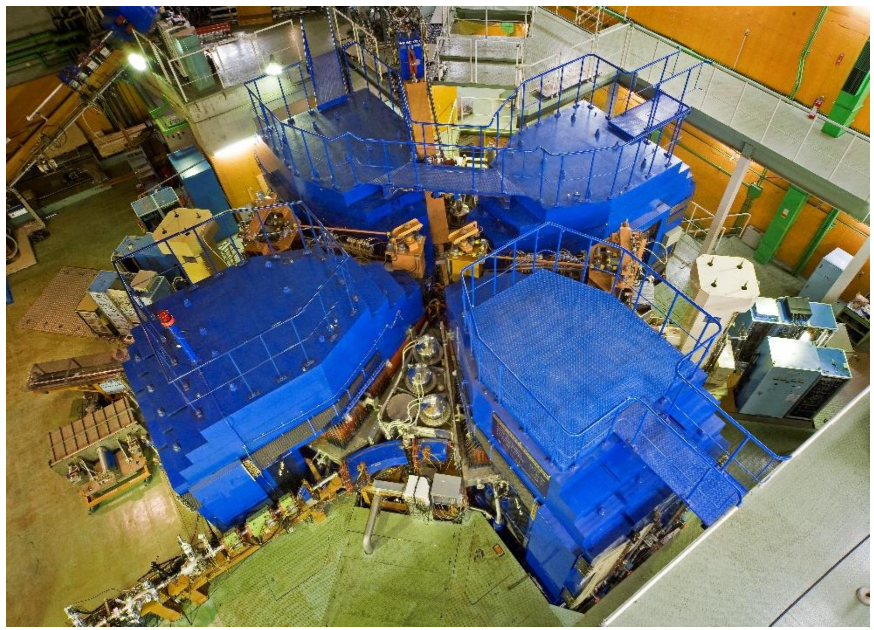
Upgrade and current status of high-frequency systems for RIKEN Ring Cyclotron



Kazunari Yamada

RIKEN Nishina Center

MOAI02, Cyclotrons2022, Dec. 5th, 2022

Contents

RIKEN RI Beam Factory (RIBF)

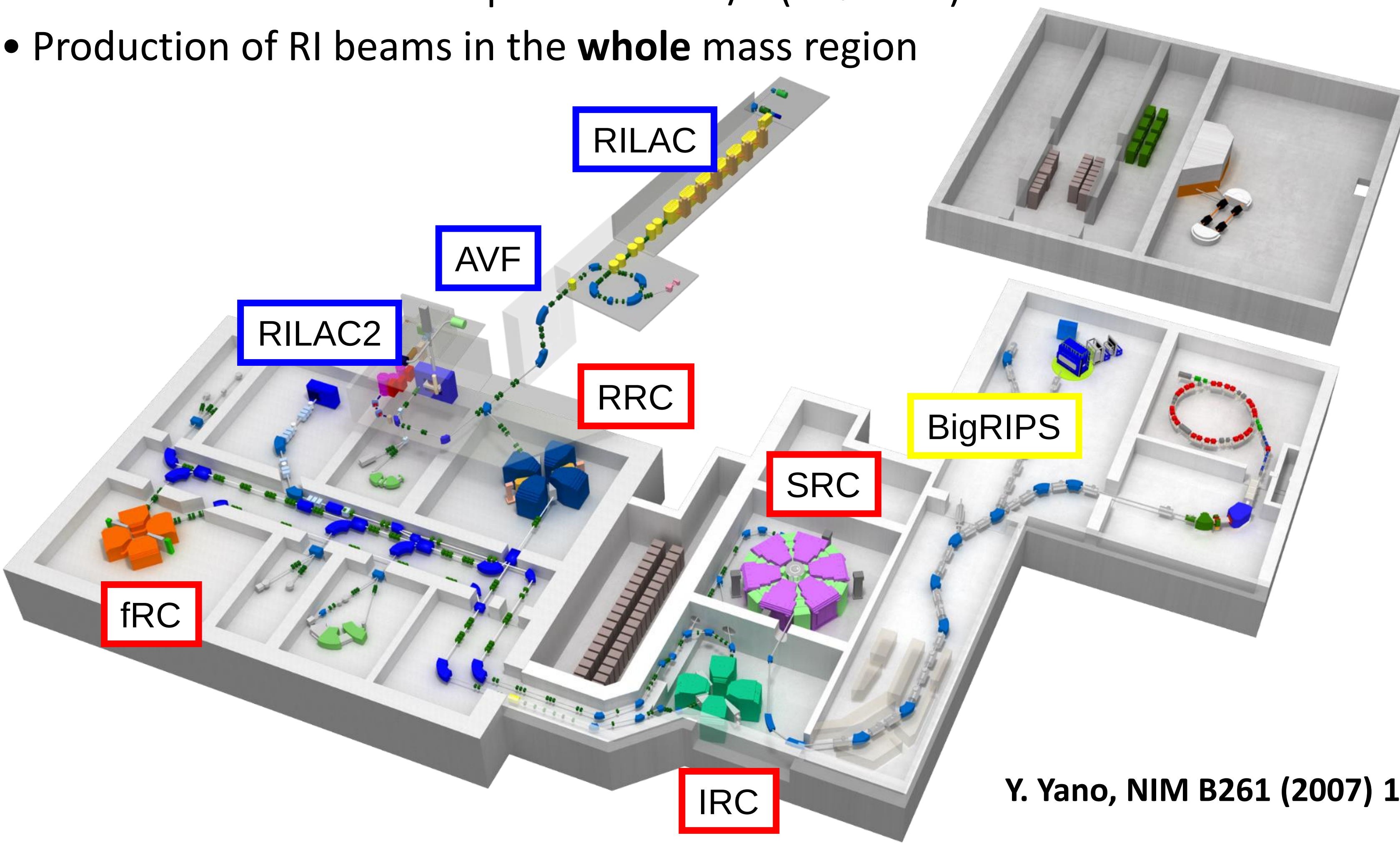
3 Injectors (2 linacs, 1 AVF cyclotron)

4 Boosters (4 ring cyclotrons)

RI beam separator

Scientific goals of RIBF:
- Establish ultimate nuclear model
- Elucidate elements synthesis
- Promote application of ion beams

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



Y. Yano, NIM B261 (2007) 1009.

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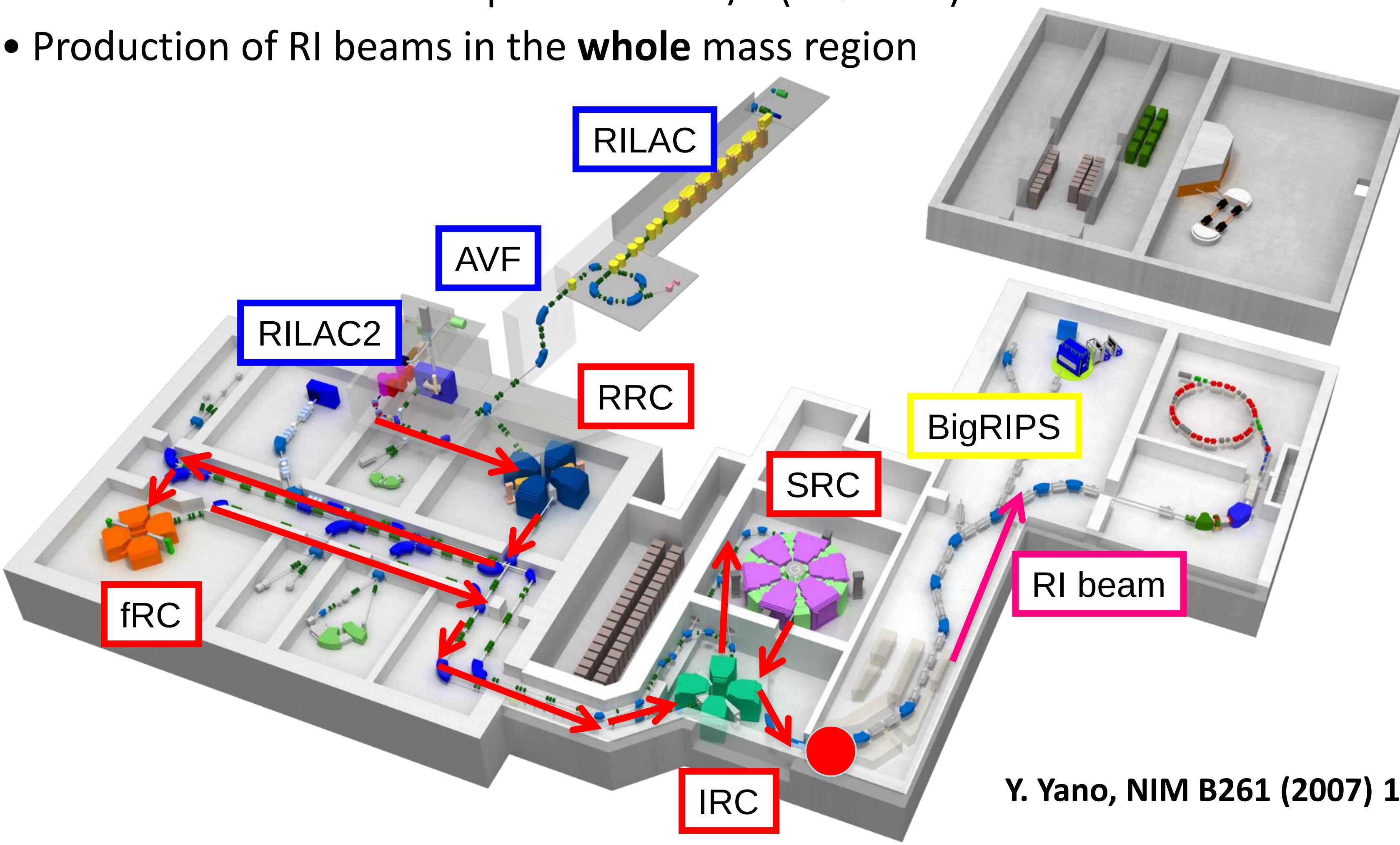
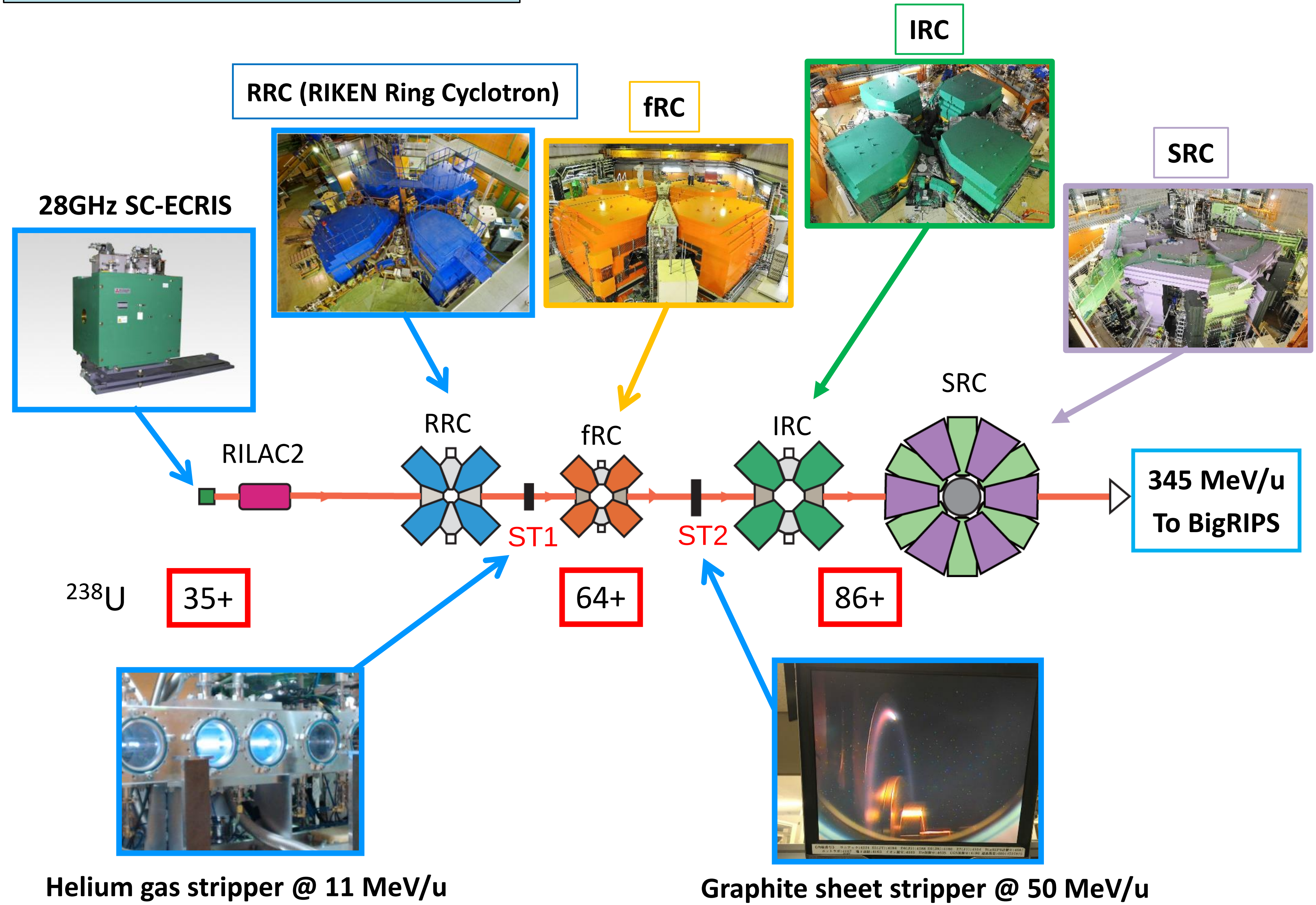
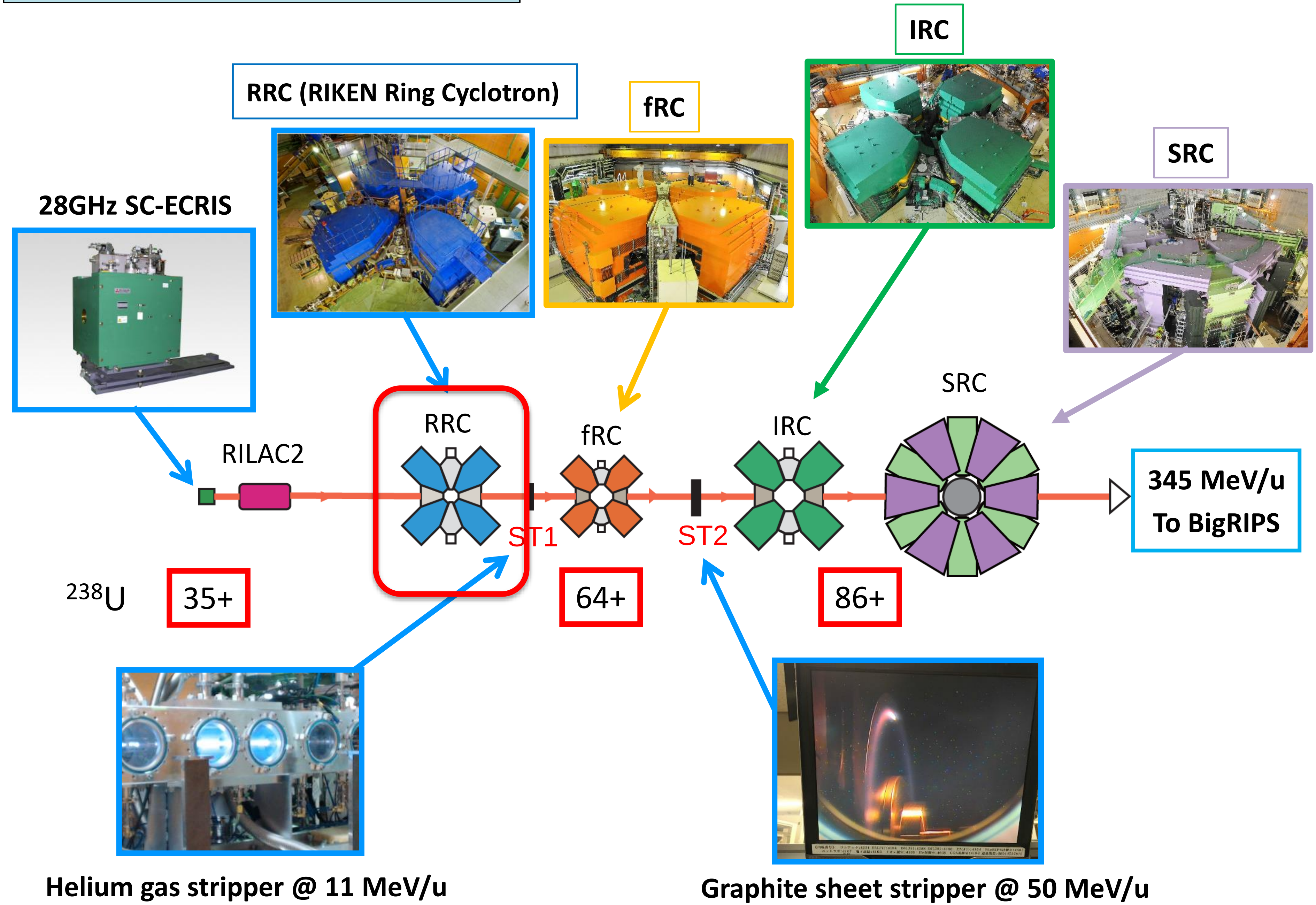


