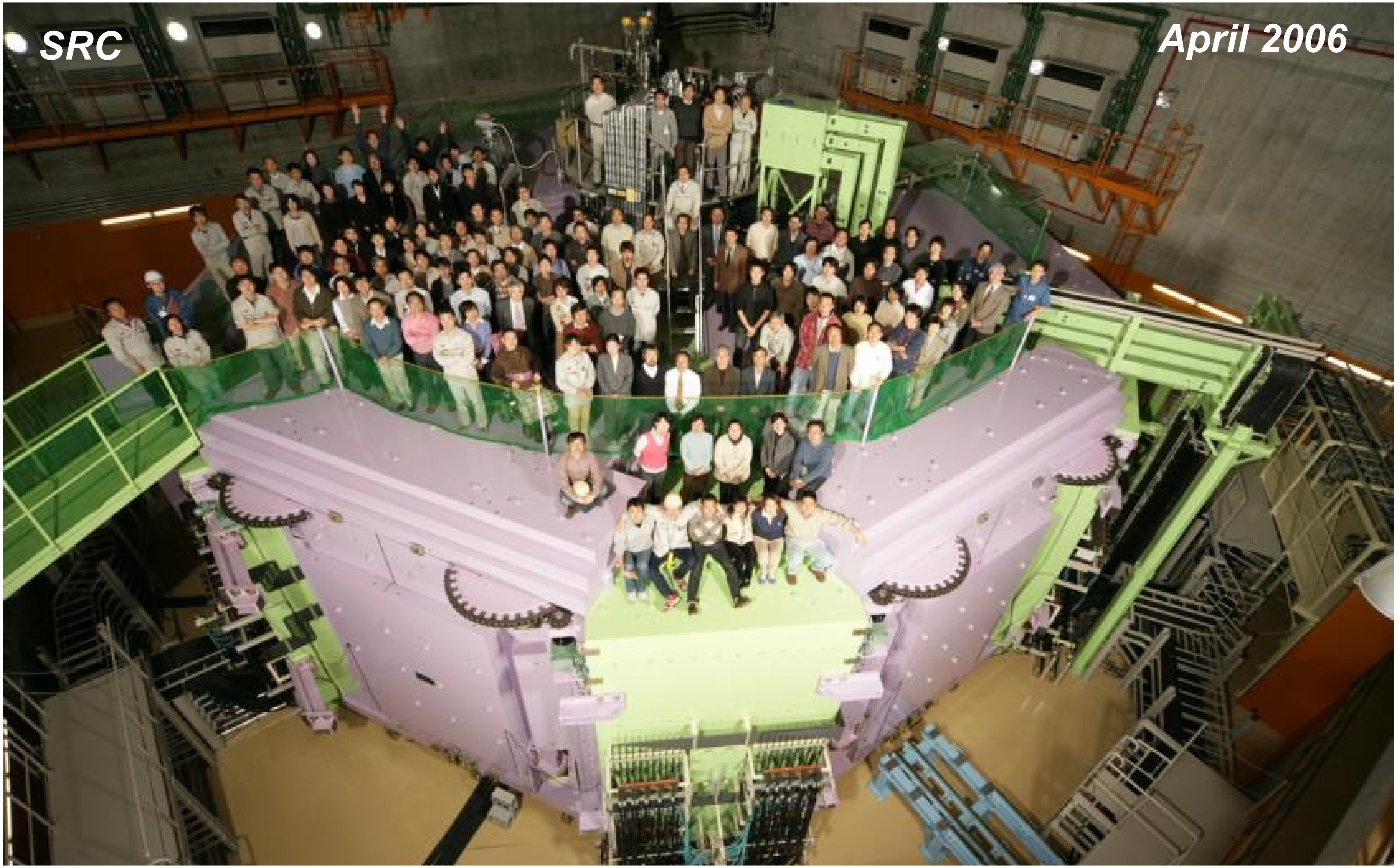
Operational experience and upgrade plan of the RIKEN RI beam factory

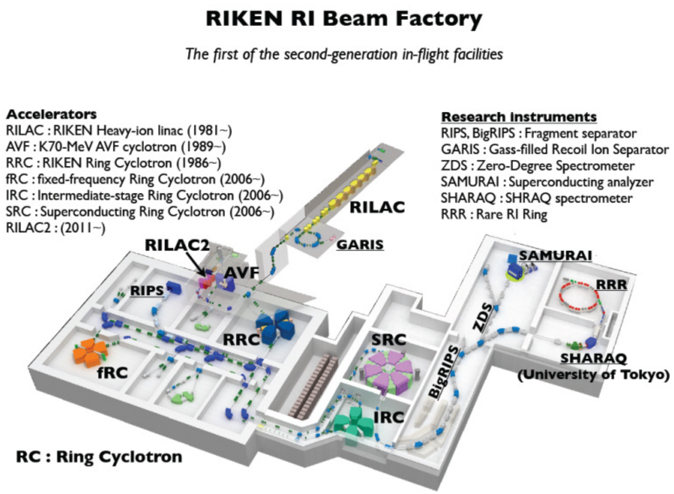


RIKEN Nishina Center for Accelerator-Based Science Accelerator Group

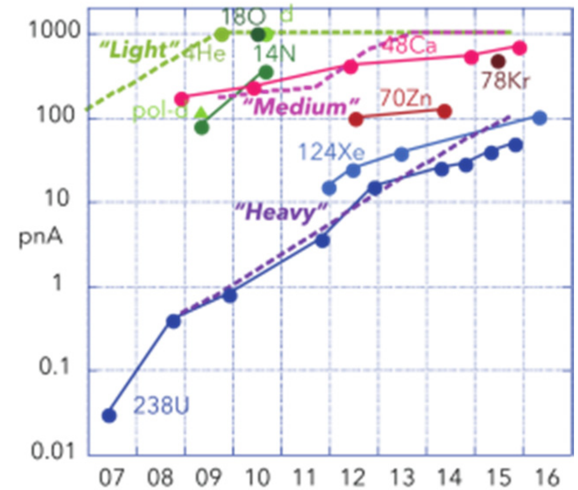
Hiroki Okuno

Preview

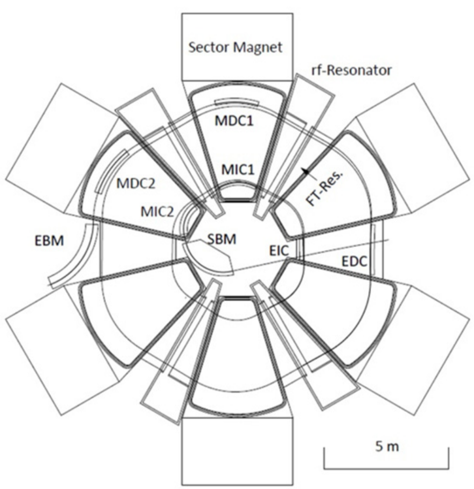
Introduction to RIBF



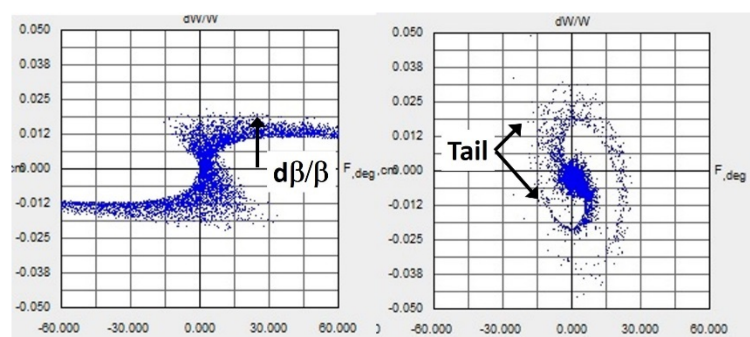
Operation of RIBF for 10 yrs



A new upgrade plan

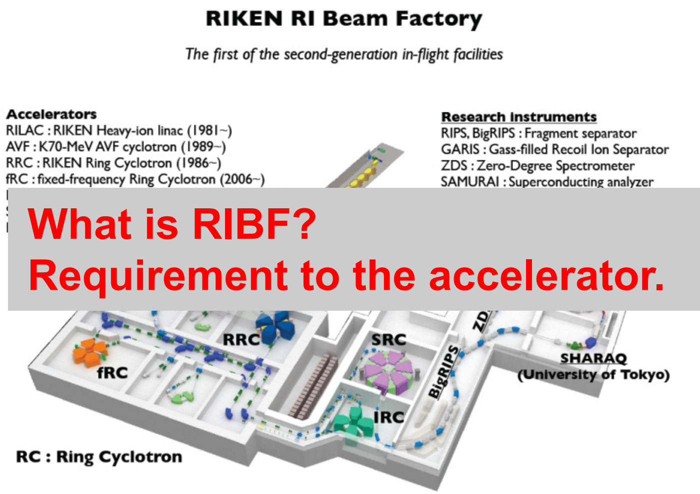


Some issues for the realization of the upgrade plan



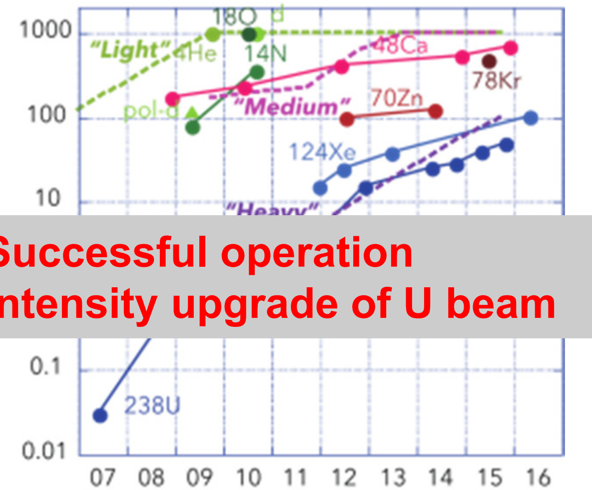
Preview

Introduction to RIBF



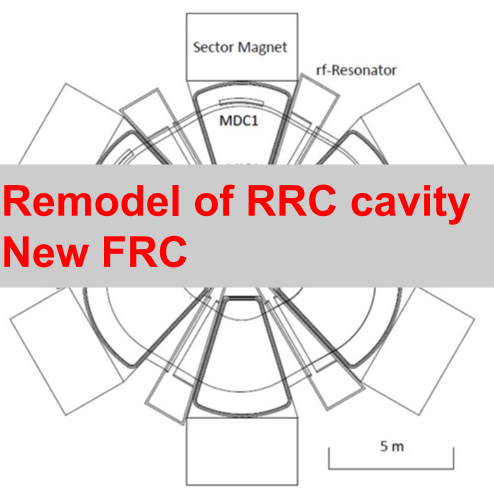
What is RIBF?
Requirement to the accelerator.

Operation of RIBF for 10 yrs



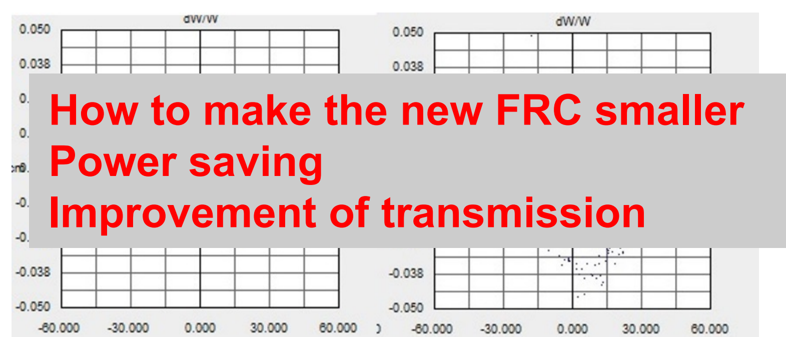
Successful operation
Intensity upgrade of U beam

A new upgrade plan



Remodel of RRC cavity
New FRC

Some issues for the realization of the upgrade plan



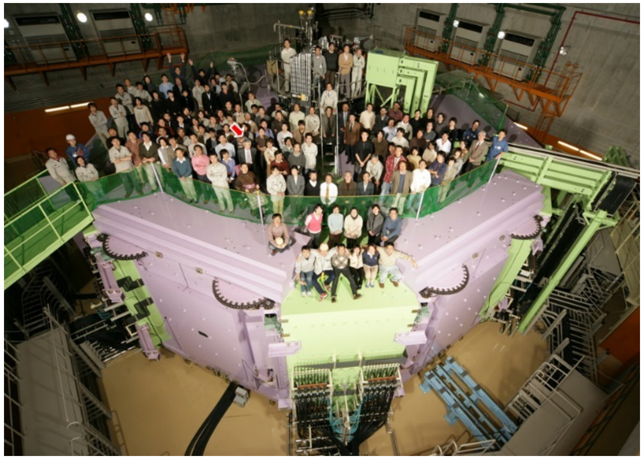
How to make the new FRC smaller
Power saving
Improvement of transmission

A funny rule in RIKEN Wako-campus

1966: 160cm cyclotron

1986: RIKEN Ring Cyclotron

2006: SRC

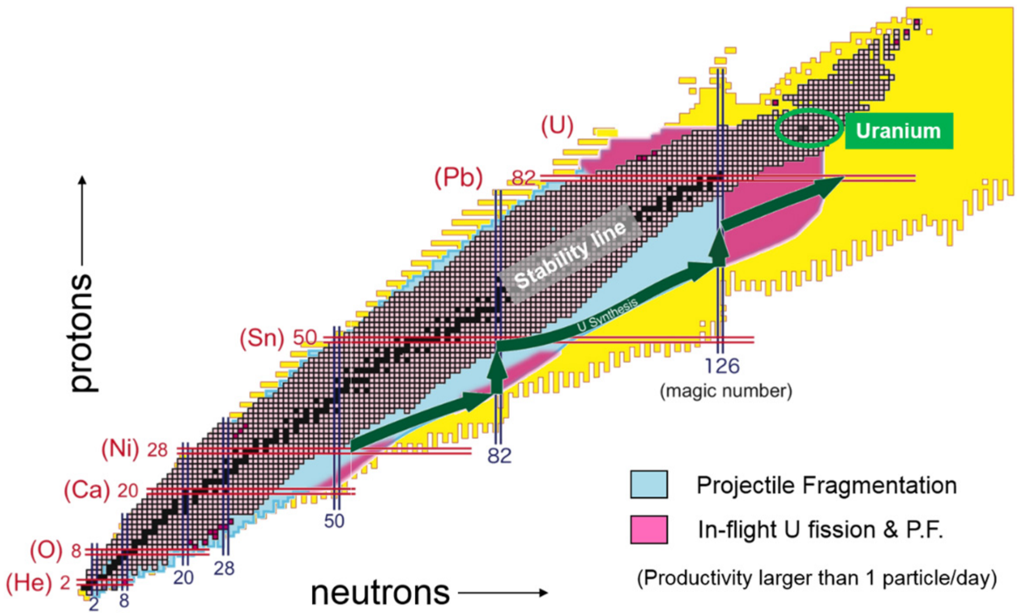


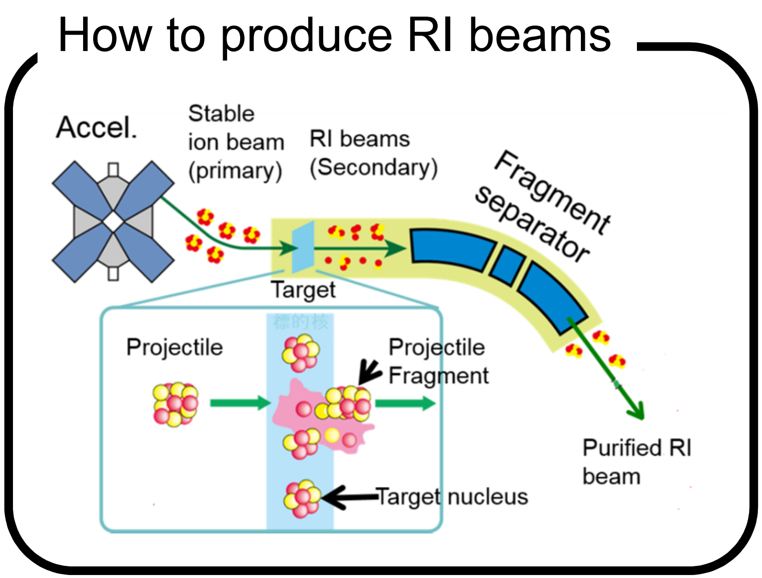
2026: What kind of cyclotron?

