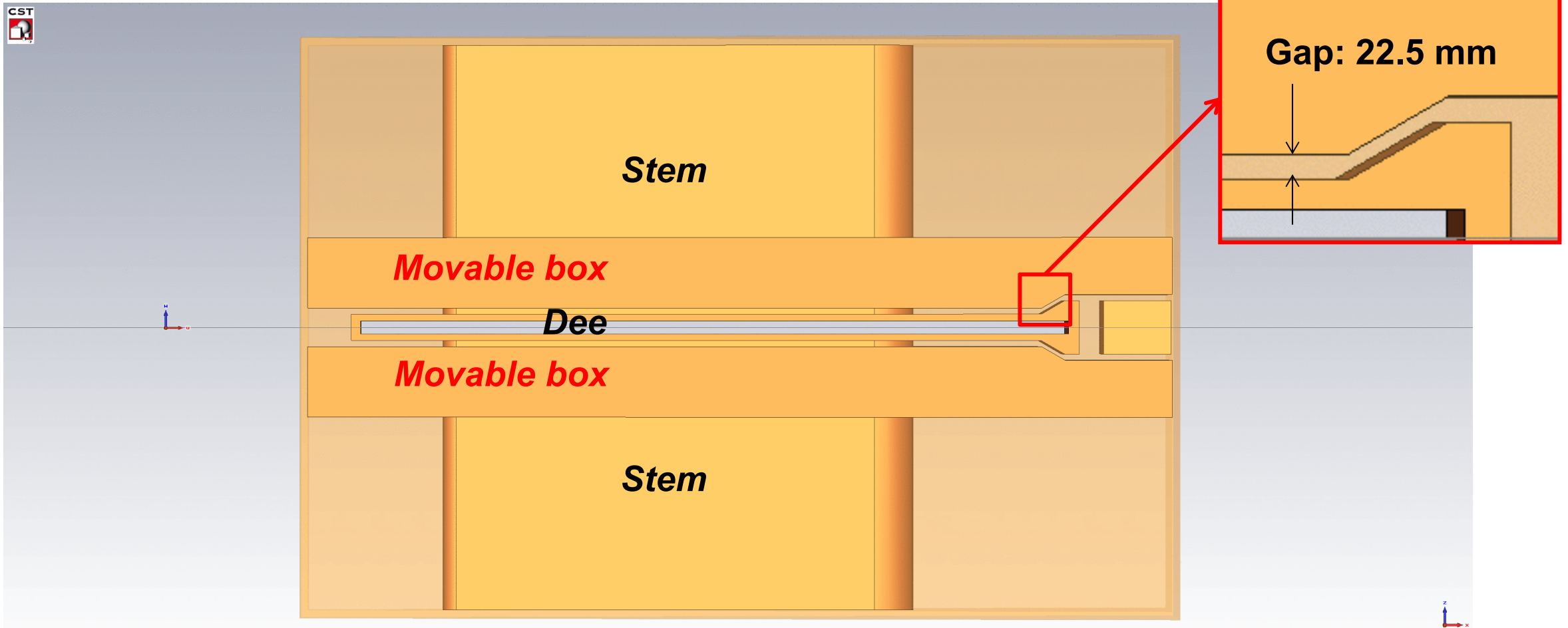
- Half-wavelength
- Variable frequency: **20** – 45 MHz (design)
- Very compact at low frequency

Movable-box type resonator



RRC cavity

Frequency for uranium acceleration: **18.25 MHz**
→ Out of the design range



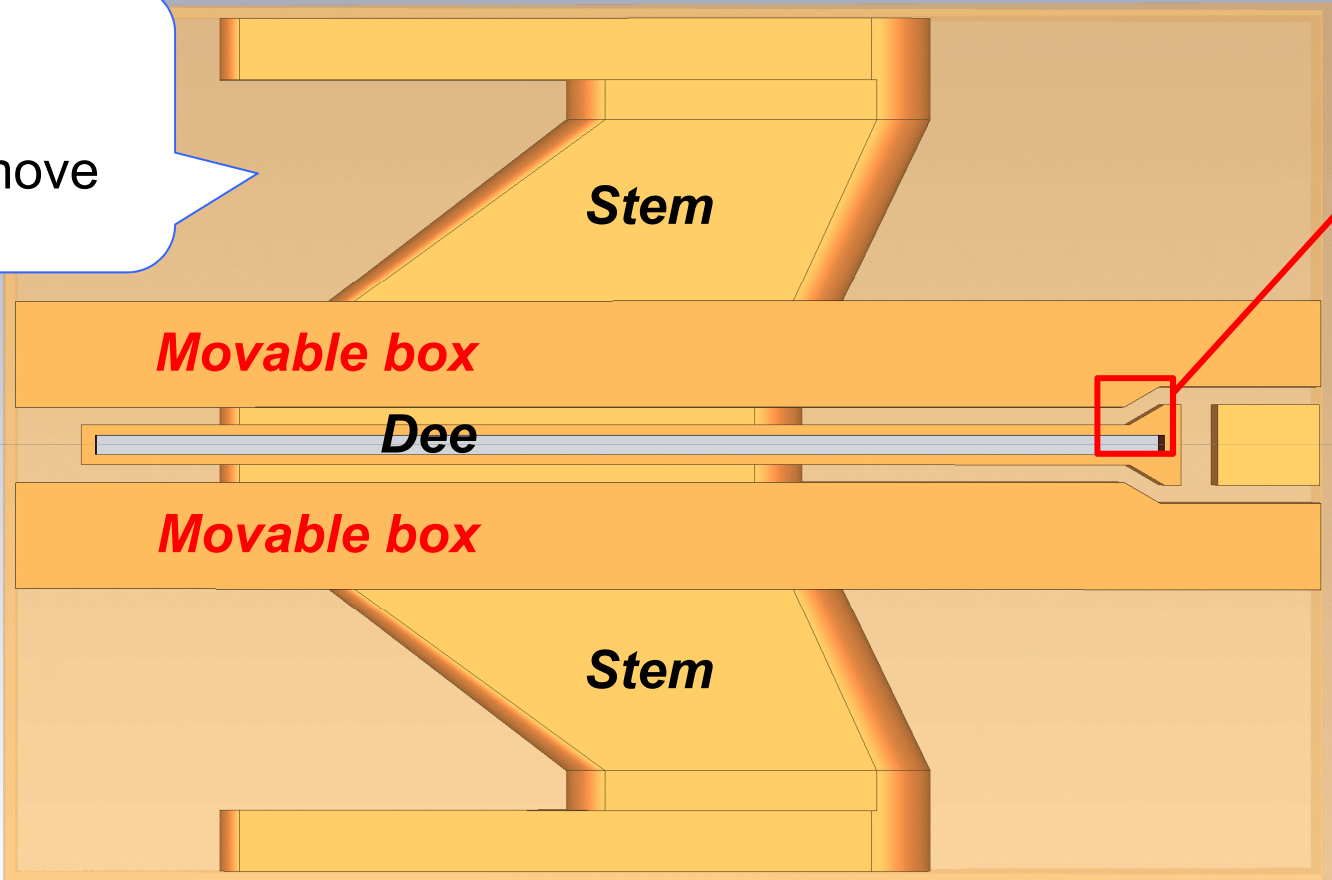
Gap between dee and MBOX: **22.5 mm**
→ Low shunt-impedance and frequent discharge
→ Limit maximum voltage ~ **85 kV**

