New developments in low-Z gas stripper system at RIKEN Radioactive Isotope Beam Factory (RIBF)

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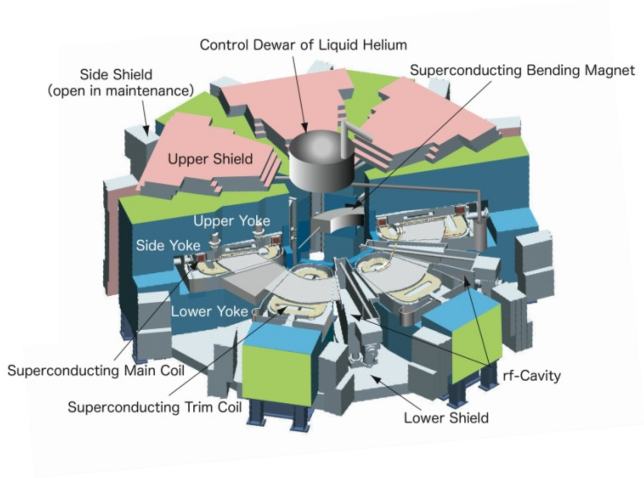
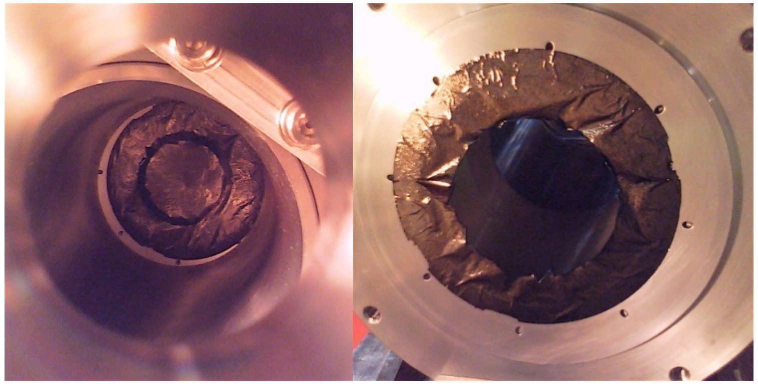
(RIKEN Nishina Center, Wako)

Preview

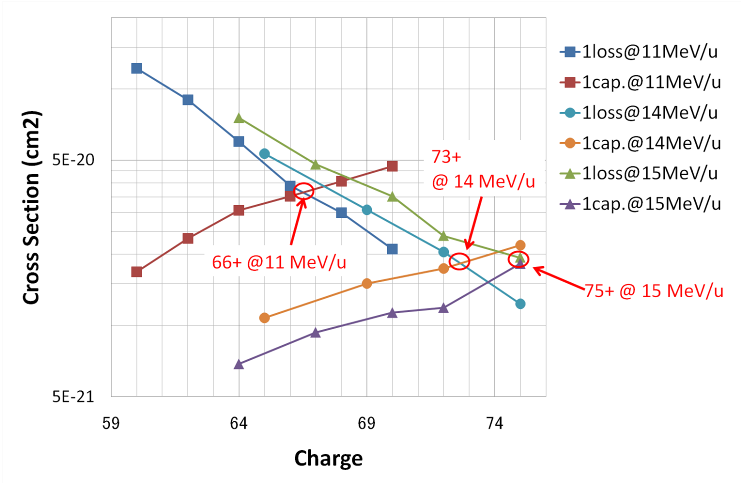
Introduction to RIBF and charge strippers for U acceleration in the world



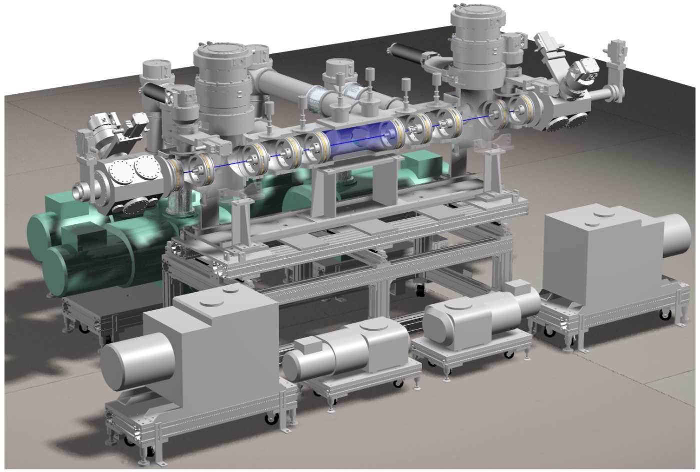
Problems with the charge strippers at RIBF



R&D results on low-Z gas stripper

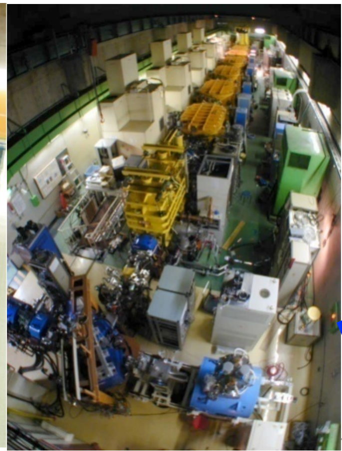


Commissioning status of an actual machine for He gas stripping



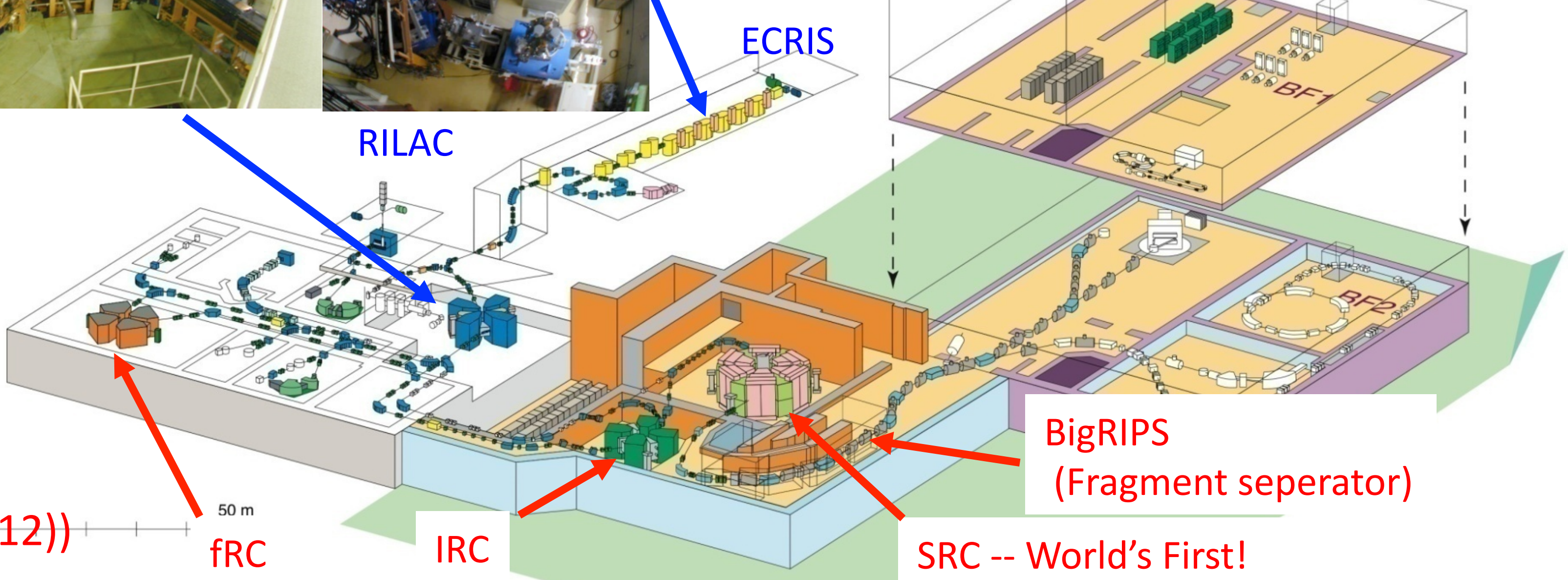
Introduction to RIKEN RI Beam Factory (RIBF)

RRC



RILAC

The old facility (1975 to 1990)



RIBF

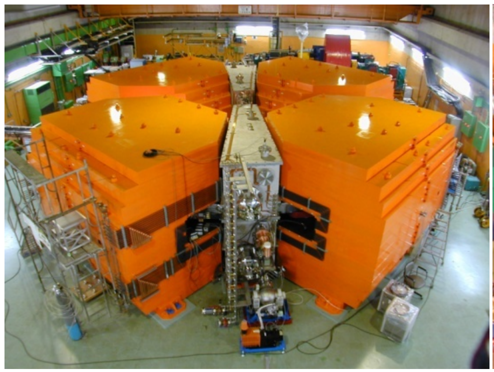
(1997 to (2012))

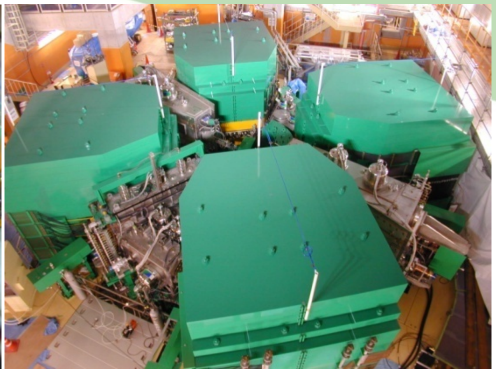
BigRIPS
(Fragment seperator)

fRC

IRC

SRC -- World's First!