?

Goal of RIBF

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

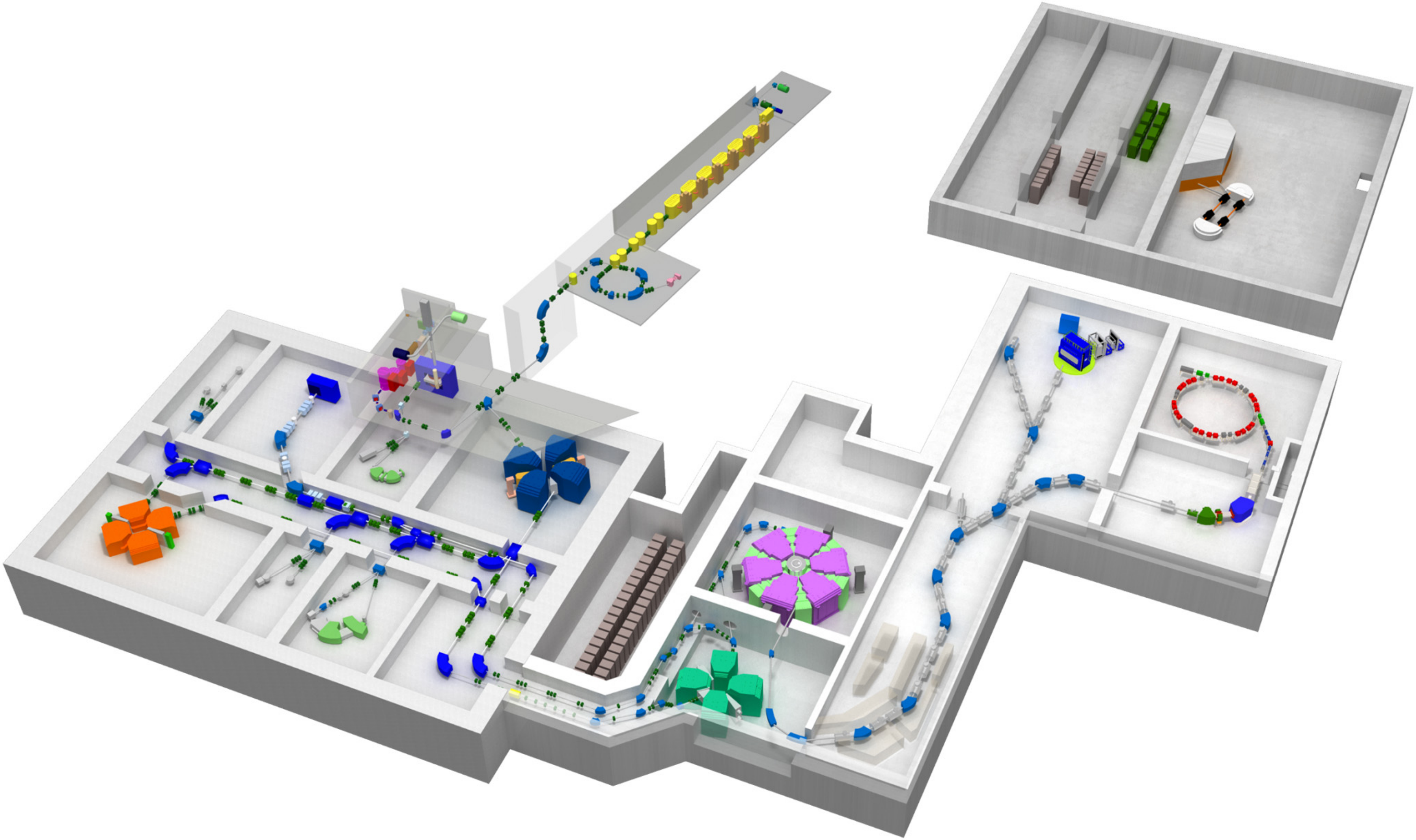




- RI beams are generated by fragmentation or fission of high speed heavy ion beams.
- Accelerator complex is required to produce high speed heavy ion beams with high intensity.

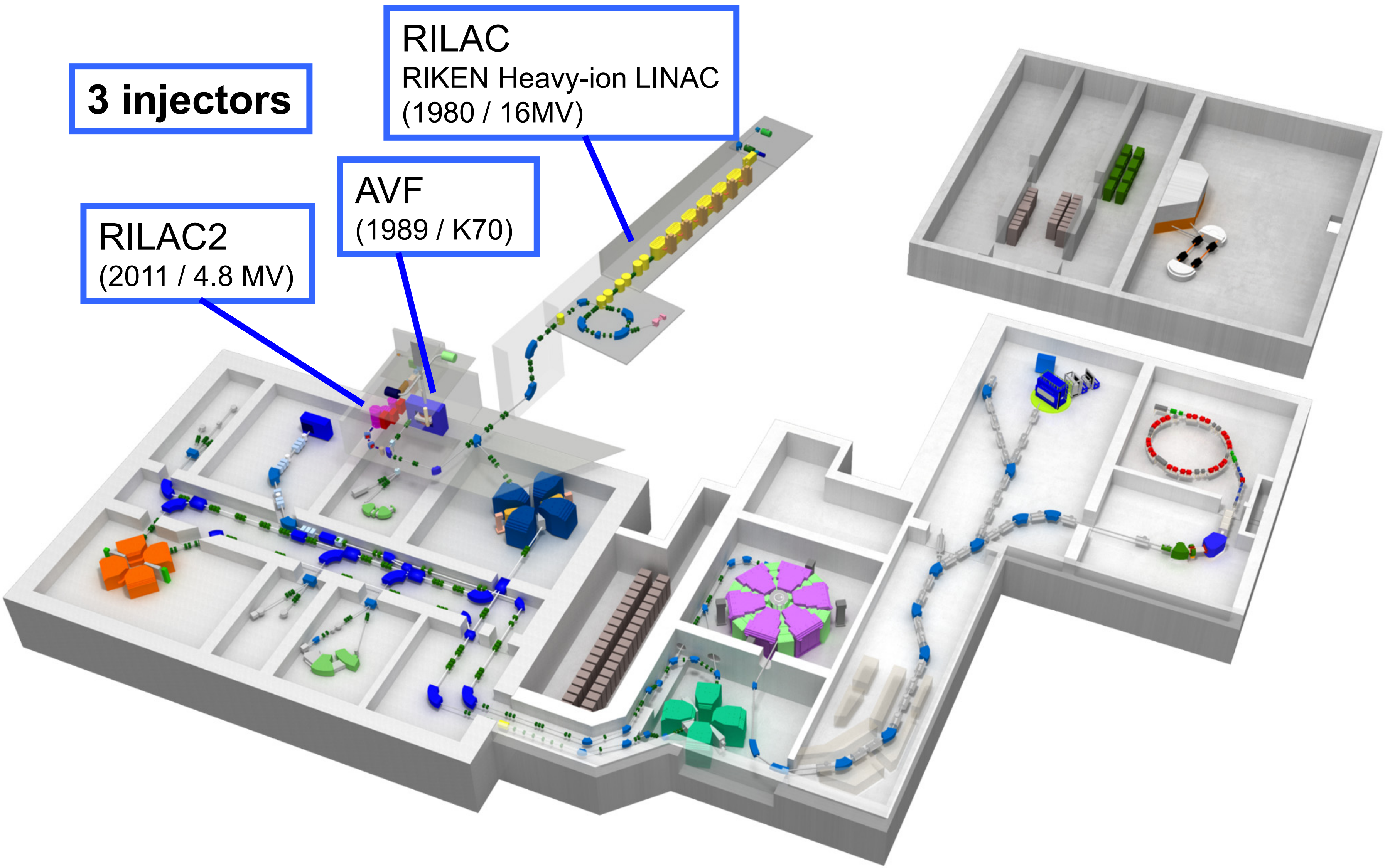
RIBF accelerators

Y. Yano, NIM B261 (2007) 1009.



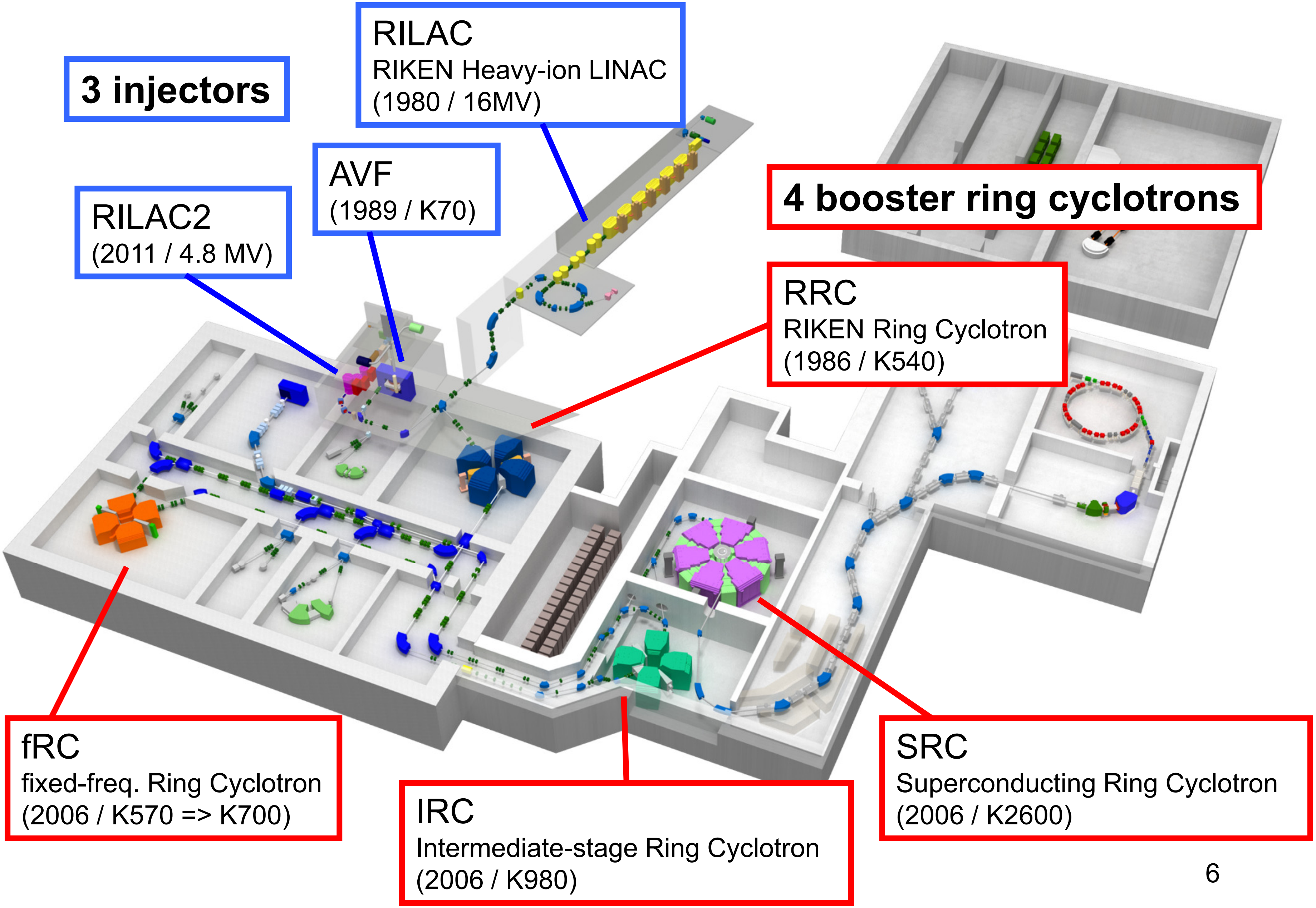
Y. Yano, NIM B261 (2007) 1009.