Space-charge limit:

$$I_{\text{lim}} = \frac{U_f}{f_n \cdot 2.8k\Omega} \left(\frac{\Delta\phi}{2\pi} \right) \frac{\beta_{\text{max}}}{N^3} \propto V^3$$

Modified cavity of RRC

New slanted stem structure
 → Frequency range move to lower side.



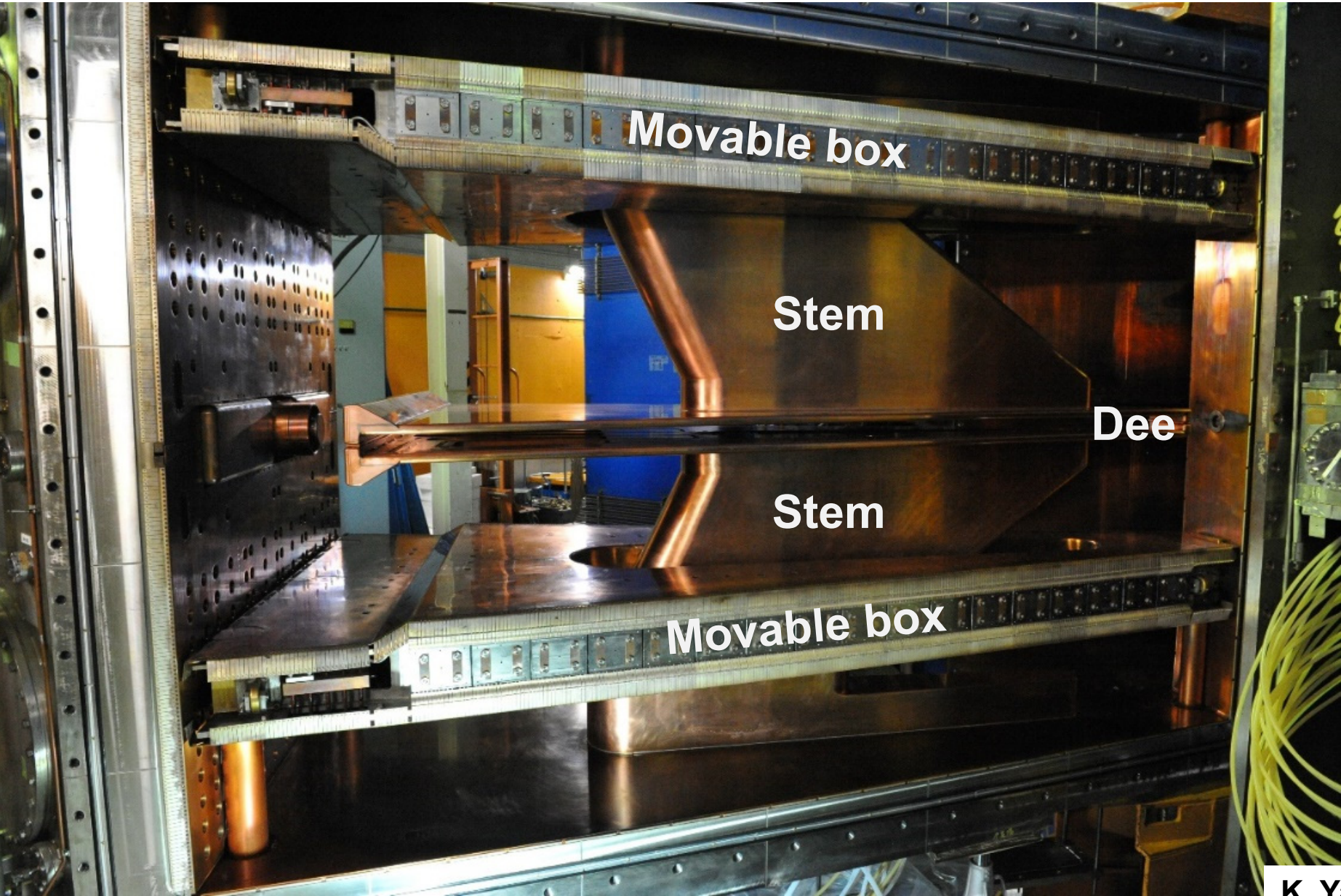
Increased inductance helps to reduce the capacitance for the same frequency.

Reduced capacitance resulted in the increased shunt impedance.

	Original cavity	→ Modified cavity
Frequency:	20 – 46 MHz	→ 16 – 38 MHz
Shunt impedance:	~ 40 kΩ @ 18 MHz	→ 85 kΩ @ 18 MHz

