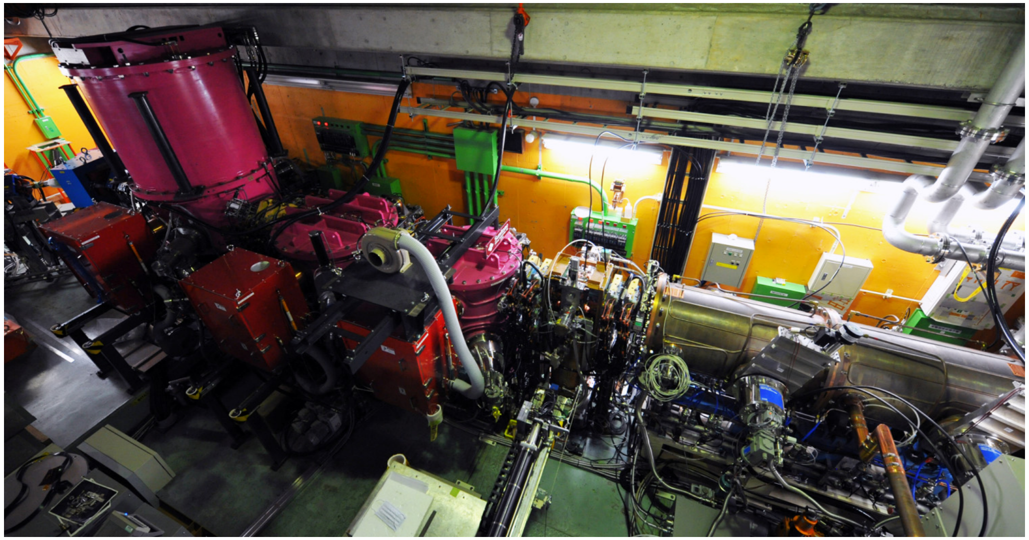
Beam Commissioning and Operation of New Linac Injector for RIKEN RI Beam Factory



RIKEN Nishina Center

Kazunari Yamada, K. Suda, S. Arai, M. Fujimaki, T. Fujinawa, H. Fujisawa, N. Fukunishi, Y. Higurashi, E. Ikezawa, H. Imao, O. Kamigaito, M. Kase, M. Komiyama, K. Kumagai, T. Maie, T. Nakagawa, J. Ohnishi, H. Okuno, N. Sakamoto, H. Watanabe, T. Watanabe, Y. Watanabe, H. Yamasawa, Y. Sato (J-PARC center, KEK), A. Goto (NIRS)

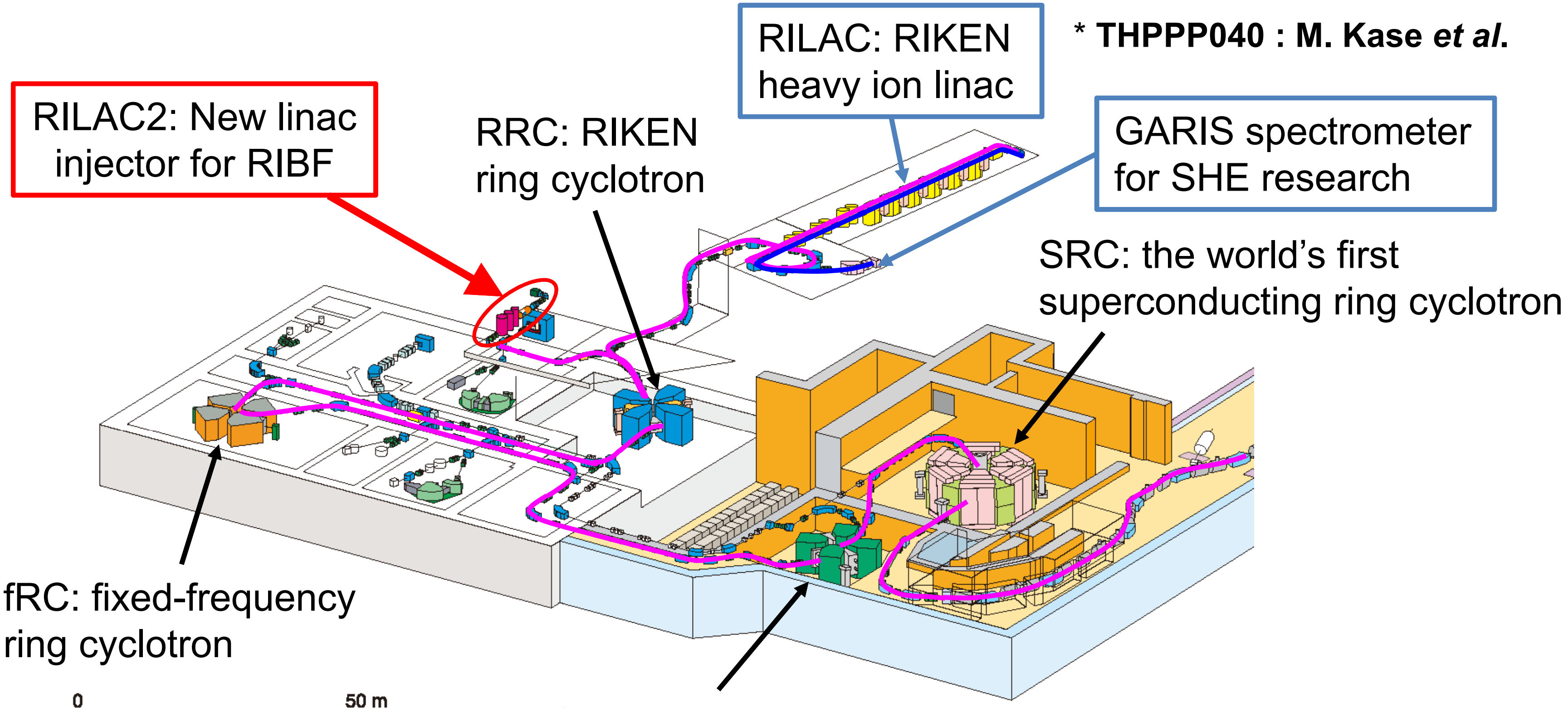
Subject of RIKEN Nishina Center

- RI beam factory (RIBF)

  Producing the world's most intense RI beams over the entire range of atomic masses by powerful heavy ion beams accelerated up to $v/c \approx 0.7$ (U beam has a first priority)

- Synthesis of super-heavy elements (SHEs)

RILAC plays a role of {
injector for RIBF experiment
accelerator for SHE research* ⇨ Function conflicting



