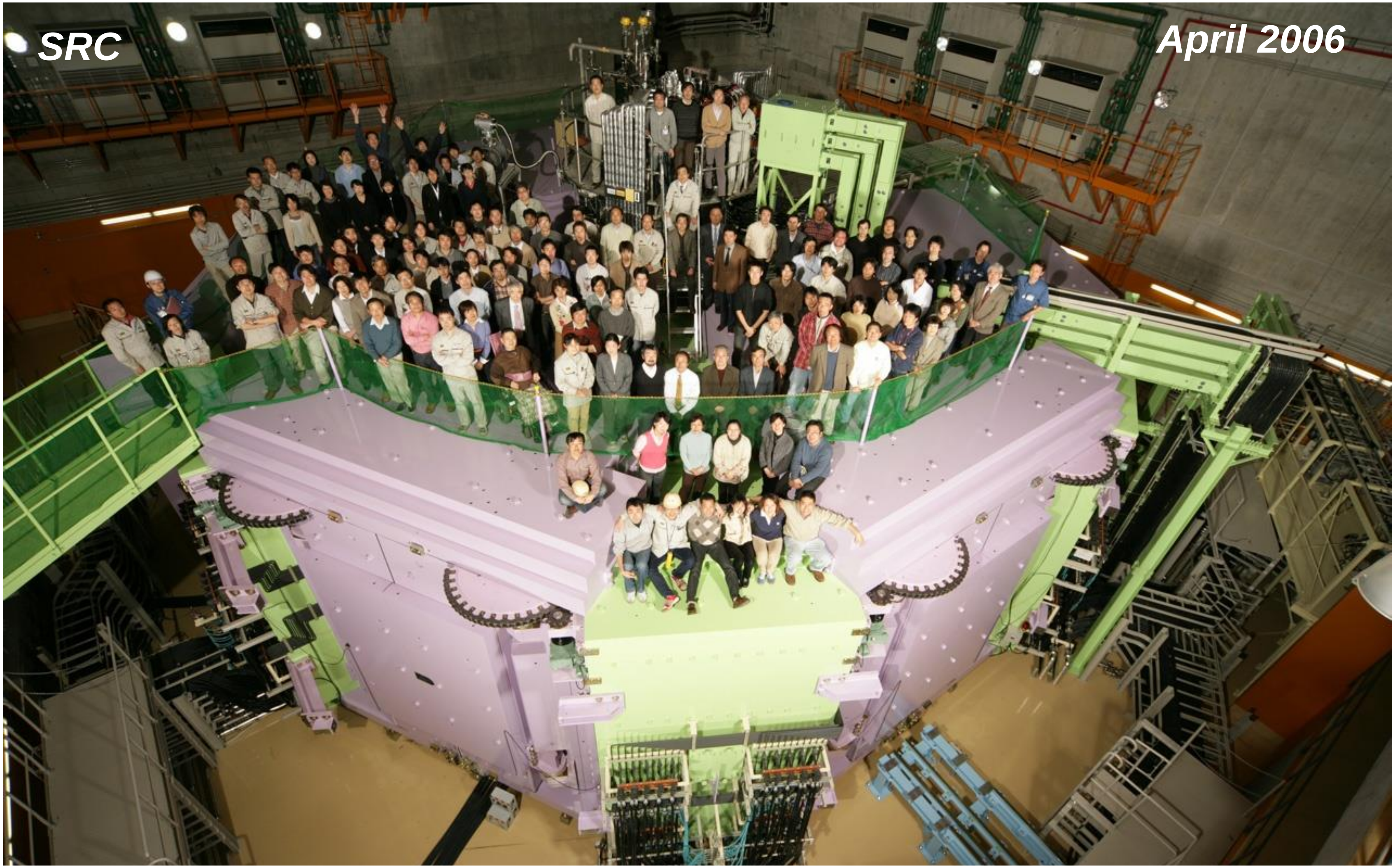
Experience with stripping of heavy ion beams



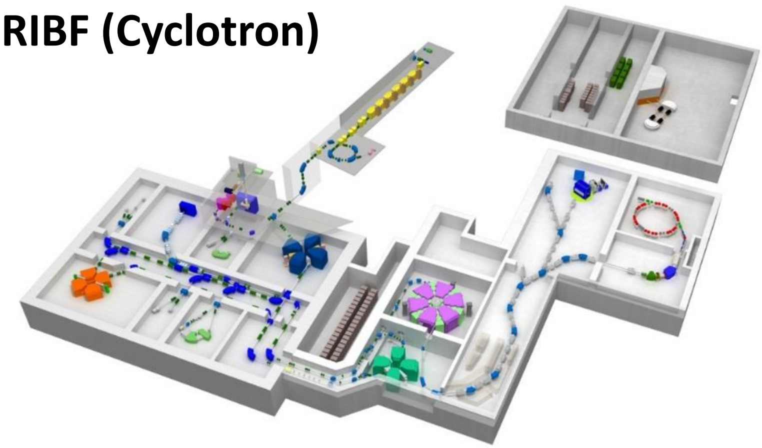
RIKEN Nishina Center for Accelerator-Based Science Accelerator Group

Hiroki Okuno

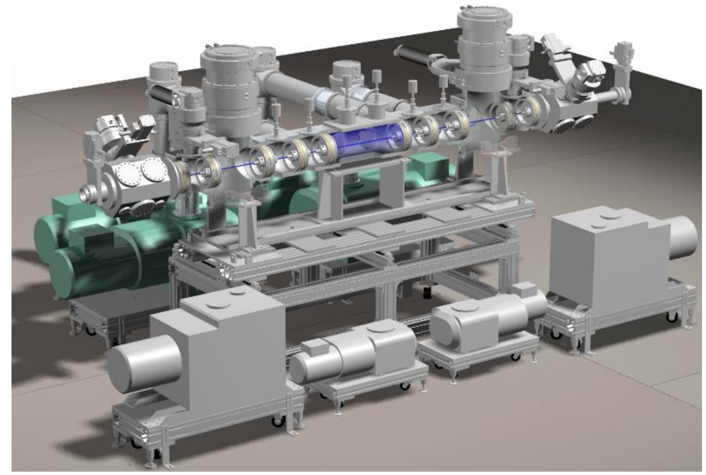
Preview

Introduction to charge strippers

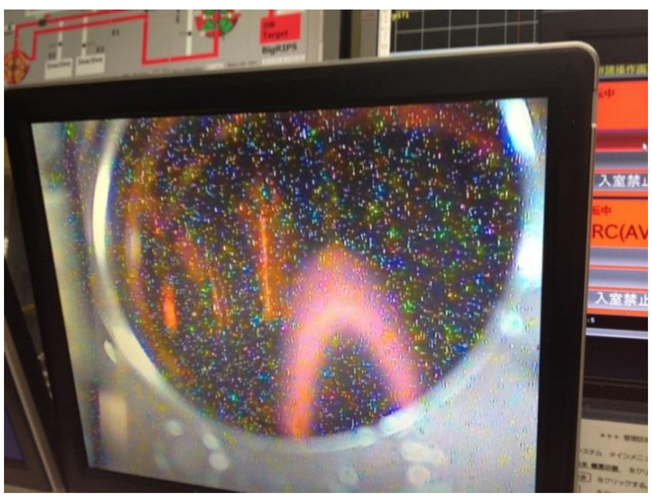
RIBF (Cyclotron)



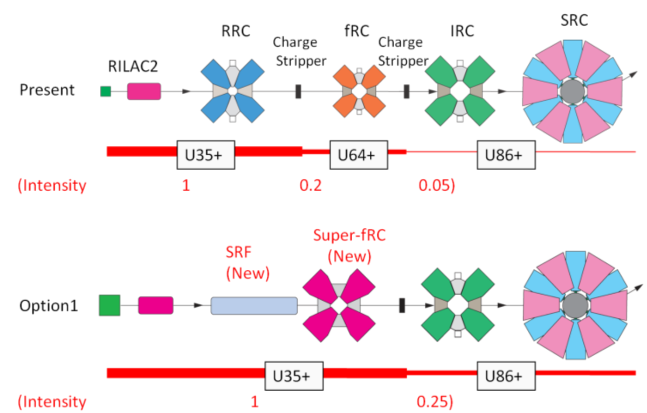
R&D results for FAIR, FRIB and RIBF



Operational experiences at RIBF

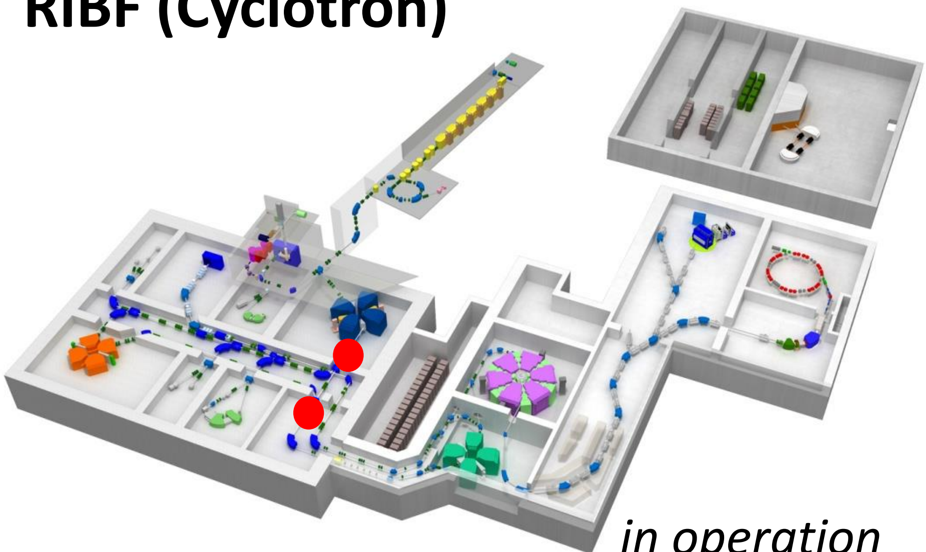


Outlook and summary



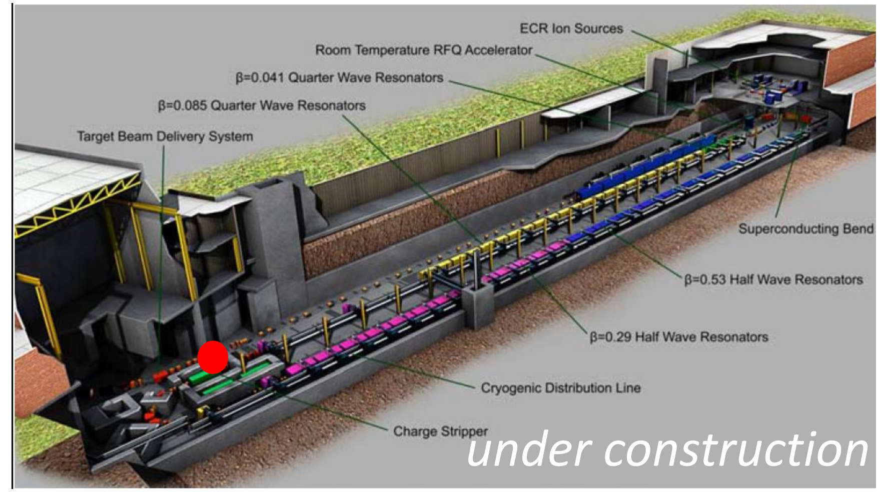
The three heavy ion accelerator facilities