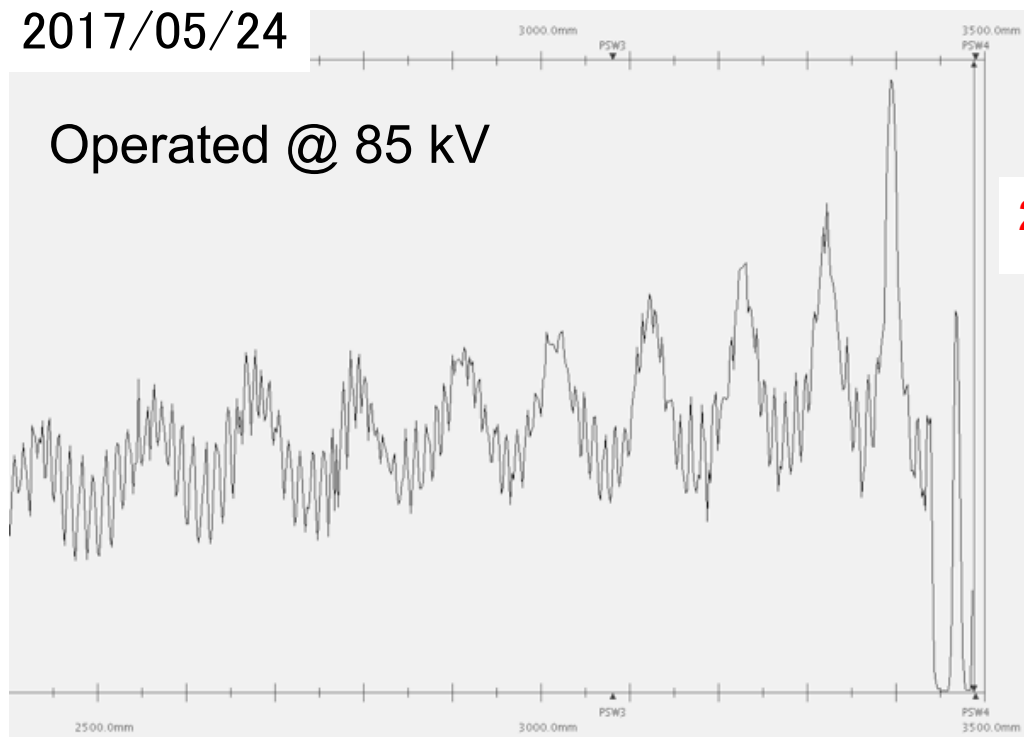
Modified cavity of RRC

Dee and stems were replaced in March 2018.

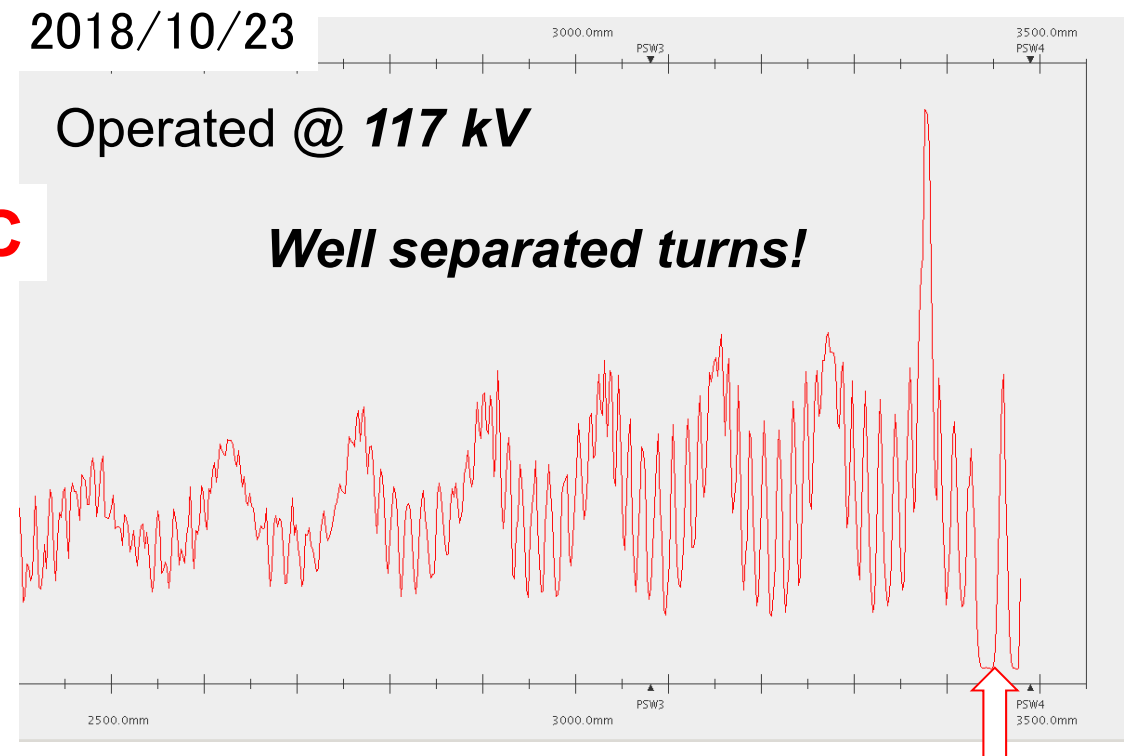
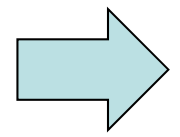


