Operational experience with the RIKEN RIBF accelerator complex

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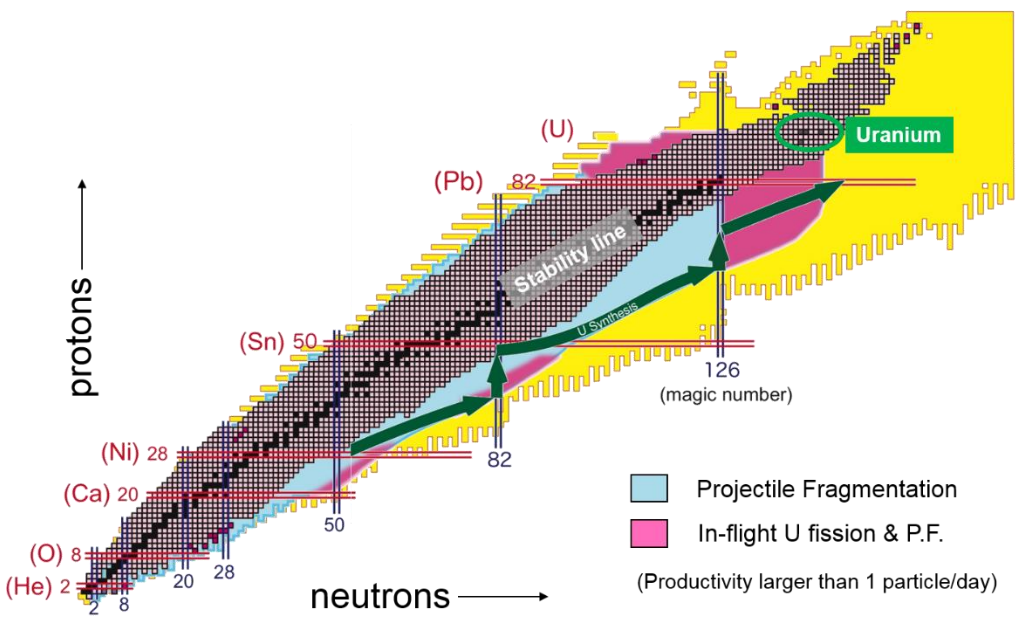
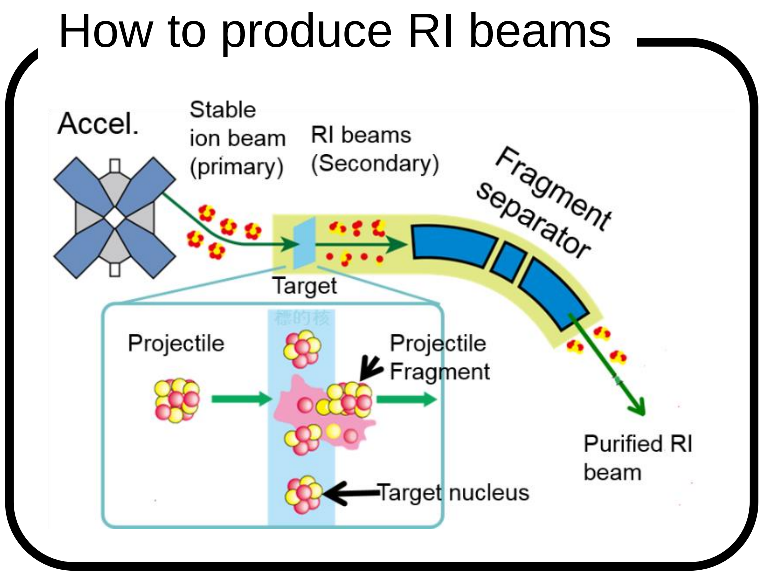
Goal of RIBF

- Great expansion of the nuclear chart (new 1000 kinds of isotope, exotic nuclei)
- Challenge to solve the big puzzle of element genesis (r-prosess = U-synthesis)
- Promotion of industrial and biological applications