RIBF (Cyclotron)



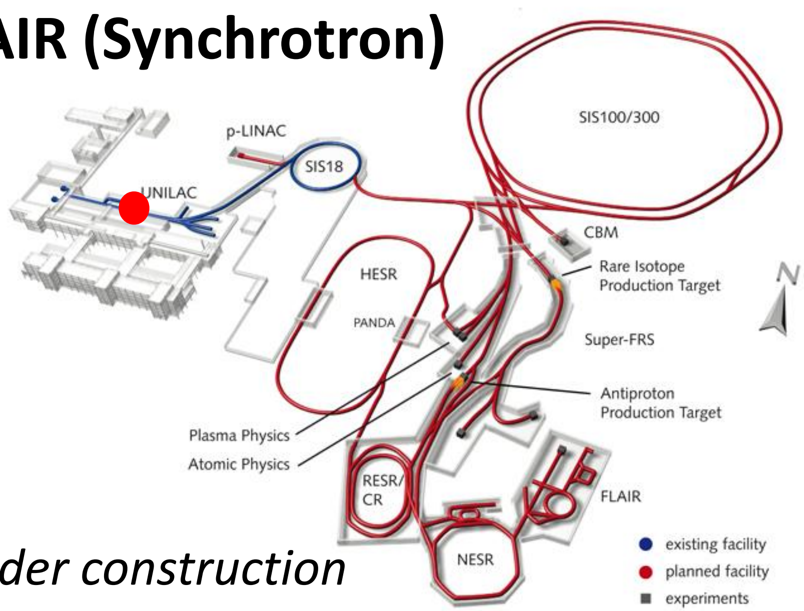
in operation

FRIB (Sc Linac)



under construction

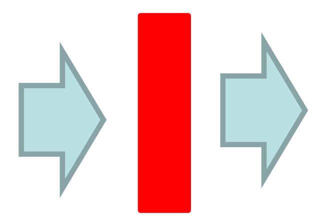
FAIR (Synchrotron)



under construction

Charge stripper

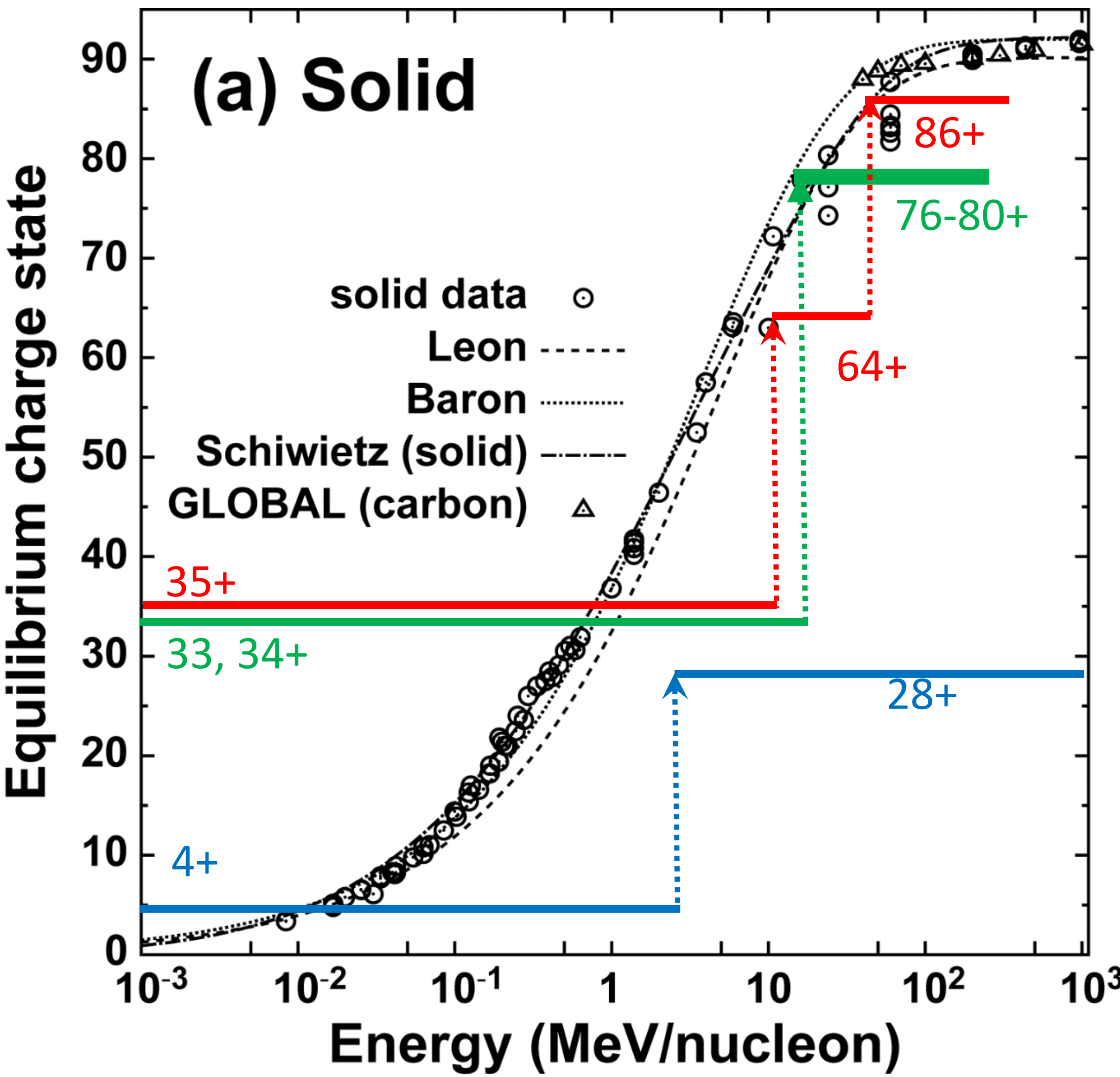
$$d\mathbf{v}/dt = Q/M\ (\ \mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$^{238}U^{35+}$  $^{238}U^{71+}$

Equilibrium charge state (e-loss =e-cap.)
an increasing function of $E_{proj.}$

Charge strippers for uranium ion acceleration

Uranium ion => dE/dx is largest.
(Largest heat deposit and heaviest radiation damage)



RIBF (345 MeV/u, 23%x28%, He x Be)

FRIB (200 MeV/u, 80%, Li)

FAIR (1 GeV/u, 14%, N_2)

General requirements on charge strippers

- **High charge state**
  - Reduction of total accelerating voltage and cost
  - **Density effect** in solid/liquid →~20% higher charge states compared to gas
  - Suppression of e- capture in **low-Z material** ←low velocity of electrons ($v_{1s} \propto Zc/137$)
- **High stripping efficiency**
  - Typical stripping efficiency = **10%-30%**
  - Using too many strippers decreases beam intensity to zero.
  - **Shell effect** helps for high stripping efficiency.
- **Small energy spread**
  - **Uniform thickness**
  - **Charge state energy straggling**
- **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.

STRs for Uranium

- H_2(pulsed) :FAIR
- He :1st for RIBF
- Li :FRIB, RAON
- Be :2nd for RIBF

Pulsed H_2 gas stripper at FAIR/GSI

A new record intensity of **7.8 mA** for uranium beams at UNILAC has been achieved on November 4, 2014. This substantially exceeds the old record of about 5 mA, achieved in 2007. This became possible thanks to modifications in the gas stripper section.

Modification:

Old “ N_2 gas-jet target” => New ”Pulsed H_2 gas stripper ”

to create targets of highest density in a cell for the duration of the beam passage)

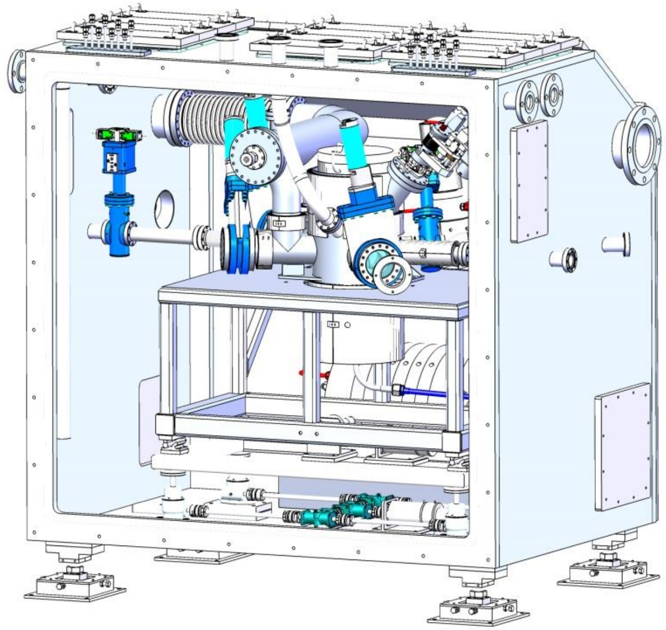
This pulsing is a very smart way to overcome the difficulty in confinement of thick hydrogen gas.