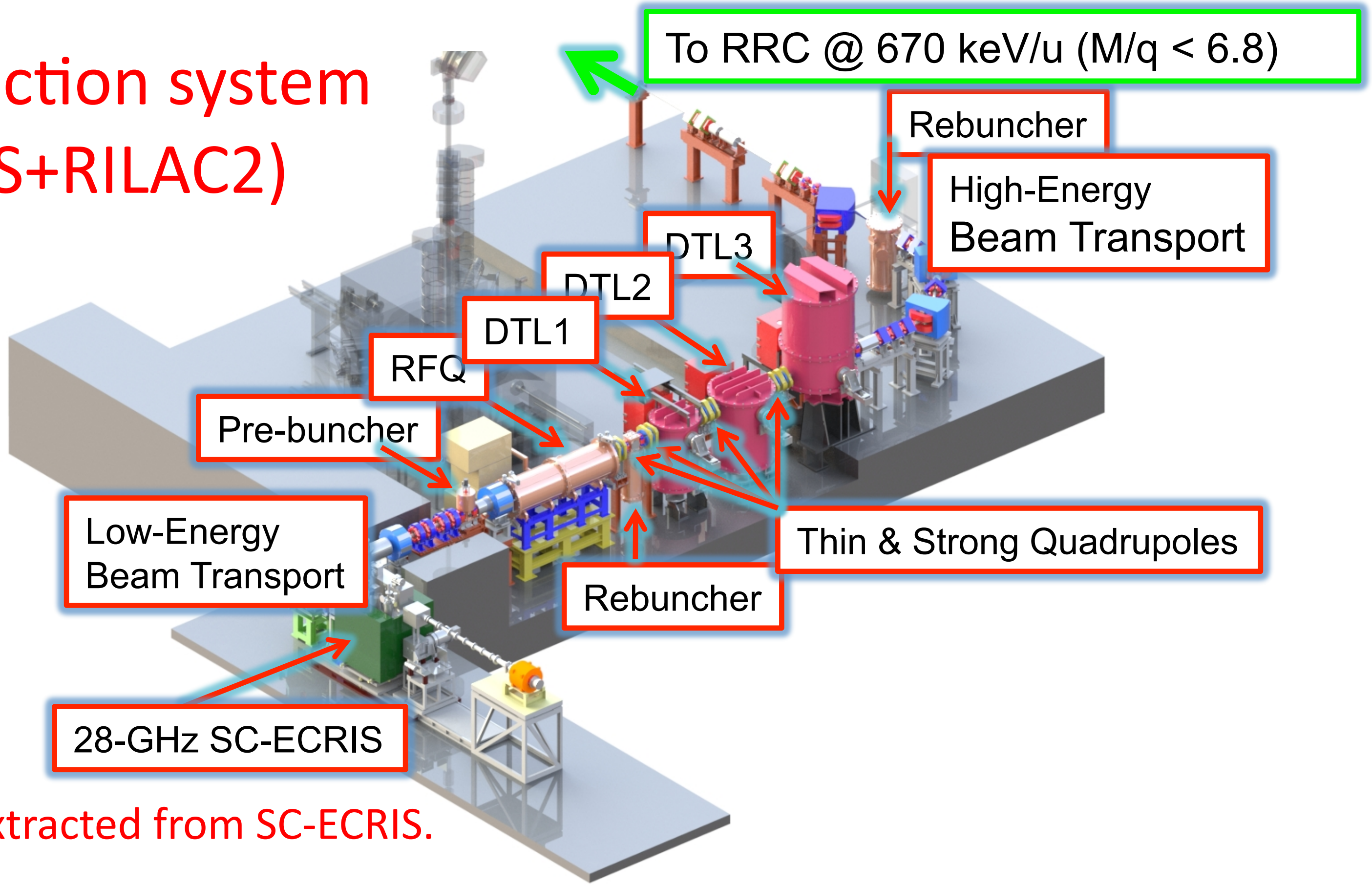




History of RIBF

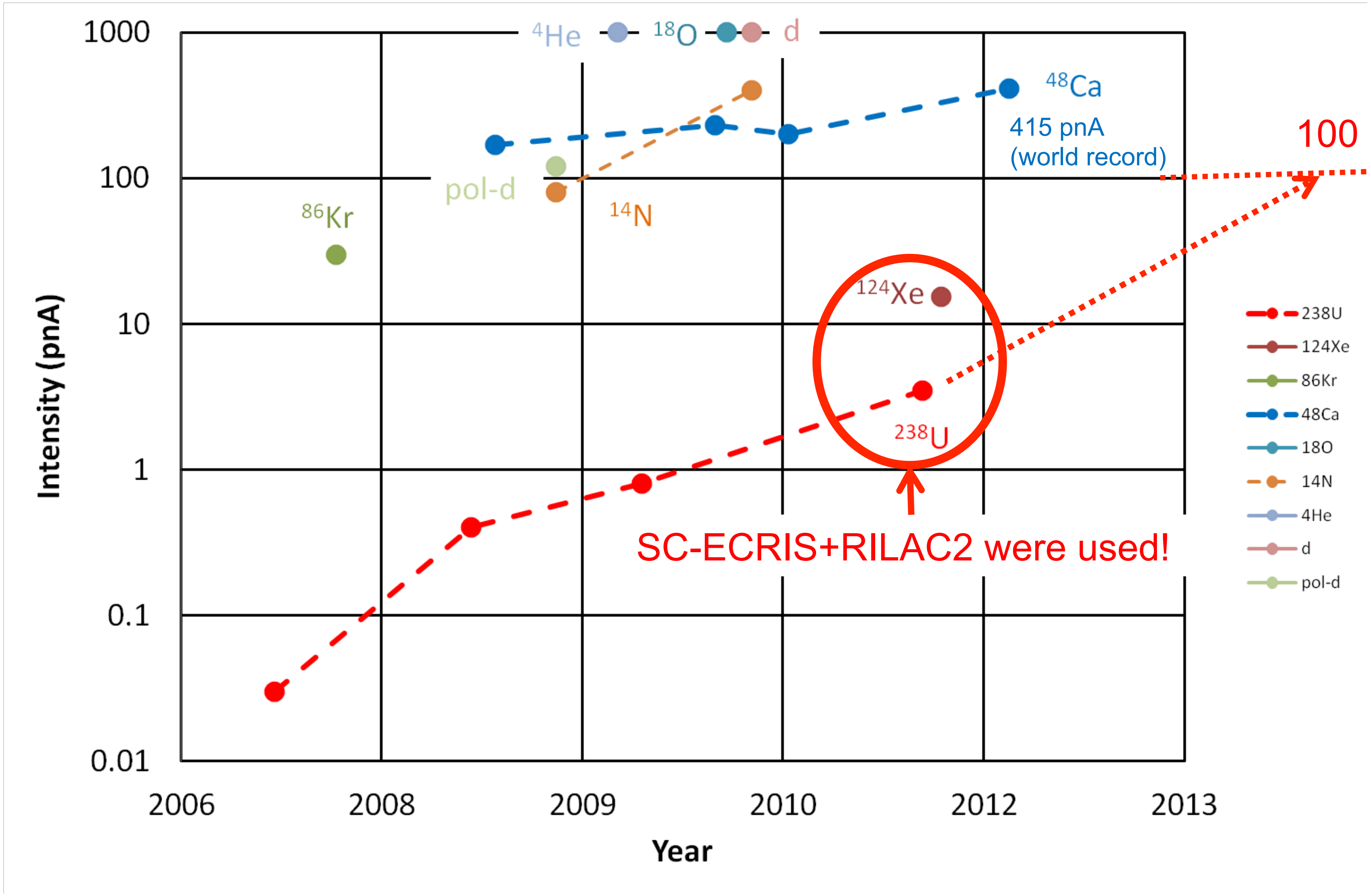
1997- : Project started.
2006 28th Dec : The first beam from SRC.
2007- 2012 : Improvement, improvement…
2011 Oct.- : New injection system for intensity upgrade of U beam

New injection system (SC-ECRIS+RILAC2)



U^{35+} is extracted from SC-ECRIS.

Achieved Beam Intensities (Goal 1 pμA = 6 x 10^{12} #/s)



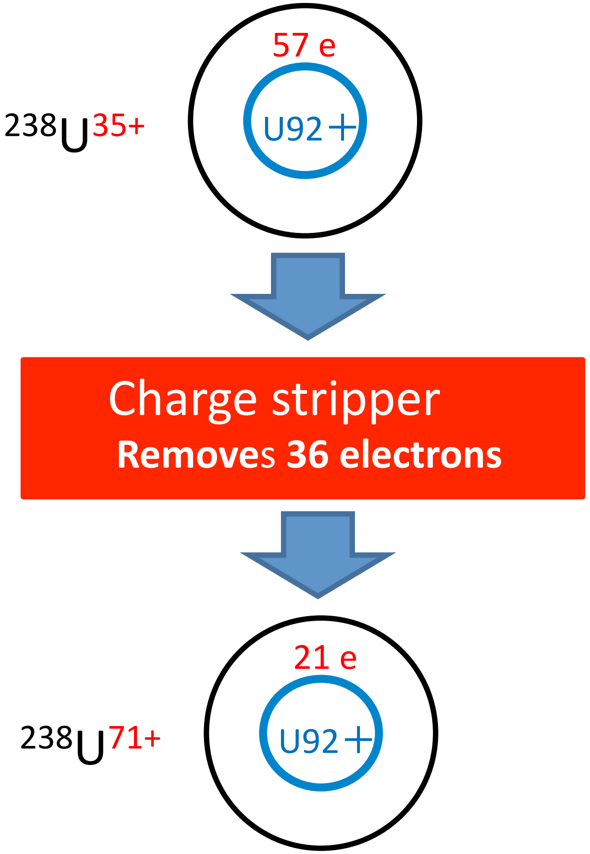
Problems w.r.t. charge strippers will be more severe!!

Function of charge stripper

Equation of motion for accelerators

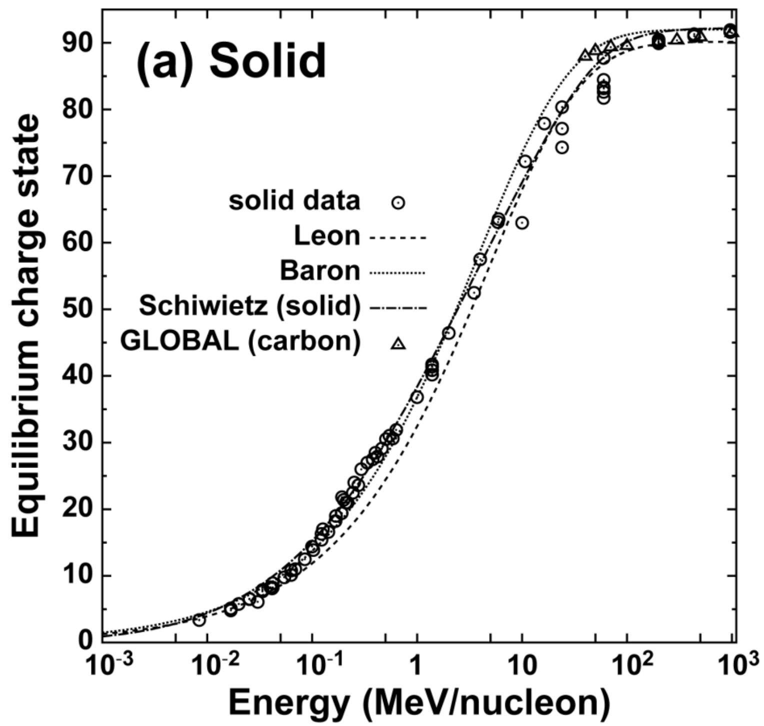
$$d\mathbf{v}/dt = Q/M\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Sensitivity to E and B　　Acceleration　　Bending or focusing



Charge equilibrium

Electron loss = Electron capture

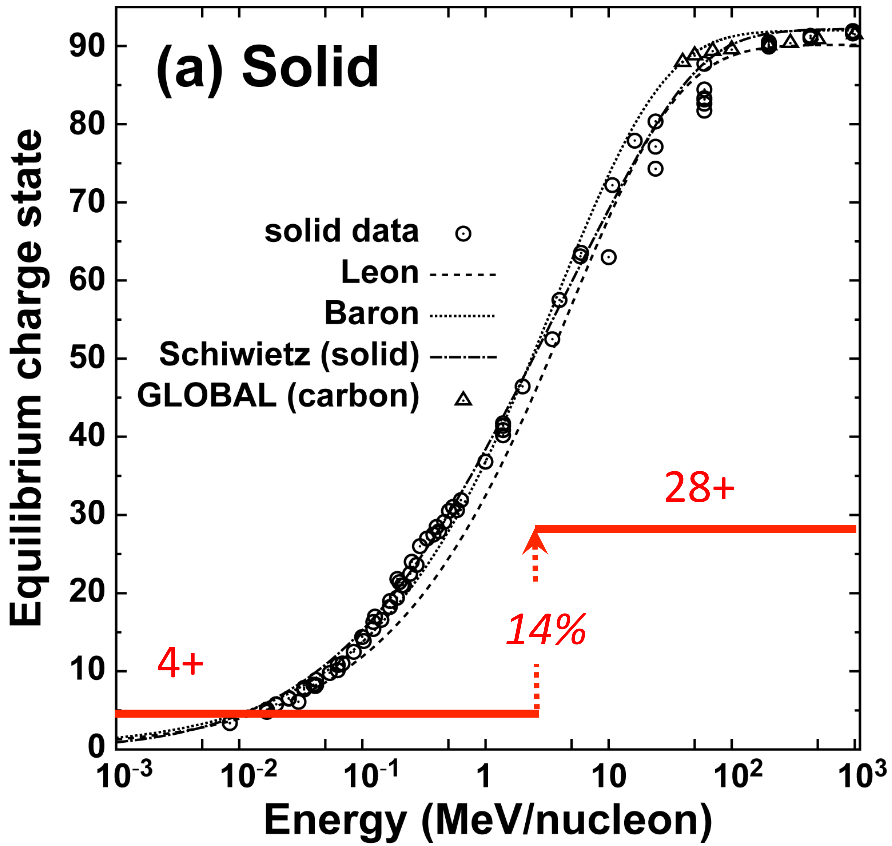


General requirements on charge strippers

- **High charge state**
  - Reduction total accelerating voltage and cost
  - Density effect in solid/liquid => ~20% higher charge states compared to gas
- **High stripping efficiency**
  - Typical stripping efficiency = 10%-30%
  - Using too many strippers decreases beam intensity to zero.
- **Long lifetime**
  - Lifetime of carbon foil is inversely proportional to beam intensity.
  - Lifetime-related problems are critical to high-power beam operation.
- **Good stability**
  - Contributes to stable operation of the acceleration complex.
- **Uniform thickness**
  - Energy spread after the stripper, emittance growth in the longitudinal direction

