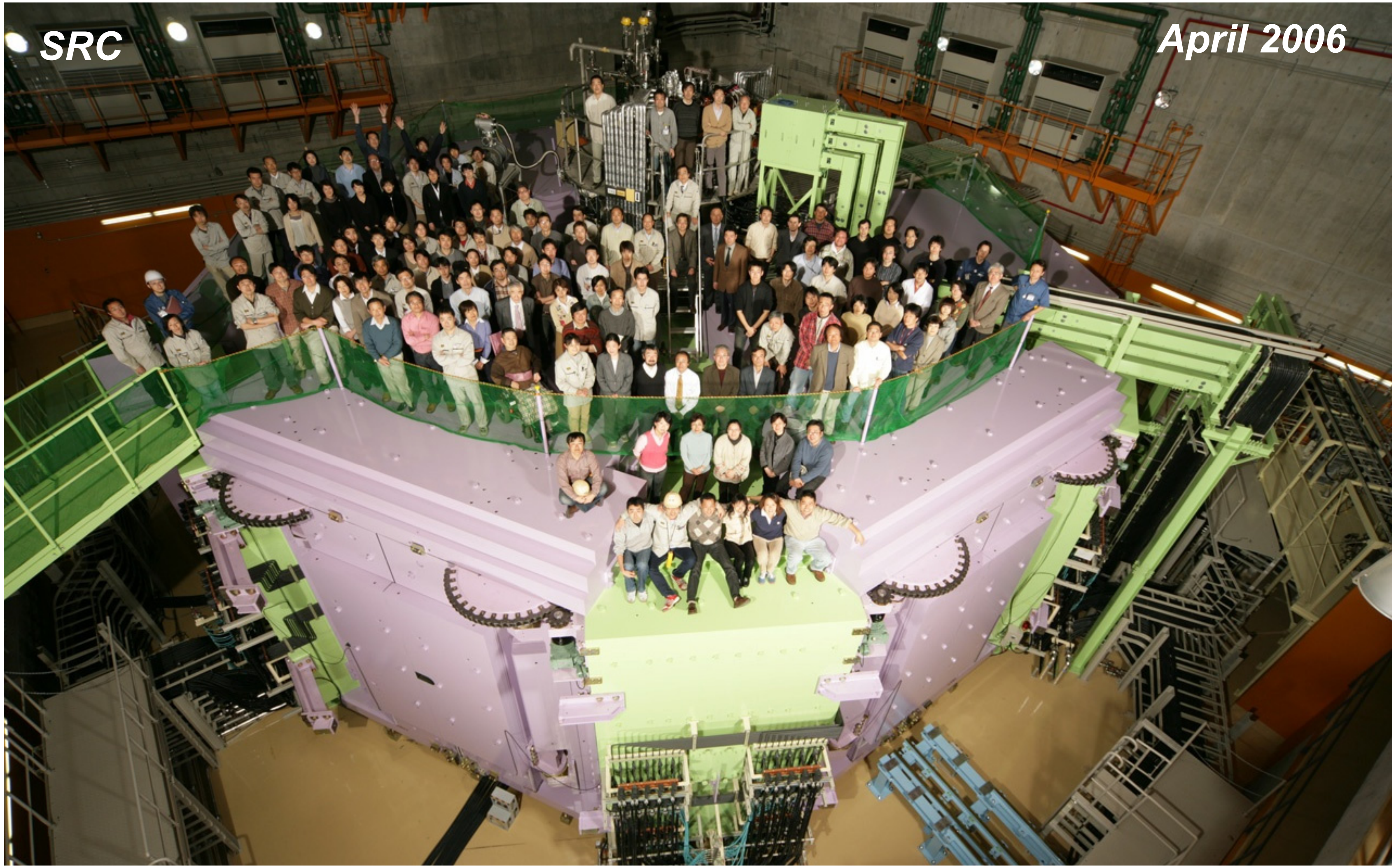
Present status of and recent developments at RIKEN RIBF

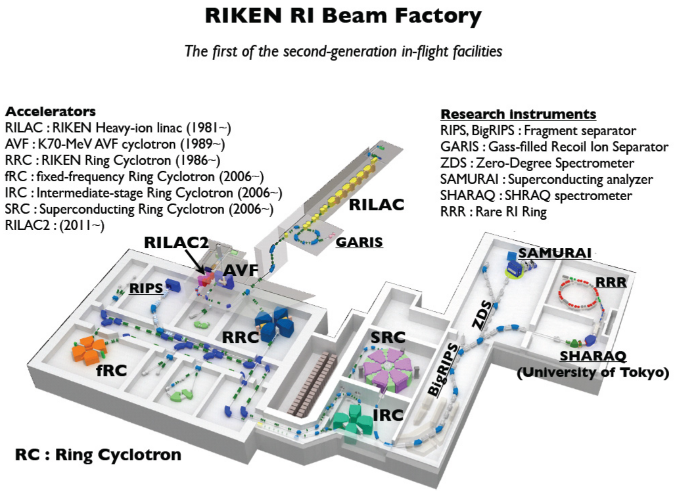


RIKEN Nishina Center for Accelerator-Based Science Accelerator Group

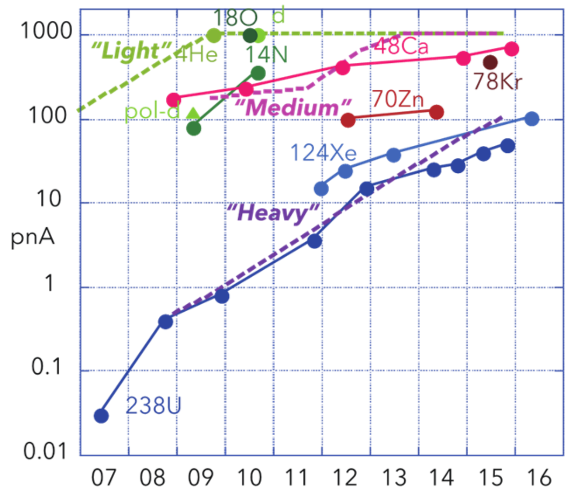
Hiroki Okuno

Preview

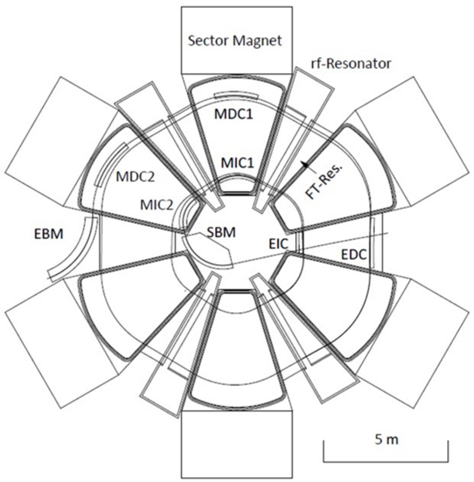
Introduction to RIBF



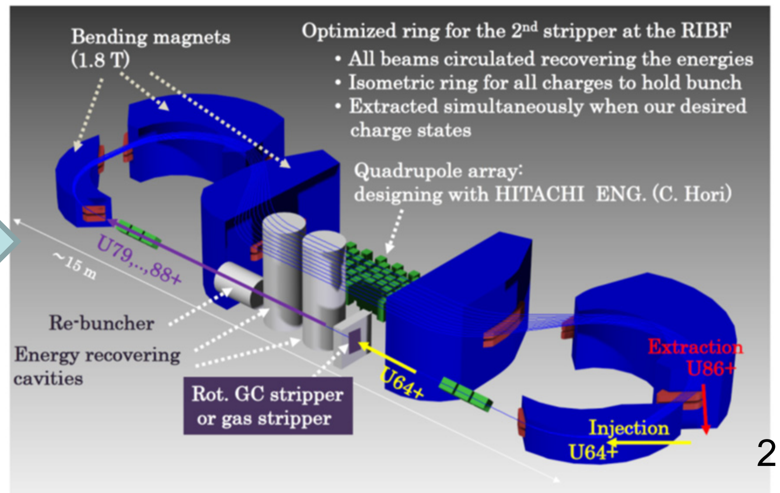
Operation of RIBF for 12 yrs



An upgrade plan



Budget-friendly version



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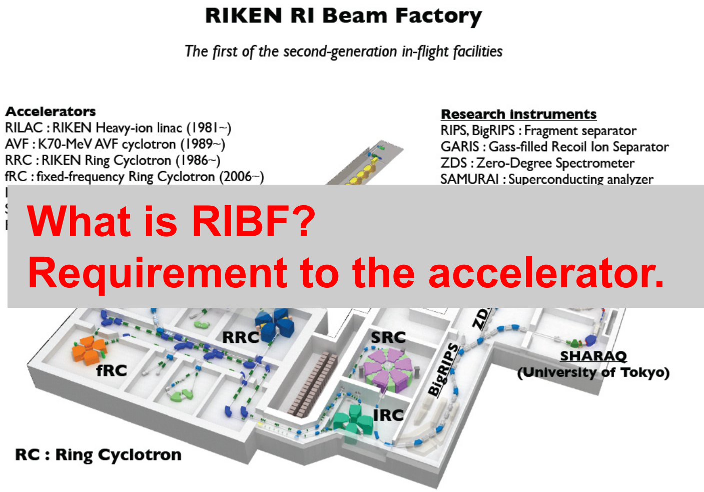

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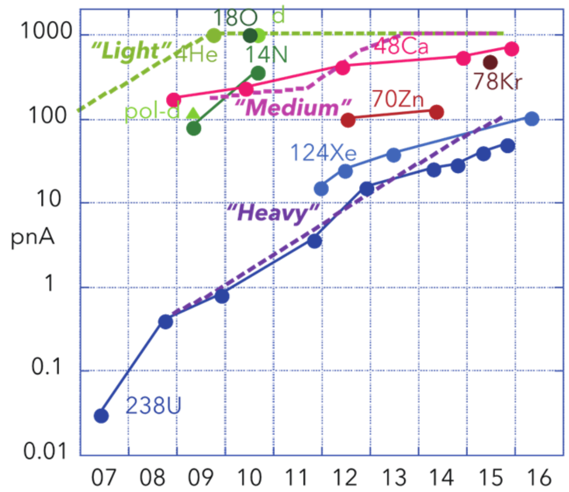

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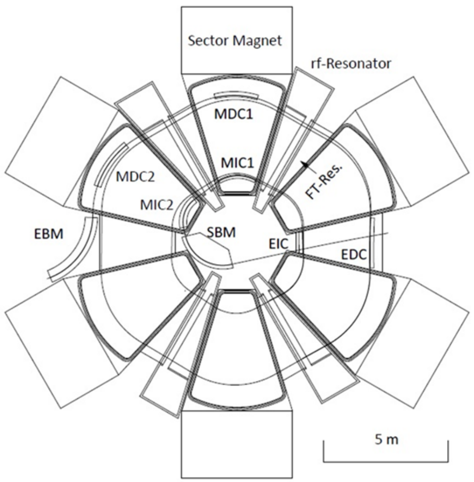

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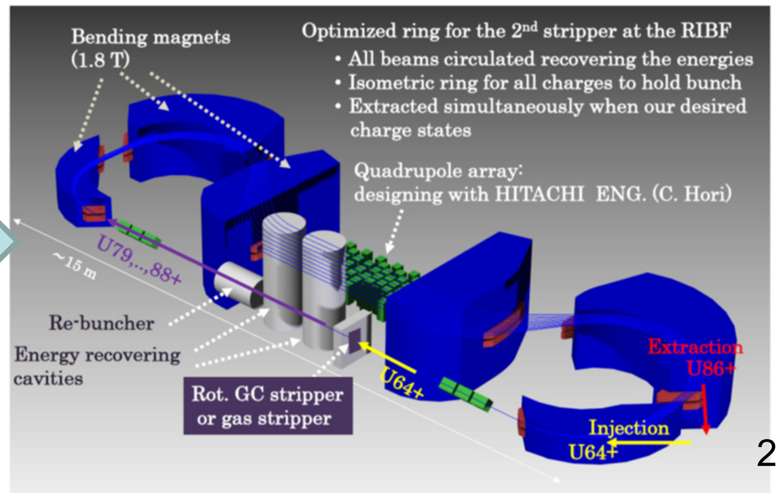

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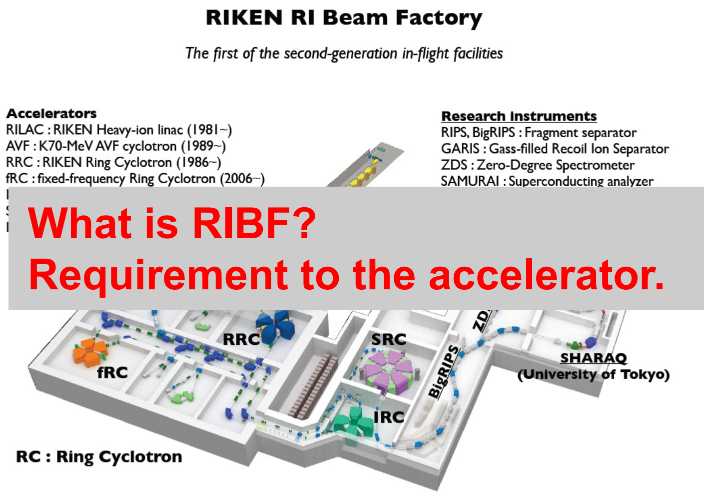
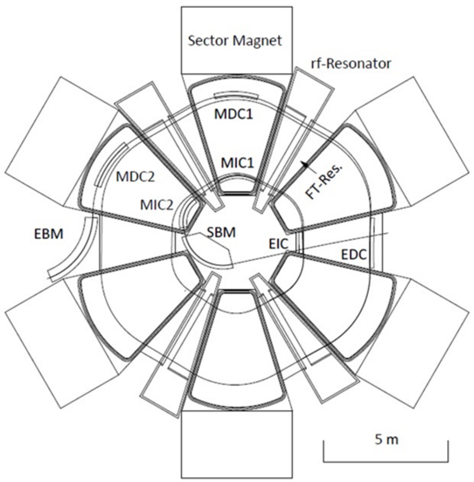


What is RIBF?
Requirement to the accelerator.

Operation of RIBF for 12 yrs

Successful operation
Lessons learnt

An upgrade plan



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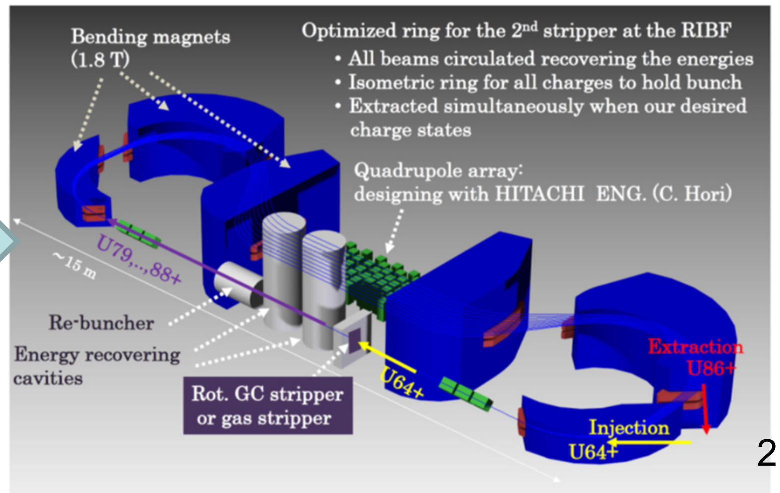

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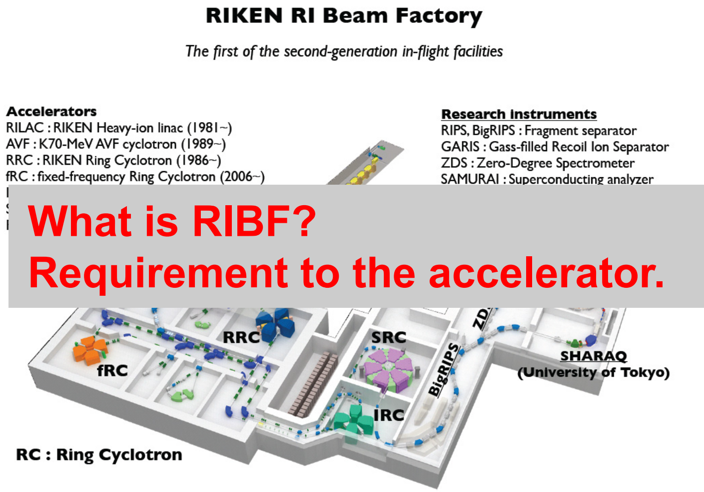

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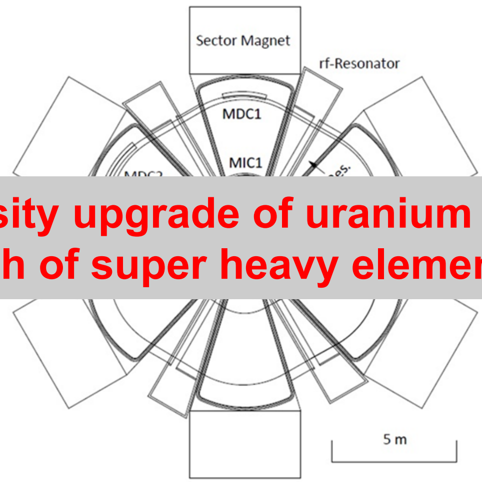
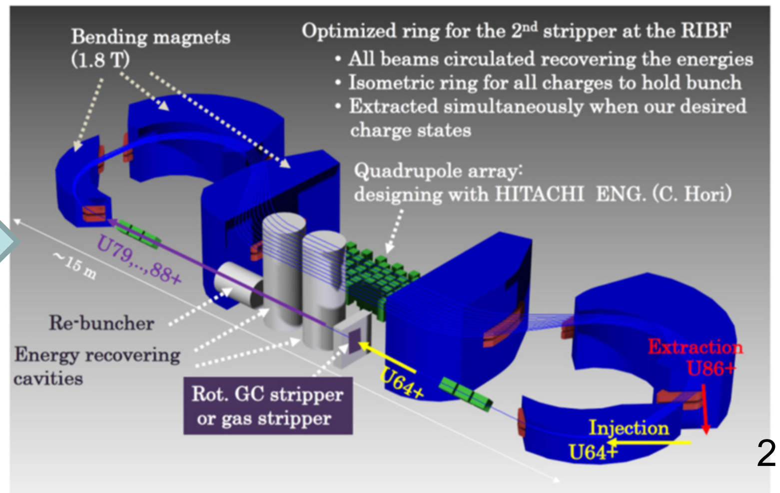


Intensity upgrade of uranium beam
Search of super heavy elements

Budget-friendly version



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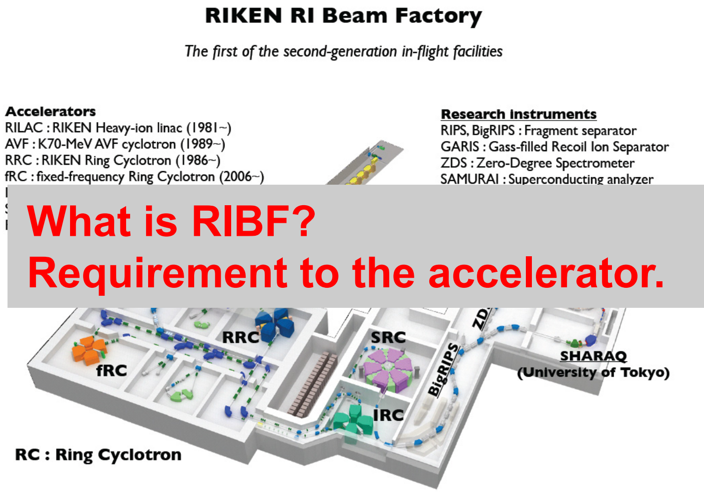

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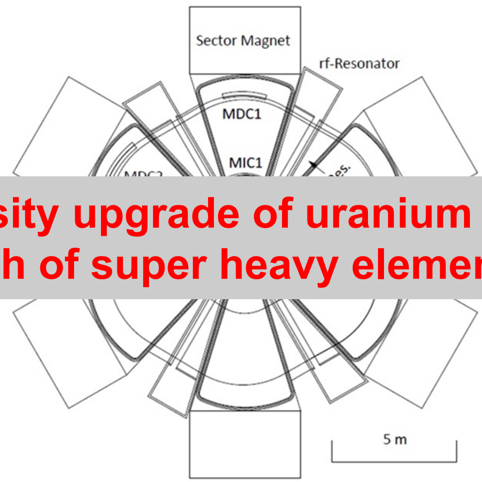