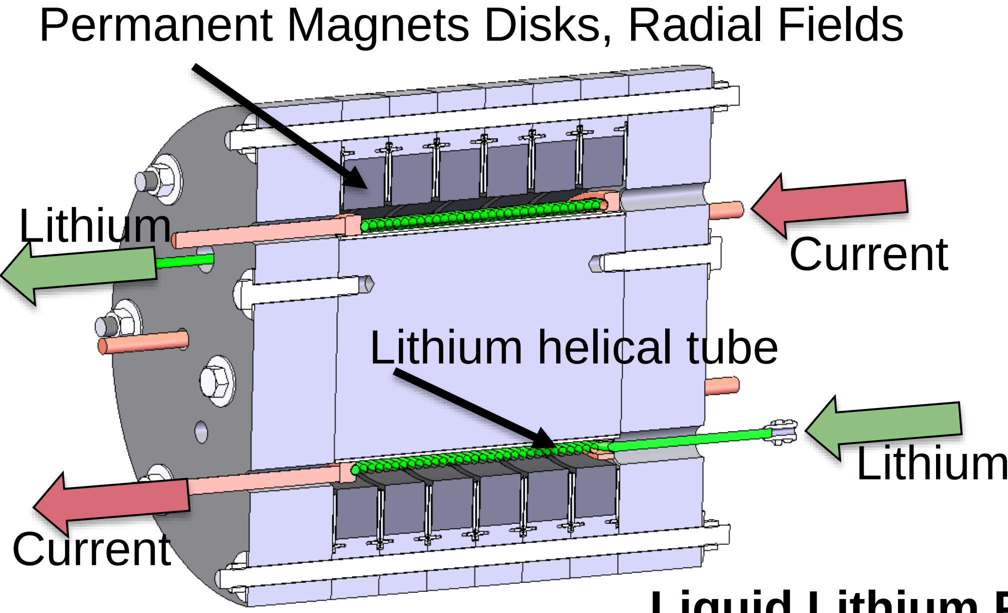
(The details of the new pulsed H2 gas stripper will be appeared in "P. Scharrer et al., submitted to J. Radioanal. Nucl. Chem., Proc. INTDS2014, Odaiba)

Courtesy W. Barth / Ch. Düllmann / P. Scharrer (GSI/HIM)

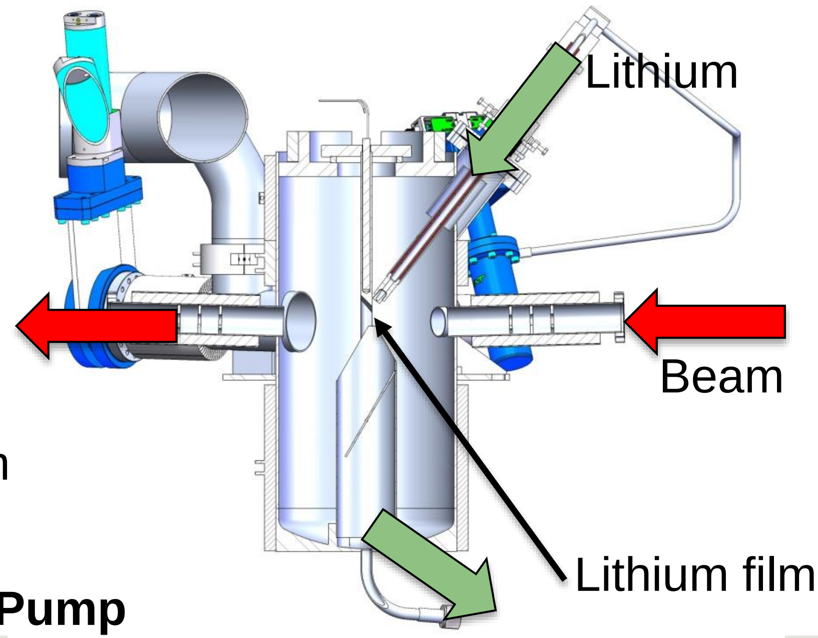
FRIB Liquid Lithium Charge Stripper

Developed in collaboration with Argonne National Laboratory (ANL)
Length = 2 m
Light ions to Uranium (~ 17 MeV/u)
Power deposition ~ 30 kW/mm^3
Lithium film: 10 microns thick, 10 mm wide, v = 50 m/s, T~ 200 C

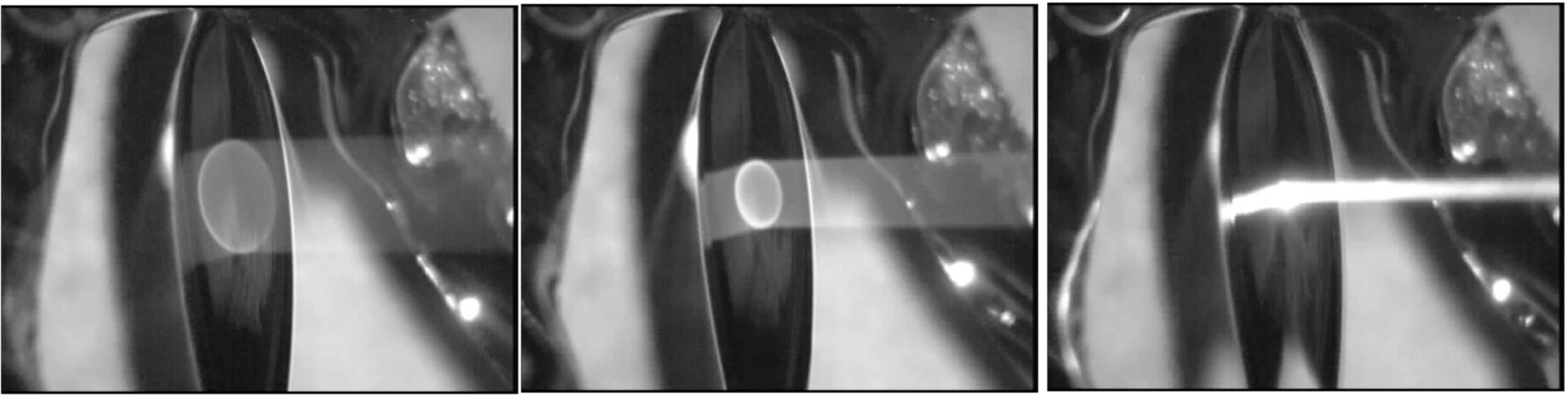




Liquid Lithium Pump



Courtesy F. Marti



Experimental work with beam:

Proton beam from the LEDA (LANL) source was deposited on the liquid lithium film with power density deposition similar to the maximum expected at FRIB when accelerating 400 kW of Uranium

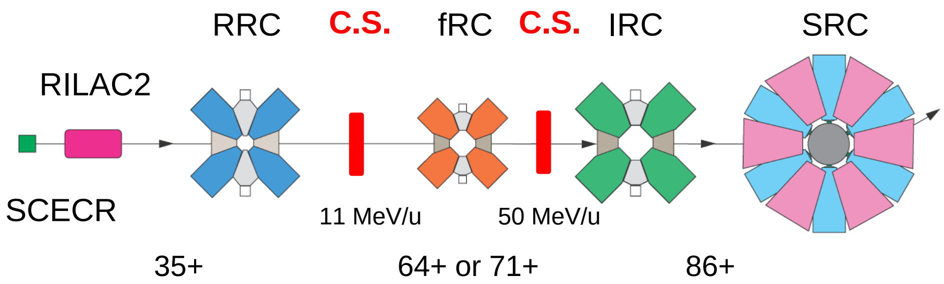
The film was not perturbed at the beam impact point.

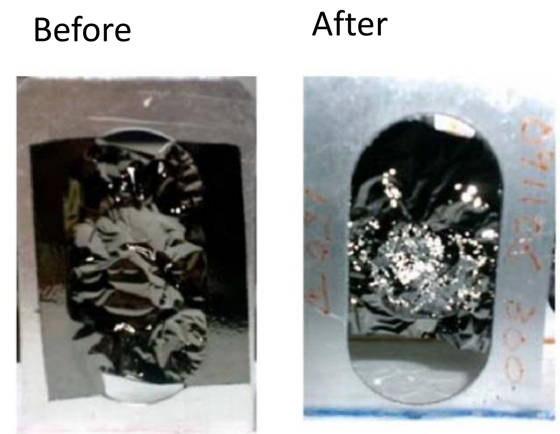
Next steps:

Construction of the charge stripper module within the next 6 months with continuous flow, tests of stability and reliability

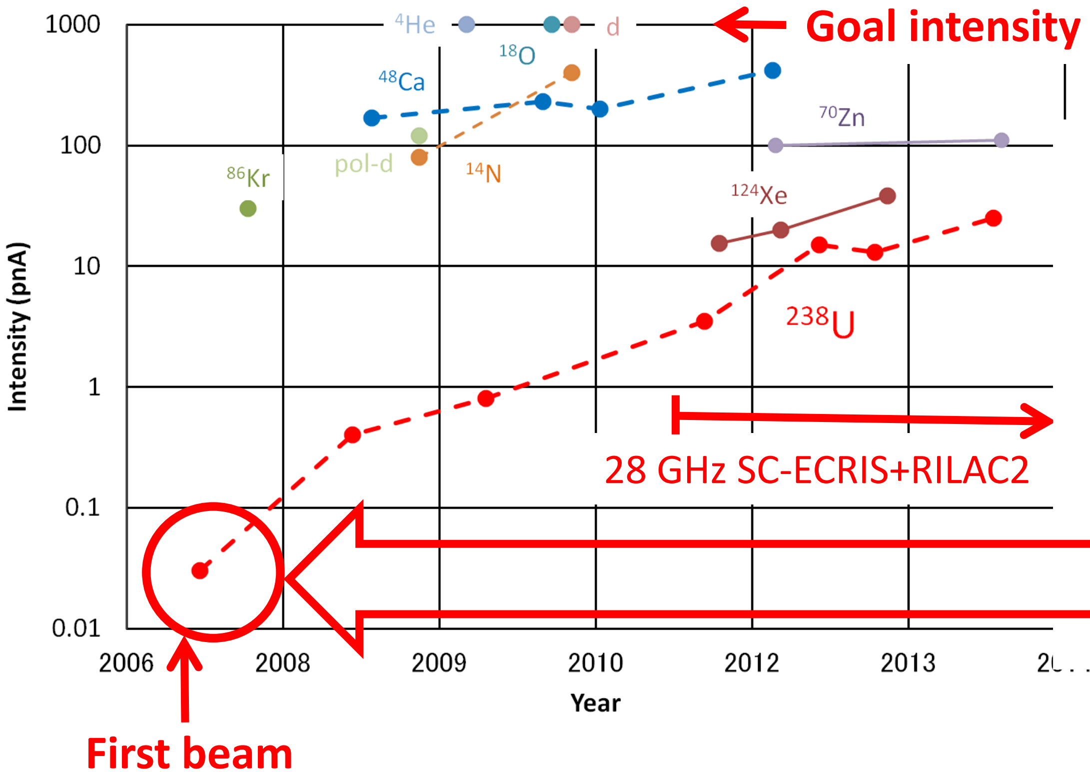
Courtesy F. Marti

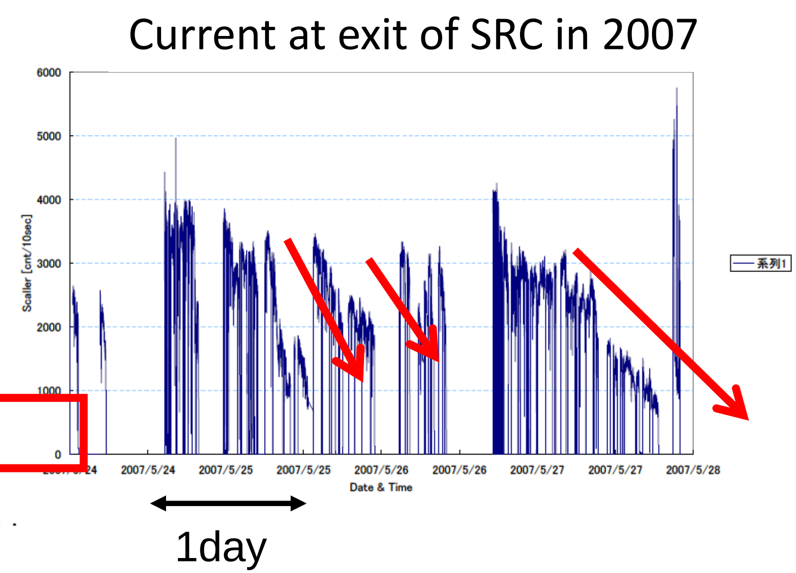
R&D studies at RIBF (motivation)