Y. Yano, NIM B261 (2007) 1009.

Uranium acceleration

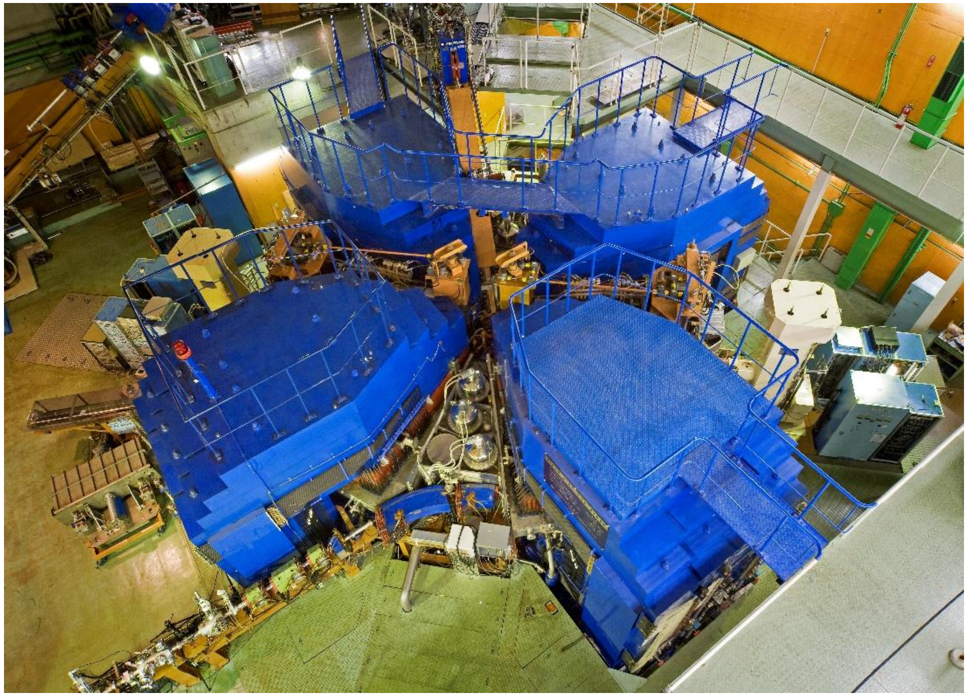


Uranium acceleration



RIKEN Ring Cyclotron (RRC)

- Normal-conducting isochronous ring cyclotron
- In operation **since 1987**
- Max. 135 MeV/u for light ions up to *A*≈30
- Frequently used in the RIBF accelerator complex

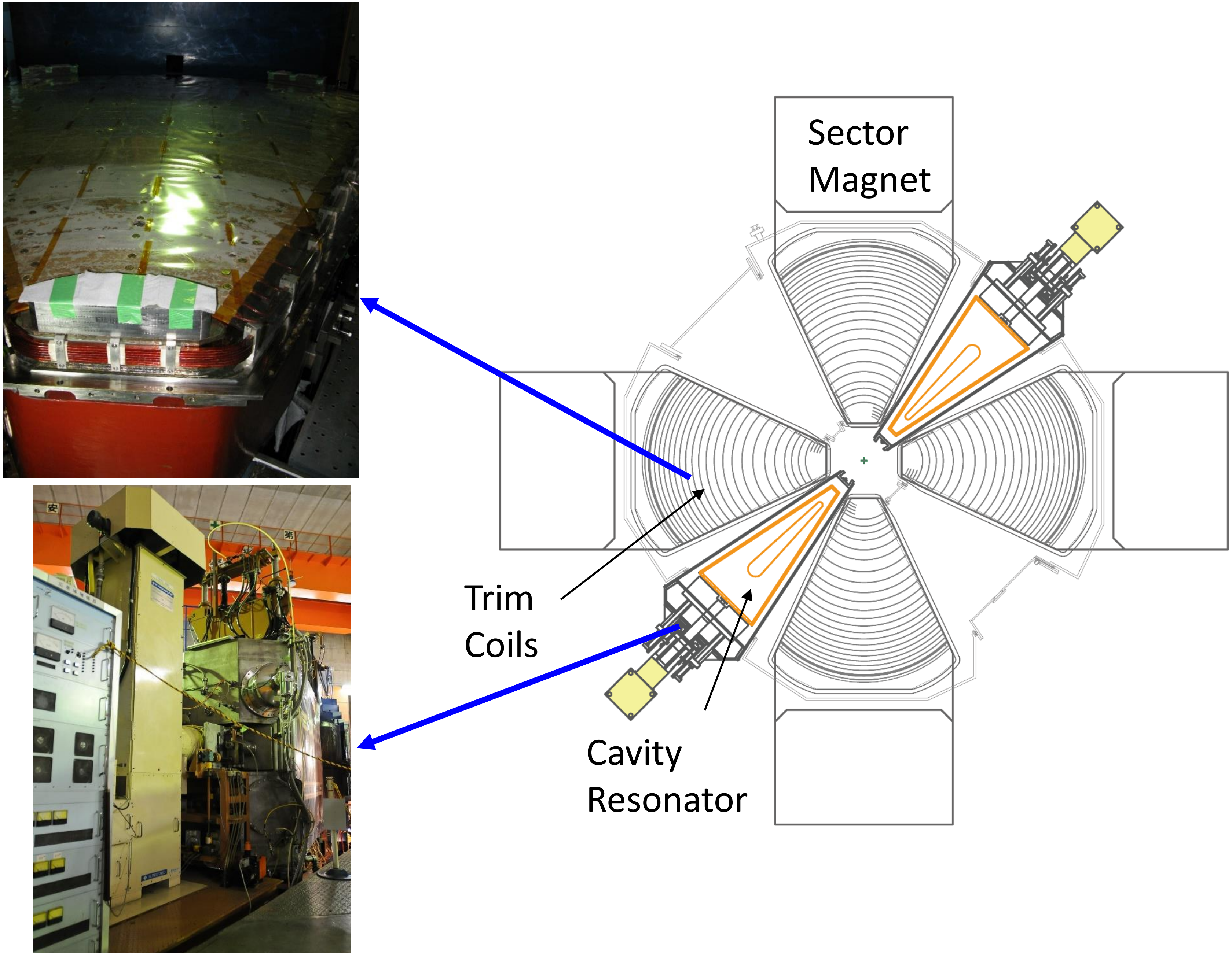


Specifications of RRC

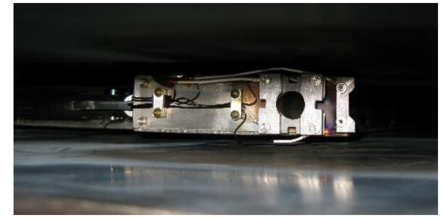
K-value	540 MeV
Sectors	4
Sector angle	50°
Pole gap	80 mm
Maximum field	1.6 T
Trim coils	26
Velocity gain	4.0
Mean injection radius	89 cm
Mean extraction radius	356 cm
Acceleration cavities	2
Frequency range	18-42 MHz
Harmonics	5, 9, etc.

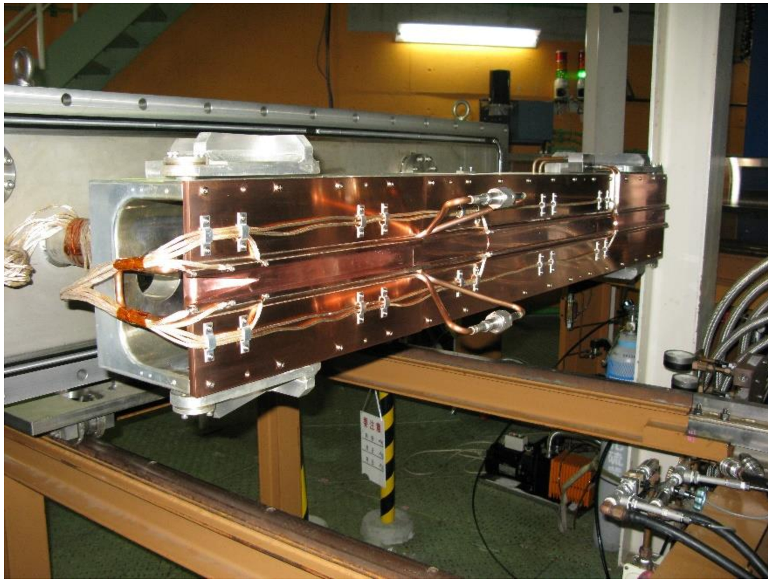
Y. Yano, Proc. of Cyclotrons **1992**, 102 (1992).

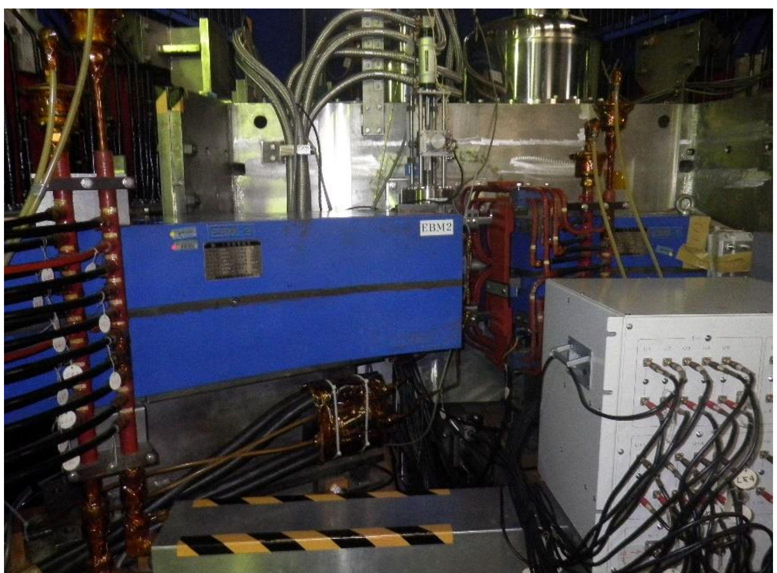
RIKEN Ring Cyclotron (RRC)

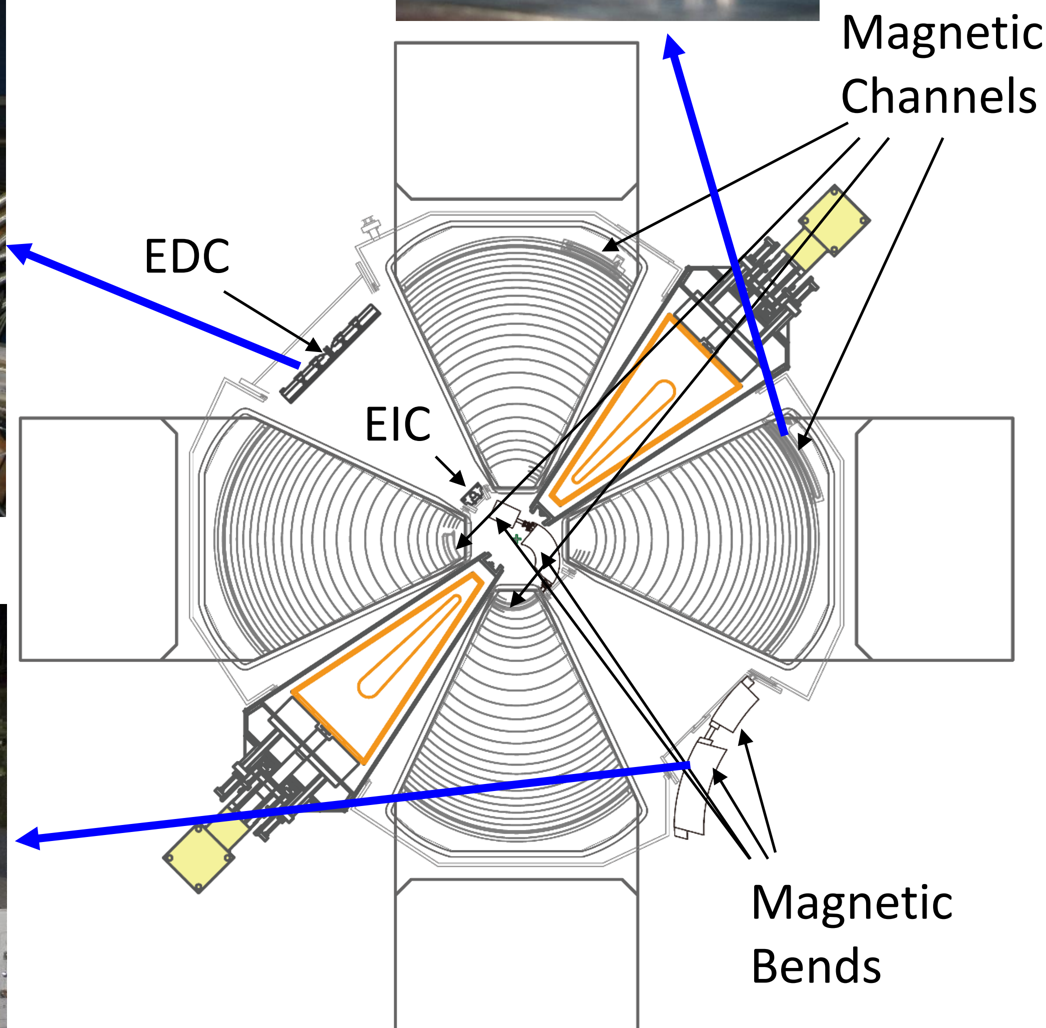


RIKEN Ring Cyclotron (RRC)









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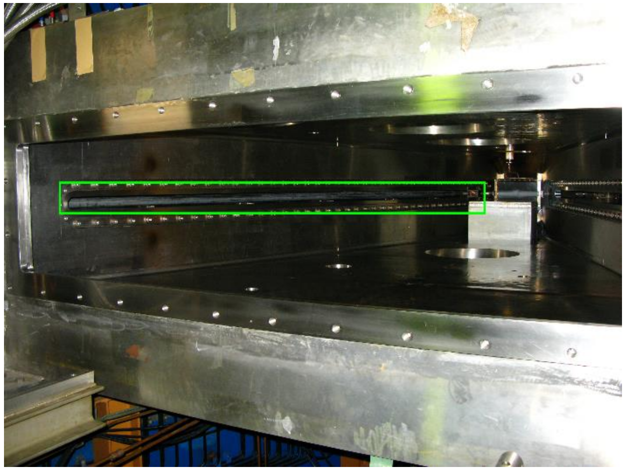
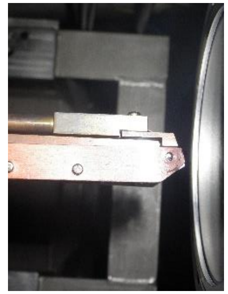
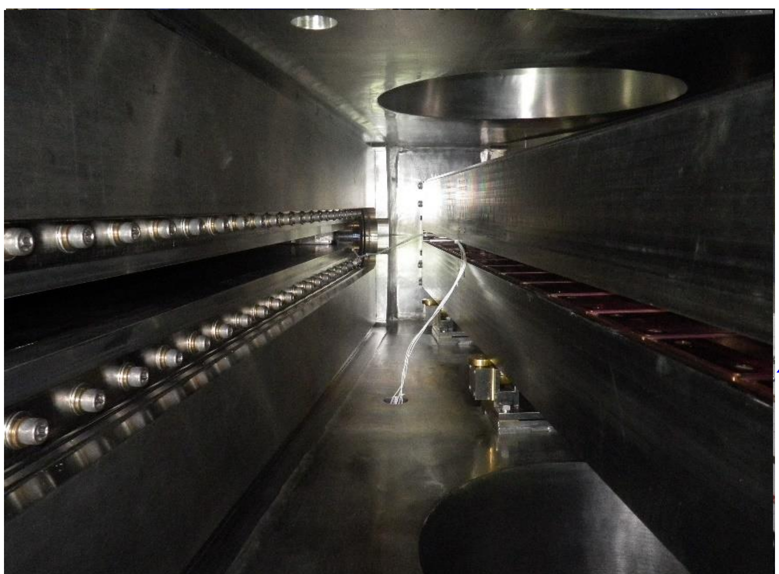
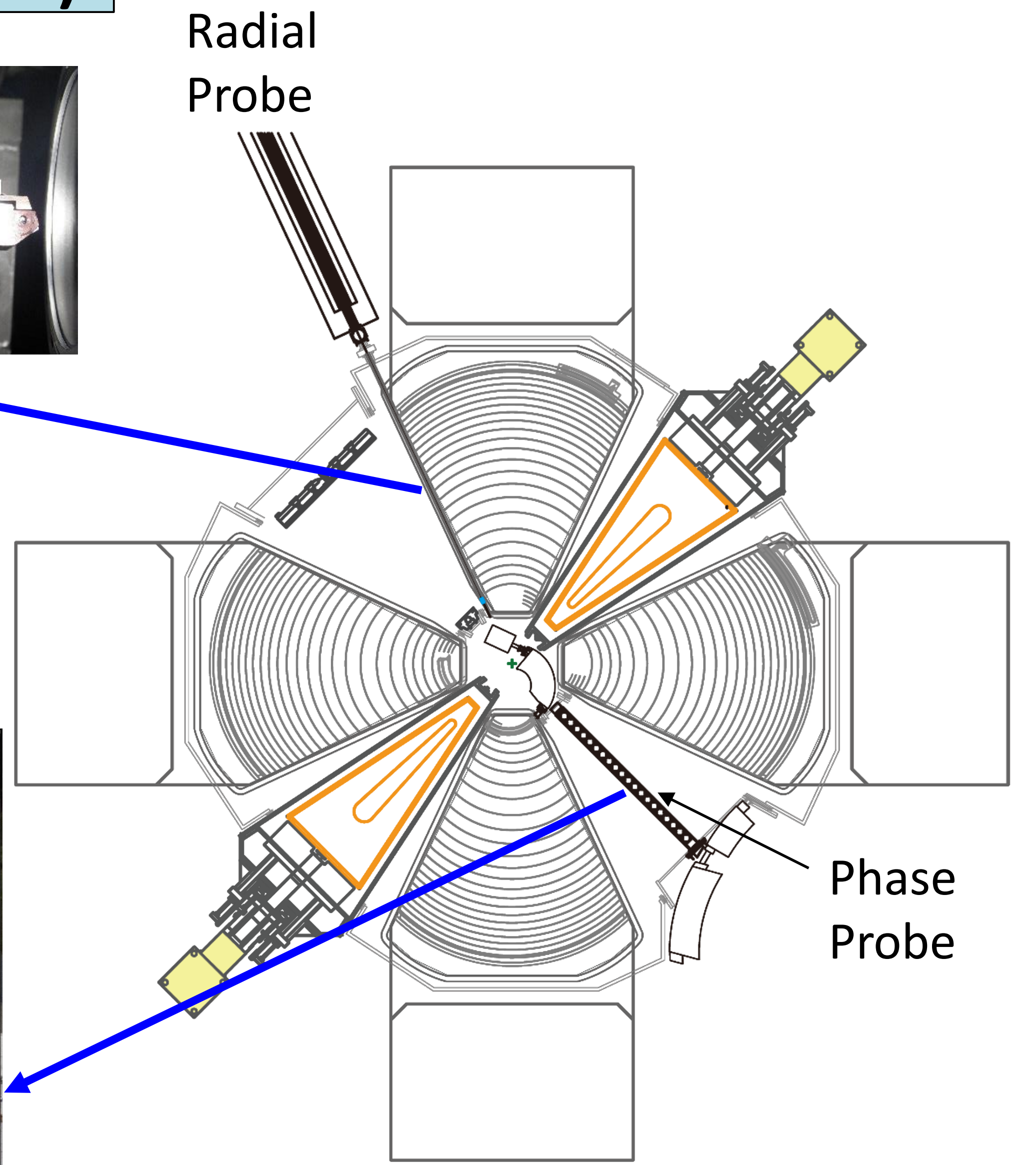
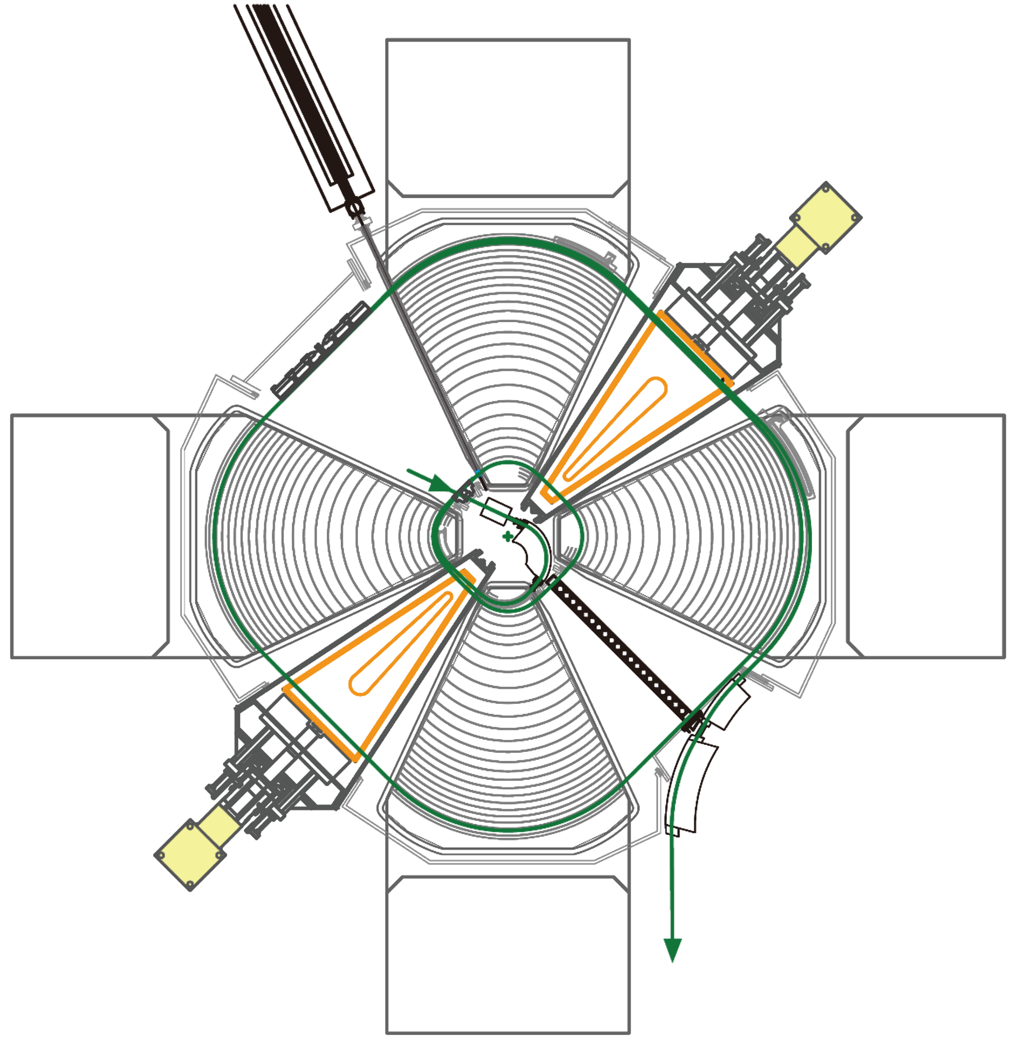