**Higher voltage
achieved!!
> 150 kV
@ 18.25 MHz**

Effect of modification 1: Turn separation in RRC



^{238}U in RRC

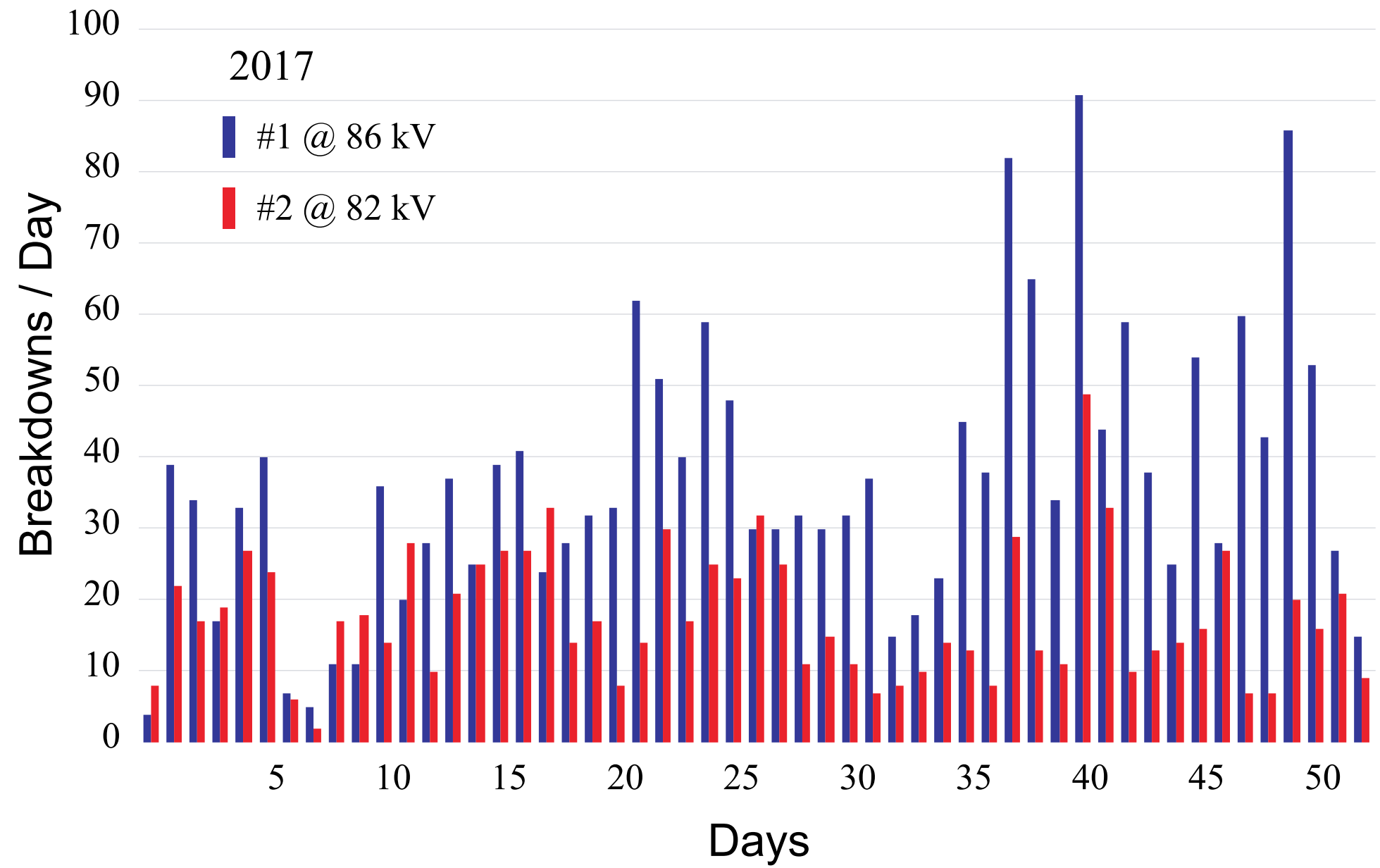


The beam loss was reduced to 1/3 of the 85-kV operation.

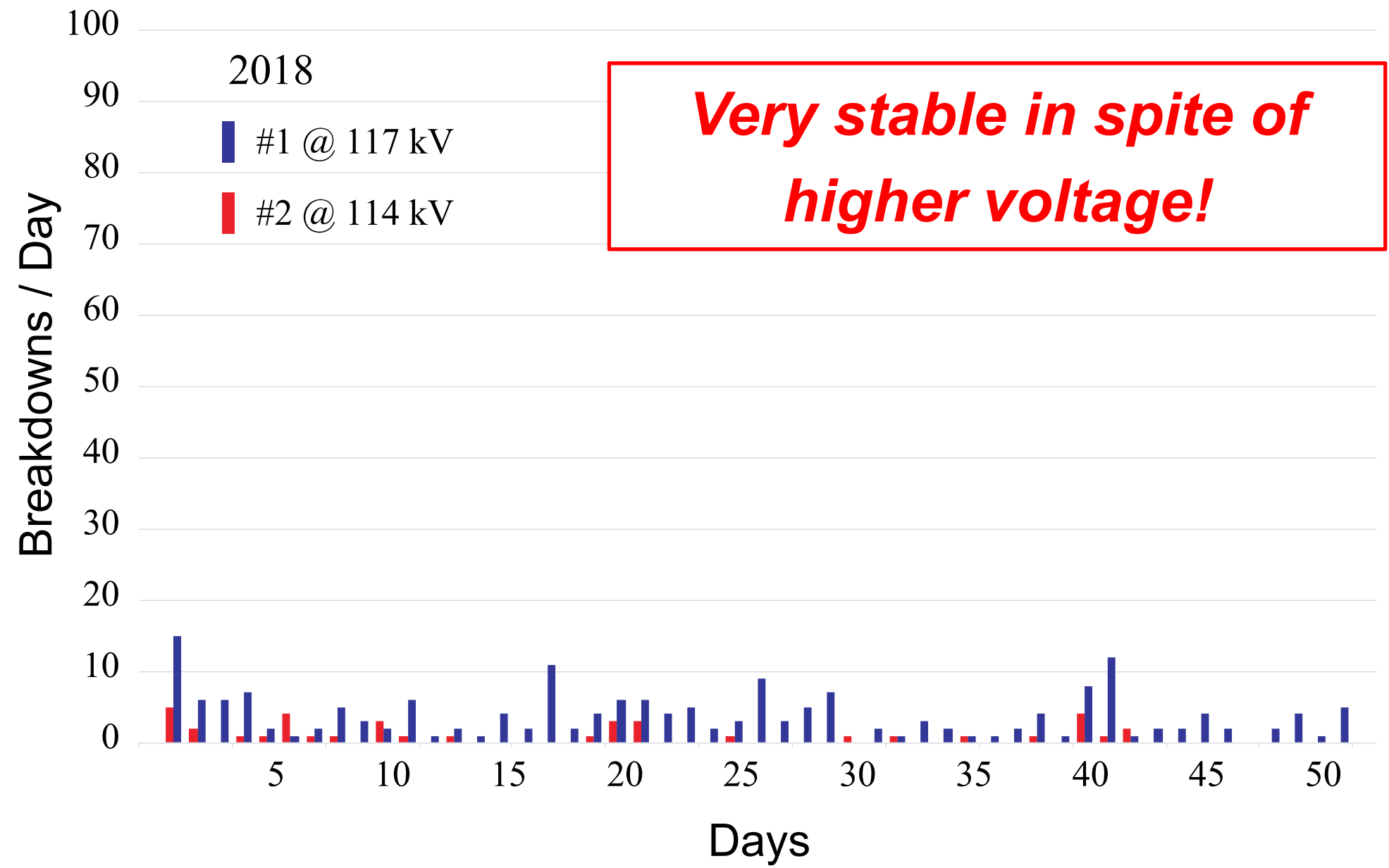
^{124}Xe -beam intensity from SRC has greatly increased!