RILAC: RIKEN heavy ion linac

RILAC2: New linac injector for RIBF

RRC: RIKEN ring cyclotron

GARIS spectrometer for SHE research

SRC: the world's first superconducting ring cyclotron

fRC: fixed-frequency ring cyclotron

IRC: Intermediate-stage ring cyclotron

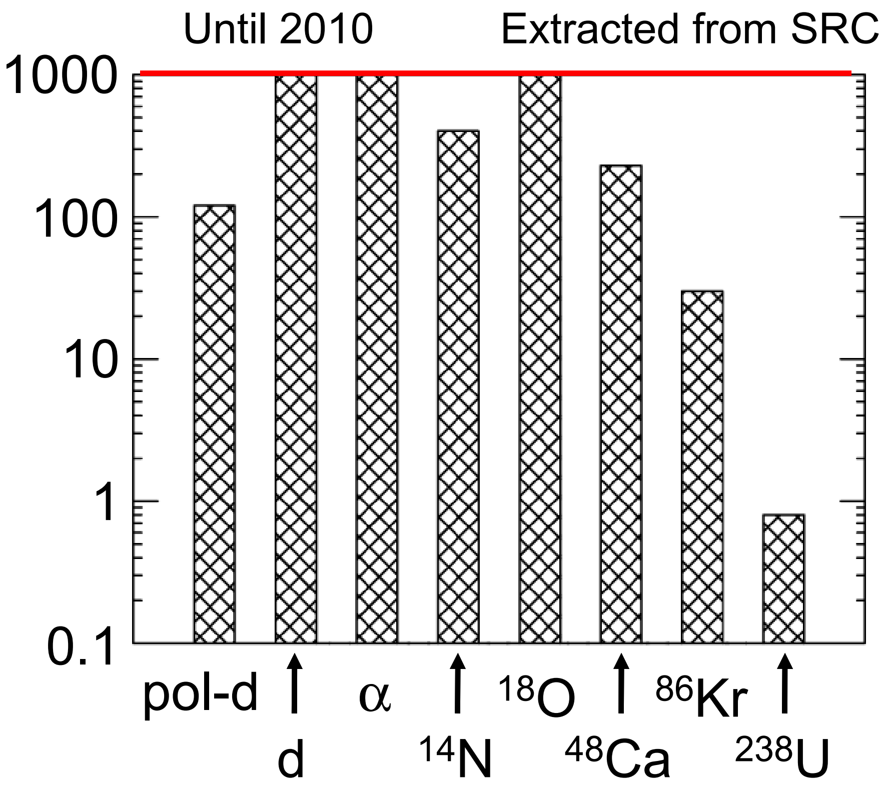
Entire view of RIBF accelerators

* **THPPP040 : M. Kase *et al*.**

Role of new linac injector RILAC2

- Independent operation of RIBF experiments and SHE research
- Intensity upgrade of U, Xe beams

Maximum beam intensity at RIBF(pnA)



d, α, ^{18}O beam (RILAC-RRC-IRC-SRC)

1 pμA

(6 × 10^{12} particles/s, max. 6.2 kW)

⇨ Attained a goal of RIBF

^{48}Ca beam (RILAC-RRC-IRC-SRC)

230 pnA (3.8 kW)

⇨ Best in the world

^{238}U beam (RILAC-RRC-fRC-IRC-SRC)

0.8 pnA (2009/12)

⇨ **Insufficient**

- Deficiency of beam current from an ion source
- Deterioration of RILAC (over 30 years old)
  → vacuum leak, rf instability

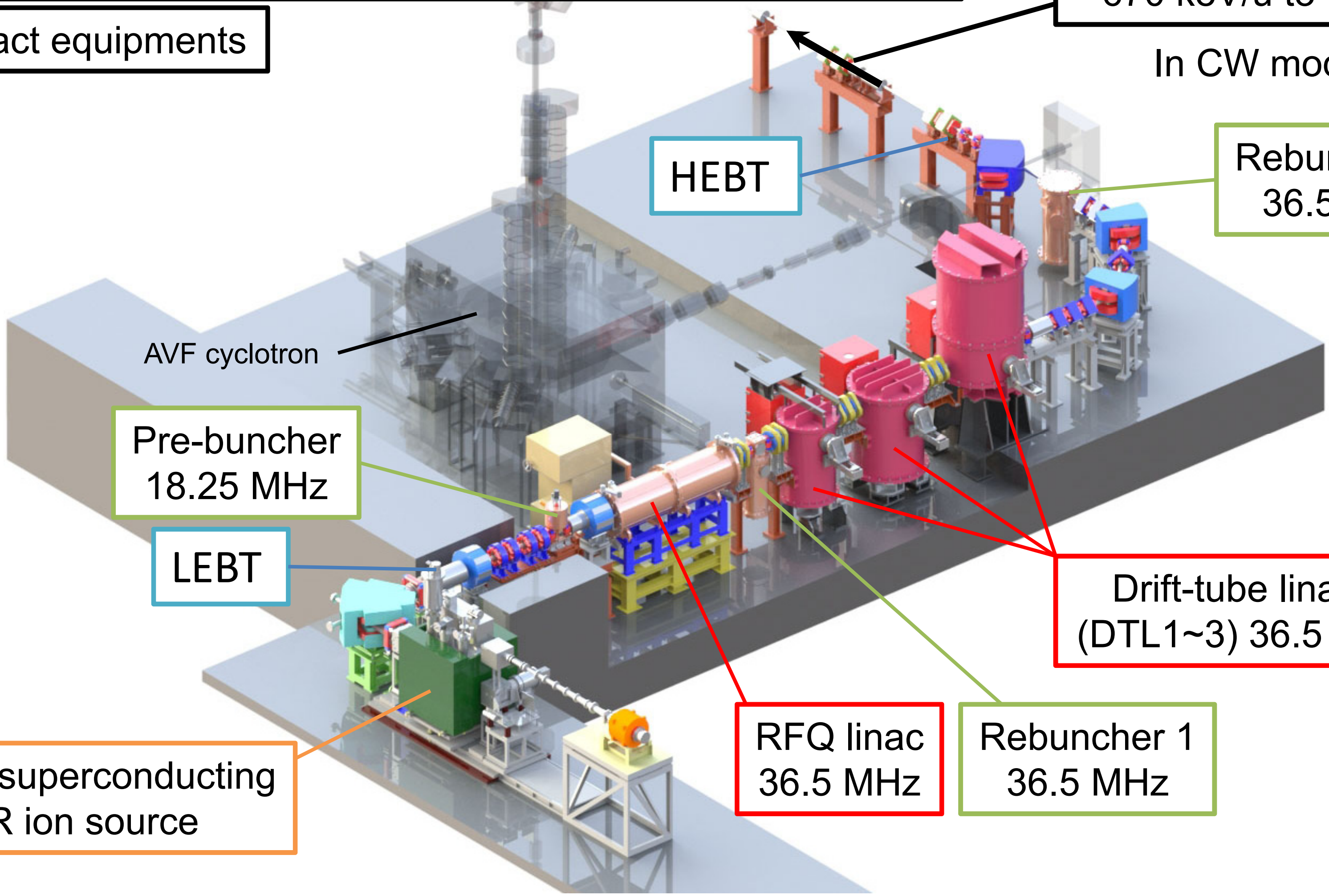
Key features of RILAC2

New SC-ECRIS ⇨ Increase beam intensity

Required RF stability ⇨ Improve transmission
- $\Delta V < \pm 0.1\%$
- $\Delta\phi < \pm 0.1^\circ$