Achieved beam intensity





History of R&D on the 1st stripper

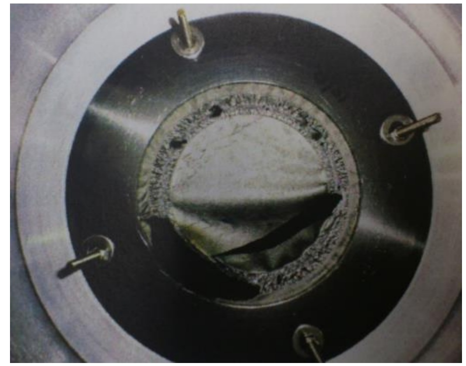
Foil

Rotating cylinder with a large foil

Carbon NanoTube foil

Slow rotation

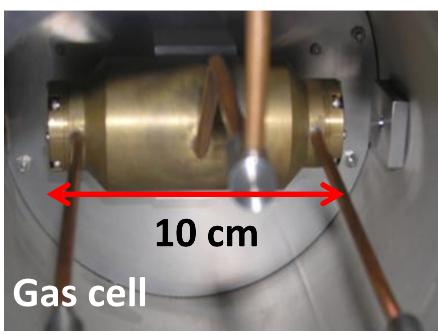
CNT-SDC foils (User run in 2011)



2008 2009 2010 2011 2012 2013 2014

Gas

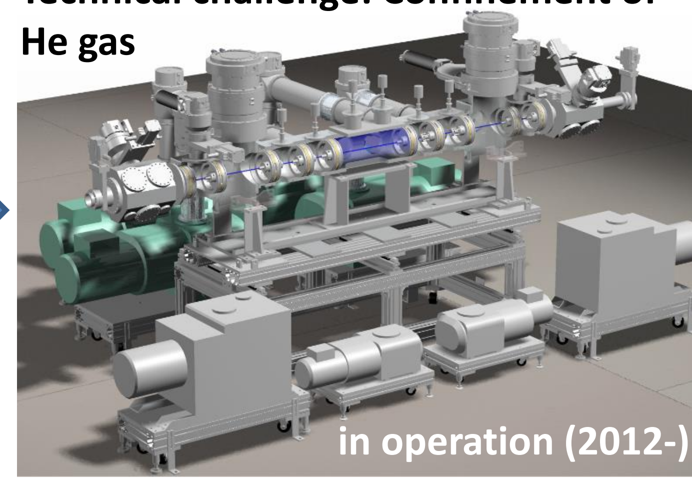
Charge states in N_2, Ar, CO_2 Is lower than acceptable charges.



He gas stripper
8 m and 0.5 m prototypes

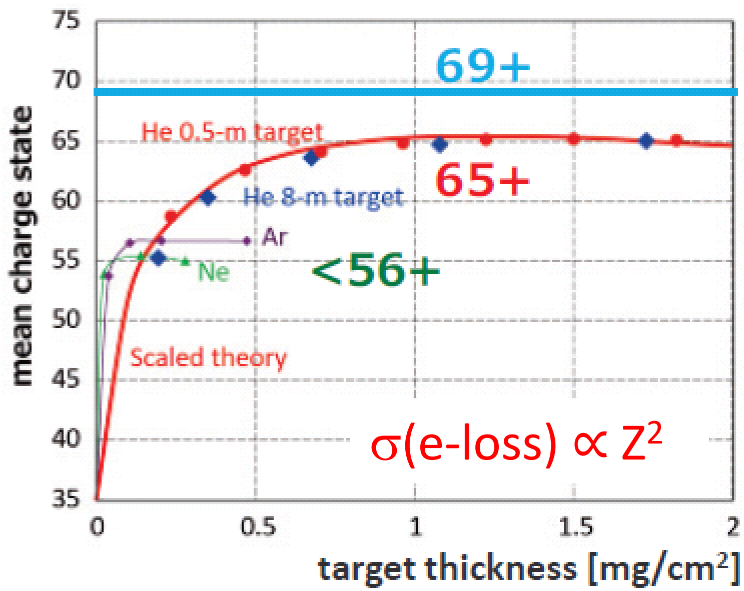
Cross section of e-loss and e-cap in Low-Z gas

Technical challenge: Confinement of He gas

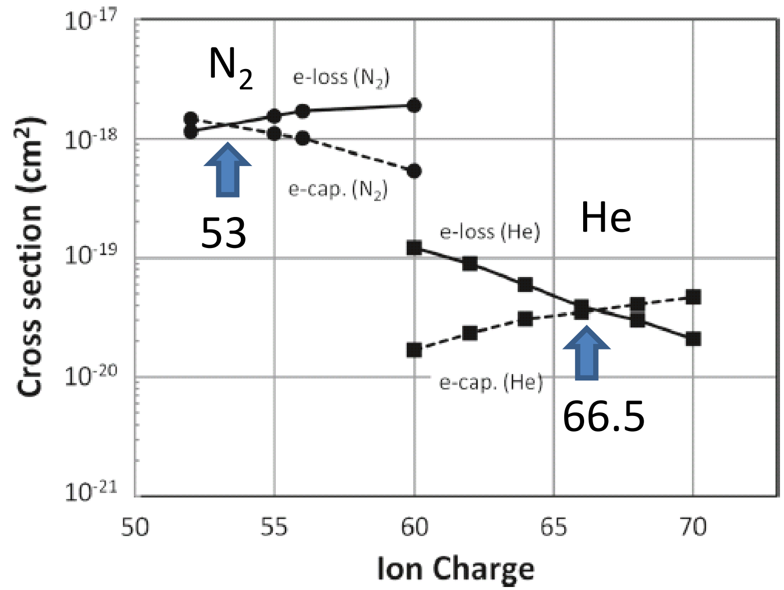


Fundamental data for the 1st charge stripper

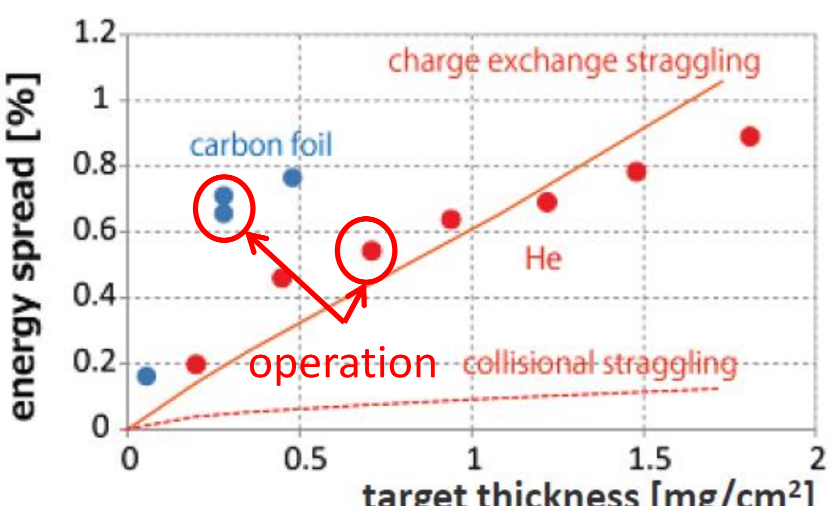
Charge evolution



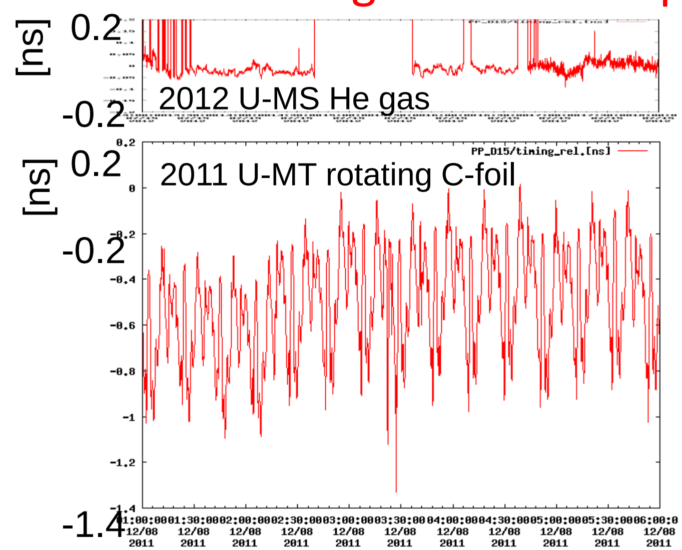
σ(1e-loss) and σ (1e-cap)



Energy spread measured w/ scinti.

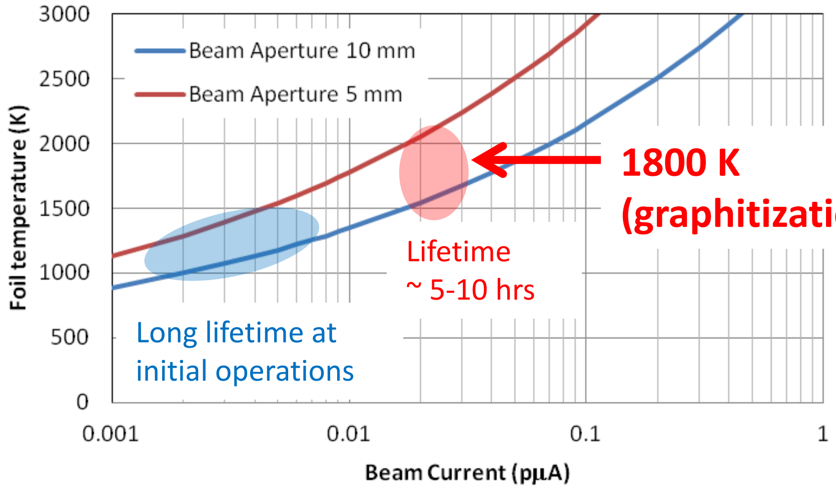


Jitter of beam timing after the stripper



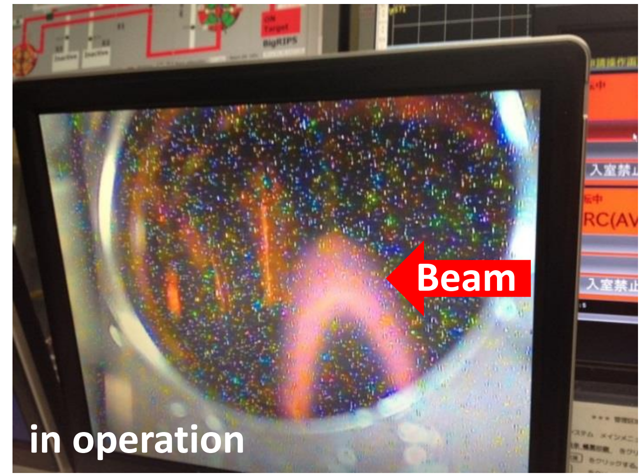
History of R&D on the 2nd stripper

Foil



1800 K (graphitization..)

Rotating Be disk in operation



Wheels of Be, Ti and C were tested.