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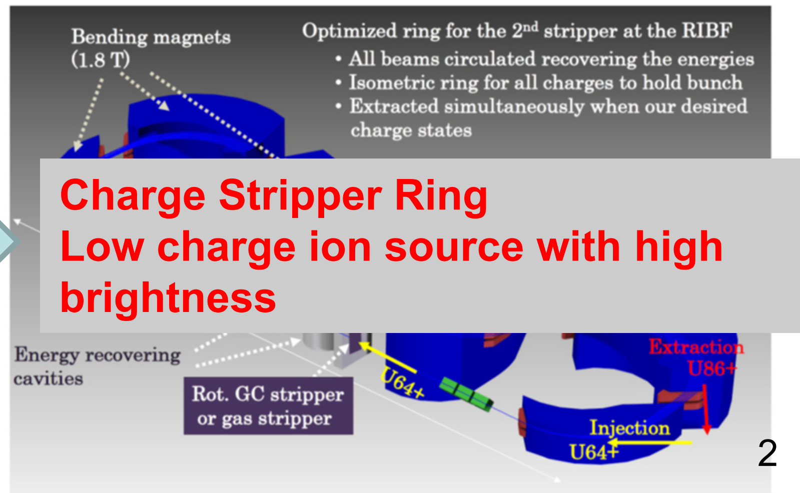
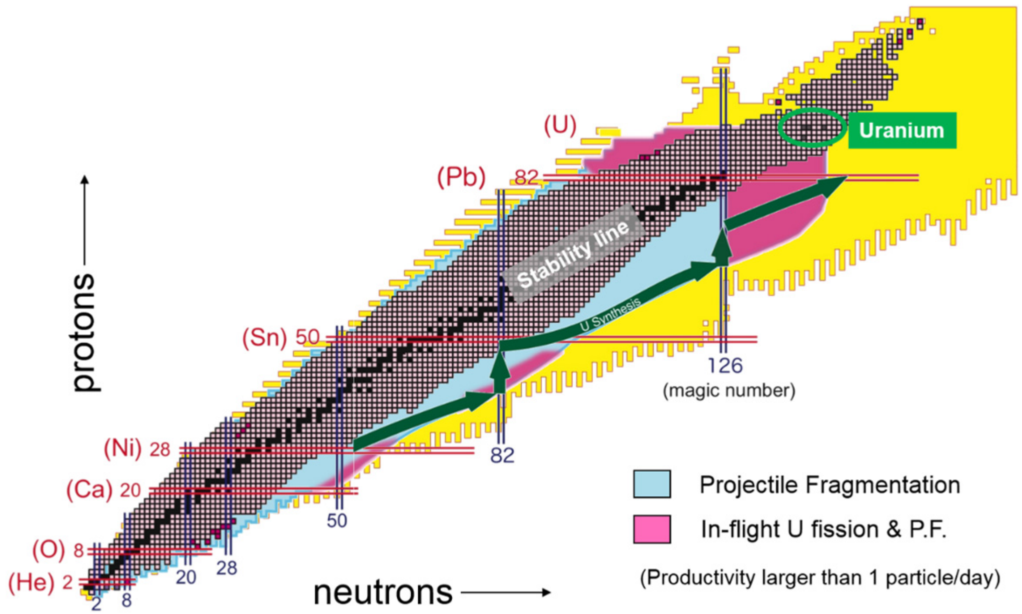
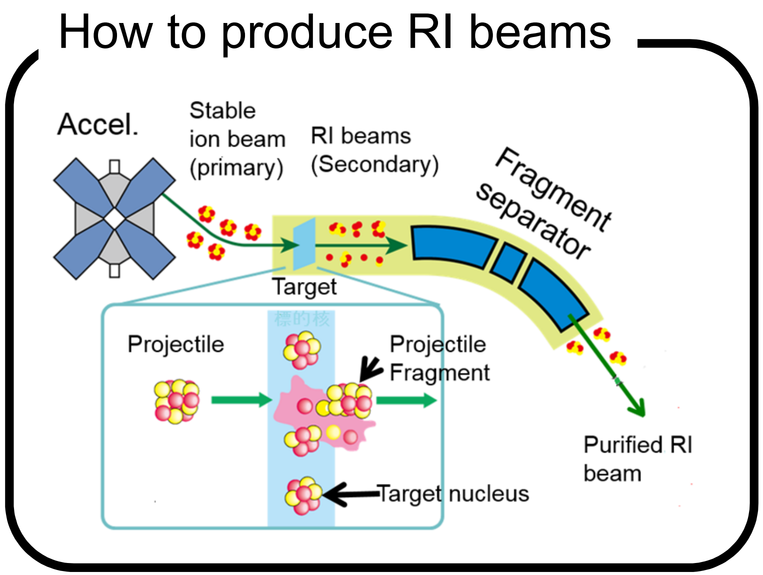


Charge Stripper Ring
Low charge ion source with high brightness

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

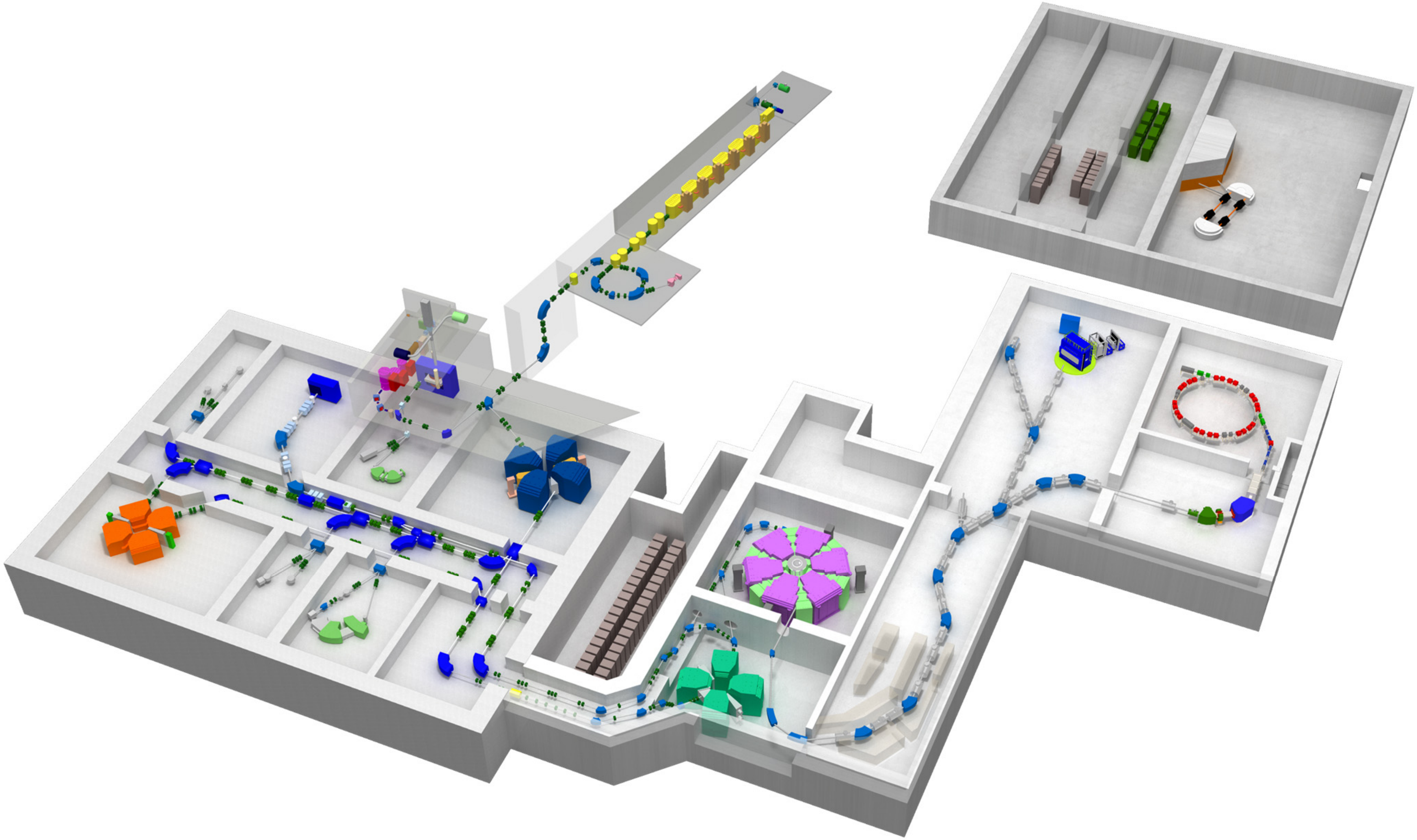




- RI beams are produced through fragmentation or fission of high speed heavy ion beams.
- This method requires accelerator complex to produce high speed heavy ion beams with high intensity.

RIBF accelerators

Y. Yano, NIM B261 (2007) 1009.



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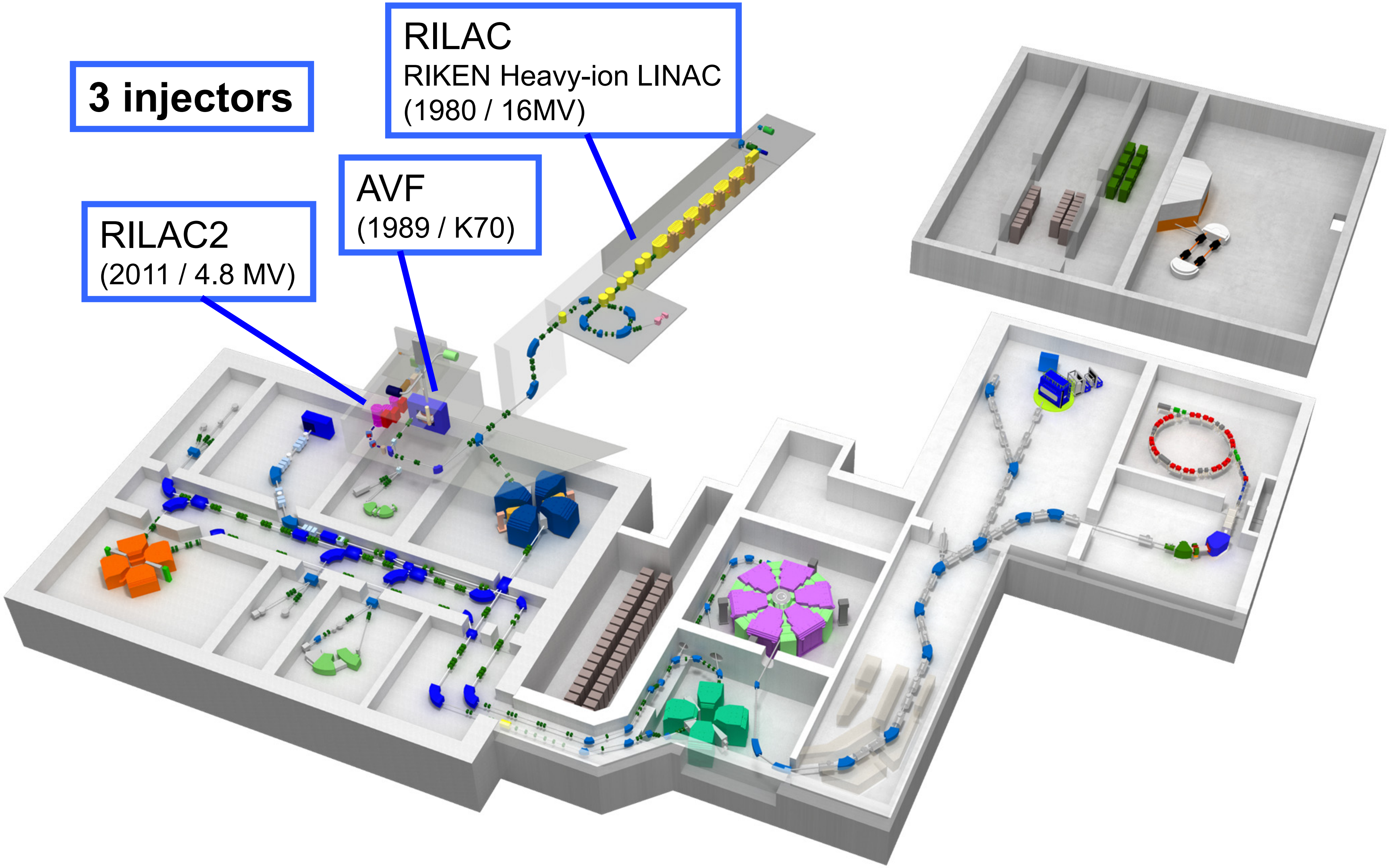

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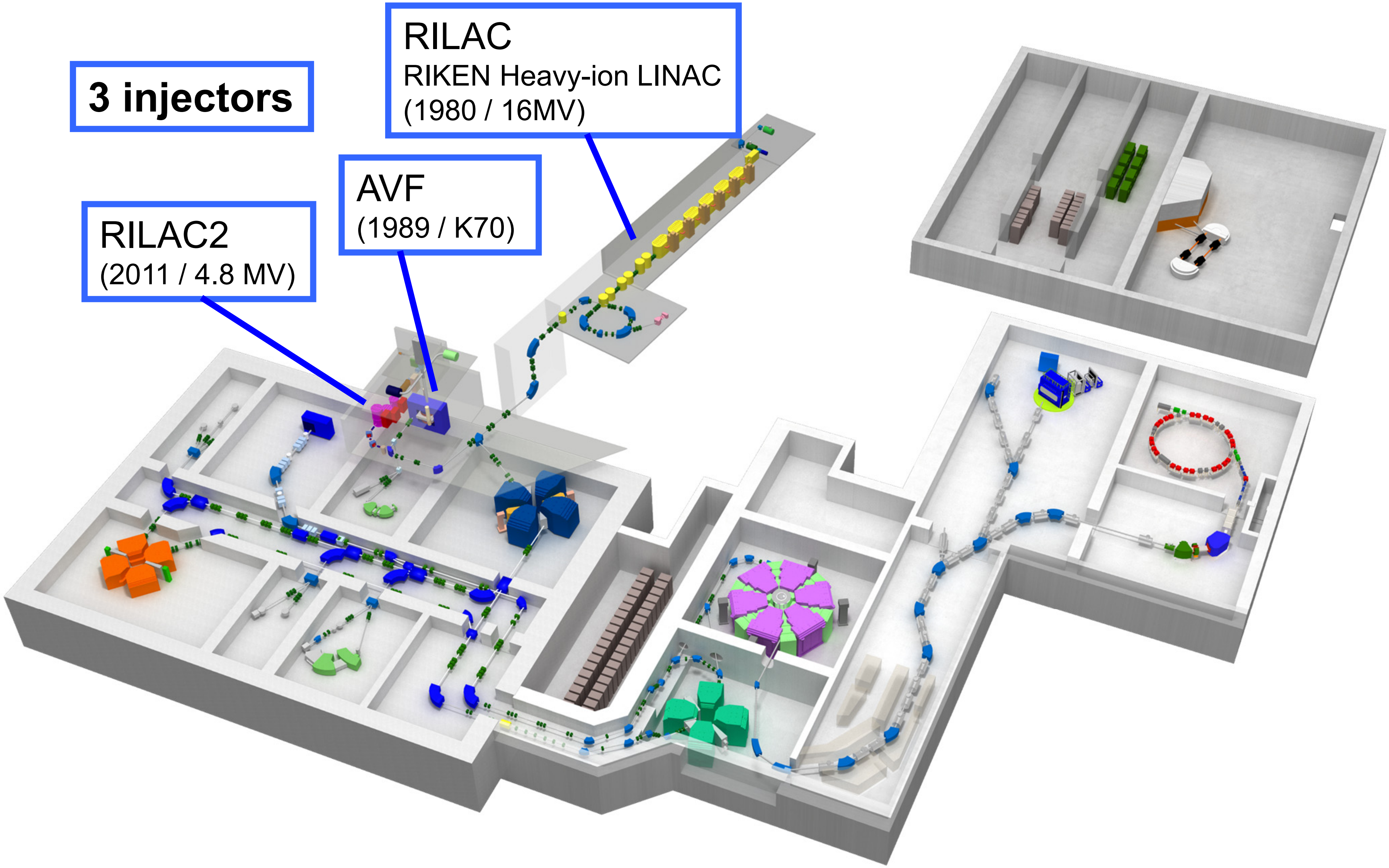

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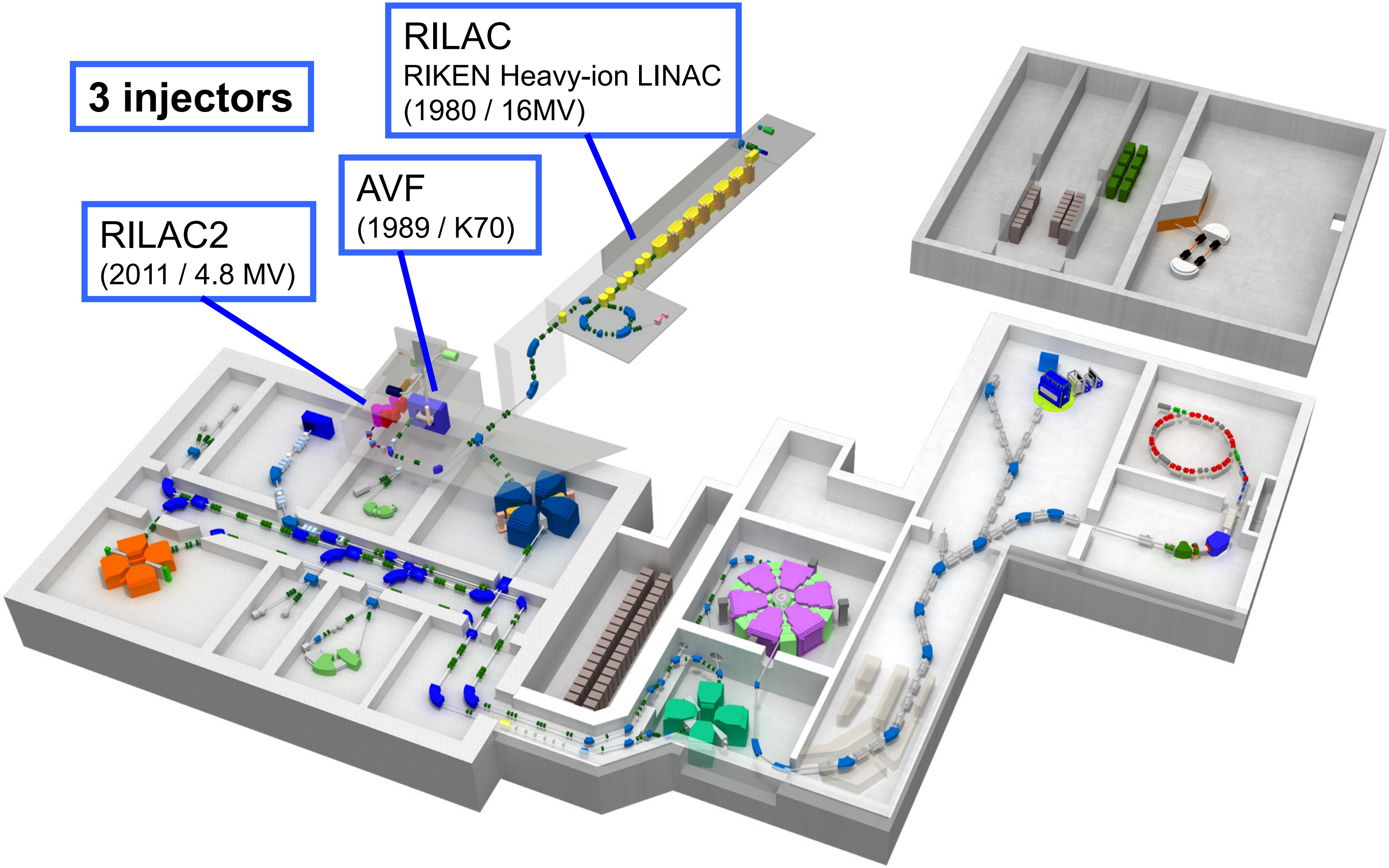