RIBF accelerators



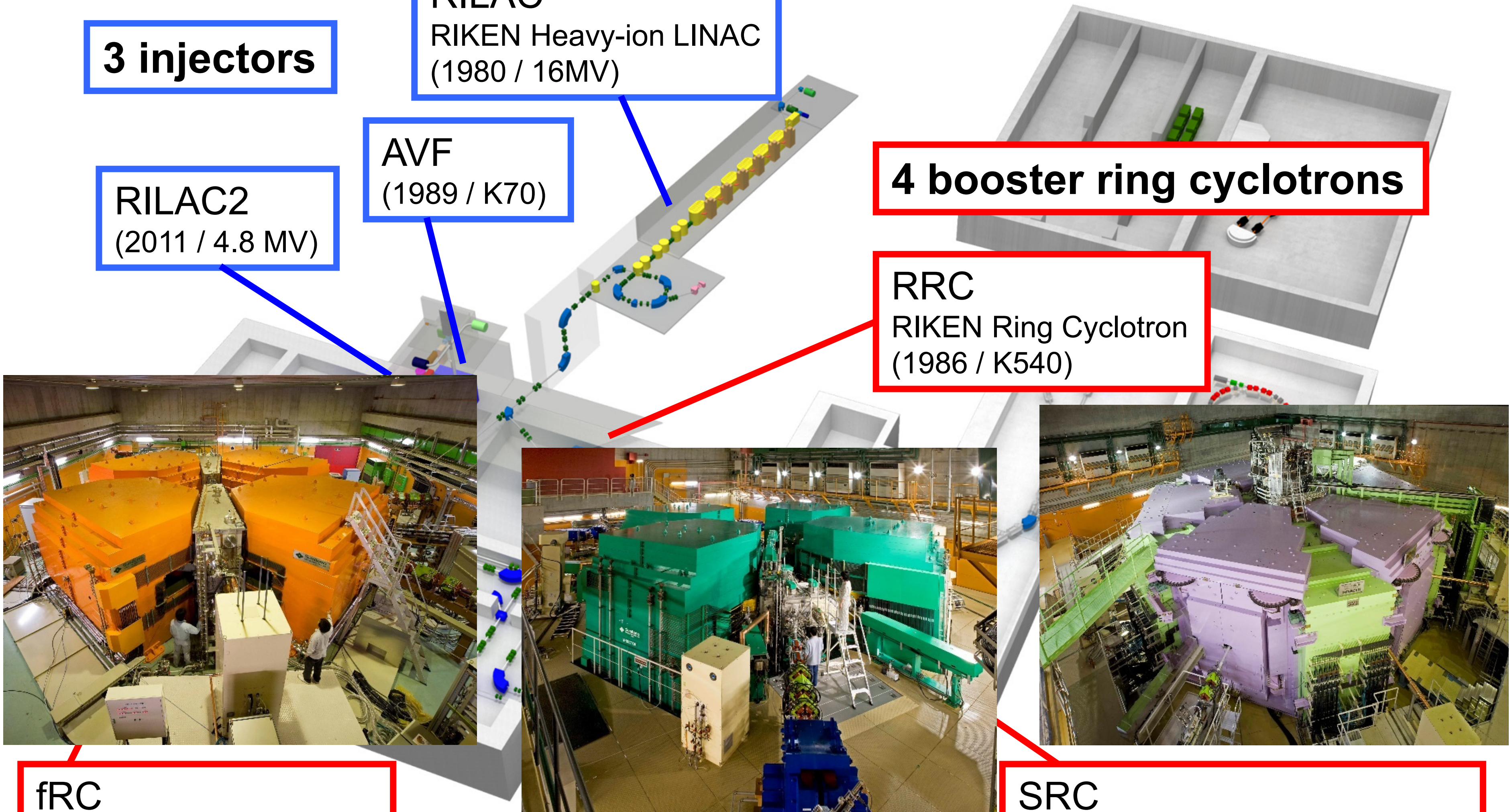
Y. Yano, NIM B261 (2007) 1009.

RIBF accelerators



RIBF accelerators

Y. Yano, NIM B261 (2007) 1009.

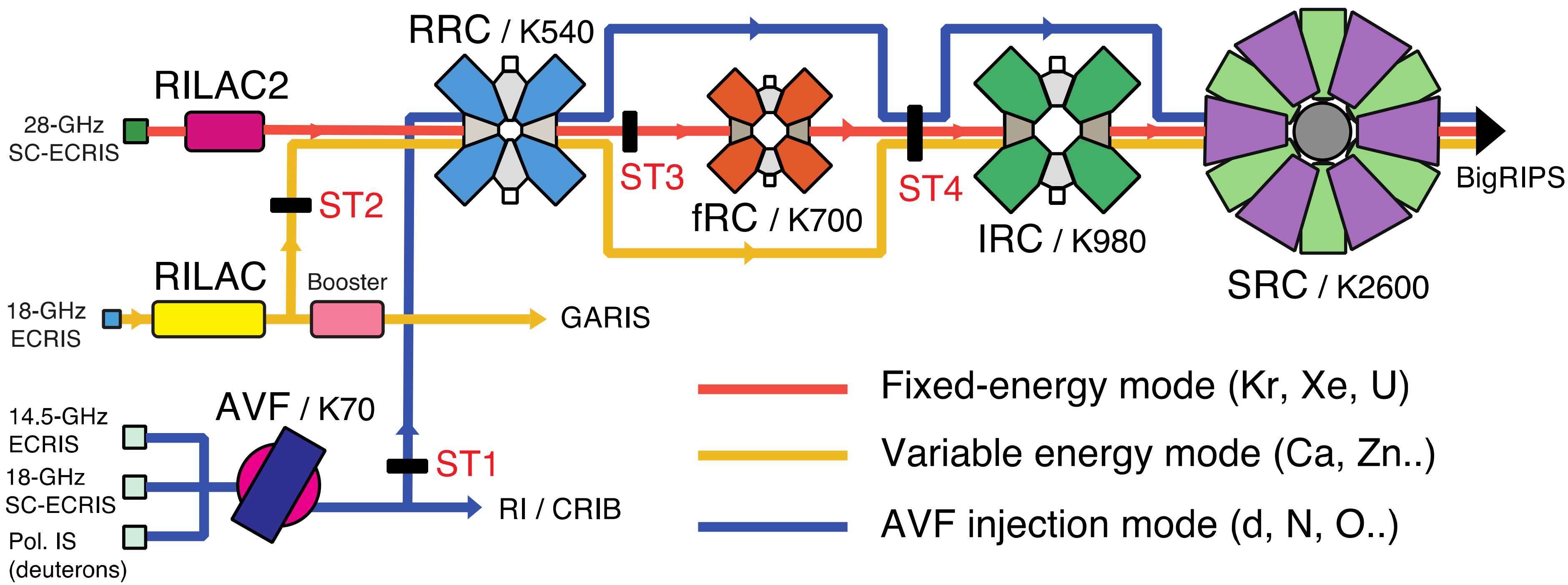


Acceleration modes

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

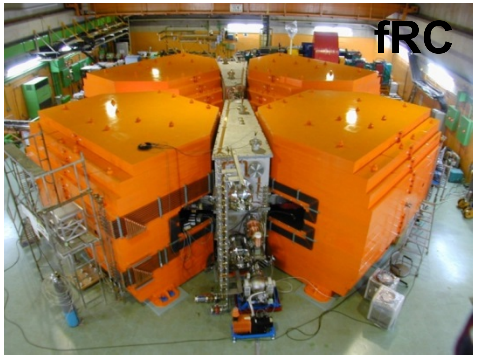
Specifications of RIBF ring cyclotrons

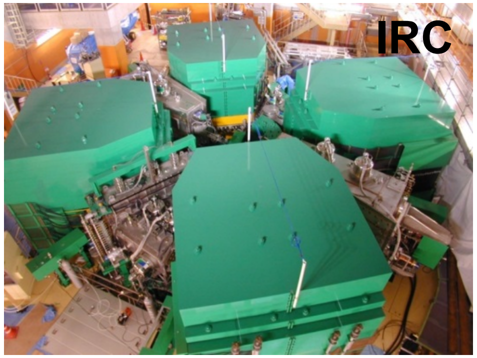
Challenging

	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

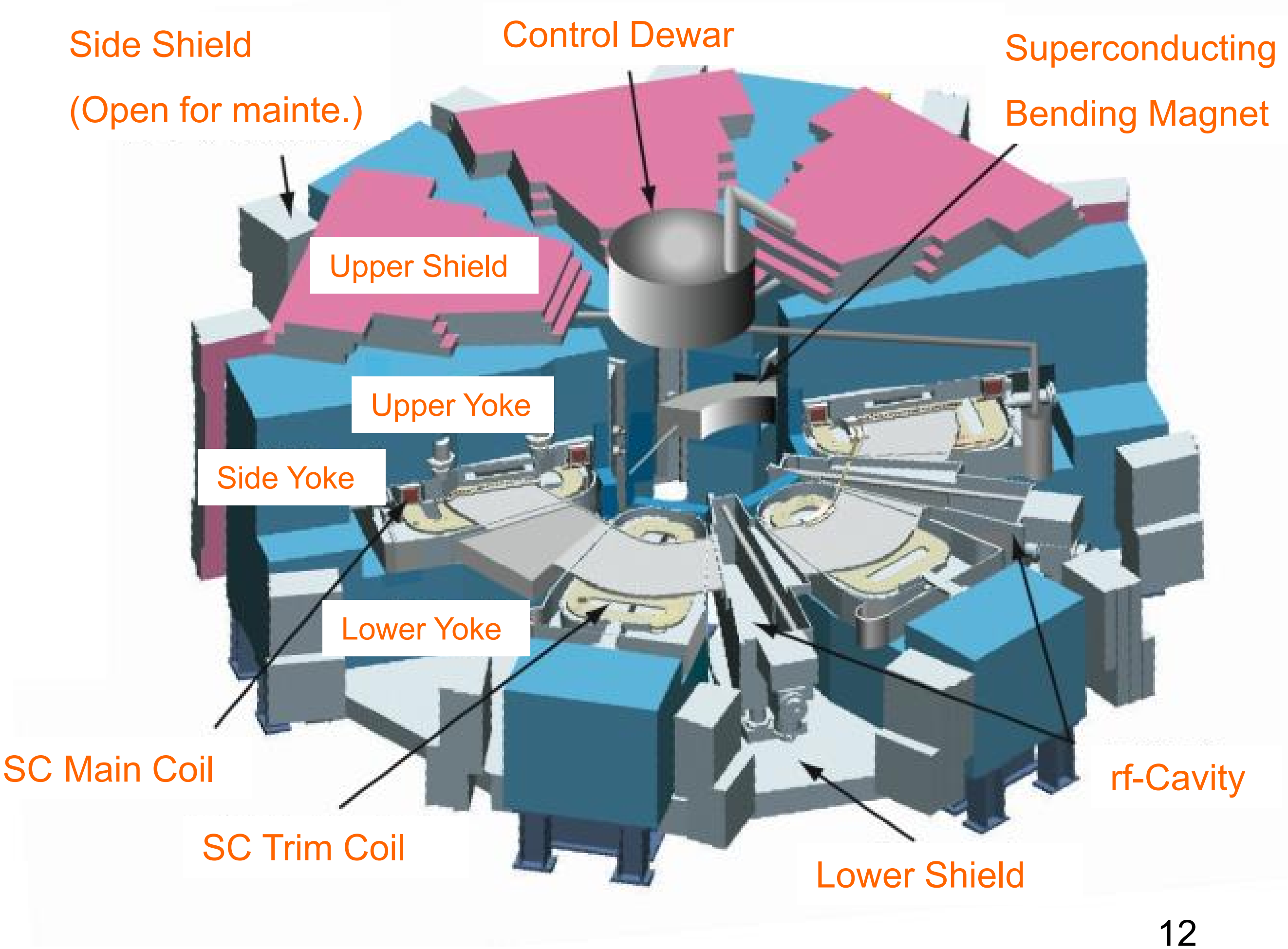




SRC: the World's First Superconducting Ring Cyclotron

K: the maximum bending power of extracted beam from the cyclotron

K = 2,600 MeV
Max. Field: 3.8T (235 MJ)
Rf frequency: 18-38 MHz
Total acc. voltage: 640 MV
Weight: 8,300 tons
Diameter: 19m Height: 8m



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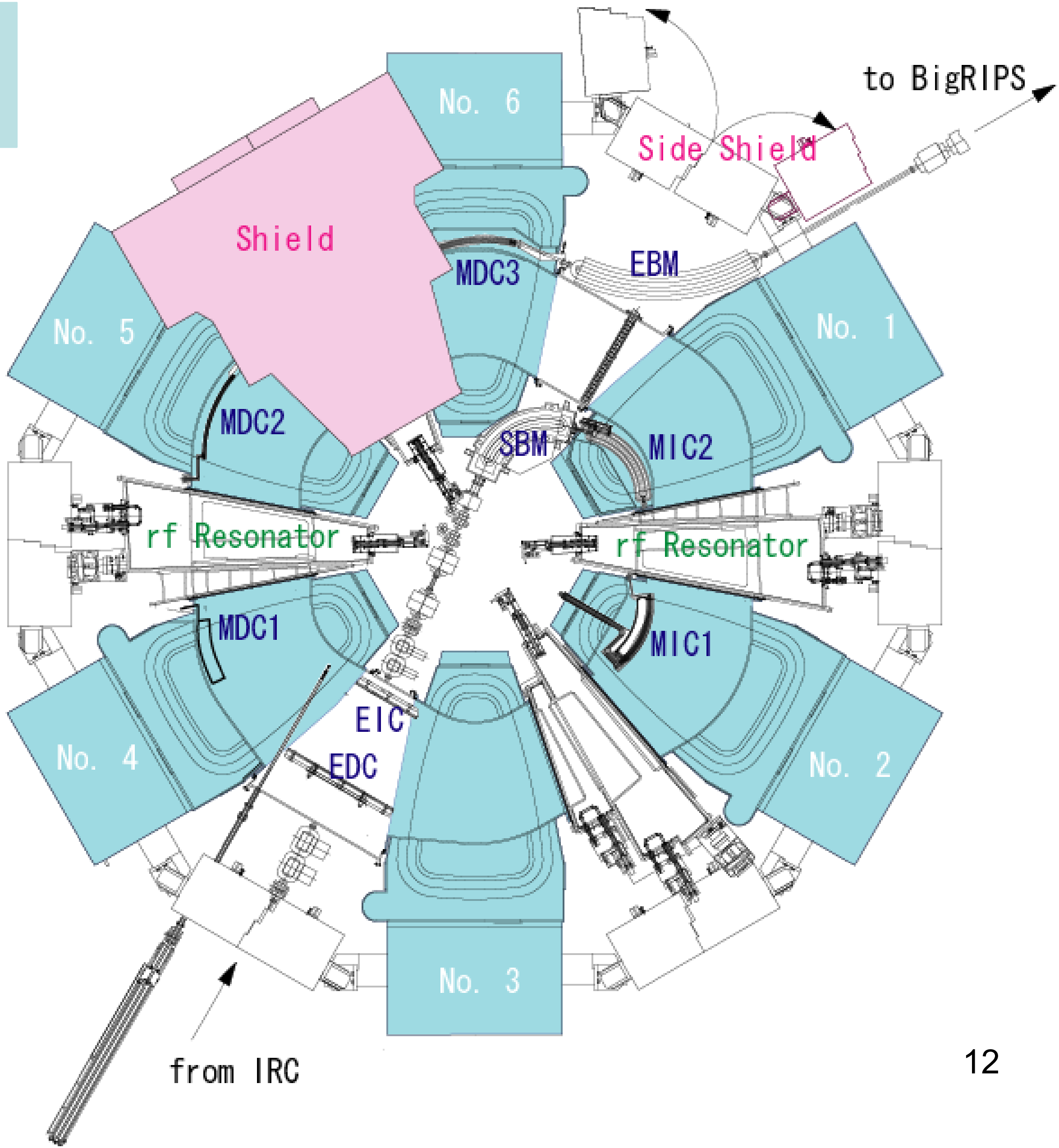
K = 2,600 MeV
Max. Field: 3.8T (235 MJ)
Rf frequency: 18-38 MHz
Total acc. voltage: 640 MV
Weight: 8,300 tons
Diameter: 19m Height: 8m

Sector Magnets :6
Rf Resonator :4
Injection elements:
Extraction elements:



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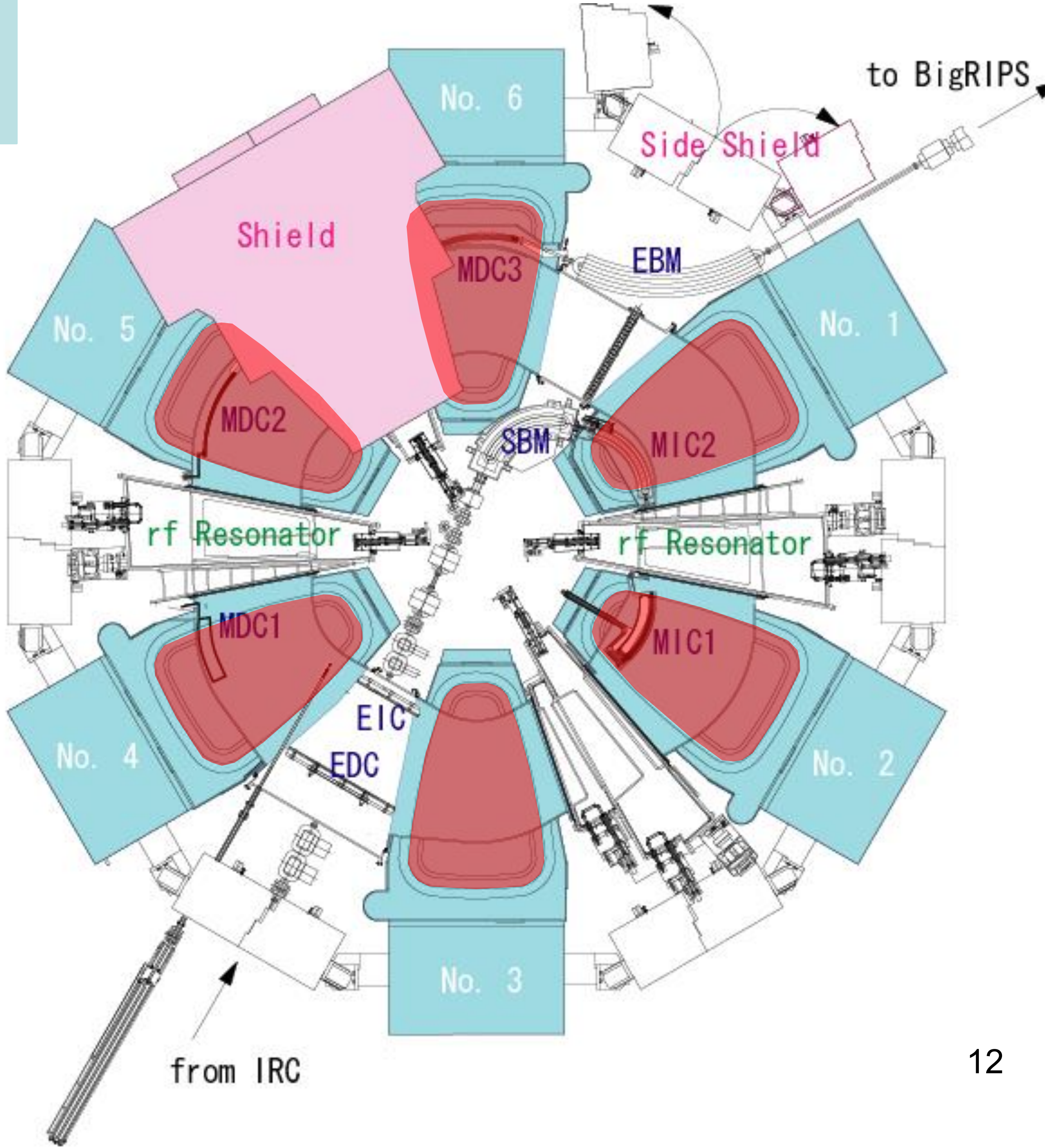

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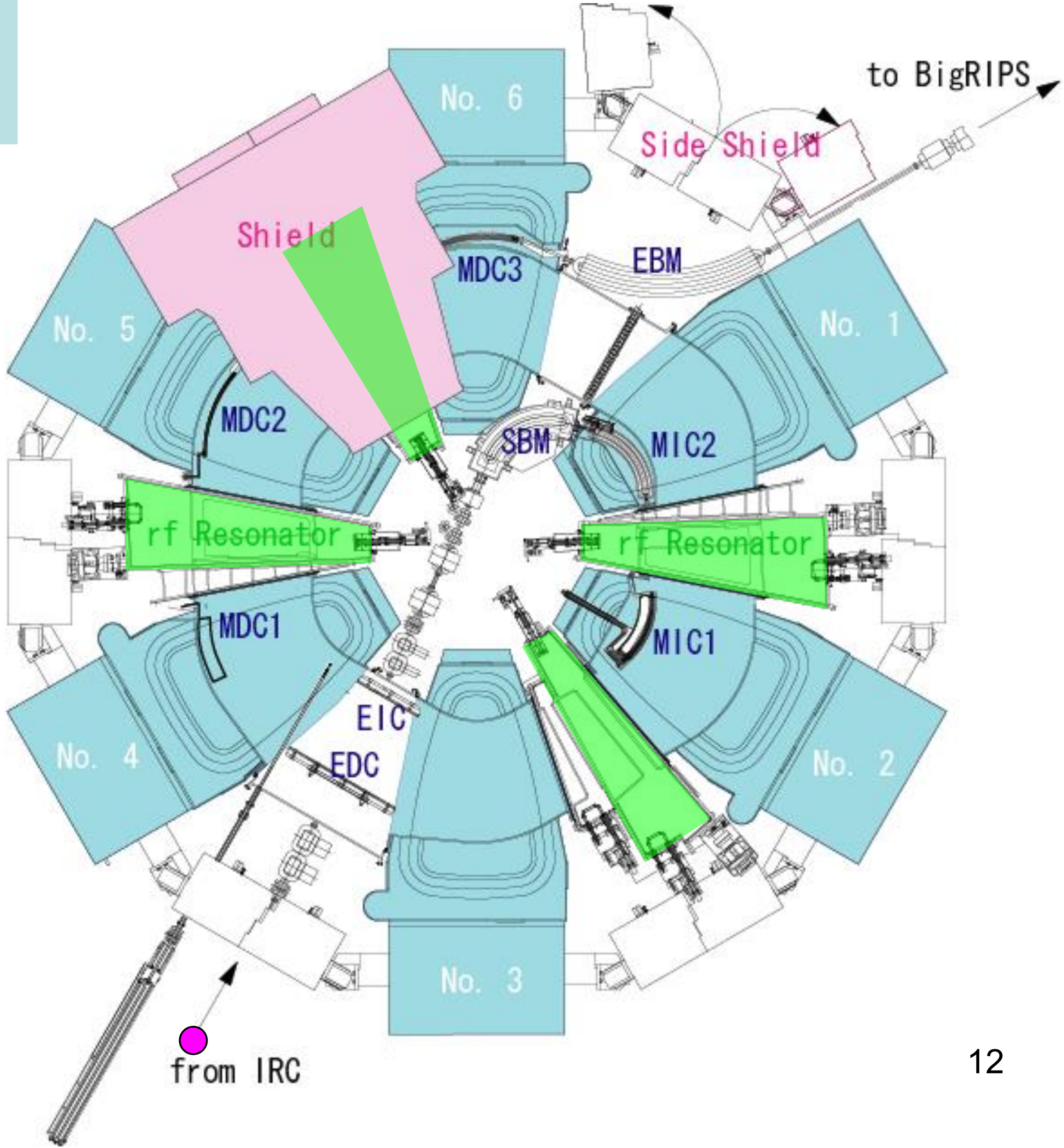

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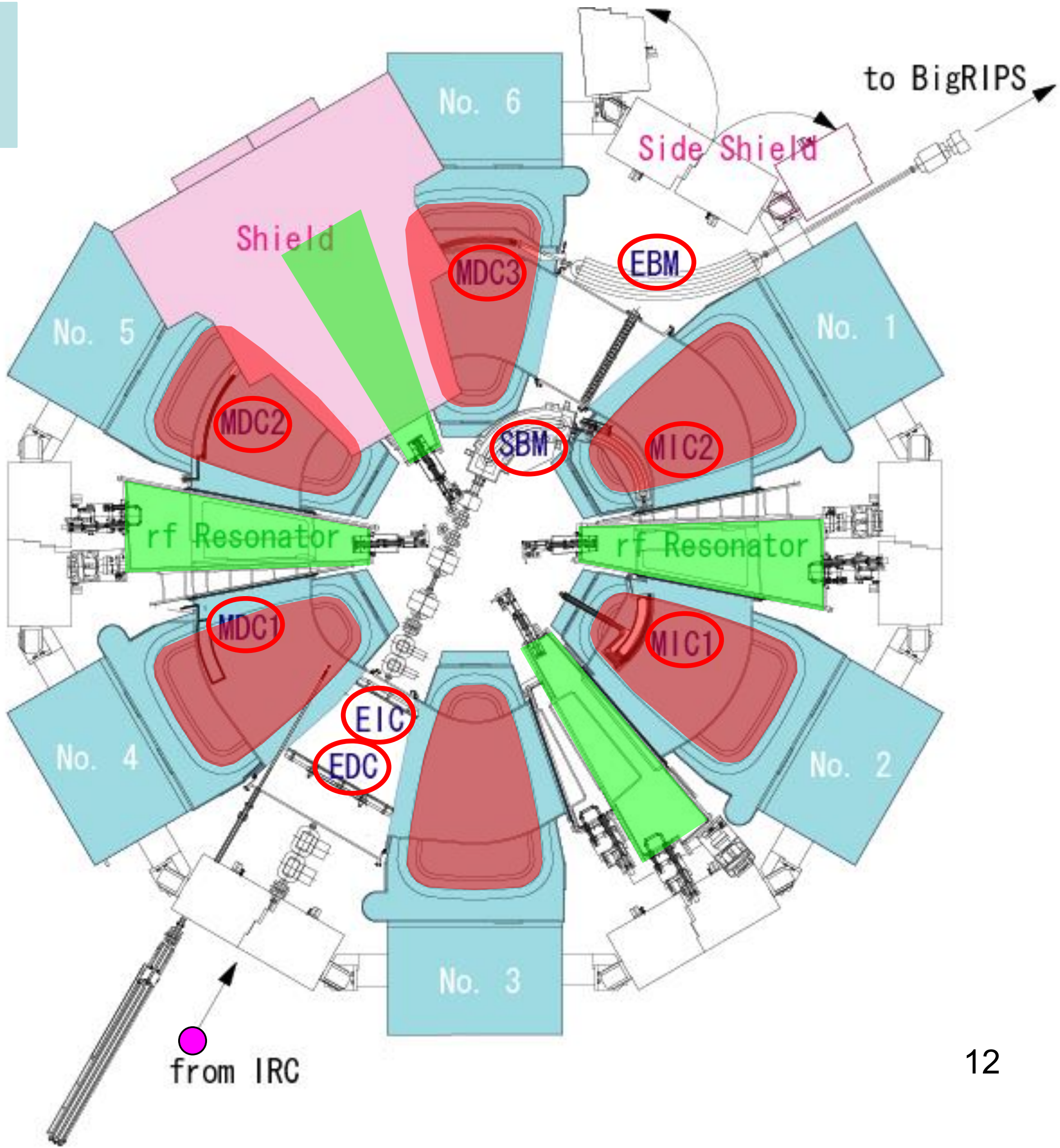
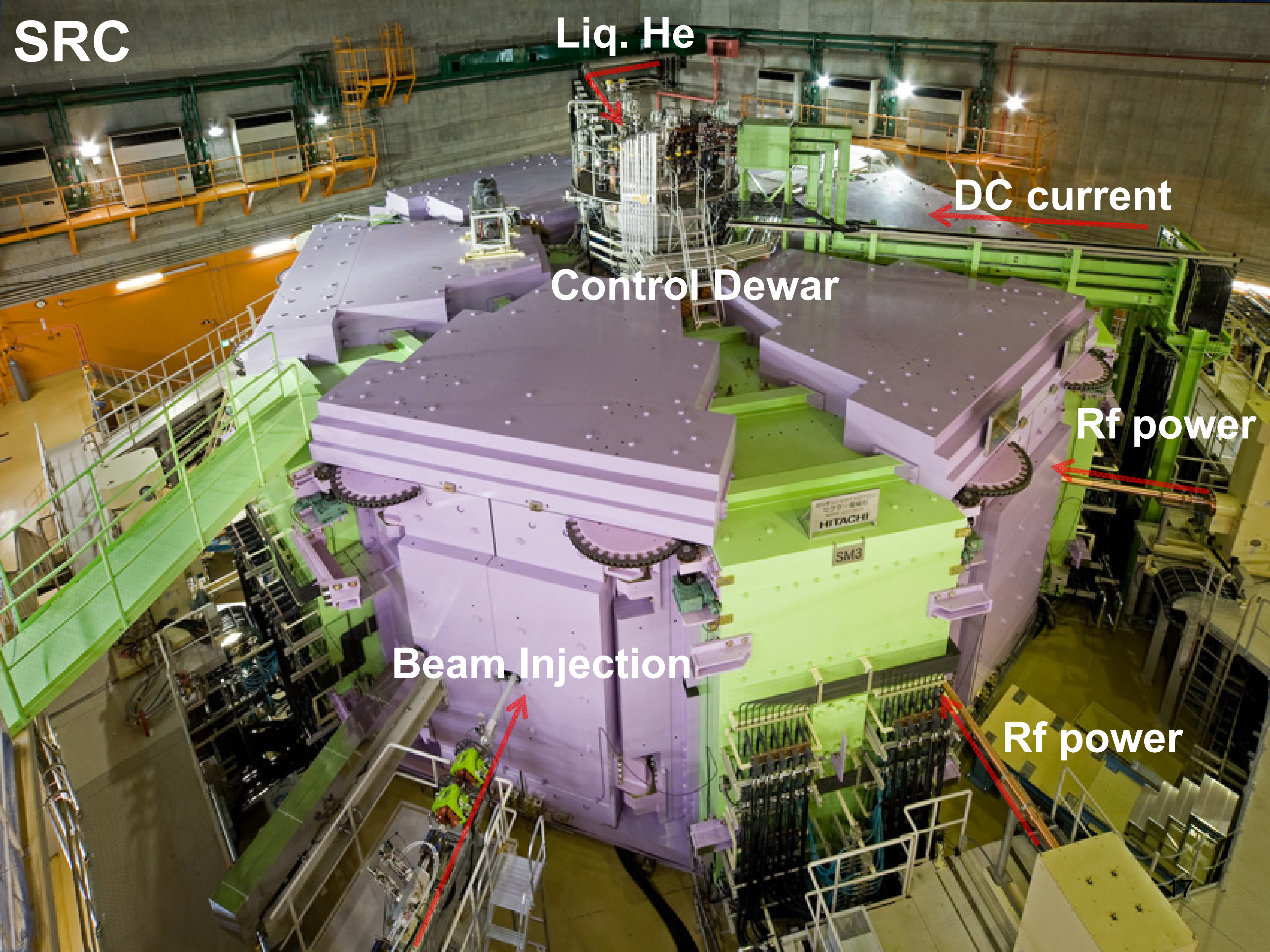
Weight: 8,300 tons
Diameter: 19m Height: 8m