Higher vacuum level ~10^{-6} Pa

Compact equipments



m/q ratio ~7
($^{238}U^{35+}$, $^{124}Xe^{19+,20+}$)
~670 keV/u to RRC

In CW mode

HEBT

Rebuncher 2
36.5 MHz

AVF cyclotron

Pre-buncher
18.25 MHz

LEBT

Drift-tube linacs
(DTL1~3) 36.5 MHz

RFQ linac
36.5 MHz

Rebuncher 1
36.5 MHz

28-GHz superconducting
ECR ion source

Key features of RILAC2

New SC-ECRIS ⇒ Increase beam intensity

Re

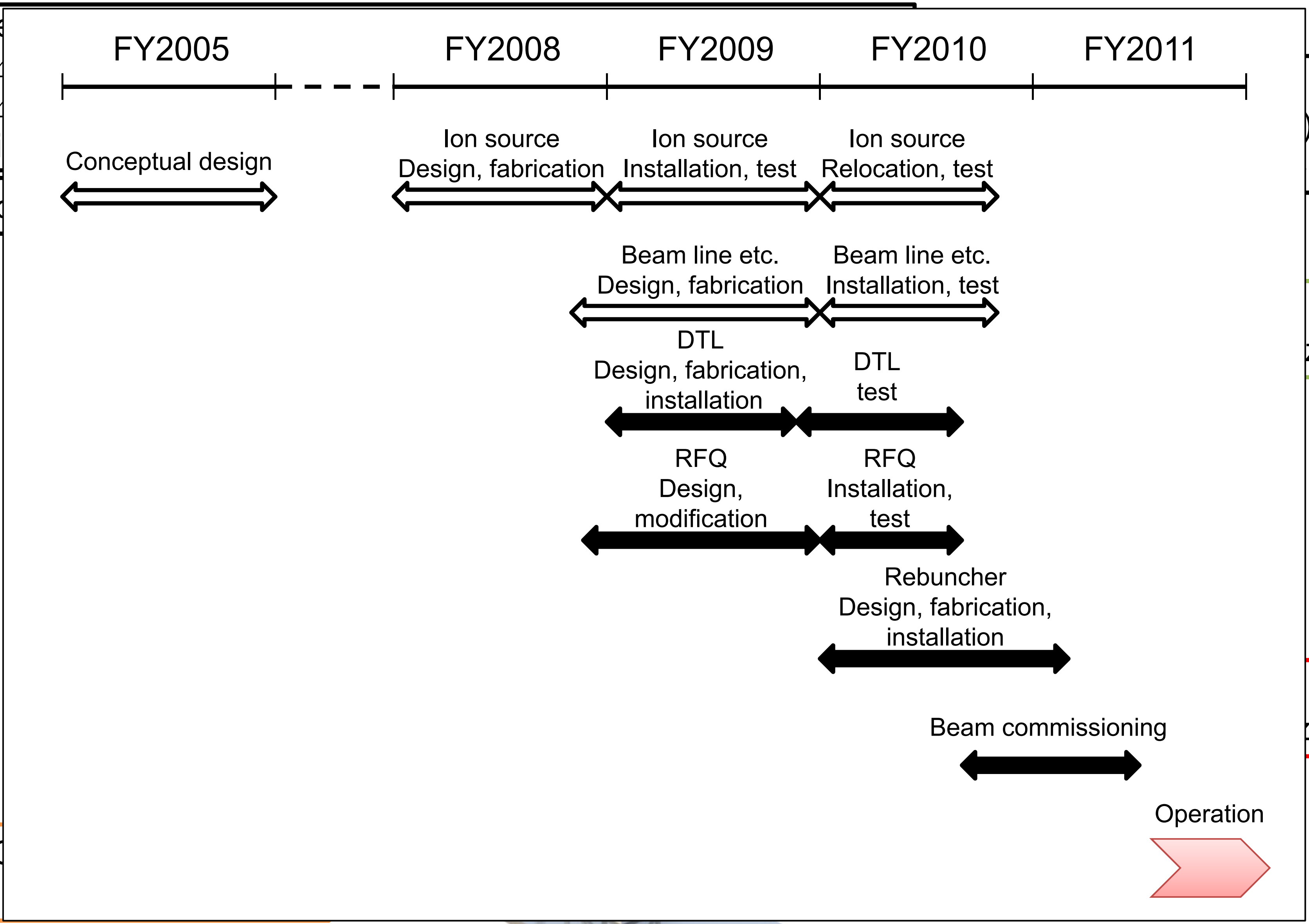
Hi

Co

28-C

r 2

z


FY2005

FY2008

FY2009

FY2010

FY2011

Conceptual design

Ion source
Design, fabrication

Ion source
Installation, test

Ion source
Relocation, test

Beam line etc.
Design, fabrication

Beam line etc.
Installation, test

DTL
Design, fabrication, installation

DTL
test

RFQ
Design, modification

RFQ
Installation, test

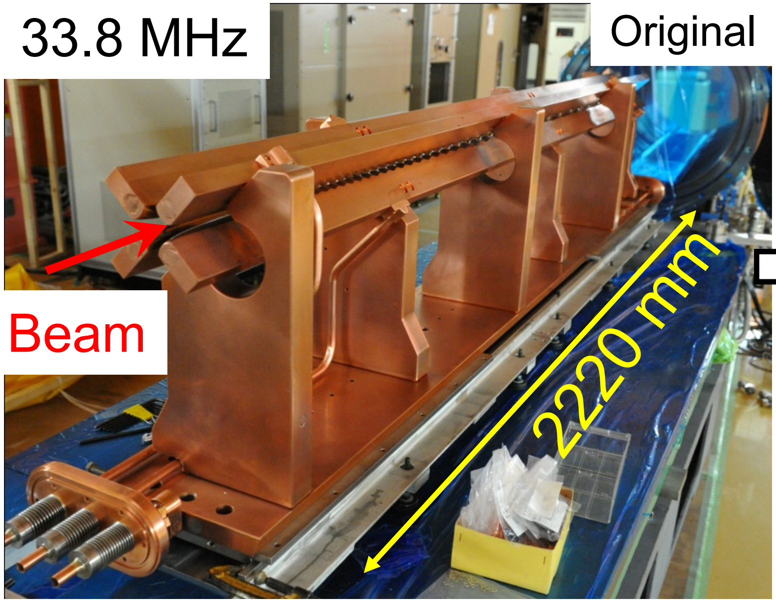
Rebuncher
Design, fabrication, installation