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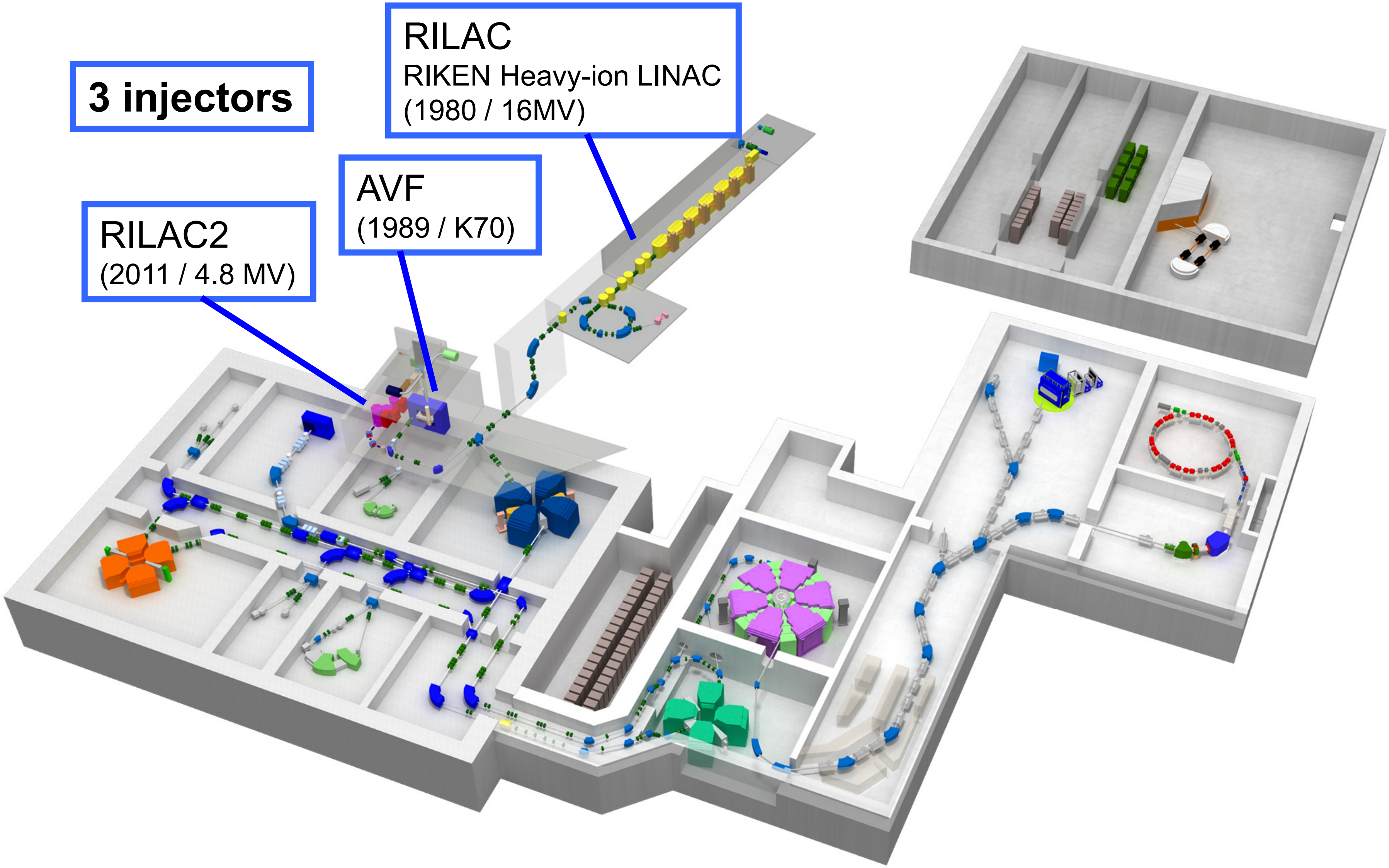

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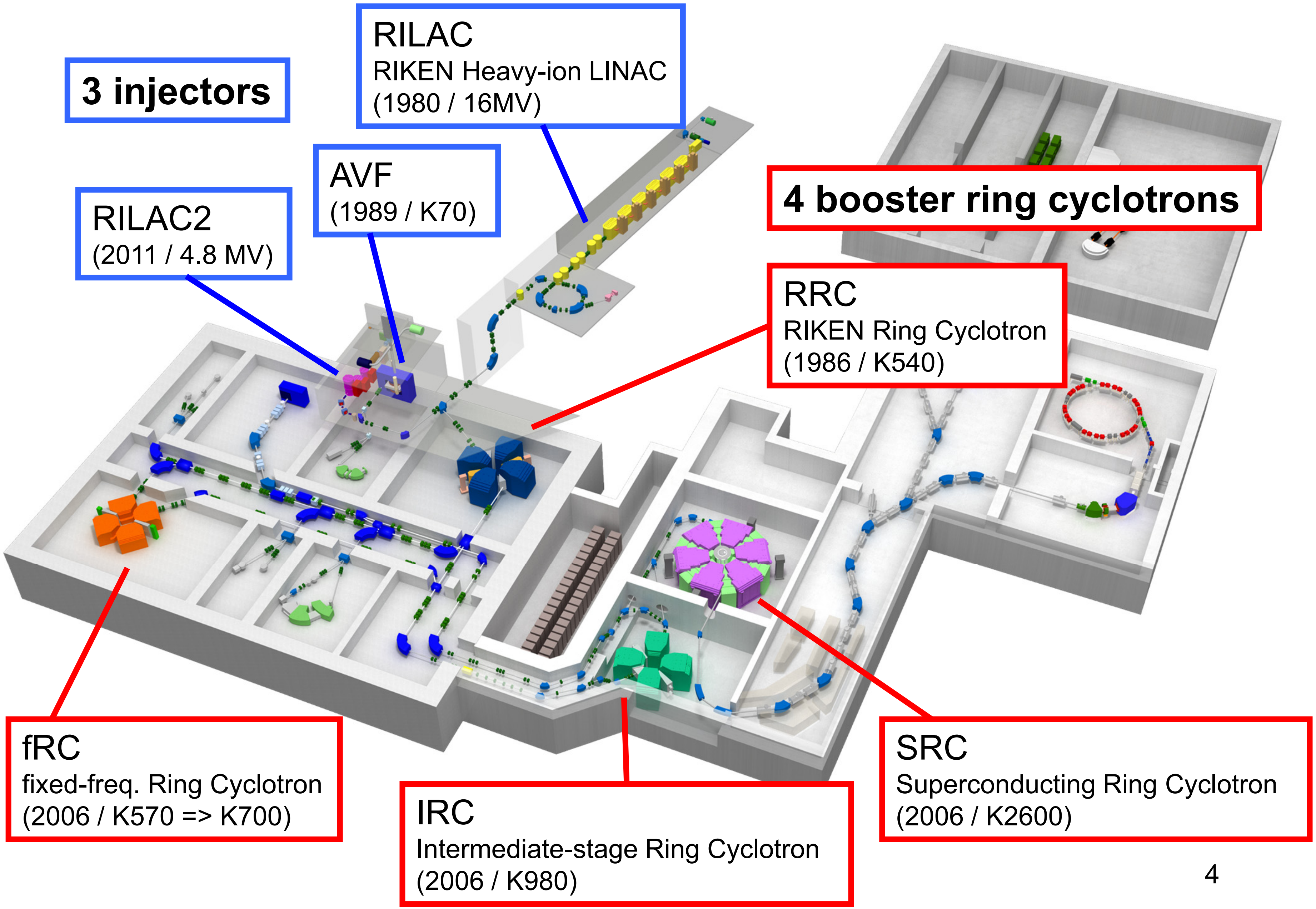

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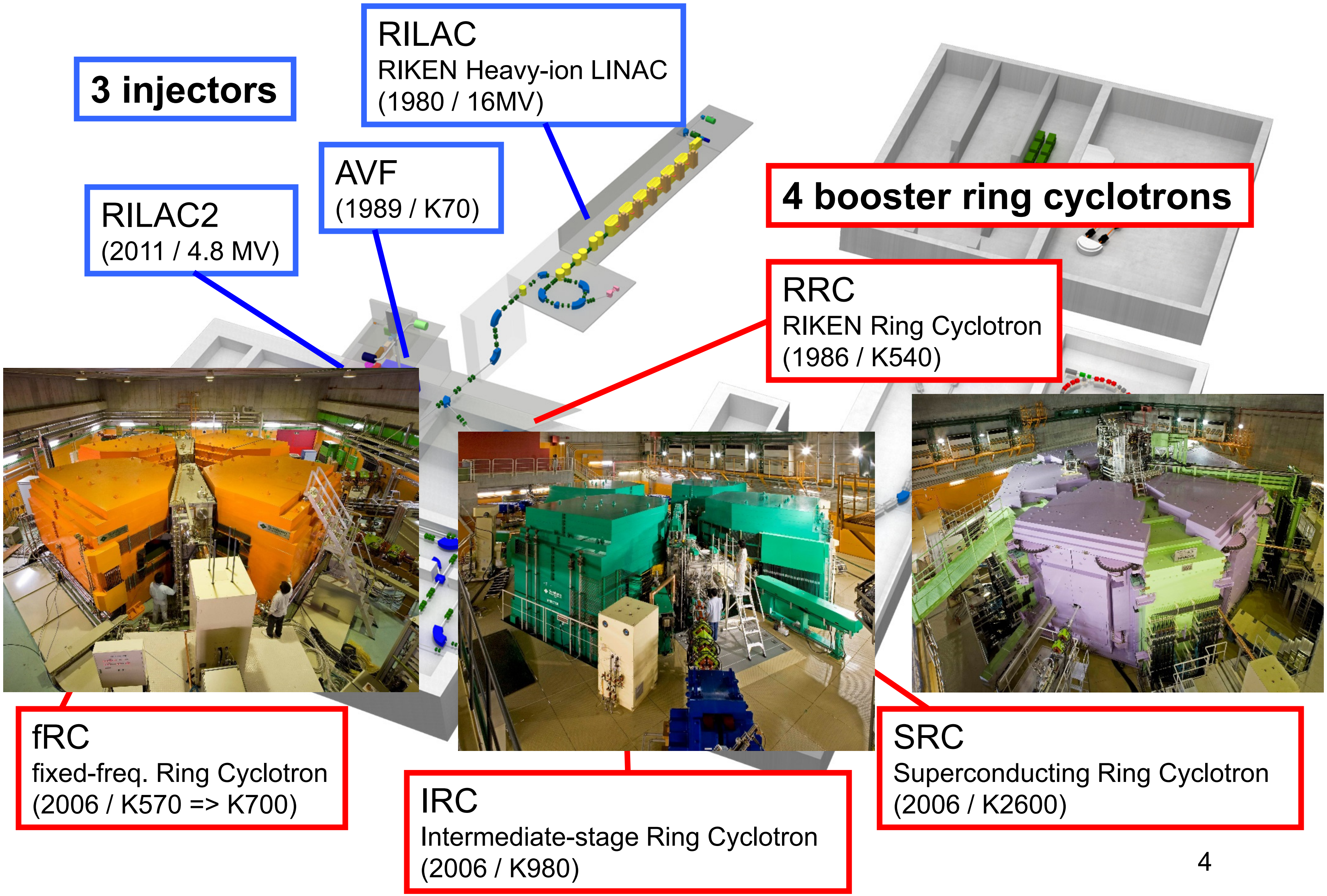
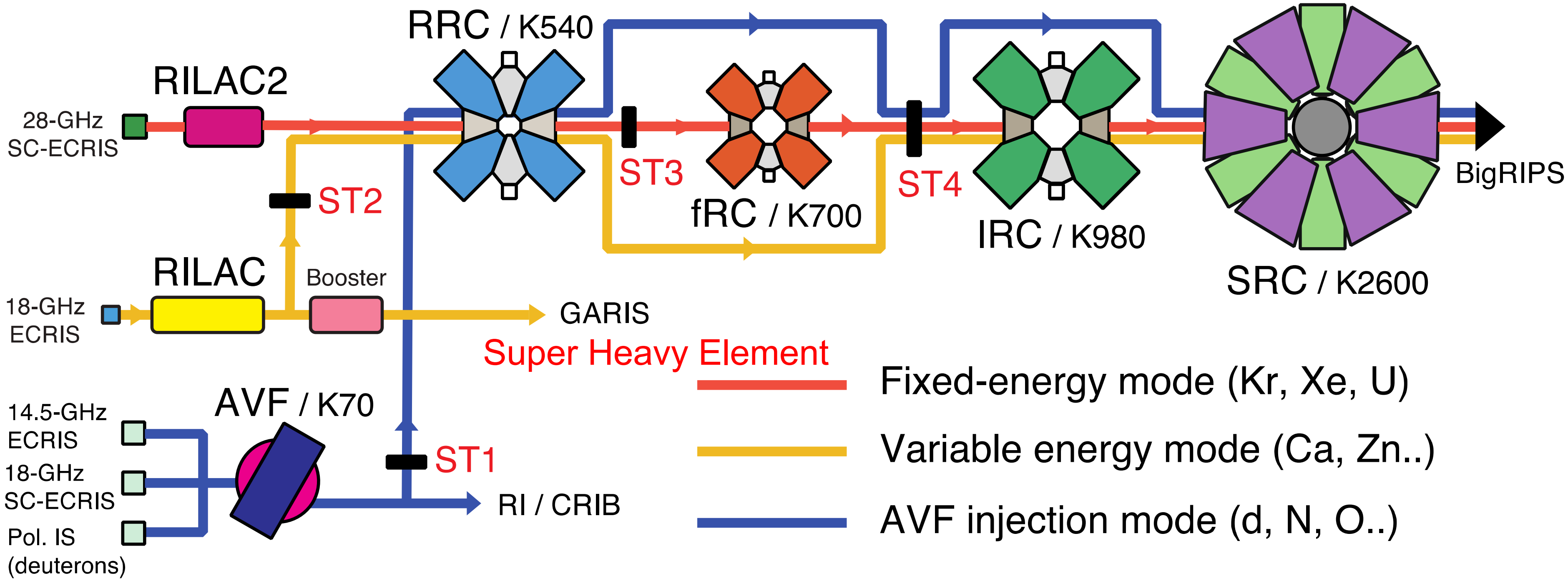


Acceleration modes

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

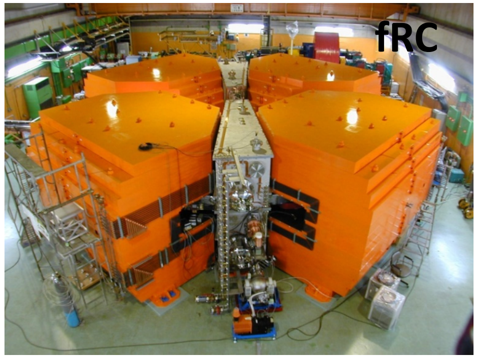
Specifications of RIBF ring cyclotrons

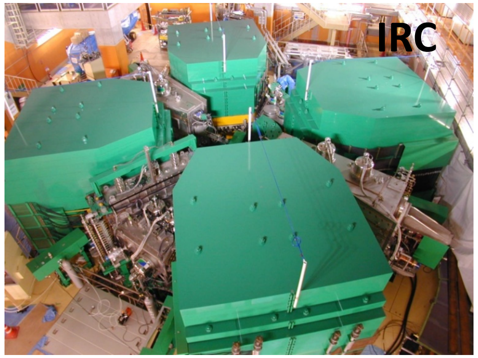
Challenging

	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

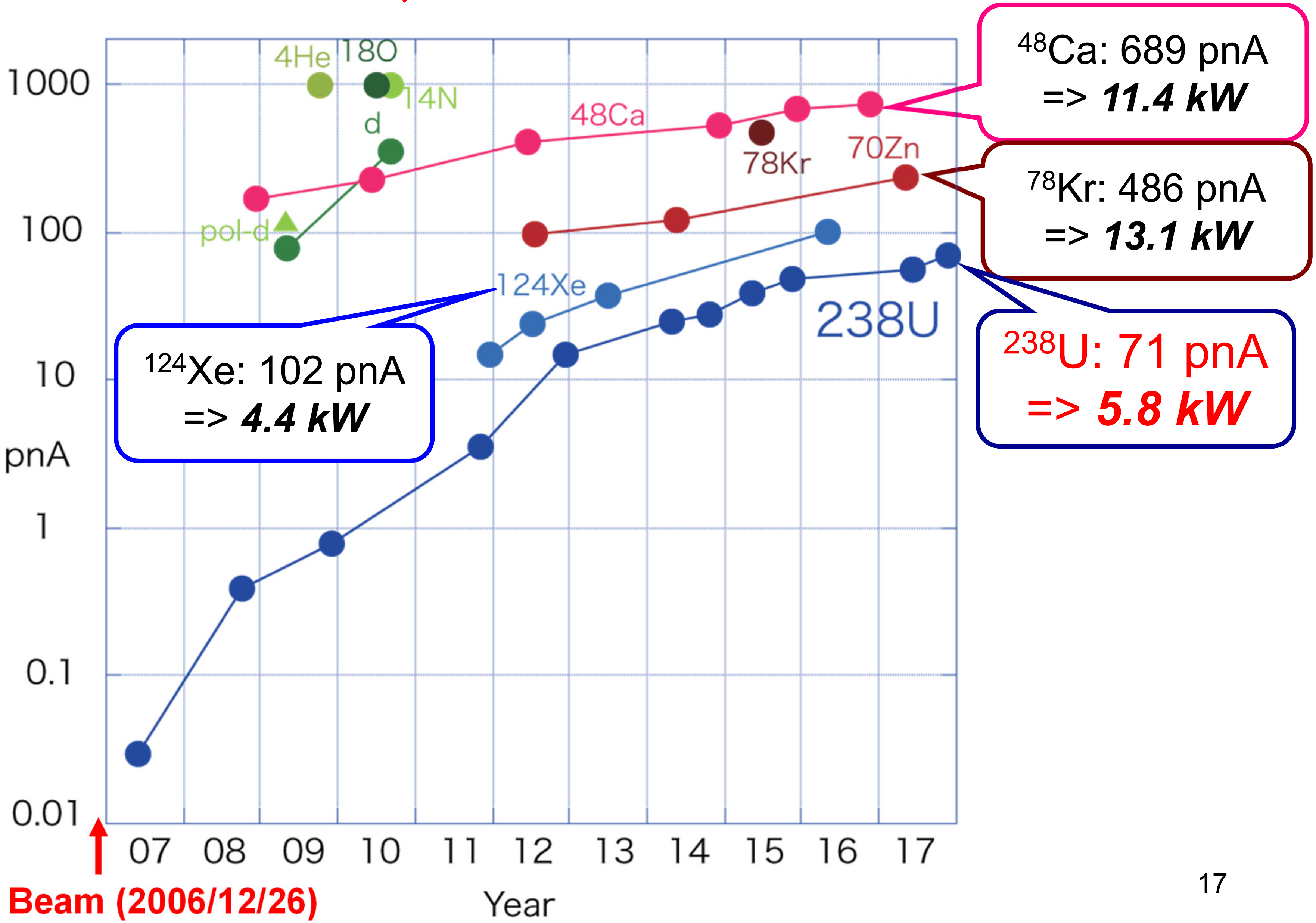
SC : superconducting, NC : normal conducting, FT : flattop resonator





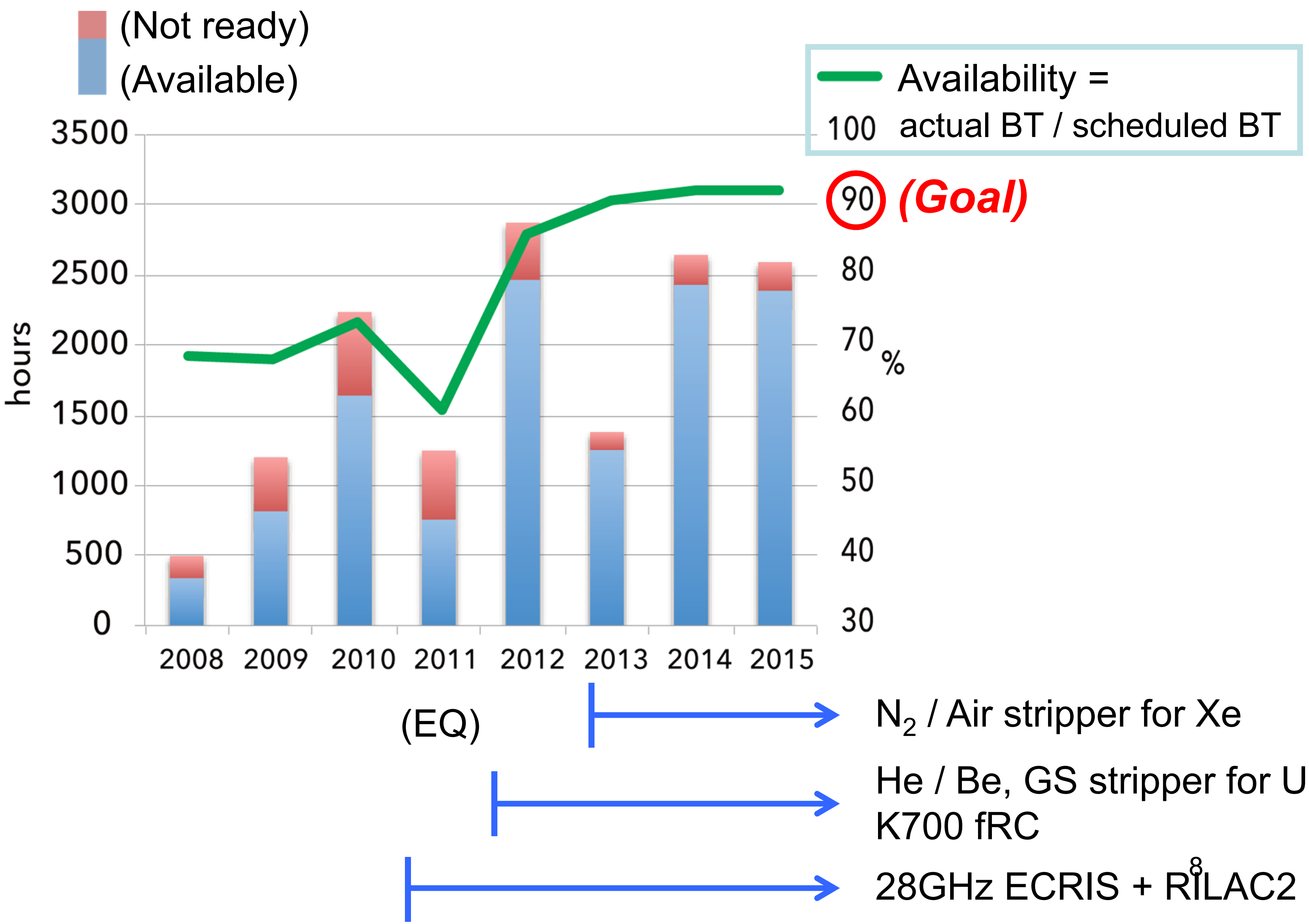
History of accelerator performance

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



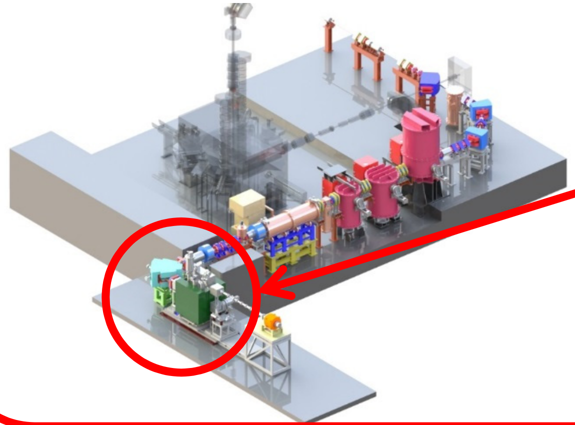
First Beam (2006/12/26)