Sector Magnets :6
Rf Resonator :4
Injection elements:
Extraction elements:

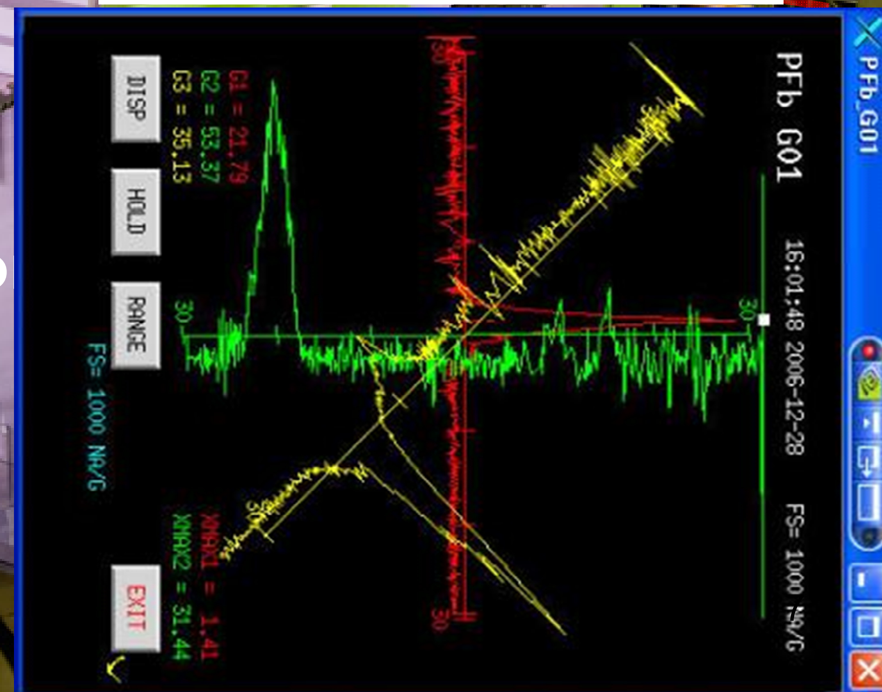
Self Magnetic Shield
Self Radiation Shield



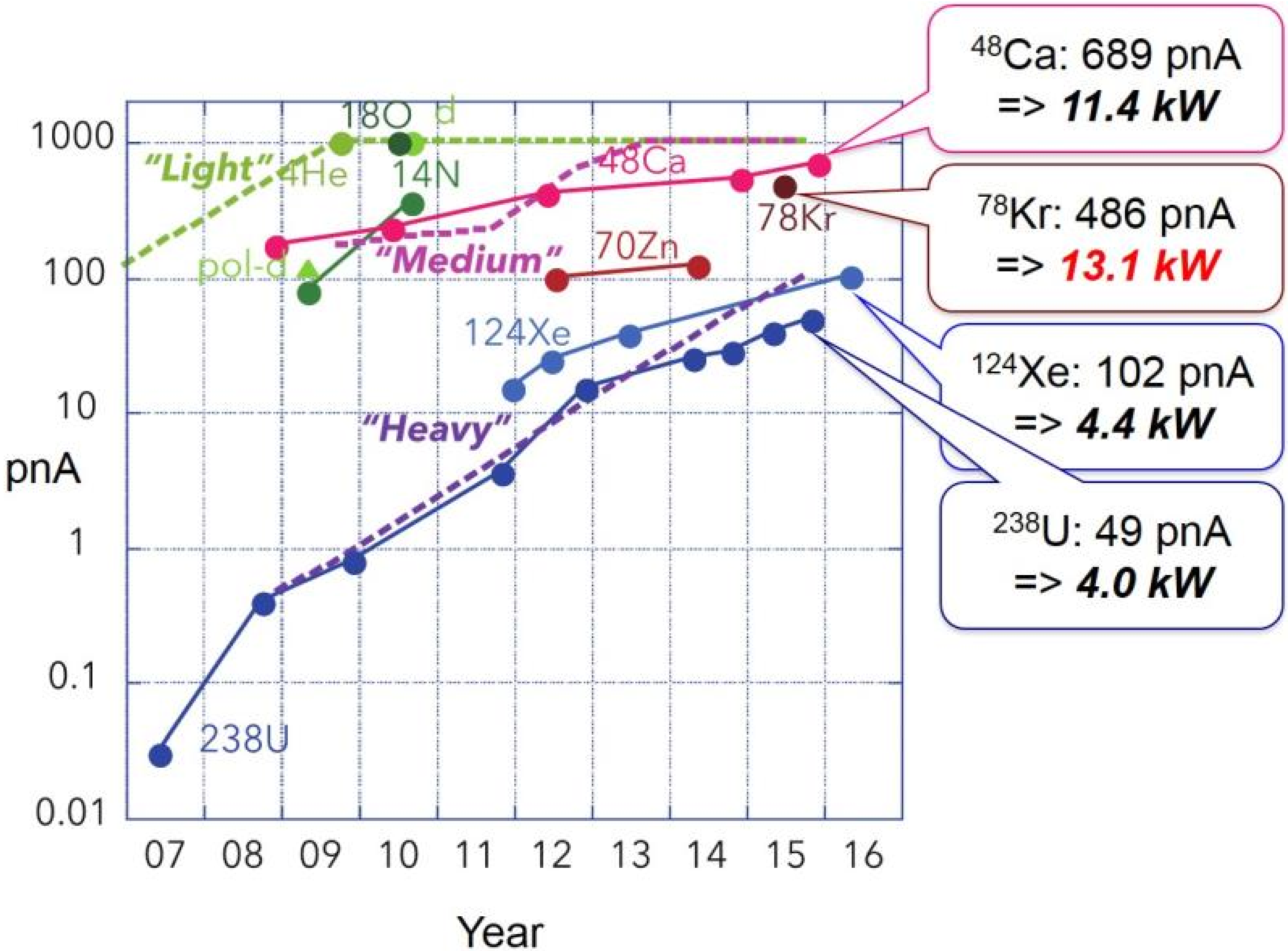

SRC
Liq. He
DC current
Control Dewar
Rf power
HITACHI
SM3
Beam Injection
Rf power

The First Beam 2006/12/28!

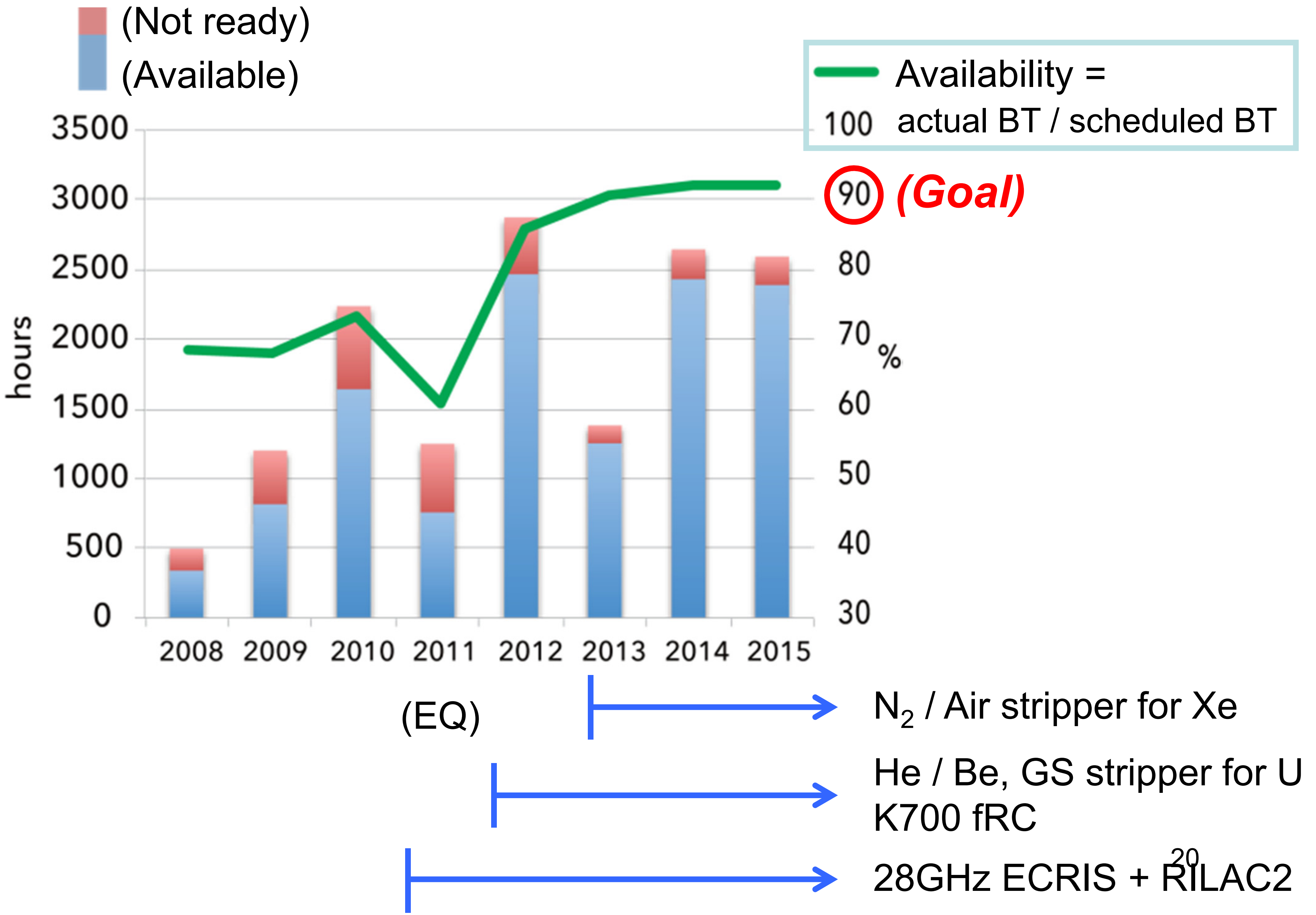
Beam profile at the exit of SRC



History of accelerator performance

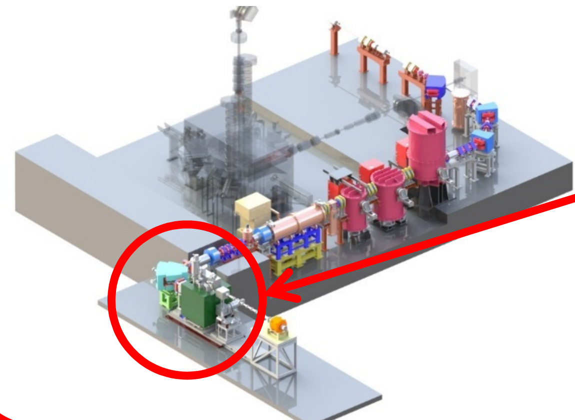


History of accelerator availability

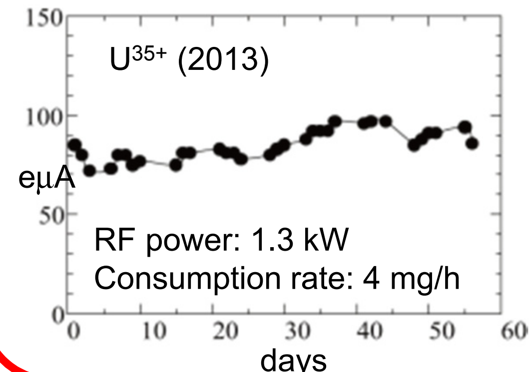


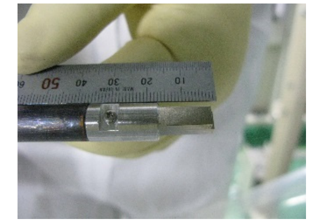
Major upgrade during 2011-16 for U-beam

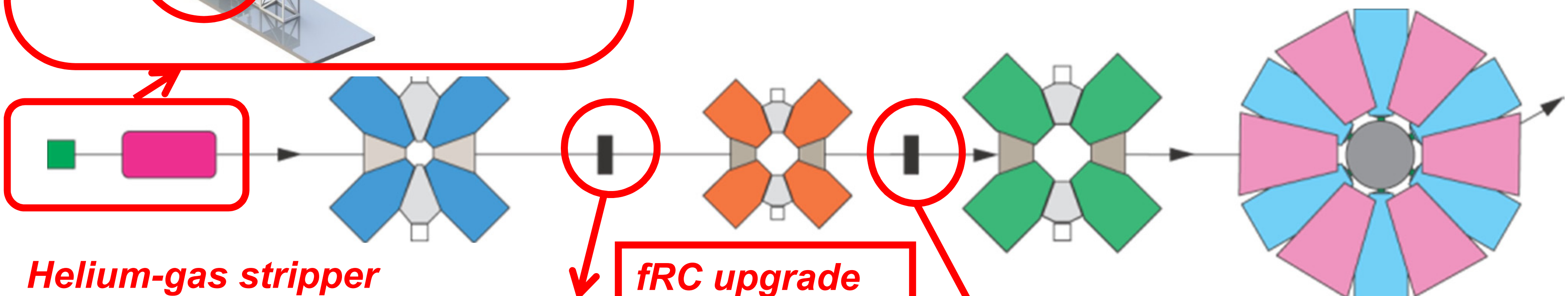
RILAC2



28GHz ECRIS

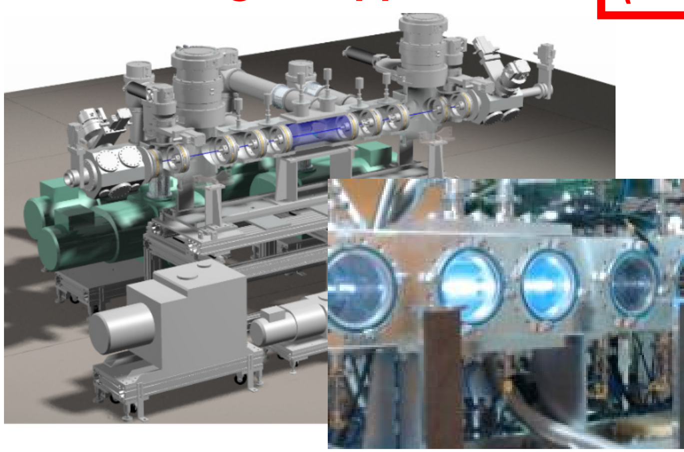






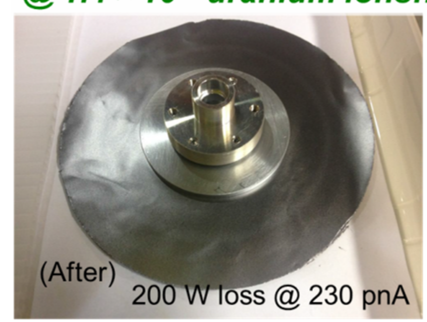
Helium-gas stripper for the 1st Charge stripper

fRC upgrade (K570=>K700)



Highly-oriented graphene sheet for the second stripper

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



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.