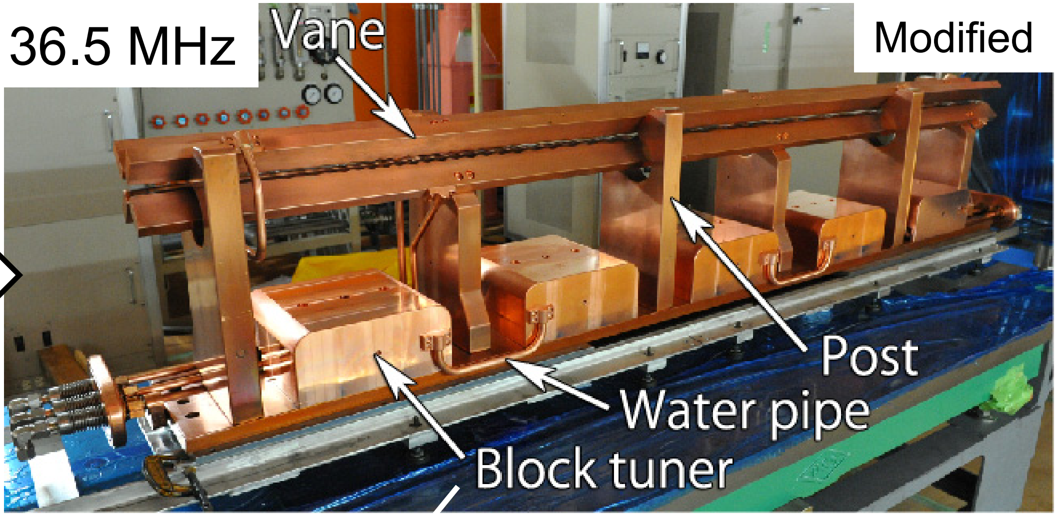
Beam commissioning

Operation

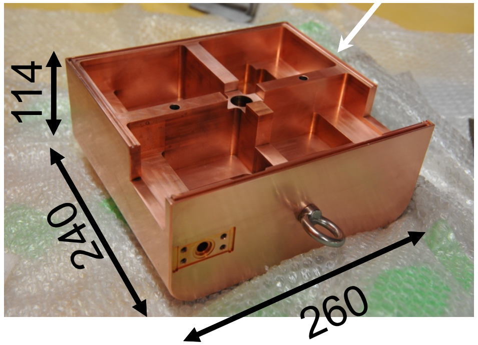
CW 4-rod RFQ linac

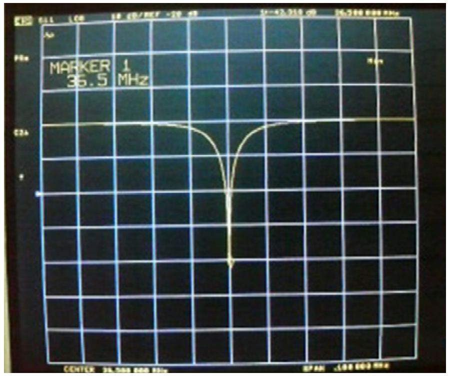
Recycled a 4-rod RFQ linac kindly provided by Kyoto University.





Frequency	36.5 MHz
Duty	100 %
m/*q* ratio	7
Input energy	3.28 keV/u
Output energy	100.3 keV/u
Input emittance	200π mm·mrad
Vane length	225.6 cm
Intervane voltage	42.0 kV
Mean aperture (r_0)	8.0 mm
Max. modulation (m)	2.35
Focusing strength (B)	6.785
Final synchronous phase	-29.6˚
Unloaded Q	5000
Shunt impedance	~50 kΩ
Required rf power	~18 kW





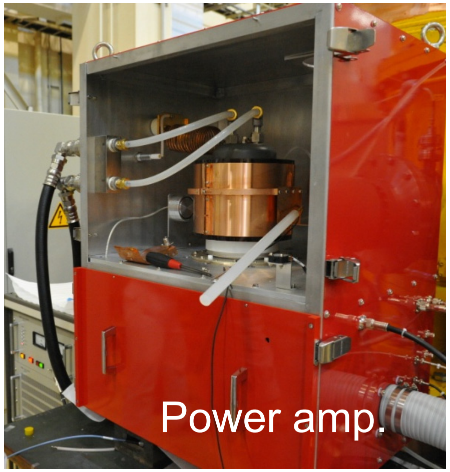
Resonant frequency f_0 : 33.8 MHz → 36.5 MHz
m/q ≈ 7 ions accelerated to 100 keV/u without changing vane electrodes.
Unloaded Q : 5400 → 5000 (measured)

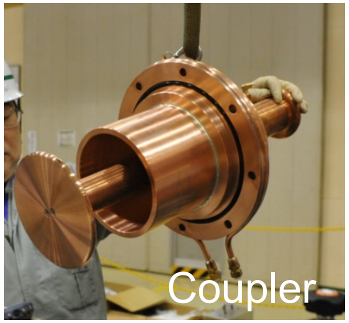
Drift-tube linacs

- Low-β : 0.015～0.038
- CW-QWR, 36.5 MHz
- Directly coupled with rf amplifier for saving space and cost

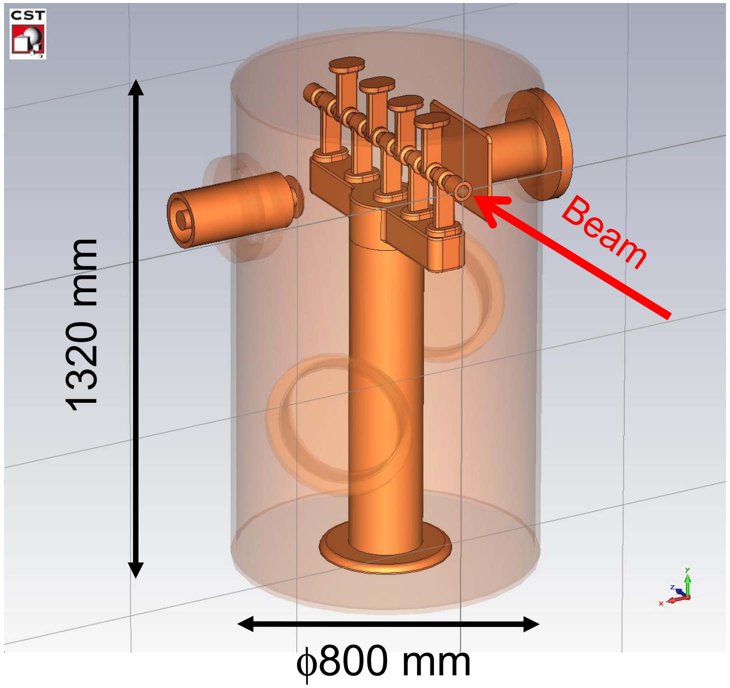
Frequency (Resonator) ⇔ Coupling Load impedance (coupler, amp.)