History of accelerator availability

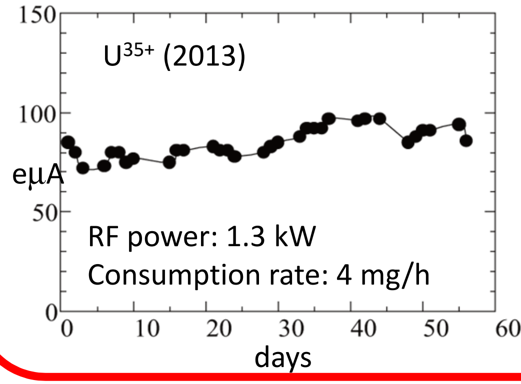


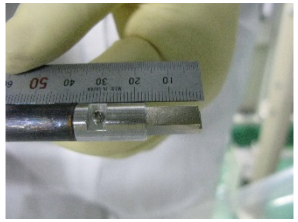
Major upgrade during 2011-18 for U-beam

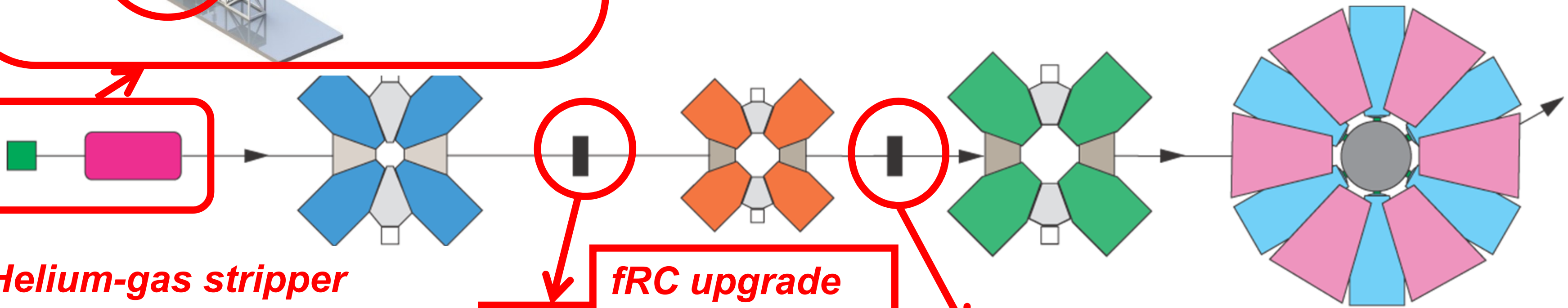
RILAC2



28GHz ECRIS

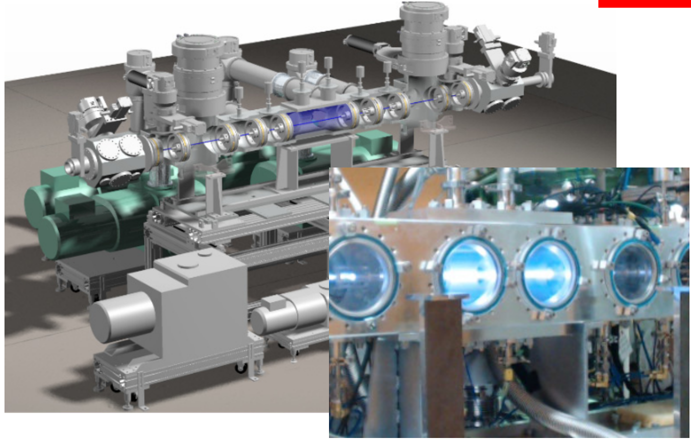






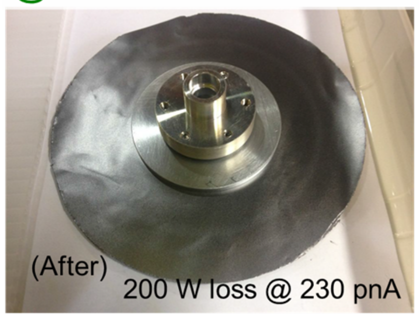
Helium-gas stripper for the 1st Charge stripper

fRC upgrade (K570=>K700)



Highly-oriented graphene sheet for the second stripper

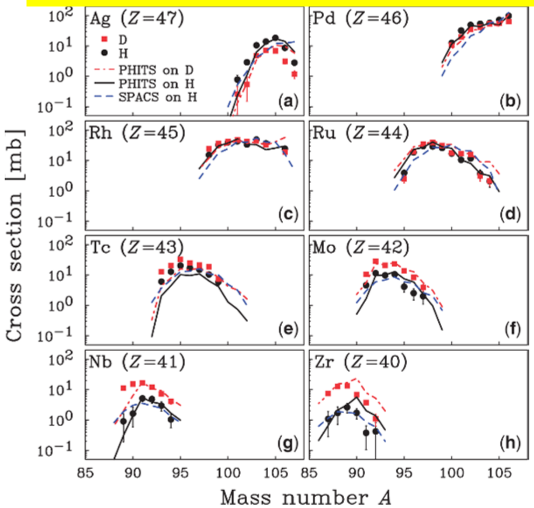
No damage @ 1.4×10^{18} uranium ions!!



Important Scientific achievements

- Naming right of Element 113 (Nh)
- New isotope (176)
- New magic number
- RI production
- Plant breeding
- LLFP nuclear data
- etc.

The name of 113th element



Cross section of LLFP

Anomalies in magic numbers

New isotopes

Lessons learned from the operational experiences

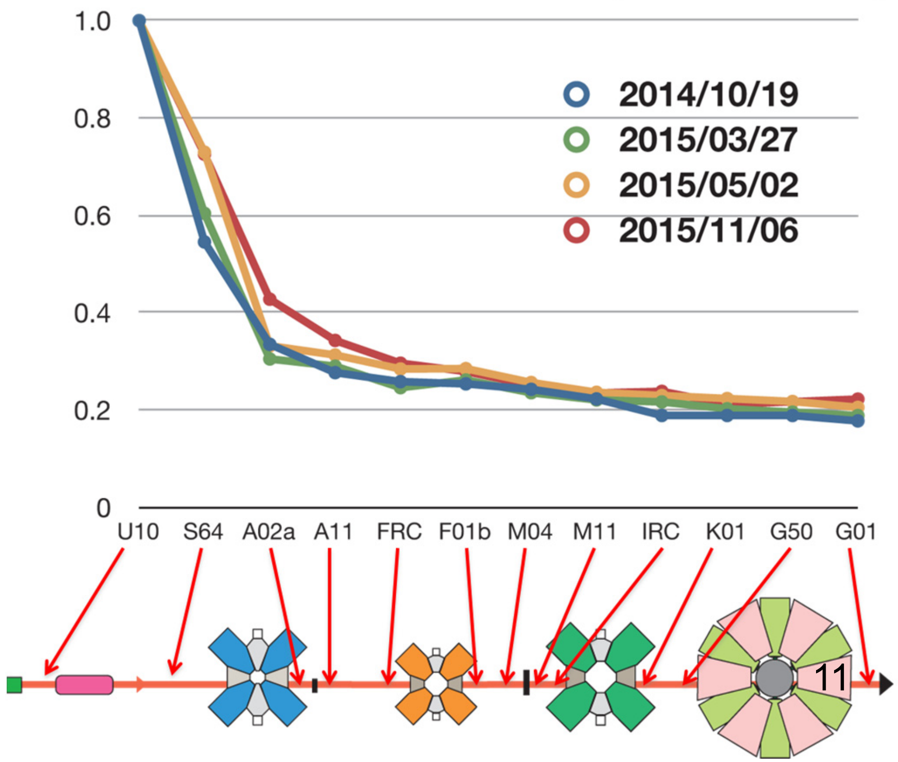
- It is very tough business to operate the accelerator complex where four cyclotrons are connected in series. (Inj./ext. four times, energy matching between the cyclotrons and single turn extraction)
- Multi-step charge stripping should be avoided and thickness of the charge stripper should be as thin as possible.
- Space charge effect is very intense in the low energy ring cyclotron (RRC)
- About 20% of beams from the ion source can reach at the exit of the SRC.

(cf. PSI ~30%)

(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 R. Baartman, Proc. of Cyclotrons2013 WE2PB01.

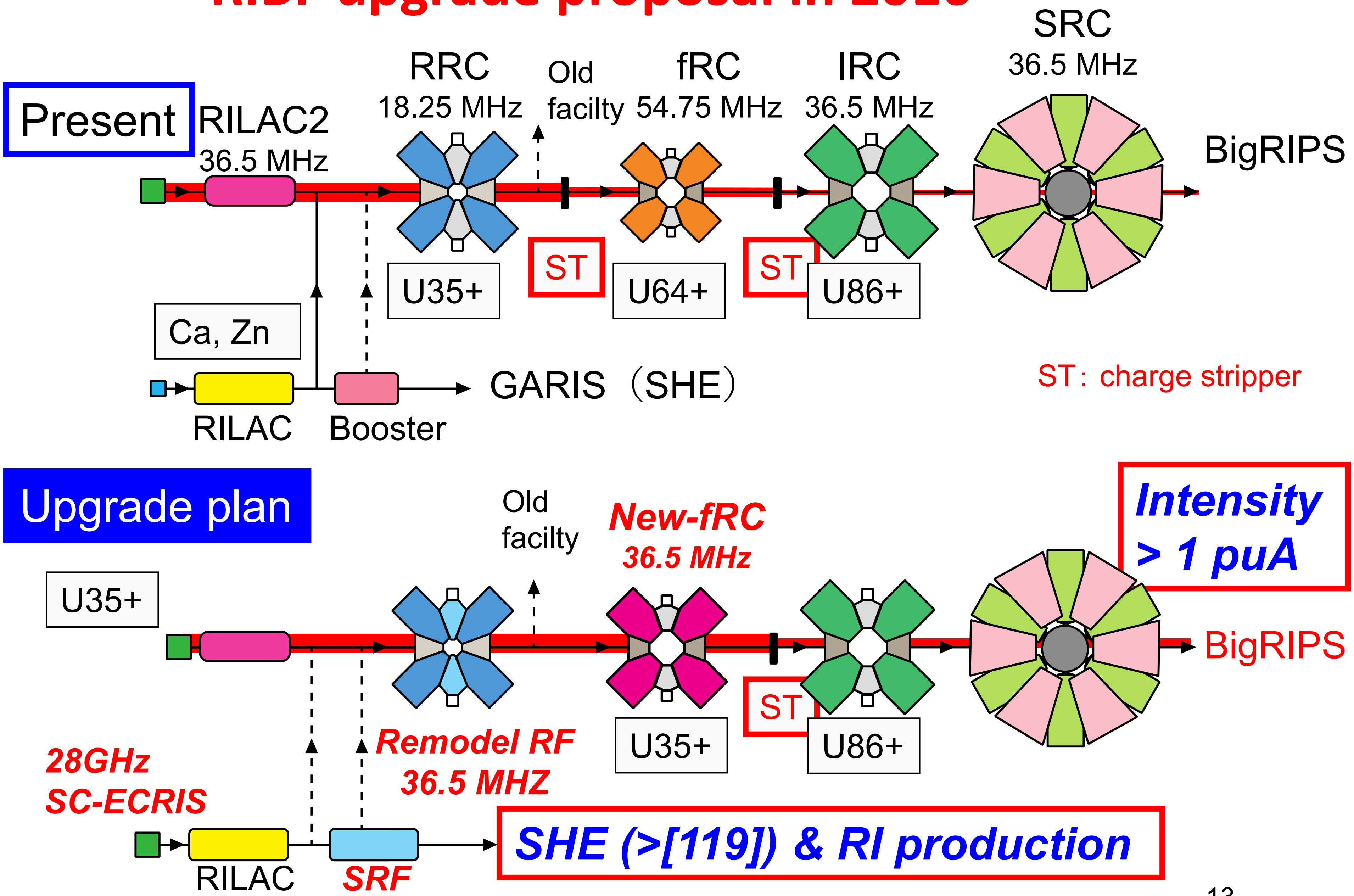
For uranium beam: excluding c.s. efficiency



Outline of a new upgrade program

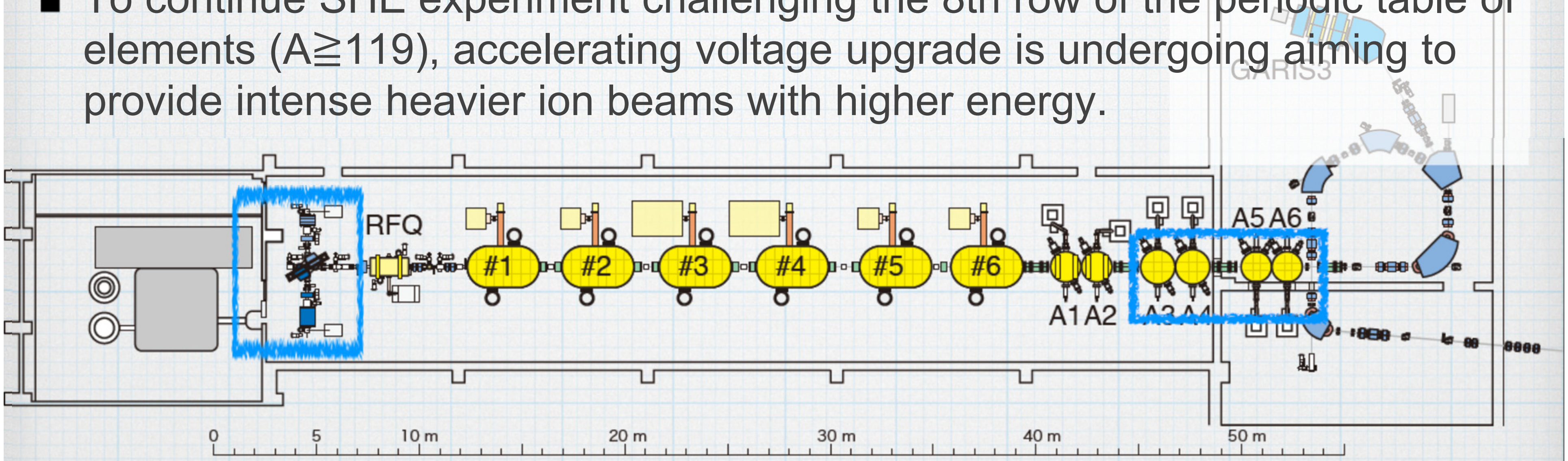
- Goal
  - More than 1 pμA of uranium beam with the energy of 345 MeV/u
  - Synthesis of the super heavy elements (element 119 and 120,,,,)
- Components
  - Increase the space charge limit in the low energy cyclotron of RRC
    - **Remodel of the RRC cavity to get higher voltage**
  - Skip the first stripper. The existing FRC should be replaced with the new one so as to accept U35+
    - **Design and construction of the new FRC**
  - **Upgrade of the RILAC by adding the superconducting RF linac**
- Constraint
  - We can't afford a new building (We have to install the new FRC in an experimental room of the existing building.)

RIBF upgrade proposal in 2016



Upgrade Plan of the RIKEN Heavy Ion LINAC (RILAC)

- RILAC consists of RFQ and 12 DTLs to provide intense heavy-ion beams to perform super heavy element search (SHE) experiment.
- For 113 element $^{70}Zn^{14+}$ (**A/q = 5**) was accelerated to **5 MeV/u**.
- To continue SHE experiment challenging the 8th row of the periodic table of elements (A≧119), accelerating voltage upgrade is undergoing aiming to provide intense heavier ion beams with higher energy.



- Upgrade Goal: Ions **A/q = 6** will be accelerated up to **6.5 MeV/u**.
- The last four DTL tanks will be replaced by superconducting linac based on quarter wave resonator. The 18GHz ECR ion source will be replaced with the 28 GHz ECR ion source.

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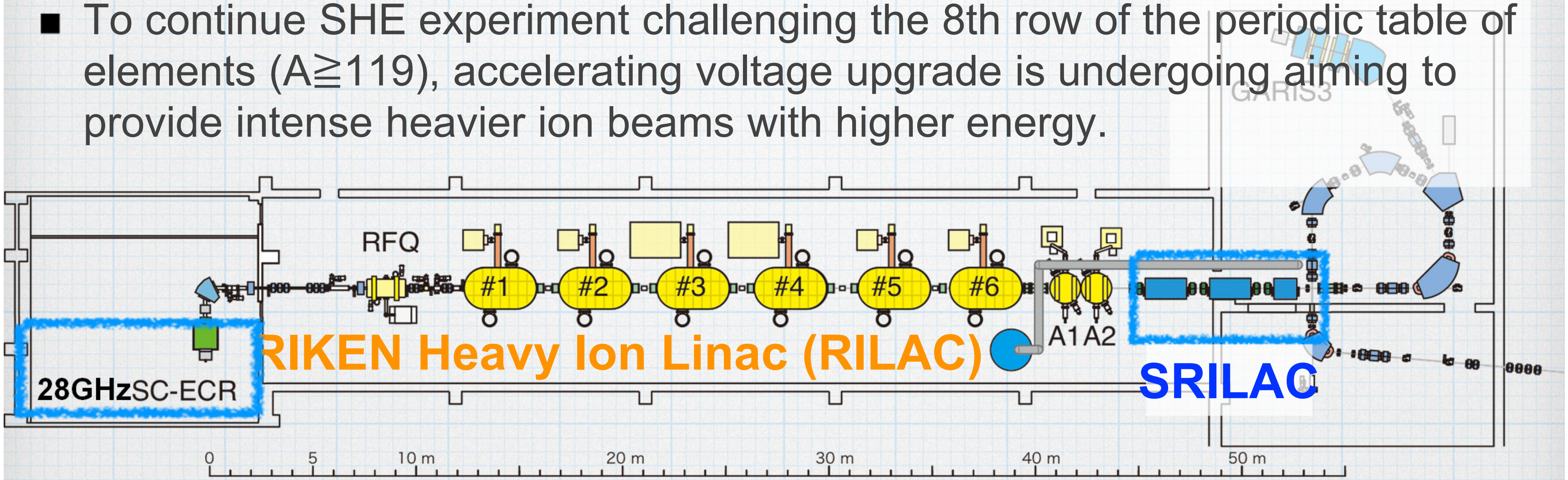

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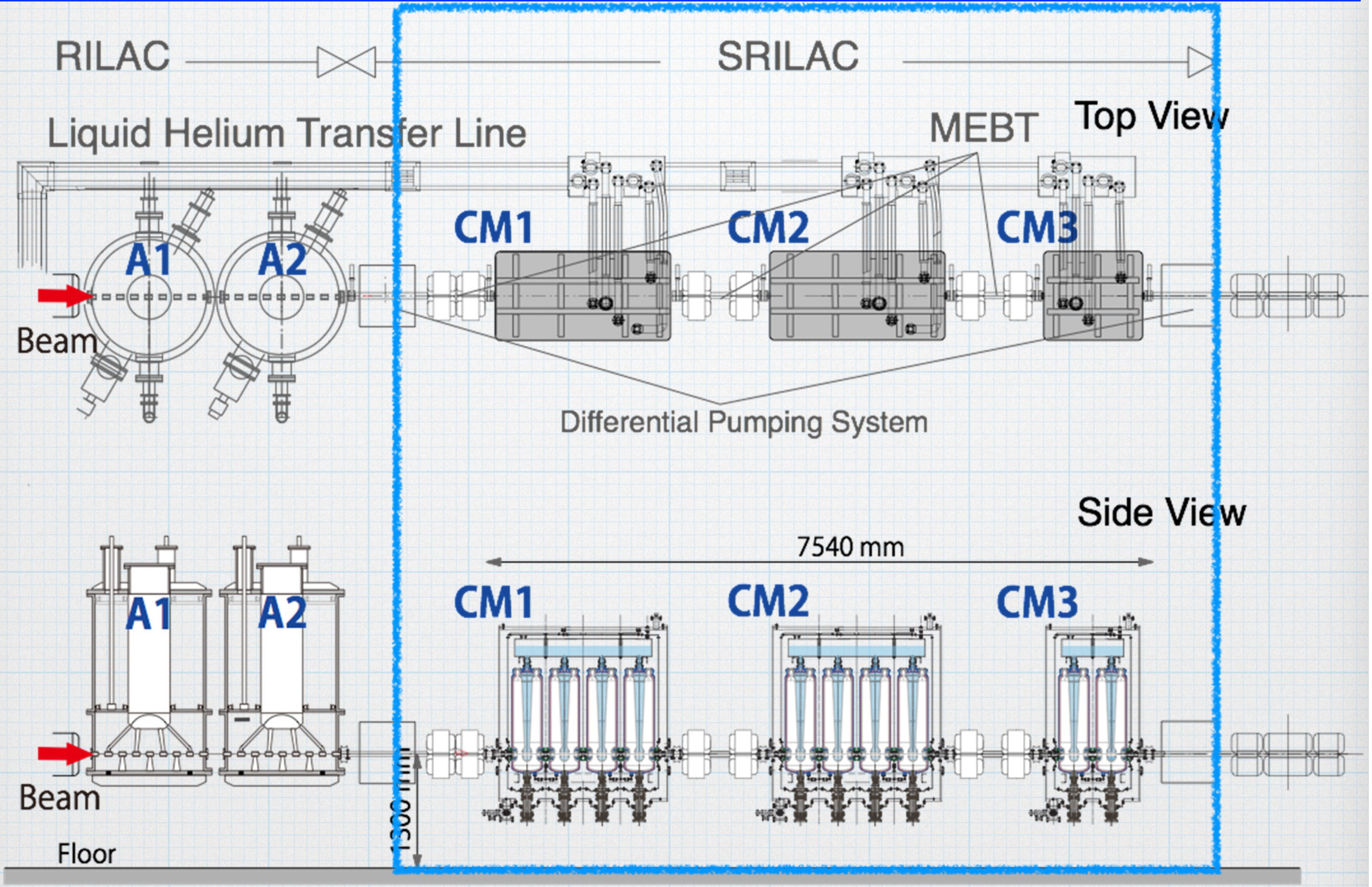
Overview of SRILAC