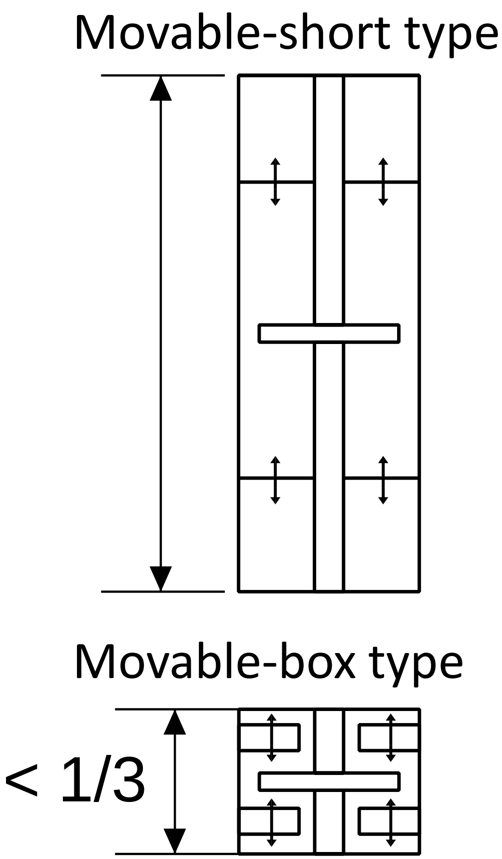
RIKEN Ring Cyclotron (RRC)

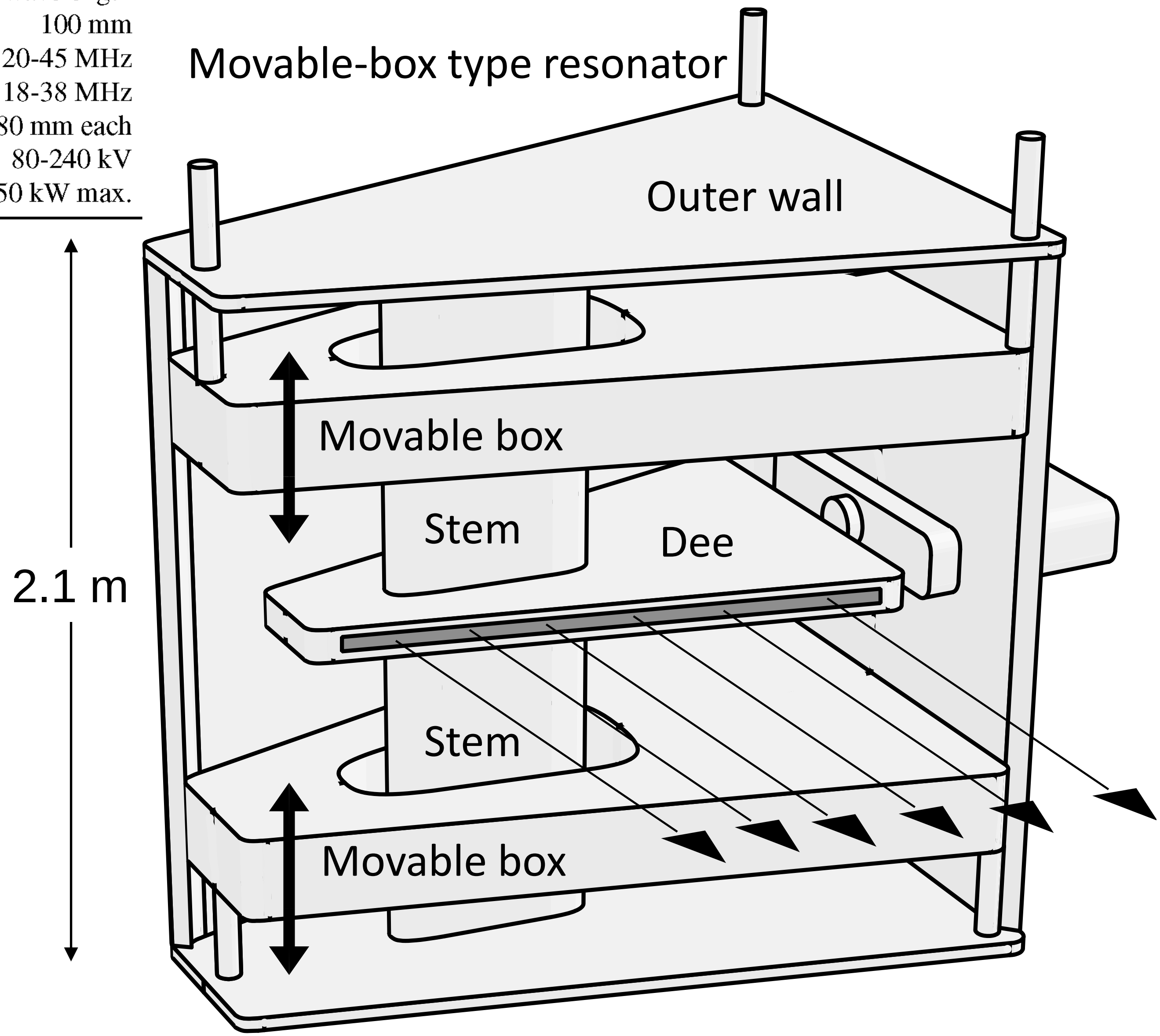


High-frequency system of RRC

Cavity resonators	2 (no flat-top)
Type	2-gap half-wavelength
Gap	100 mm
Frequency range (design)	20-45 MHz
Frequency range (actual use)	18-38 MHz
Stroke of MBOX	680 mm each
Dee voltage	80-240 kV
Rf power input	150 kW max.

Very compact at low frequency by large capacitance



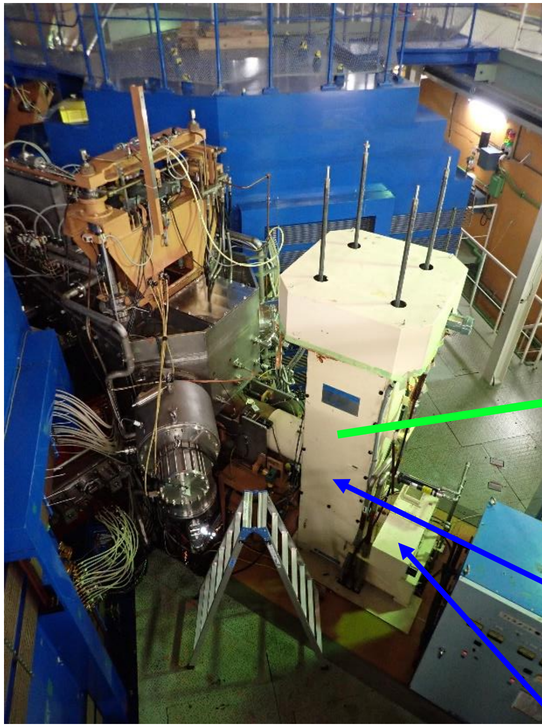


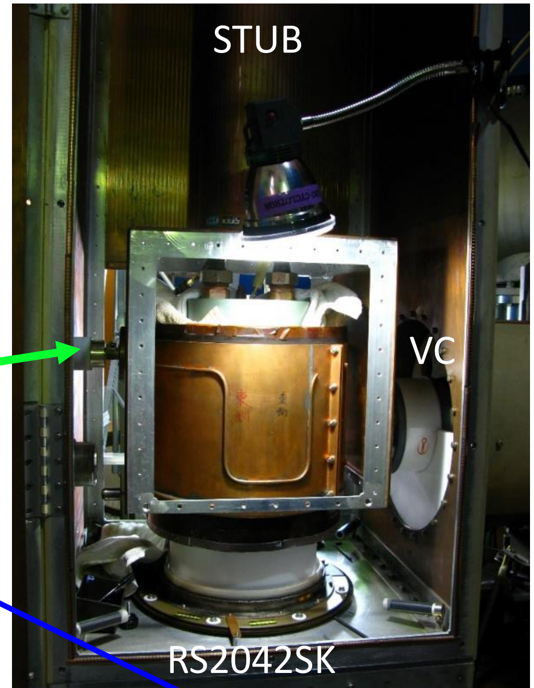
T. Fujisawa et al., NIM **A292** (1990) 1.

High-frequency system of RRC

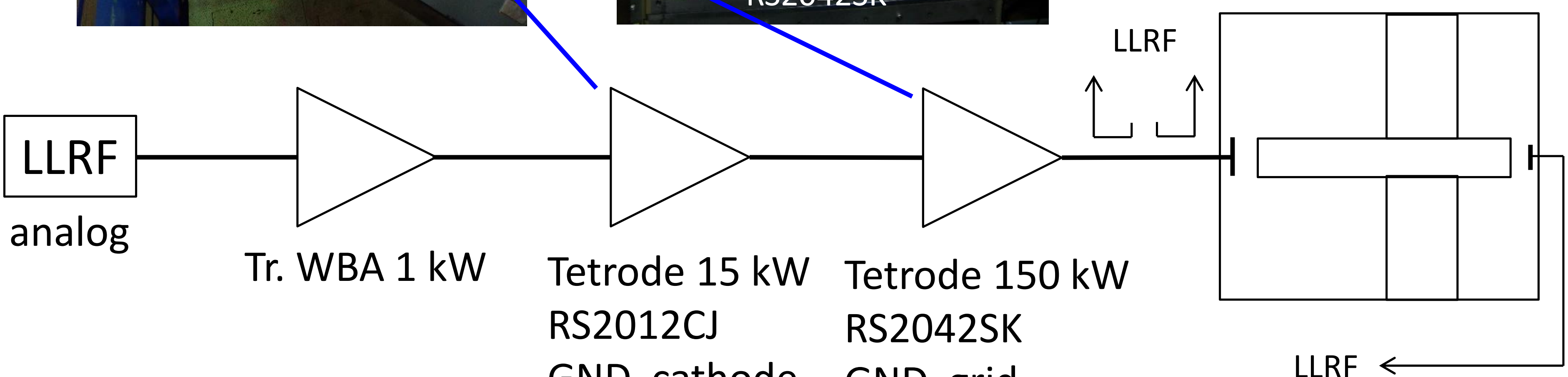
T. Fujisawa et al., Sci. Papers of IPCR79 (1985) 12.
T. Fujisawa, https://Nishina-preprints.riken.jp /article/data/521/data-1.pdf

Rf amplifiers with tetrode are used.



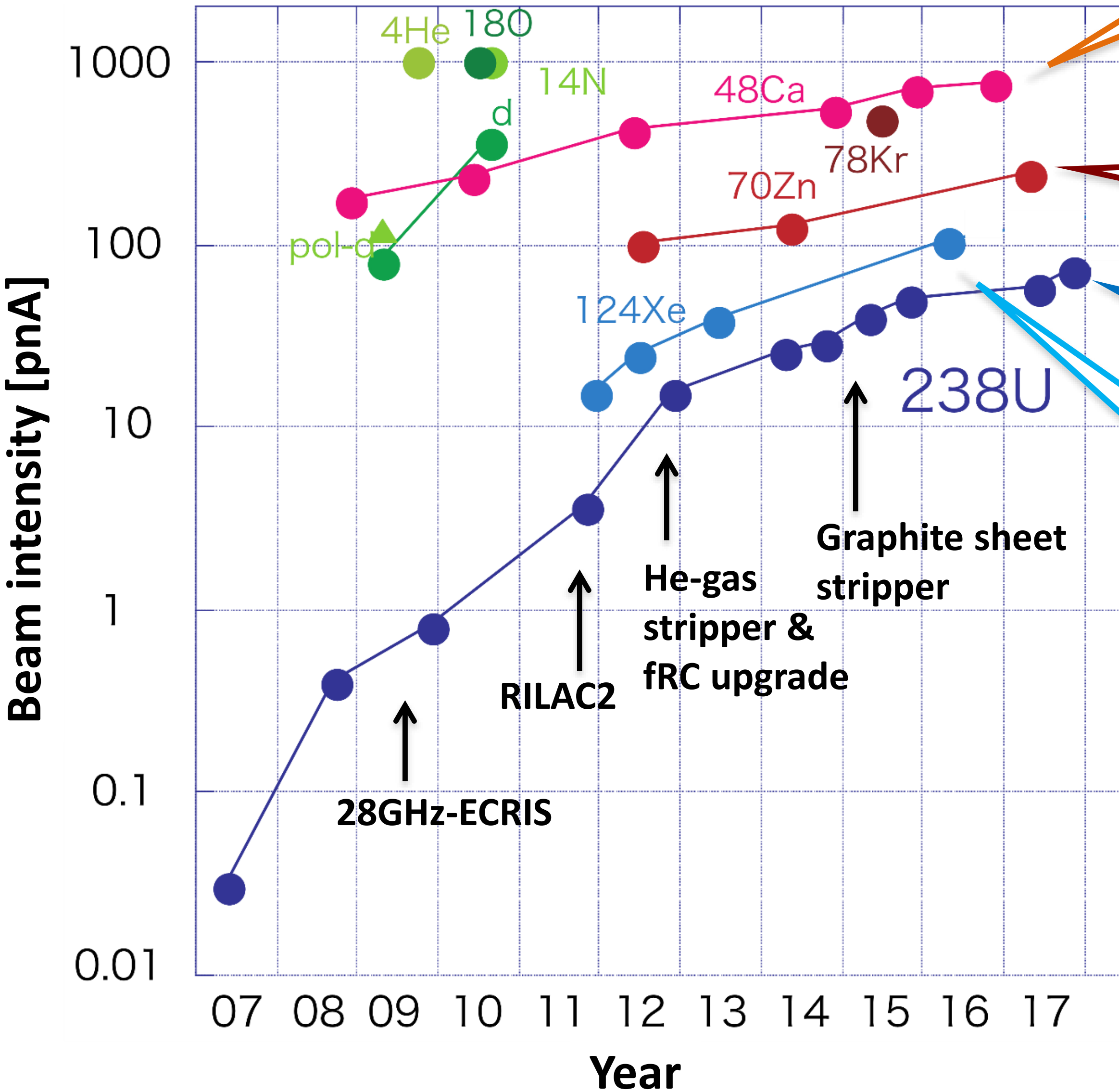


Frequency range	18-42 MHz
Rf power output	150 kW max.
Impedance matching	all pass network +variable capacitor +variable stub
LLRF	analog feedback
Voltage stability	$< 0.1\%$
Phase stability	$< 0.1^\circ$