Carefully set the target frequency





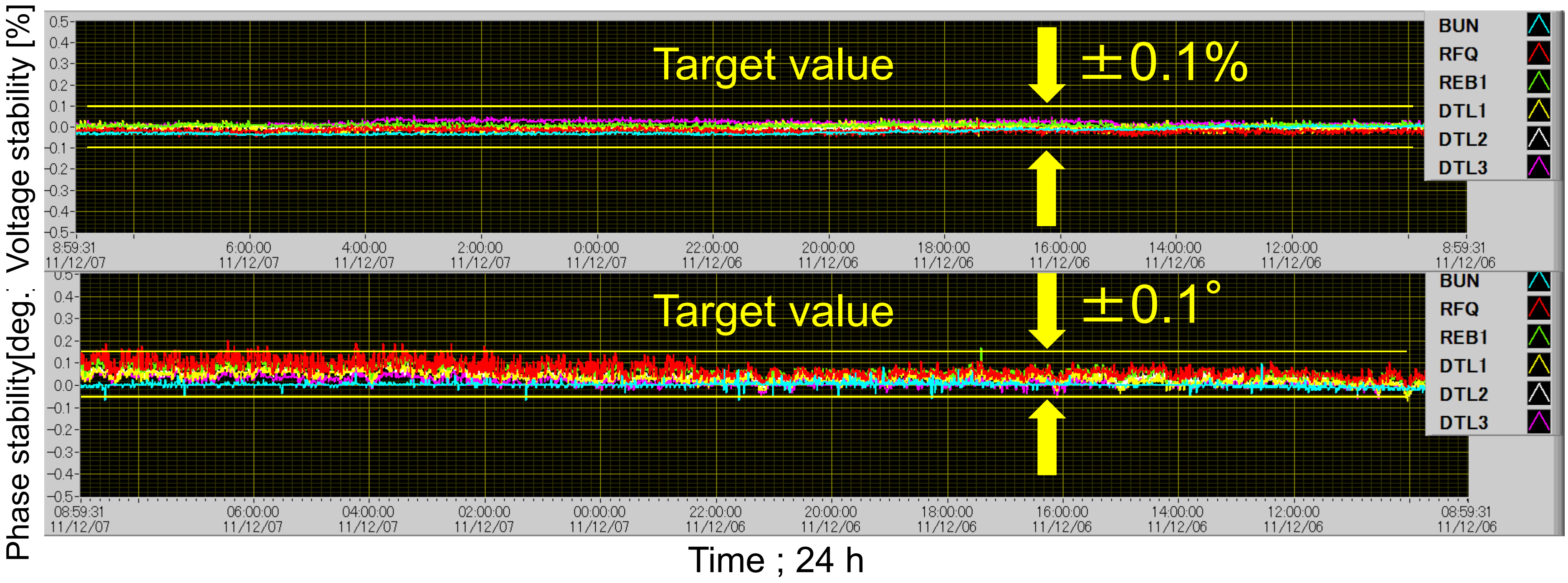
DTL1 model of MWS



	DTL1	DTL2	DLT3
Frequency (MHz)	36.5	36.5	36.5
Duty (%)	100	100	100
m/q ratio	7	7	7
Input energy (keV/u)	100	220	450
Output energy (keV/u)	220	450	680
Length (cm)	80	110	130
Height (mm)	1320	1429	1890
Gap number	10	10	8
Gap length (mm)	20	50	65
Gap voltage (kV)	110	210	260
Drift tube aperture (mm)	17.5	17.5	17.5
Peak surface field (MV/m)	8.9	9.4	9.7
Synchronous phase (deg.)	-25	-25	-25