102 pA @ RRC-80 kV (Apr. 2016) 4.4 kW \longrightarrow **173 pA @ RRC-100 kV (Jun. 2019) **7.4 kW****

Effect of modification 2: Voltage breakdown

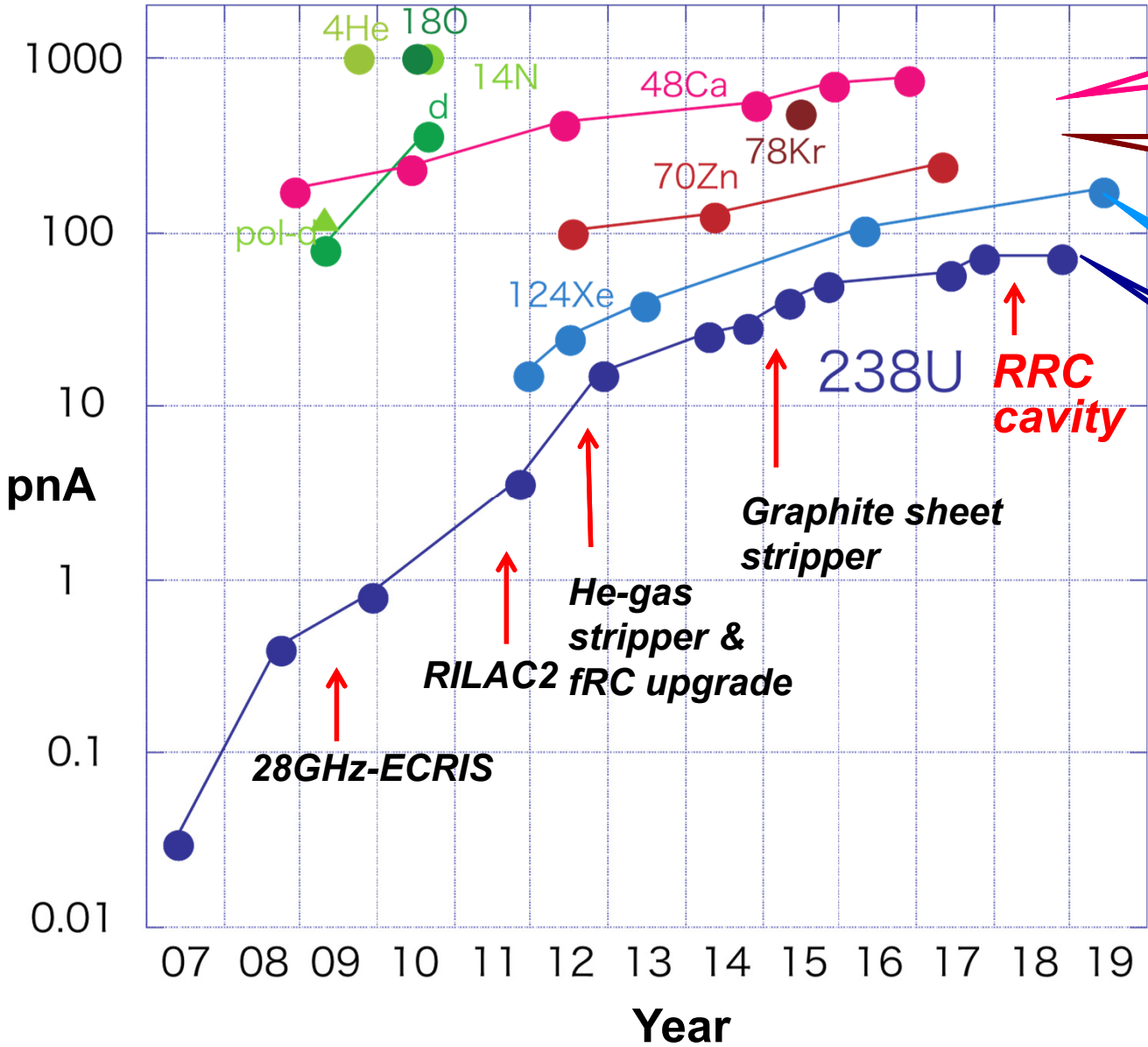


Effect of modification 2: Voltage breakdown



3) *Present status*

RIBF accelerator performance



**^{48}Ca : 738 pA
=> 12.3 kW**

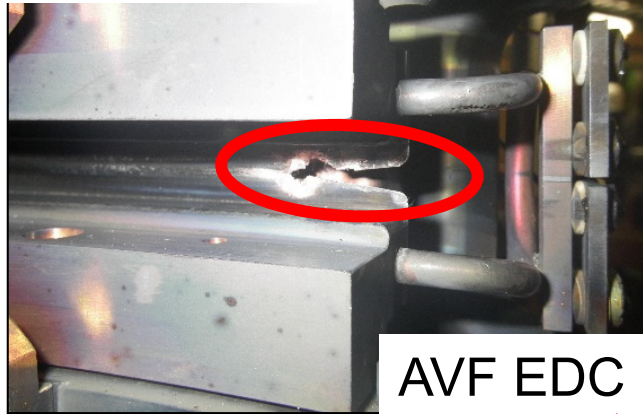
**^{78}Kr : 486 pA
=> 13.1 kW**

**^{124}Xe : 173 pA
=> 7.4 kW**

**^{238}U : 72 pA
=> 5.9 kW**

Devices damaged by ~kW beams

March 2018

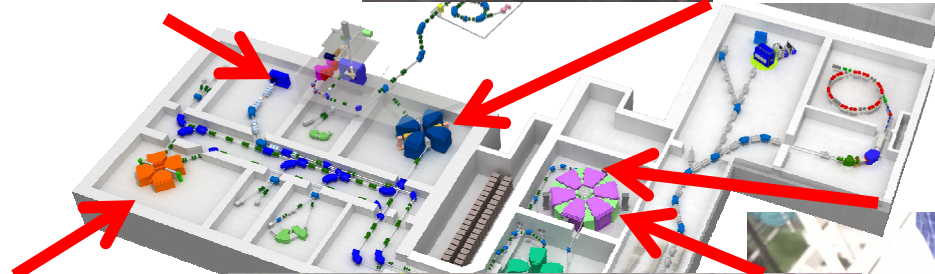


AVF EDC

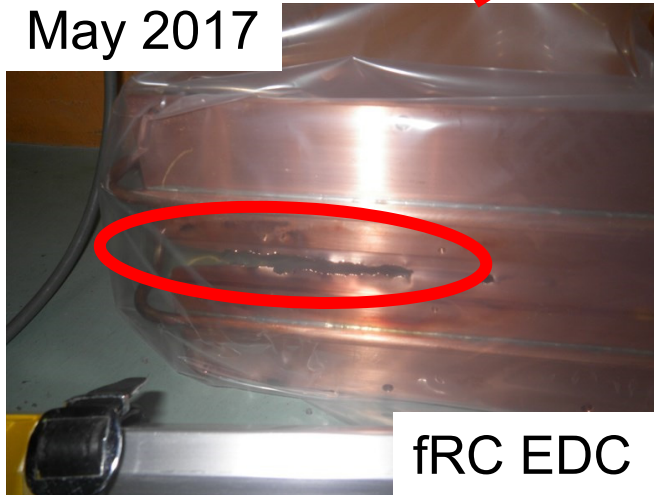