2008 2009 2010 2011 2012 2013 2014

Gas

Gas stripper for R&D

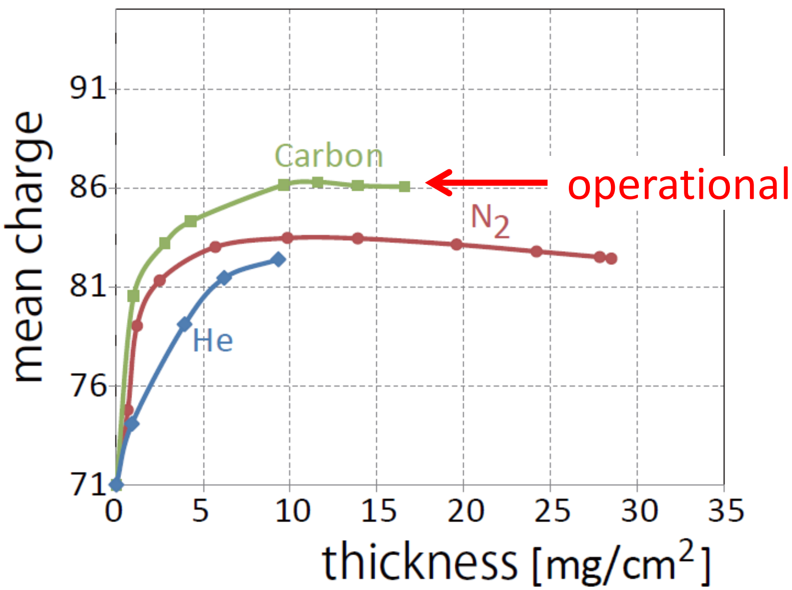
Low charge state in gas

Air gas stripper (Xe beam)

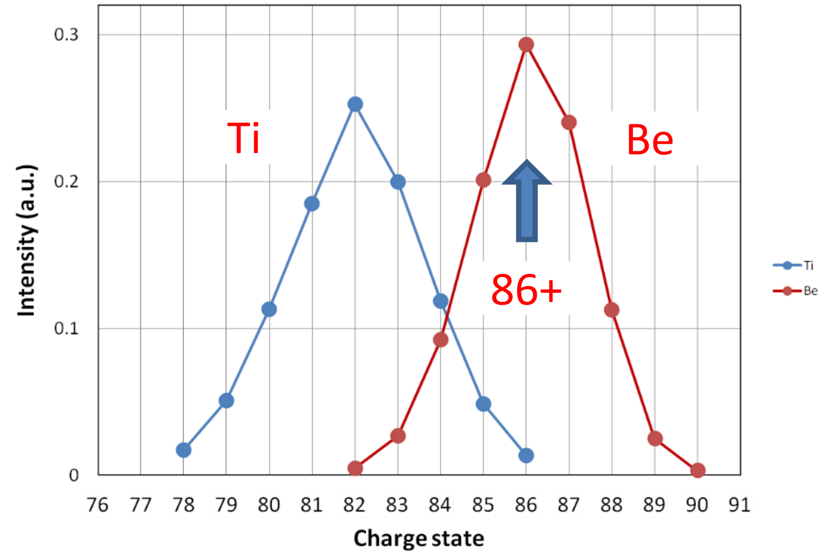
in operation

Fundamental data for the 2nd charge stripper

Mean charges in the gases

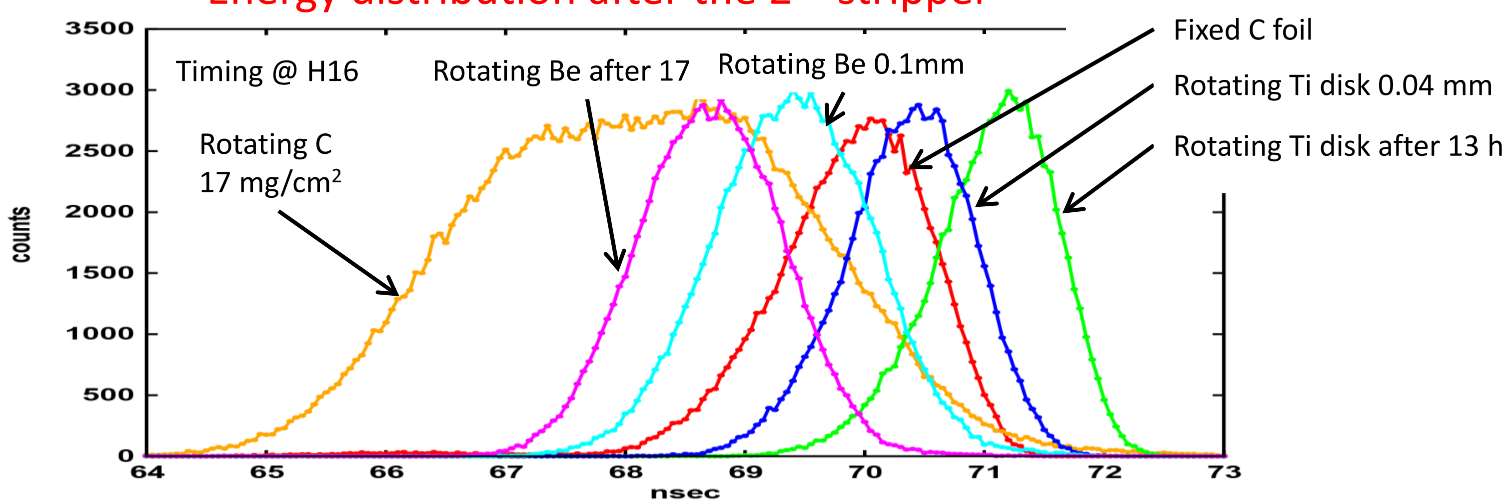


Q dist. after the wheel of Be and Ti

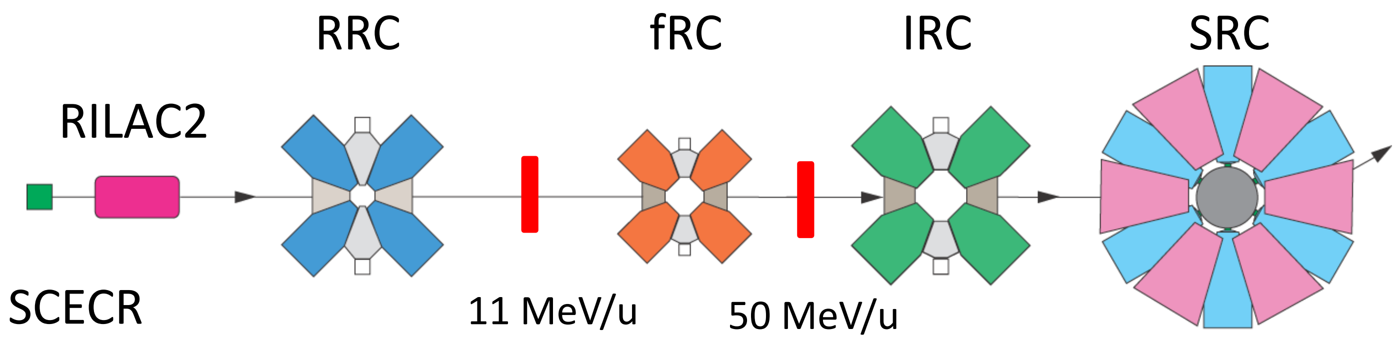


Q dist. after C disk could not measured.

Energy distribution after the 2nd stripper



Solutions to charge strippers for U accelerations



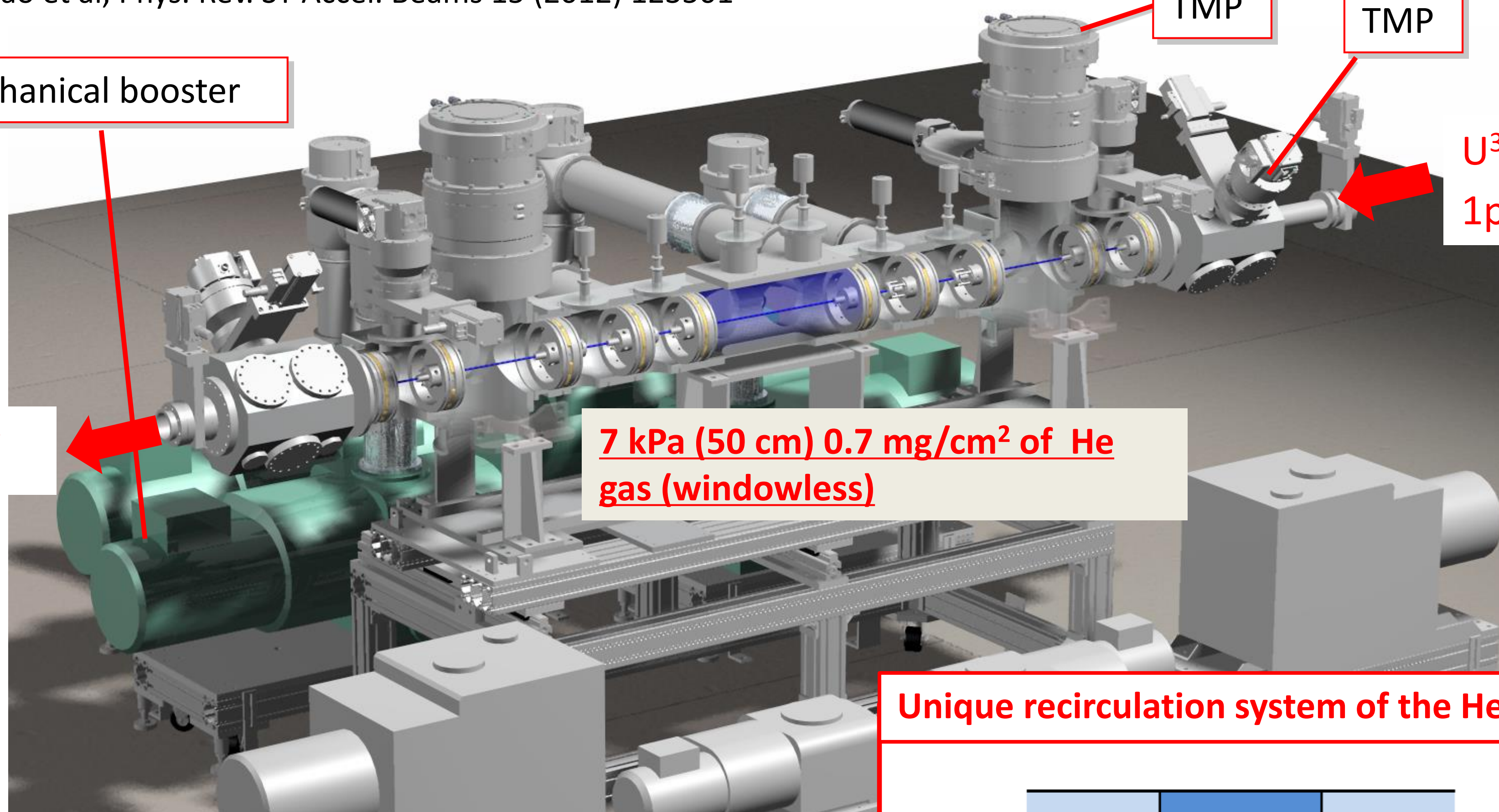
Year	Q1	1st C.S.	Q2	2nd C.S.	Q3	Ext. Curr
‘07-’09	35+	C-foils	71+	C-foils	86+	0.8 pnA
2011	35+	Rotating CNT-based foil	71+	C-foils	86+	2.4 pnA
2012-	35+	**He gas** **Low-Z gas**	**64+**	**Rotating Be disk**	86+	15 pnA 25 pnA