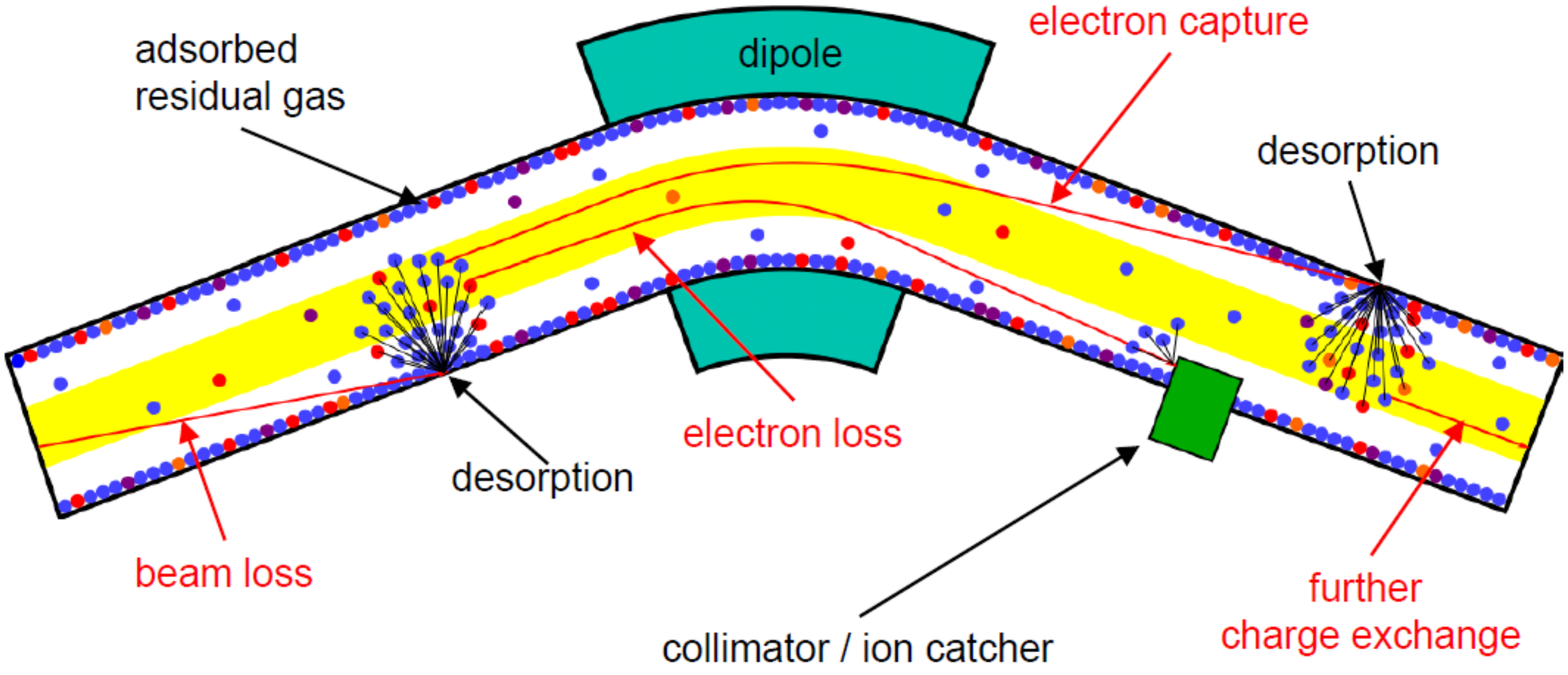
Uranium accelerators: FAIR@GSI, FRIB@MSU, RIBF@RIKEN

FAIR@GSI

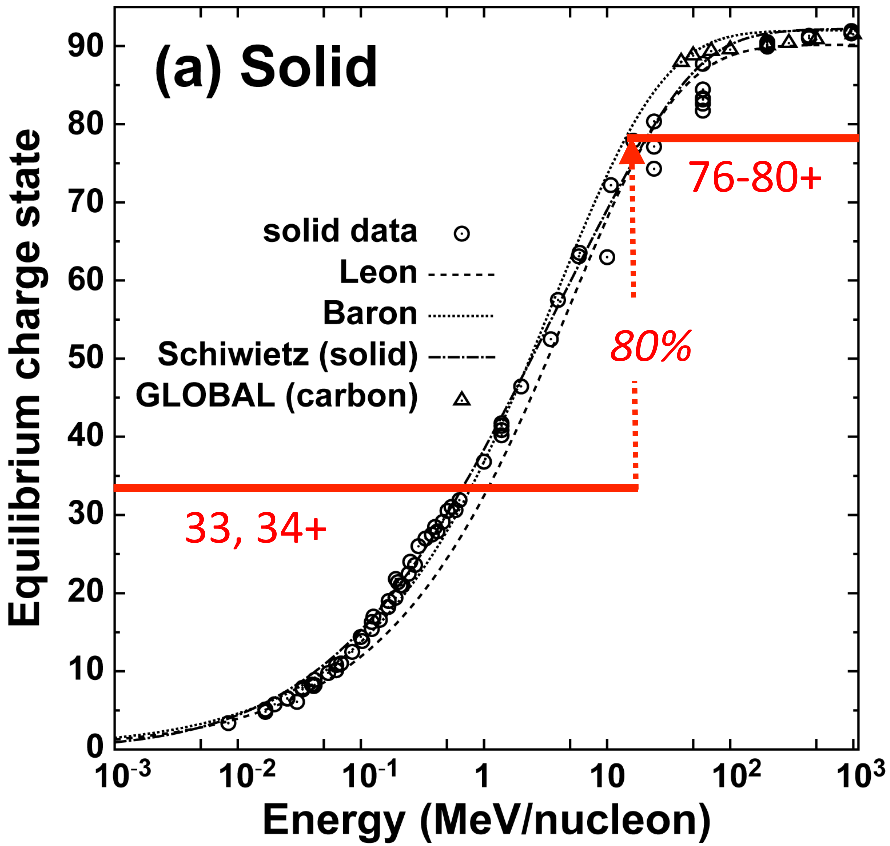


	FAIR
Final energy of U (MeV/nucleon)	1000
Type of accelerator	Synchrotron
Number of strippers	1
Stripping energy (MeV/nucleon)	1.4
Charge state	4+ → 28+
Stripping efficiency	~14%
Beam power at stripper (kW)	300 (pulsed)
Type of stripper	N_2 gas (supersonic gas jet)
Technical challenge	Dynamic Vacuum

Dynamic Vacuum

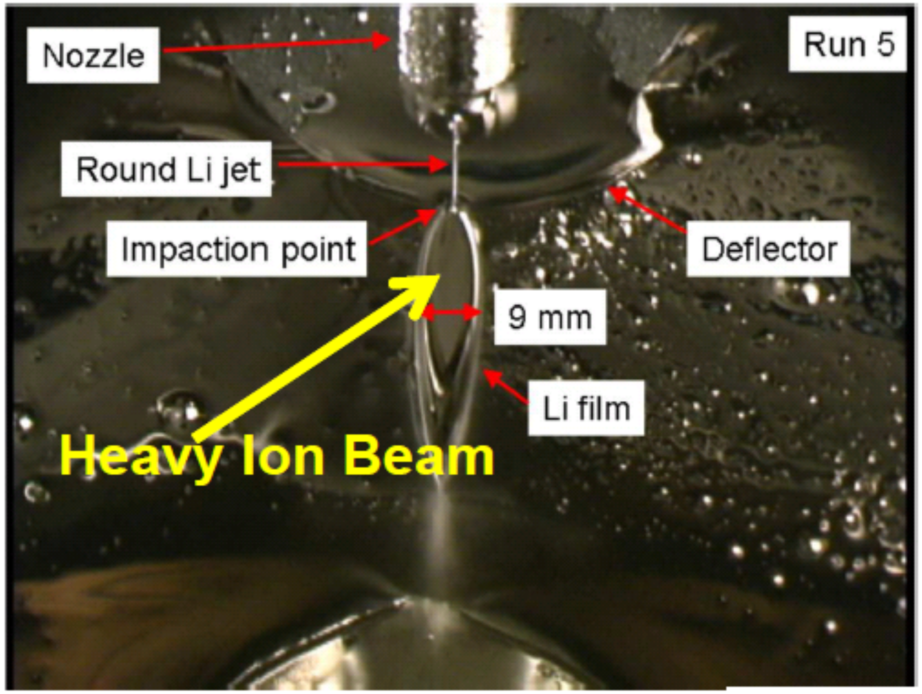


FRIB@MSU



	FRIB
Final energy of U (MeV/nucleon)	200
Type of accelerator	SRF linac
Number of strippers	1
Stripping energy (MeV/nucleon)	16.3
Charge state	33+, 34+ => 76+,77+, 78+,79+,80+
Stripping efficiency	~80%
Beam power at stripper (kW)	40
Type of stripper	Liquid Li film (baseline) He gas with Plasma Windows (alternative)
Technical challenge	Liquid Li film Plasma Window

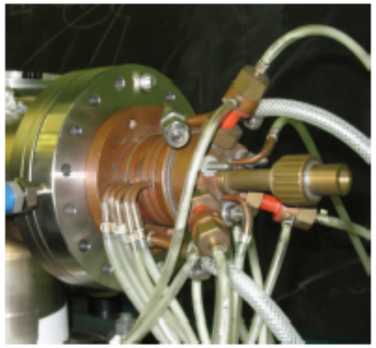
Liquid lithium stripper
J. Nolen, C. Reed and Y. Momozaki (ANL)



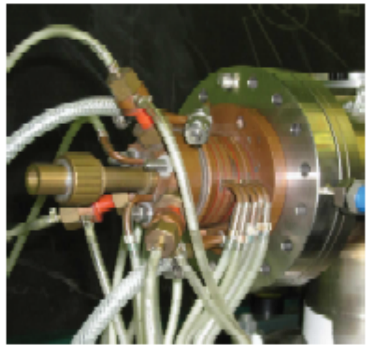
Development of a liquid lithium thin film for use as a heavy ion beam stripper
JInst. **4** (2009) P04005

Y. Momozaki[a,1] J. Nolen,[b] C. Reed,[a] V. Novick[a] and J. Specht[b]

Plasma Window Contained Gas Stripper
Hershcovitch, Thieberger et al (BNL)

