High Beam Power Operations at RIKEN RIBF

Technical Developments, Challenges and Resolutions

1) Overview of RIKEN RIBF
2) Technical developments
3) Present status
4) Future plan

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on behalf of

Accelerator Group

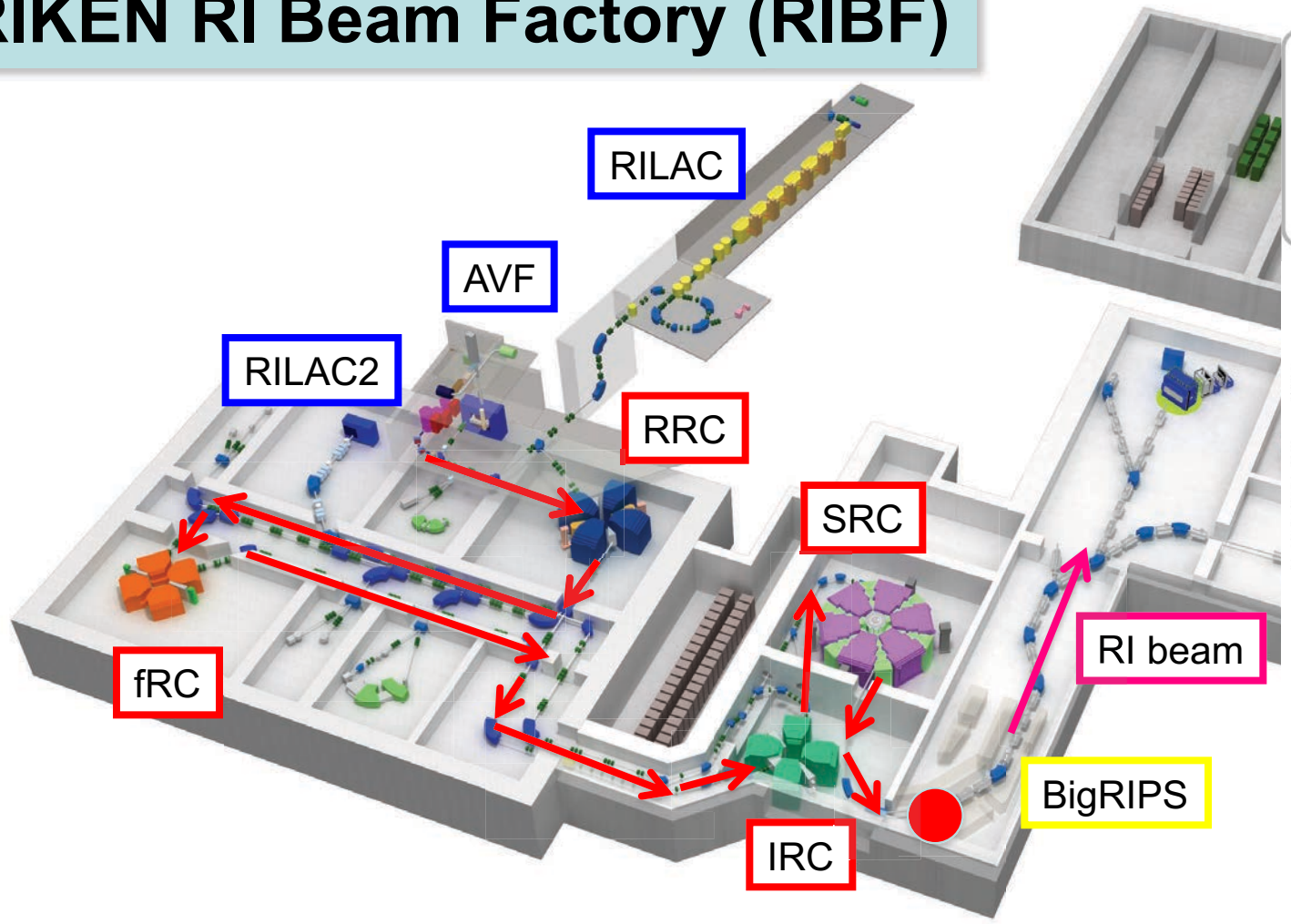
RIKEN Nishina Center for Accelerator-Based Science

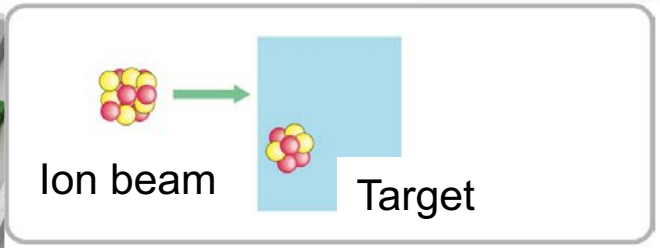
HIAT 2022 | Darmstadt

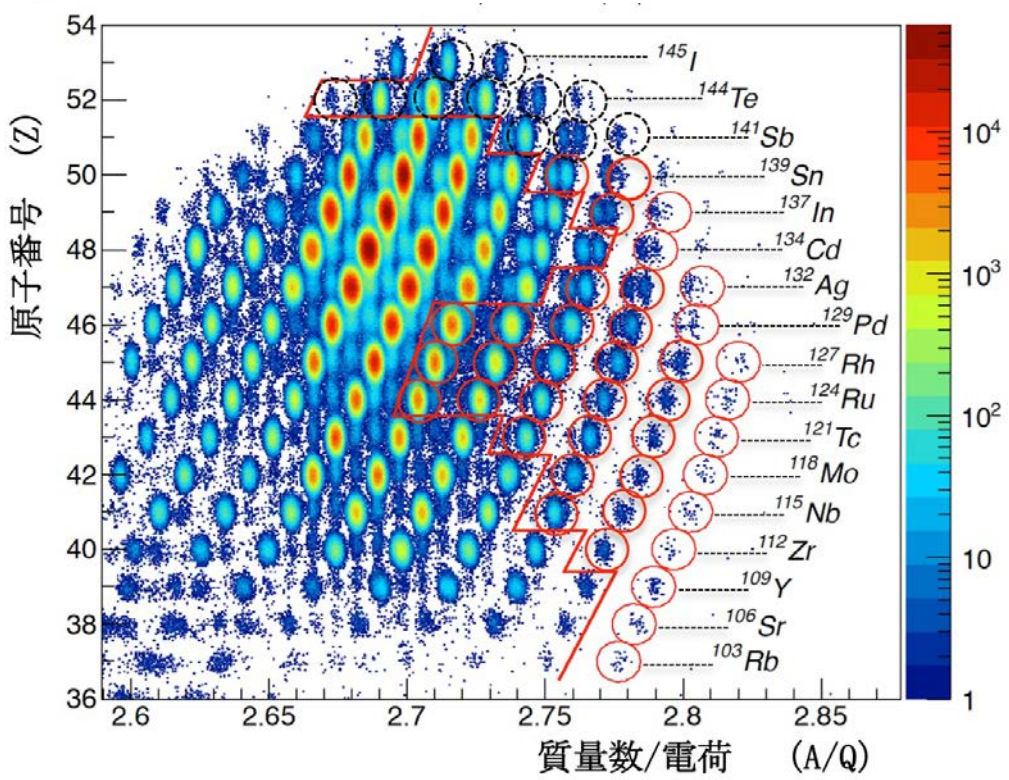
1) Overview of RIKEN RIBF

RIKEN RI Beam Factory (RIBF)

Y. Yano, NIM B261 (2007) 1009.







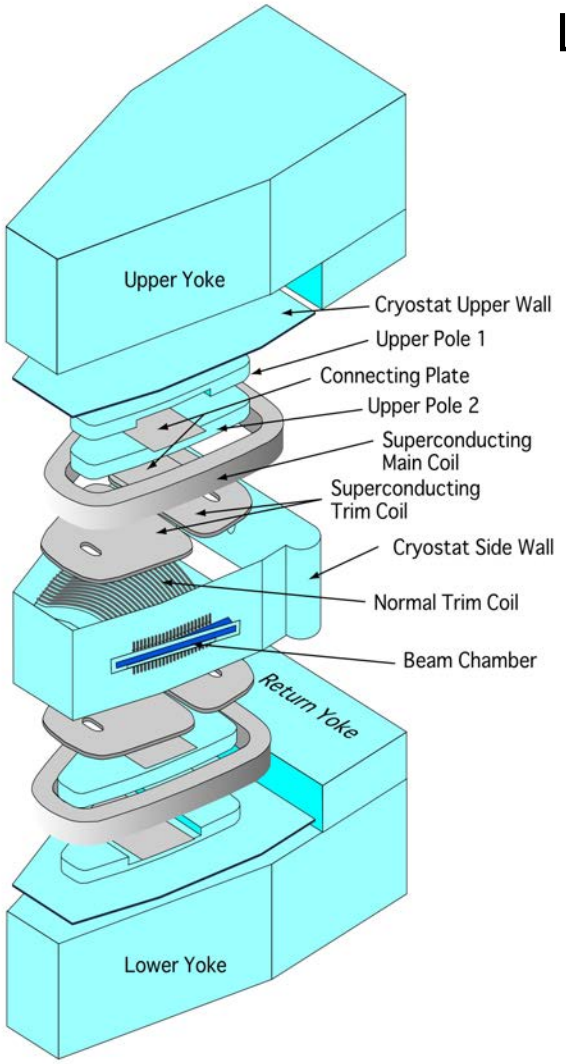
3 Injectors + 4 Booster cyclotrons + RI Beam separator capable of

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

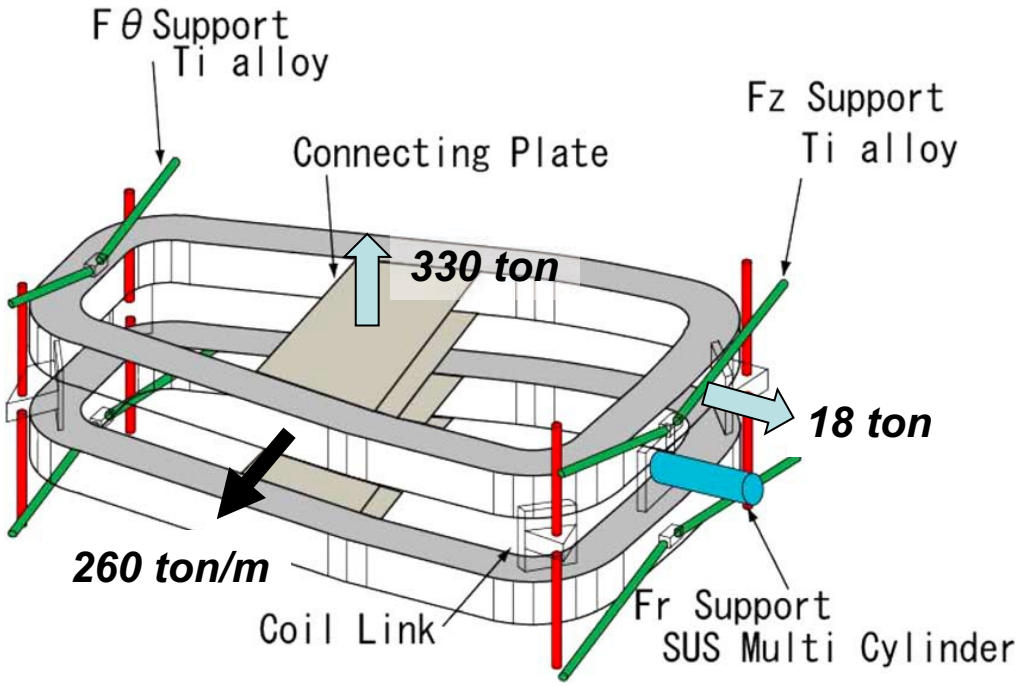
The biggest challenge: SRC
(Superconducting Ring Cyclotron)

H. Okuno et al., IEEE Trans. Applied Superconductivity, 17 (2007) 1063.

Number of sectors	6
Pole Gap	714 mm (max)
Max. magnetic field	3.8 T
Main coil current	5,000 A
Main coil turn number	396 × 2/sector
Number of trim coils	4(SC)+22(NC)
Power consumption	620 W @4.5K
	4000 W @70K
(total)	1,100 kW @RT
Stored energy	240 MJ



Large magnetic force on the cold mass



First beam: Dec.28, 2006

World's first superconduting RING cyclotron

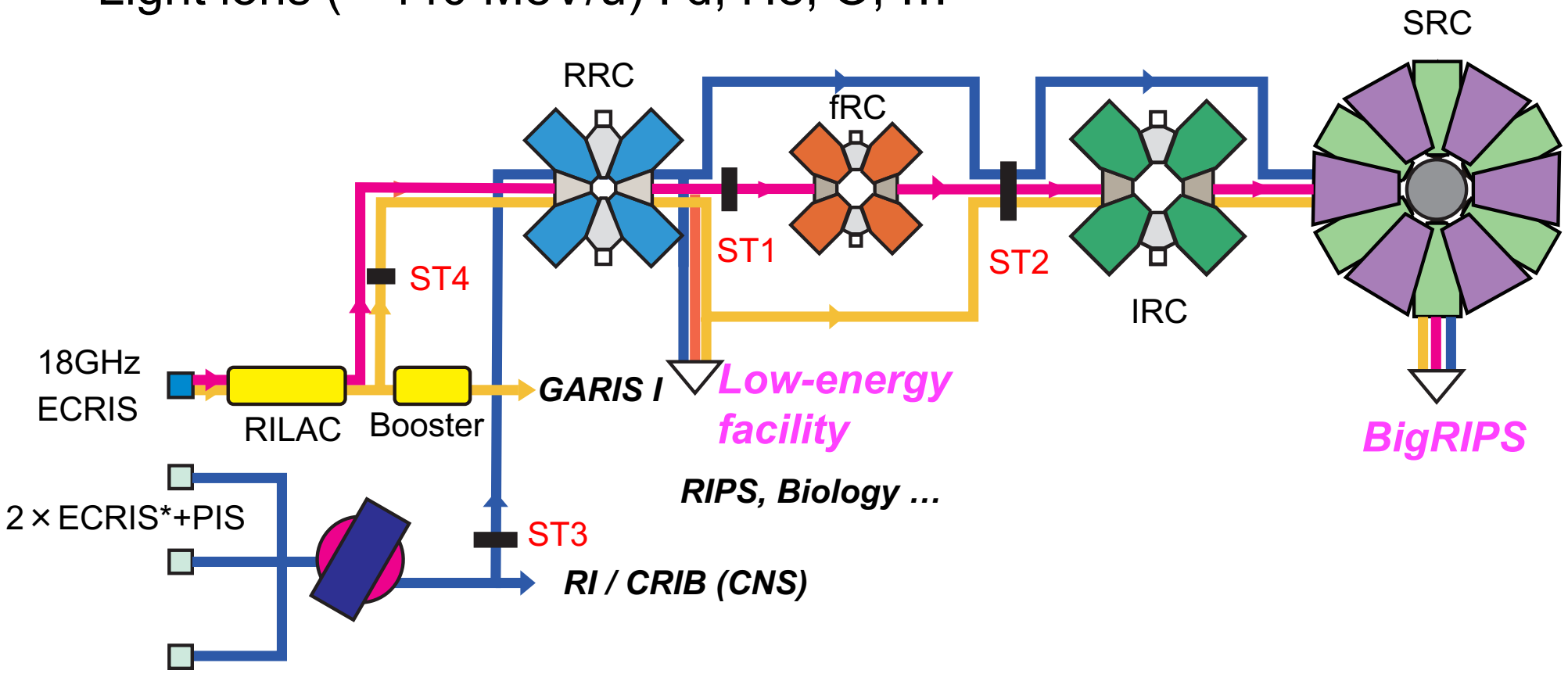
B_{max}= 3.8 T, K = 2,600 MeV

Voltage gain = 640 MV (cw)

Total weight = 8,300 tons

Accelerator complex in 2007 (when RIBF started.)