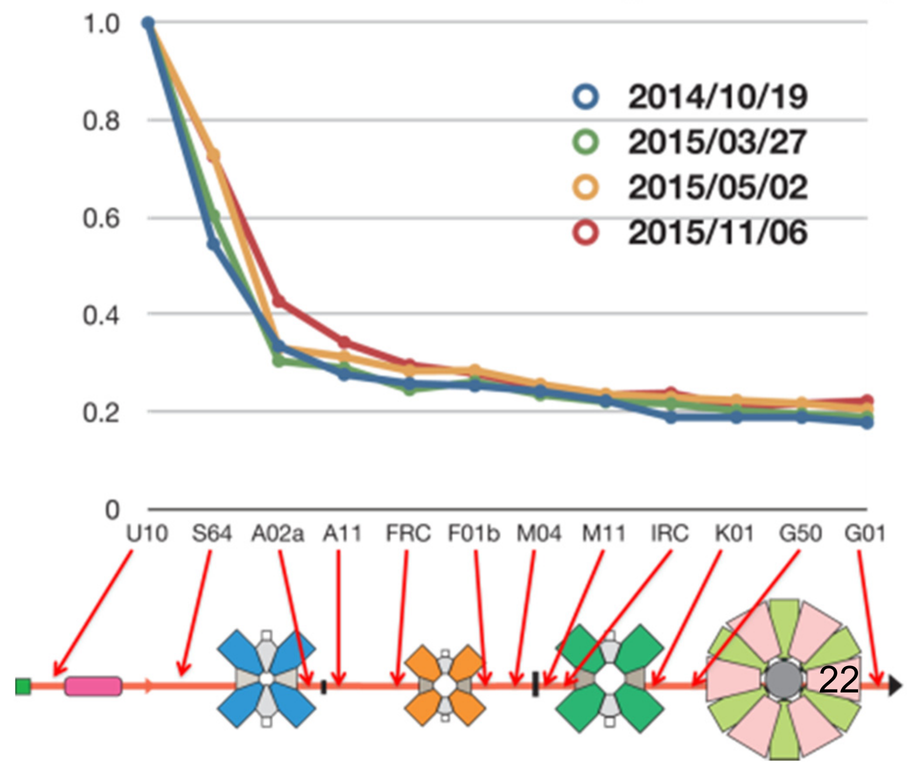
  (cf. PSI ~30%)

(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

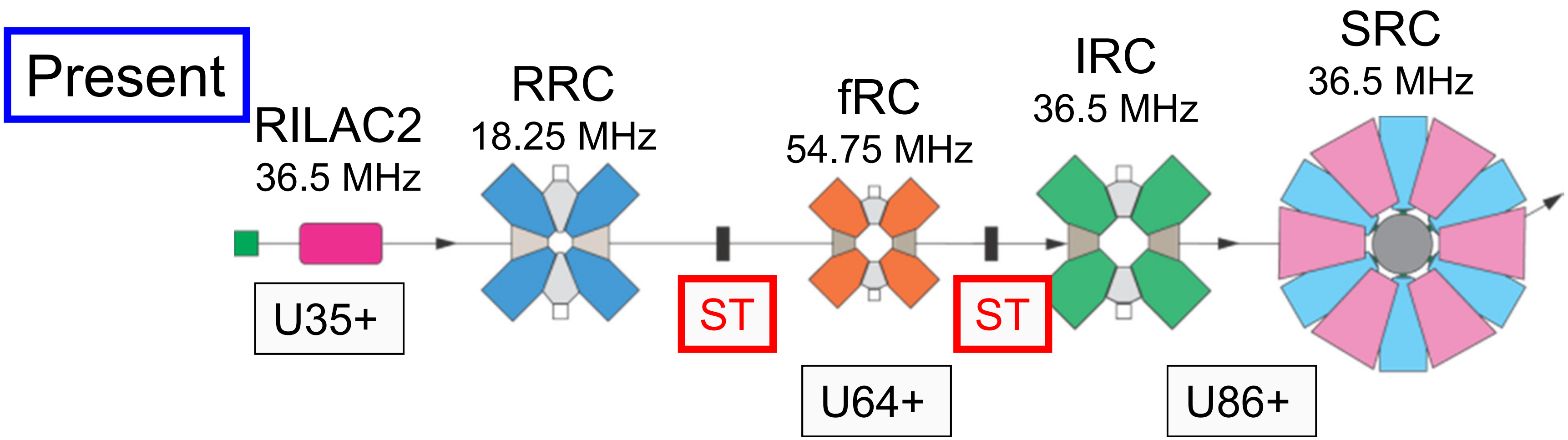


Outline of a new upgrade program

- 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

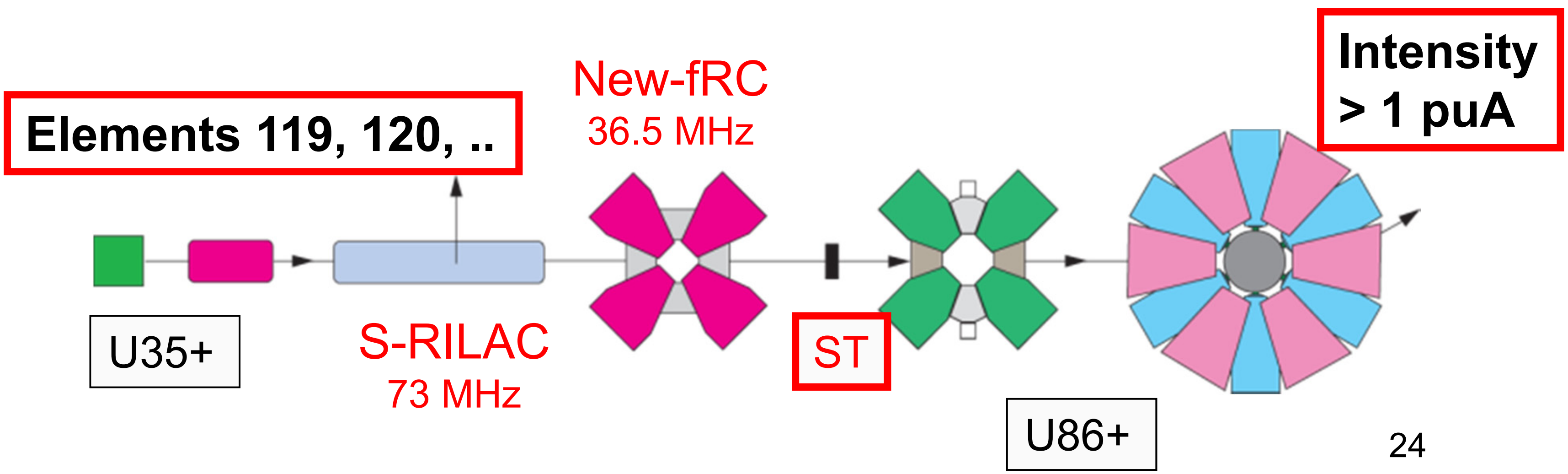
approved in the Japan's stimulus package!
- Constraint
  - We can't afford a new building (We have to install the new FRC in an experimental room of the existing building.)

RIBF upgrade proposal in 2013

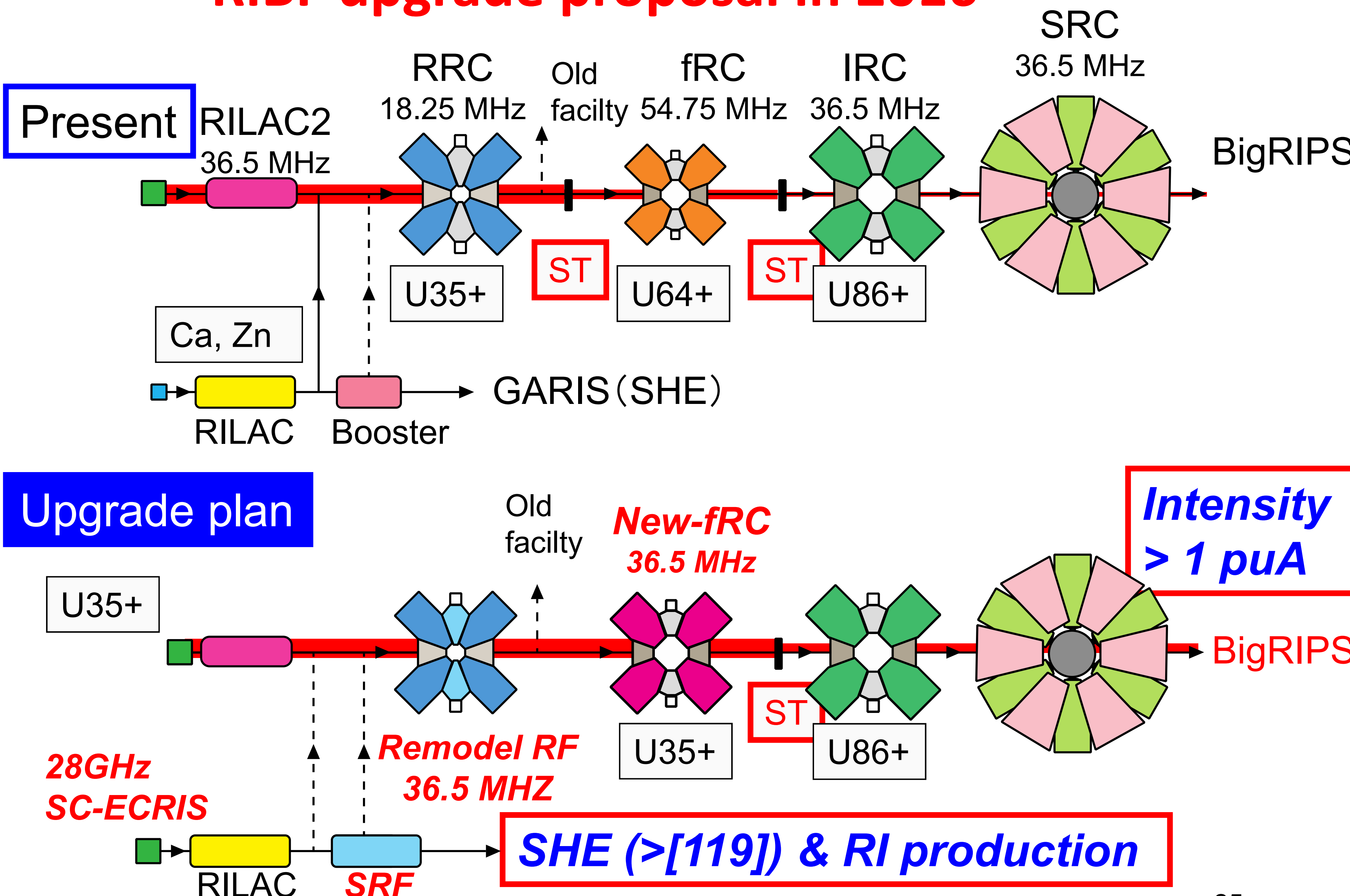


Upgrade plan

- Single stripping stage => New fRC
- Supercondcuting linac injector



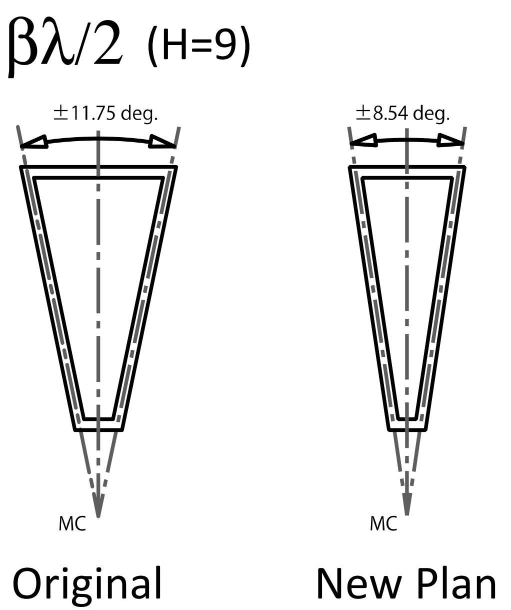
RIBF upgrade proposal in 2016

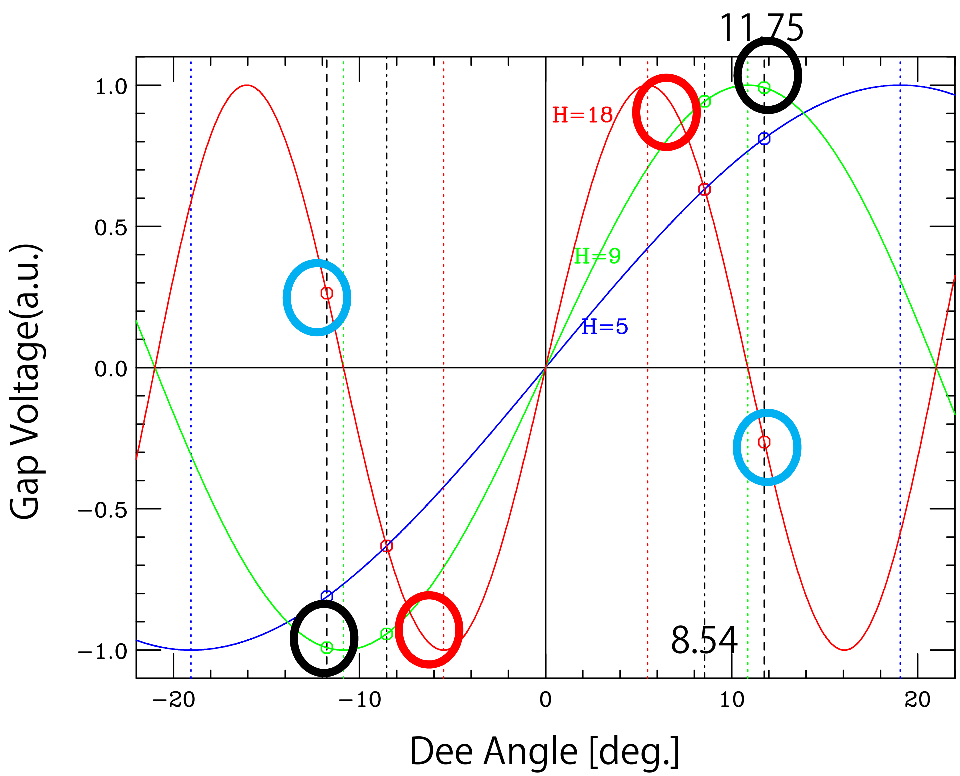


Remodel of the RRC cavity - concept

- The RRC cavity has double gaps and its dee angle is optimized for H=9.
- Its operation with a frequency of 18.25 MHz (H=9) limits rf gap voltage to around 1/3 of that with frequency of 36.5 MHz due to its structure.
- Operation with H=18 (36.5 MHz) doesn't make sense because the effective voltage with the original dee angle is 25% of gap voltage.
- We need change the dee angle to ±8 deg. to get higher effective voltage in the operation with a frequency of 36.5 MHz (H=18)

This remodel will increase the space charge limit by a factor of about 10.