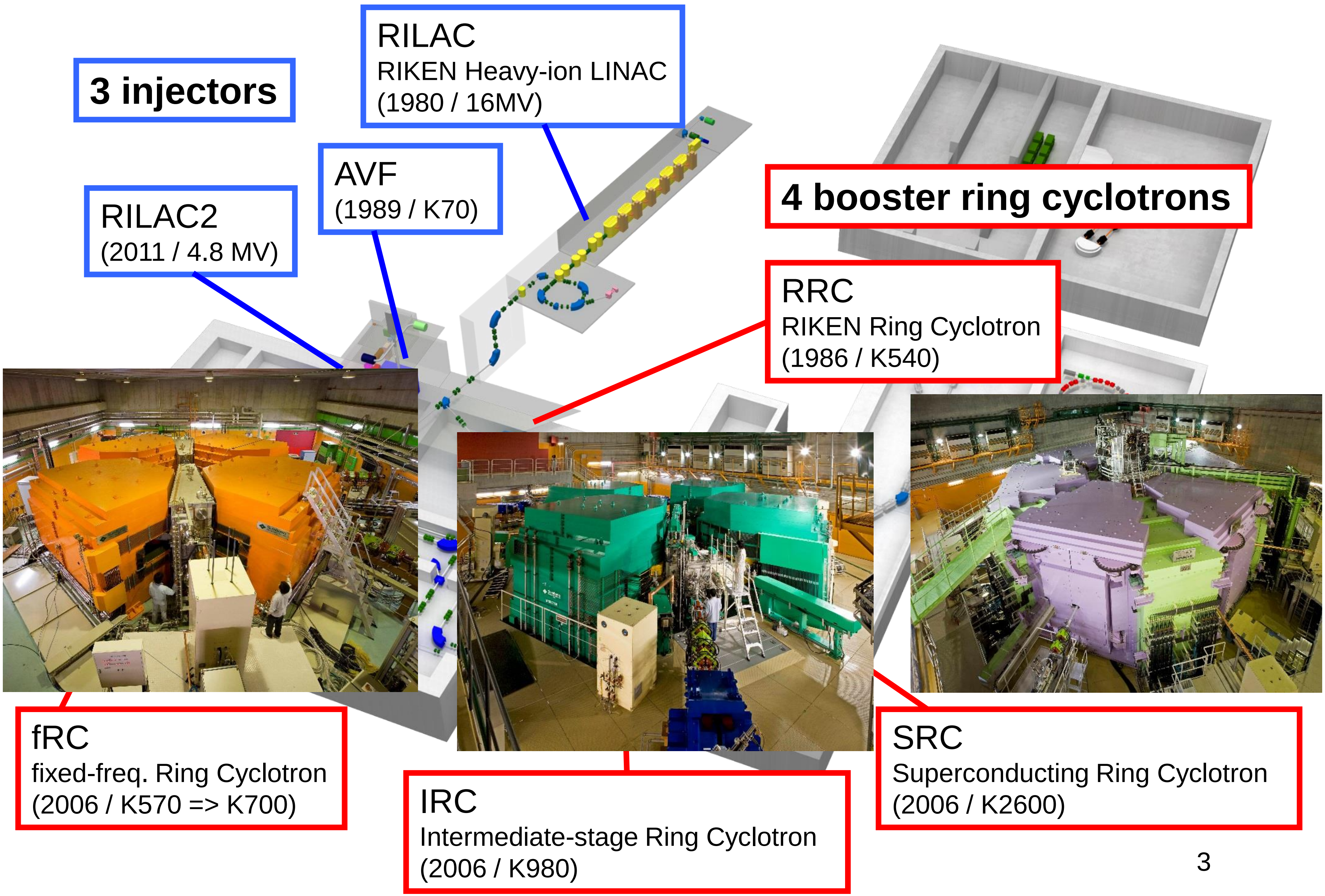




- RI beams are generated by fragmentation or fission of high-speed heavy ion beams.
- Accelerator complex is required to produce high speed heavy ion beams with high intensity.