RF voltage stability and phase stability

RF fluctuation of RILAC2 over one day



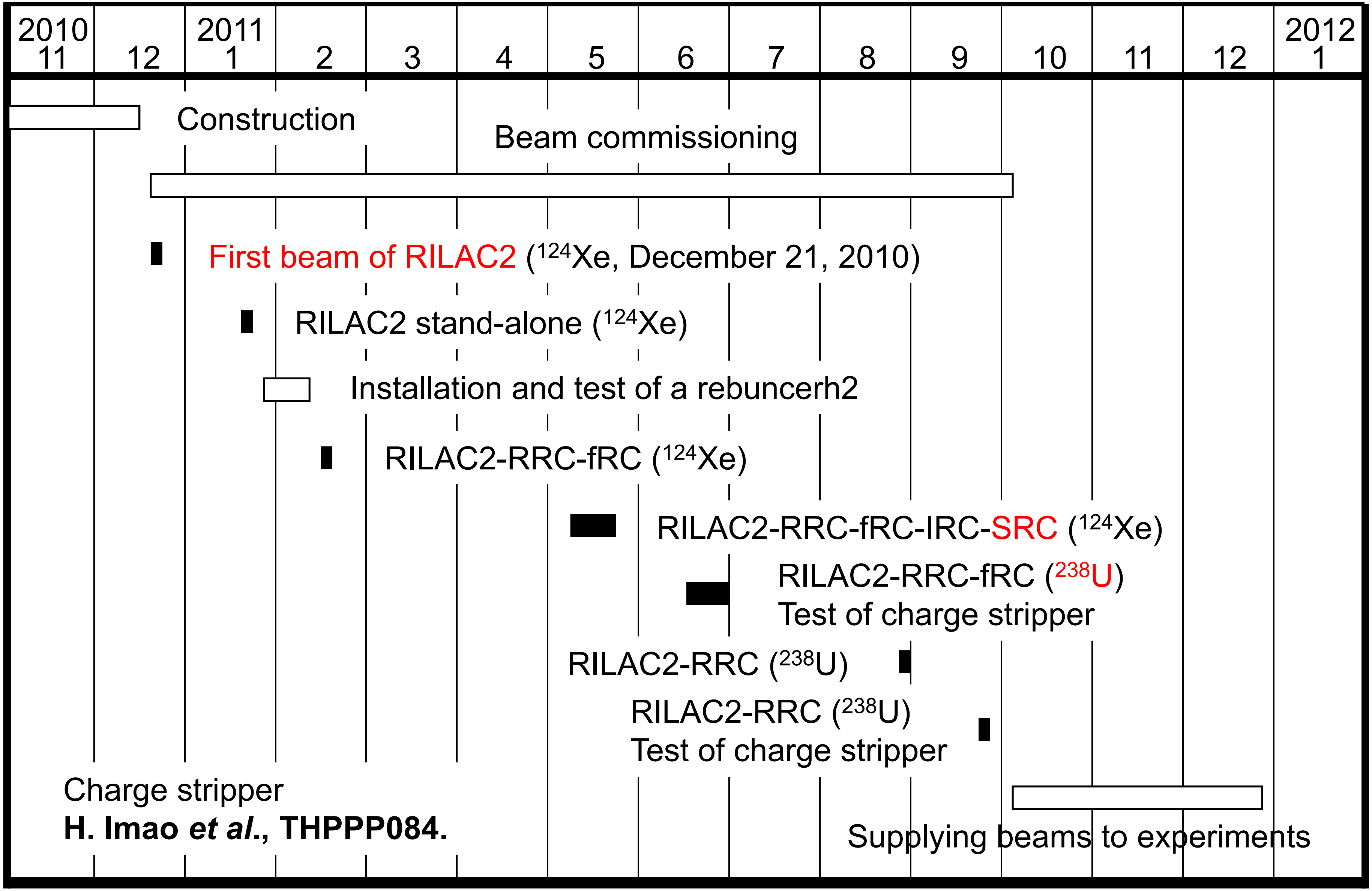
Target value ±0.1%

Target value ±0.1°

Voltage stability : < ±0.1%
Phase stability : ~ ±0.1° ⇨ Sufficient to attain the target values

History of RILAC2 beam commissioning

Successfully commissioned on schedule



Construction

Beam commissioning

First beam of RILAC2 (^{124}Xe, December 21, 2010)

RILAC2 stand-alone (^{124}Xe)

Installation and test of a rebuncerh2

RILAC2-RRC-fRC (^{124}Xe)

RILAC2-RRC-fRC-IRC-SRC (^{124}Xe)

RILAC2-RRC-fRC (^{238}U)
Test of charge stripper

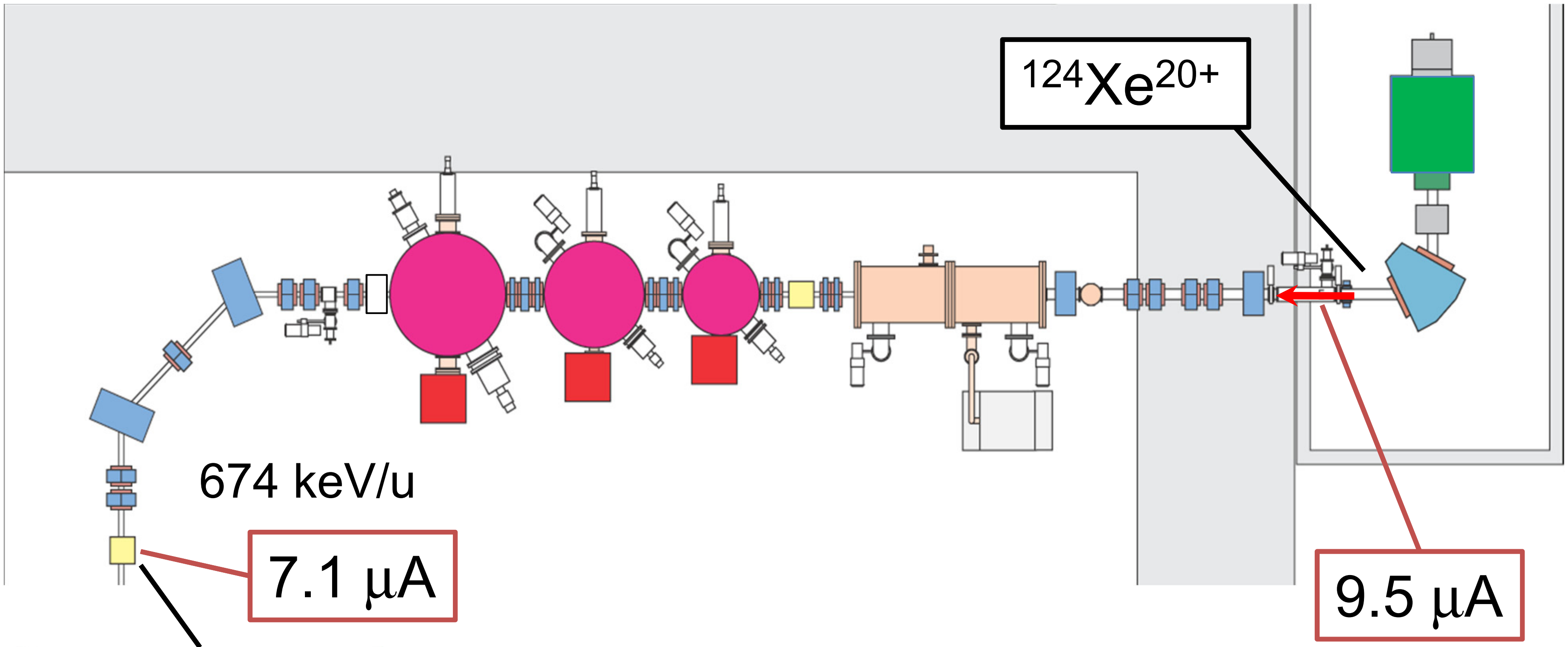
RILAC2-RRC (^{238}U)

RILAC2-RRC (^{238}U)
Test of charge stripper

Charge stripper
H. Imao *et al*., THPPP084.

Supplying beams to experiments

First beam of RILAC2



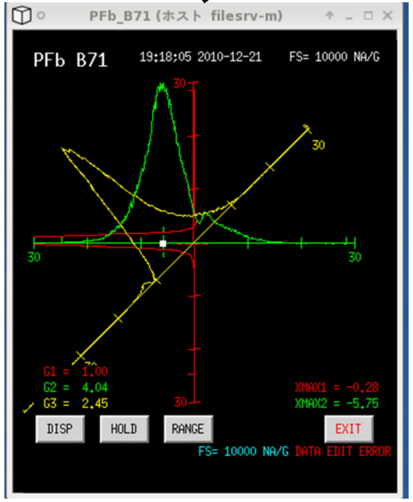
$^{124}Xe^{20+}$

674 keV/u

7.1 µA

9.5 µA

Trimmed by a slit.



PFb B71 19:18;05 2010-12-21 FS= 10000 NA/G

G1 = 1.00
G2 = 4.04
G3 = 2.45

XMAX1 = -0.28
XMAX2 = -5.75

FS= 10000 NA/G DATA EDIT ERROR

Beam profile measured by a wire scanner.

Started on December 21, 2010
Succeeded in accelerating the first beam on day 1.