Upgrade of FRC

Beam is increasing!

He-gas stripper @ 11 MeV/u (1st stripper)

H. Imao et al, Phys. Rev. ST Accel. Beams 15 (2012) 123501



He circulating volume: 300 m^3/day

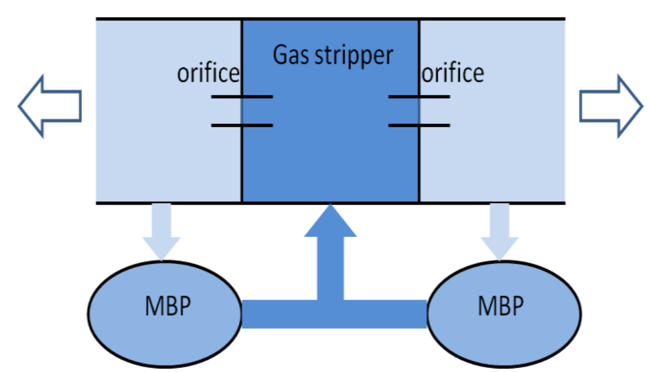
5 stage differential pumping: 21 pumps

8 order pressure reduction: 7,000 Pa => 10^{-5} Pa

Large beam aperture: > ϕ 10 mm

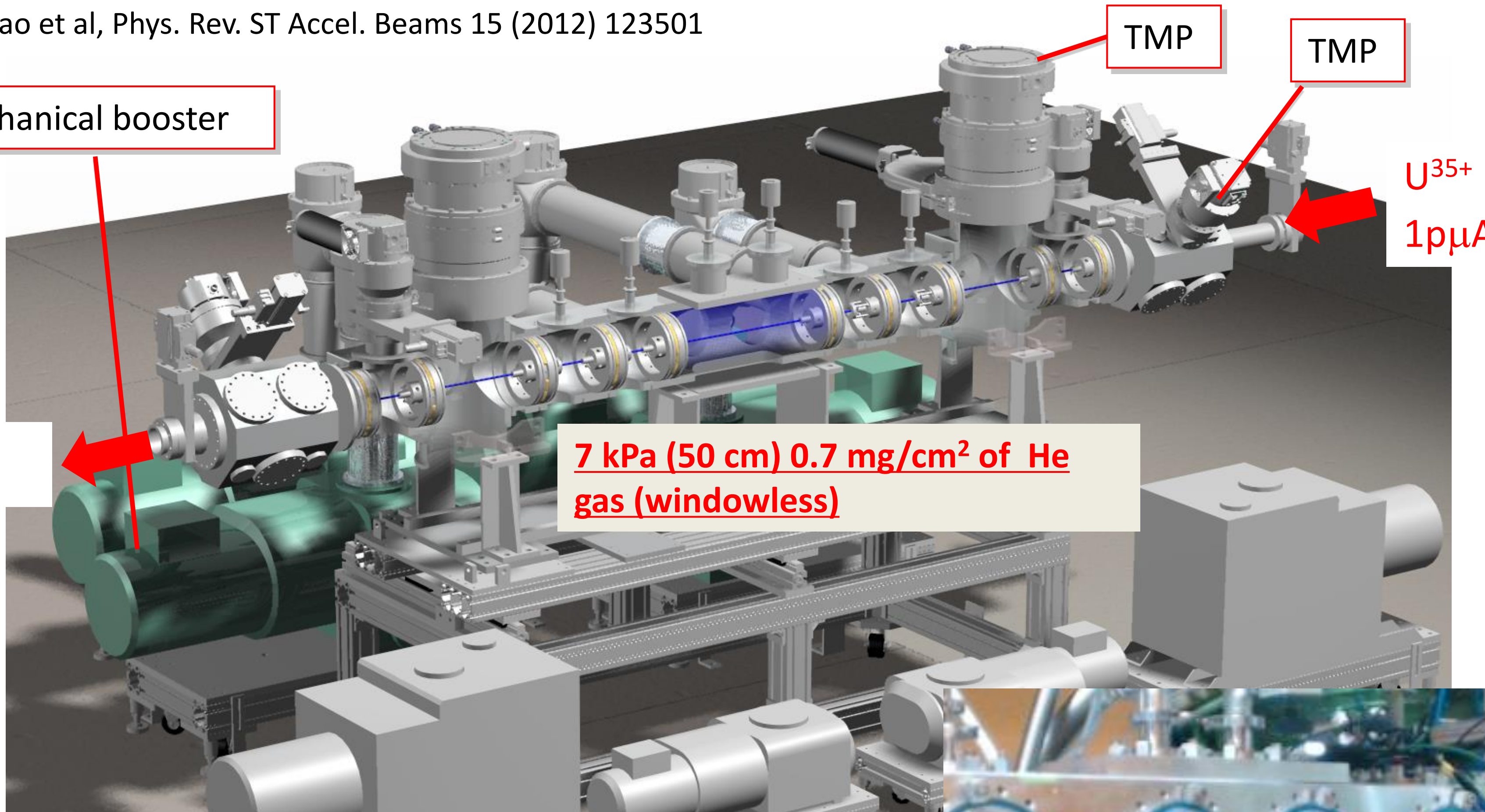
Unique recycling system

Unique recirculation system of the He Gas



He-gas stripper @ 11 MeV/u (1st stripper)

H. Imao et al, Phys. Rev. ST Accel. Beams 15 (2012) 123501



He circulating volume: 300 m^3/day

5 stage differential pumping: 21 pumps

8 order pressure reduction: 7,000 Pa => 10^{-5} Pa

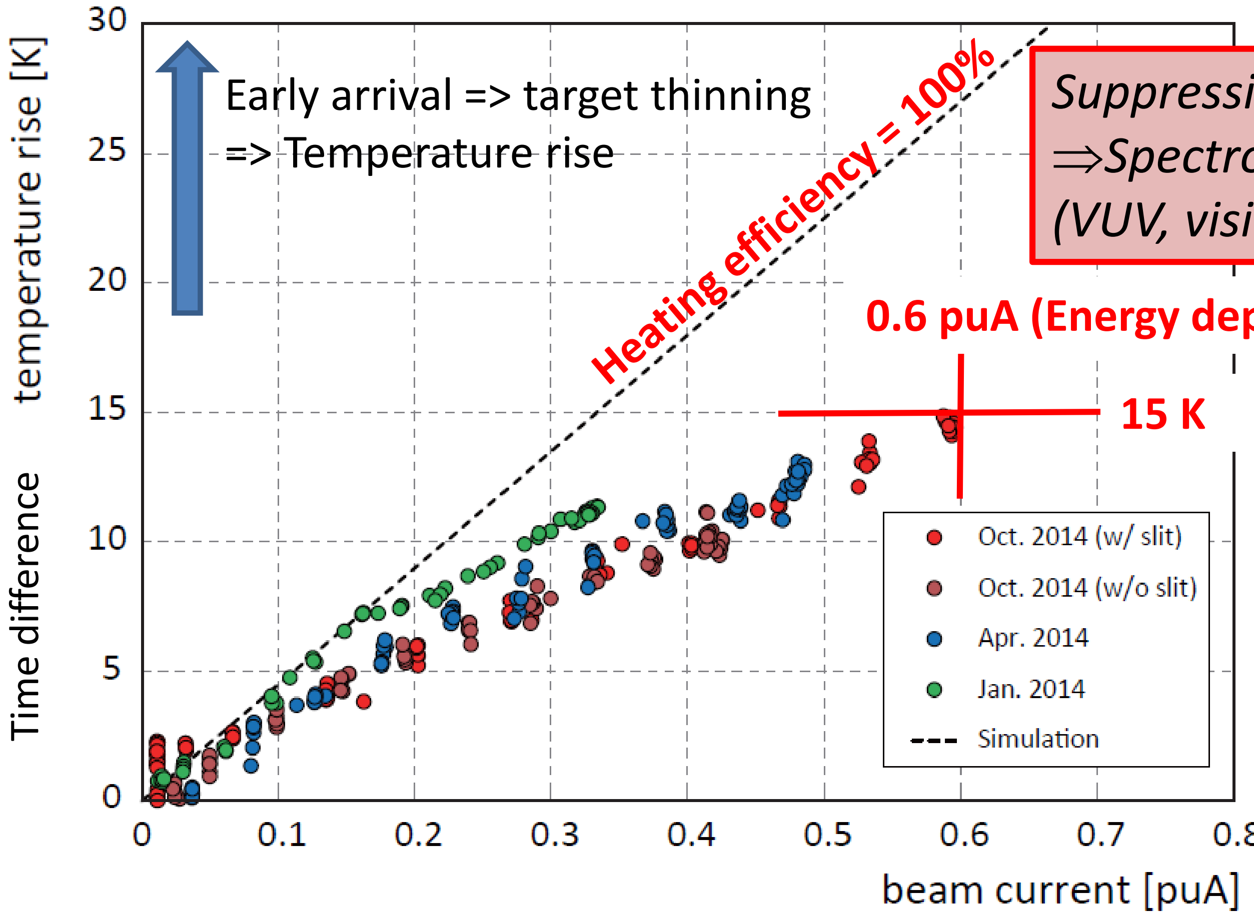
Large beam aperture: > ϕ 10 mm

Unique recycling system

Target thinning by heat load

Target thinning caused by the heat load due to uranium beams will determine the application limit of gas stripper.