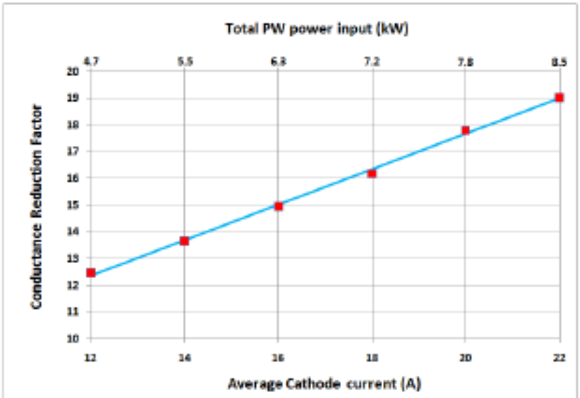


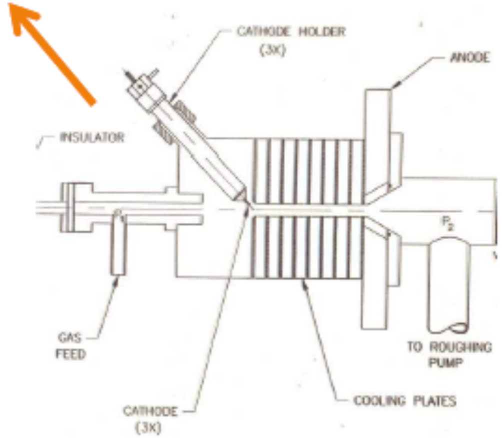
BROOKHAVEN NATIONAL LABORATORY



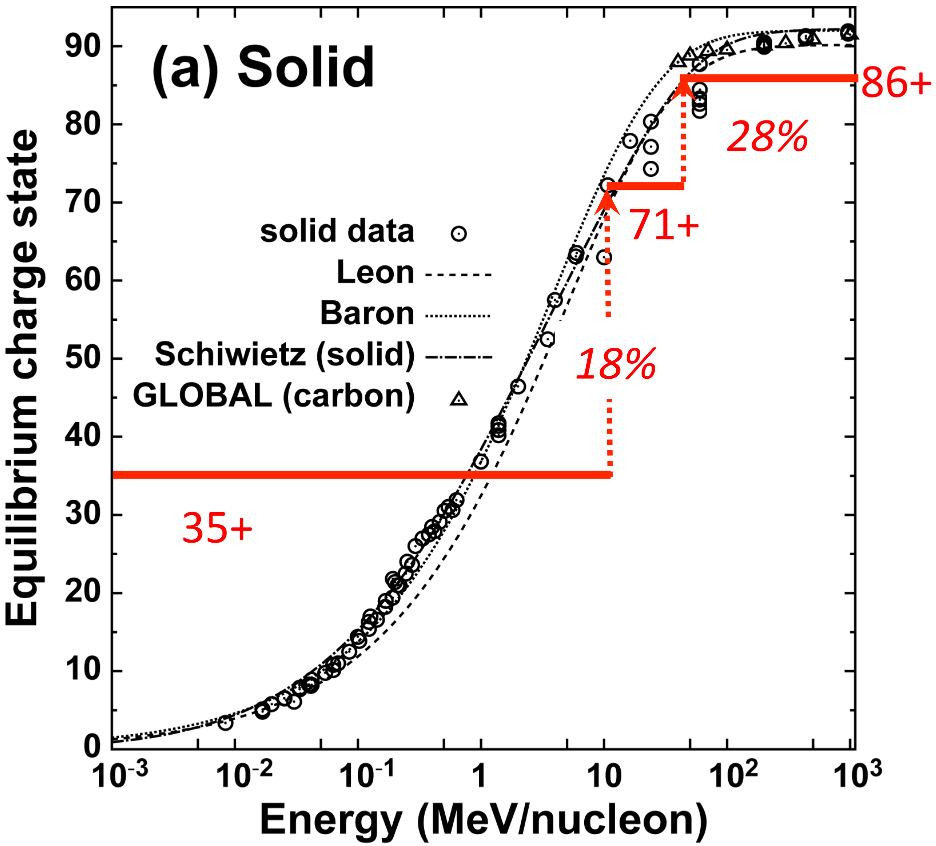
U $^{33+}$ Beam → Plasma window | He gas at 300 mbar | Plasma window → U $^{71+}$ Beam

Conduction reduction factor ~ 20
We need to increase beam aperture (2 mm→ 6 mm)



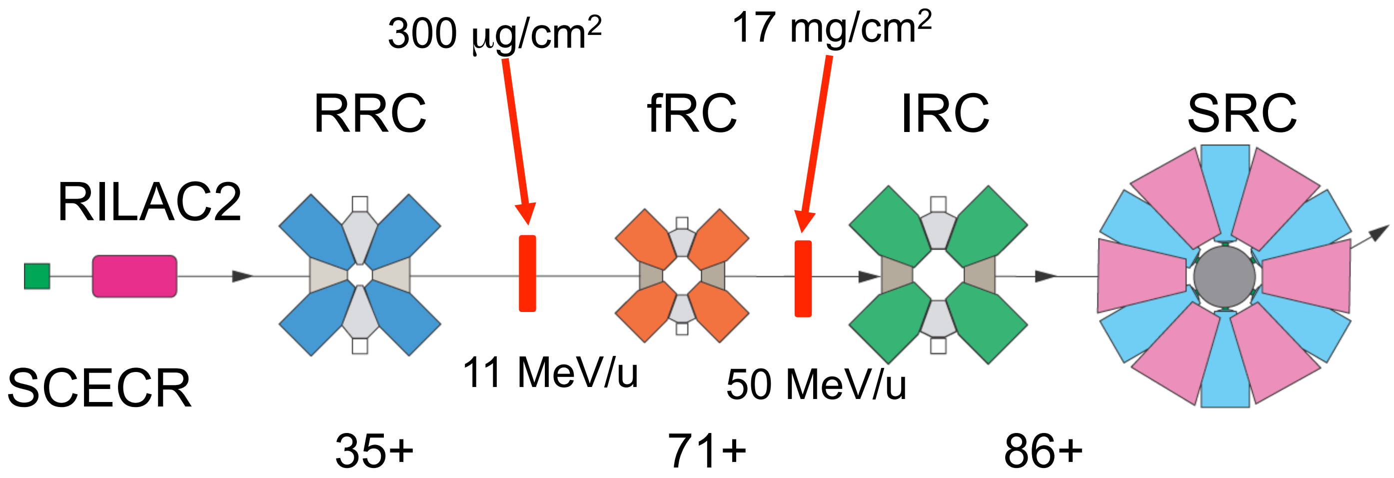


RIBF@RIKEN



	RIBF
Final energy of U (MeV/nucleon)	345
Type of accelerator	Cyclotron
Number of strippers	2
Stripping energy (MeV/nucleon)	11 and 51
Charge state	35+→71+/65+→86+
Stripping efficiency	**~5% Invention!**
Beam power at stripper (kW)	7.5
Type of stripper	1st stripper C-foil => He gas 2nd stripper C-foil => Wheel?
Technical challenge	He gas confinement

Uranium Acceleration at RIBF

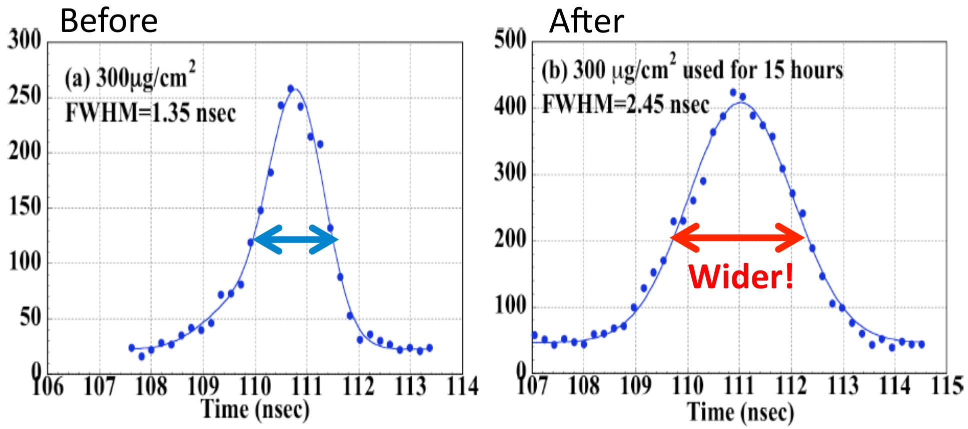


We should think about the first stripper more seriously.

Before

After

Momentum spread after the stripper



Requirements on the first stripper

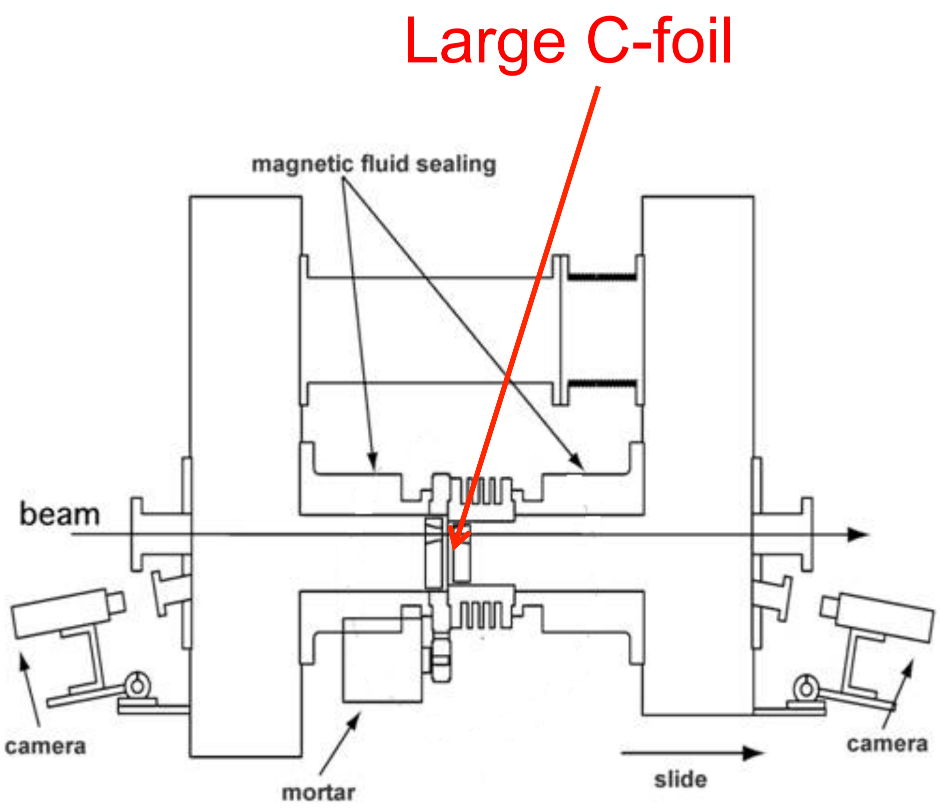
Item	Value	Effect on the cyclotron-based complex (RIBF)	Fixed C-foil
Charge state	>69	Output energy: constant Sector field: increased	71+ ○
Lifetime	> 1 week (100 eμA)	Replacement of foil requires careful tuning	12 h (1.4 eμA) ×
Uniformity	<10%	Extraction efficiency	~10% △