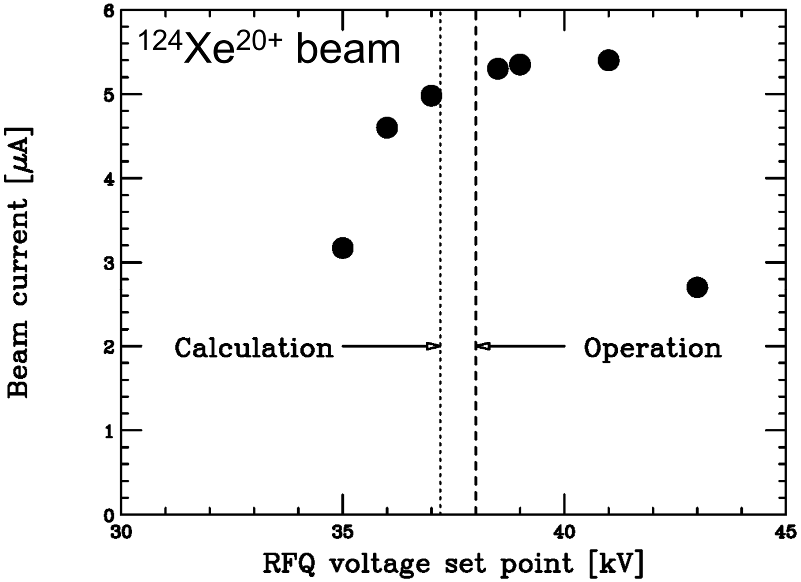
Beam transmission efficiency ~75%

Decision of operation parameters

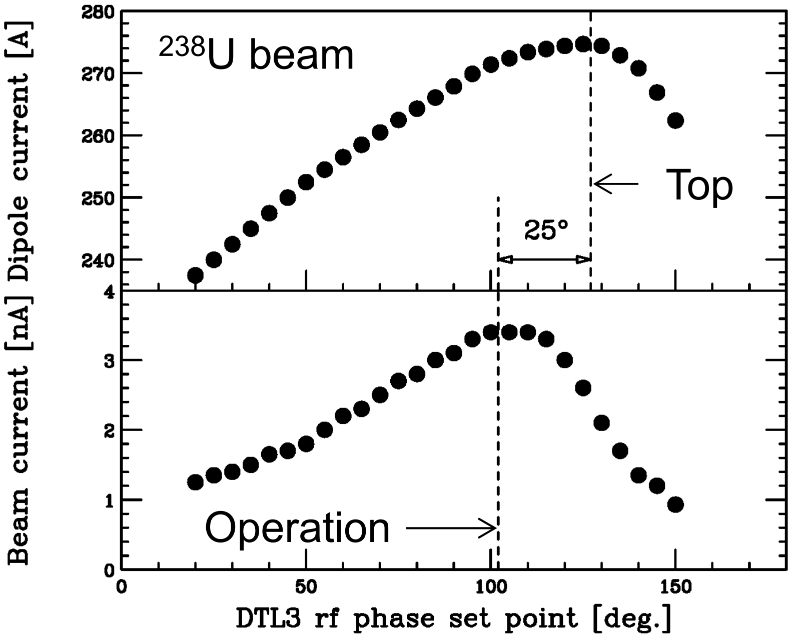
Started with parameters of designed value.

Parameters were made fine adjustments to increase beam transmission by measuring the beam current.

RFQ voltage setting vs. beam current downstream of bending magnet.



DTL3 rf phase setting vs. beam current downstream of bending magnet.



Parameters are consistent with designed value.

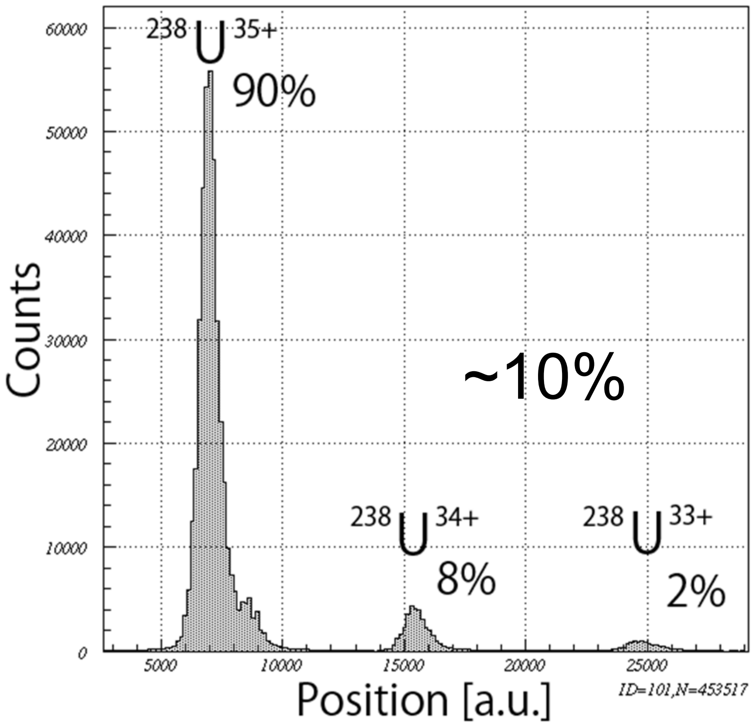
Beam loss caused by electron capture reactions

Loss of the uranium beam occurred in each section between the bending magnets of HEBT due to low vacuum level.