Matching circuits are omitted from figure

Performance of RIBF until 2017



^{48}Ca: 738 pnA
=> **12.2 kW**

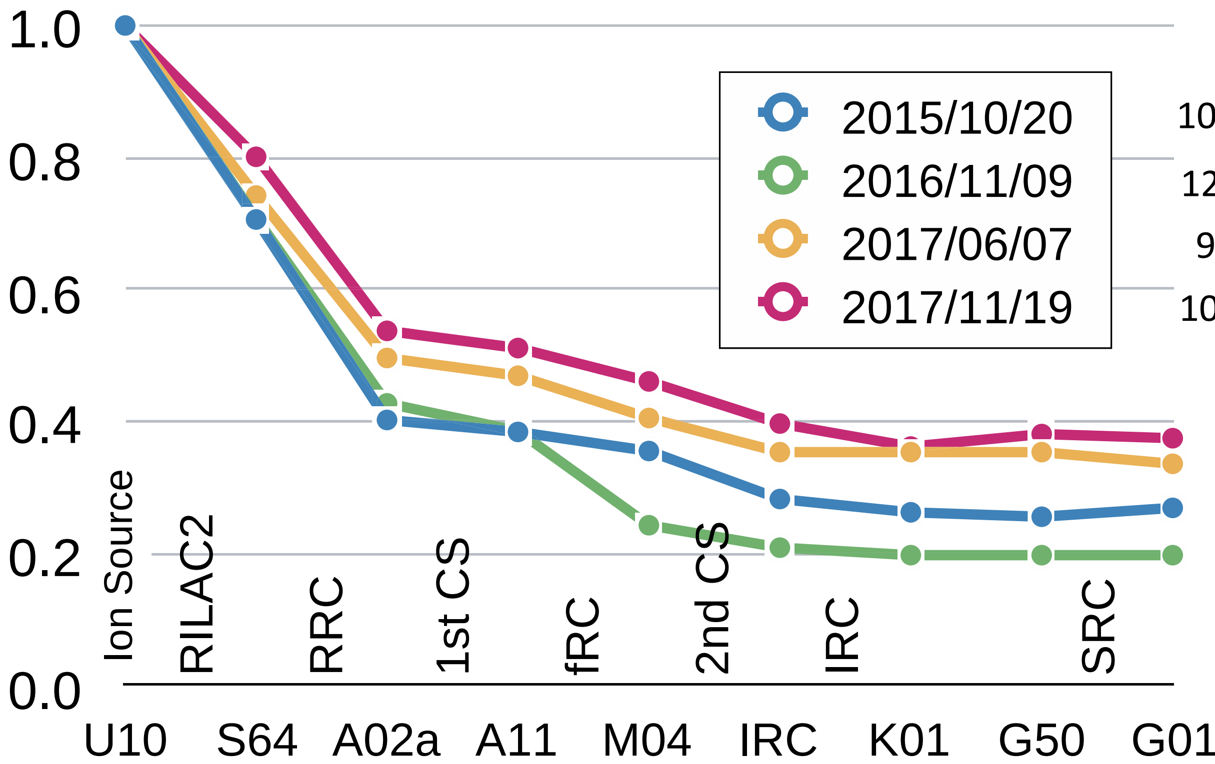
^{78}Kr: 486 pnA
=> **13.1 kW**

^{238}U: 71 pnA
=> **5.8 kW**

^{124}Xe: 102 pnA
=> **4.4 kW**

Transmission efficiency*

*Stripping efficiency is excluled.



102 eμA @ IS → 47 pnA @ SRC

120 eμA @ IS → 40 pnA @ SRC

97 eμA @ IS → 55 pnA @ SRC

108 eμA @ IS → 69 pnA @ SRC

345-MeV/nucleon ^{238}U

49 pnA (Nov. 2015) →

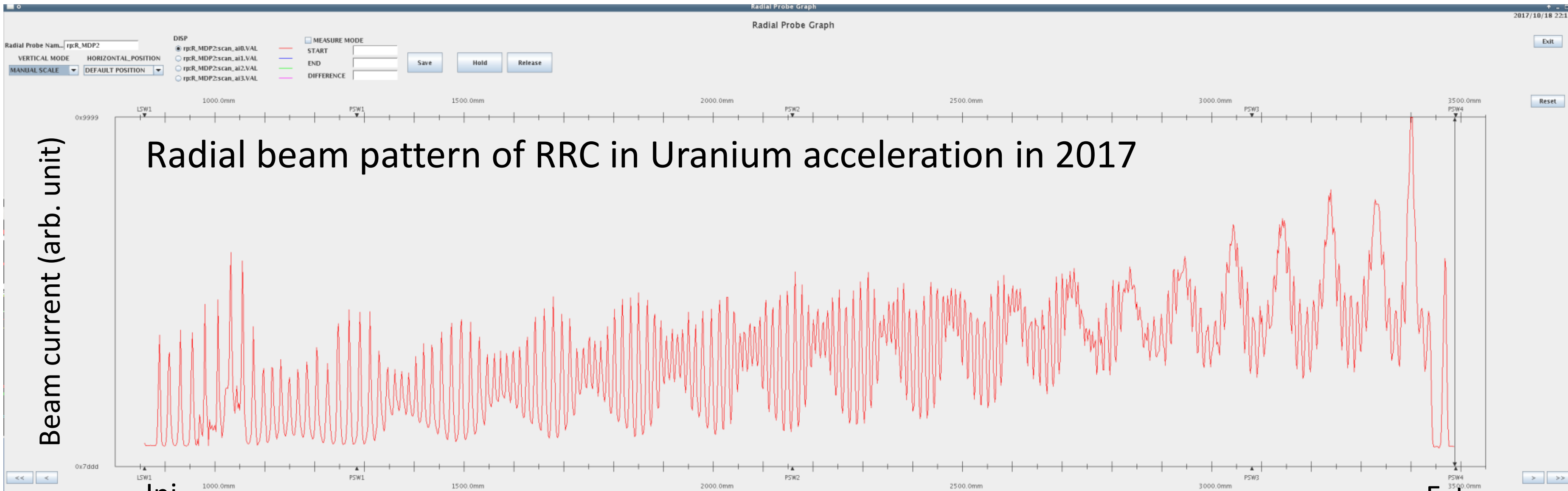
71 pnA max.(Nov. 2017)

The accuracy of the Faraday cups sometimes makes efficiency appear to be increasing downstream.

Insufficient voltage in Uranium acceleration

Uranium acceleration: f_0 = **18.25 MHz**, V_{gap} = **85 kV**

Insufficient voltage limits the beam intensity due to the space charge effect.



Example for space charge limit

$$I_{\max} = \frac{h}{2 g_r \xi^3 \beta^3 \gamma \nu_x^4} \frac{V_{\rm rf}^3}{V_m^2 Z_0}$$

R. Baartman,Proc. of Cyclotrons2013, 305 (2013).

RRC parameters

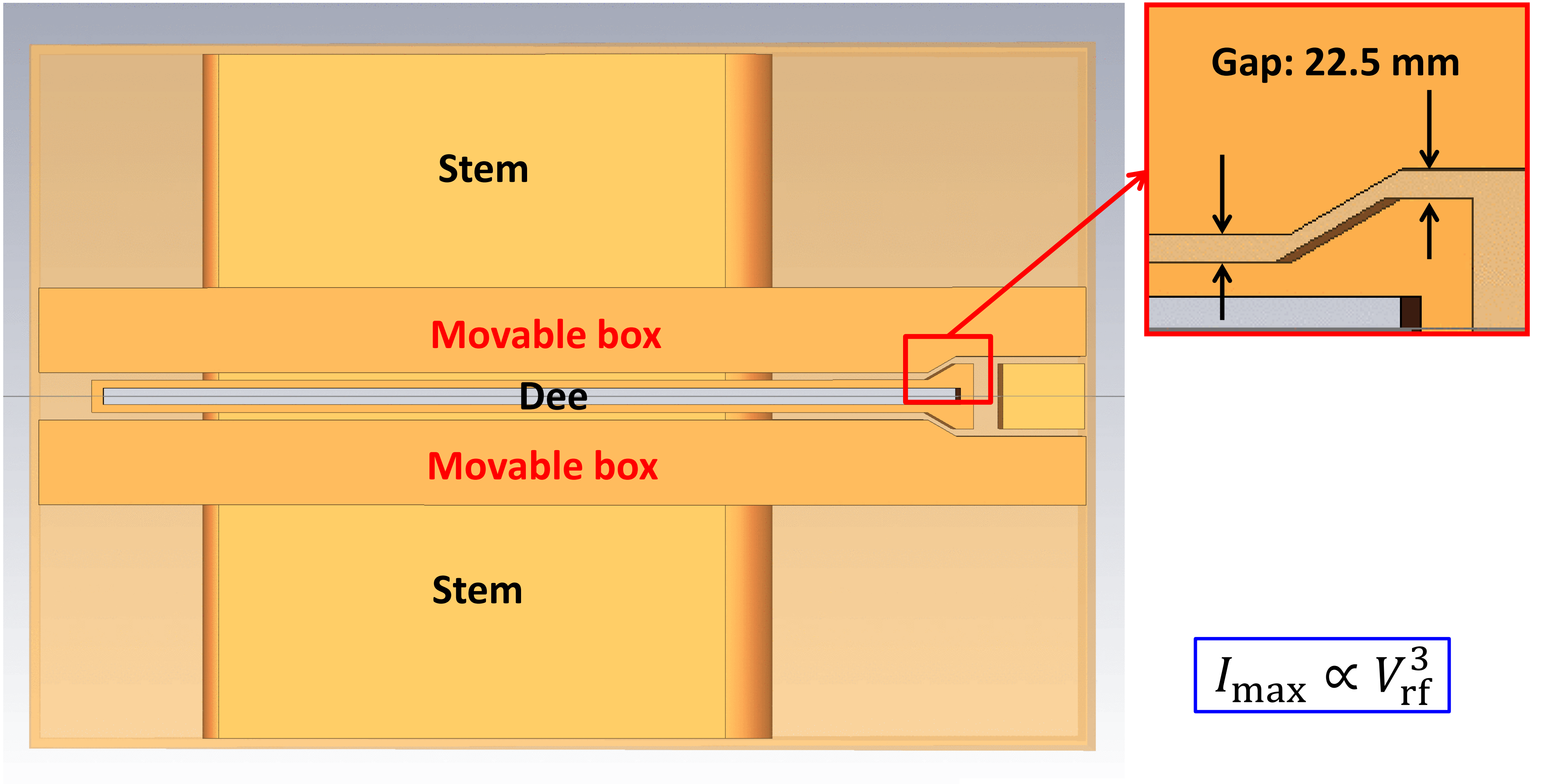
$$h = 9, g_r = 1, \xi = 2.7, \beta = 0.15, \gamma = 1.0115,$$
$$\nu_x = 1.1, V_{\rm rf} = 300\ \text{kV}, V_m = 6334\ \text{MV}, Z_0 = 377\ \Omega$$

$I_{\max} = 2.3$ pμA for $^{238}U^{35+}$

Why so low voltage?

Frequency for uranium acceleration: **18.25 MHz**

→ Out of the design range (20 ~ 45 MHz)



$$I_{\mathrm{max}} \propto V_{\mathrm{rf}}^3$$

Gap between dee and movable box: **22.5 mm**

→ Low shunt-impedance and frequent discharge

→ Limit maximum voltage ~ **85 kV**

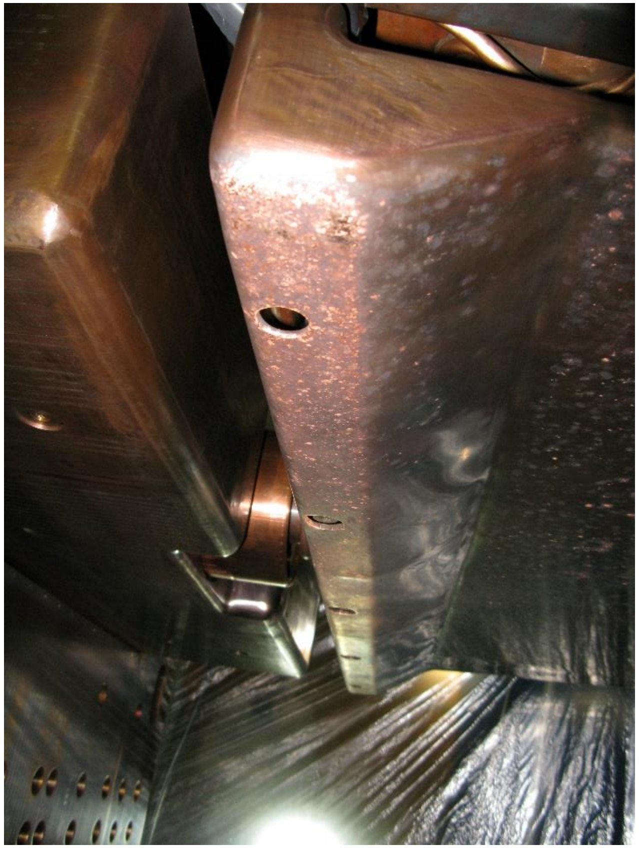
Frequency range (design)	20-45 MHz
Shunt impedance (calc.)	61-594 kΩ
Shunt impedance at 18.4 MHz (calc.)	48.4 kΩ
Q_0 at 18.4 MHz (calc.)	8865
Maximum voltage at 18.25 MHz	85 kV

Frequent discharge in original cavity

Numerous discharge marks were observed on the inner surface during maintenance.

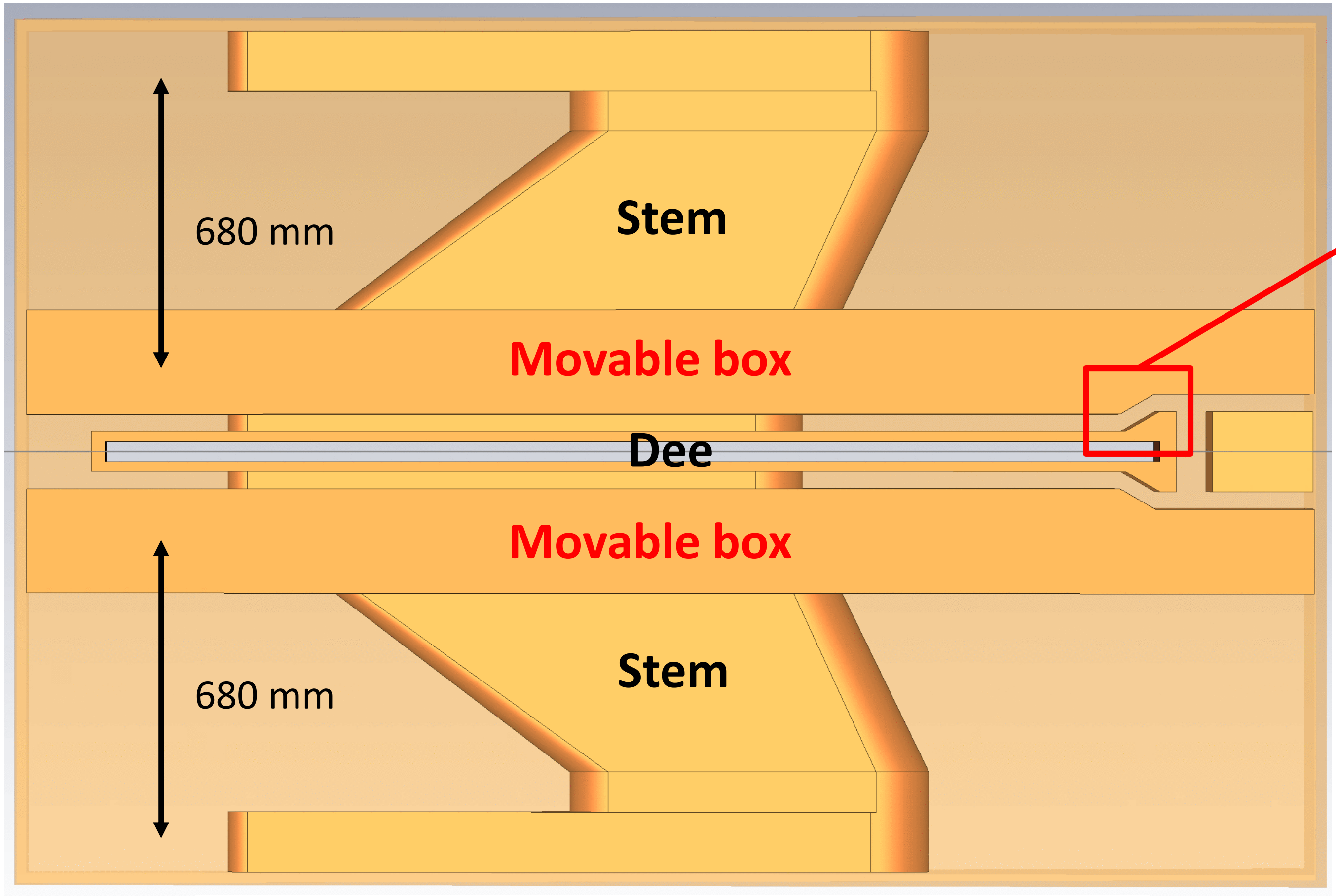
Movable box

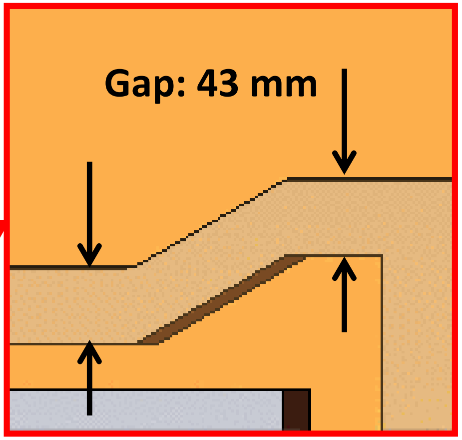
Dee



Modification of RRC cavity

New slanted stem structure was adopted to shift frequency range to lower side.
Increased inductance helps to reduce the capacitance for the same frequency.
Reduced capacitance resulted in the increased shunt impedance.