Design Specification of SRILAC

Design Parameters	
Number of cavities	10 QWRs
Frequency (MHz)	73.0 (c.w.)
E_{inj} (MeV/u)	3.6 (A/q = 6, $\varepsilon_{x,y}$=3 mm・mrad)
E_{ext} (MeV/u)	6.5
Gap Voltage (MV)	1.2 MV
Synchronous Phase (deg.)	-25
E_{acc} (MV/m)	6.8
Target Q_0	1×10^9 at 4.5K
Beam Current (μA)	<100 μA
RF bandwidth(Hz)	±60
Q_{ext}	1×10^6 — 4.5×10^6
Amplifier Output Power (kW)	7.5

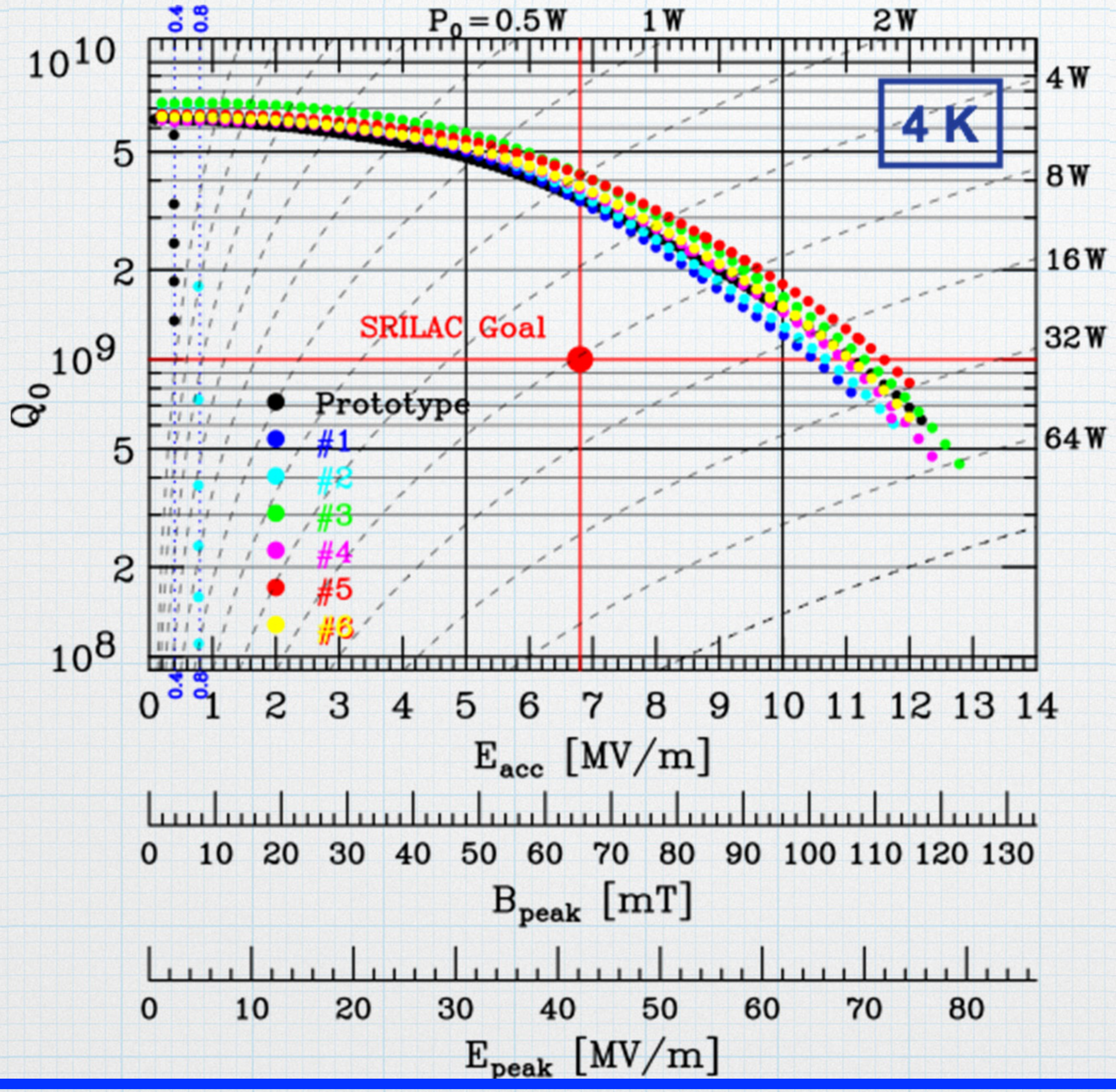
Overall acceleration voltage of the SRILAC is 18 MV for A/q = 6

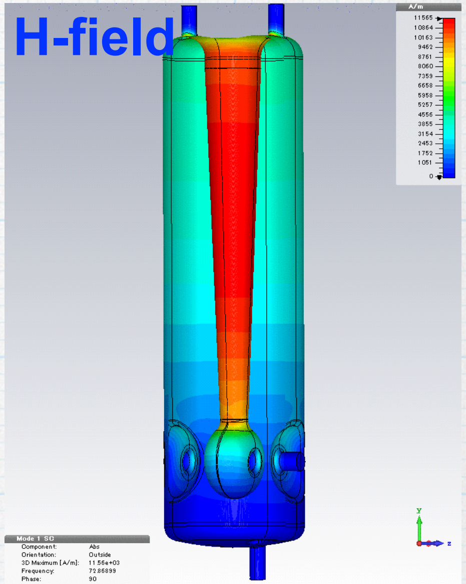
Production of QWRs




Validation of Bulk Cavities

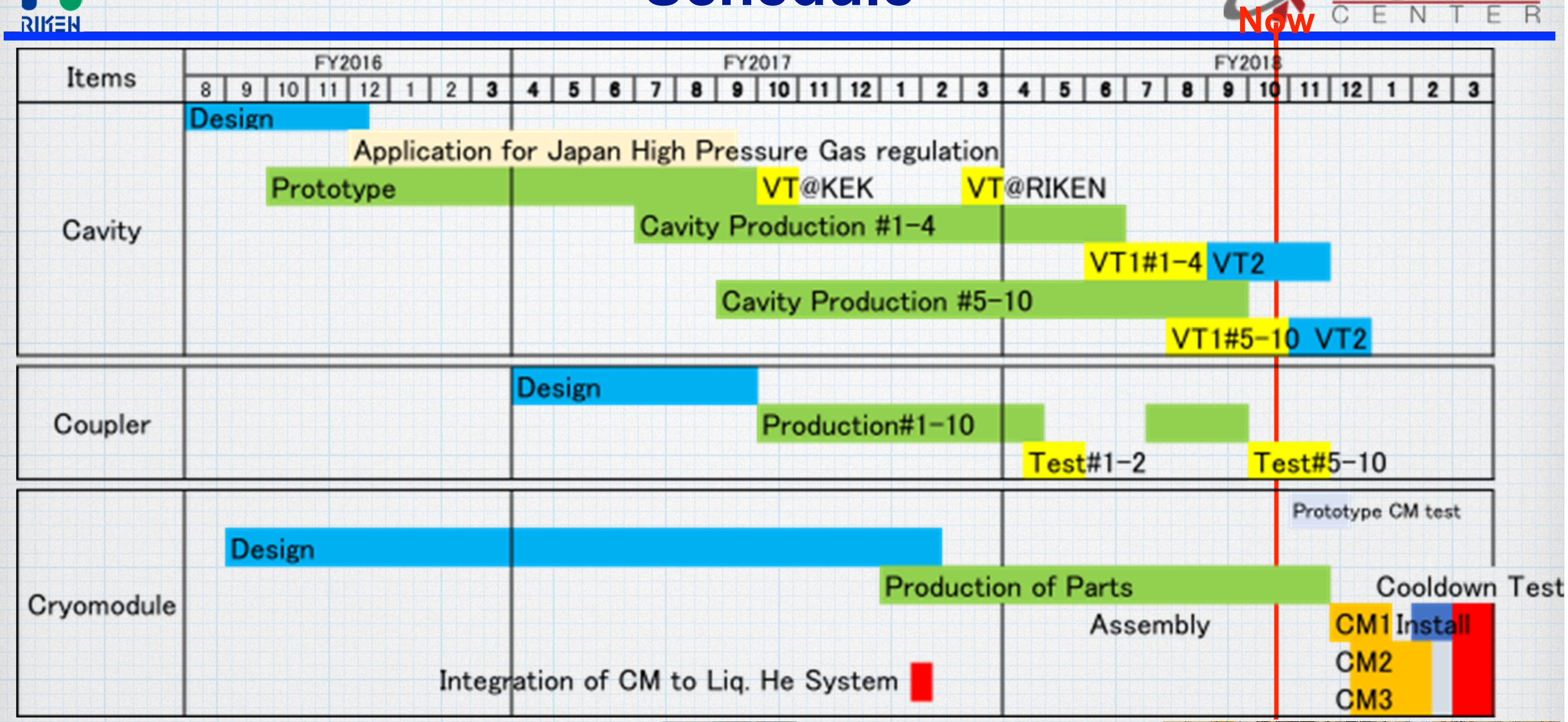
- Validations of six bulk cavities were finished.





Parameters	
Frequency (MHz)	73.0(c.w.)
Optimum β	0.08
R_{sh}/Q_0 (Ω)	578
G (=R_{sh}/Q_0)	22.4
V_{acc}(MV)	2
E_{acc} (MV/m)	6.8
E_{peak}/E_{acc}	6.0
B_{peak}/E_{acc}	9.5
Target Q_0	1×10^9 (4 K)

Schedule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Items
FY2016
FY2017
FY2018
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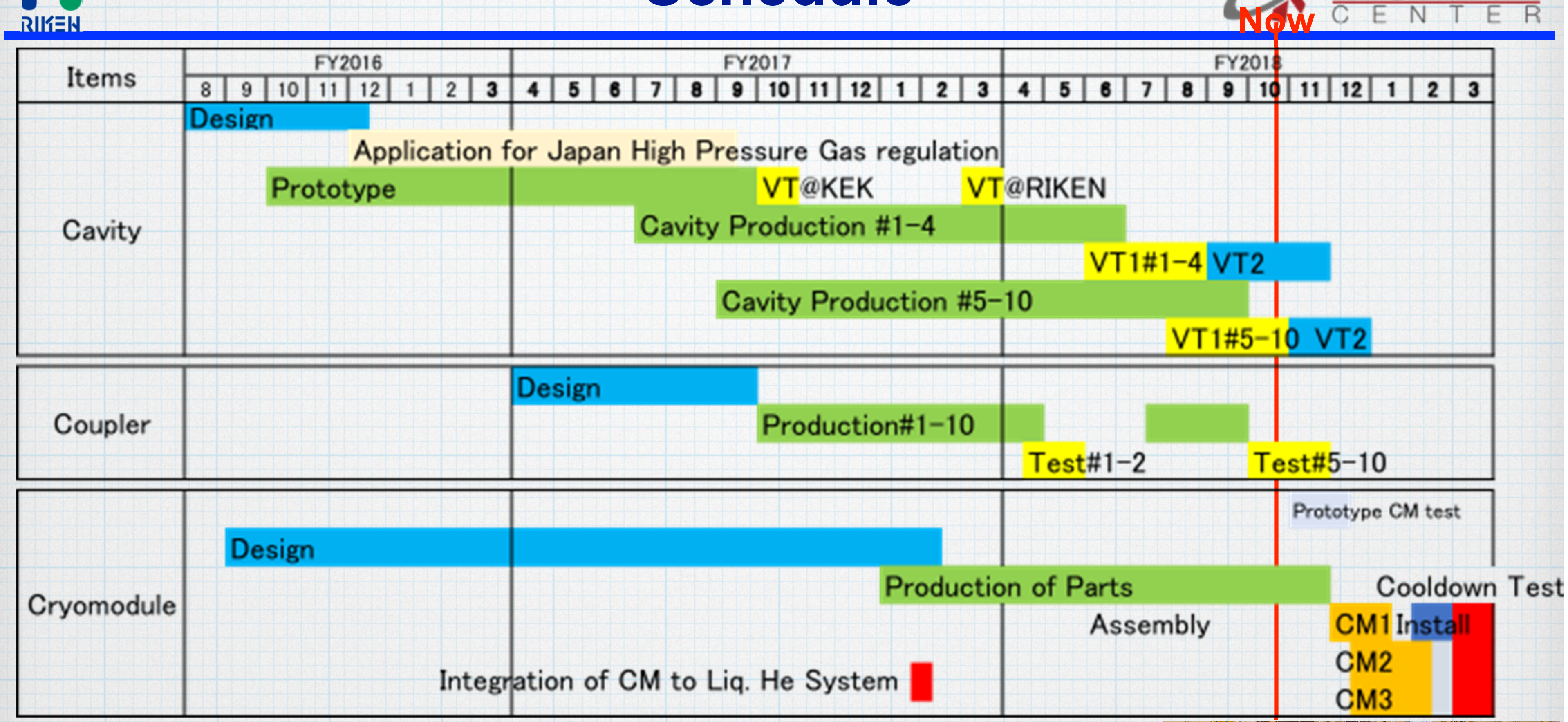
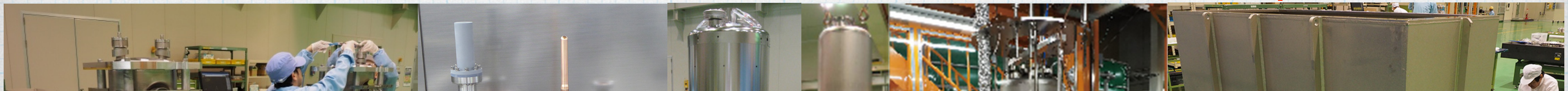
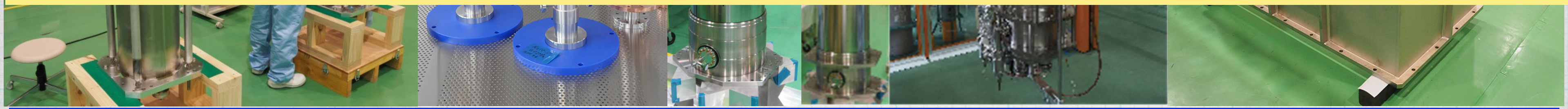
Cavity
Design
Application for Japan High Pressure Gas regulation
Prototype
VT@KEK
VT@RIKEN
Cavity Production #1-4
VT1#1-4
VT2
Cavity Production #5-10
VT1#5-10
VT2
Coupler
Design
Production#1-10
Test#1-2
Test#5-10
Cryomodule
Prototype CM test
Design
Production of Parts
Cooldown Test
Assembly
CM1
Install
CM2
CM3
Integration of CM to Liq. He System

Schedule

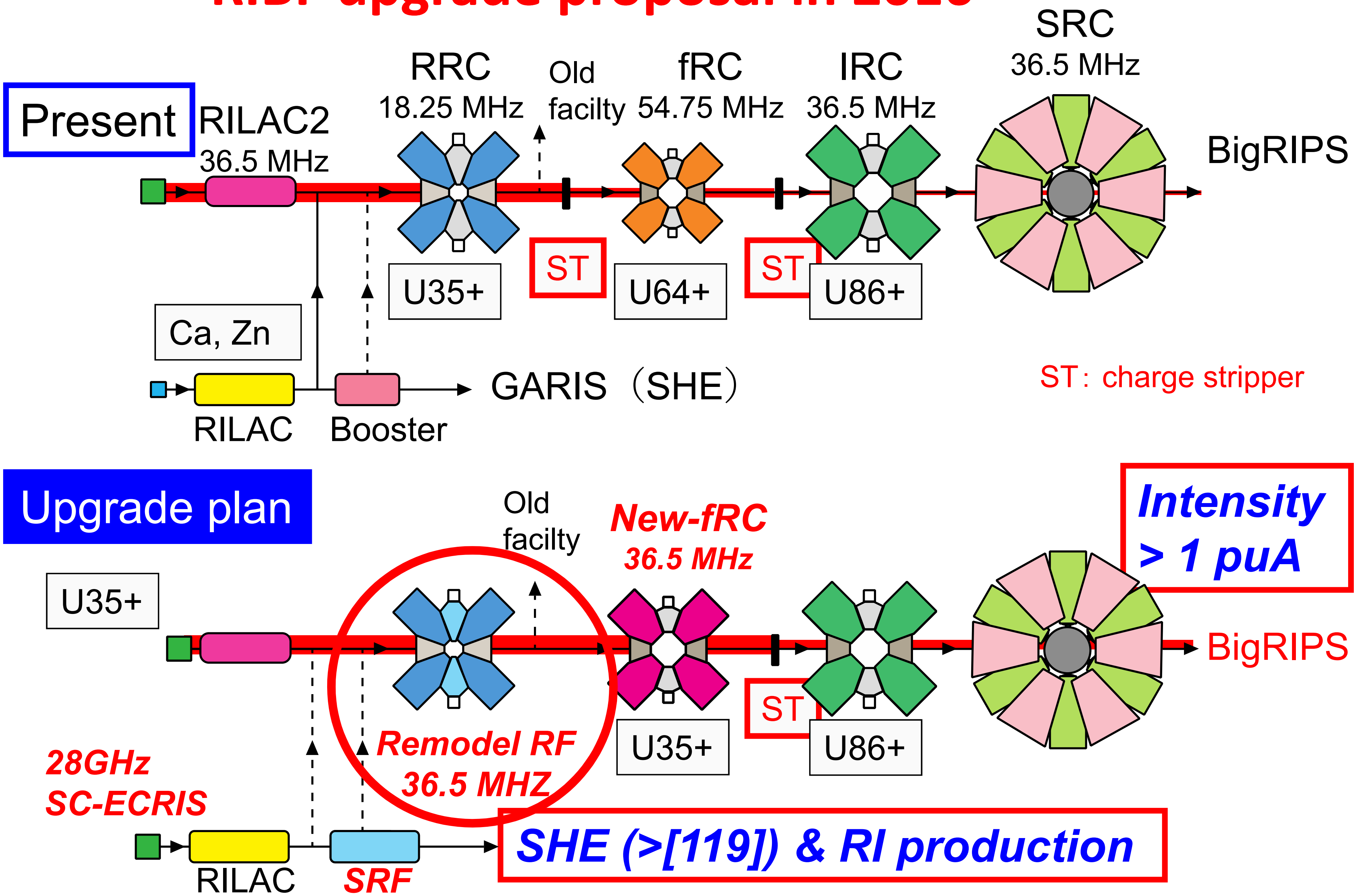




We had started experiments for the element 119 using RILAC2+RRC.
It will continue until completion of the SRILAC.