May 2016



RRC MDC

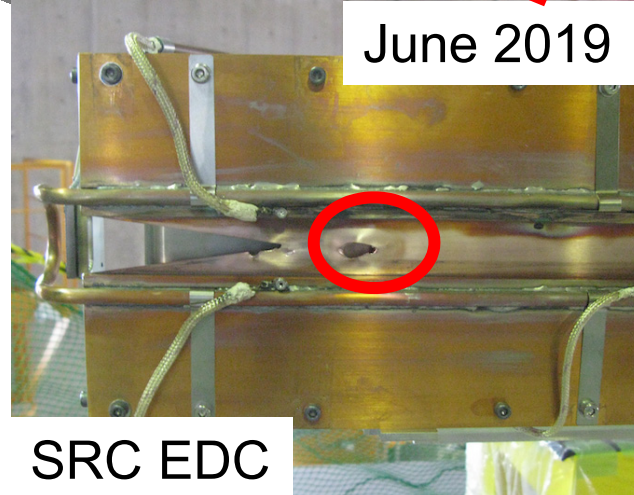


May 2017



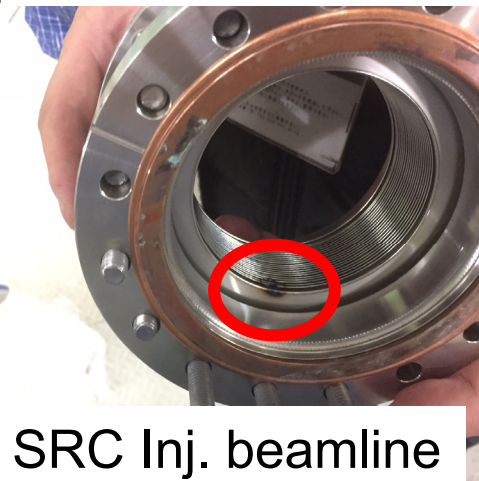
fRC EDC

June 2019



SRC EDC

April 2017



SRC Inj. beamline

We need:

- very careful tuning.
- stable devices
e.g. power supplies, RF,..
- properly working control system.
- fast beam interlock system.
- and so on..

4) Future plan

Worldwide efforts

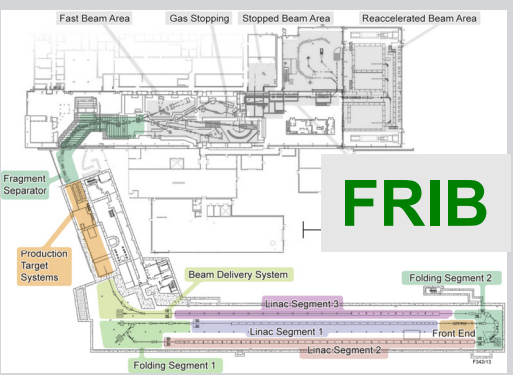
100 m
↔

SIS 100/200

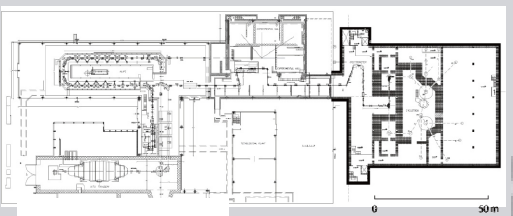
FAIR



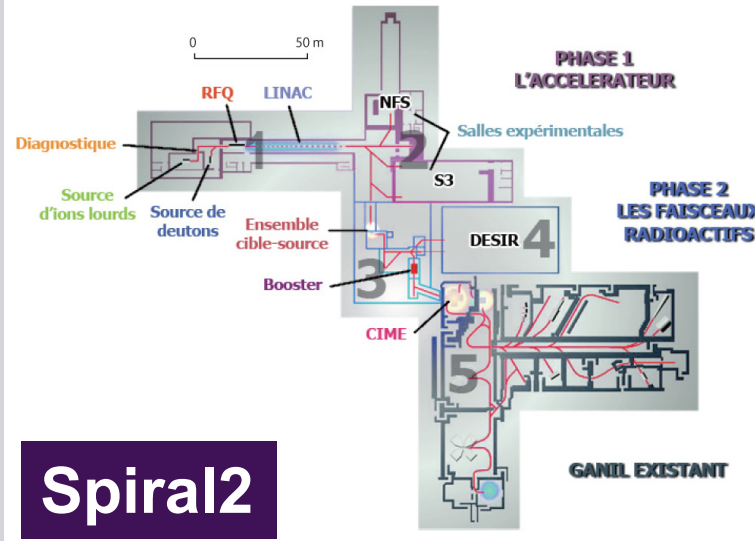
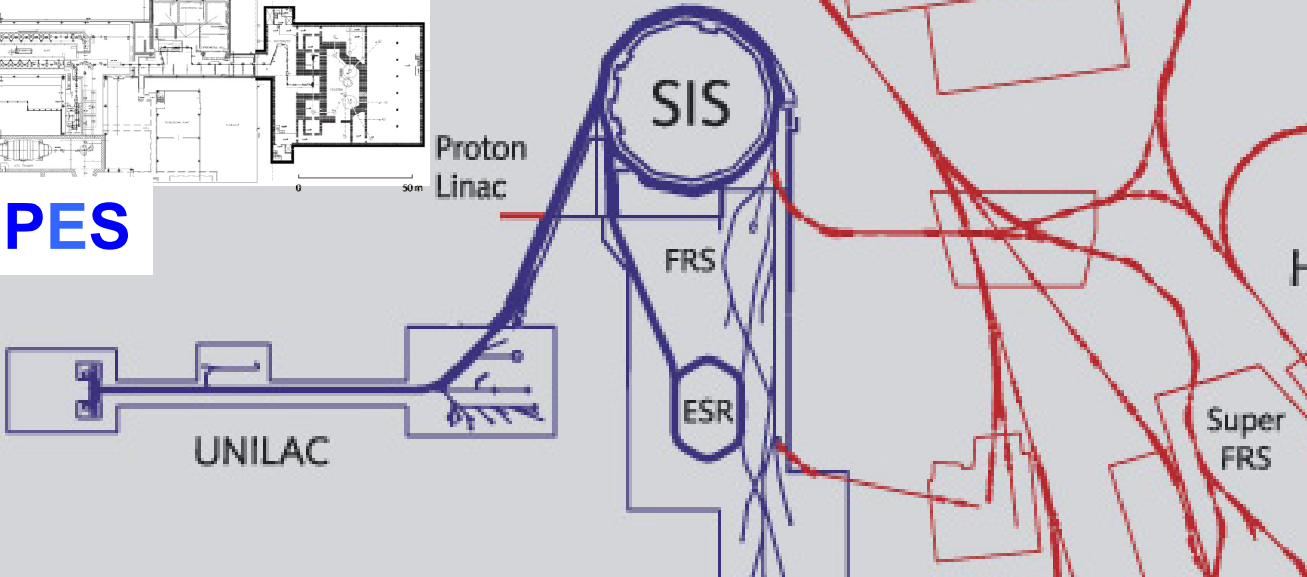
RIBF