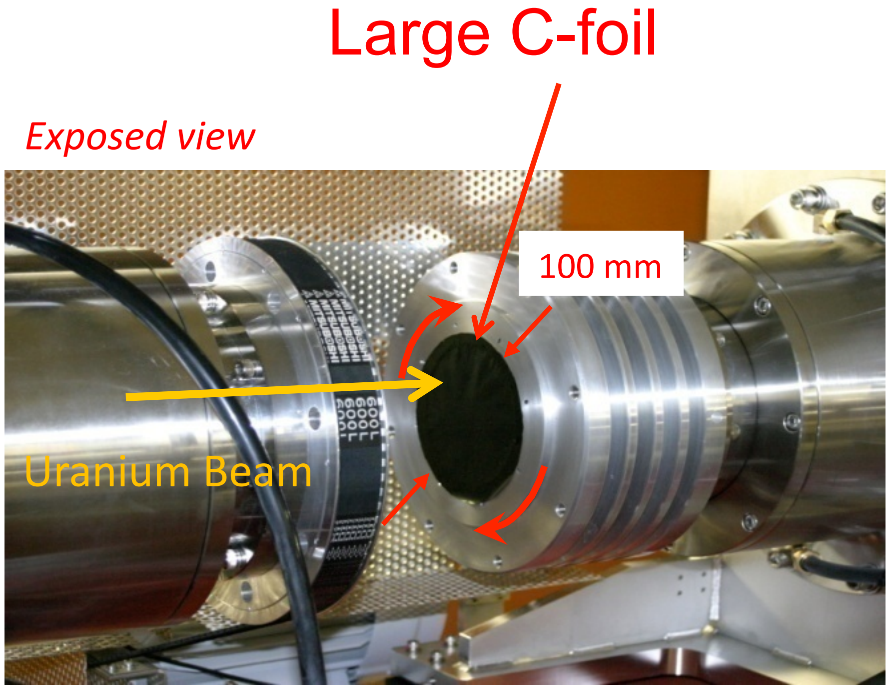
R&D programs for the first stripper (2008-)

1: Large carbon foil on a rotating cylinder

2: N_2 gas stripper

Large C-foil on a rotating cylinder

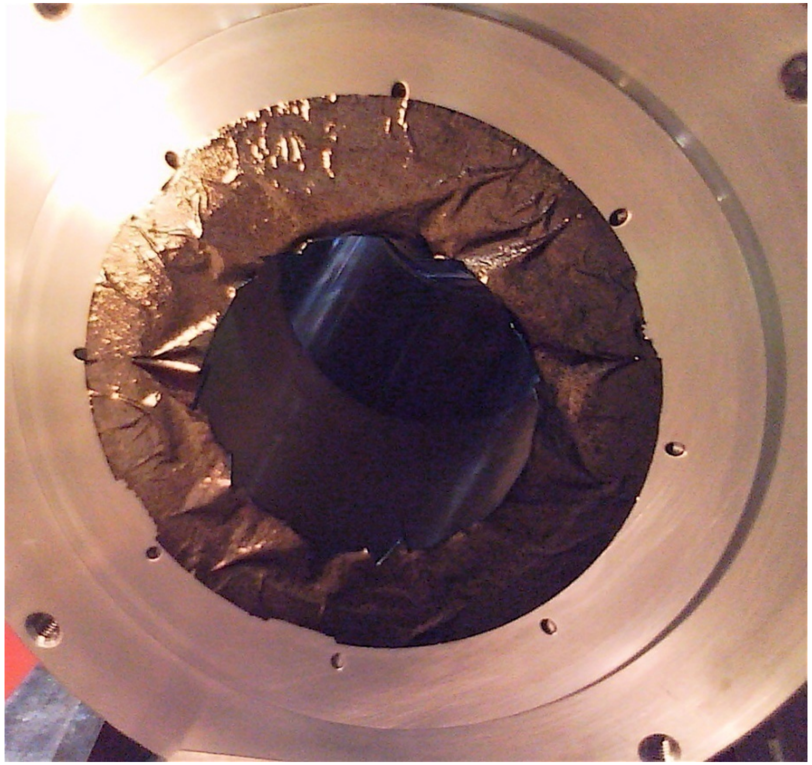




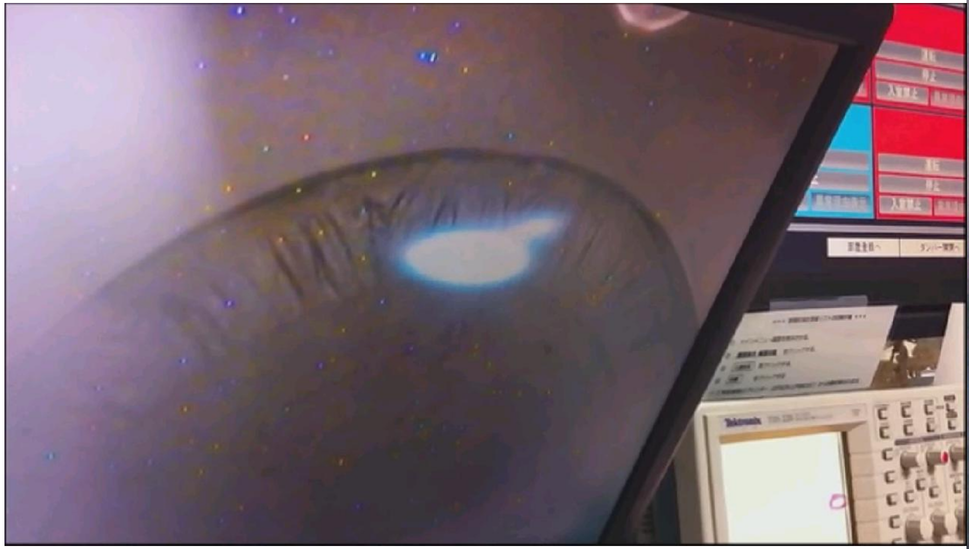
Lifetime 60 times longer than that of the fixed foil.

The first test for the rotating stripper (May 2008)

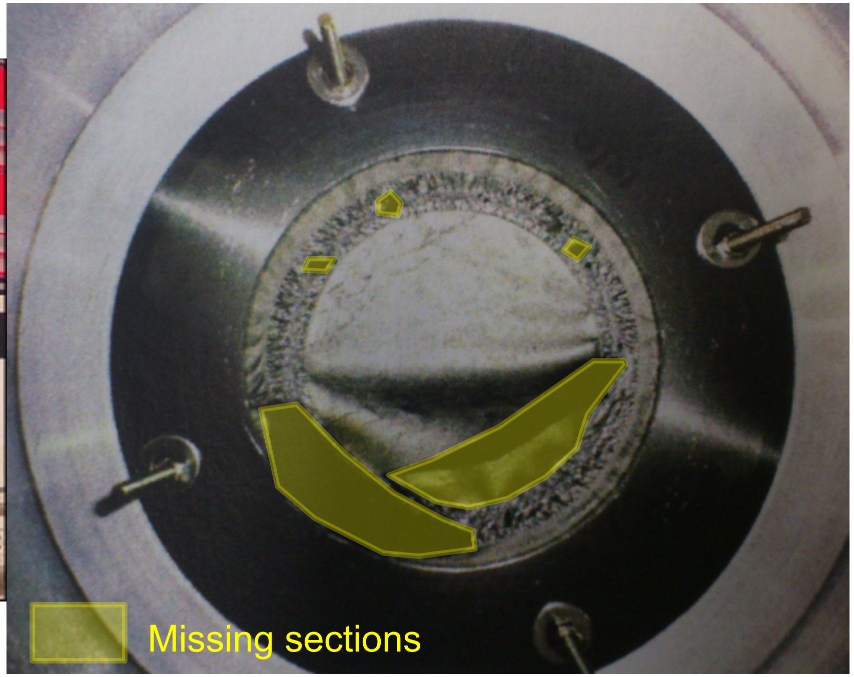
A rotating foil was tested in May 2008 => Broke shortly, 15 min
Rotation speed ~ 100 rpm



Very slowly rotating CNT-based foils can survive for 3 - 4 days (10 eμA).



Video of the irradiation on the rotating foil though it is very difficult to recognize its rotation.



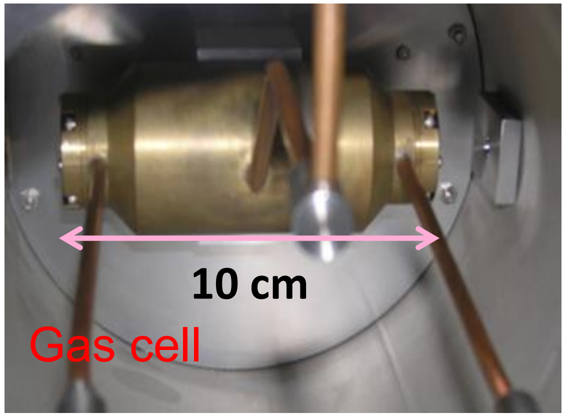
Some foil sections were missing after 3-4 days when the foil should be replaced.

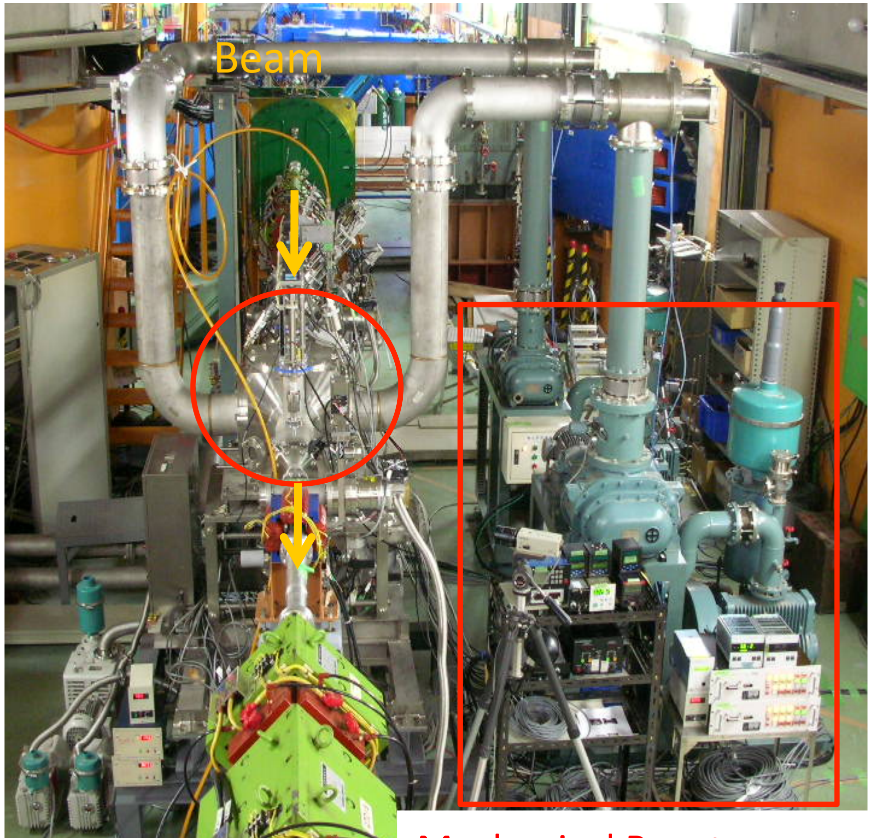
This stripping system was successfully used in a U beam campaign last year, when the new injector system (RILAC2) started operation as an actual injector.

R&D programs for N_2 gas stripper

Gas stripper (N_2):

1. Free from lifetime-related problems.
2. Lower equilibrium charge state Qe.
   (absence of density effect)
3. Measurement of Qe using a gas target with differential pumping system.