Y. Yano, NIM B261 (2007) 1009.

RIBF accelerators

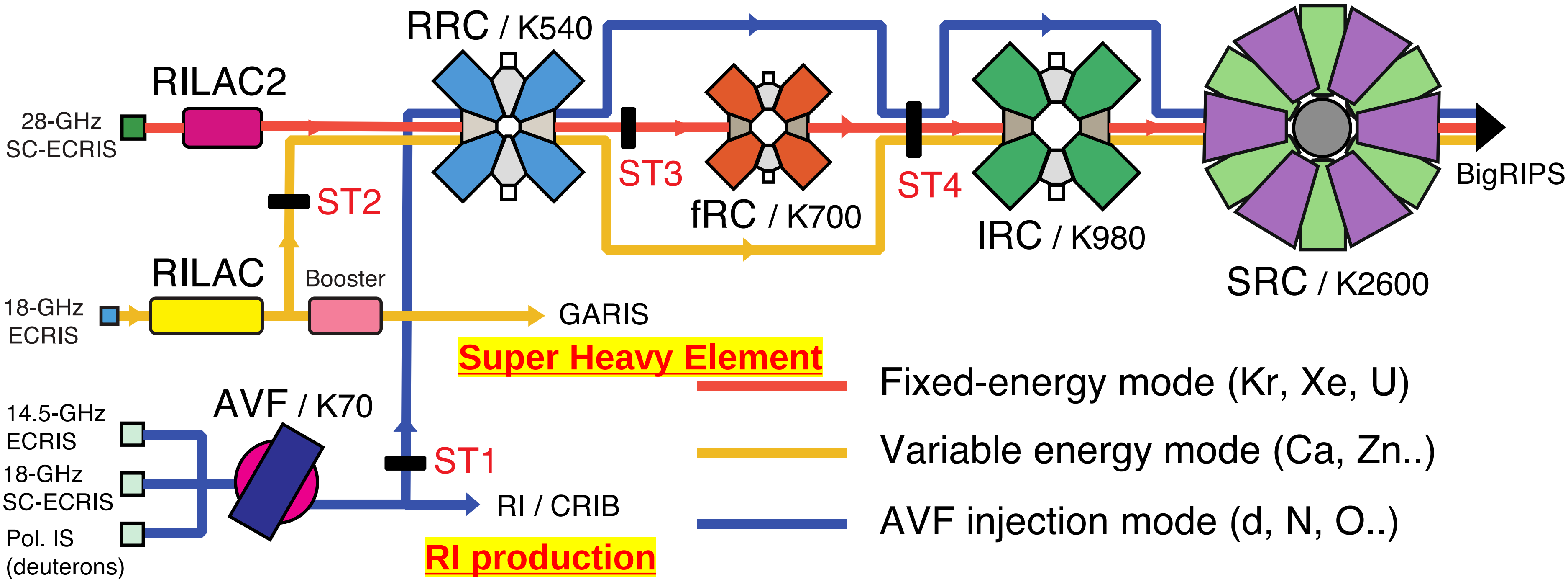


Acceleration modes

Accelerate ALL ions (from H_2^+ to U), up to 70% of the light speed, in CW mode

3 injectors + 4 booster ring cyclotrons

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



STn: charge stripper

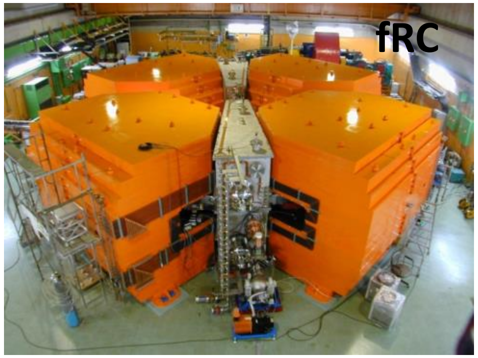
Specifications of RIBF ring cyclotrons

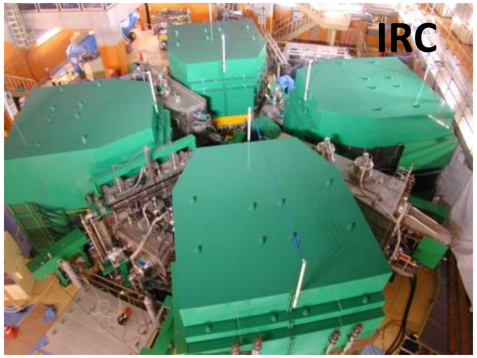
Challenging

	RRC (1986~)	fRC	IRC	SRC
K-number (MeV)	540	700	980	2600
R_{inj} (cm)	89	156	277	356
R_{ext} (cm)	356	330	415	536
Weight (tons)	2400	1300	2900	8300
Sector magnets	4	4	4	6
Number of trim coils (/ main coil)	26	10	20	4 (SC) 22 (NC)
Trim coil currents (A)	600	200	600	3000 (SC) 1200 (NC)
RF resonators	2	2+FT	2+FT	4+FT
Frequency range (MHz)	18～38	54.75	18～38	18～38
Acceleration voltage (MV)*	0.28	0.8	1.1	2.0
Turn separation (cm)*	0.7	1.3	1.3	1.8