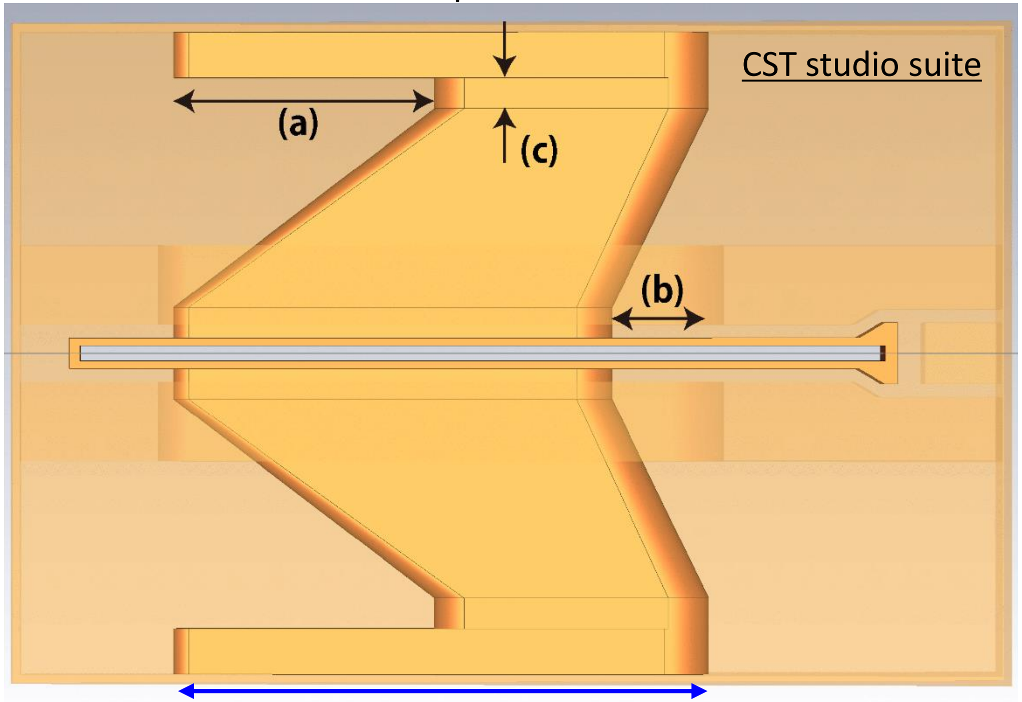
	Original cavity	Modified cavity
Frequency range (design)	20-45 MHz	16-38.8 MHz
Shunt impedance (calc.)	61-594 kΩ	78-451 kΩ
Shunt impedance at 18.25 MHz (calc.)	∼ 48 kΩ	∼ 99 kΩ
Maximum voltage at 18.25 MHz	∼85 kV	>120 kV

Voltage at **18.25 MHz** can be increased by **a factor of 1.5 or more**.

Design of modified cavity

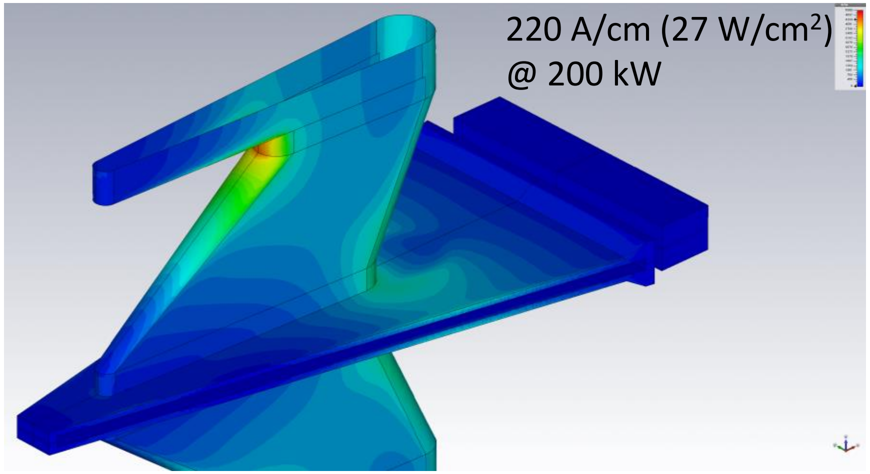
We decided to modify the cavity by replacing only its inner conductor (**Stem & Dee**).
3D electromagnetic calculations were performed to optimize the shape.

Free parameters

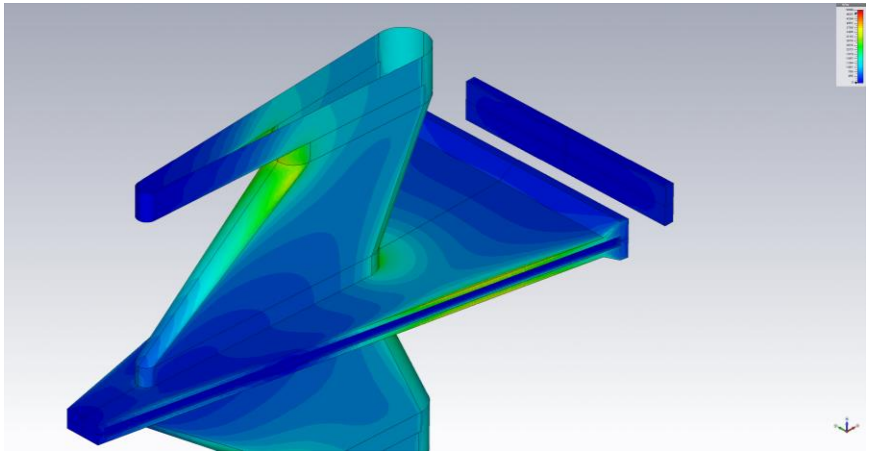


Mounting part has the same dimensions.

Rf current distribution @ 18.2 MHz



Rf current distribution @ 38.8 MHz



Design parameters (calc.)

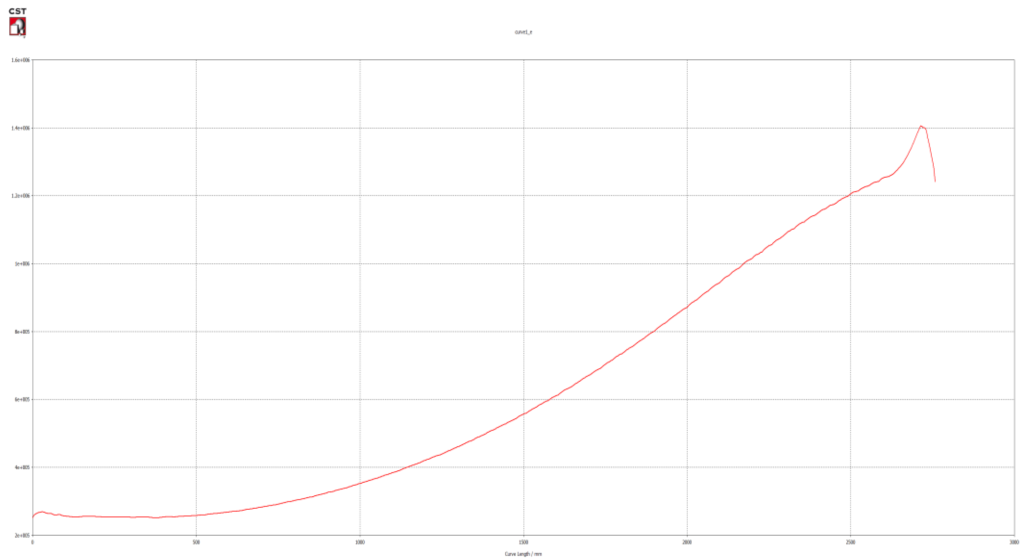
Frequency range	16-38.8 MHz
Stroke of MBOX	680 mm each
Shunt impedance	78-451 kΩ
Shunt impedance at 18.25 MHz	99.4 kΩ
Q_0	11160
Rf power input	200 kW max.
Material	oxygen-free copper

Radial voltage distribution

Radial voltage distribution was taken into account to maintain the bunch compression effect by high-frequency magnetic field.

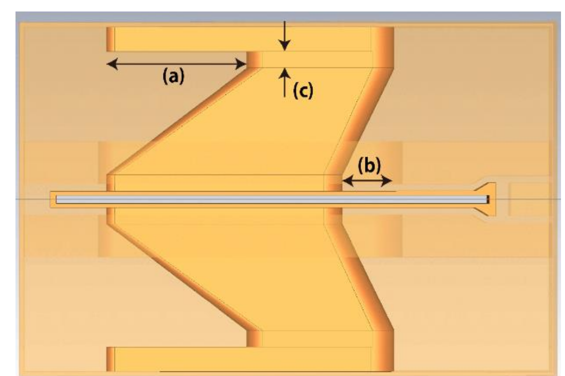
38.8 MHz original

W. Joho, Part. Accel. 6, 41 (1974).

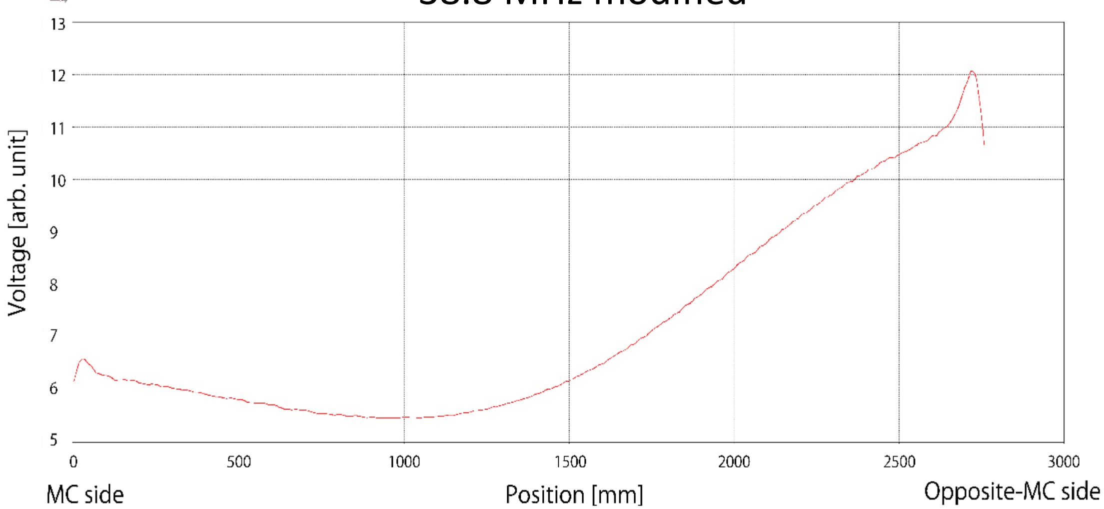


Radially increasing distribution is required.
(Especially at higher frequencies.)

Dimension **(b)** helps to compensate for mid-sag.



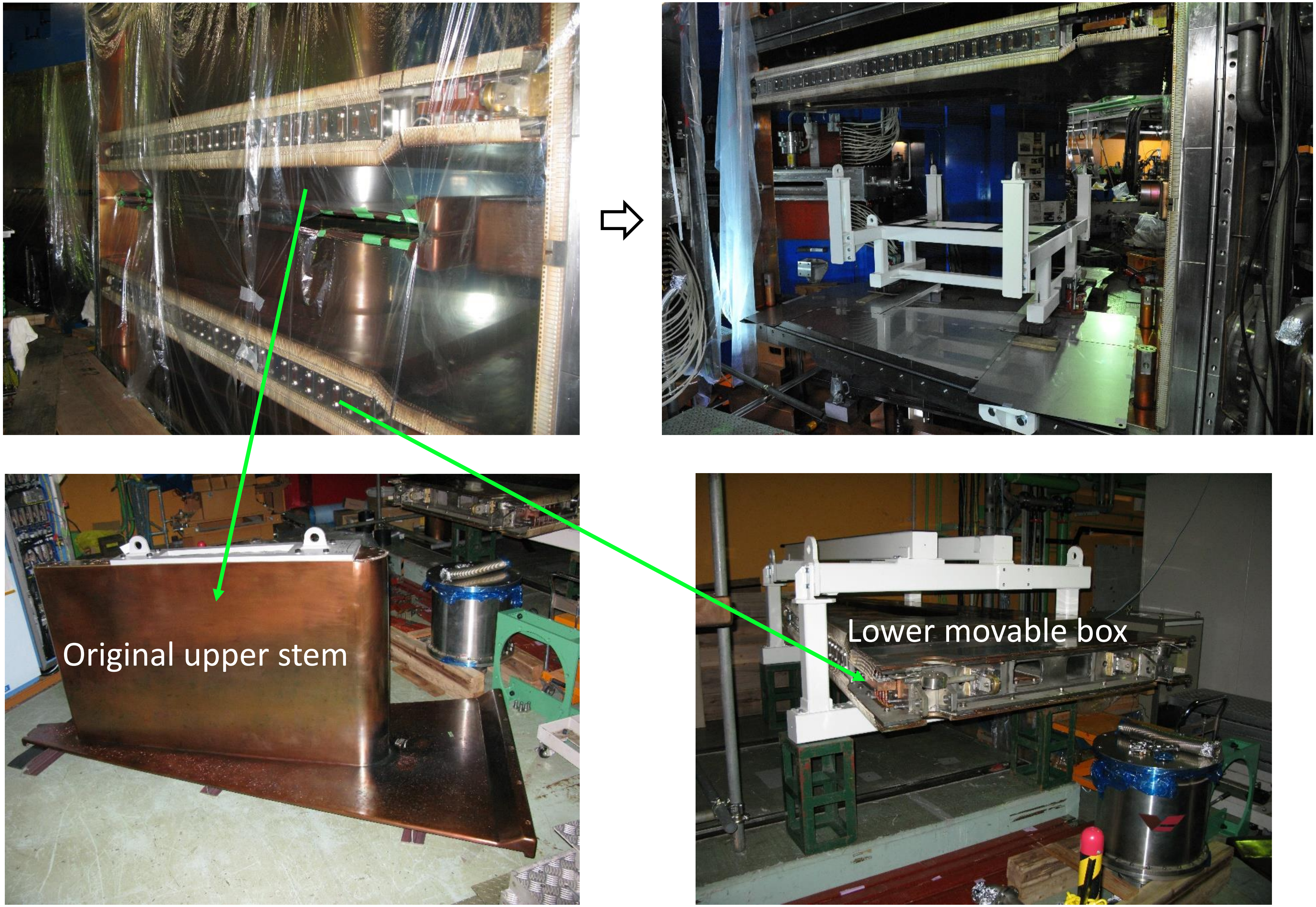
38.8 MHz modified



The mid-sag was kept to a level that did not affect.

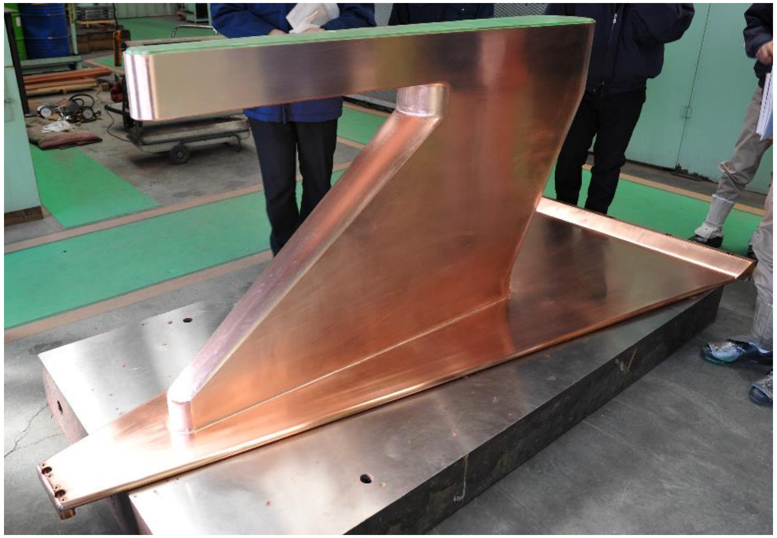
Modification work

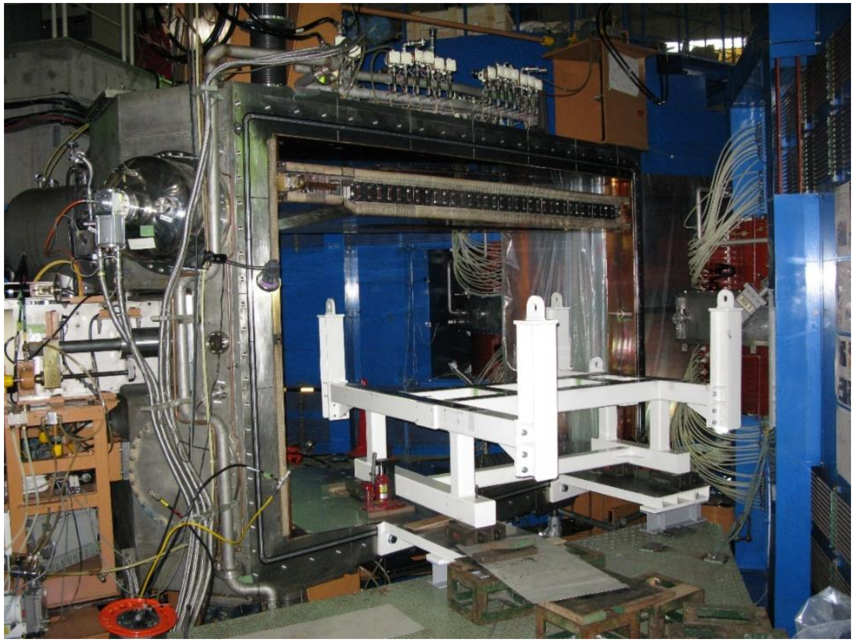
Disassembly of the original cavity (2018)

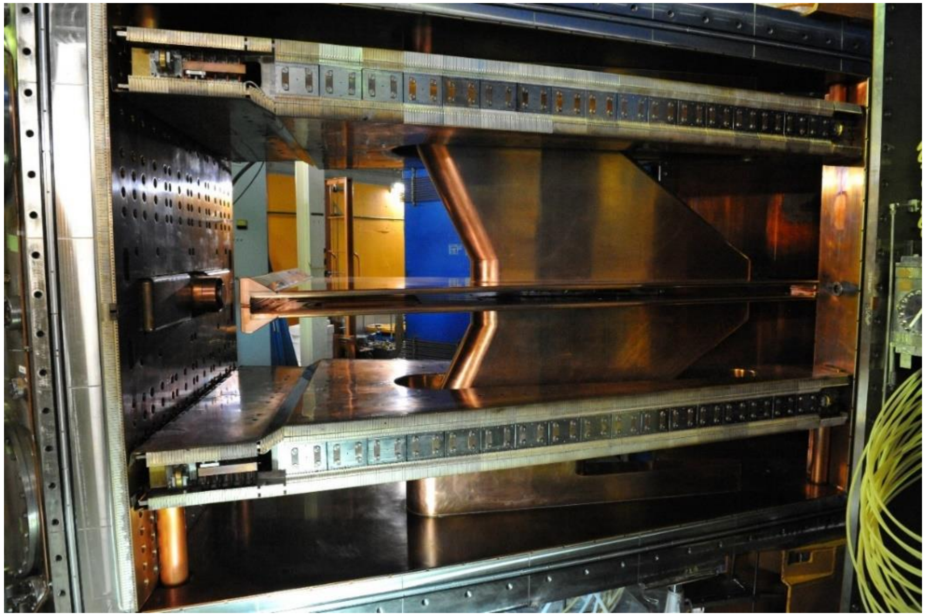


Modification work

Assembly of the new inner conductor (2018)





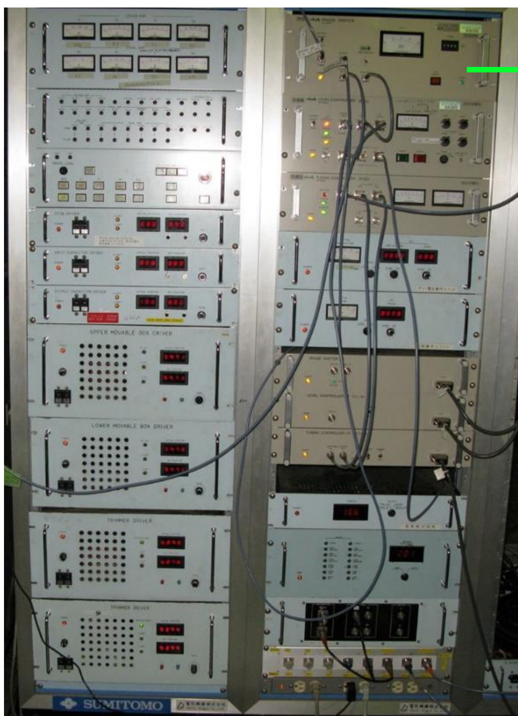


Completed!