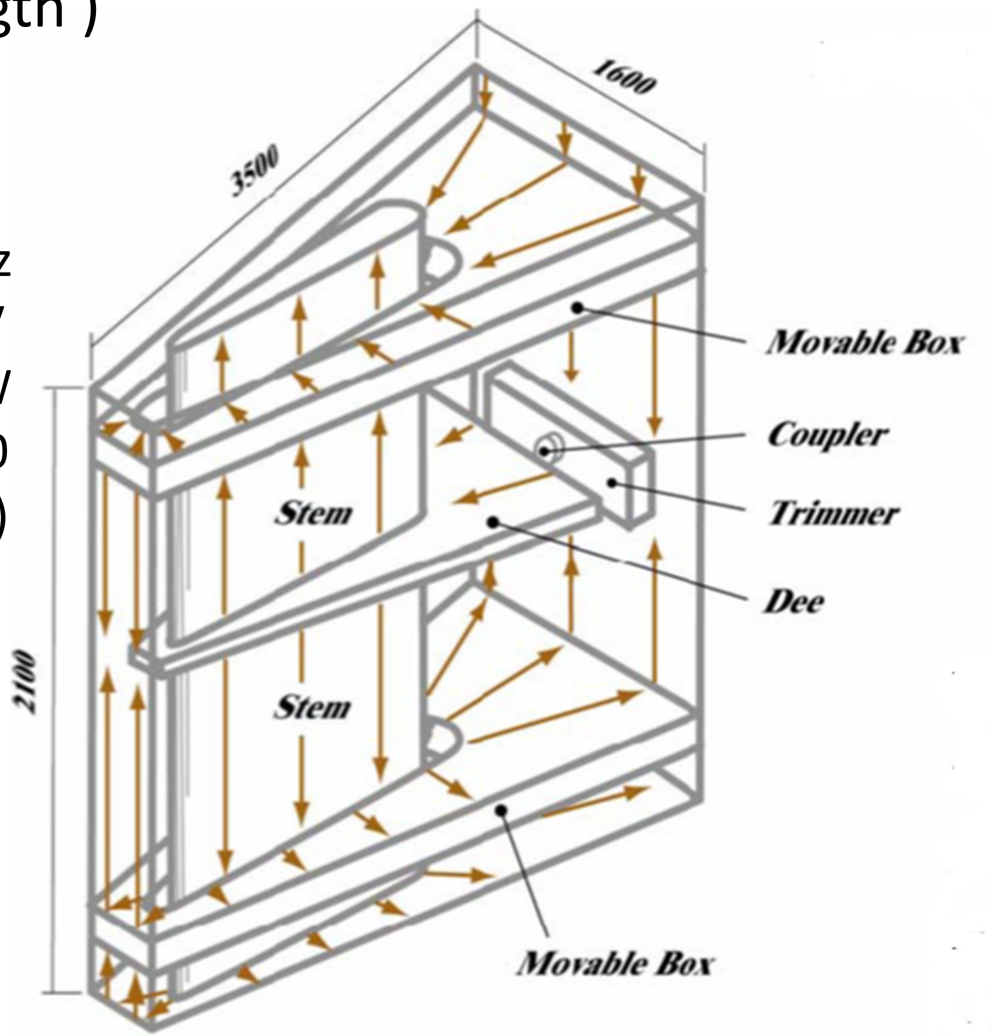
RIBF upgrade proposal in 2016



Structure of the cavity for RRC

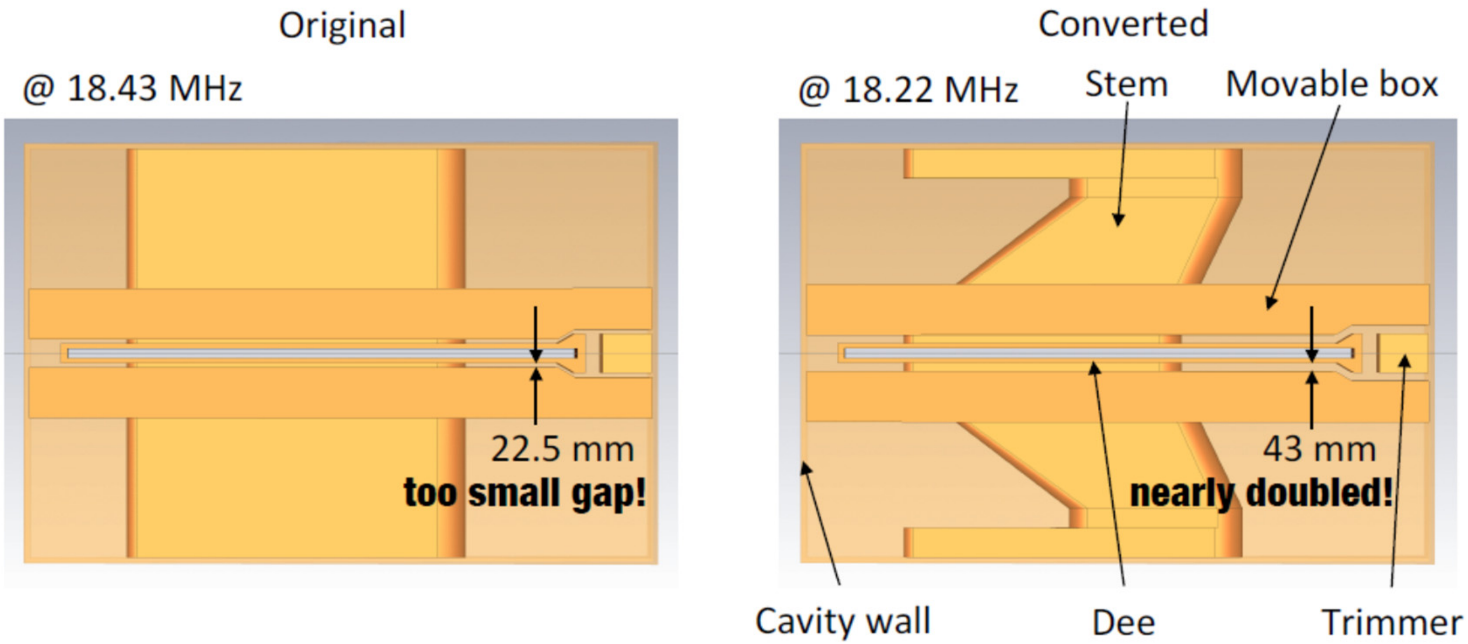
Coaxial type cavity (Half wave length)
Frequency tunable: movable box

Frequency	18.0-45.0 MHz
Acc. voltage at 45.0 MHz	300kV
RF-power dissipation at 45.0MHz	150 kW
Q-value at 45.0 MHz	12000
Size	3.5m (L) x 1.6m(W) 2.1 m (H)



Towards Higher Acceleration Voltage of RRC

✓70 pnA (uranium beam) is nearly the space charge limit of RRC.
low acceleration voltage ← too low operating frequency
✓Modify frequency characteristic by introducing the slanted stem structure



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

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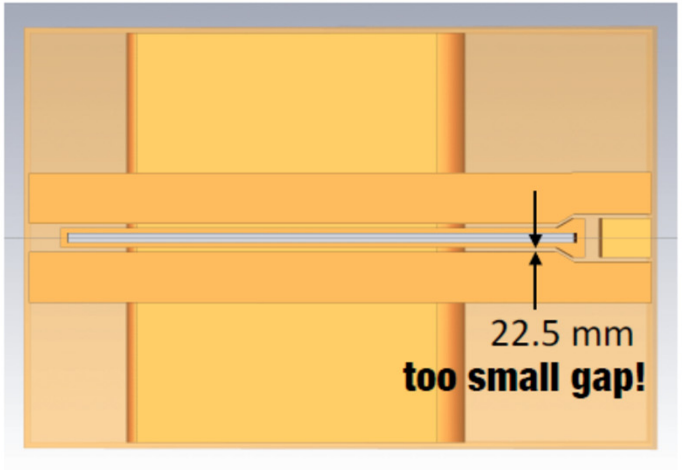
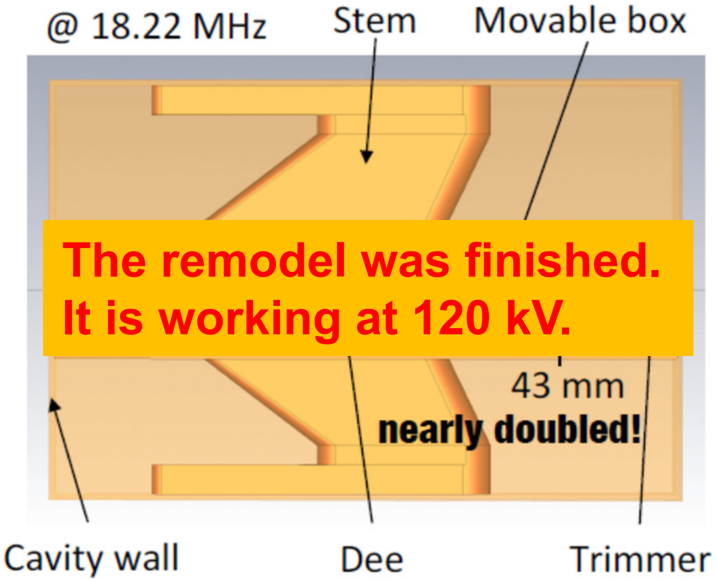
Original

@ 18.43 MHz



Converted

@ 18.22 MHz



The remodel was finished. It is working at 120 kV.

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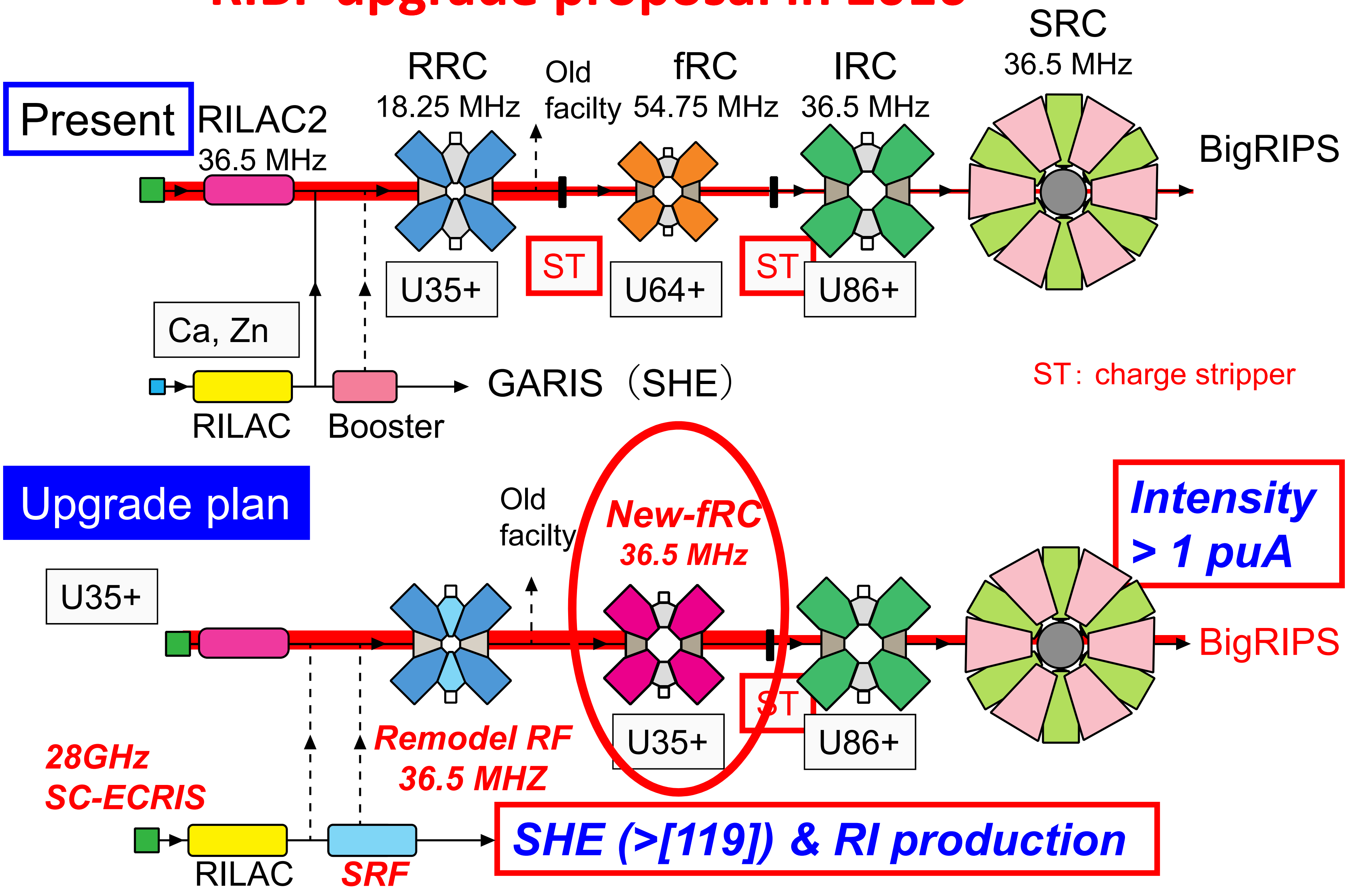
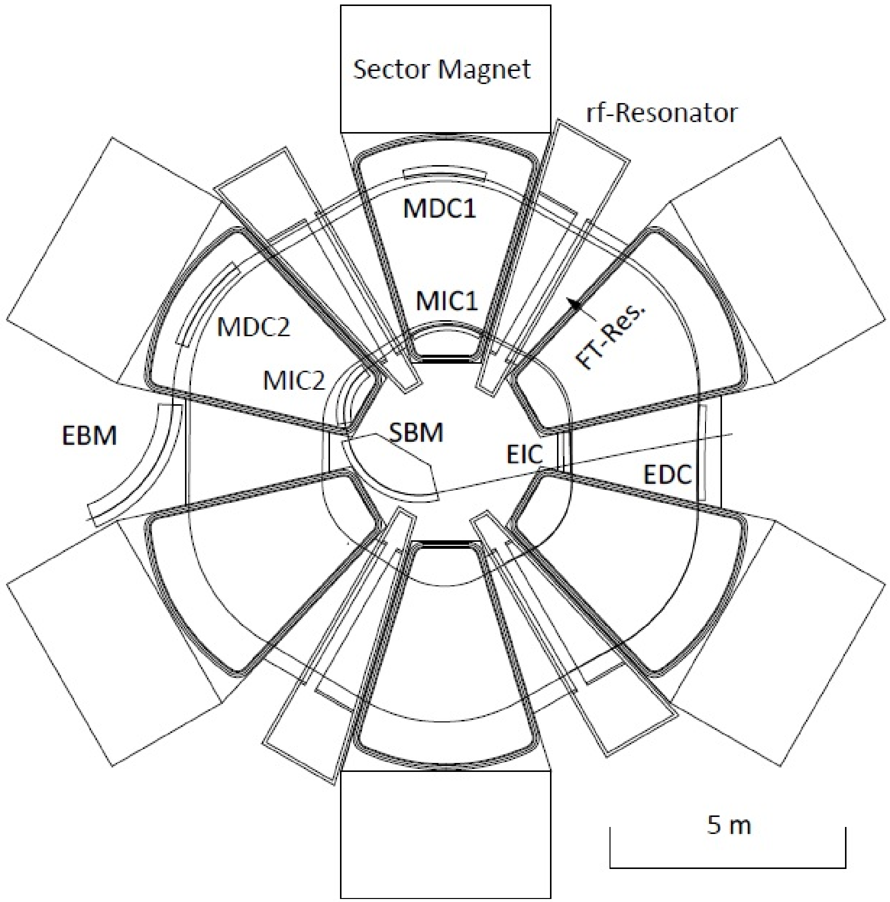
RIBF upgrade proposal in 2016



Conceptual design of the new FRC – Specification and Plan view

	New FRC	Existing FRC
K-value	2200	700
Sectors	6	4
Rf-Cavities	4+FT	2+FT
Rf-frequency (MHz)	36.5	54.75
Rinj. (m)	2.76	1.56
Rext. (m)	5.67	3.30
Velocity gain	2.1	2.1
Diameter (m)	19	10.8
Height (m)	6.6	3.34
Weight (ton)	8100 (7500*)	1320
Δr (cm)	1.5	1.3

*prospect for weight reduction



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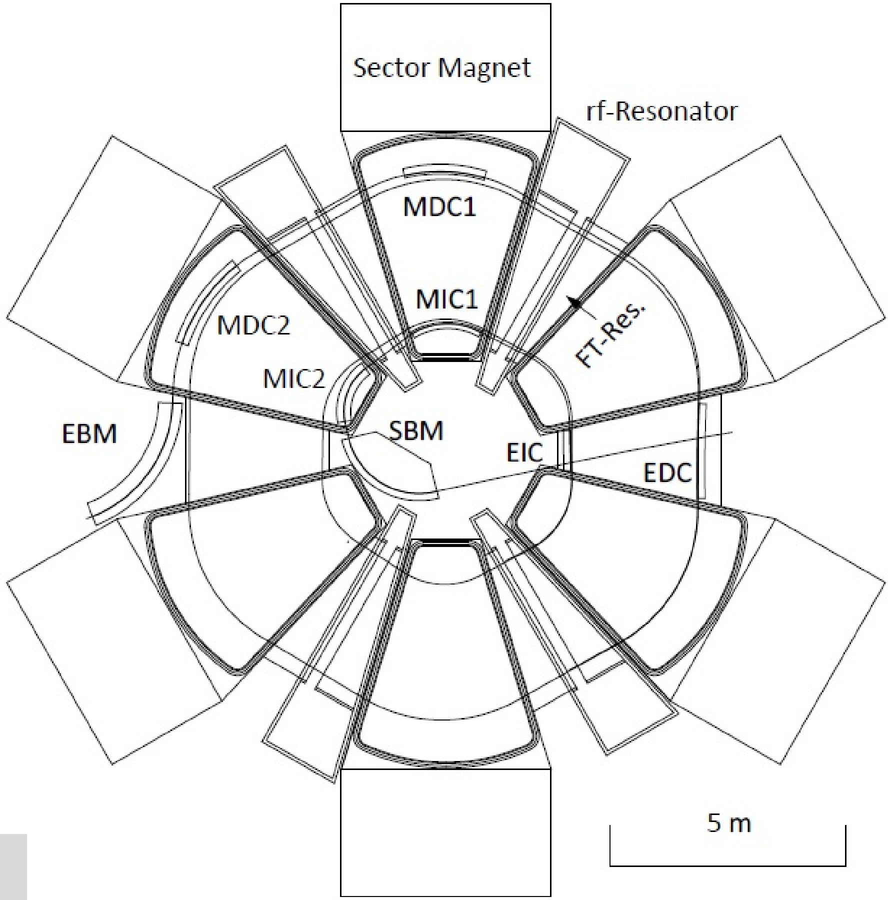
Very heavy

*prospect for weight reduction



Budget friendly version for upgrade of intensity of uranium beam without change of the goal

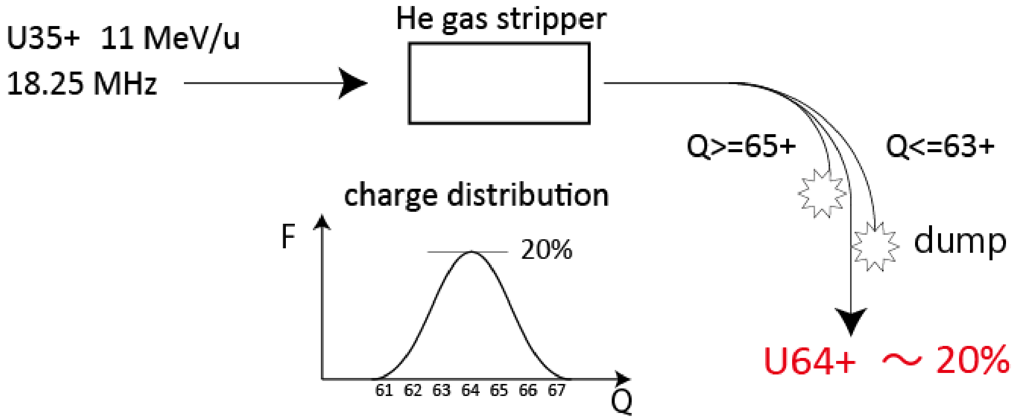
- Charge Stripper Ring
  - Aim at increasing of stripping efficiency up to 100%

    (Normally 6% in two step charge stripping)
- Low Charge state ion source
  - Aim at high brightness ion source with low charge state

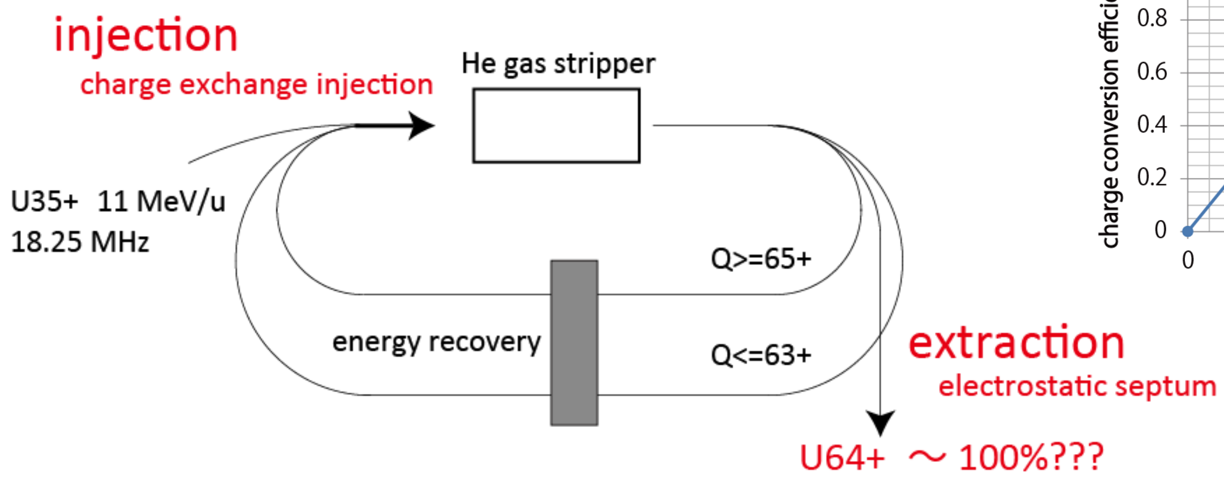
    (Highly charge ion source tends to increase beam emittance as beam intensity increases.)