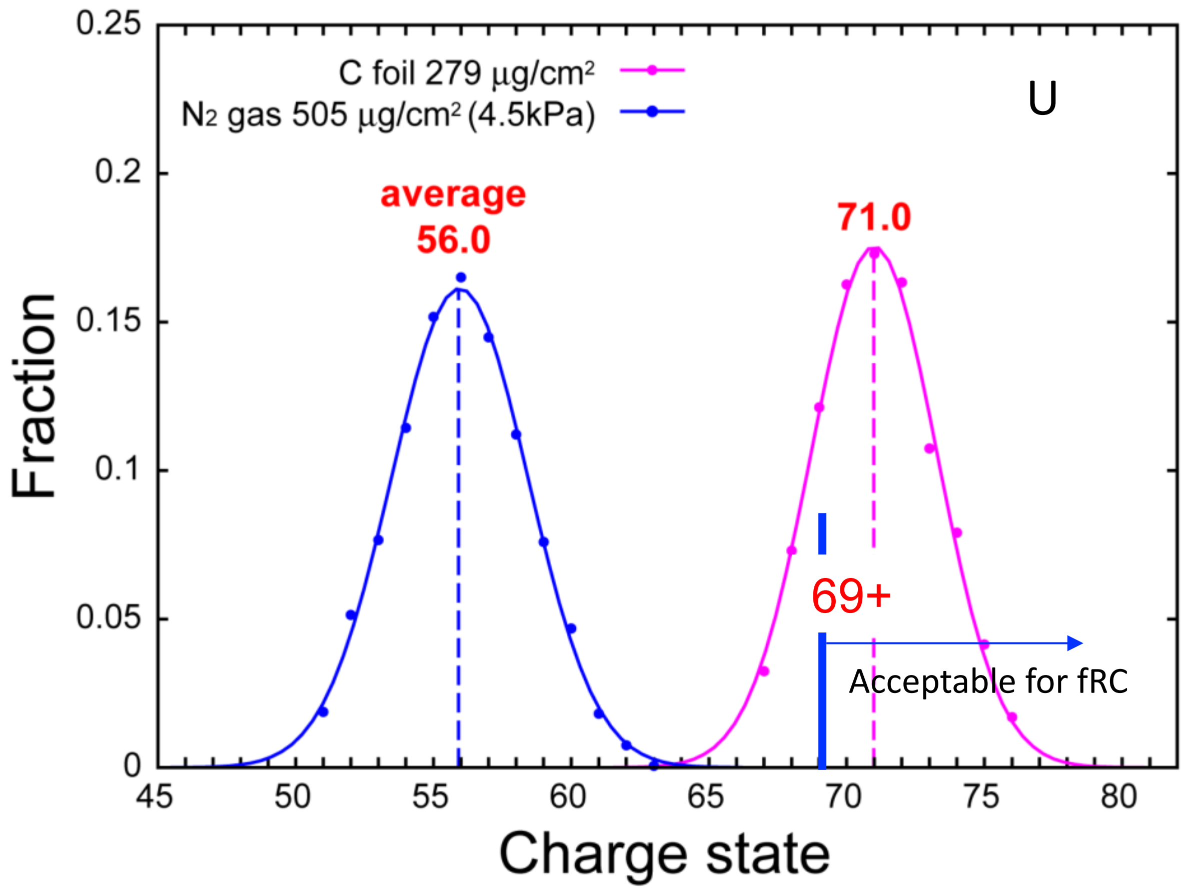




Mechanical Booster pumps

A set of test results about gas stripper (Feb./ March 2009)

- U beam: The average charge state with the gas stripper is far below the acceptable charge state for the fRC, 69+.

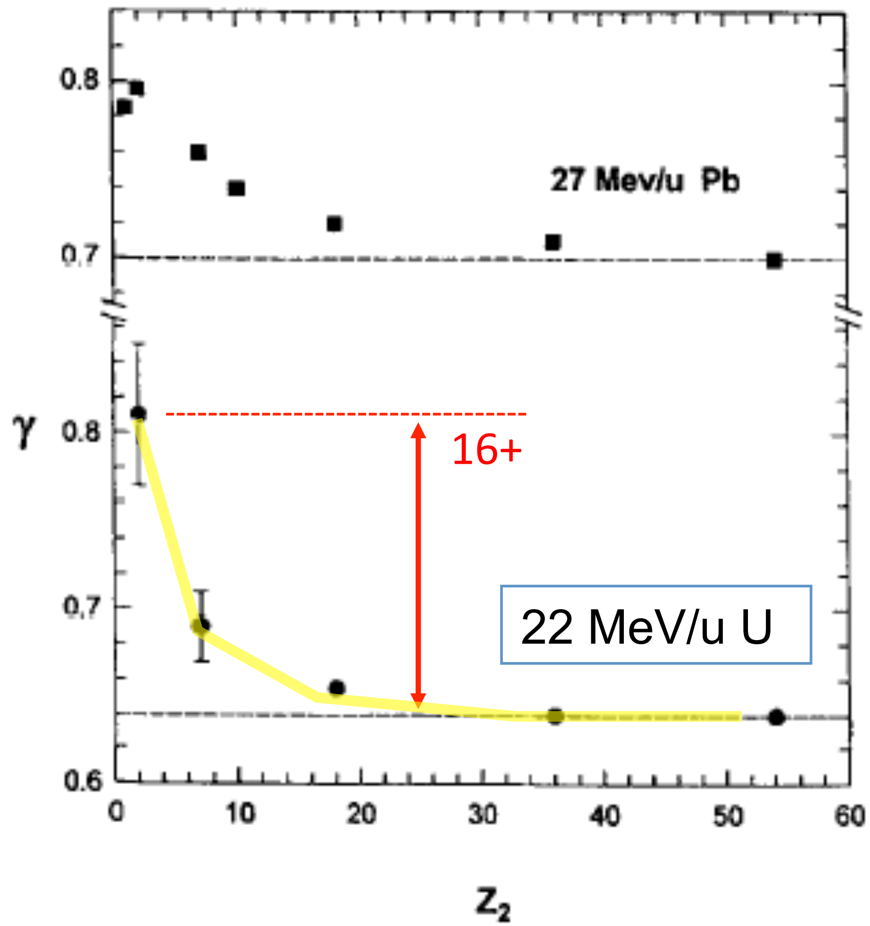


Summary of the R&D studies

Item	Value	Fixed C- foil	Large C-foil on a rotating cylinder	N_2 gas	Low-Z gas
Charge state	>69	71+	71+ ○	56+ ×	**Higher?**
Lifetime	> 1 week (100 eμA)	12 h (1.4 eμA)	4-5 days (10 eμA) ×	Sufficiently long ○	Sufficiently long ○
Uniformity	<10%	~10%	>10% ×	~0% ○	~0% ○

Example of charge state of U in He (22 MeV/u)

Effective charge



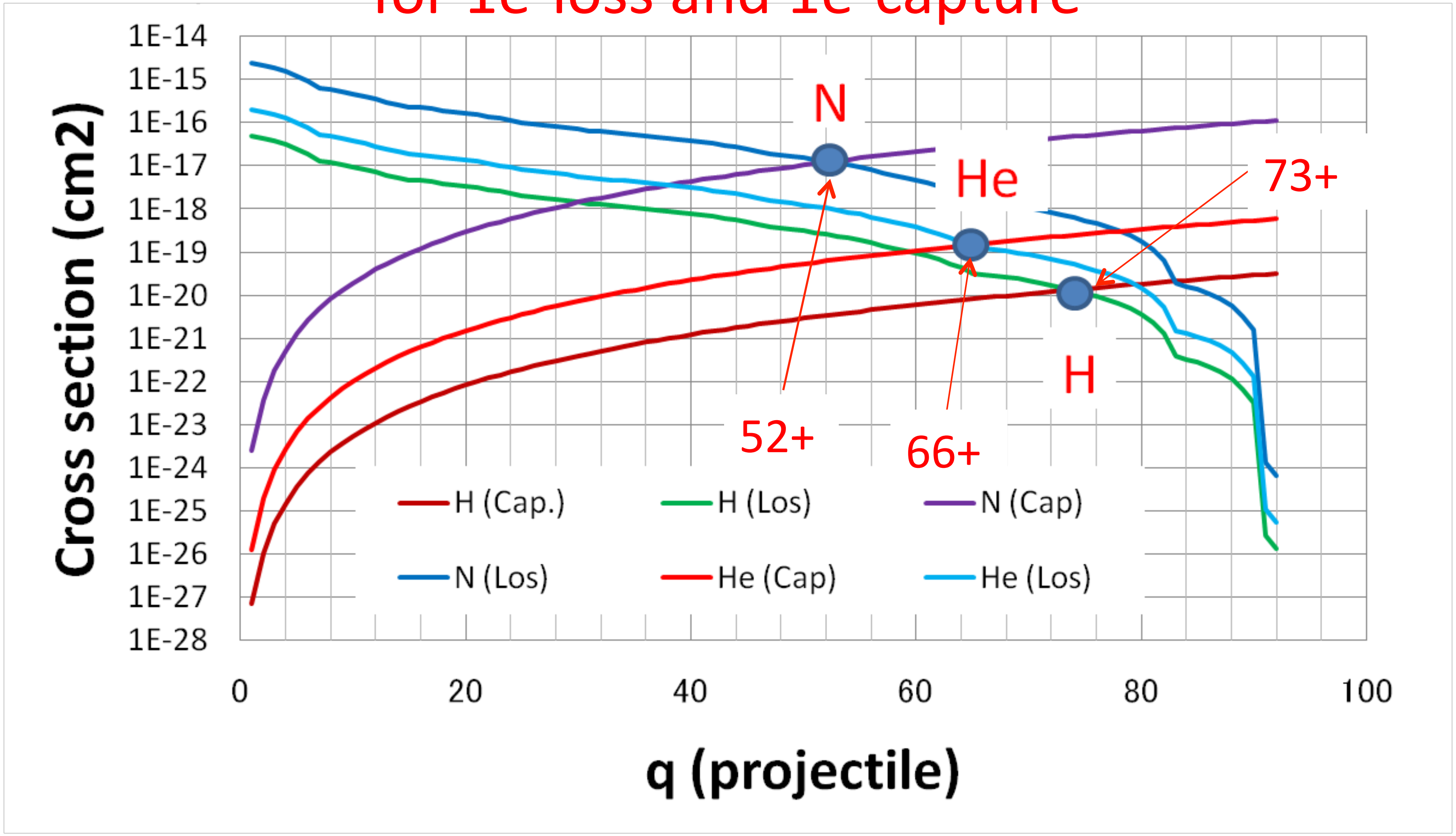
NIMB 107 (1996) 9

Enhancement of the effective charge in the low-Z gas region
←suppression of electron capture process

Stripping energy at RIBF: 11 MeV/u

Can we expect higher charge states in the low-Z gas for our gas stripping?