Renewal of rf control systems

- The hardware relay logic was replaced by a **PLC**.
- Motors and drivers for cavity resonators were replaced.
- All components are directly controlled by the PLC.
- Remote control interface was shifted to Ethernet base.

Old system



New system

LLRFs were used as it.

Merit of the renewal

- Fast rf recovery time
- Significantly reduces amplifier damage
- Improved resolution of voltage and phase set points

Renewal of grid power supplies

The aging grid power supply was also updated.
They were used for over **30 years** (unrepairable and unstable).
Since they are placed in a radiation environment, they were manufactured using a standard logic IC, etc. **without using a microcontroller**.

Old power supplies

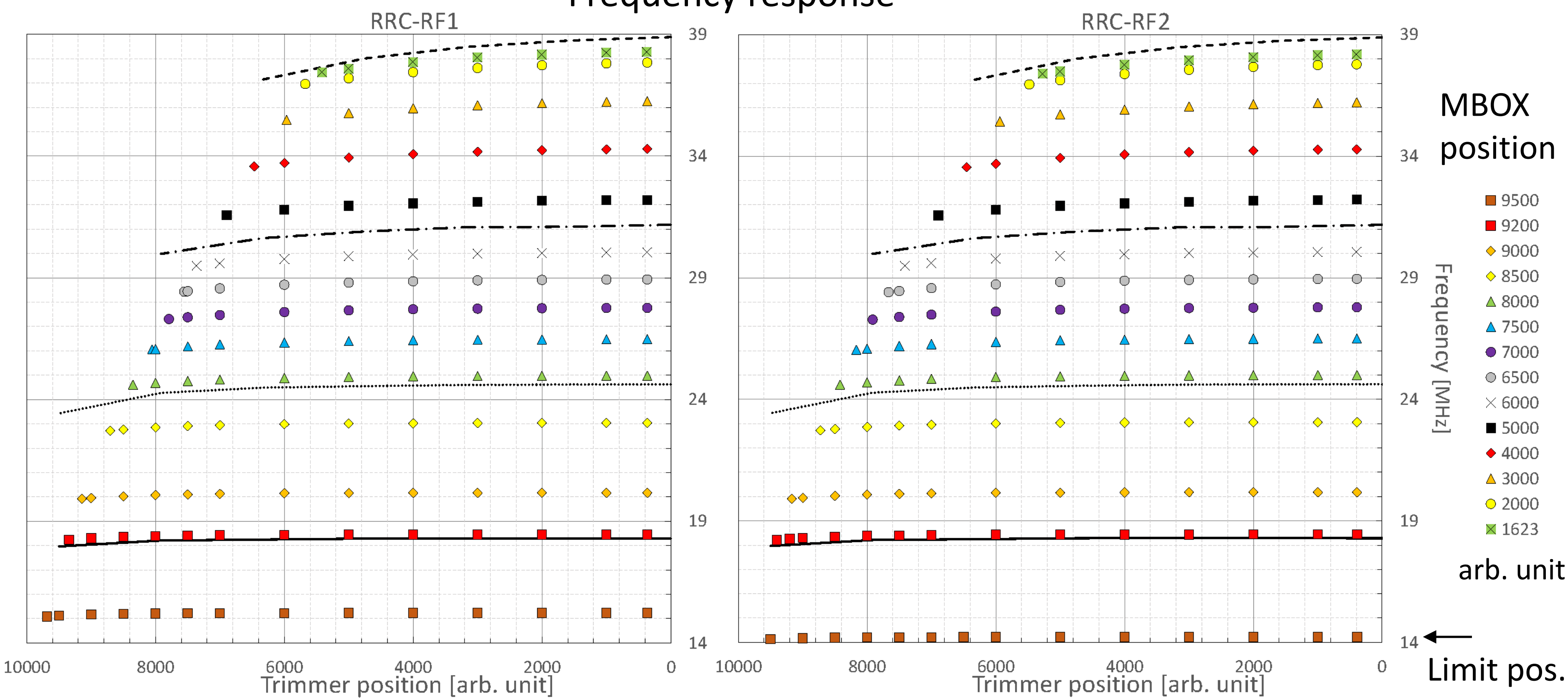
New power supplies

Results of low power test

Frequency response of the modified resonator measured with a network analyzer.

→ The frequency response is **almost exactly as expected** from the calculations.

Frequency response



MBOX position: —— 13 mm (gap 43 mm) ······· 100 mm — · · — 300 mm ---- 680 mm

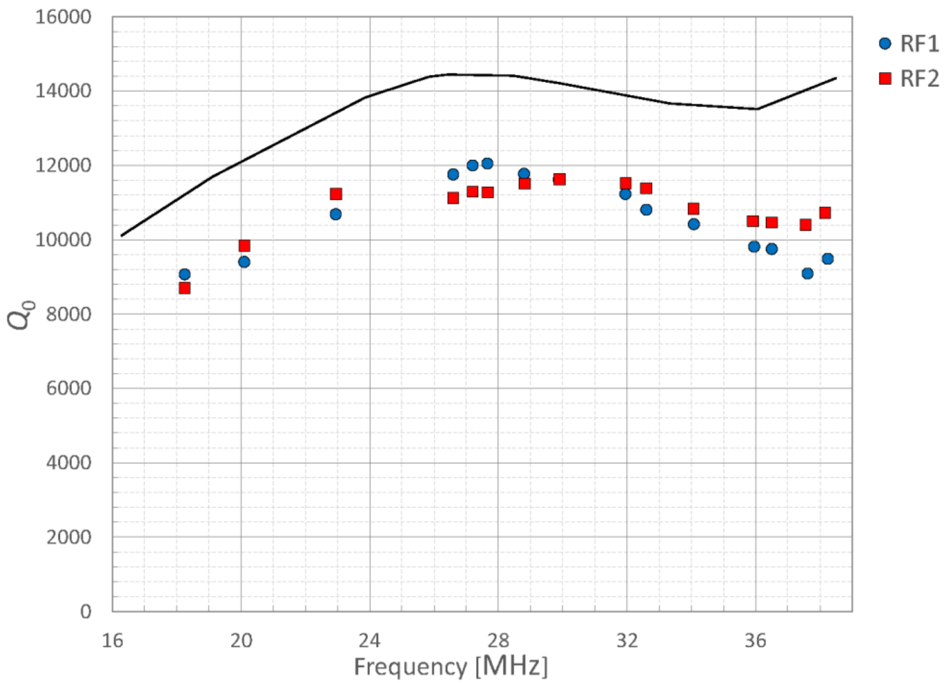
Each point is the measured value and the curve is the calculated result.

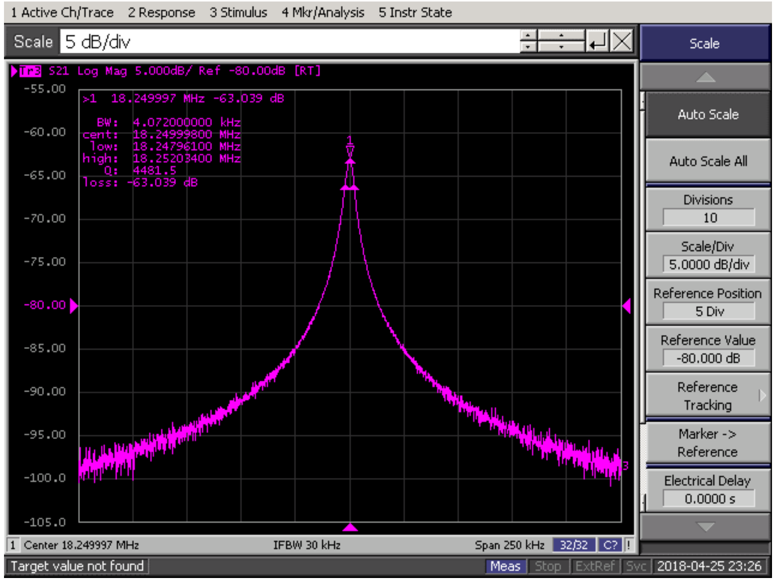
Results of low power test

Quality factors were also measured with a network analyzer.

The quality factor at each frequency was **almost 80%** of the calculation.
→ The results were as expected.

Internal quality factor Q_0





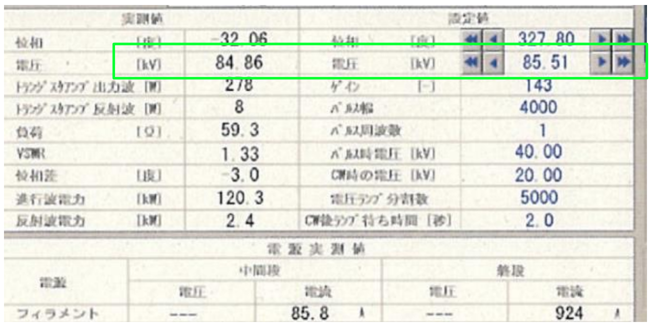
Each point is the measured value
and the curve is the calculated result.

Results of high power test

160 kV operation was achieved by increasing the anode voltage of the final-stage tetrode from 10 kV to 12 kV.

The modification of the RRC cavity was successfully commissioned. The acceleration voltage was increased from 85 kV to **over 150 kV**.