FRIB

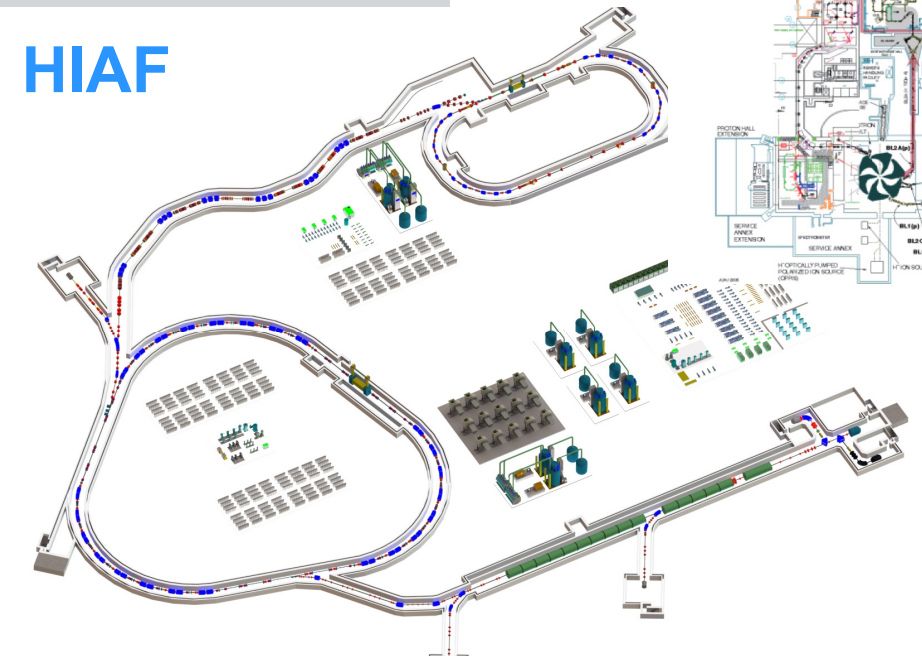
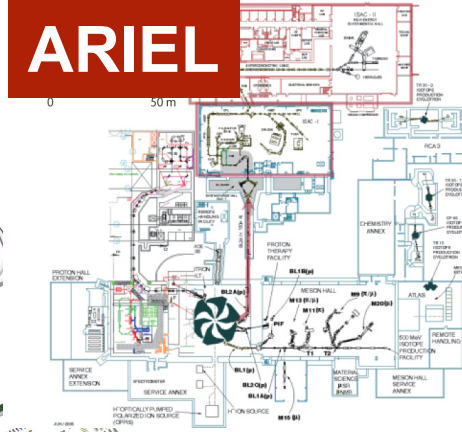