*uranium acceleration

SC : superconducting, NC : normal conducting, FT : flattop resonator

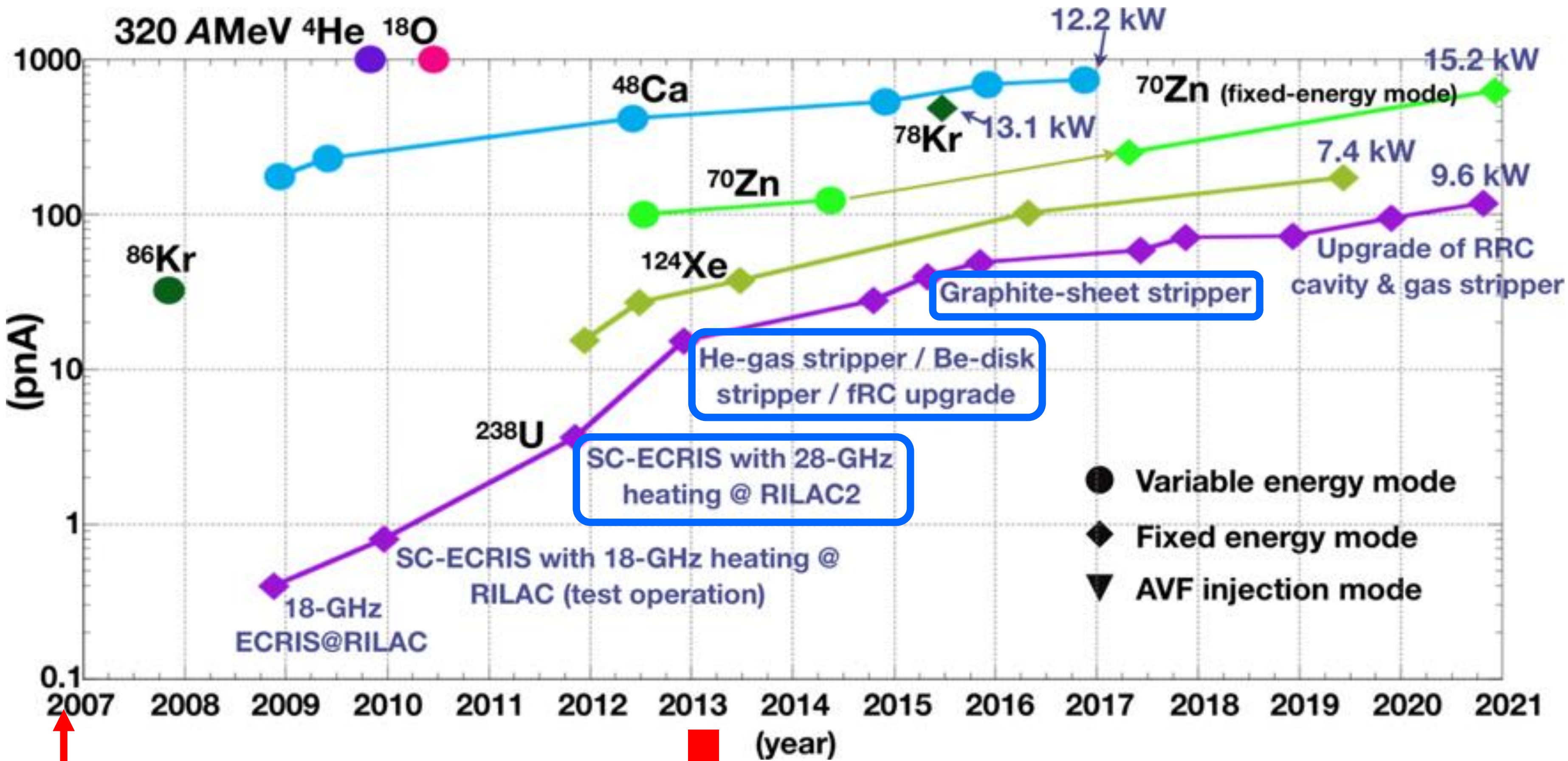




History of accelerator performance

Our goal: 1pμA (6 x 10^{12} #/s) for all elements

^{48}Ca 736 nA → 12.2 kW	^{70}Zn 629 nA → 15.2 kW	^{124}Xe 173 nA → 7.4 kW	^{238}U 117 nA → 9.6 kW

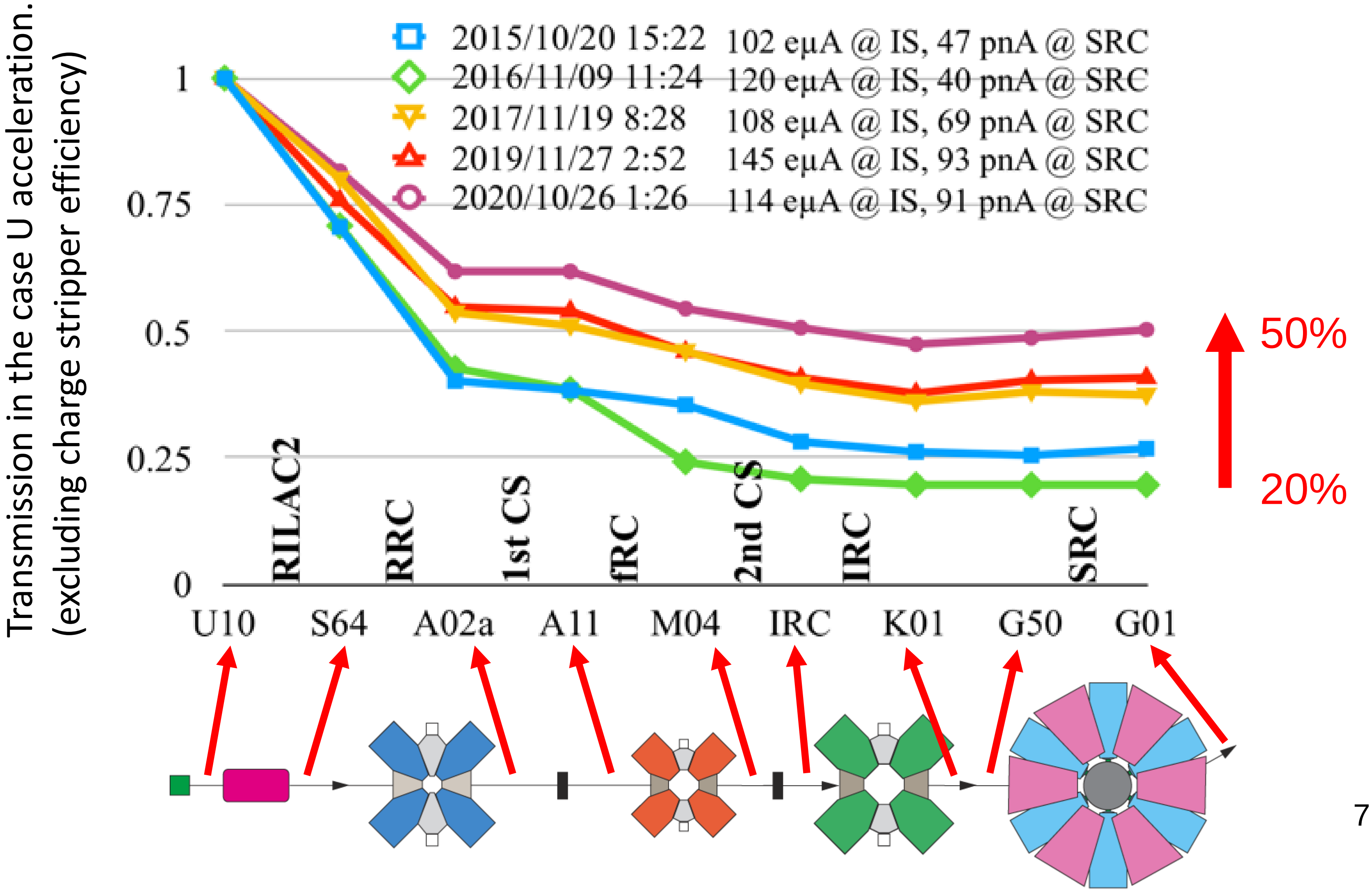


First Beam (2006/12/26)