RF#1

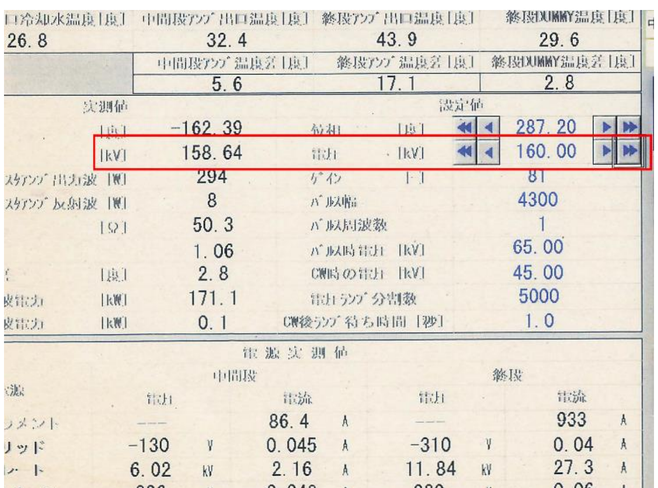


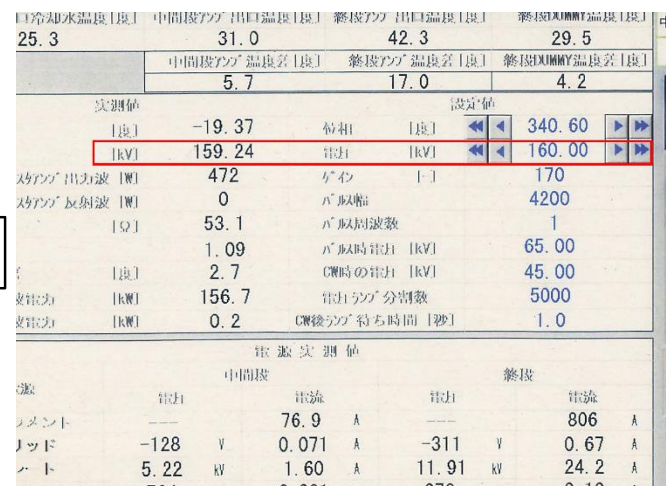
RF#2

2017/10

⇩

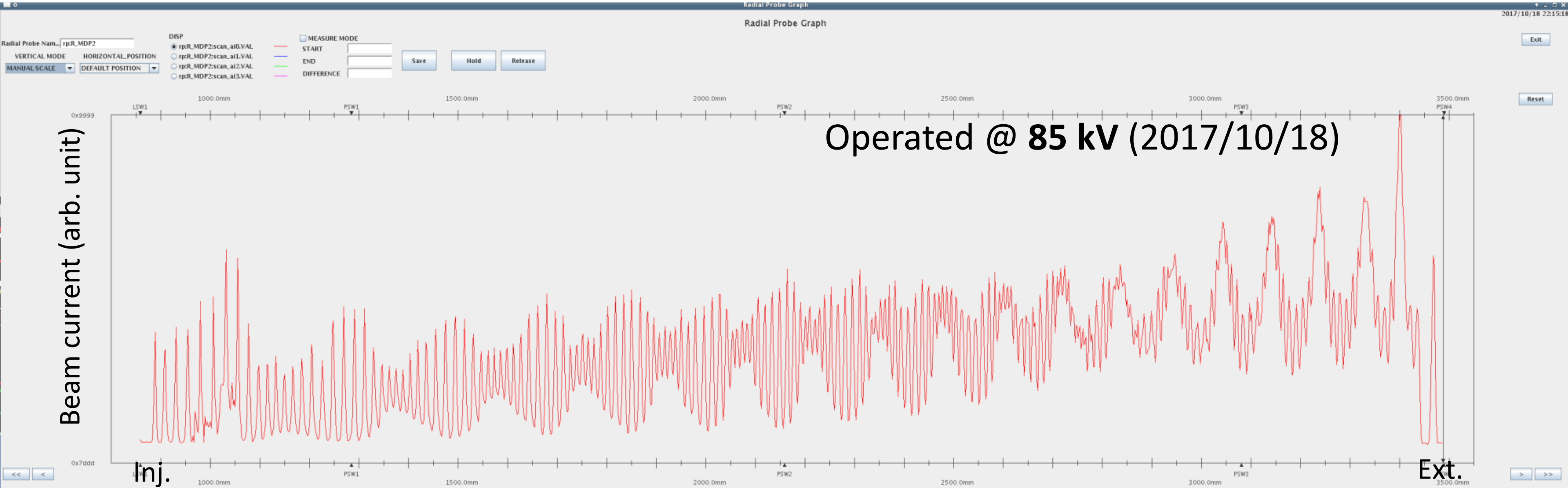
2019/07

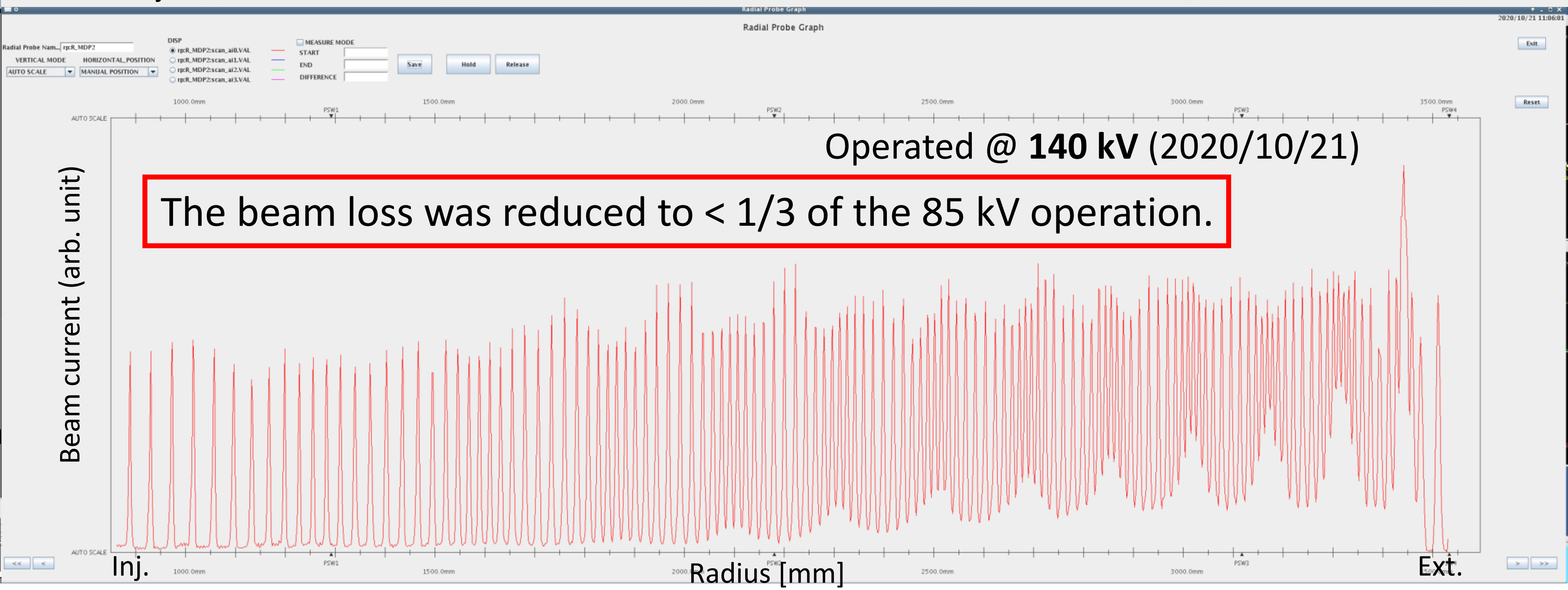




Effects of voltage enhancement

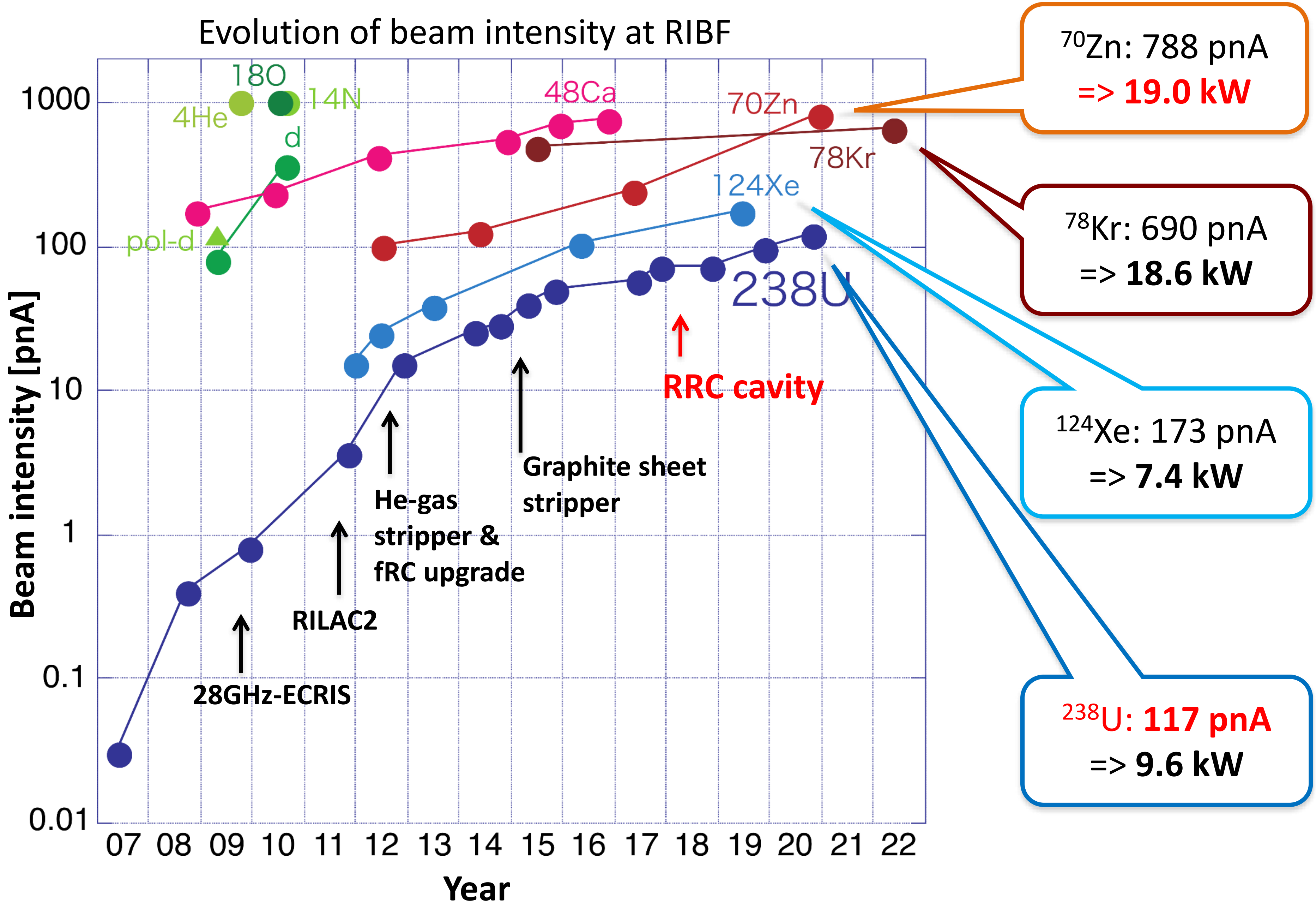
Radial beam pattern of $^{238}U^{35+}$ acceleration
N. Fukunishi





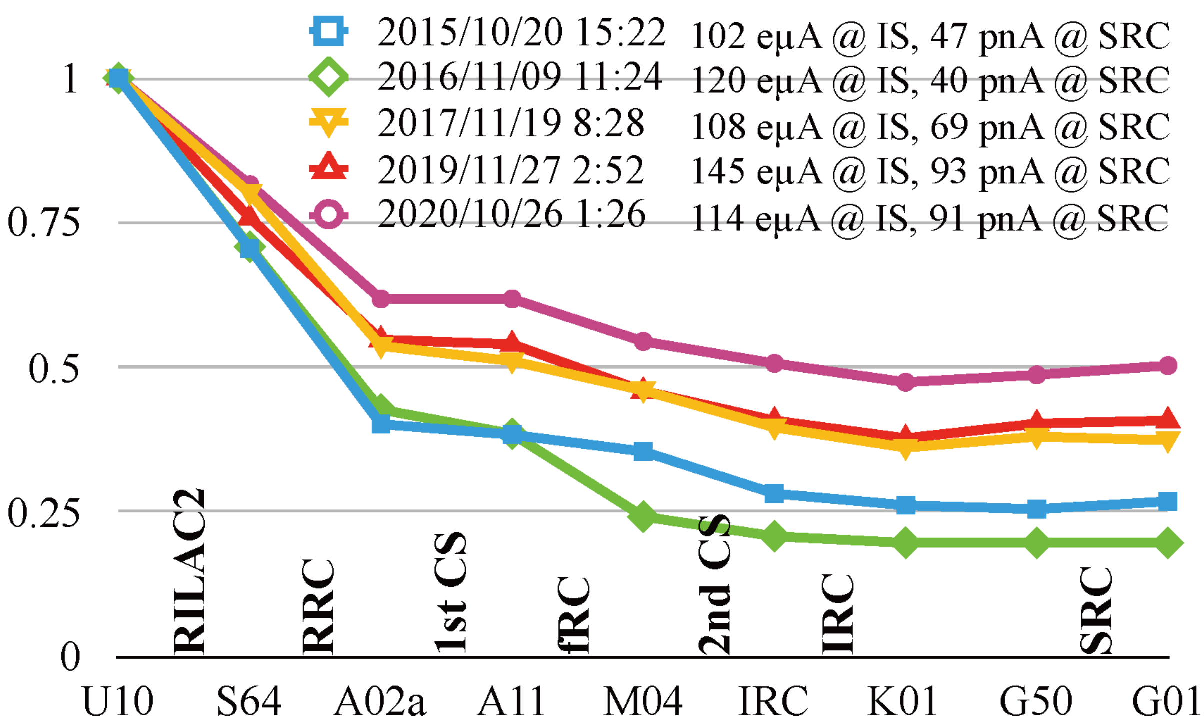
The beam loss was reduced to < 1/3 of the 85 kV operation.

Current beam intensity



Transmission efficiency*

*Stripping efficiency is excluded.



345-MeV/nucleon ^{238}U

71 pnA (Nov. 2017) →

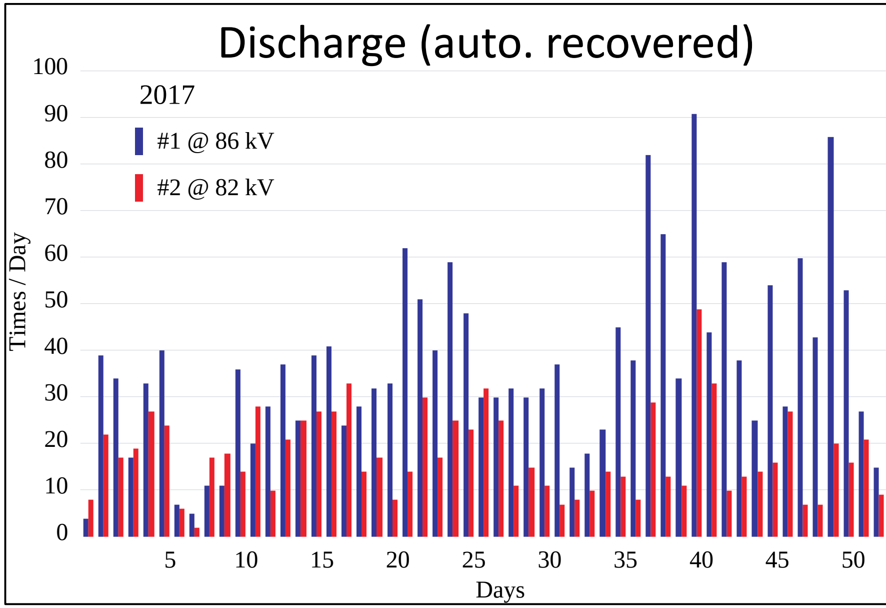
117 pnA max.(Nov. 2020)

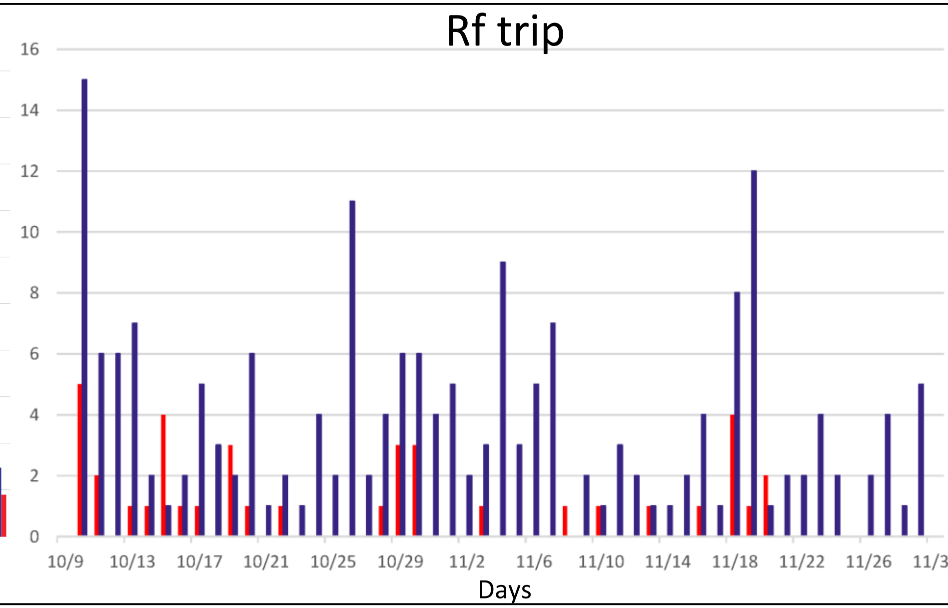
The accuracy of the Faraday cups sometimes makes efficiency appear to be increasing downstream.

Efficiency of RRC improved to about 90%.

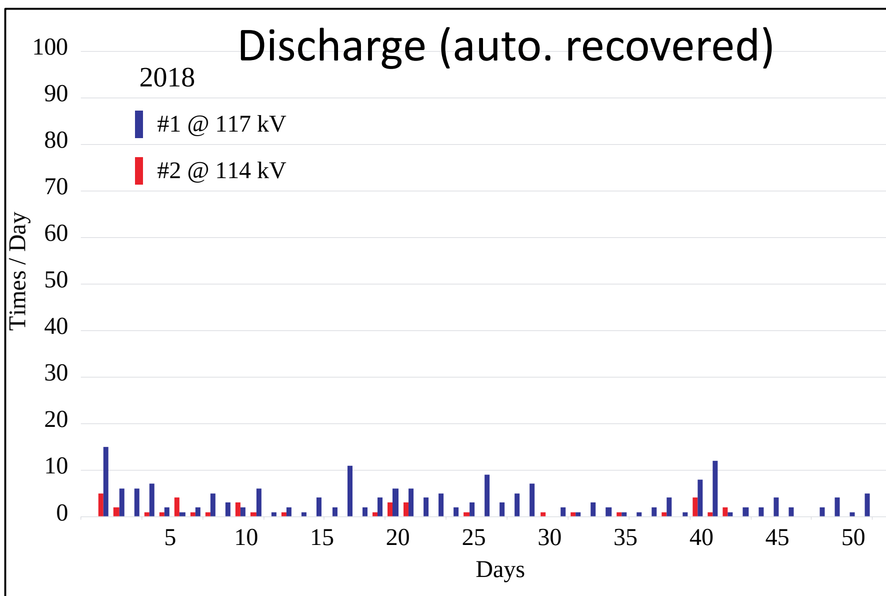
(Excluding the decelerating phase component from RILAC2 operating at 36.5 MHz.)

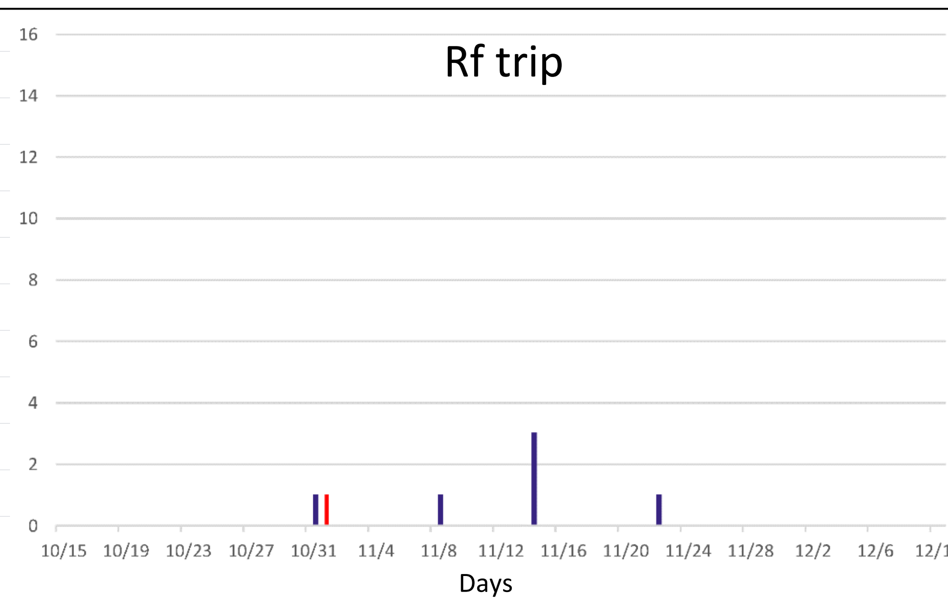
Decrease in trip rate





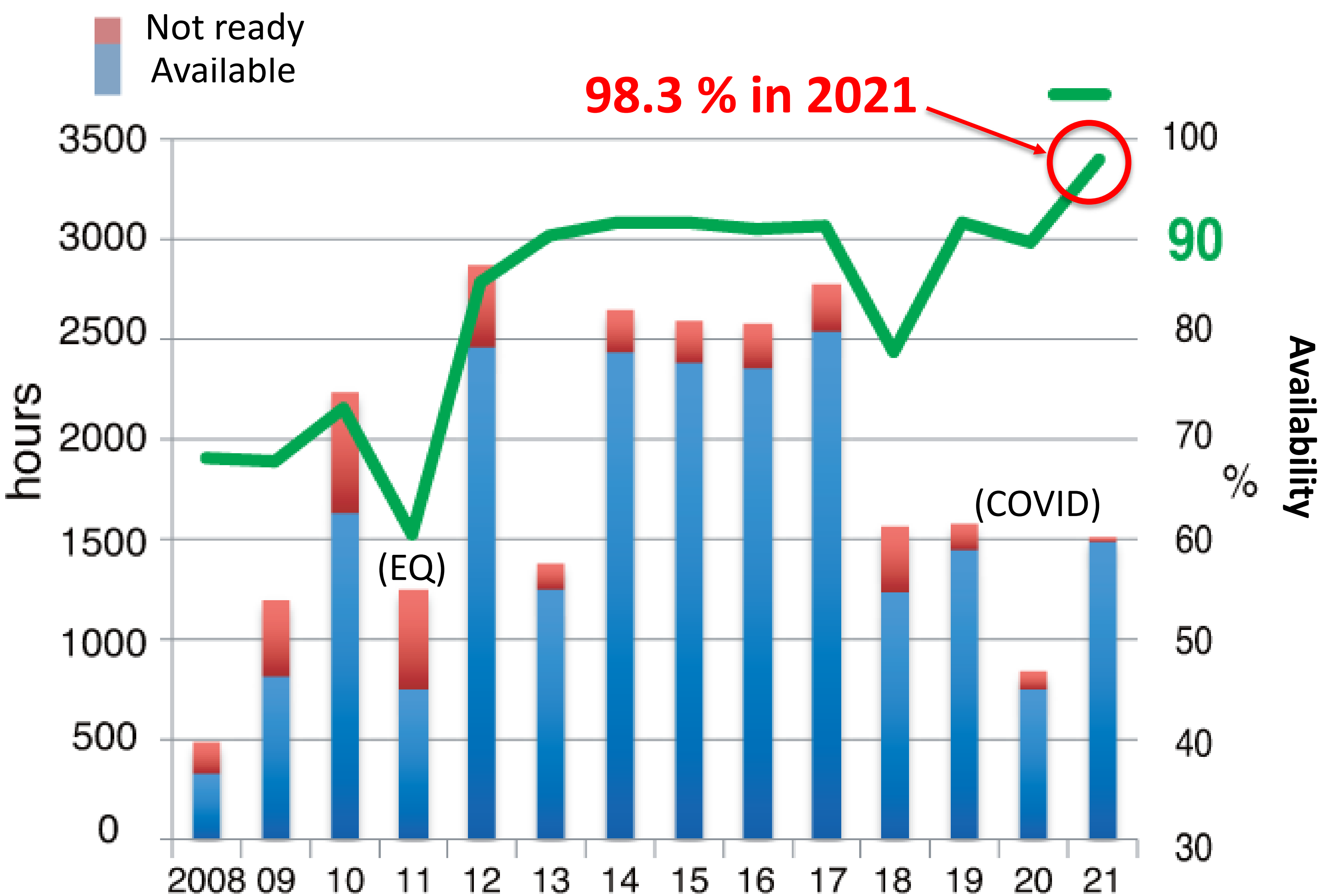
Very stable in spite of higher voltage!