- Very heavy ions (345 MeV/u) : Xe, U
- Medium-mass ions (< 400 MeV/u) : Ar, Ca, …
- Light ions (< 440 MeV/u) : d, He, O, …

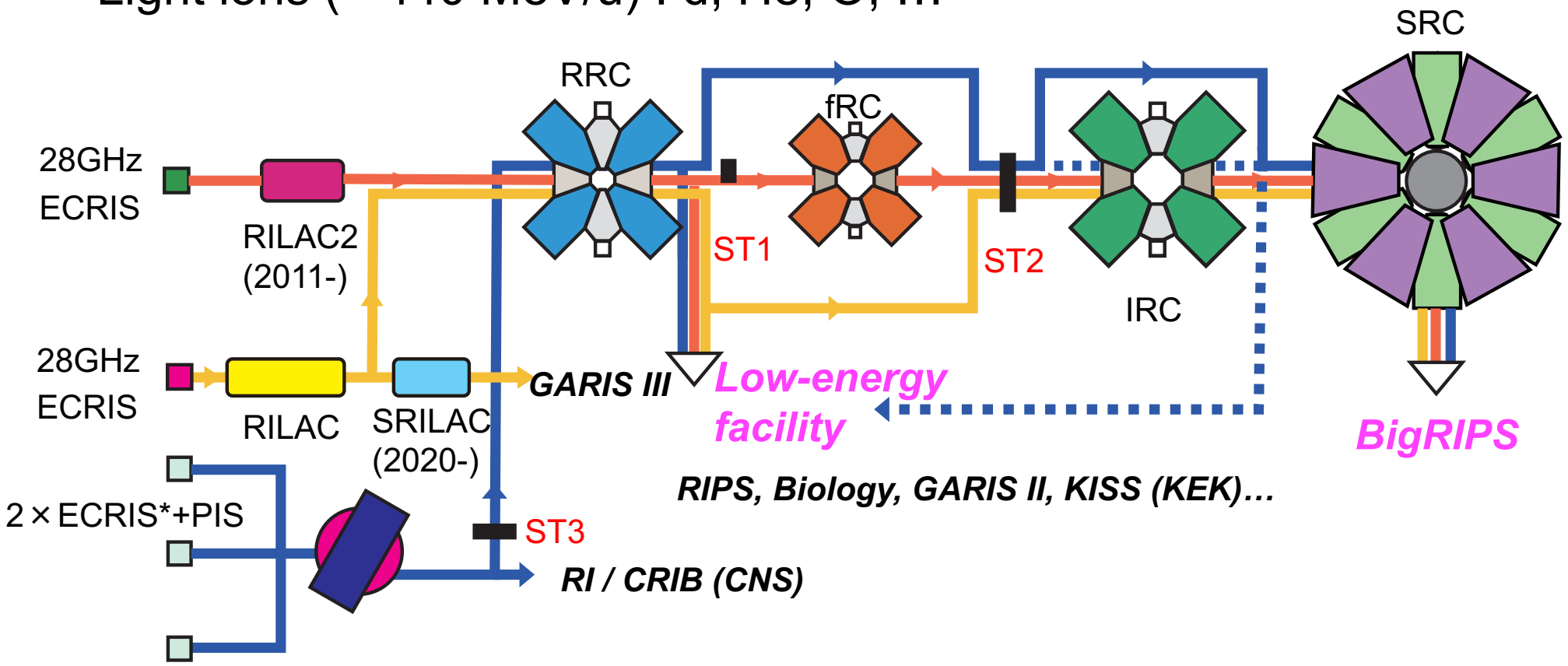


*one is operated by CNS, UTokyo

STn: charge stripper

Accelerator complex in 2022 (now)

- ~~Very~~ Heavy ions (345 MeV/u) : Zn, Kr (ST2 only), Xe, U (ST1+ST2)
- Medium-mass ions (< 400 MeV/u) : Ar, Ca, …
- Light ions (< 440 MeV/u) : d, He, O, …