Availability > 90% (2013~)

Lessons learned from the operational experiences 1

- It is very tough business to operate the accelerator complex where four cyclotrons are connected in series. (Inj./ext. four times, energy matching between the cyclotrons and single turn extraction)



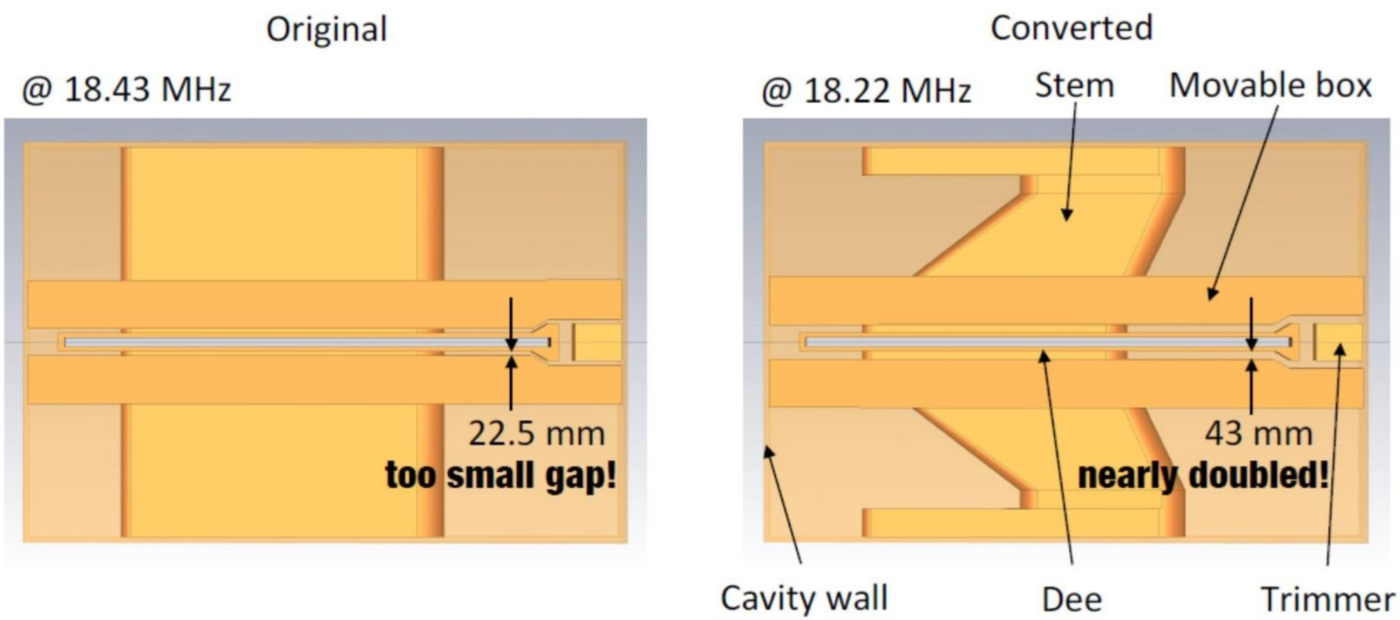
Lessons learned from the operational experiences 2

- **Space charge effect is very intense in the low energy ring cyclotron (RRC)**

(pμA)	RRC	fRC	IRC	SRC
I_lim*	0.7	4.7	6.6	5.1
I_req.	15	3	1	1

*Current limit according to Baartman's paper (Proc. of Cyclotrons2013 WE2PB01.

The RRC cavity was remodeled.