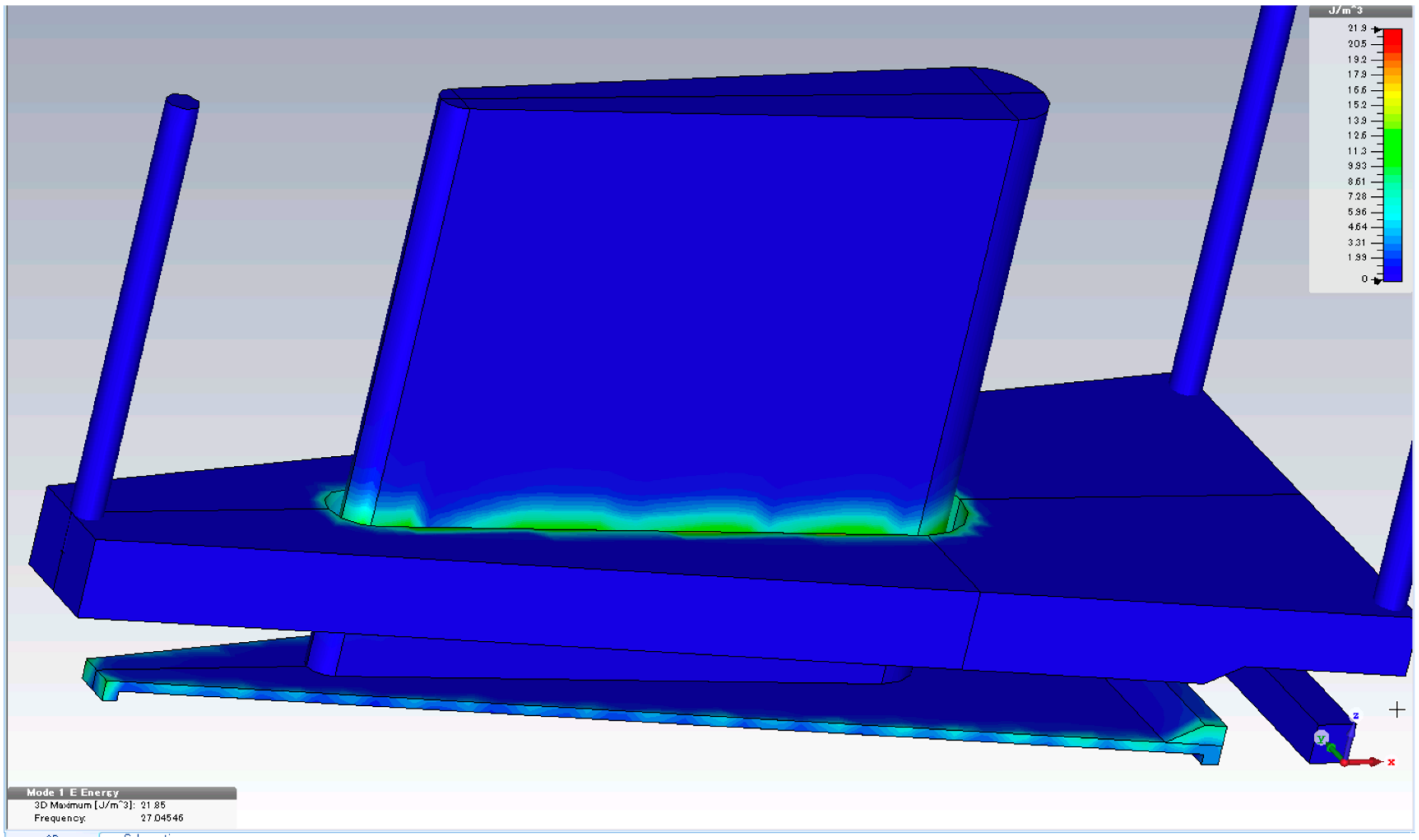




N. Sakamoto

Remodel of the RRC cavity -simulation

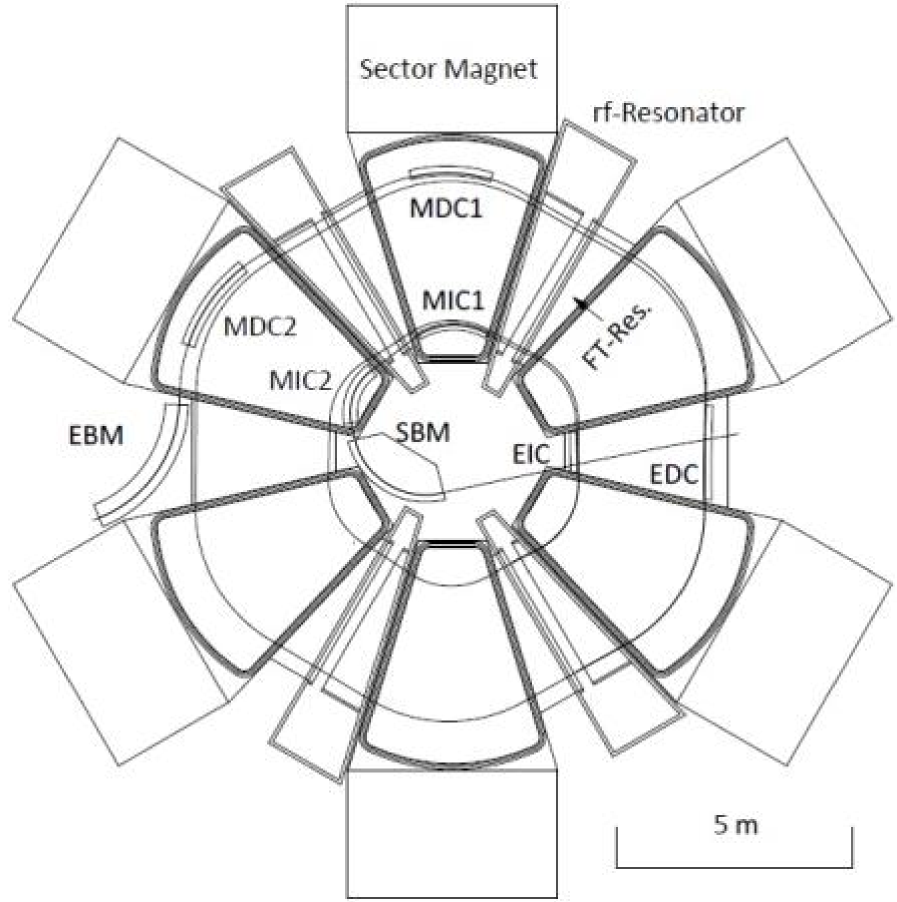
rf Frequency
Maximum electromagnetic field
Distribution of the gap voltage in the radial direction



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

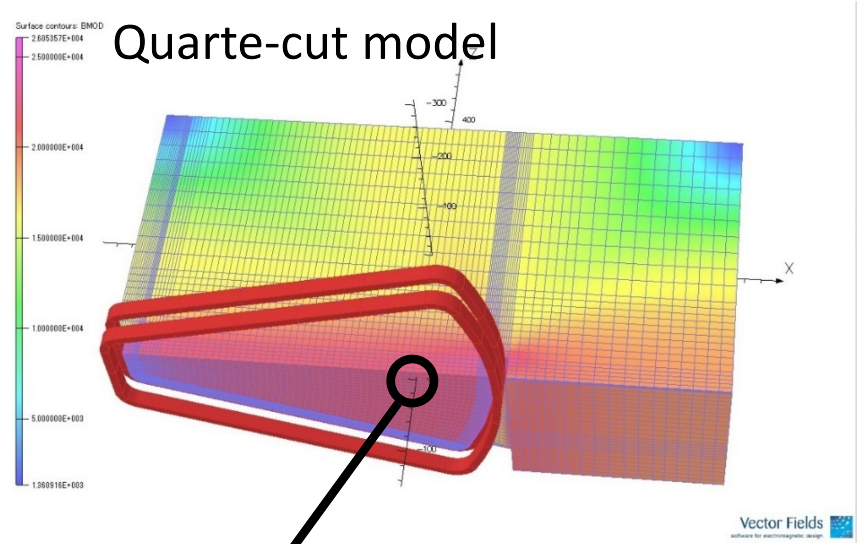


Conceptual design of the new FRC -Sector magnet

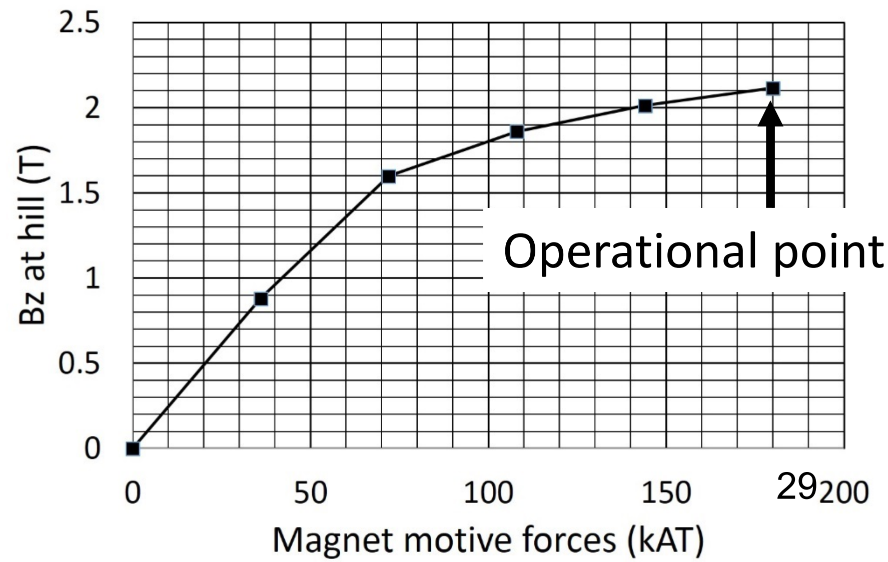
Specifications

Item	Value
Sector angle	34 degree
Bmax in the orbits	2.1 T
Pole gap	50 mm
Mag. motive forces	180 kAT
Main coil	Normal conducting
Turn no./coil	60
Hollow conductor	16 x 16 mm^2 with a hollow of 9mm ϕ
Operational current	1500 A
Power Consumption	2.4 MW

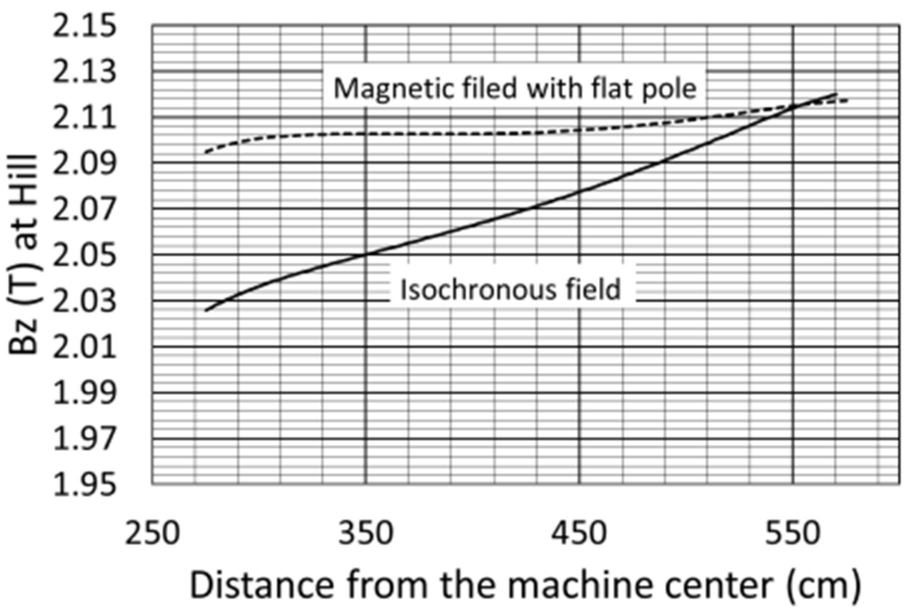
Quarte-cut model

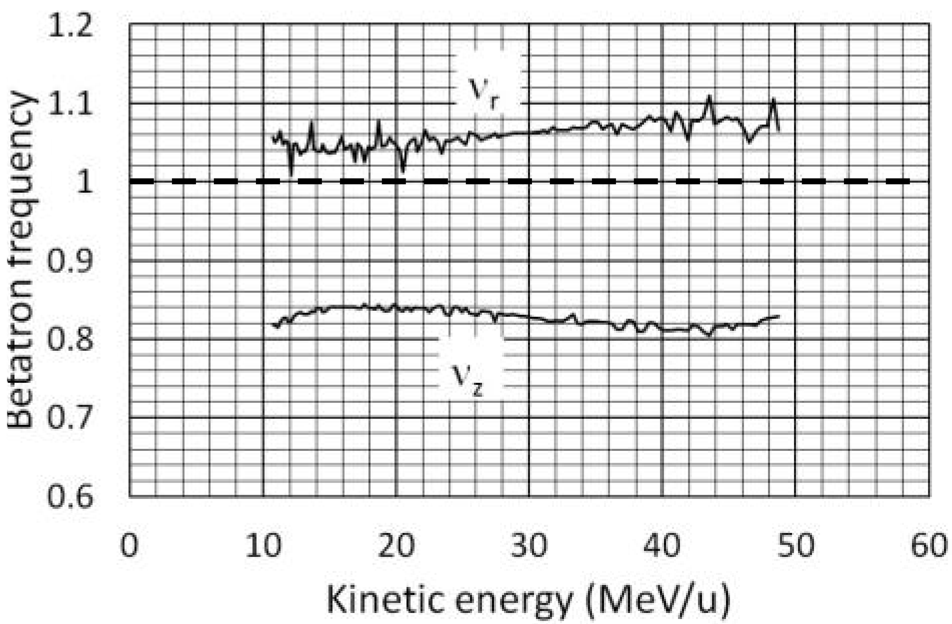


Excitation curve



Conceptual design of the new FRC
-Isochronous field and betatron frequency ν_r-ν_z