*one is operated by CNS, UTokyo

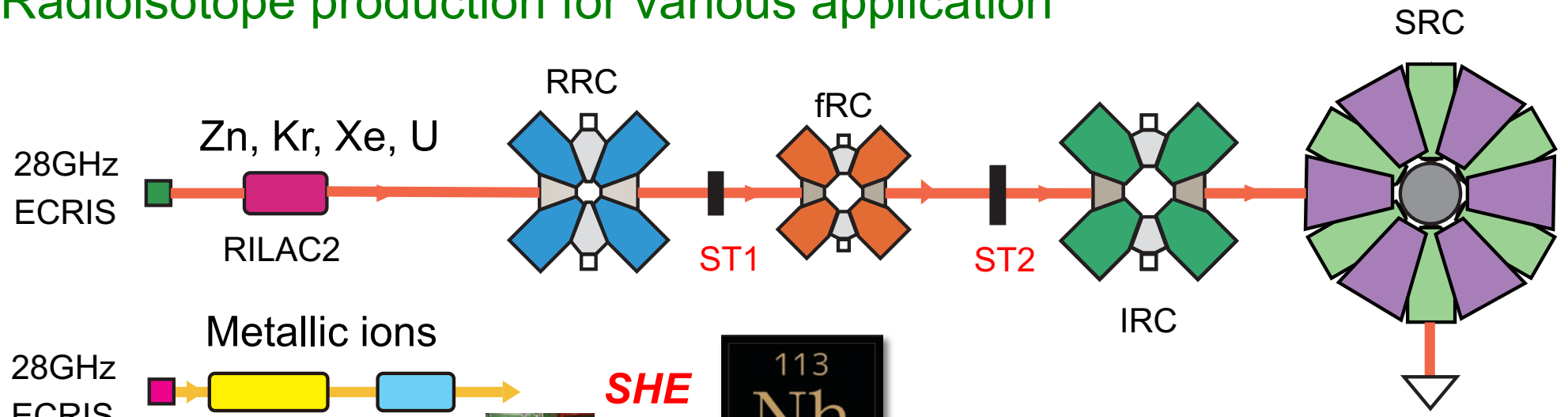
STn: charge stripper

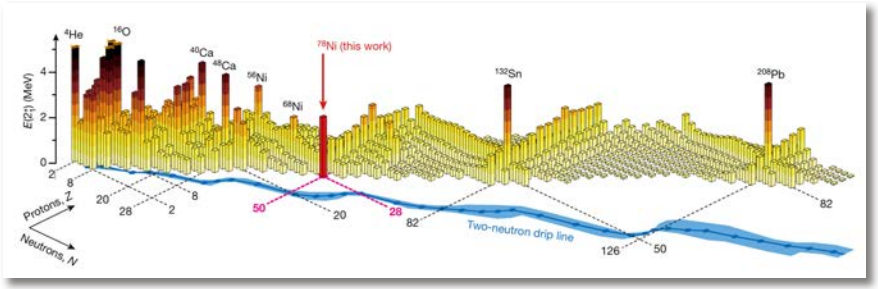
Independent operation

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

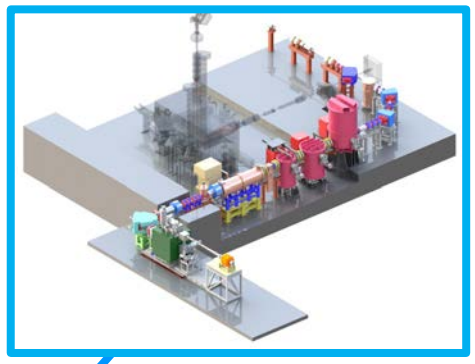
+ Super-Heavy Element research

+ Radioisotope production for various application





R&D for improving beam intensity & stability of *uranium* beam



RILAC2

28GHz SC-ECRIS

SRC

fRC

RRC

ST1

ST2

IRC

Uranium beam

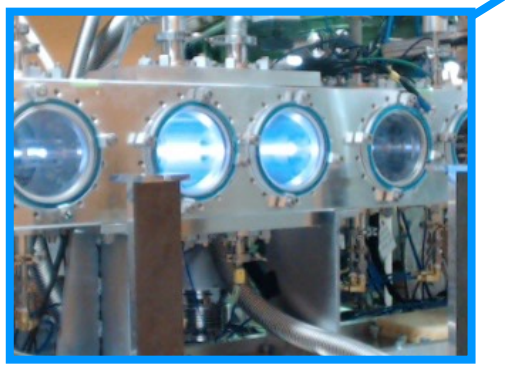
35+

64+

86+

BigRIPS

345 MeV/u



Two stripping stages

Helium gas stripper @ 11 MeV/u

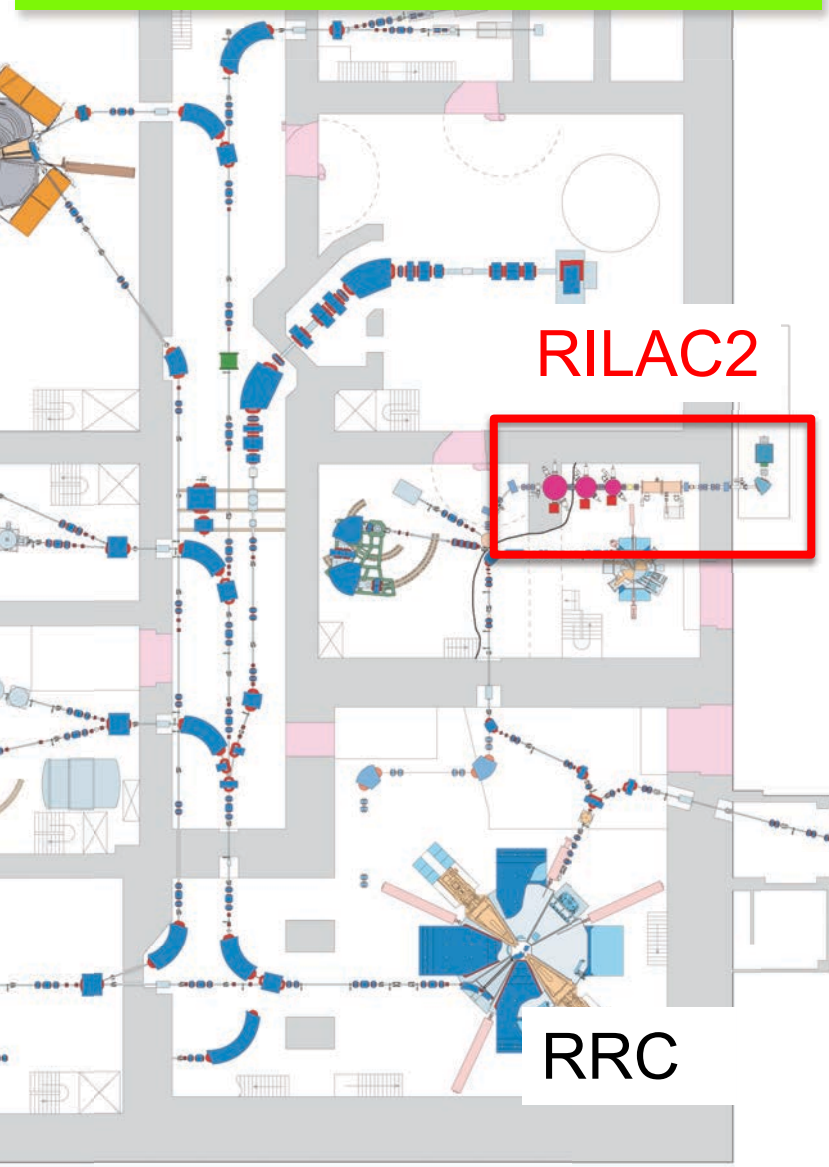
Graphite sheet stripper @ 50 MeV/u

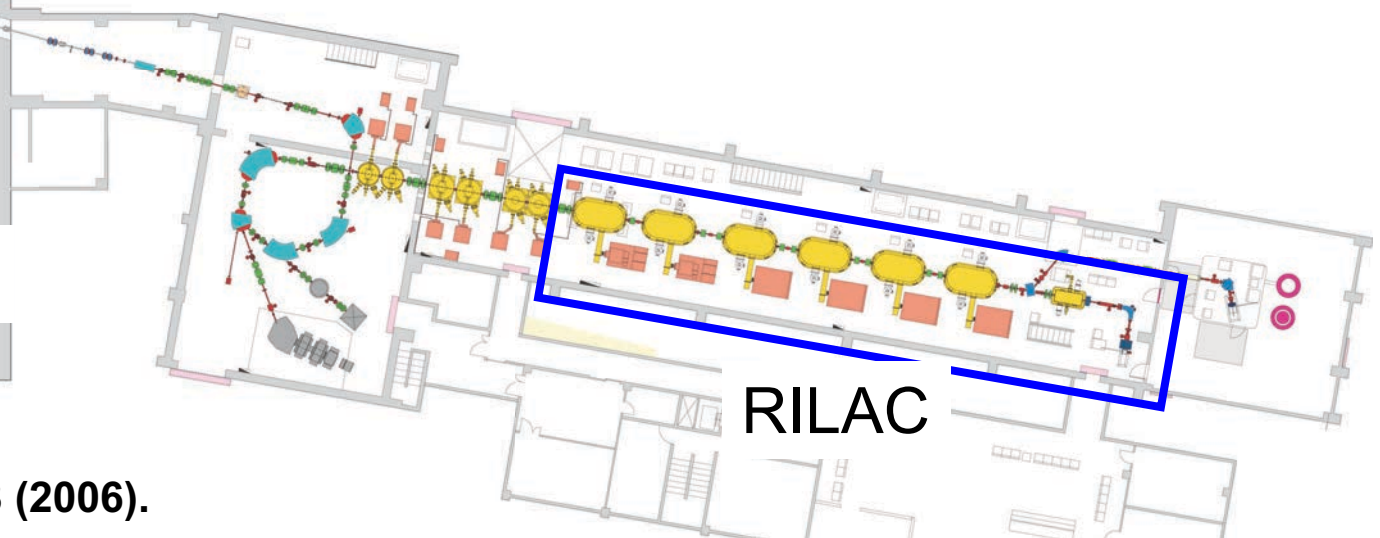
2) Technical developments

New injector: RILAC2

• 2005: Design study started

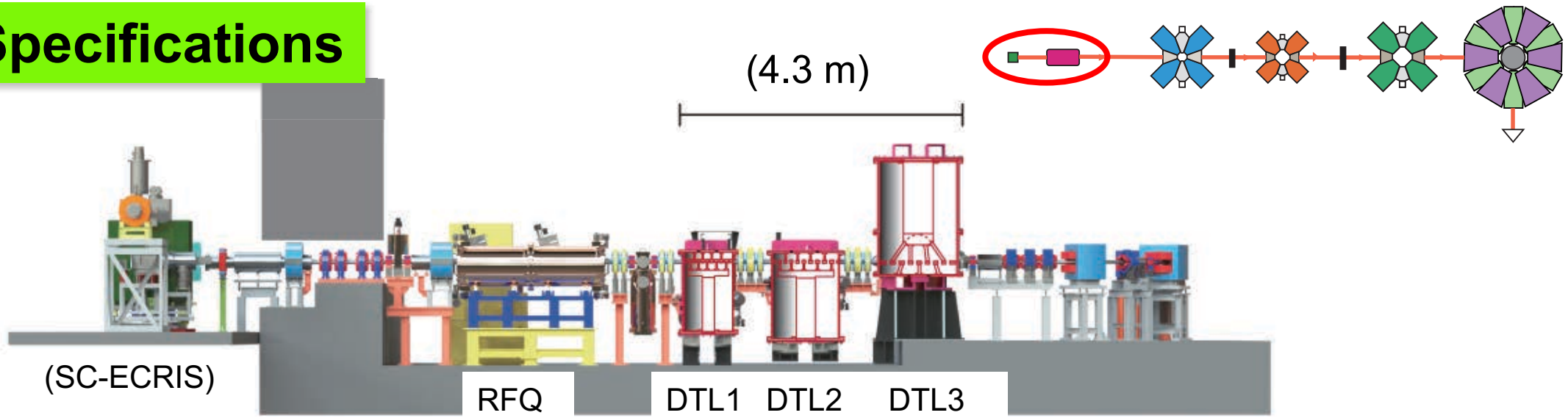
	RILAC	RILAC2
Frequency	18 – 38 MHz	36.5 MHz
Voltage	16 MV	4.7 MV
Max. M/q	26 - 6	6.8
Dist. from RRC	~ 77 m	~ 36 m
RF cavities	RFQ+6DTL	RFQ+3DTL
Vacuum (Pa)	10^{-5} ~ 10^{-4}	10^{-6} ~ 10^{-5}
Ion source	NC 18GHz	SC 28GHz





O. K. et al., PASJ4 & LAM31, WP78 (2006).

RILAC2 Specifications



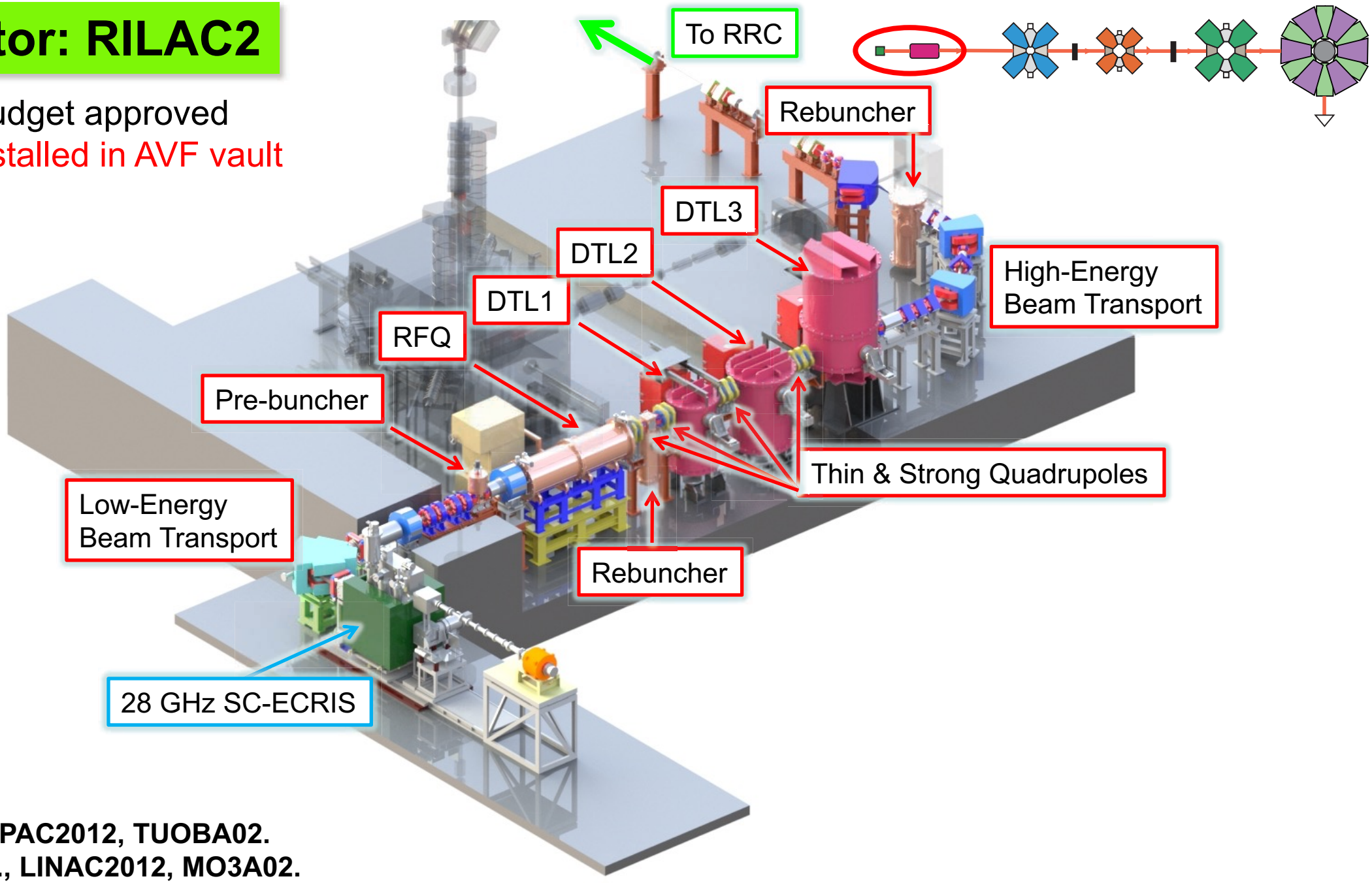
	RFQ	DTL1	DTL2	DTL3
Freq. (MHz)	36.5			
Duty (%)	100			
M/q	6.8			
Ein/Eout (keV/u)	3.3/100	100/220	220/450	450/670
Cell No.	(93)	10	10	8
Gap Voltage (kV)	42	110	210	260
Power (kW)	***18***	***7***	***13***	***20***

Modest rf-power consumption

K. Yamada et al., IPAC2012, TUOBA02.
N. Sakamoto et al., LINAC2012, MO3A02.
K. Suda et al., NIM A 722 (2013) 55.

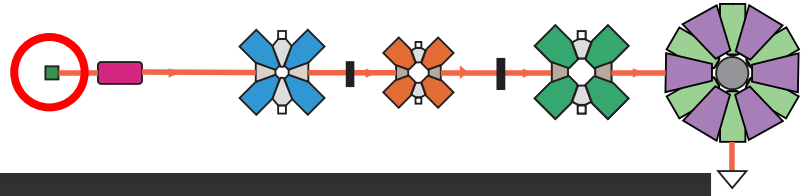
New injector: RILAC2

- Dec. 2008: Budget approved
- Mar. 2010: Installed in AVF vault

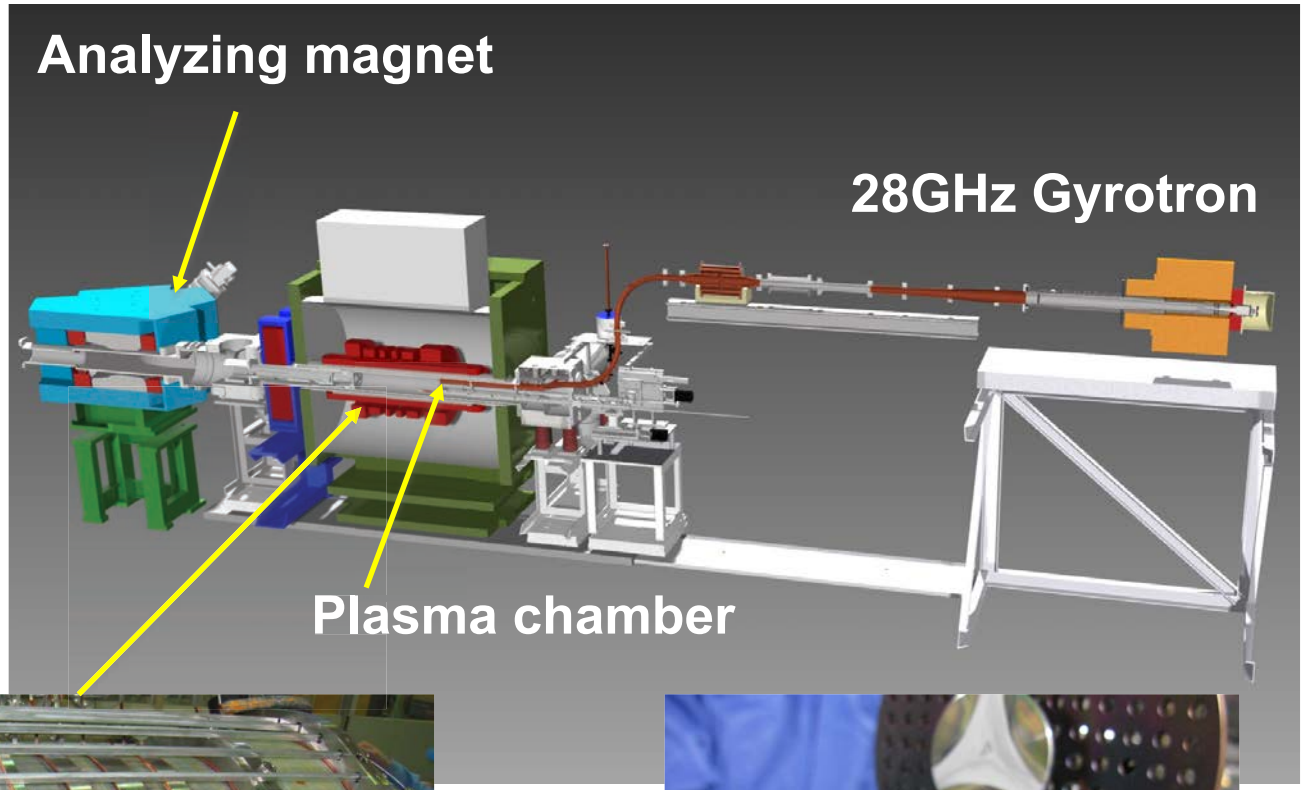


K. Yamada et al., IPAC2012, TUOBA02.
N. Sakamoto et al., LINAC2012, MO3A02.
K. Suda et al., NIM A 722 (2013) 55.

28GHz ECR ion source



Completed in 2008.
Installed at RILAC2 in 2010.