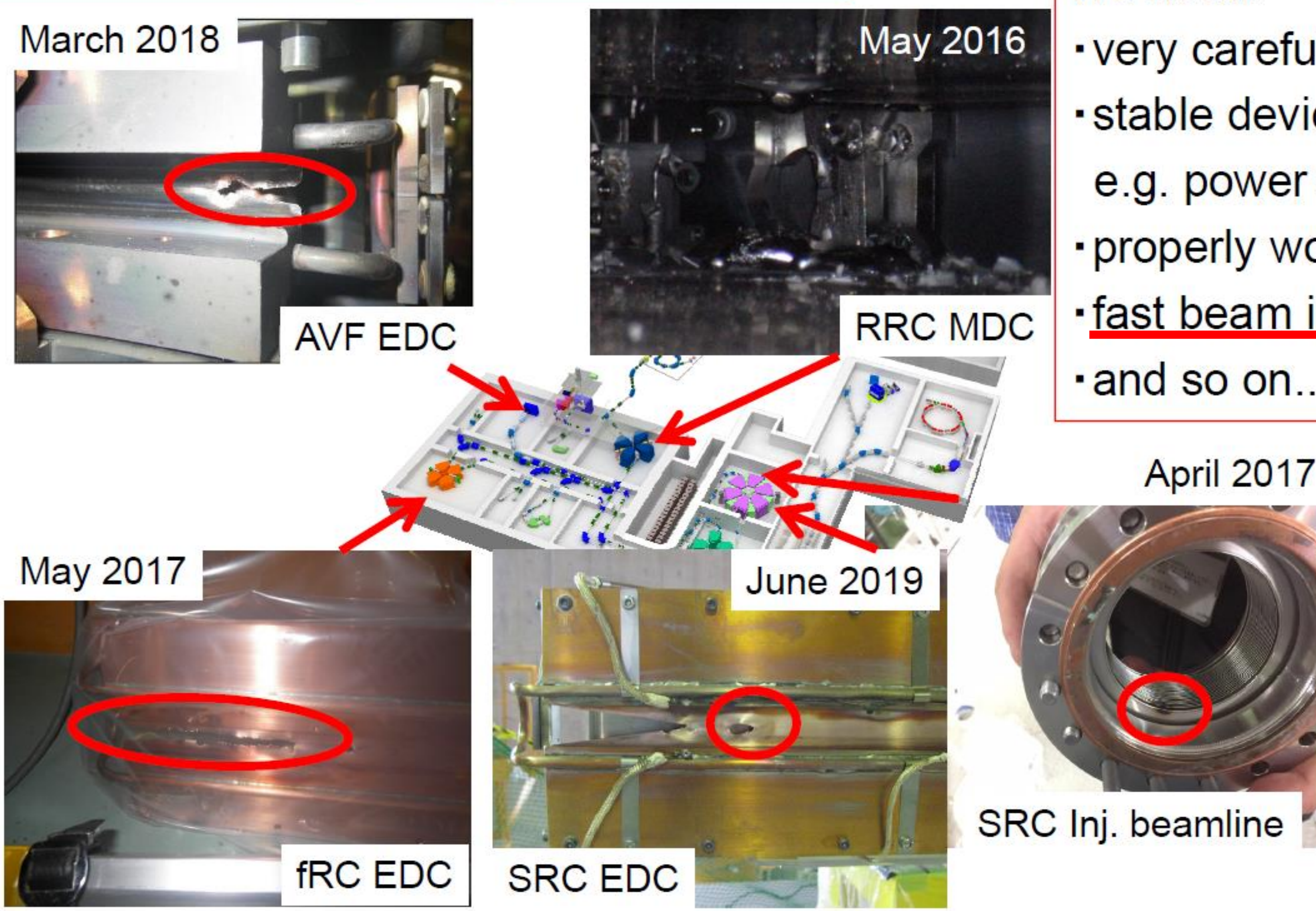
Original		Converted
20 - 46 MHz	RF frequency	16 - 38.8 MHz
61 - 594 kΩ	Shunt Impedance (calc.)	78 - 451 kΩ
48 kΩ @ 18.43 MHz	Shunt Impedance (calc.)	99.4 kΩ @ 18.22 MHz
~90 kV @ 18.25 MHz	RF Peak Voltage	~150 kV @ 18.25 MHz

Working at 120 kV

Lessons learned from the operational experiences 3

- Heavy beams with ~kW power easily give damages the critical parts such as EDCs.
- dE/dx of uranium beam is about 1000 times higher than of that of protons at 11 MeV/u.

Devices damaged by ~kW beams



We need:

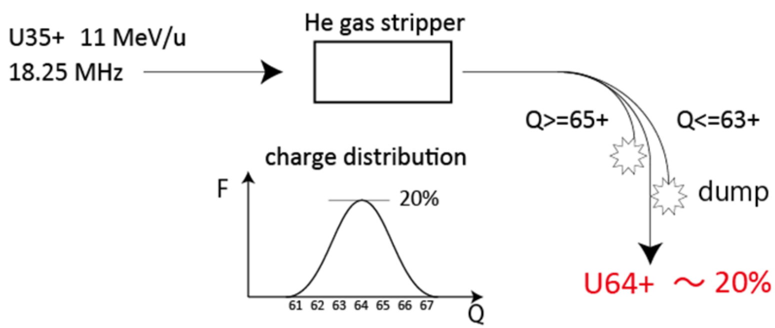
- very careful tuning.
- stable devices
  e.g. power supplies, RF,..
- properly working control system.
- fast beam interlock system.
- and so on..

Lessons learned from the operational experiences 4.