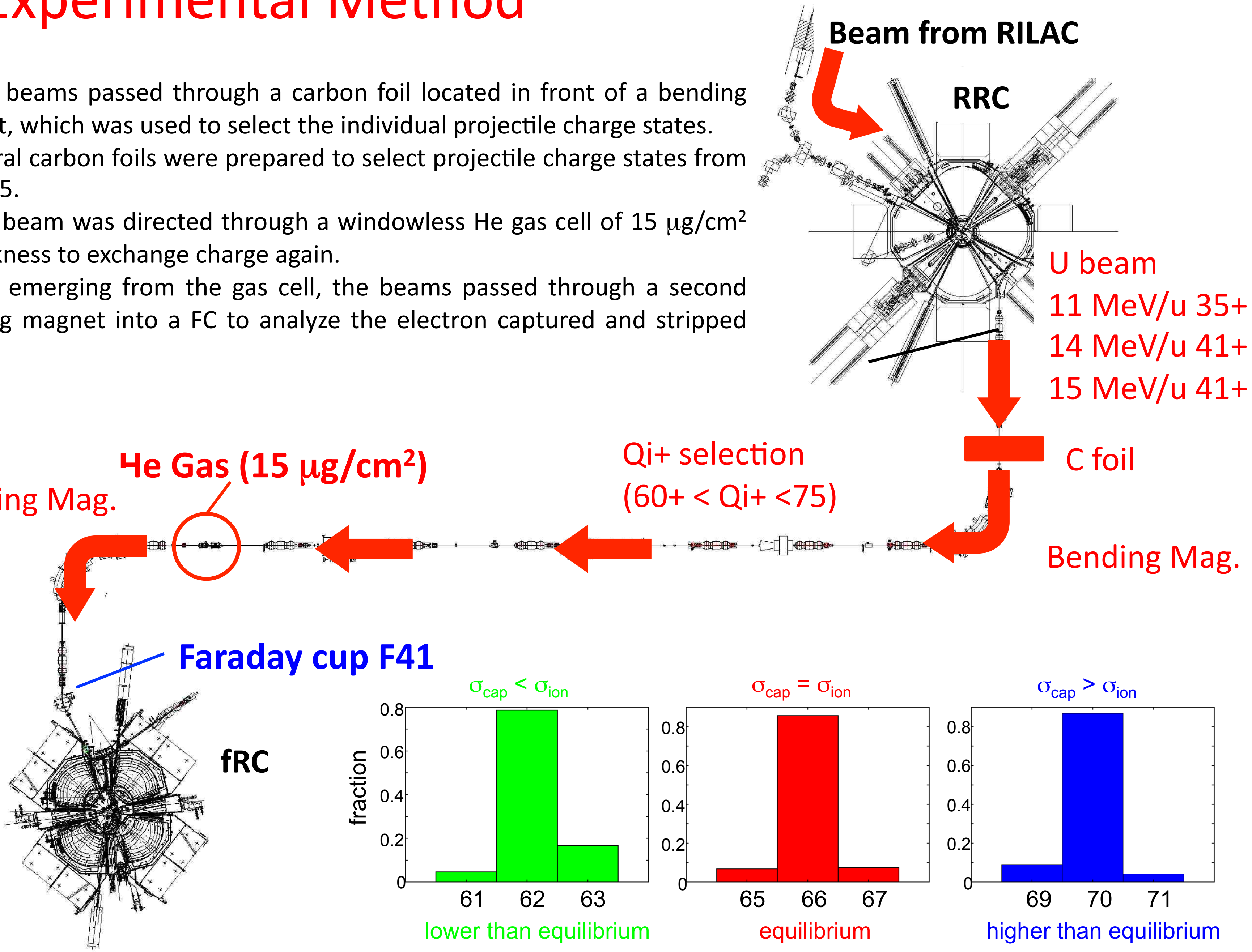
A simple estimation of cross sections for 1e-loss and 1e-capture



Loss: M. Gryzinski, Phys. Rev. 138 (1965) A305. (Binary Encounter Model)
Capture: A.S. Schlachter, et. al., Phys. Rev. A 27 (1983) 3372.

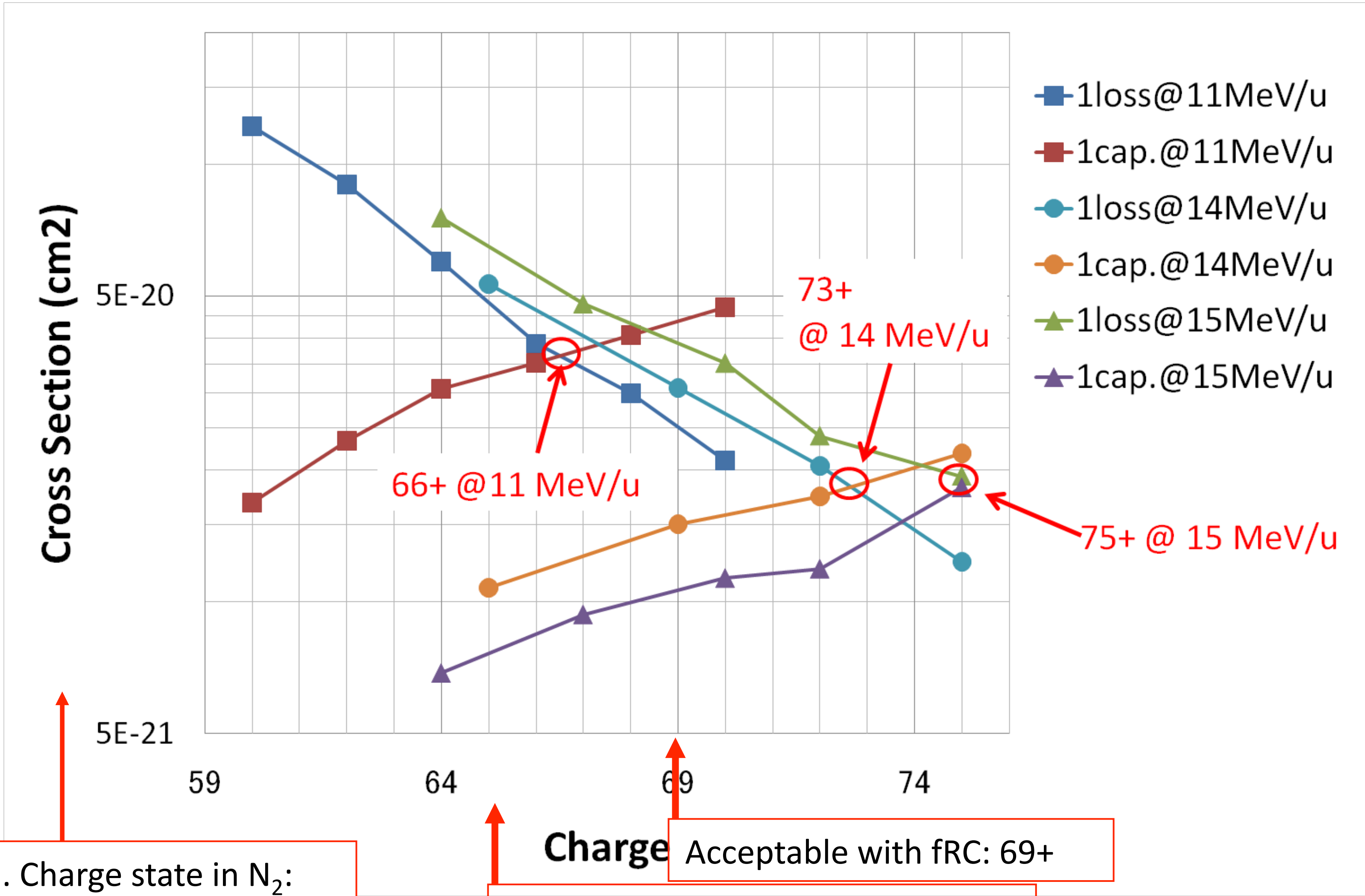
Experimental Method

- The beams passed through a carbon foil located in front of a bending magnet, which was used to select the individual projectile charge states.
- Several carbon foils were prepared to select projectile charge states from 60 to 75.
- Each beam was directed through a windowless He gas cell of 15 μg/cm^2 in thickness to exchange charge again.
- After emerging from the gas cell, the beams passed through a second bending magnet into a FC to analyze the electron captured and stripped ions.



Measured Results

Electron capture and loss cross sections of U in He-gas were measured to estimate the equilibrium charge state.



Eq. Charge state in N_2: 56+ @ 11 MeV/u

Acceptable with fRC: 69+

Acceptable with modified fRC: 65+

Difficulty in accumulation of low-Z gas

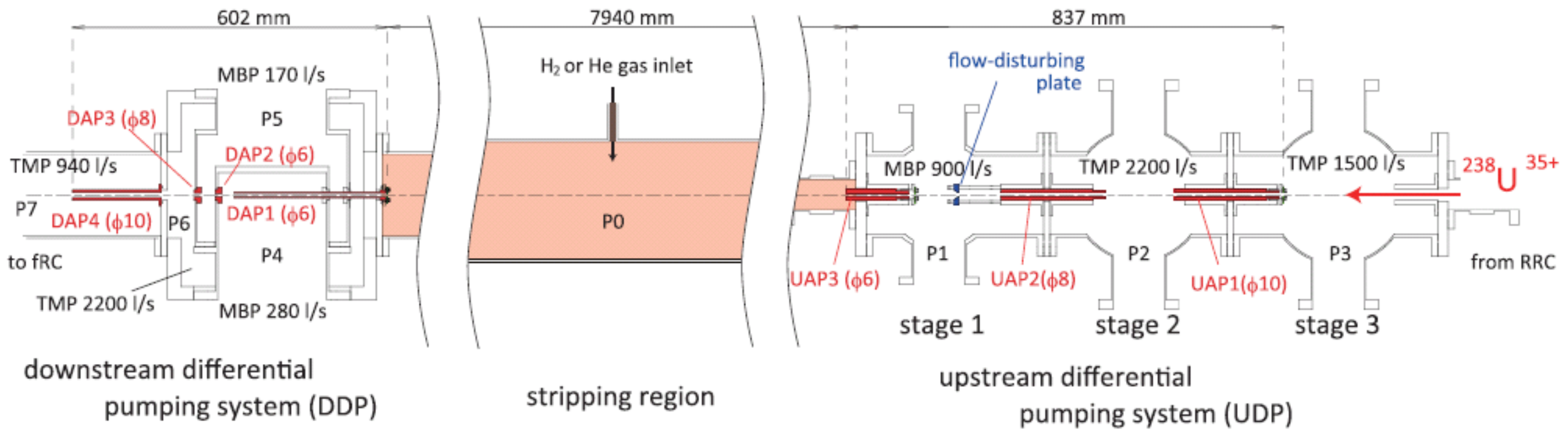
The existing gas stripper: He ～15 μg/cm^2 (0.7 kPa)
(cf. N_2 1.3 mg/cm^2)
About 1 mg/cm^2 of low-Z gas is necessary to be accumulated to obtain higher charge states.
→ *A new device to make it possible …*

Two options

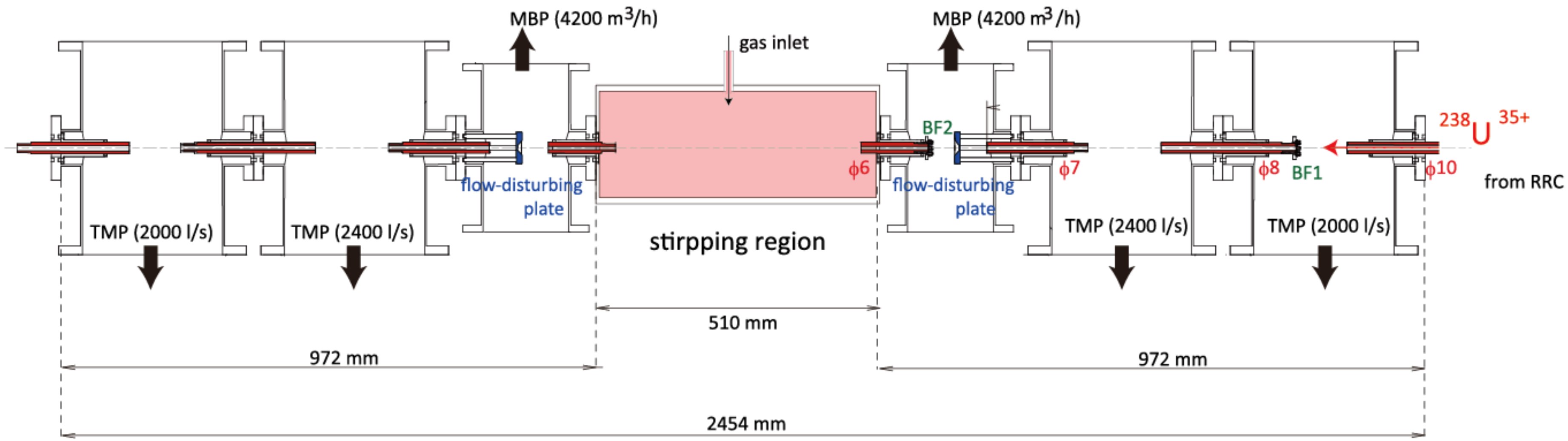
1. Plasma Windows
   => special techniques to design and operate them.
   => We began the R&D works on the PW with A. Herschcovith.
2. big Mechanical Booster Pumps (MBP)
   => They are big but commercially available.
   => We initiated He gas accumulation of about 1 mg/cm^2 to measure charge distribution and energy spread using them.