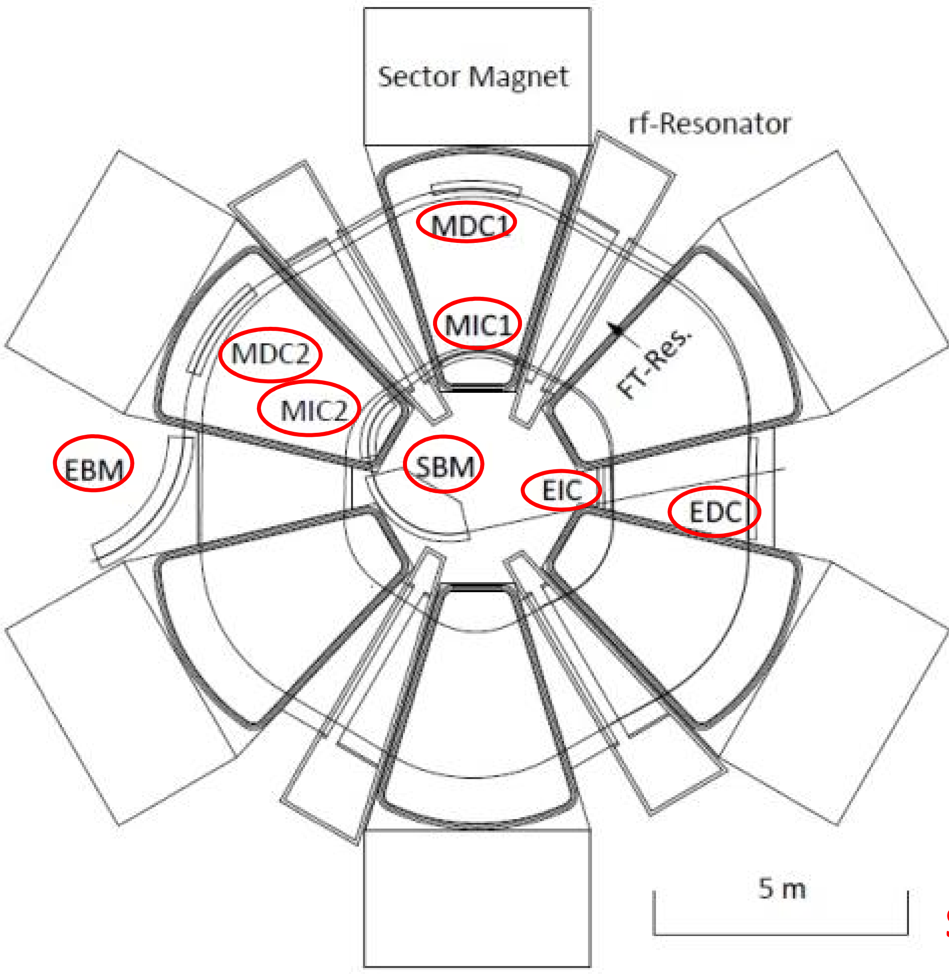




The isochronous field can be realized by tuning pole shape with small correction of trim coil currents.

ν_z =1 (imperfection resonance) can be avoided.

Conceptual design of the new FRC -Injection and extraction elements



	Length (m)	B or E (T or kV/cm)
Injection		
SBM	2.43	2.1
MIC2	1.28	0.7
MIC1	1.53	0.22
EIC	0.86	90
Extraction		
EDC	2.02	90
MDC1	1.74	0.15
MDC2	2.05	0.25
EBM	3.13	2.5

Similar elements to those in SRC can be used.

Some issues for the realization of the upgrade plan

We can find no essential problems in the three components:

1) remodel of the RRC cavity

2) conceptual design of the new FRC

3) upgrade of the RILAC

- How to make the new fRC smaller
  - Higher charge states from the Ion source (ex. U^{42+})
  - Recycle of the existing
- Use superconducting coils for power saving
- Improvements of the transmission efficiency
  - Reconsider of buncher for RFQ

How to make the new FRC smaller

1) Higher charge state such as 42+ from the next generation ECR ion source will help to make the FRC smaller ⇒save money on the new building

H.W. Zhao ICIS2013

"Highly charged ion sources reduce the cost of the project. "
"A lot of R&D work is necessary. "

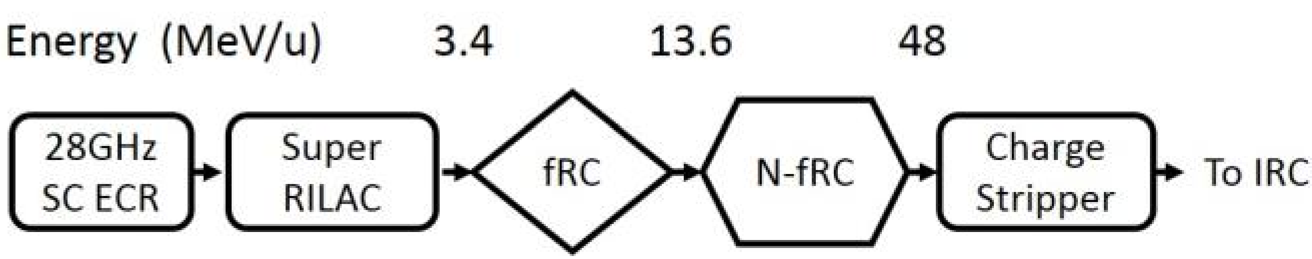
How much budget can a highly charged ion source save for a 100 MeV/u SC heavy ion linac

	$^{238}U^{34+}$	$^{238}U^{46+}$	$^{238}U^{55+}$
Injection E (MeV/u)	1.3	1.3	1.3
Output E (MeV/u)	100	100	100
Design I_{max} (emA)	1.0	1.0	1.0
SC cavity	HWR009+HWR015+ Spoke021	HWR009+HWR015+ Spoke021	HWR009+HWR015+ Spoke021
SC cavities	44+100+248=392	40+92+176=308	32+80+152=264
Solenoids	78	65	55
CRM Reduced		11	16
Total length (m)	288	225	197
Budget reduced		70 M$ (MP not included)	100 M$ (MP not included)

H.W.Zhao, ICIS2013, Japan, Sept.8-13, 2013

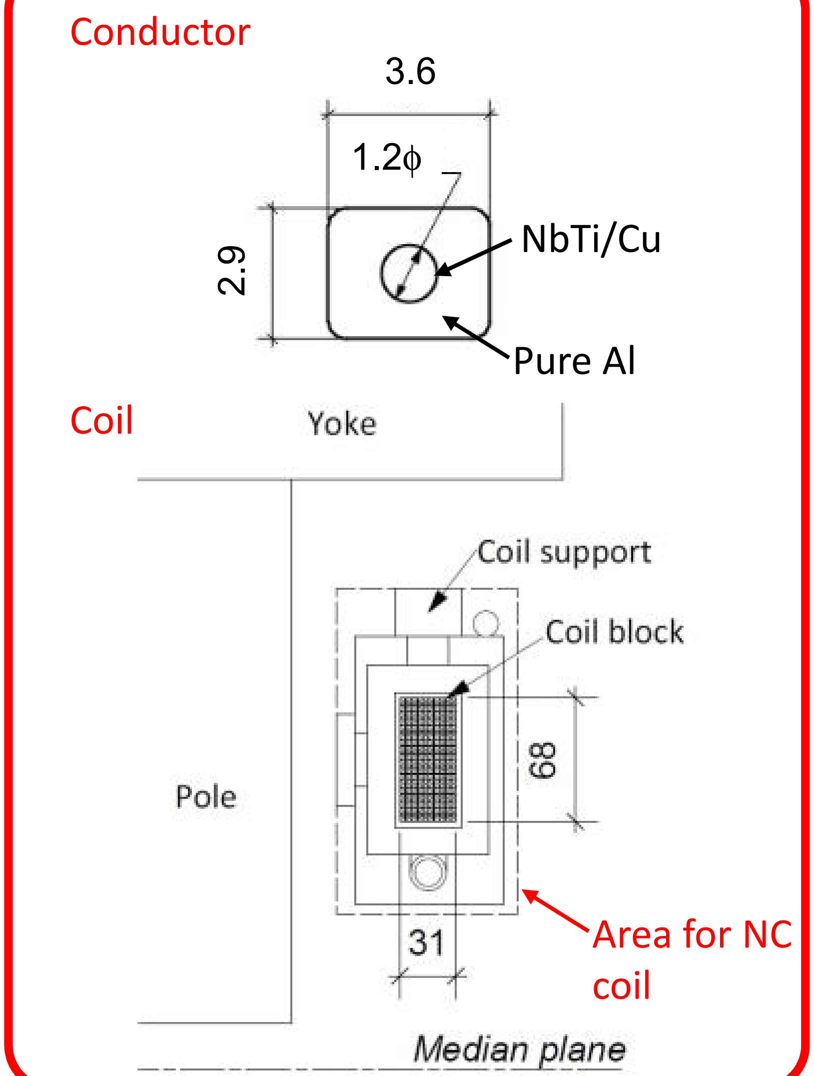
2) Reuse the existing FRC
⇒injection energy:
(10.8⇒13.6 MeV/u)
⇒Injection radius
(2.75⇒3.14 m)

・The pole area and the return-yoke volume can be reduced.



Usage of superconducting coils for power saving

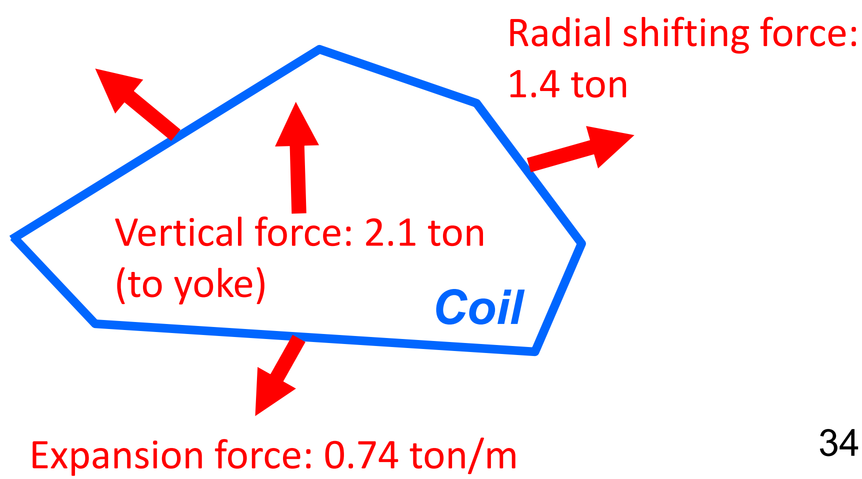
New FRC with the normal conducting coils: Power consumption > 2 MW
⇒Options of making the main coil of the superconducting wire for power saving



Conductor:
Al stabilized superconducting Nb/Ti wire

Coil size:	31 x 68 mm^2
Perimeter:	14.1 m
Operational current:	1000 A
Maximum field in the coil:	1.4T
Coil formation:	epoxy-impregnated
Cooling:	indirectly

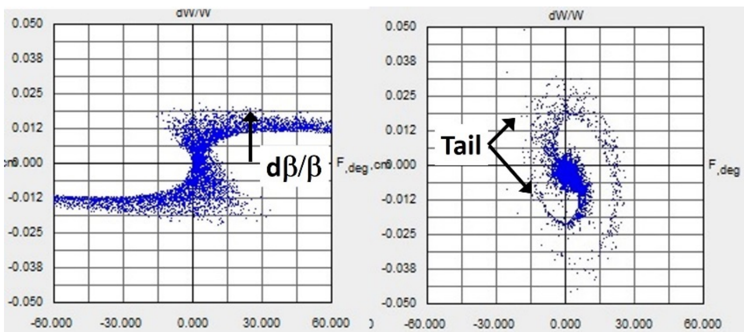
Electromagnetic forces: **1/100 of those in SRC**



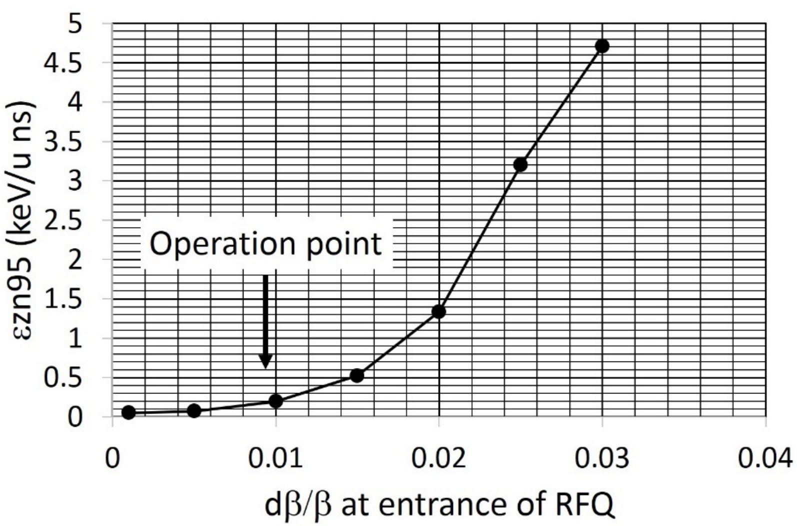
Improvement of the transmission efficiency -Reconsider of buncher for RFQ

Longitudinal bunch shape at entrance and exit of RFQ

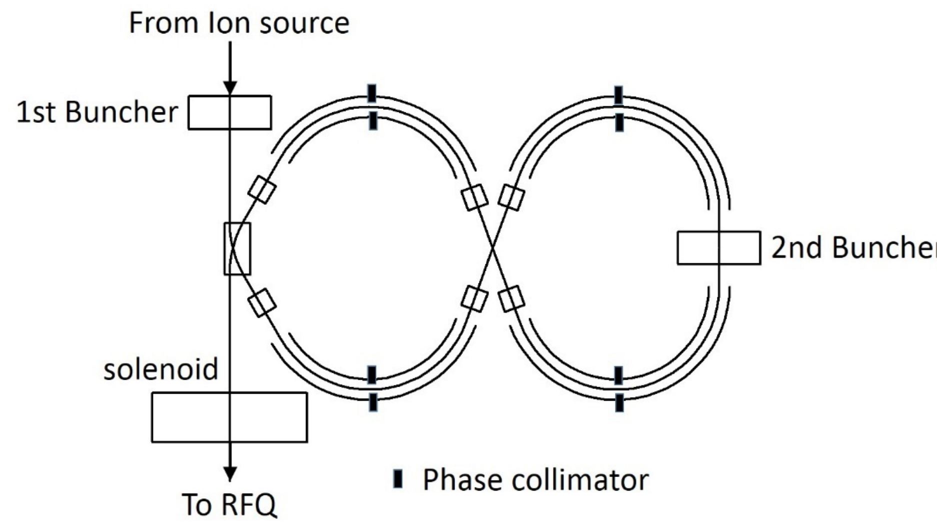
Entrance **Exit**



Longitudinal emittance at the exit of RFQ



An idea for sophisticated bunching system with phase collimation.



Summary

- We have just started an upgrade program for increasing beam intensity mainly of uranium ion based on the successful operational experience for ten years since the first beam at the end of 2006.
- The program includes the three components.
    - Space charge limit in the low energy cyclotron of RRC will be increased by the remodeling the rf resonators.
    - The existing fRC will be replaced with a new one to skip the first charge stripper.
    - Upgrade of the RILAC by adding the superconducting RF resonators
- Although we have some issues for the realization of this program, we hope the first beam by 2025 from the new upgraded acceleration complex.