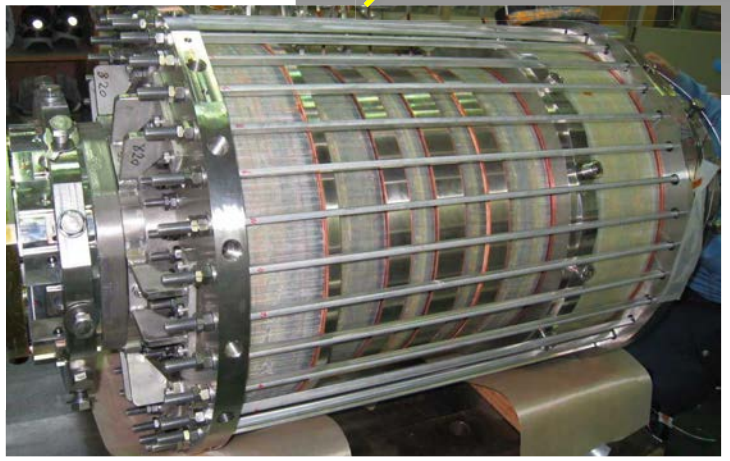


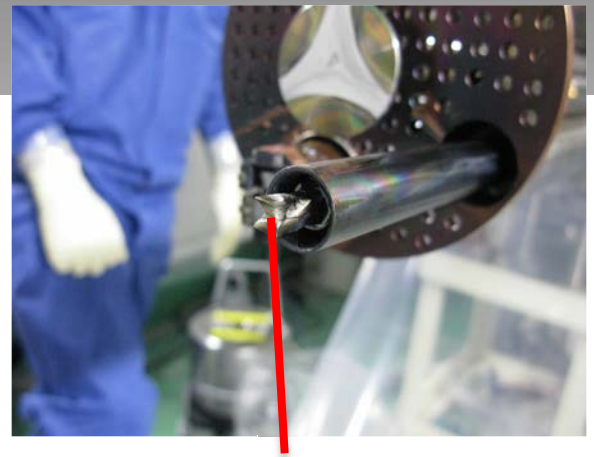
SC sextupole + SC solenoid

Stored Energy : 0.8MJ

NbTi-copper conductor

Bath-cooled in liquid helium

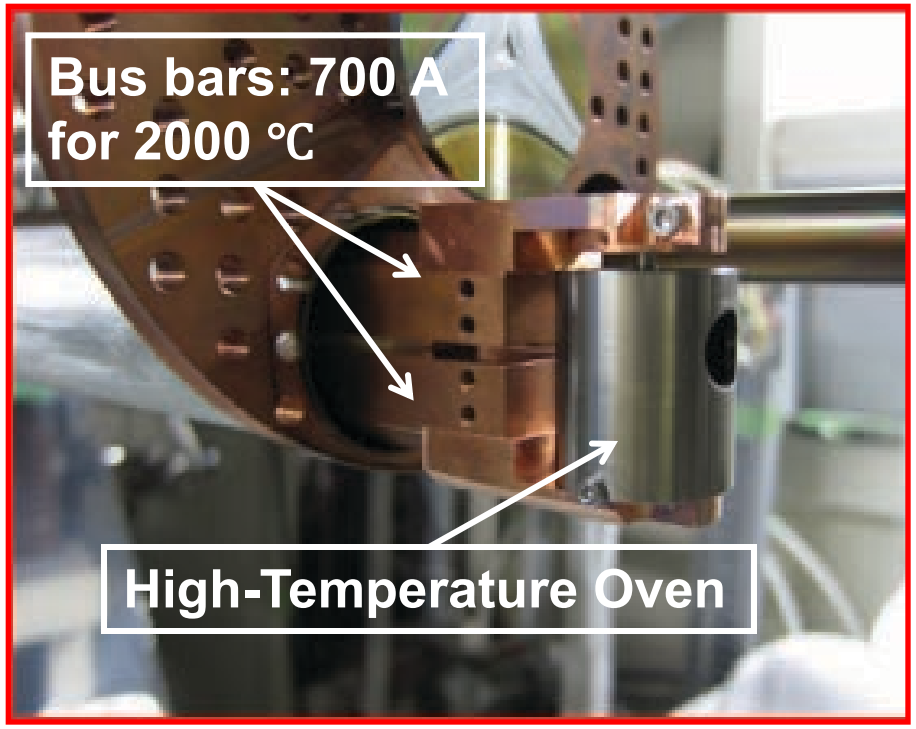


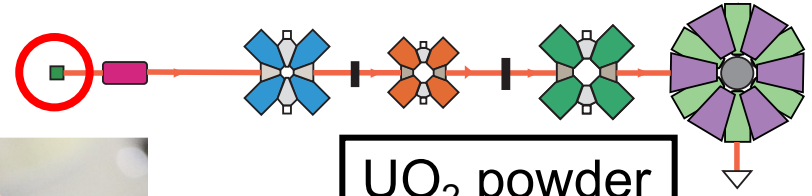


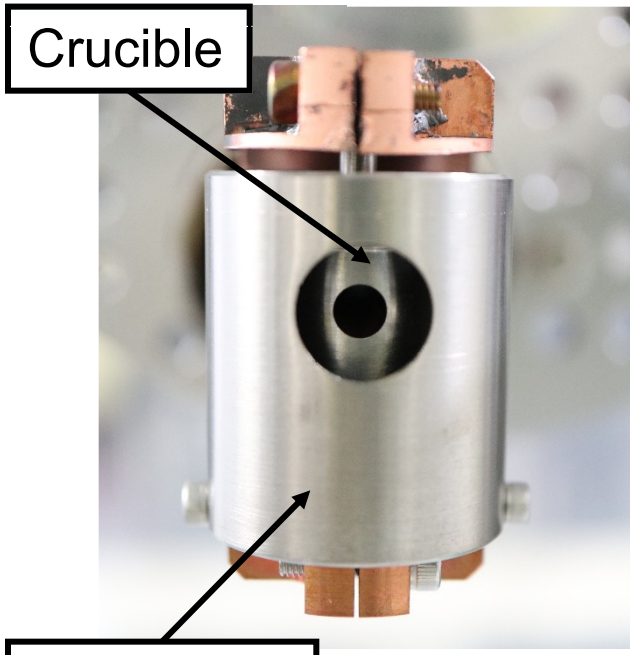
Uranium rod (until 2016)

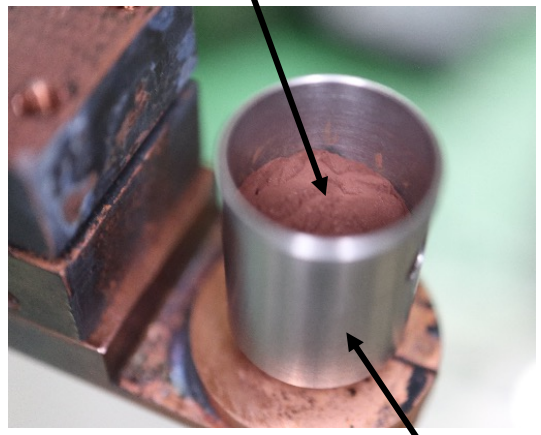
T. Nakagawa et al., RSI 79 (2008) 02A327.

High temperature oven for 28GHz ECRIS



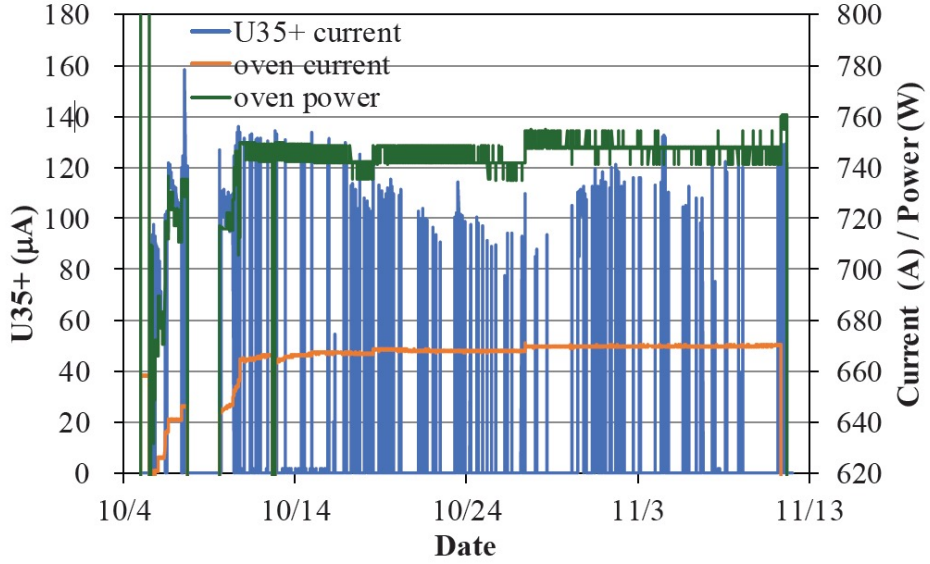






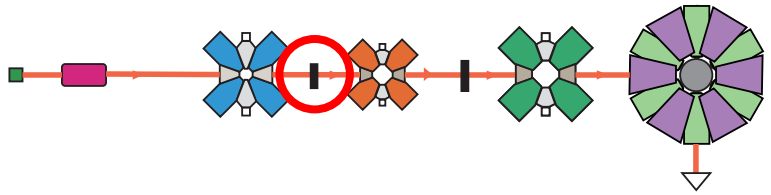
- The High-Temperature Oven method has been used since 2016.
- Average beam current of U35+

→100 − 120 micro-A @ ion source.



J. Ohnishi et al., ECRIS'18, WEB4

Charge strippers before 2011



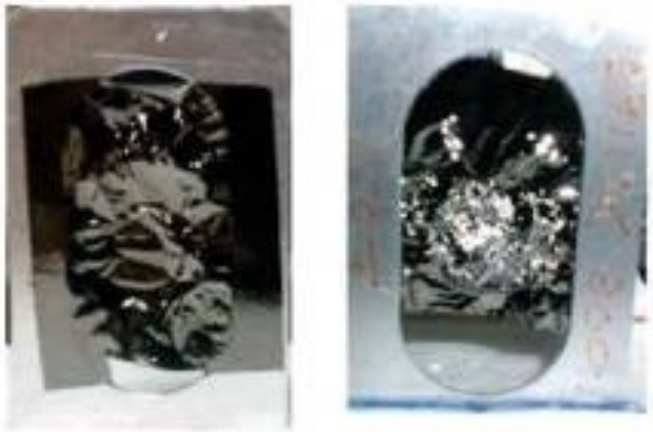
1st Stripper at 11 MeV/u, U35+ → U71+

thickness non-uniformity, poor thermal conductivity

→ Principal bottleneck of uranium acceleration

~ 2009: Carbon-foil

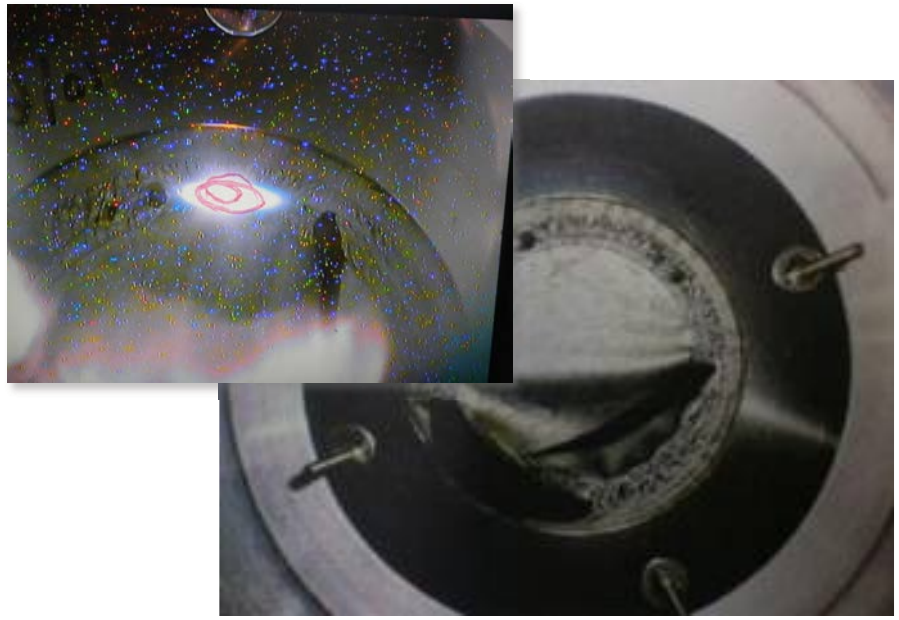
Thickness: less than 2 μm



Lifetime:
<12 hours @ 0.03 pμA...

2011: Rotating CNT-foil

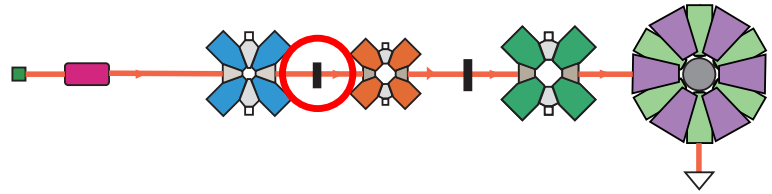
Lifetime:
< 100 hours @ 0.3 pμA



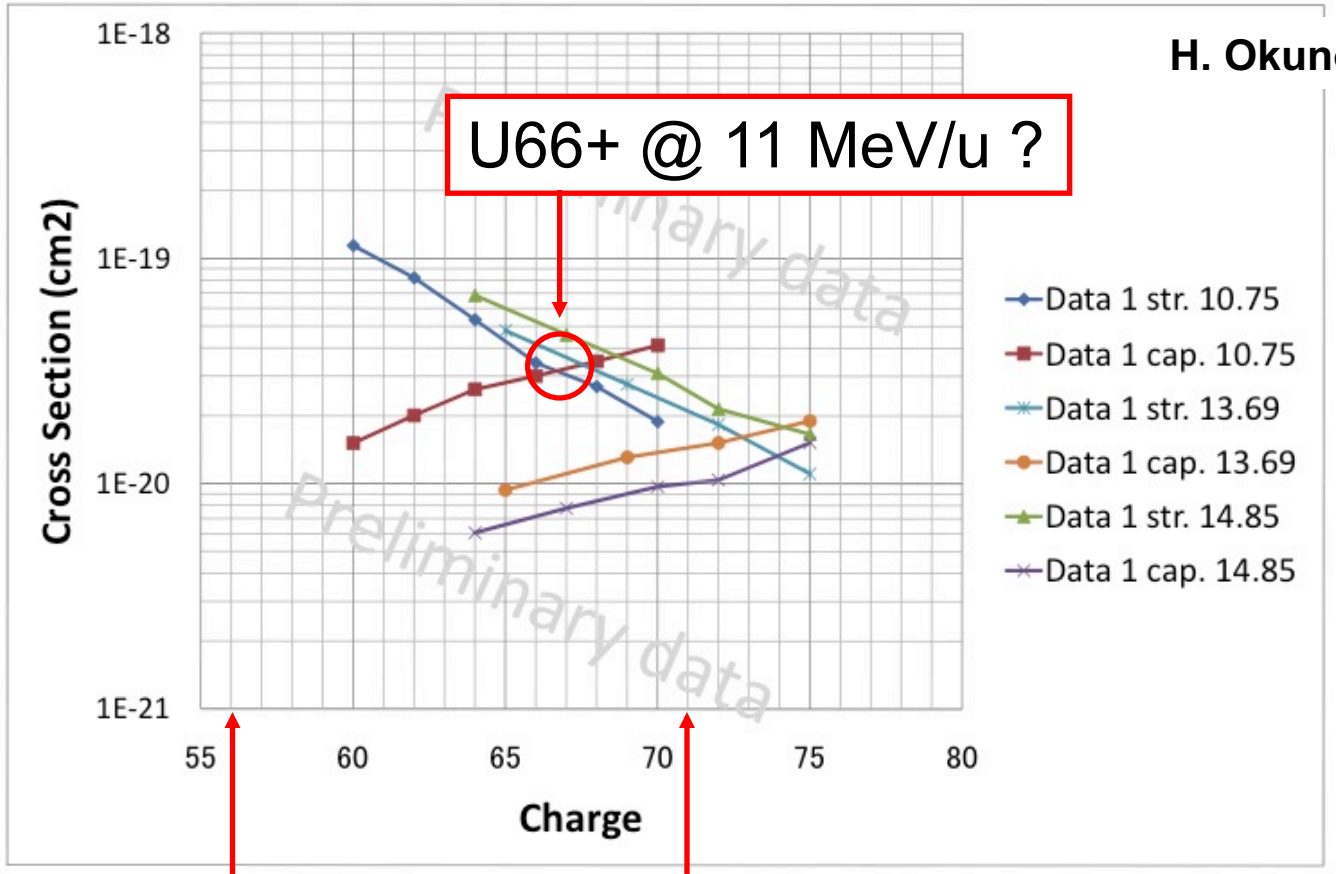
Goal : 5 pμA ...