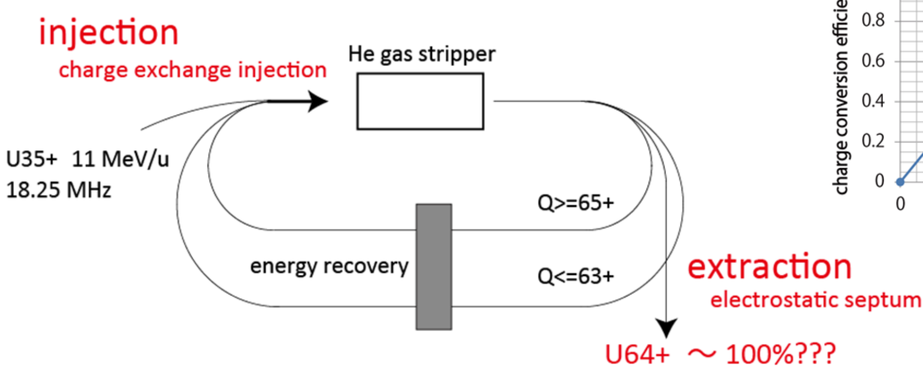
- **Multi-step charge stripping should be avoided, and thickness of the charge stripper should be as thin as possible.**
- **Charge stripper Ring will be installed!**

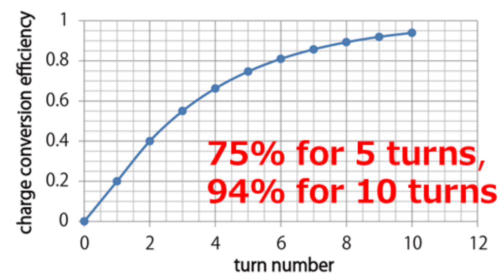
Concept of stripper ring

Present scheme at RIBF (conventional)



Stripper-ring scheme



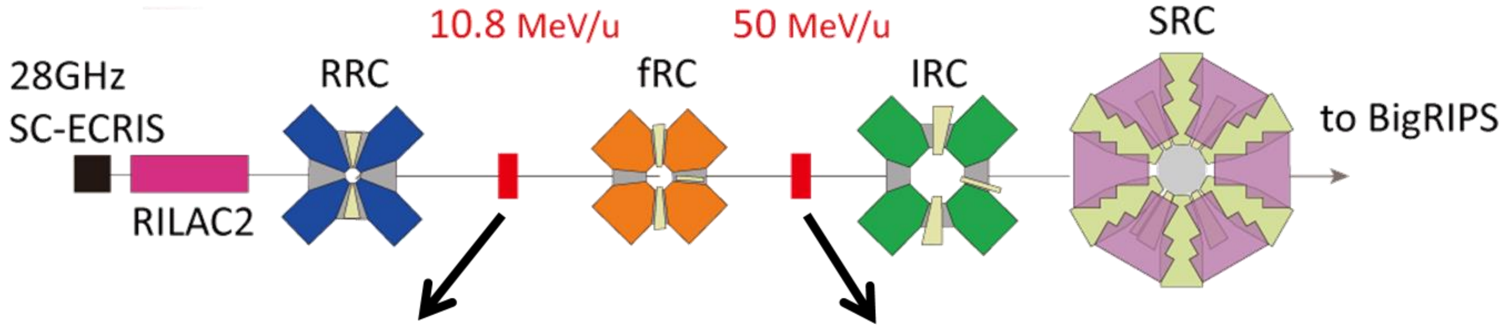


The bunch structure must be preserved to match to acceptance of the subsequent cyclotrons (e.g., 18.25 MHz at RIBF).

H. Imao

Lessons learned from the operational experiences 4

Charge stripper ring (CSR)

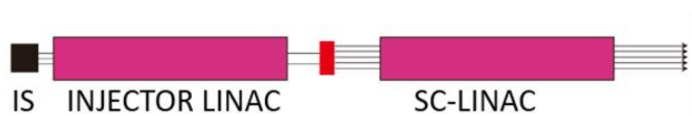


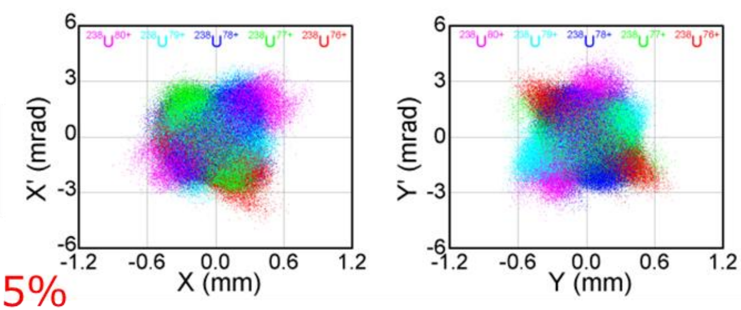
1． He gas stripper
35+⇒64+ (20%)

2． Rotating C-disk stripper
64+⇒86+ (30%)

Total charge conversion efficiency < 6%

FRIB uses multi-charge acc.