Beam availability

Availability = actual BT / scheduled BT

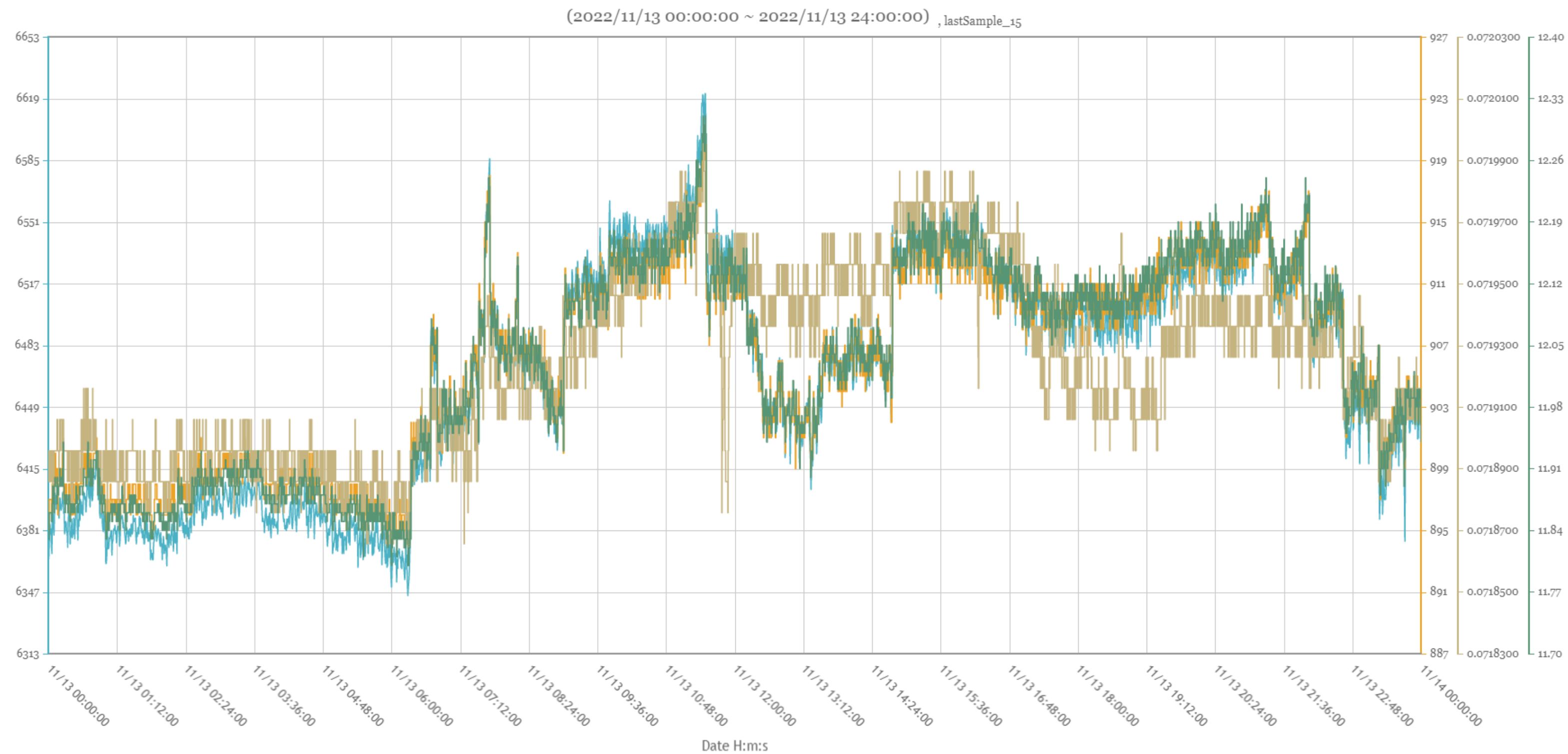


Present issue

The phenomenon of beam transmission efficiency decreasing under the **influence of receiving voltage fluctuations** is clearly visible.

RF voltage is **changing slightly** (< 0.1%) despite feedback.

- 6600 V receiving voltage
- Filament current of tetrode
- Anode voltage of tetrode
- Resonator#1 voltage (monitored by lock-in amp.)



Plans for near future

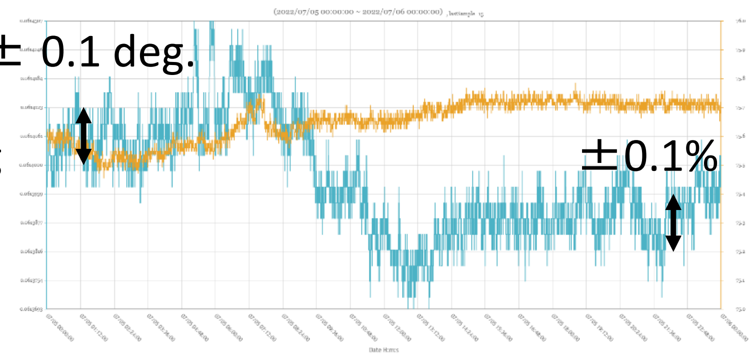
Currently rf voltage is fine-tuned manually by the operator.

Digital low-level circuit will be introduced next year.

A similar circuit was introduced into the RFQ earlier.

Digital LLRF for RFQ

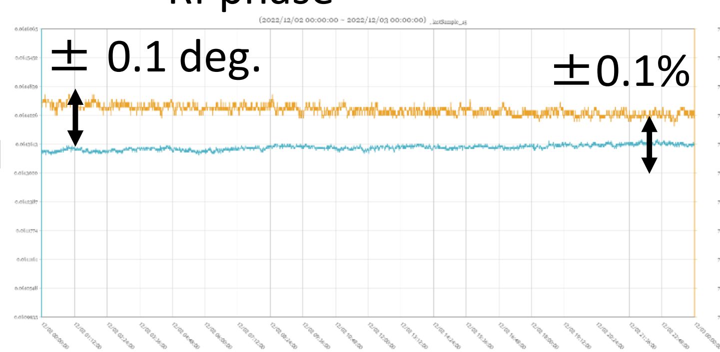
Old analog LLRF



Rf voltage

Rf phase

New digital LLRF



1 day

Summary

- The high-frequency systems for the RRC were upgraded in order to increase the acceleration voltage at 18.25 MHz operation by remodeling its cavity resonators and rf controllers.

- The upgrade was successfully commissioned, and the maximum gap voltage at 18.25 MHz improved from 85 kV to more than 150 kV.

- The beam intensity of ^{238}U at the RIBF was increased up to 117 pnA by overcoming the beam intensity limitation of RRC due to the space charge effect.

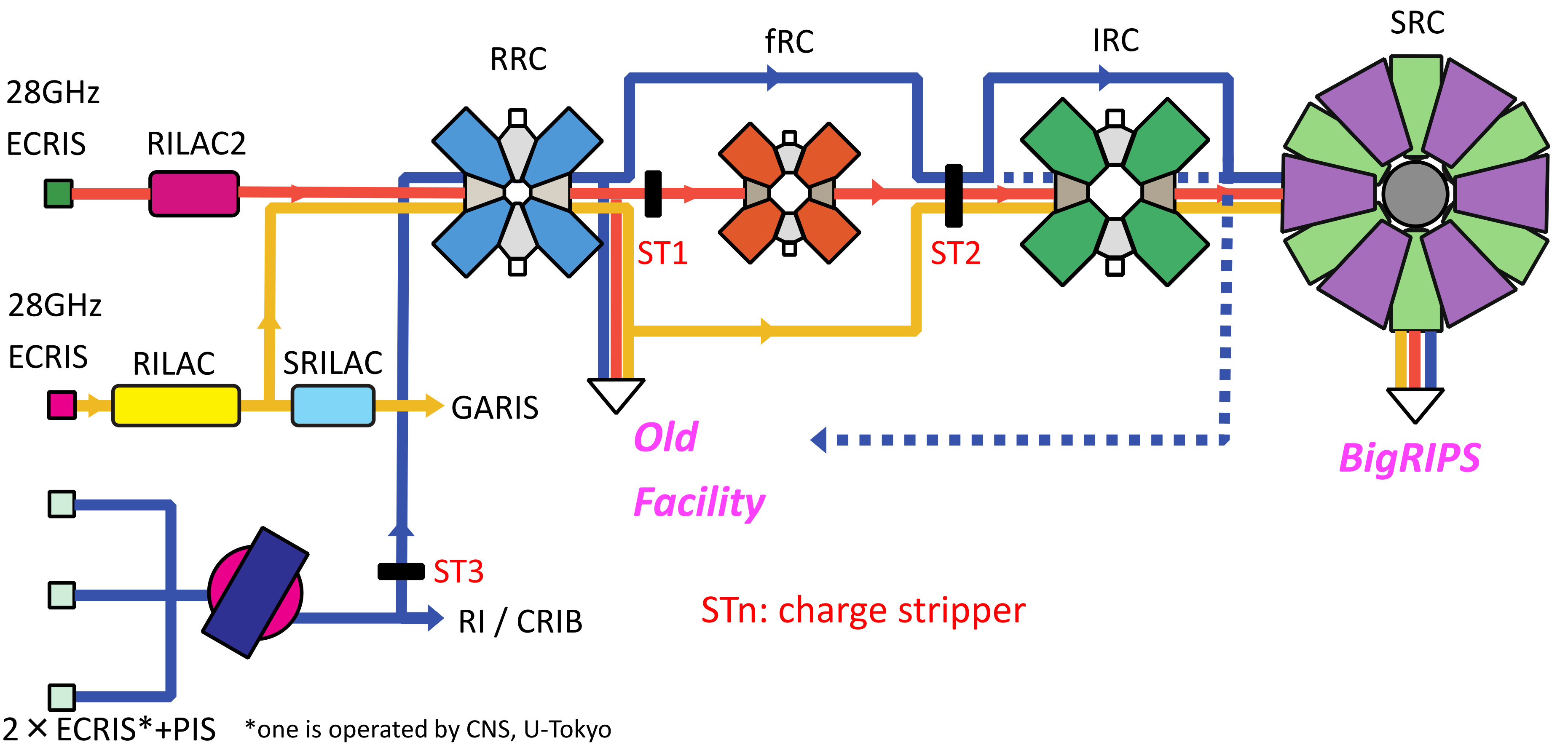
Backups

Acceleration modes of RIBF accelerators

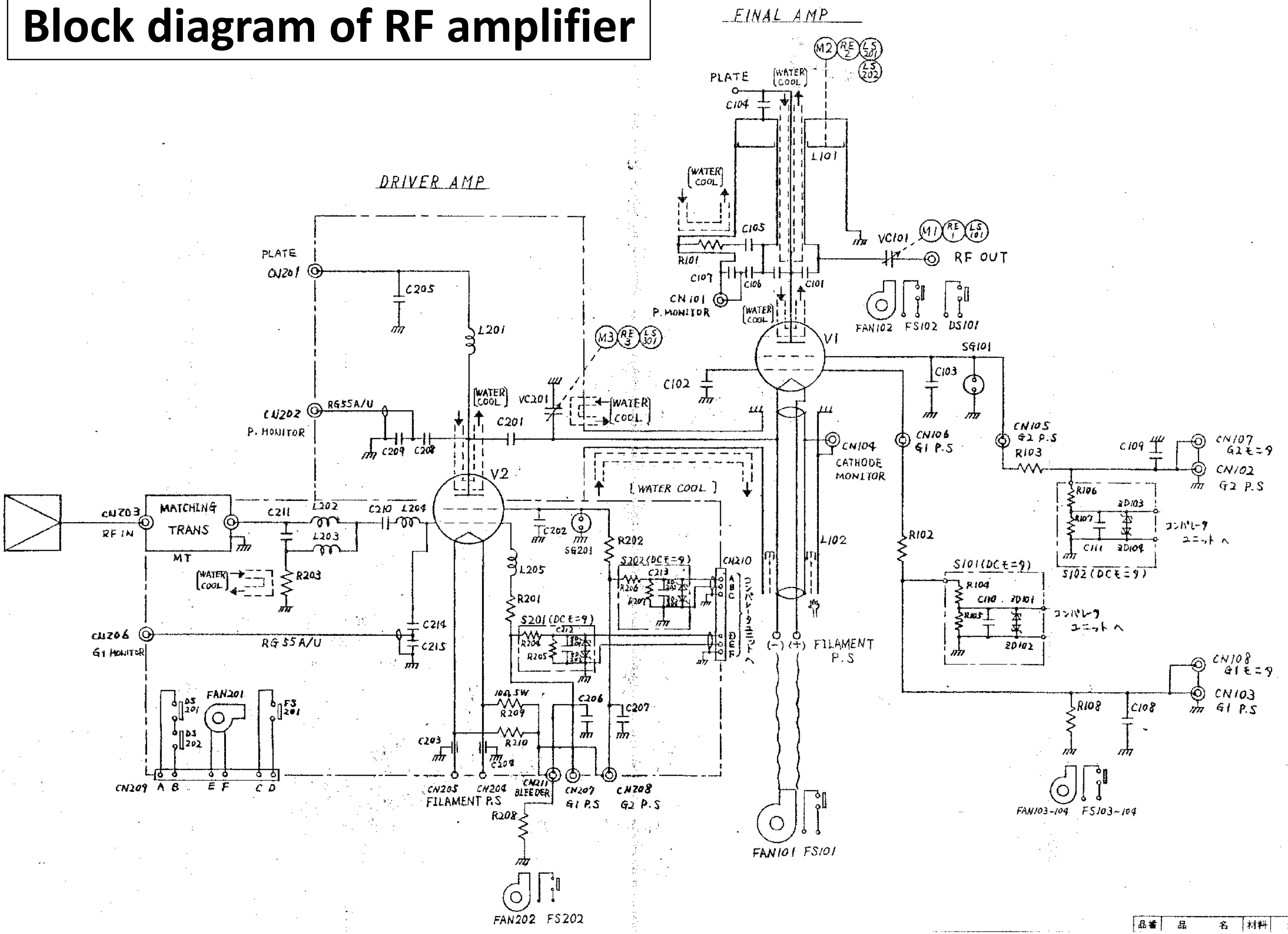
Fixed-energy mode (345 MeV/u) : Zn, Kr, Xe, ***U*** …

Variable-energy mode (< 400 MeV/u) : Ar, Ca, …

AVF-injection mode (< 440 MeV/u) : d, He, O, …



Block diagram of RF amplifier



Matching circuit of RS2042SK

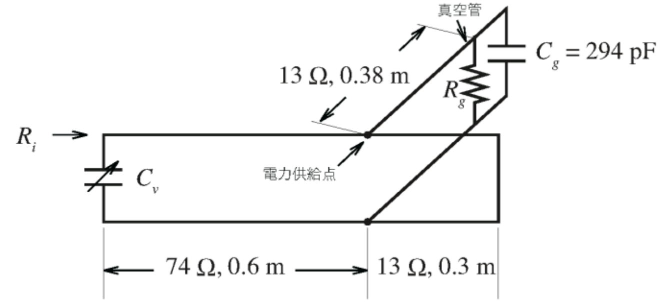
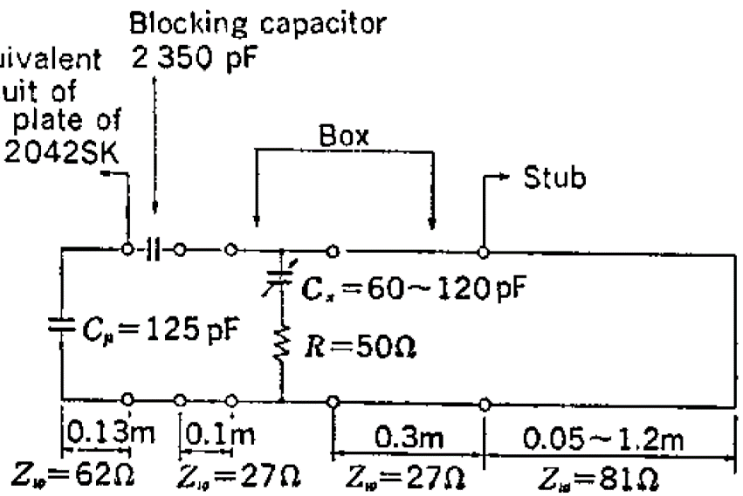
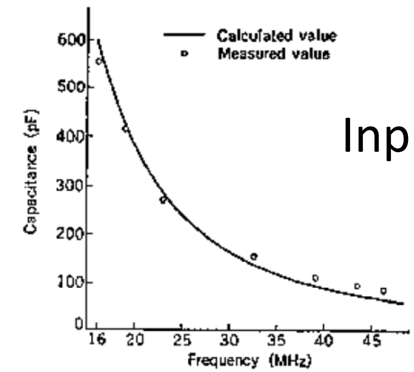


図 4.3: 理研リングサイクロトロン最終段増幅器入力回路。

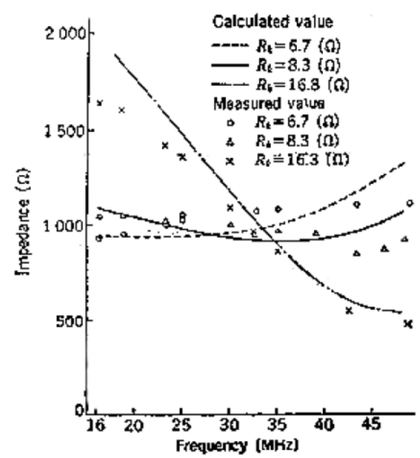
Output circuit



Input circuit



(a)



(b)

図 4.4: RS2042SK 入力回路モデルによるインピーダンス測定結果と計算結果。