Equilibrium charge state was too low in N_2 gas.. (56+)

High equilibrium charge state in helium gas



Cross sections electron stripping and capture by U were measured in helium gas.



H. Okuno et al, Phys. Rev. ST Accel. Beams 14 (2011) 033503.

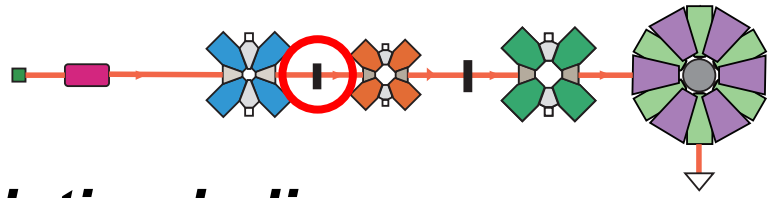
Issue:
How to store helium gas in beamline without window?

Eq. charge state in N_2:
U56+ @ 11 MeV/u

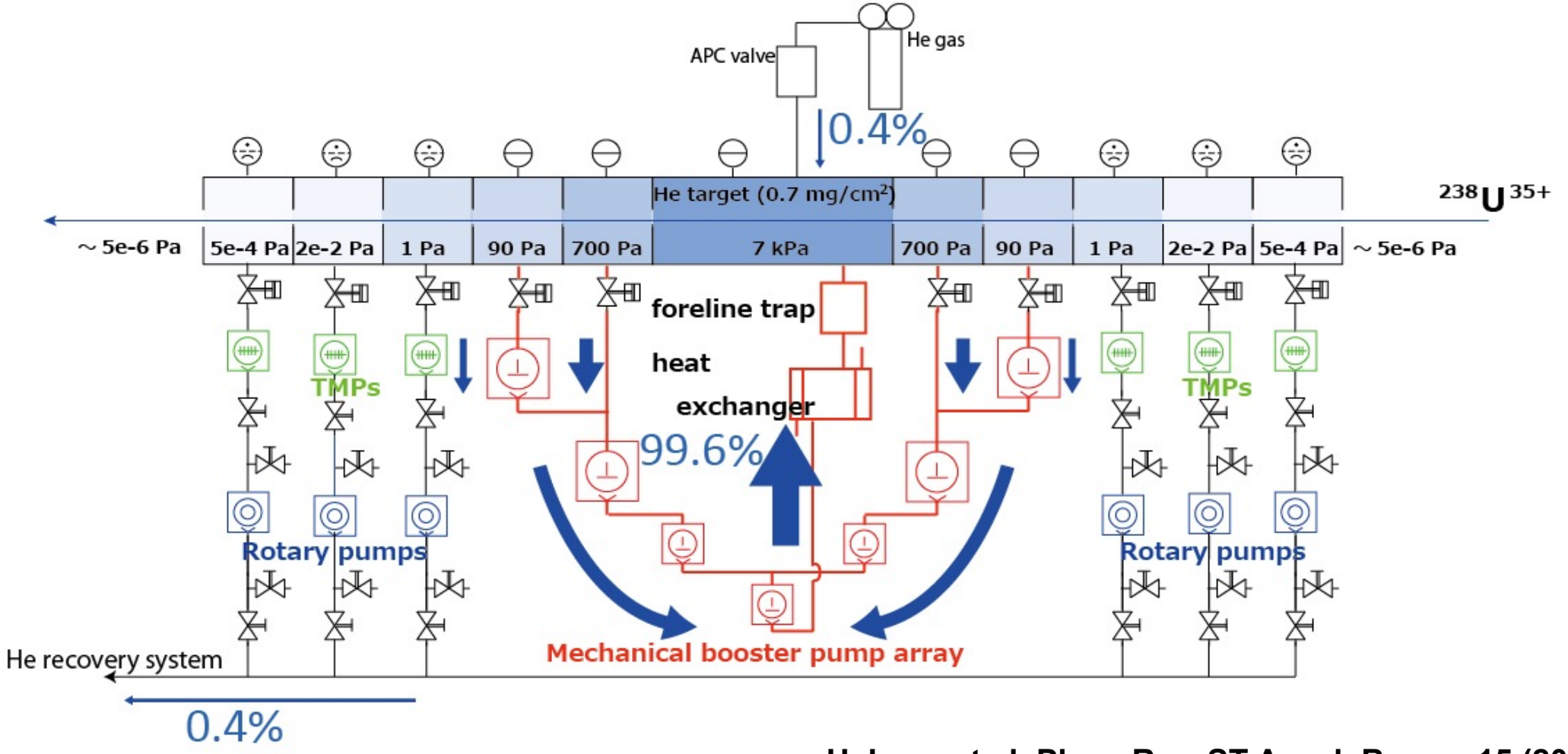
Acceptable with fRC: U69+

The power supply for the main coil of fRC was reinforced and the injection magnets were renewed to accept U64+.

Window-less helium gas stripper @ 11 MeV/u

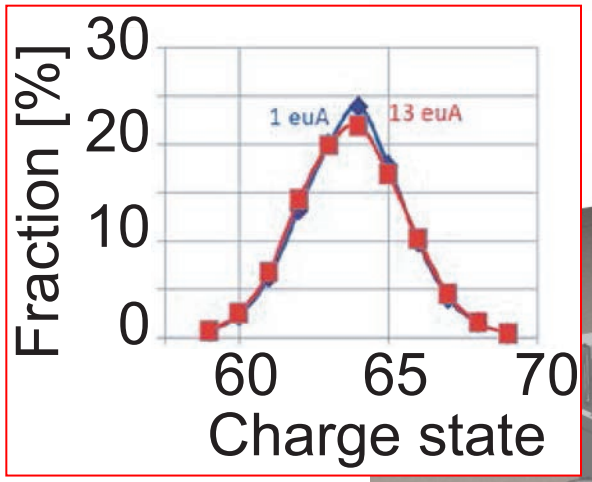


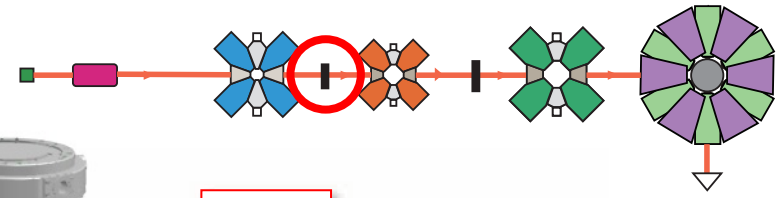
Five-stage differential pumping system recirculating helium gas

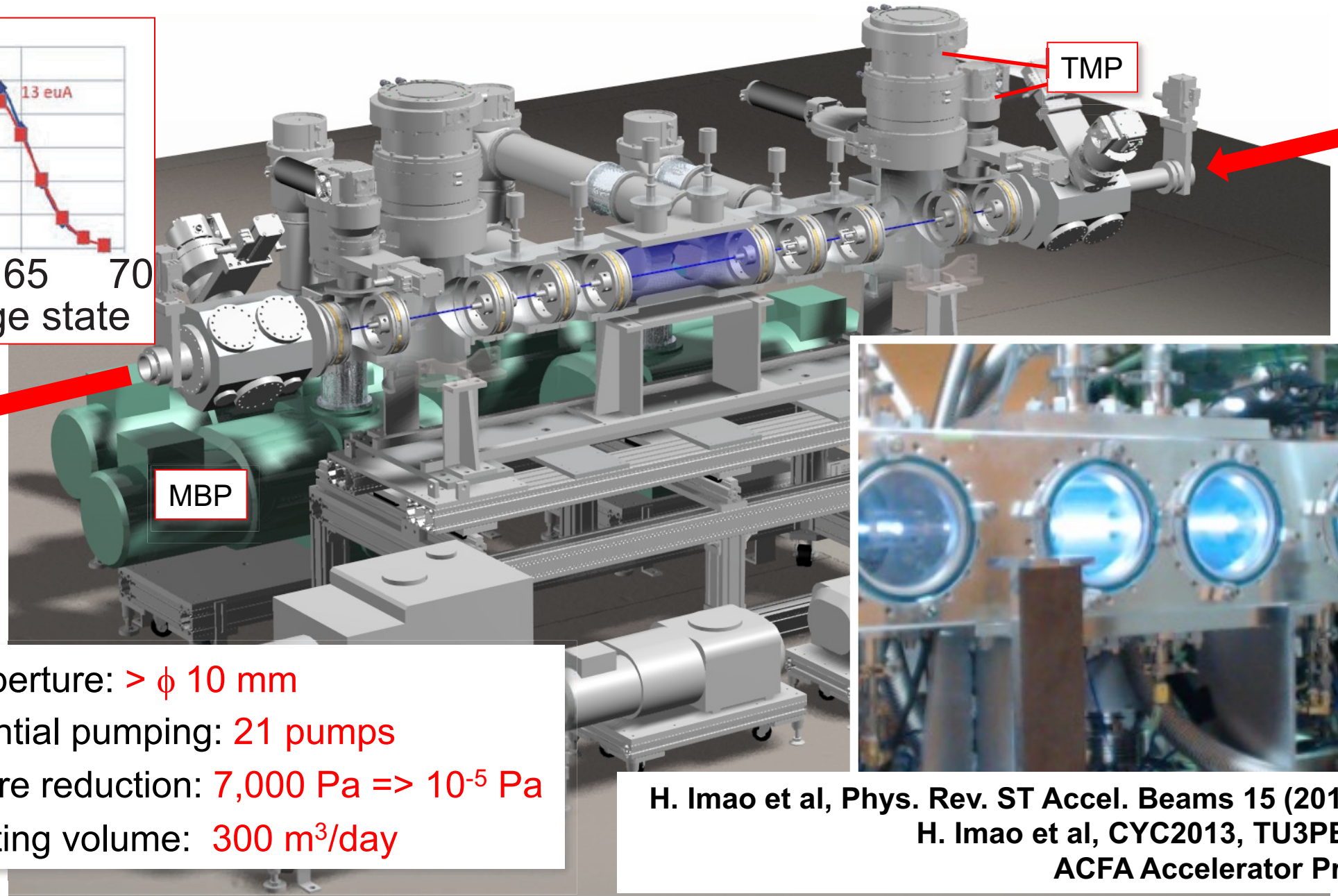


H. Imao et al, Phys. Rev. ST Accel. Beams 15 (2012) 123501.
H. Imao et al, CYC2013, TU3PB03 (2013).
ACFA Accelerator Prize (2013).

Window-less helium gas stripper @ 11 MeV/u







Large beam aperture: > ϕ 10 mm

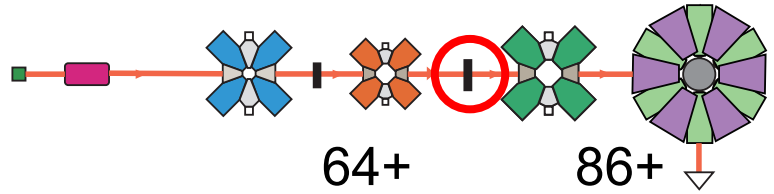
5 stage differential pumping: 21 pumps

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

Helium circulating volume: 300 m^3/day

H. Imao et al, Phys. Rev. ST Accel. Beams 15 (2012) 123501.
H. Imao et al, CYC2013, TU3PB03 (2013).
ACFA Accelerator Prize (2013).

2nd stripper for uranium @ 50 MeV/u



~2011: Carbon

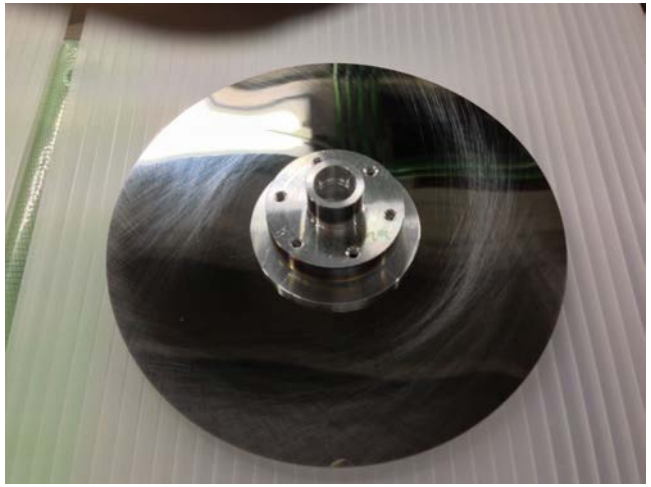
18 mg/cm^2

Lifetime: 9 hours@2 euA

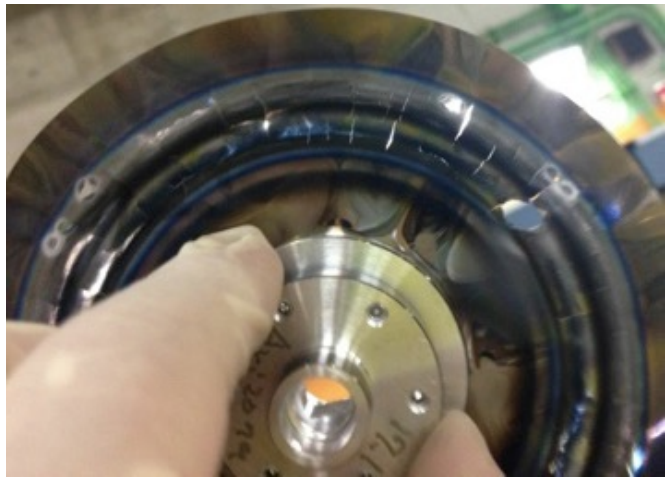
Limit: 7×10^{15} ions

2012~2014: Rotating beryllium disk

18 mg/cm^2 70 W loss @ 60 pnA



Thickness : 88 mm
Diameter : 120 mm
1,000 rpm

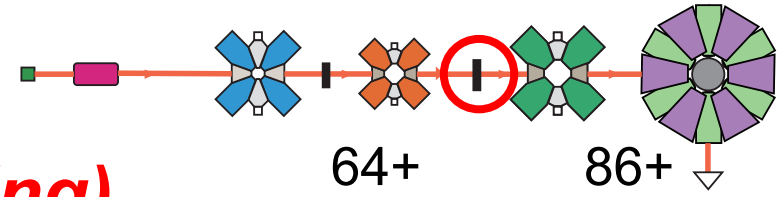


Lifetime: 20 days

Limit : 10^{18} ions

H. Hasebe et al., HIAT2015, MOA1C01.

Graphite sheet stripper for U @ 50 MeV/u

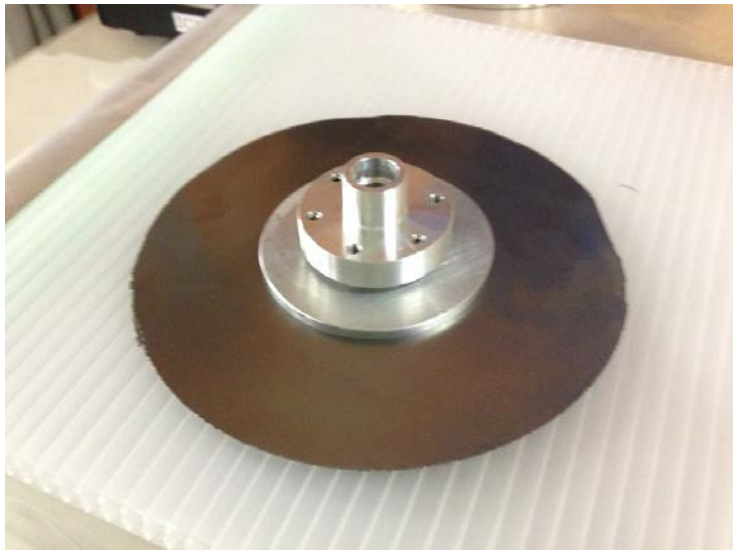


2015~: Highly-orientated graphite sheet (rotating)

by KANEKA Corporation (14 mg/cm^2)