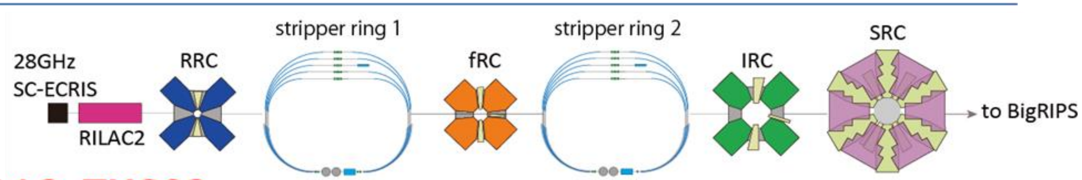


➡ aiming effective efficiency of 85%

Q. Zhao, HB2014

Charge stripper rings

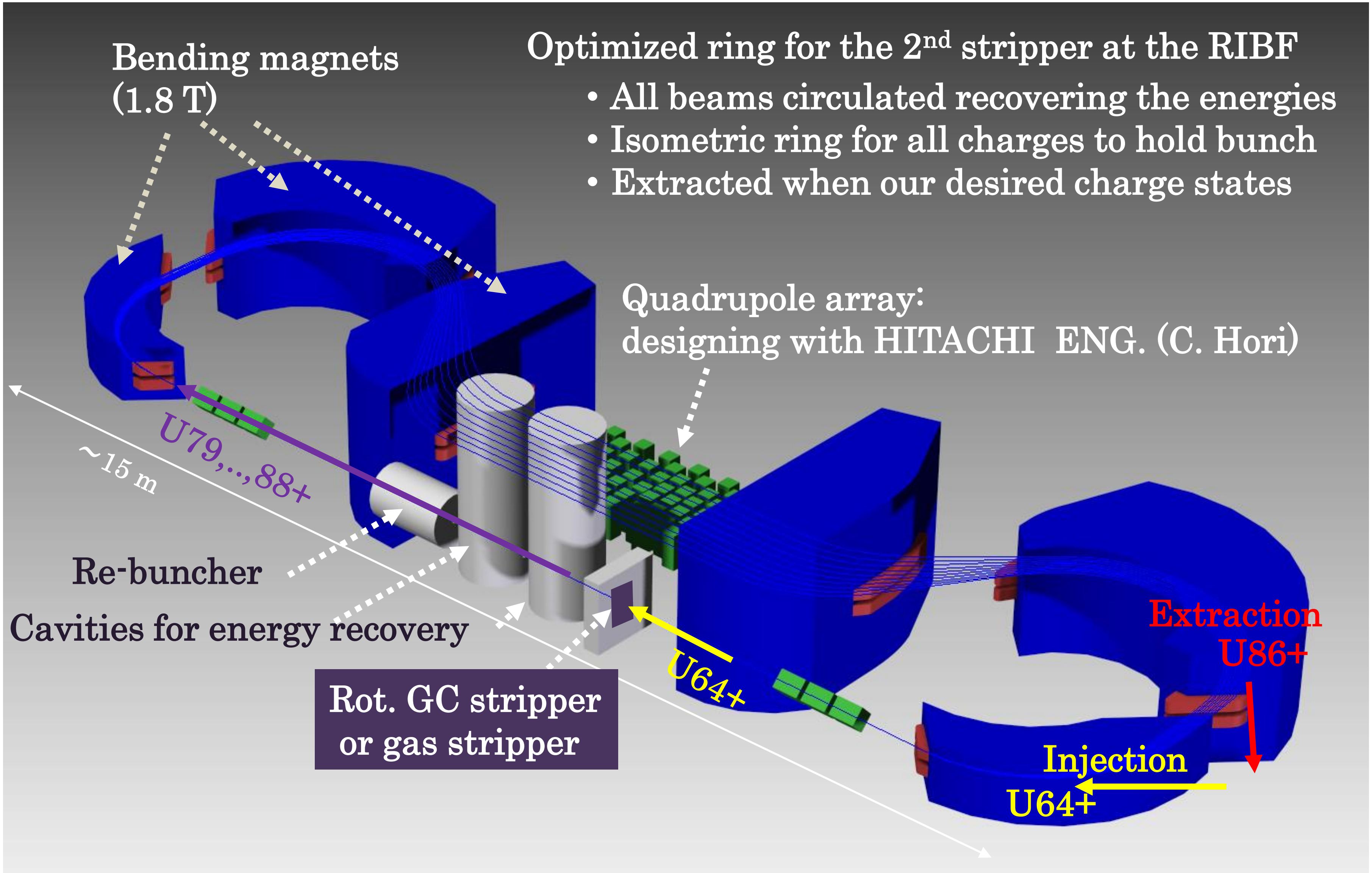
Efficiency ~100%?



H. Imao et al., Cyclotron2016, TUC02

H. Imao

Design of CSR at 50 MeV/u



H. Imao

Summary

- RIBF accelerator complex
  - The most intense heavy ion facility based on cyclotron.
  - Goal: More than 1 pμA of uranium beam with the energy of 345 MeV/u
- Successful operation for 15 years
- Lesson learnt from the operational experiences.
  - It is very tough business to operate the accelerator complex where four cyclotrons are connected in series.
    - **Transmission: 20%→ 50%**
  - Space charge effect is very intense in the RRC
  - Increase the space charge limit in the low energy cyclotron of RRC
    - **Remodel of the RRC cavity to get higher voltage**
  - kW heavy ion beam easily gives a damage to the critical parts such as EDC.
    - **We should develop fact beam interlock system for machine protection.**
  - Multi-step charge stripping should be avoided, and thickness of the charge stripper should be as thin as possible.
    - **Charge stripper Ring will be installed.**