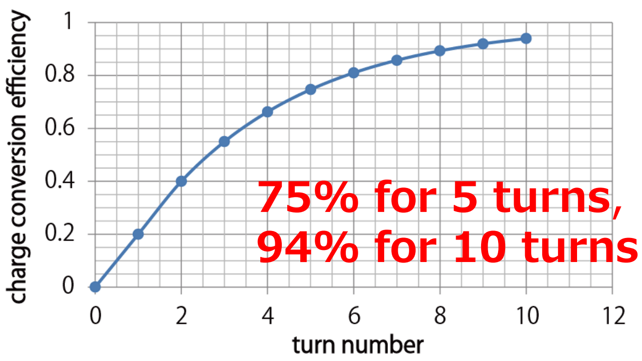
Concept of stripper ring

Present scheme at RIBF (conventional)



Stripper-ring scheme

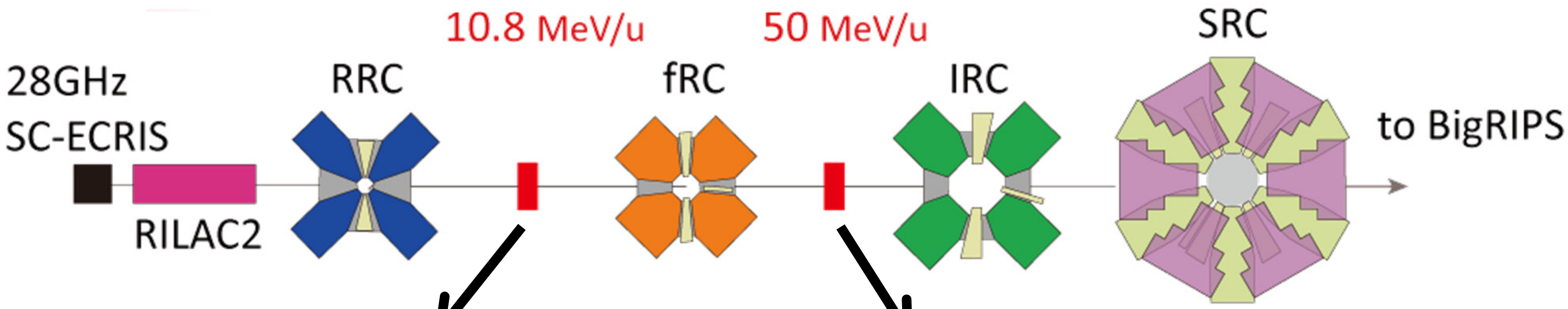




The bunch structure must be preserved to match to acceptance of the subsequent cyclotrons (e.g., 18.25 MHz at RIBF).

H. Imao

Charge stripper ring (CSR)



1． He gas stripper

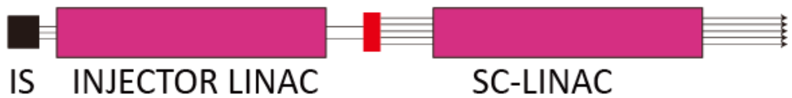
35+⇒64+ (20%)

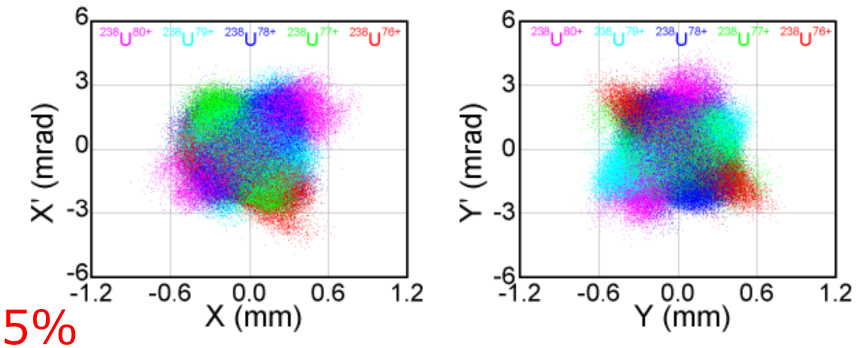
2． Rotating C-disk stripper

64+⇒86+ (30%)

Total charge conversion efficiency < 6%

FRIB uses multi-charge acc.





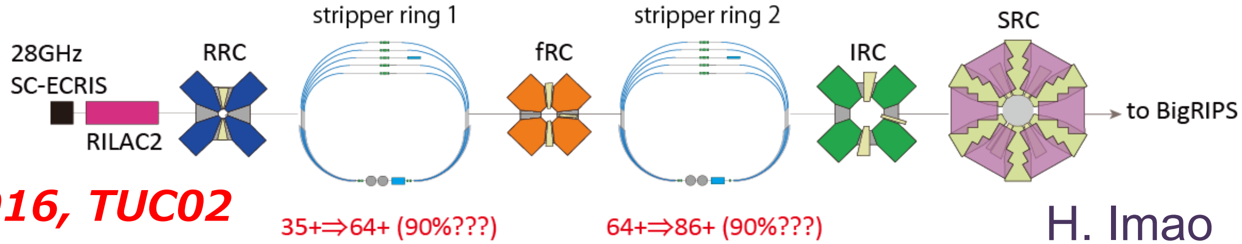
➡ aiming effective efficiency of 85%

Q. Zhao, HB2014

Charge stripper rings

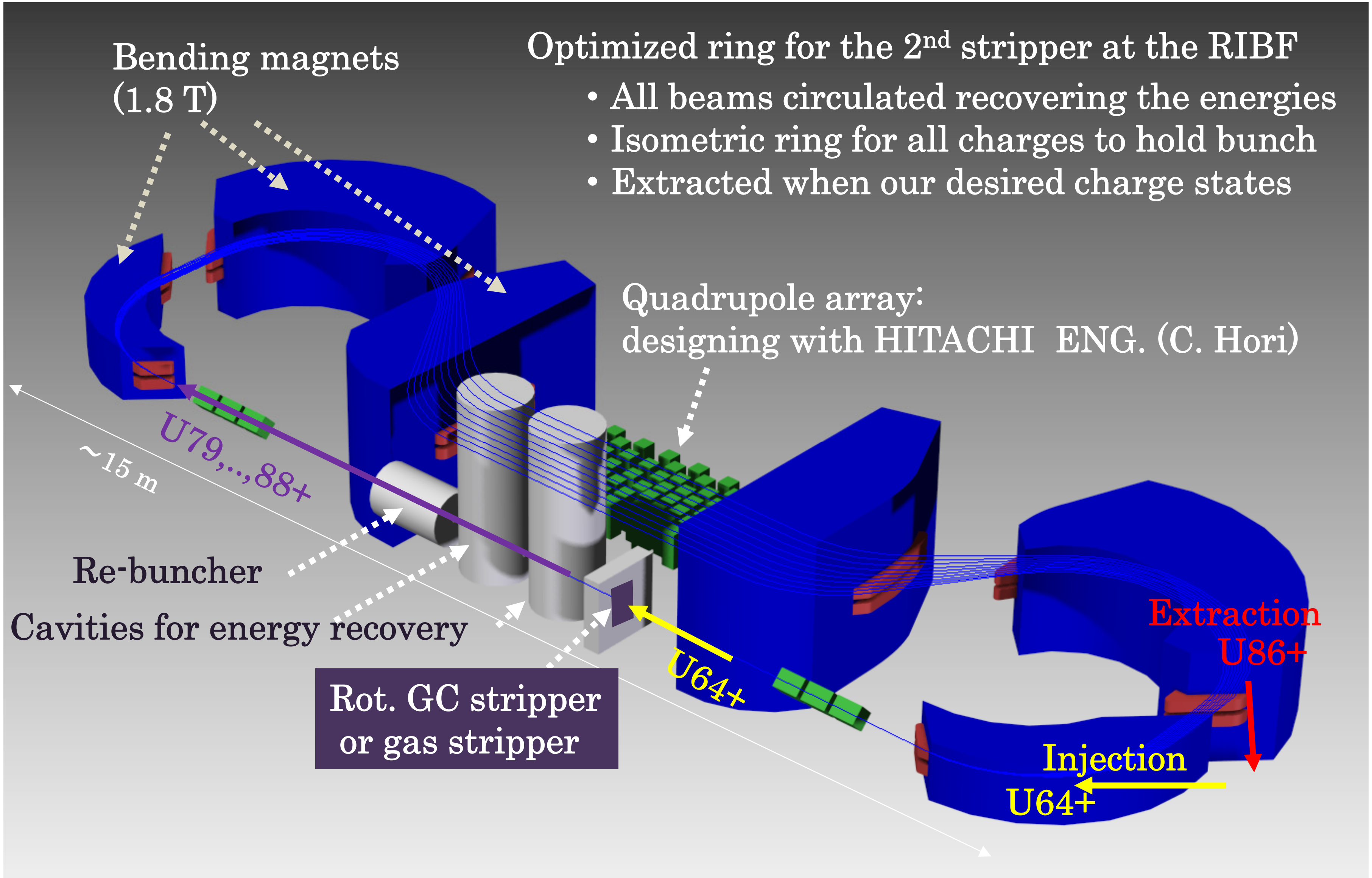
Efficiency ~100%?

H. Imao et al., Cyclotron2016, TUC02



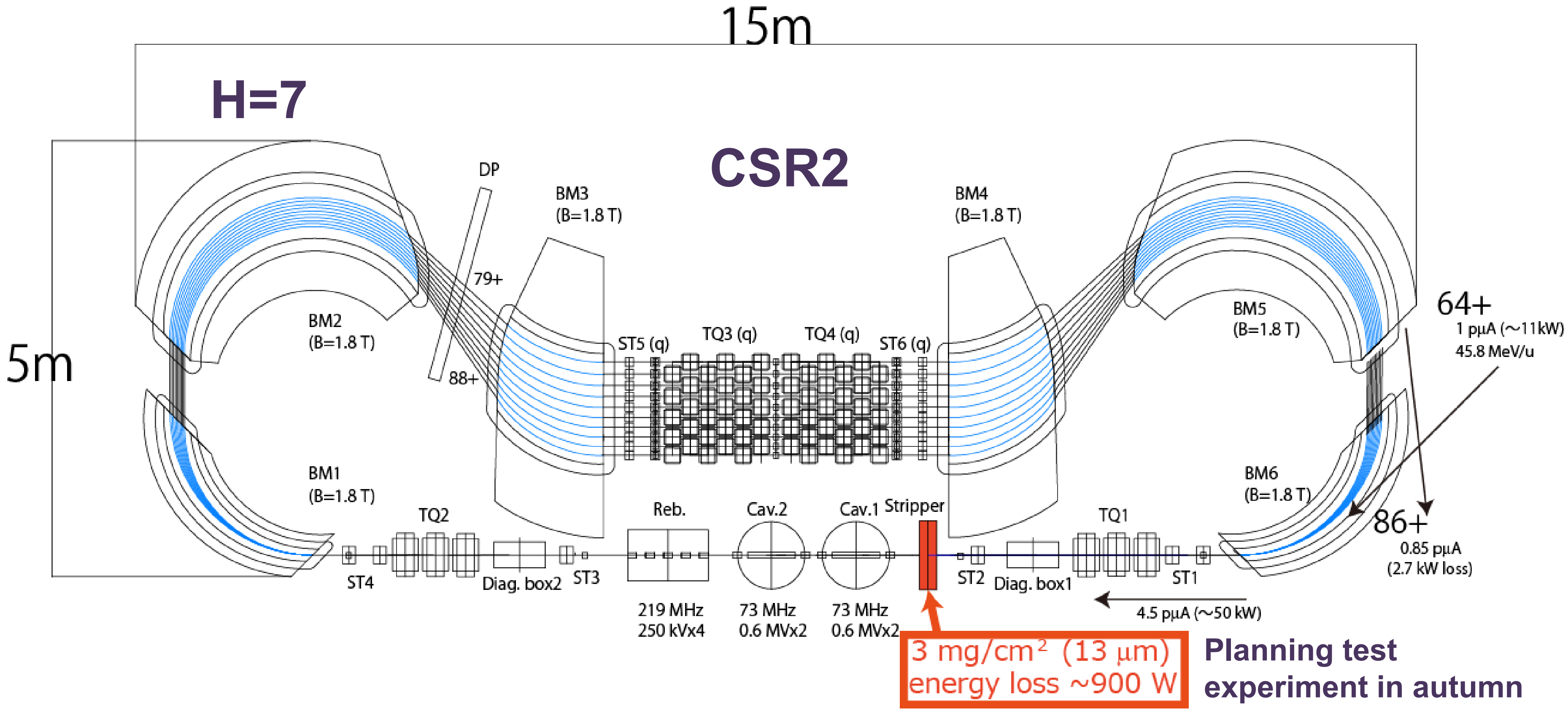
H. Imao

Design of CSR at 50 MeV/u



H. Imao

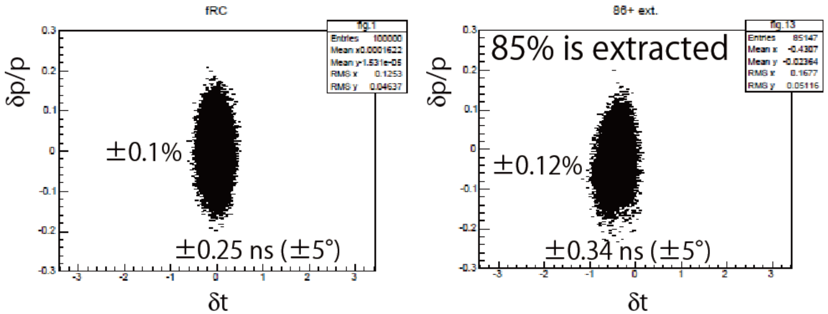
Longitudinal and transverse motions



Planning test experiment in autumn

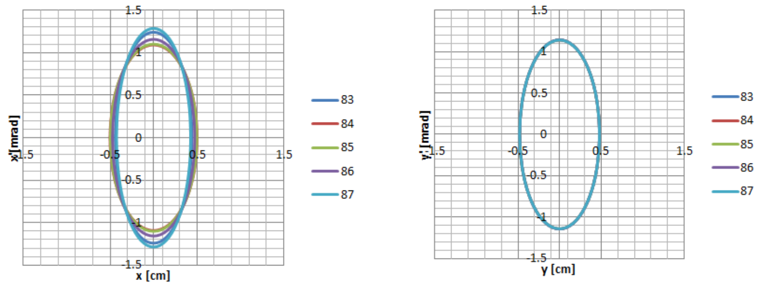
Longitudinal motions

initial beam at fRC | 86+ beams at extraction



Transverse motions

Eigen ellipses at stripper

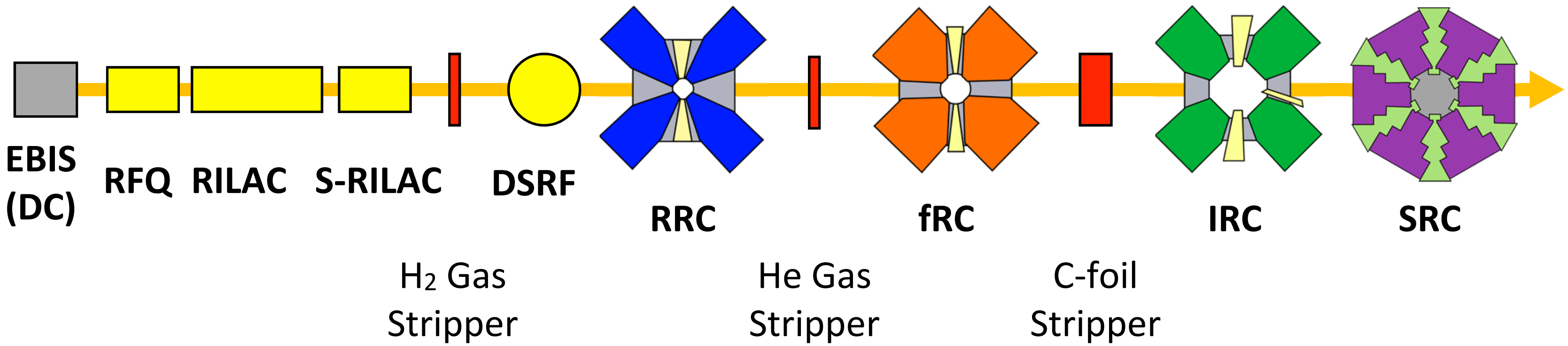


H. Imao

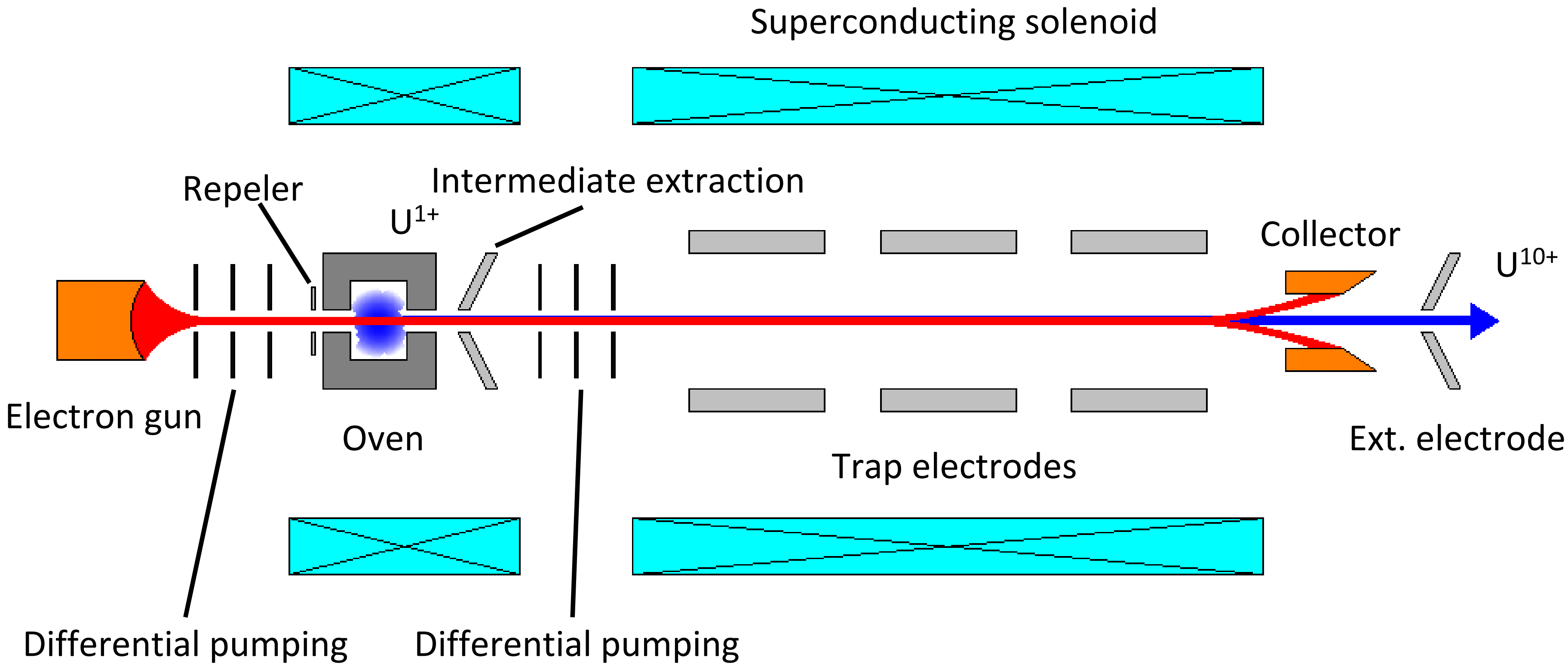
Low charge state ion source to get high brightness beam

・No change in accelerators after RRC. Just increase in beam from the ion source
・Beam emittance increases as beam intensity from the ion source.
・Increase of beam intensity from ECR keep the transmission of succeeding accelerator same.
→ We need high brightness ion source. (Low charge state ion source)

q	10+	10+	33+	33+	64+	86+	86+
E [MeV/u]		1.7	0.68	10.8	50	115	345
I [pμA]	68	68	15	15	3	1	1