Thermal conductivity in plane: ***1500 W/mK*** → 3 times that of copper

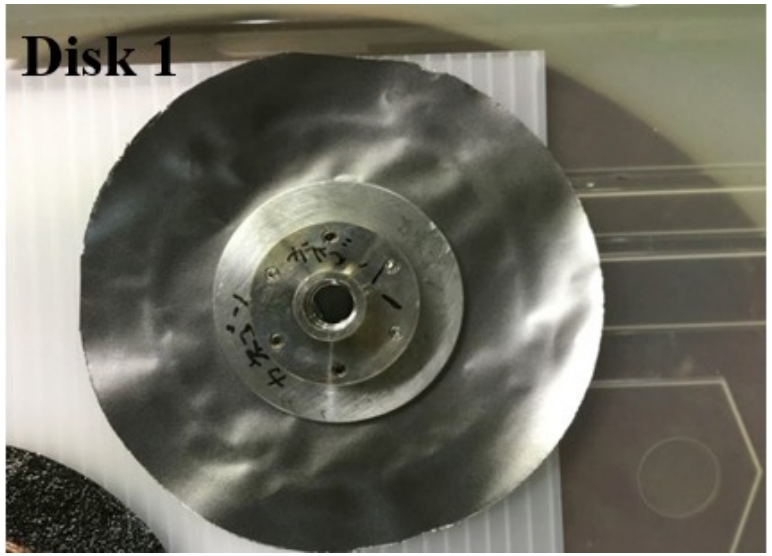
300 W loss @ 250 pnA



(Before irradiation)

300 W loss @ 250 pnA

1.4 ×10^{18} ions

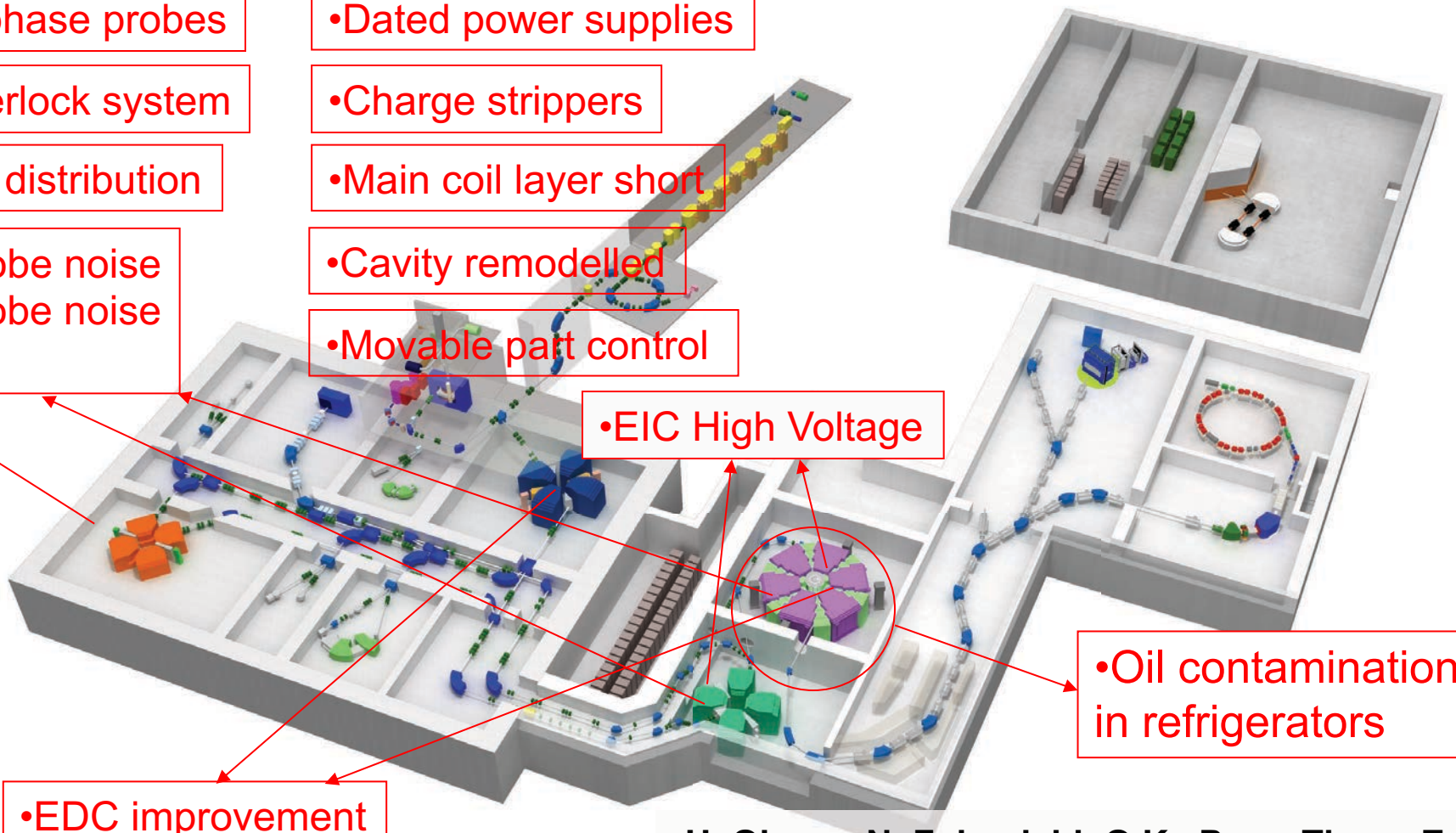


2.2 ×10^{18} ions

H. Hasebe et al., EPJ Web of Conferences 229 (2020) 01004.

Many other things..

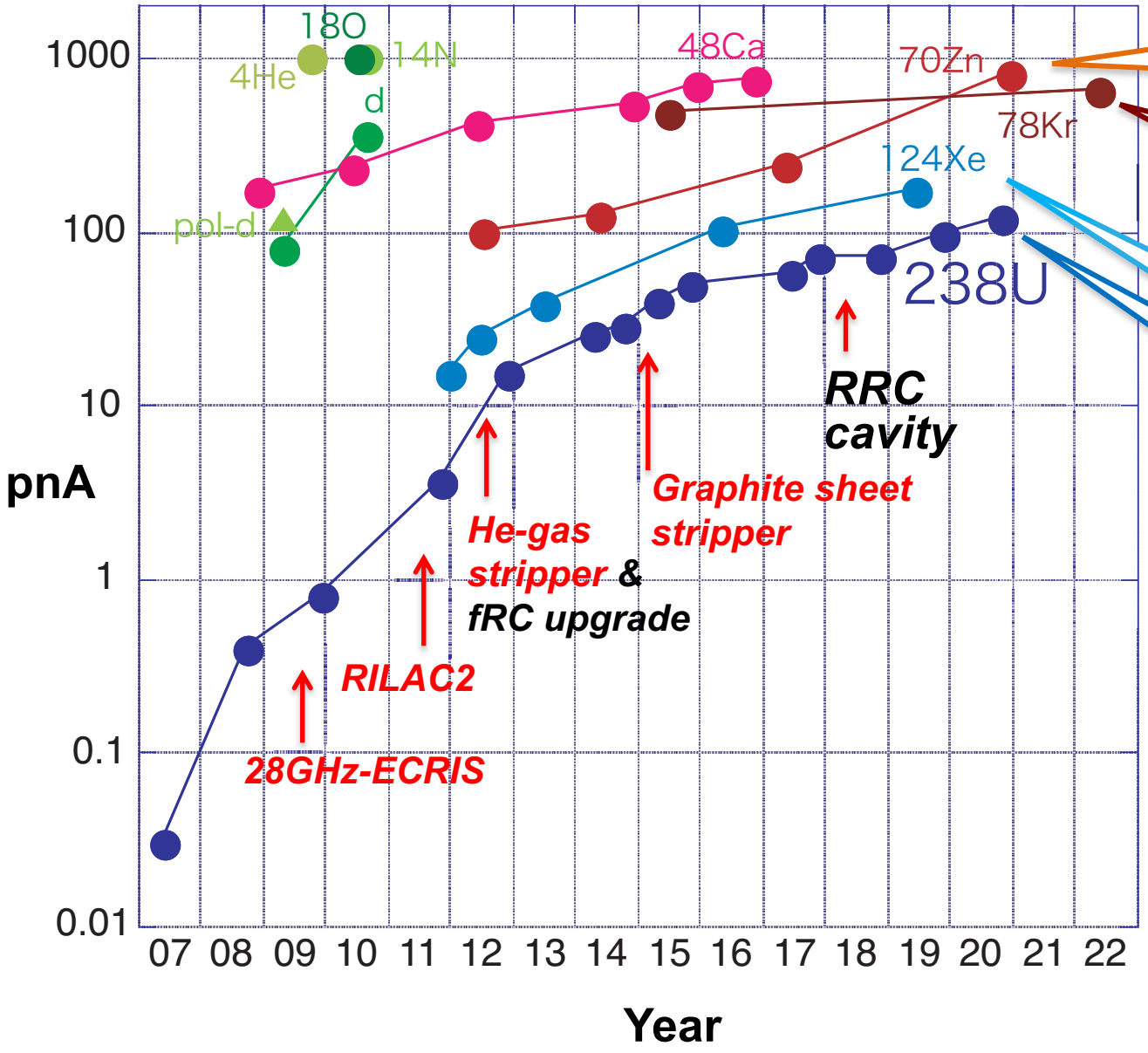
- •Cavity temp. control
- •LLRF accuracy/stability
- •Noise in phase probes
- •Beam interlock system
- •RF signal distribution
- •Phase probe noise
- •Radial probe noise
- •FT phase
- •Accuracy of Faraday cups
- •Accuracy of TOF monitors
- •Dated power supplies
- •Charge strippers
- •Main coil layer short
- •Cavity remodelled
- •Movable part control
- •Control data archiver
- •AND SO ON…..
- •EIC High Voltage
- •Oil contamination in refrigerators
- •EDC improvement