Two He gas targets with differential pumping system

1: 8-m He gas target

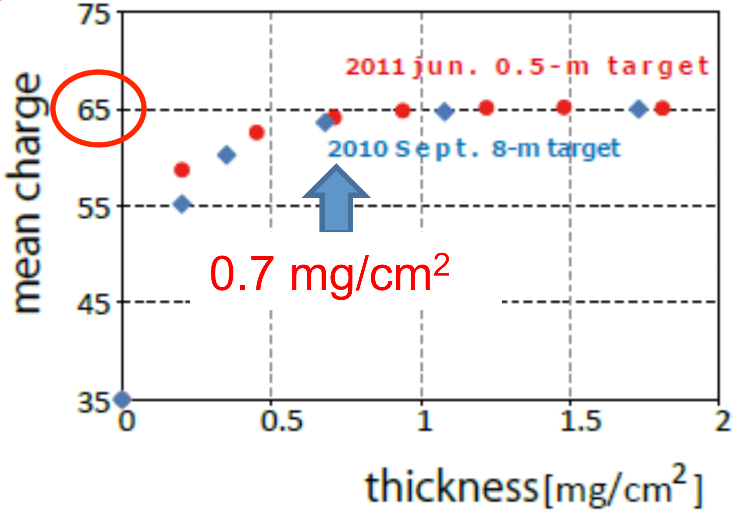


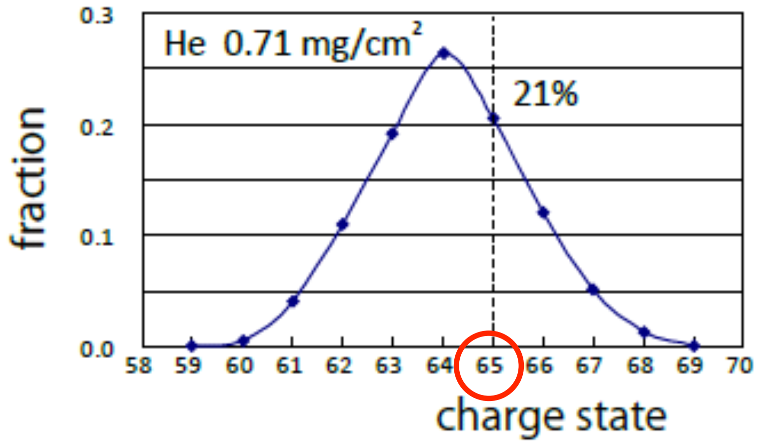
2: 0.5-m He gas target



Results (U(11 MeV/u) +He) (Sept. 2010, June, 2011)

Charge state





Energy Spread

$\Delta E/E$ (4σ) ~ 0.4% (preliminary)

Charge-exchange straggling:
H. Weick et al.,
Phys. Rev. Lett. 85 (2000) 2725.

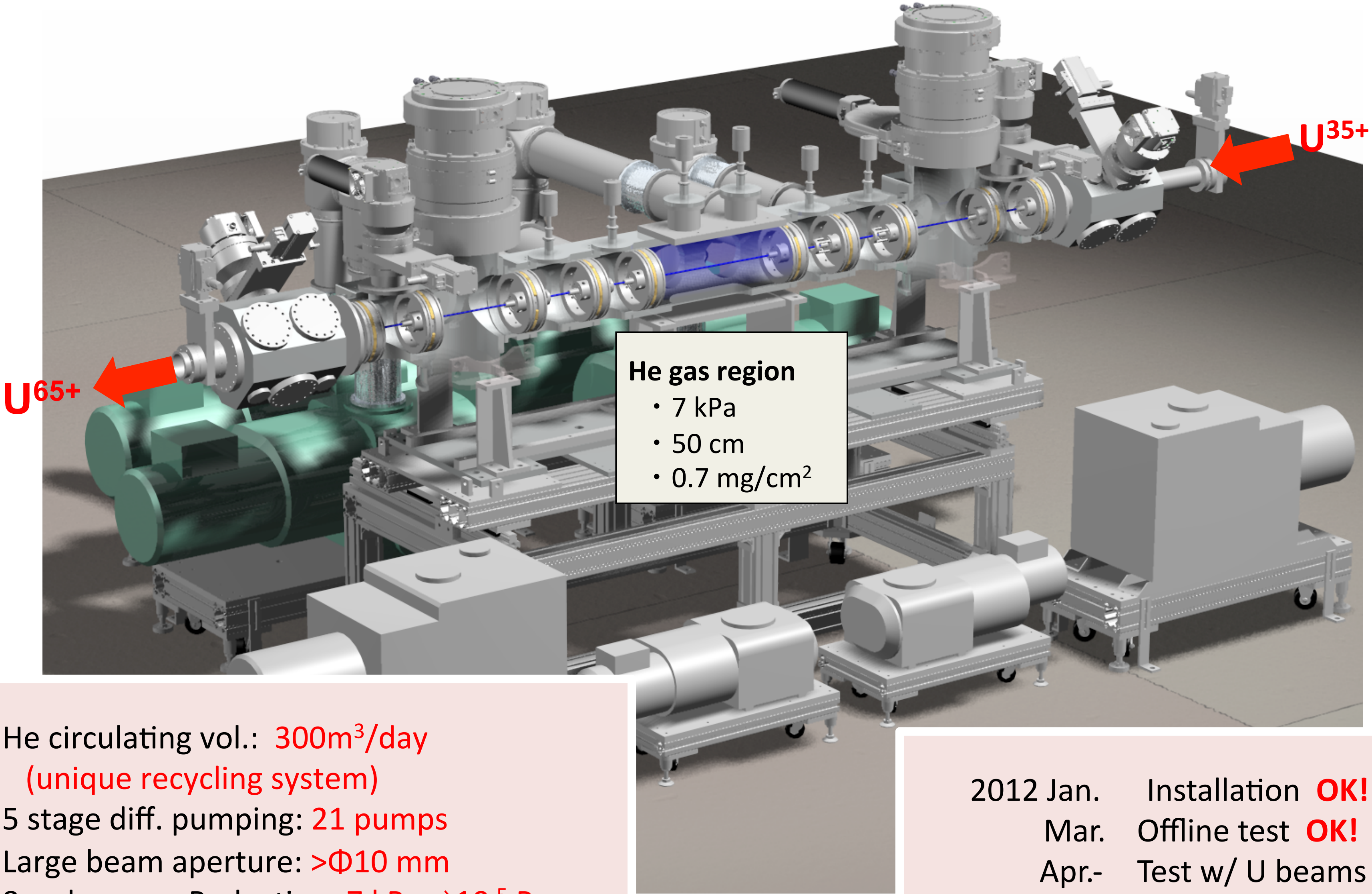
(cf. ~0.7% (preliminary)
in C-foil (300 μg/cm^2))

We decided to make an actual machine for the He gas stripping.

But there are some issues to be solved.

1. Impurity
2. Thermal issue
3. He gas recycling system

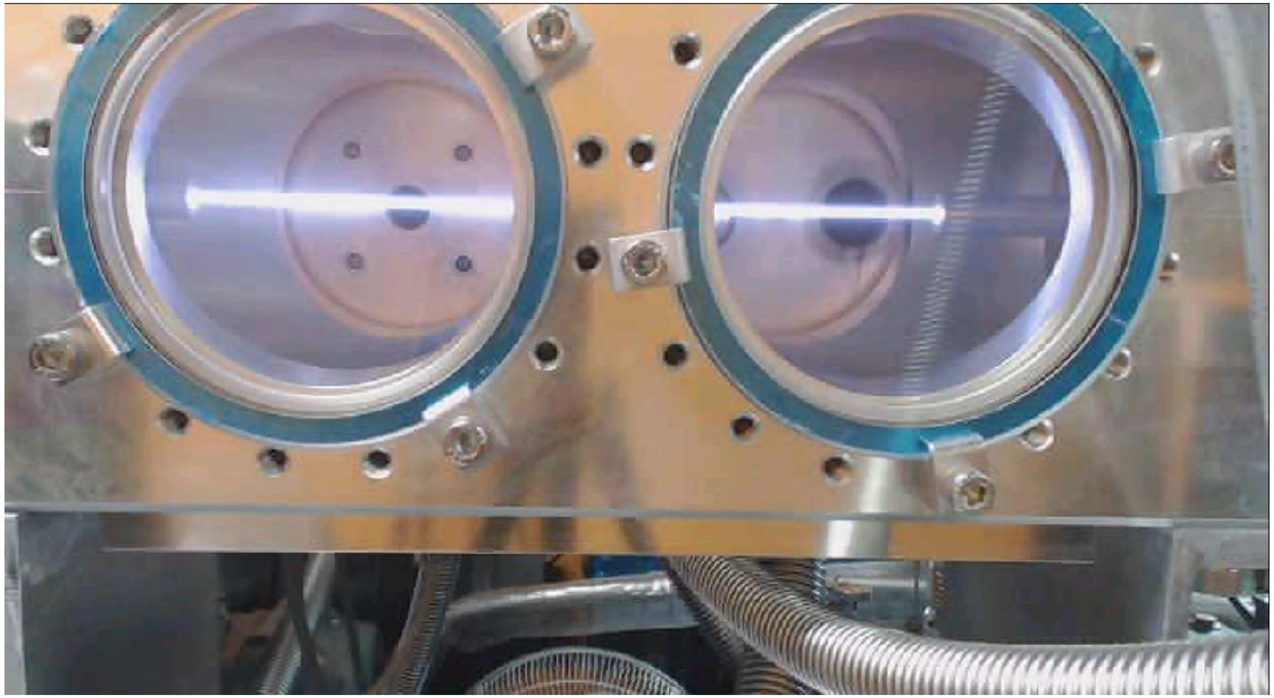
Actual machine development



He circulating vol.: 300m^3/day
(unique recycling system)
5 stage diff. pumping: 21 pumps
Large beam aperture: >Φ10 mm
8 order pres. Reduction: 7 kPa⇒10^{-5} Pa

2012 Jan. Installation **OK!**
Mar. Offline test **OK!**
Apr.- Test w/ U beams

Tests using U beams are in progress for the next U campaign scheduled in the next autumn.



Beam intensity:
13 eμA

Achieved beam intensity after He gas stripper
U65+: 36 pnA, U64+: 44 pnA
(cf U71+:~30 pnA, Oct. 2011)

Checklists: **No problems could be found thus far !!**

- Impurity: oil, water, N_2, or O_2 (Increase capture cross section)
  => Low level (No change in the charge state distribution)
- High power beam easily makes a "hole" in gas due to heat generation?
  => No sign in the charge distribution and energy spread thus far
- He gas recycling system
  =>98%: recycled + 2%: to recovery line in the laboratory. No loss of He gas

Summary

- The RIBF has been successfully operated from 2007 to 2012 after the first beam.
- The new injector system began operation in October 2011 to increase the U ion beam intensity.
- The stripper problem is still unresolved.
- However, the low-Z gas stripper is an important candidate.
- *In the process of testing the low-Z gas stripper,*
  - The electron capture and loss cross section were measured.
  - The charge evolution and energy spread were measured using a thick He gas target with the big MBP system.
- We decided to make an actual machine for the He gas stripping.
- We are testing the machine for the next U campaign in the coming autumn.
- **We should do battle with the second stripper in the near future.**