Structure of DC-EBIS to be studied

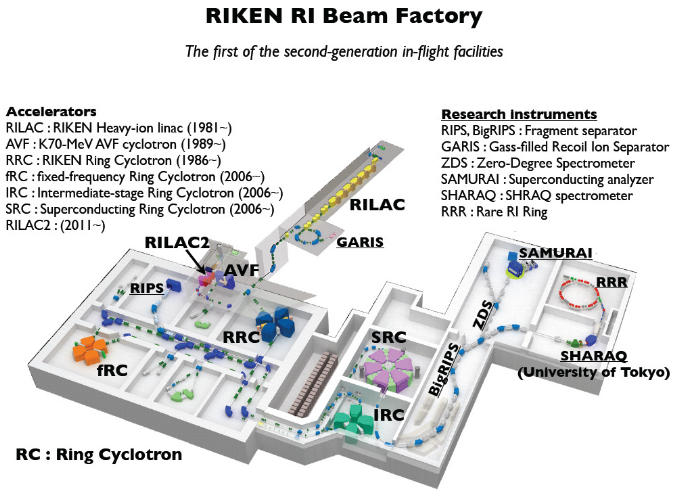


- Operation mode: Transmission mode
  → DC beam can be generated

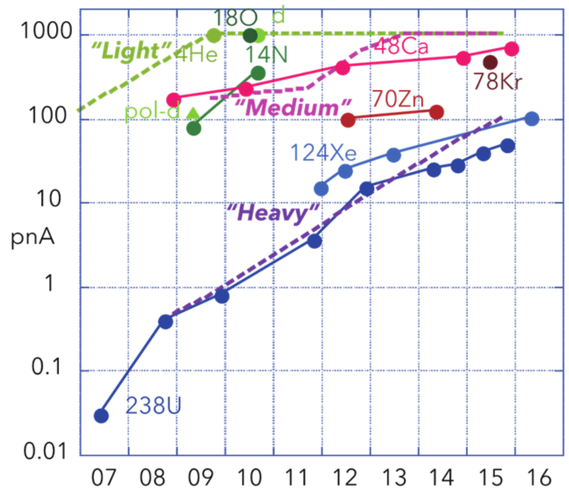
- Oven for uranium in the trajectory of electron beam
  → Low emittance beam can be generated thanks to electron beam with high quality

Review

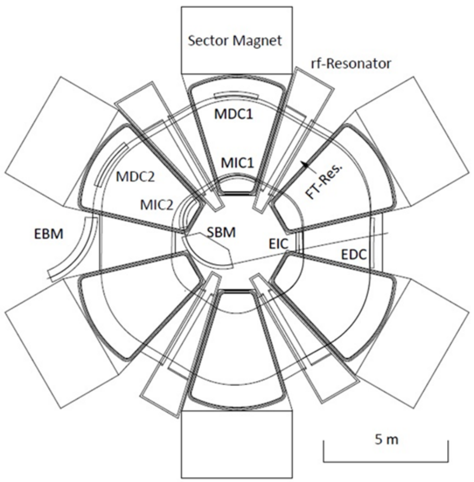
Introduction to RIBF



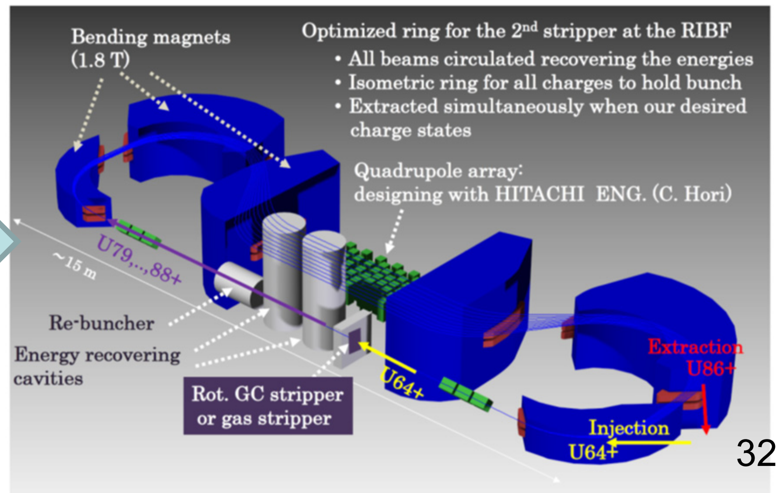
Operation of RIBF for 12 yrs



An upgrade plan



Budget-friendly version



Review

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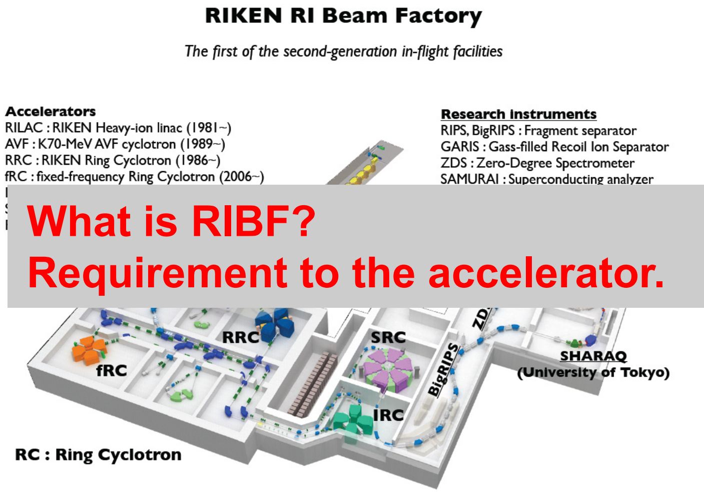

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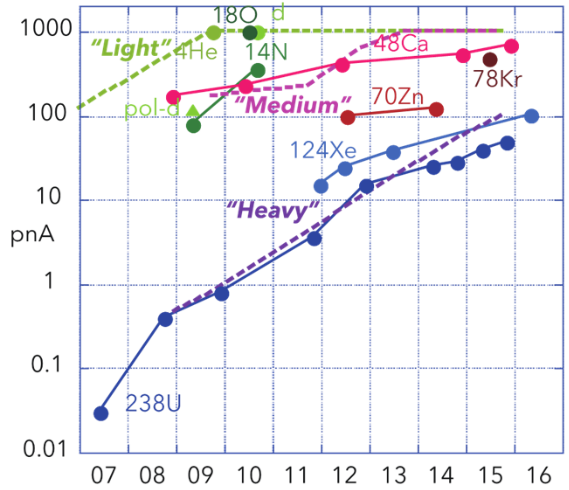

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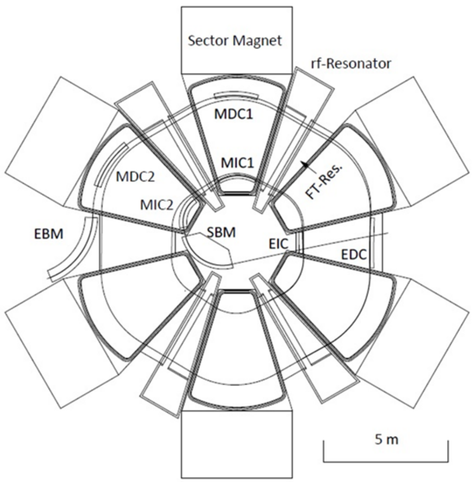

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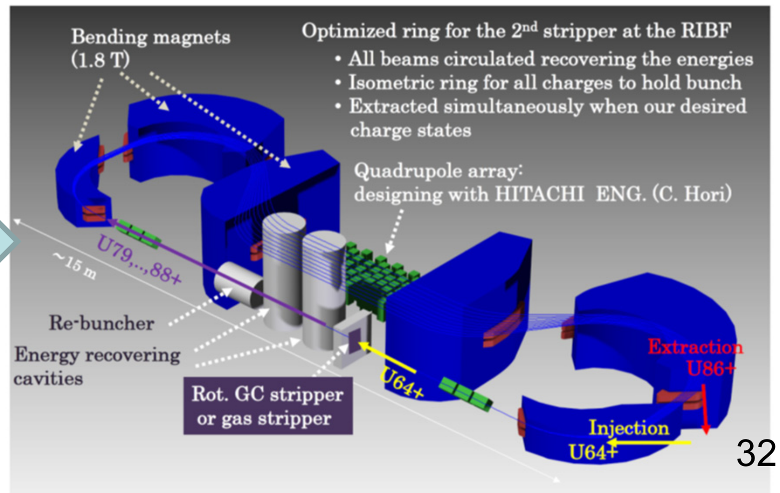

Review

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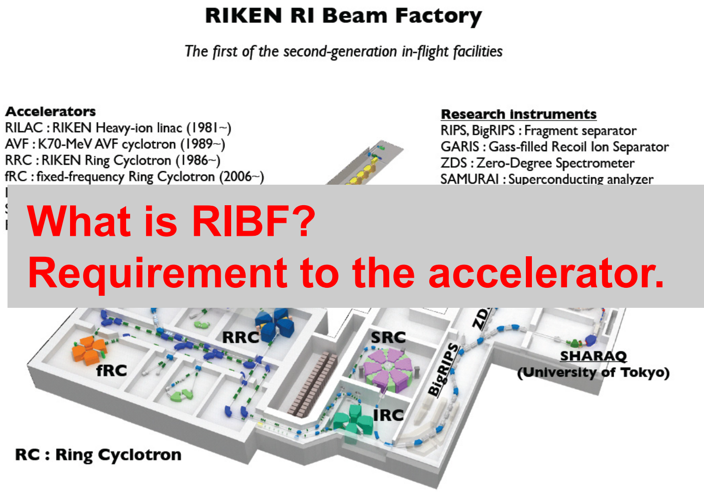
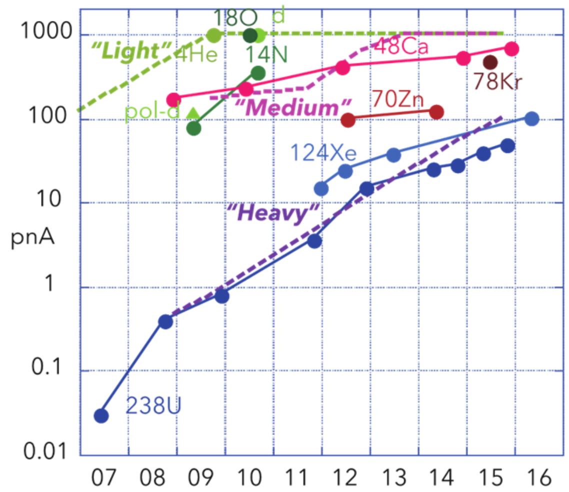


What is RIBF?
Requirement to the accelerator.

Operation of RIBF for 12 yrs



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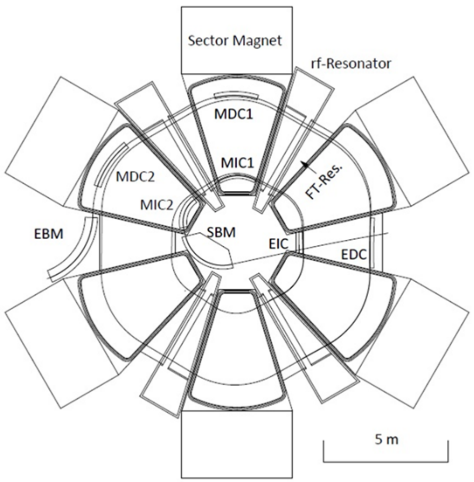

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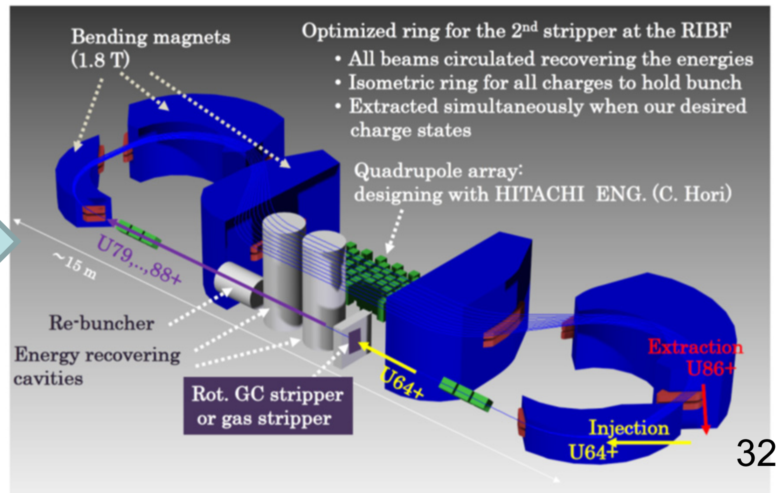

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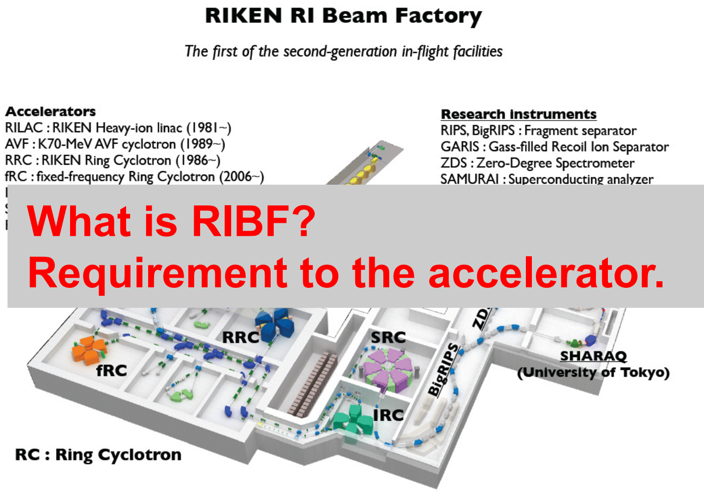

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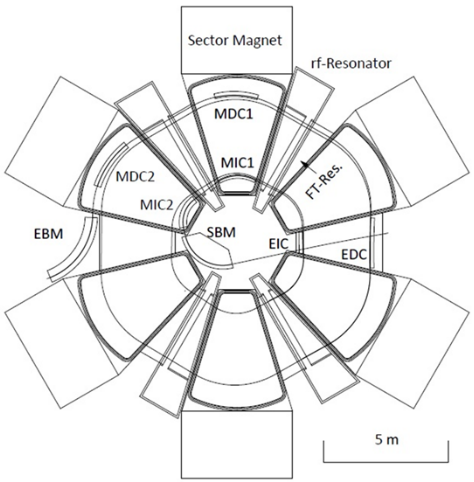

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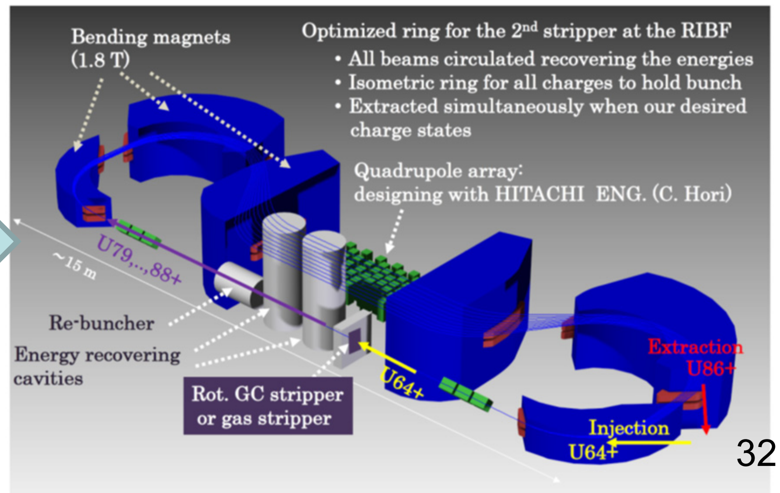

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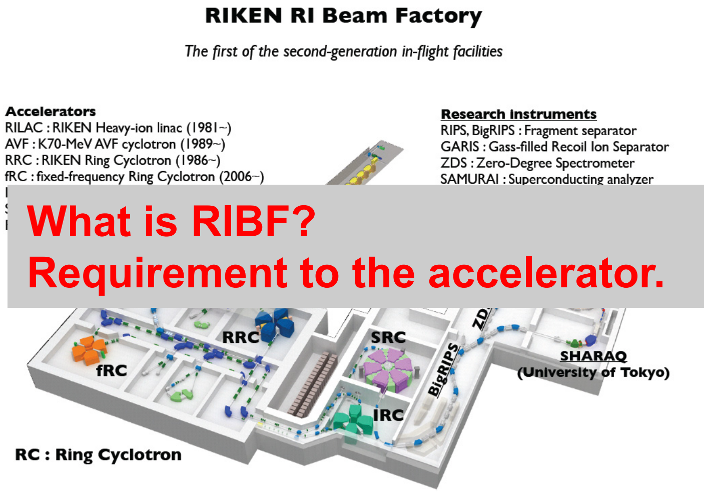

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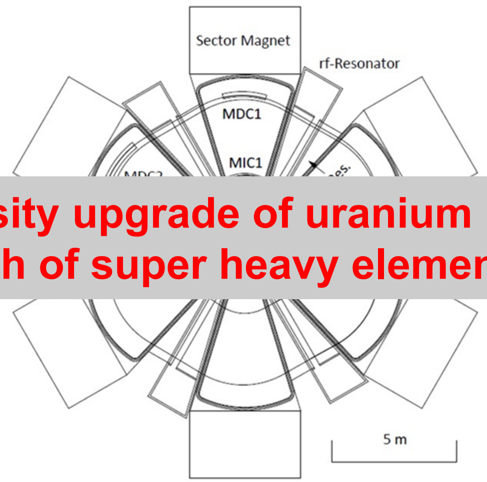
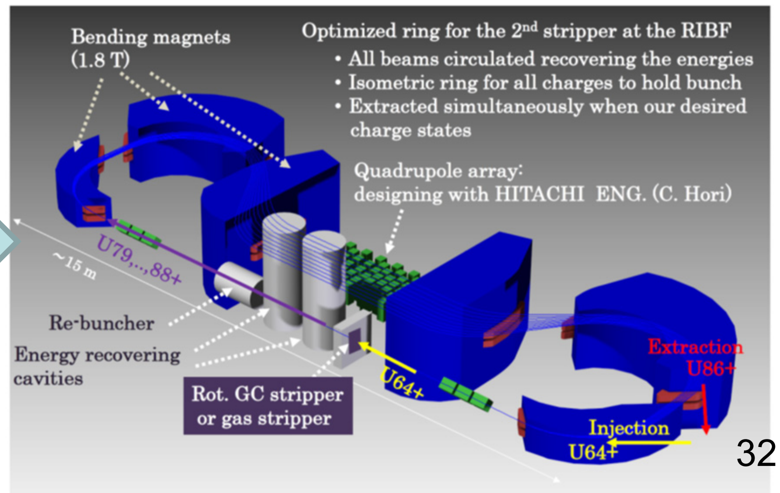
Successful operation
Lessons learnt

An upgrade plan



Intensity upgrade of uranium beam
Search of super heavy elements

Budget-friendly version



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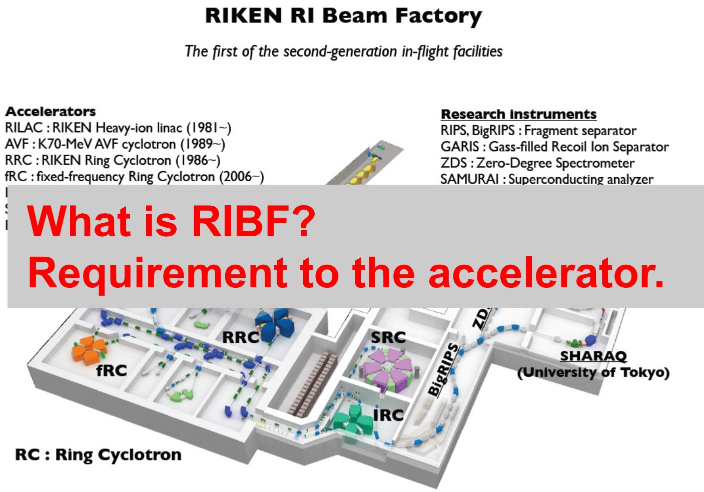

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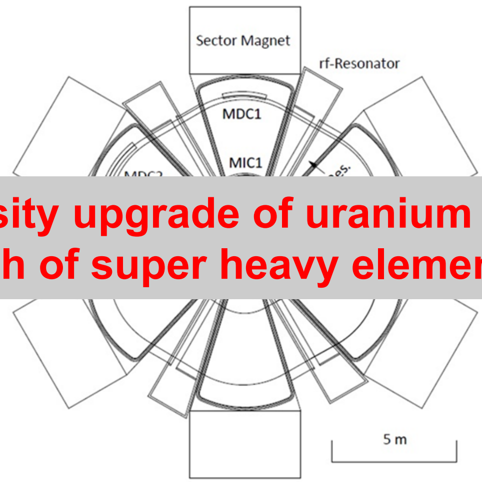

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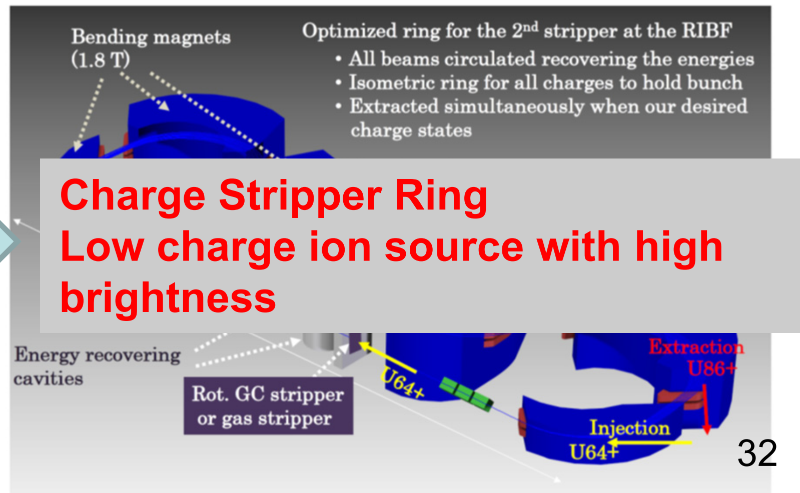

Charge Stripper Ring
Low charge ion source with high brightness