H. Okuno, N. Fukunishi, O.K., Prog. Theor. Exp. Phys. (2012) 03C002.
O.K. CYC2019, MOB01.

3) Present status

Beam intensity



^{70}Zn: 788 pnA
=> ***19.0 kW***

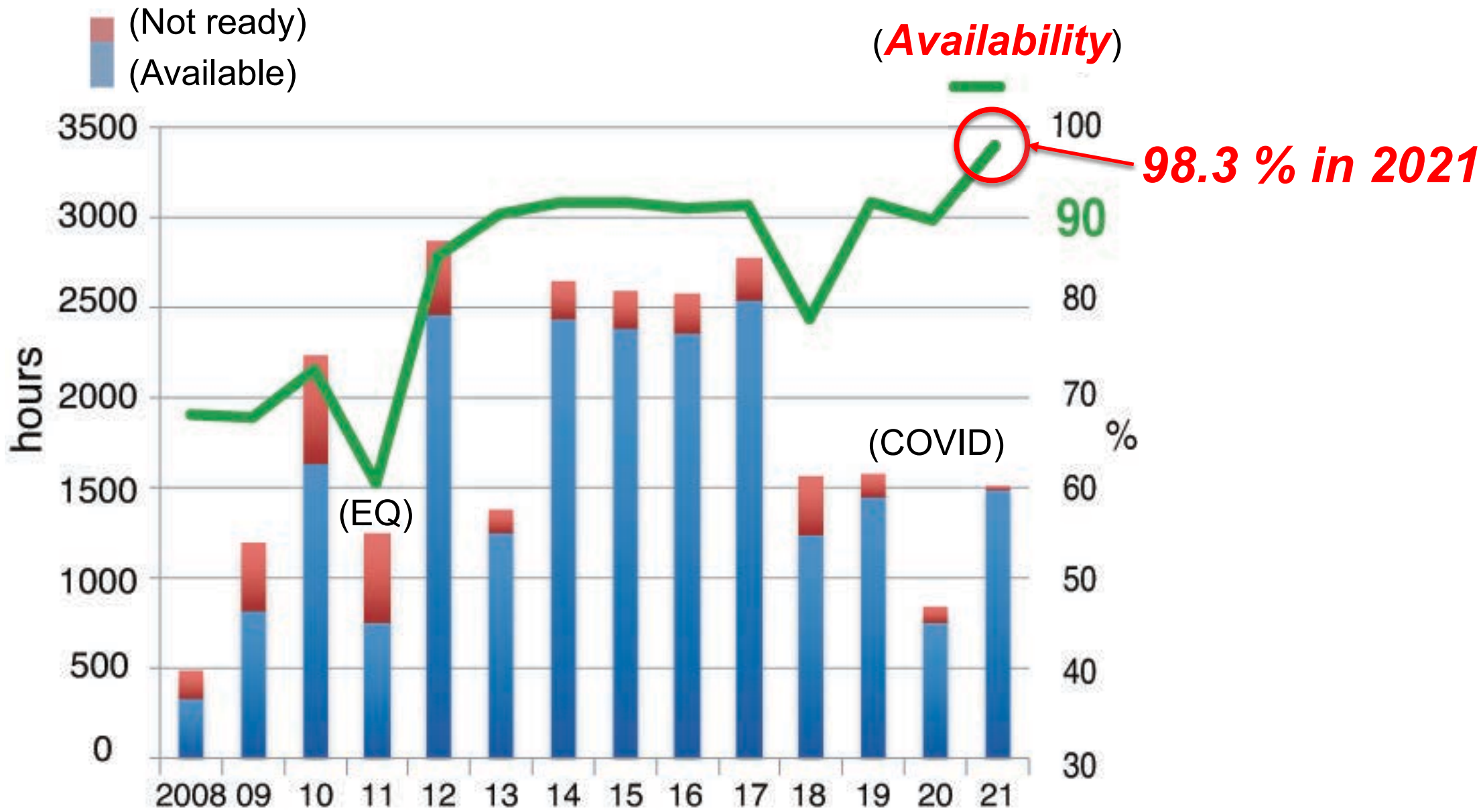
^{78}Kr: 690 pnA
=> ***18.6 kW***

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

^{238}U: 117pnA
=> ***9.6 kW***

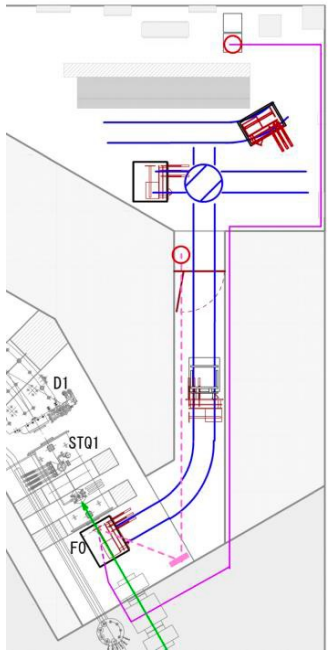
Beam availability

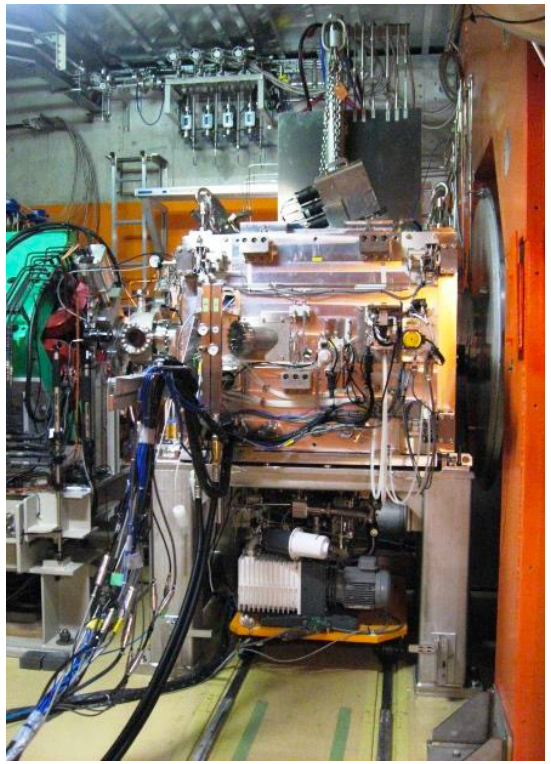
Availability =
actual BT / scheduled BT

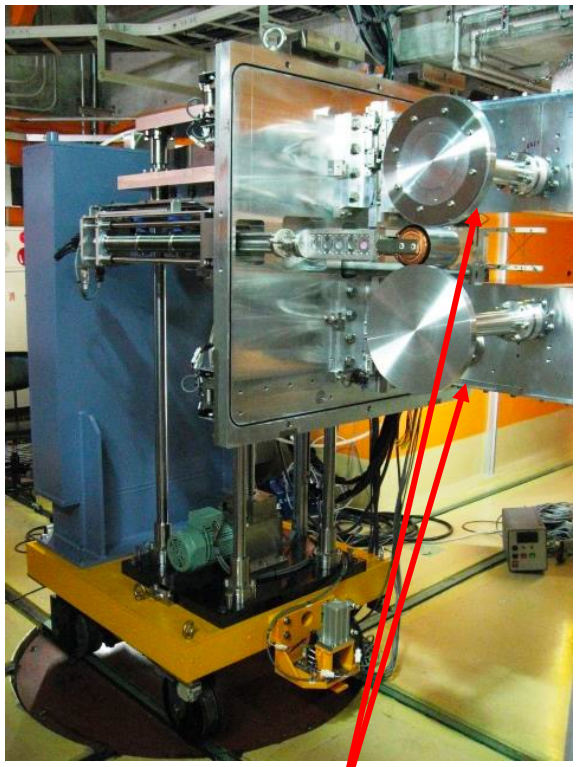


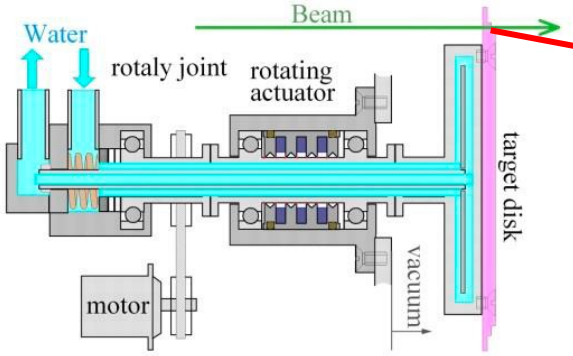
BigRIPS target

- Rotating beryllium disk
- Indirect cooling with water



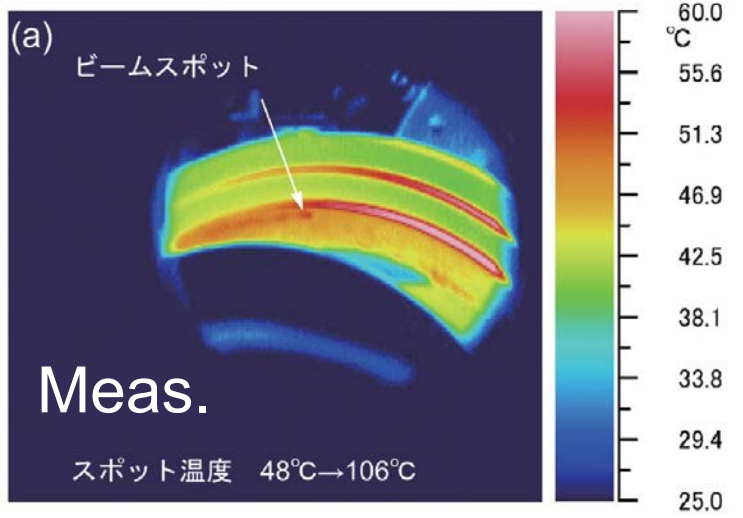


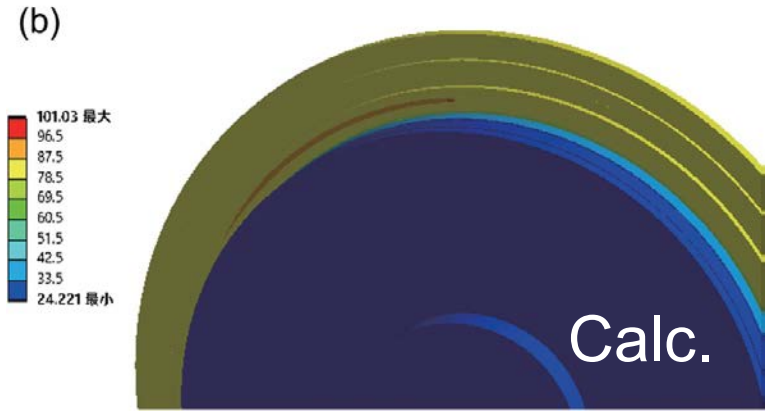




Be disk

78Kr, 280 pnA, 300 rpm (t: 5-7-10 mm)





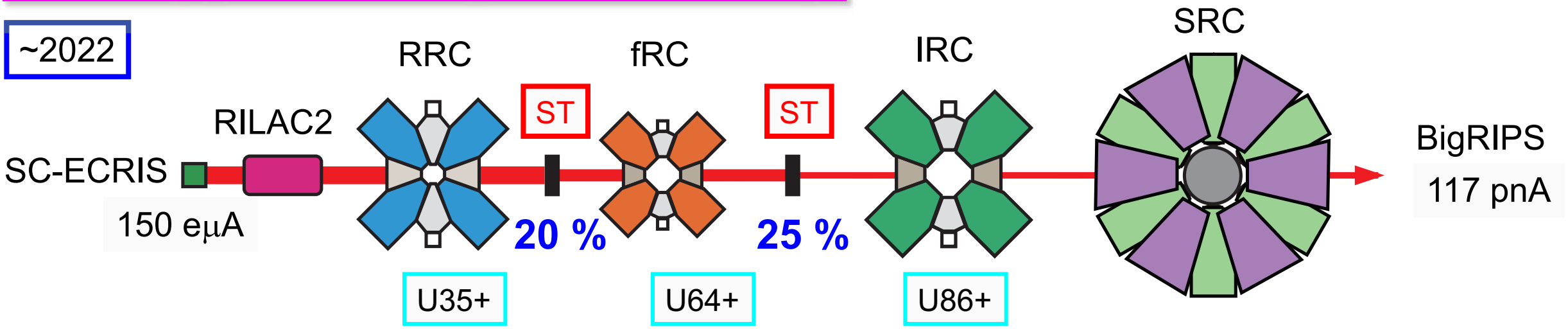
- Good agreement.
- For U 1000 pnA, 1000 rpm (t: 2-3-4 mm) would work well.

A. Yoshida et al., NIM A521 (2004) 65, A590 (2008) 204, A655 (2011) 10.

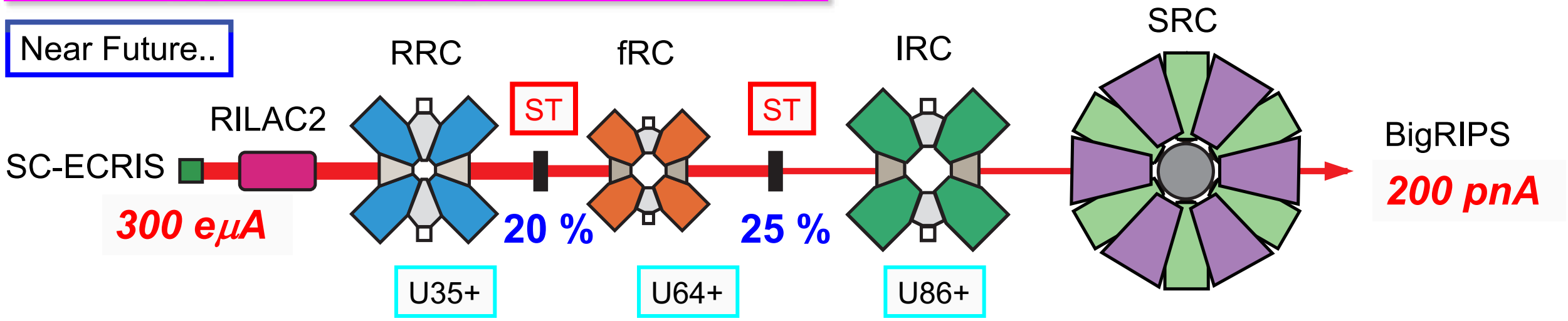
K. Yoshida, J. PASJ 18 (2021) 241.