SPES



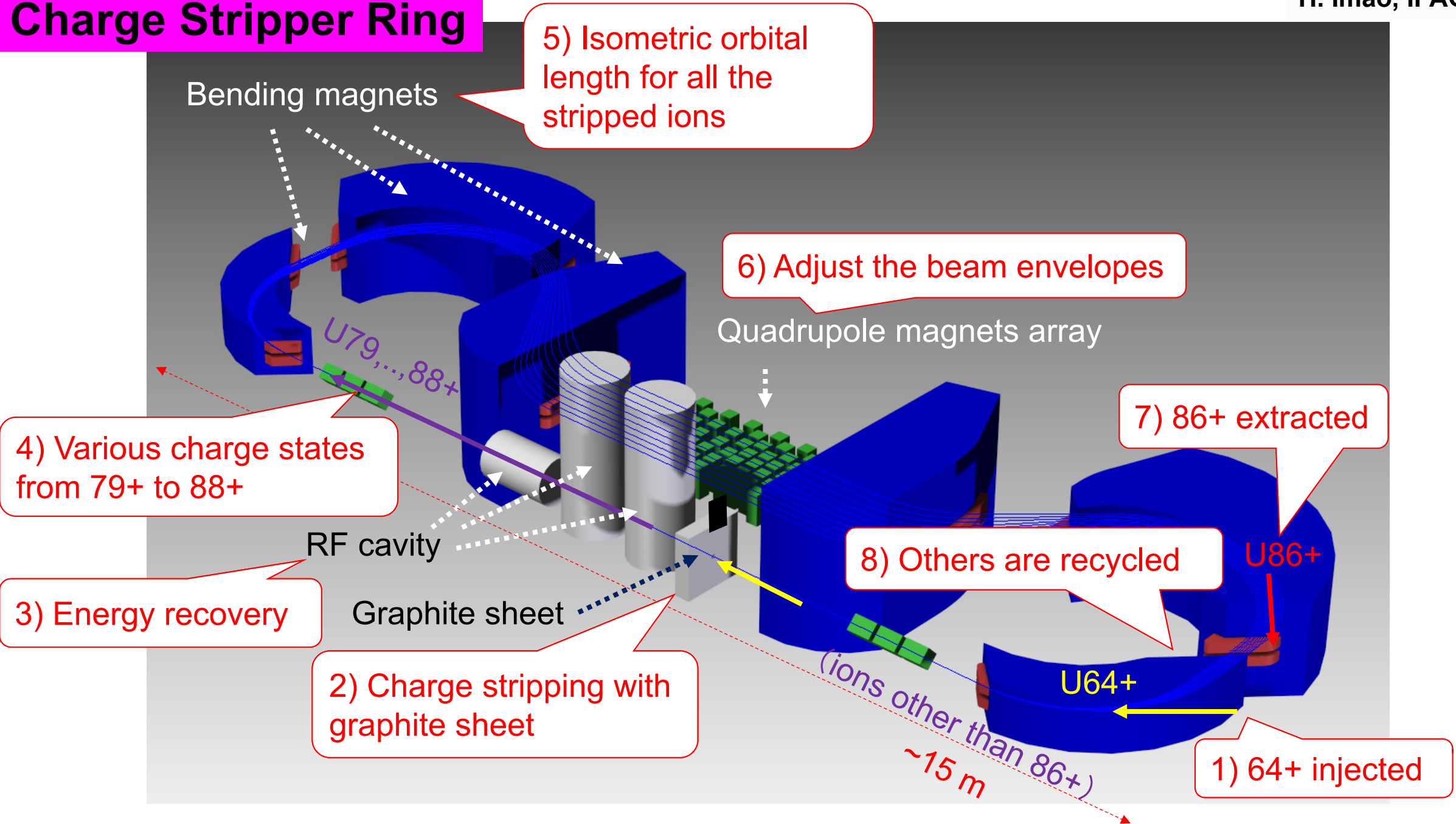
Spiral2

ARIEL



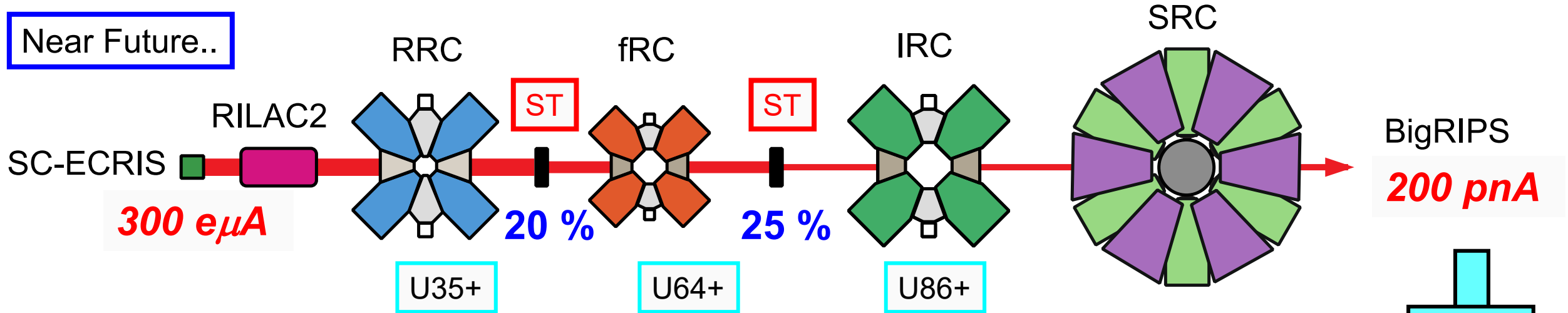
HIAF

Charge Stripper Ring

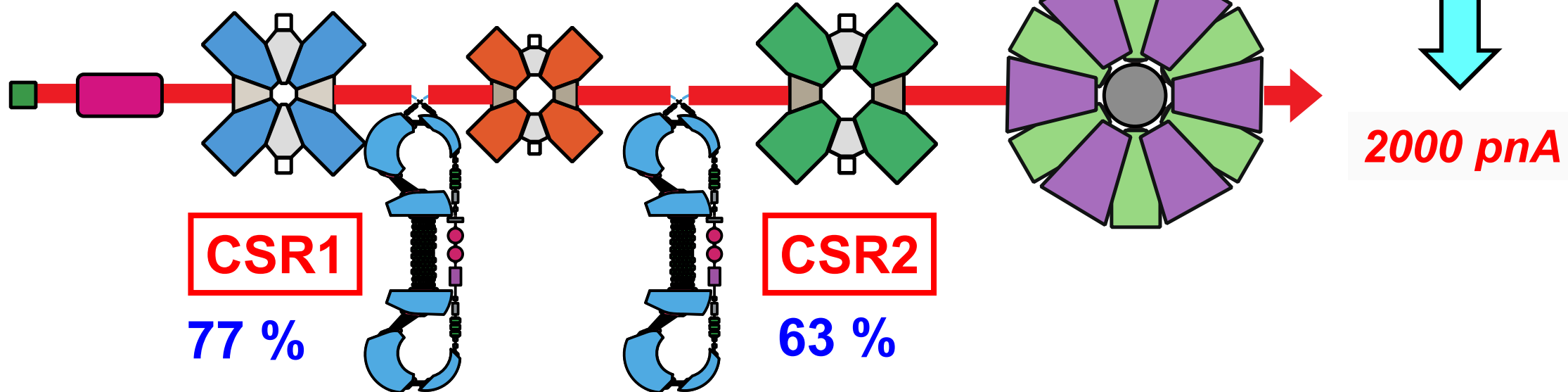


RIBF upgrade for higher U intensity

Near Future..



Upgrade Plan: **Charge Stripper Ring (CSR)**



Summary

- The performance of the RIBF accelerators is improving steadily. Recent R&Ds are focused on the increase of beam intensities of uranium and xenon.
- Over the last three years, uranium beam has increased from 49 to 72 pnA, and xenon beam has increased from 102 to 173 pnA. It will be possible to accelerate uranium beam of 200 pnA in near future.
- More than 1500 RI beams have been produced in the RIBF. Nearly 200 new isotopes have been discovered.
- The R&D of “Charge stripper ring” is under progress for the future intensity upgrade. We aim to start the upgraded RIBF in 2025.