The TOF of U^{64+} beams as a function of the beam intensity using phase probes.



Suppression mechanism?
⇒Spectroscopic study (VUV, visible light)

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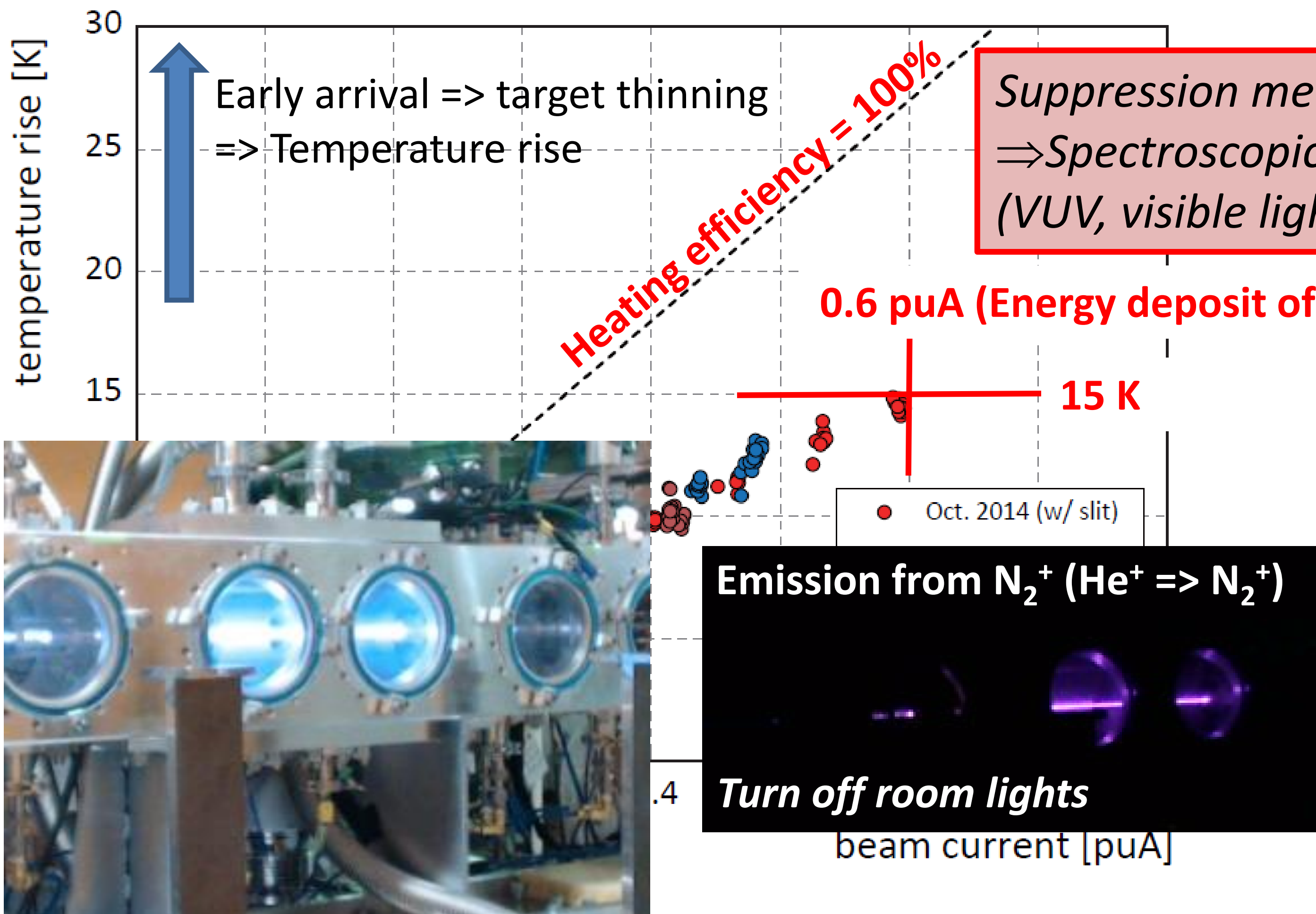


Suppression mechanism?
⇒Spectroscopic study
(VUV, visible light)

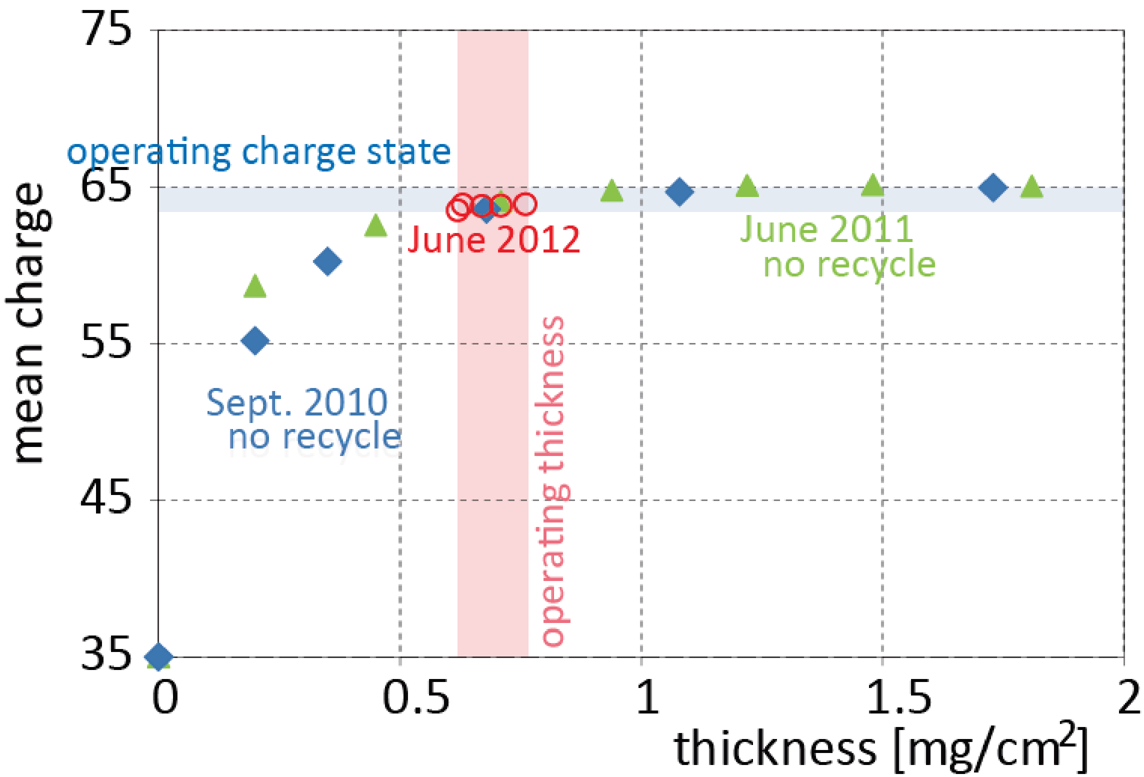
Impurity in the recirculating He gas

The charge state in He gas is sensitive to impurity

Effect of the impurity (Air, H_2O, HC) on charge state can be large

$\sigma_{cap} \propto Z^{4.2}$

(less than 100 ppm of impurity is required.)



Rotating Disk stripper

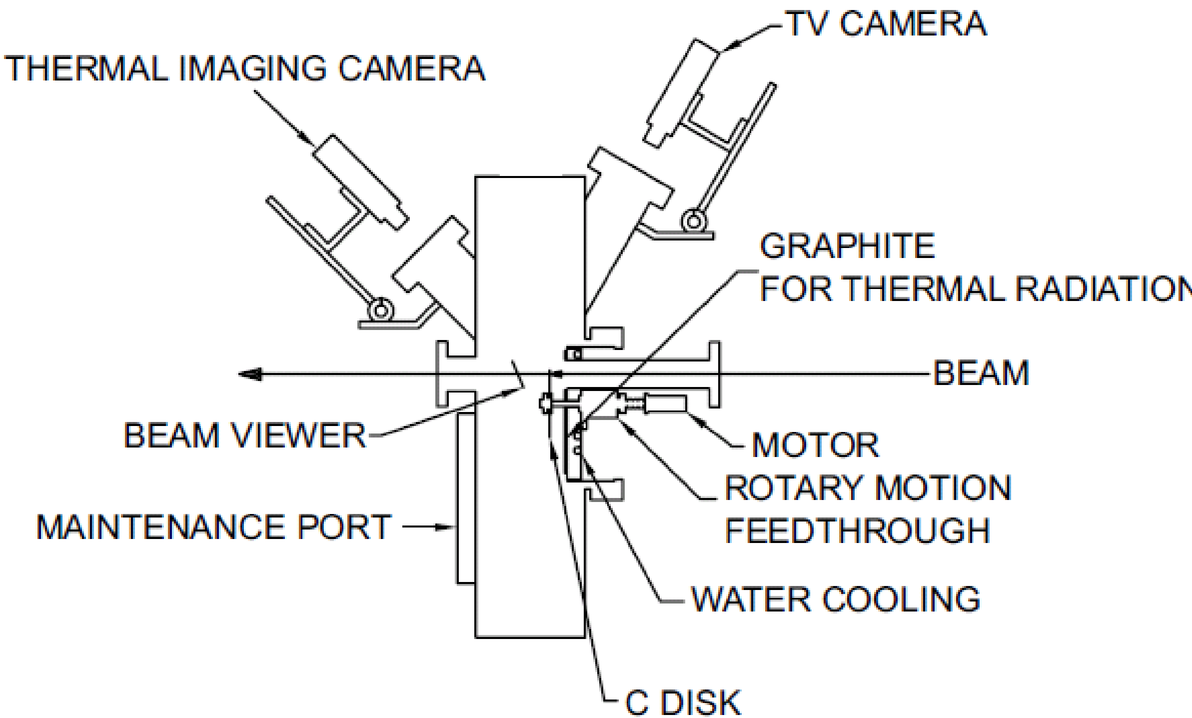
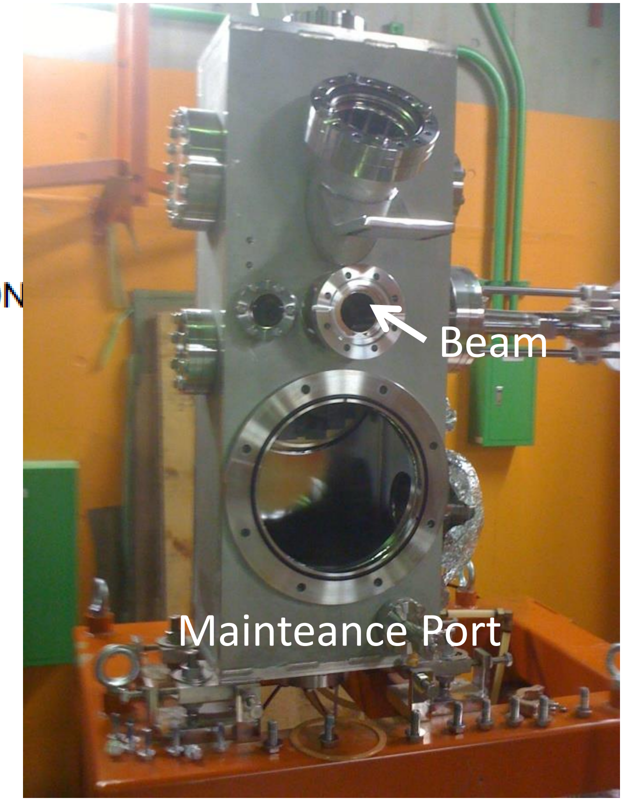


Figure 1: Schematic of rotating carbon disk stripper.