4) Future plan

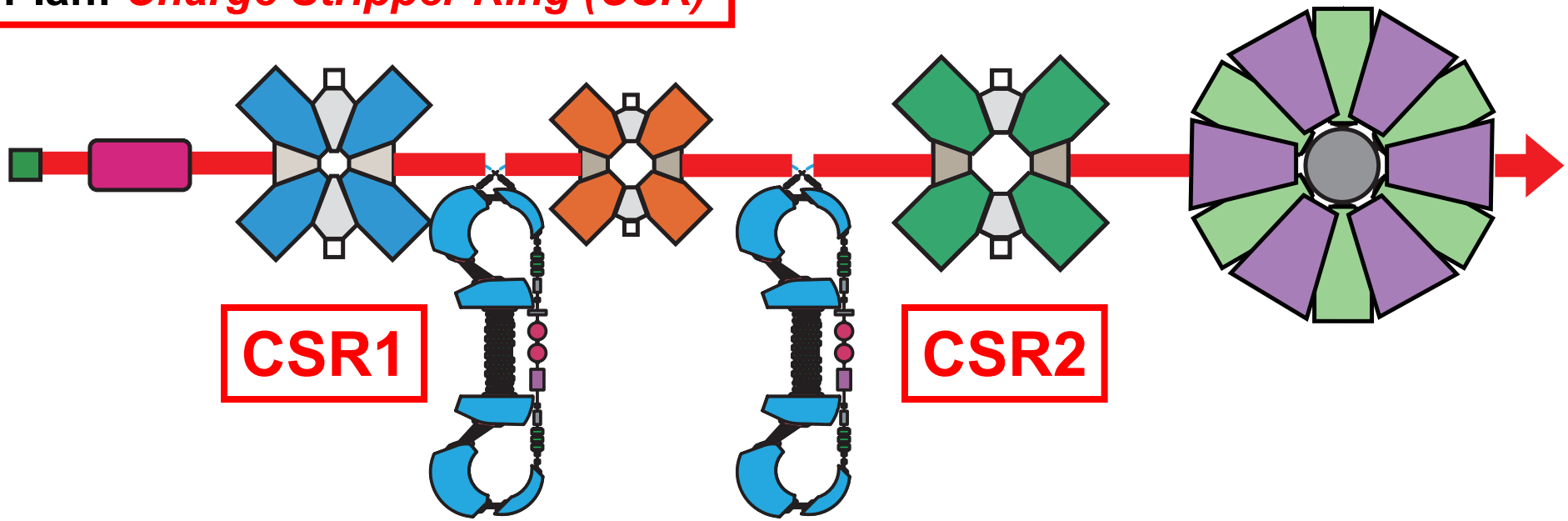
RIBF upgrade for higher U intensity



RIBF upgrade for higher U intensity

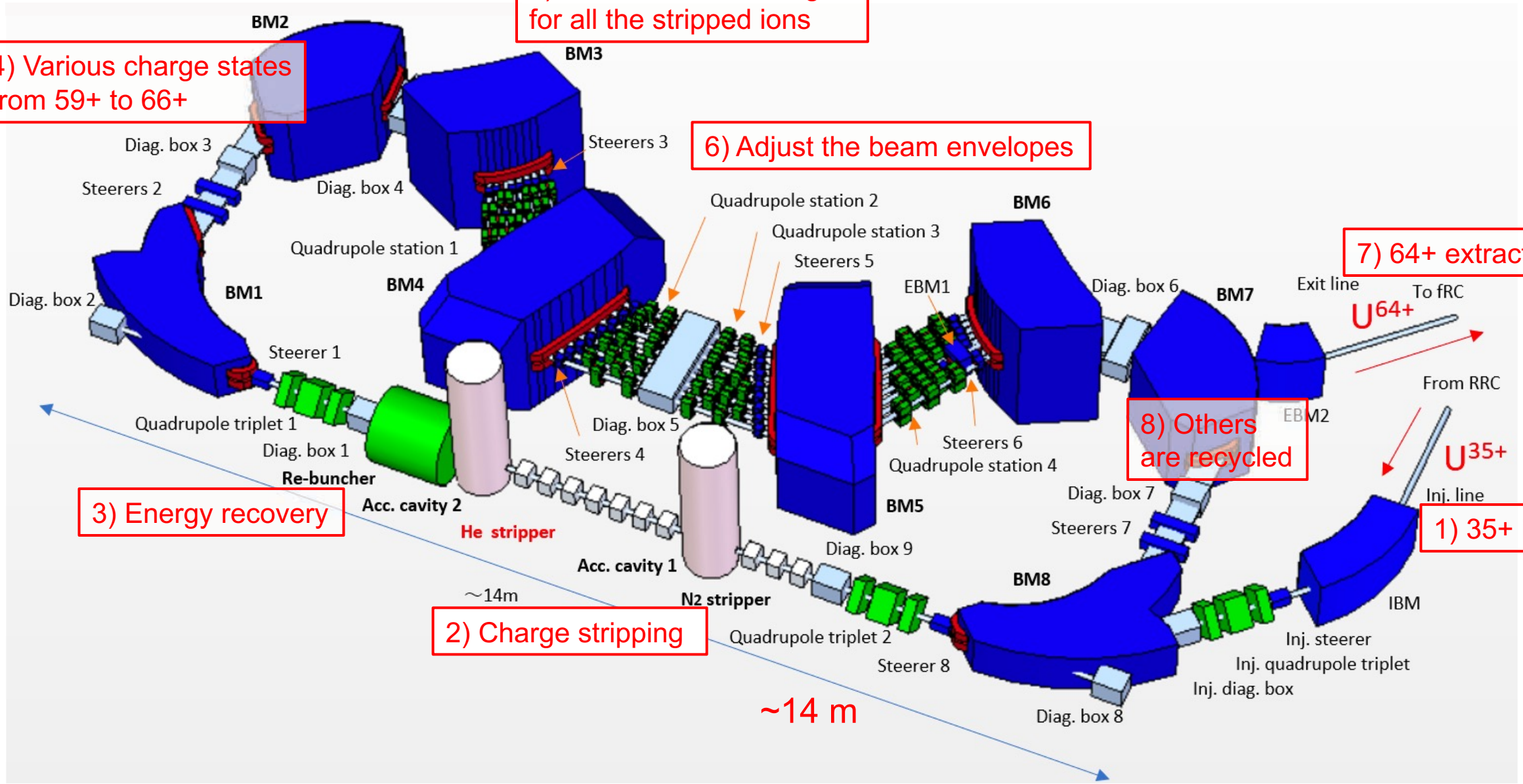


Upgrade Plan: ***Charge Stripper Ring (CSR)***



Charge Stripper Ring

H. Imao, JINST 15 (2020) P12036.

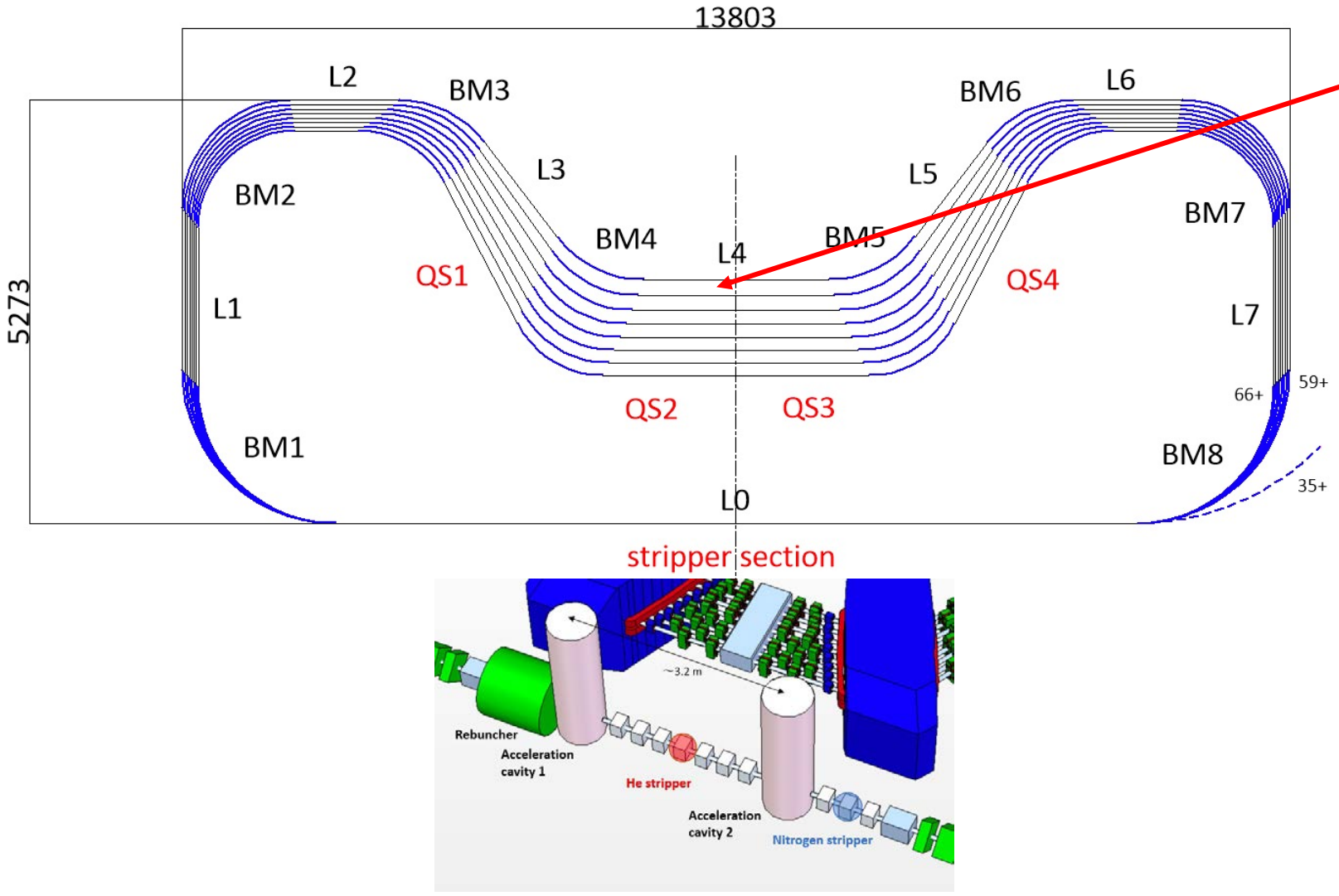


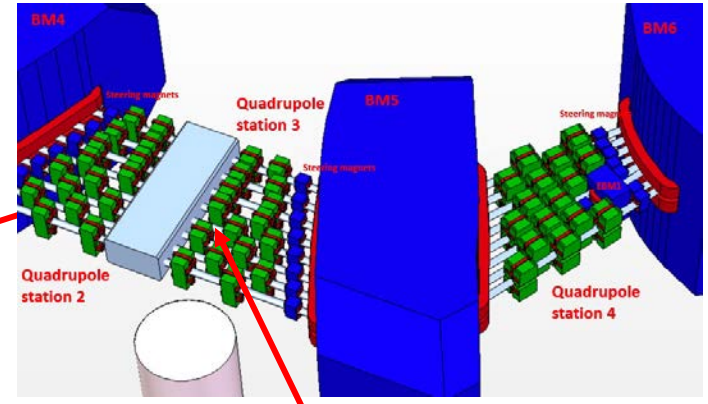
Charge Stripper Ring

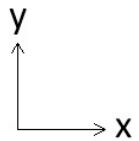
Aiming at stripping efficiency > 1/2

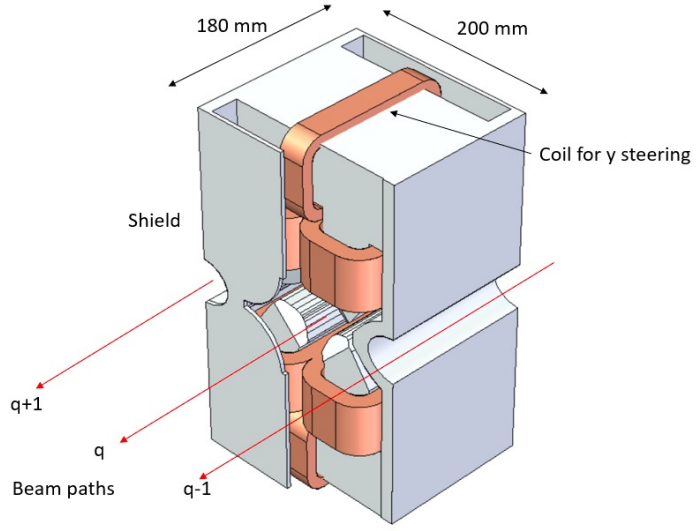
H. Imao, JINST 15 (2020) P12036.

Isometric ring with independent focusing elements
→ Compactness and emittance growth reduction



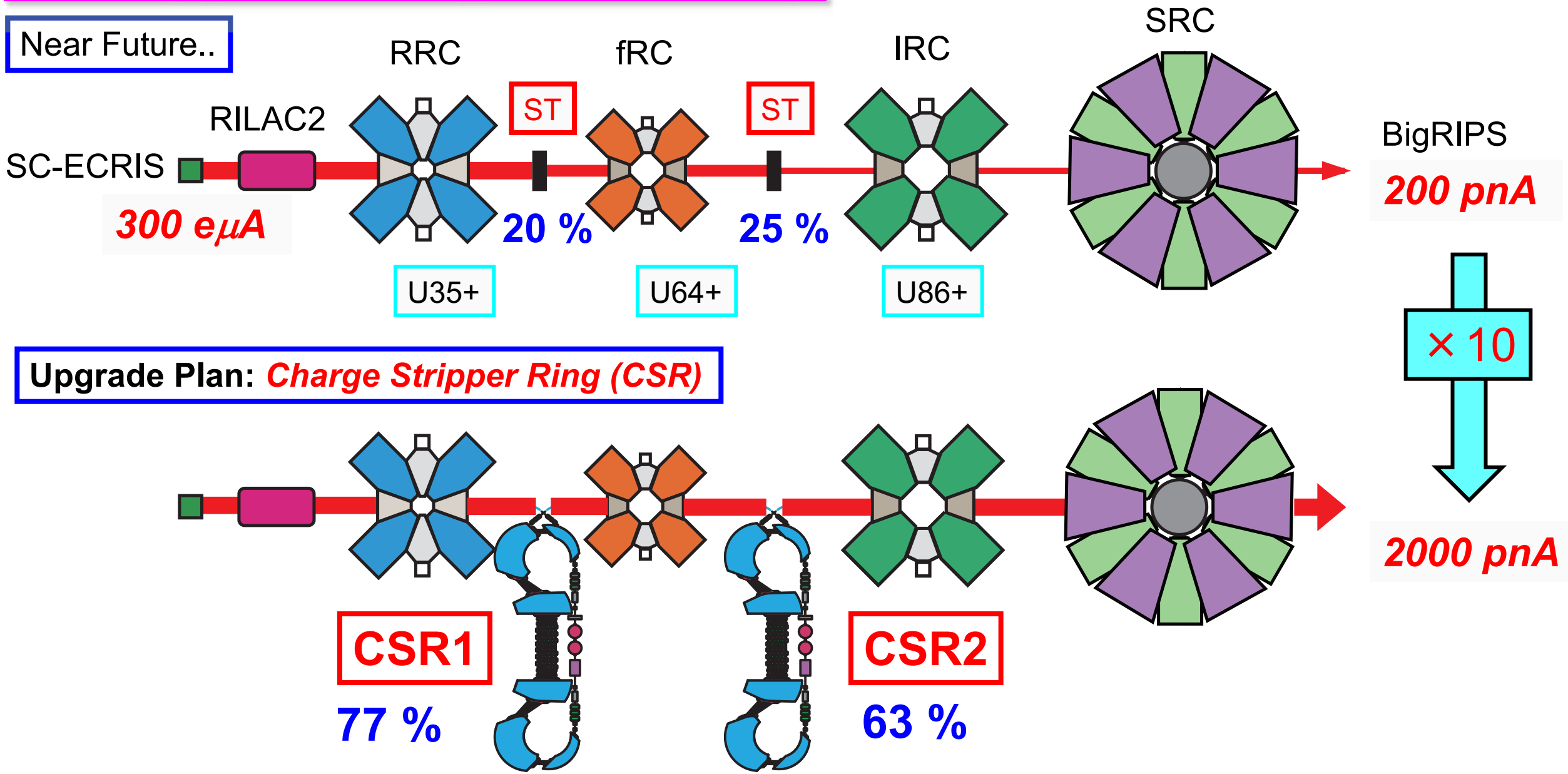






Hourglass-like quadrupole magnets
(H. Imao & C. Hori, HITACHI ENG.)

RIBF upgrade for higher U intensity



Summary

- The performance of the RIBF accelerators is improving steadily. The R&Ds have been mainly focused on the increase of beam intensities of uranium ions.

- Owing to the efforts in the last 15 years, uranium beam has increased to 117 pnA. It will be possible to accelerate uranium beam of 200 pnA in near future.

- Beam power of medium-heavy ions is reaching 20 kW.

- More than 1500 RI beams have been produced in the RIBF. Nearly 150 new isotopes have been discovered.

- The R&D of “Charge stripper ring” is under progress for the future intensity upgrade.