Rotation speed: 1000 rpm
Irradiation area: 60 times of the beam spot

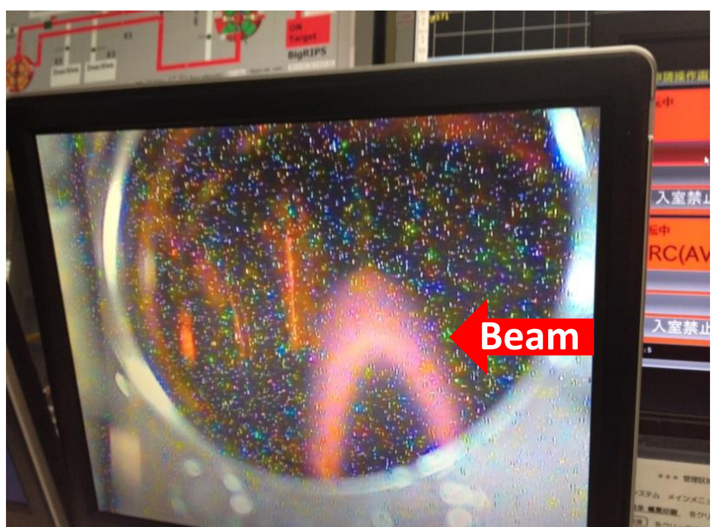
H. Ryuto, et al.

Be disk stripper(0.1 mm t) survived the U beam irradiation (90W, 160 pnA, 51 MeV/u)

Before

After (large deformation)

Beam-on



Be (ductility >400 deg.
britleness <400 deg.)
Thermal cycle
→large Deformation
→beam quality ↓

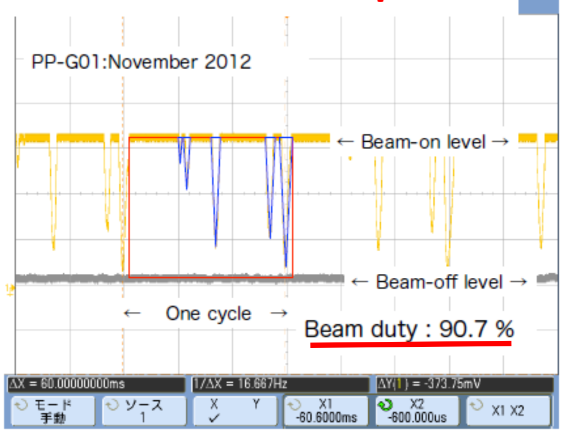
Operational experiences of the rotating Be disk

Deformation of the Be disk degrades beam quality.

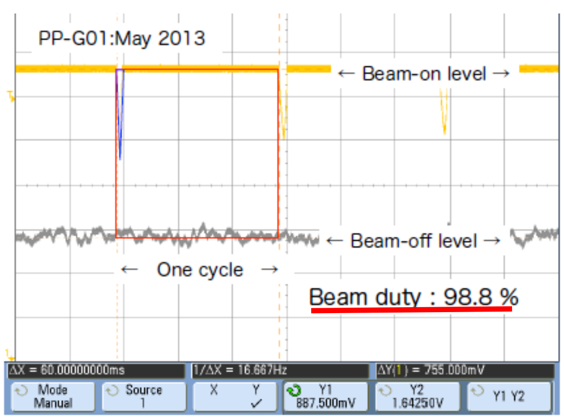
The Be disk will reach the limit in near future.

Just after irradiation

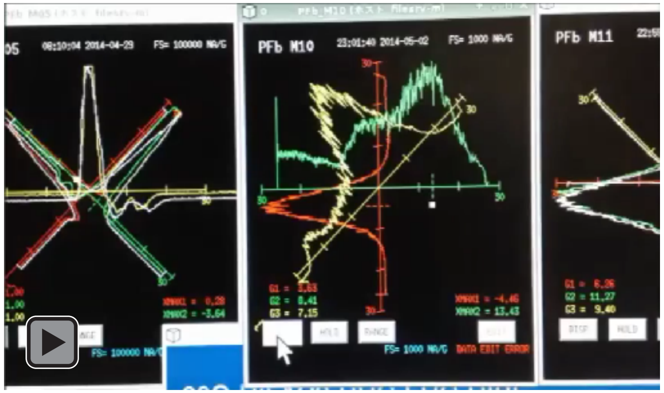
Finished with buff-polish



Polish with diamond powder



After large deformation (slow rotation)



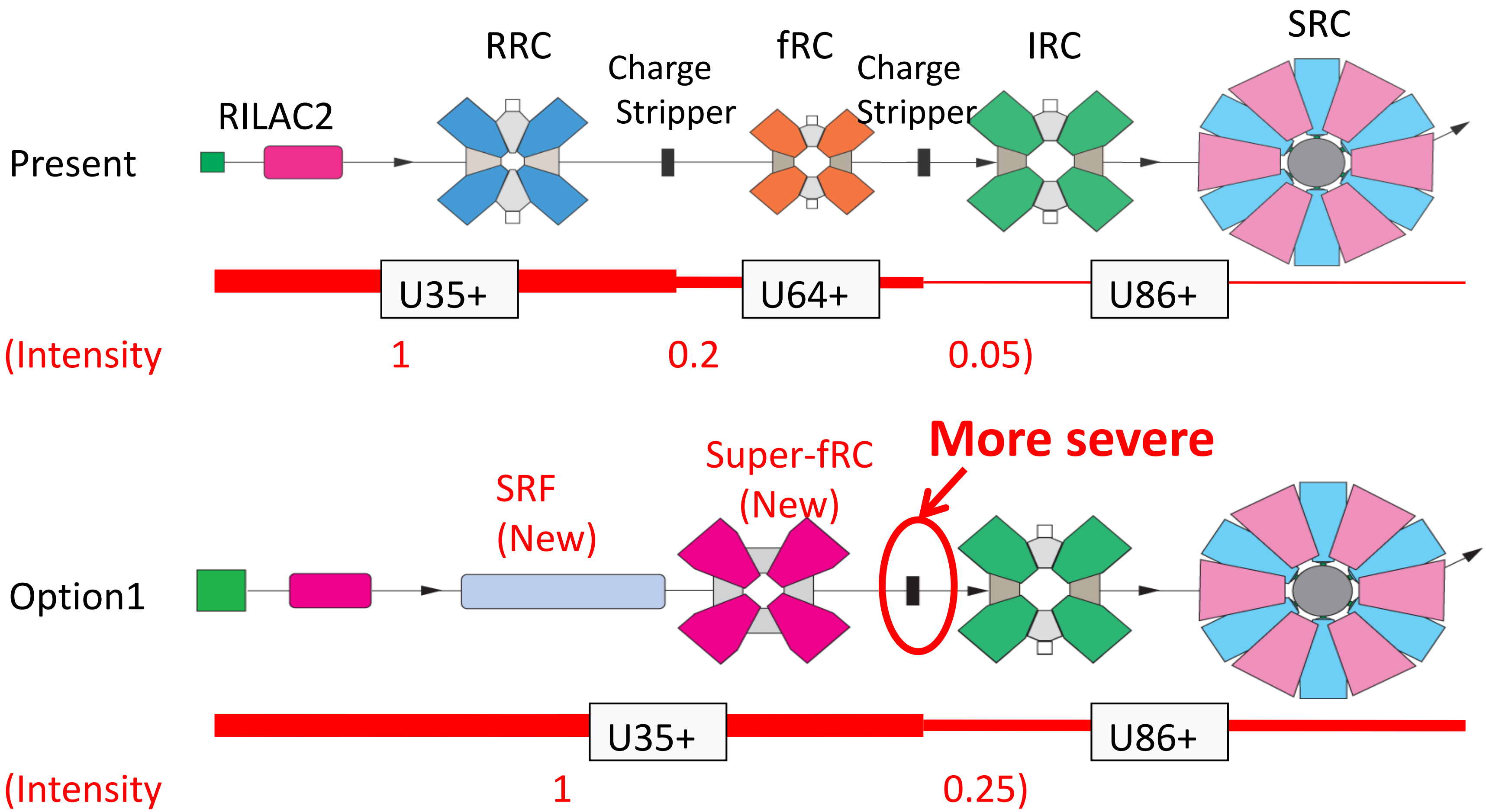
Beam profile after the bending located the downstream of the CS

FC current at the exit of the SRC

Nuclear physicists are not aware of this fluctuation.

What is the next?

We need a stripper which can survive beam irradiation with 2-3 times of the present beam intensity to realize 100 pnA at the exit of SRC



We need extensive R&D studies because this charge stripper will be more severe in the future plans.

Further R&D for the 2nd stripper

		Status/Merits	demerit	todo
Gas	CH_4 (Metan)	installed (heat dep. 80 W)	flammable	**Charge state**
Solid	Be	In operation	Large deformation	**Improve structure**
Solid	Carbon	studied	Bad uniformity	**New material**
Solid	SiC crystal	Heat resistant Radiation resistant (10^{11}Gy/month)	Charge low fragile (60 μm)	**Charge distribution** **(Qave=83.5)**
Liquid	Lithium (0.1 mm)	FRIB/ANL (0.01 mm) BNCT (>1 m)	flammable	**Study by water**

Summary

- Charge stripper is one of the key issues for the heavy ion accelerators with high intensity.
- R&D works of the liquid lithium stripper are successfully going on at FRIB.
- The bottle neck problem in the uranium acceleration has been solved by the He gas stripper at RIBF.
- The wheel of Be was successfully applied for the second stripper at RIBF.
- For further intensity upgrade, we need to R&D studies for the second stripper. (CH_4 gas, C, Be, SiC and liquid lithium).