→ about 10% in each section

Example : a section in HEBT

~5 × 10^{-5} Pa Aug. 29, 2011

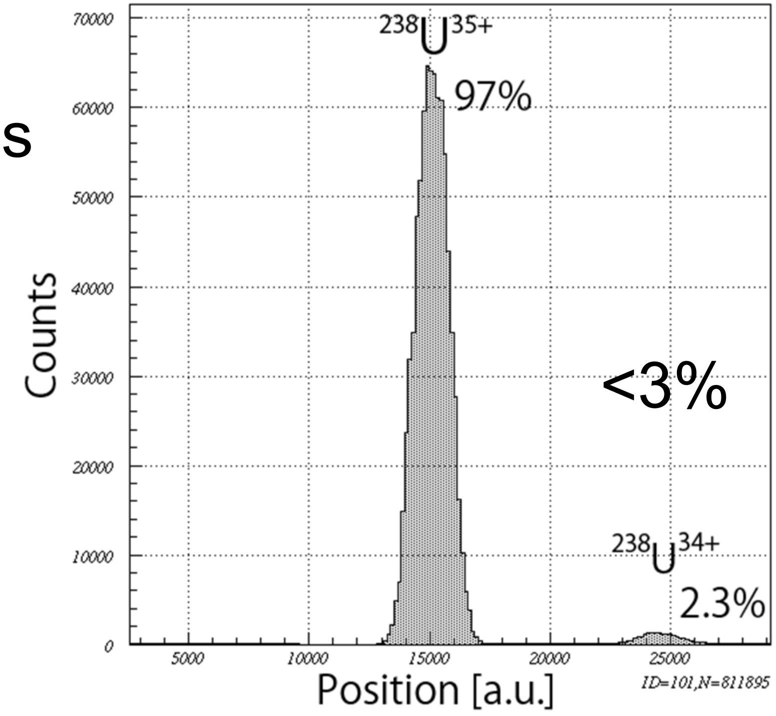


Five times improved

⇨

by appending a TMP

~1 × 10^{-5} Pa Apr. 27, 2012

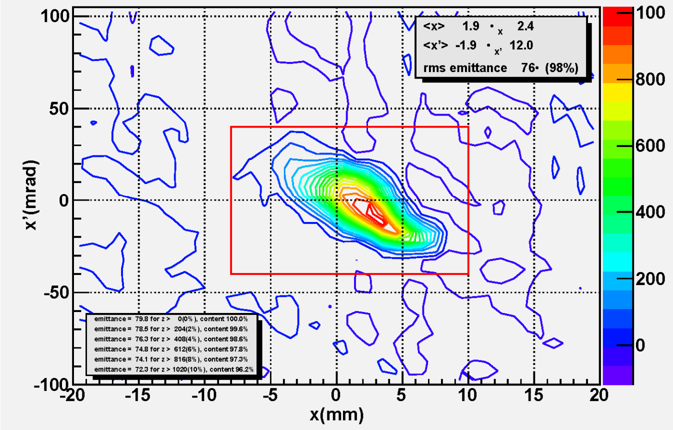


Beam transmission efficiency

Improved by optimizing rf parameters and improving the vacuum level

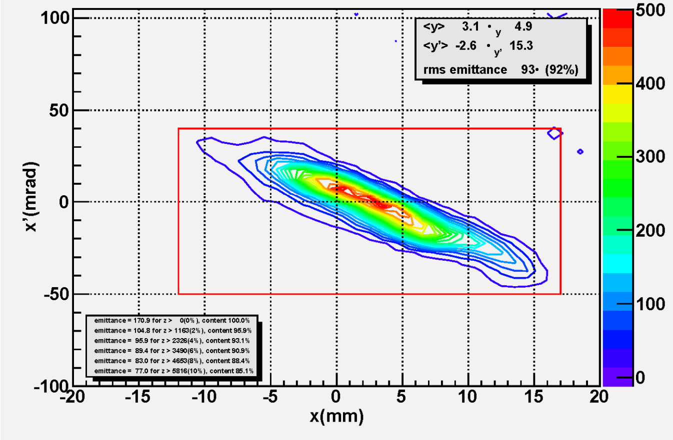
Typical 4σ emittance of uranium beam
from the SC-ECRIS.

201111191500-x Horizontal 76π mm·mrad



```
emittance =  79.8 for z >    0(0% ), content 100.0%
emittance =  78.5 for z >  204(2% ), content 99.6%
emittance =  76.3 for z >  408(4% ), content 98.6%
emittance =  74.8 for z >  612(6% ), content 97.8%
emittance =  74.1 for z >  816(8% ), content 97.3%
emittance =  72.3 for z > 1020(10% ), content 96.2%
```

201111191500-y Vertical 93π mm·mrad

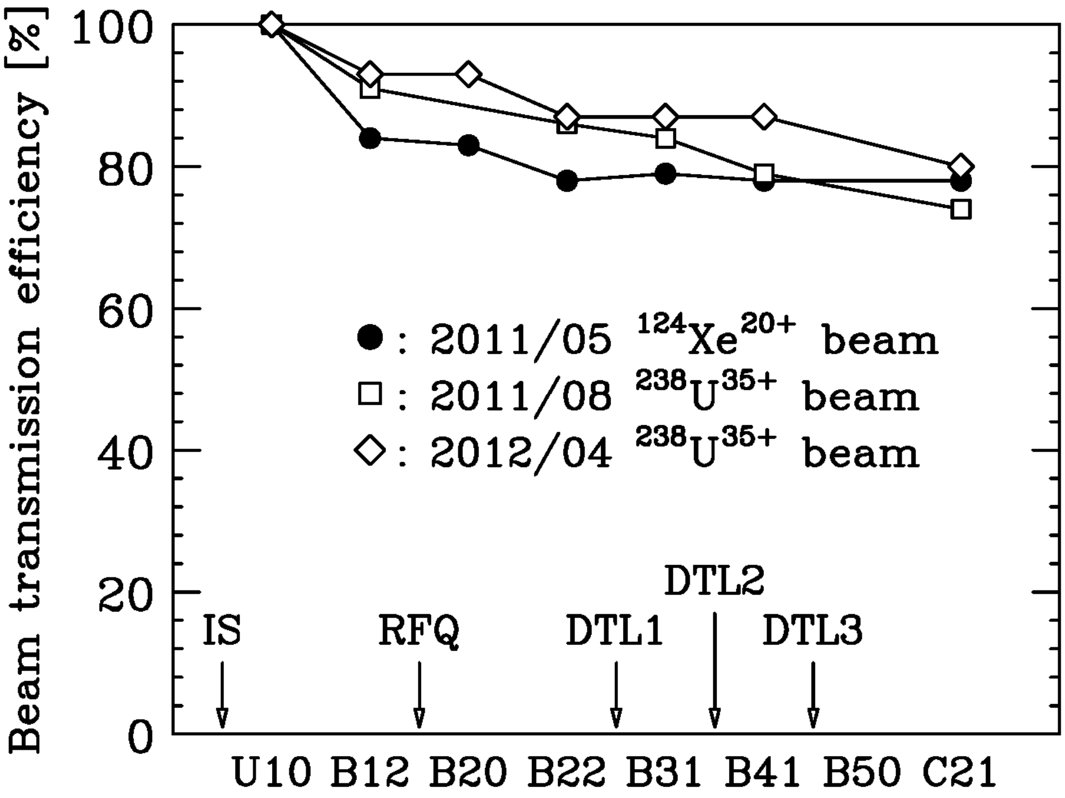


```
emittance = 170.9 for z >    0(0% ), content 100.0%
emittance = 104.8 for z > 1163(2% ), content 95.9%
emittance =  95.9 for z > 2326(4% ), content 93.1%
emittance =  89.4 for z > 3490(6% ), content 90.9%
emittance =  83.0 for z > 4653(8% ), content 88.4%
emittance =  77.0 for z > 5816(10% ), content 85.1%
```

Y. Higurashi, private communication.

^{124}Xe : 75% (2010/12) ⇨ 78% (2011/05)

^{238}U : 74% (2011/08) ⇨ 80% (2012/04)

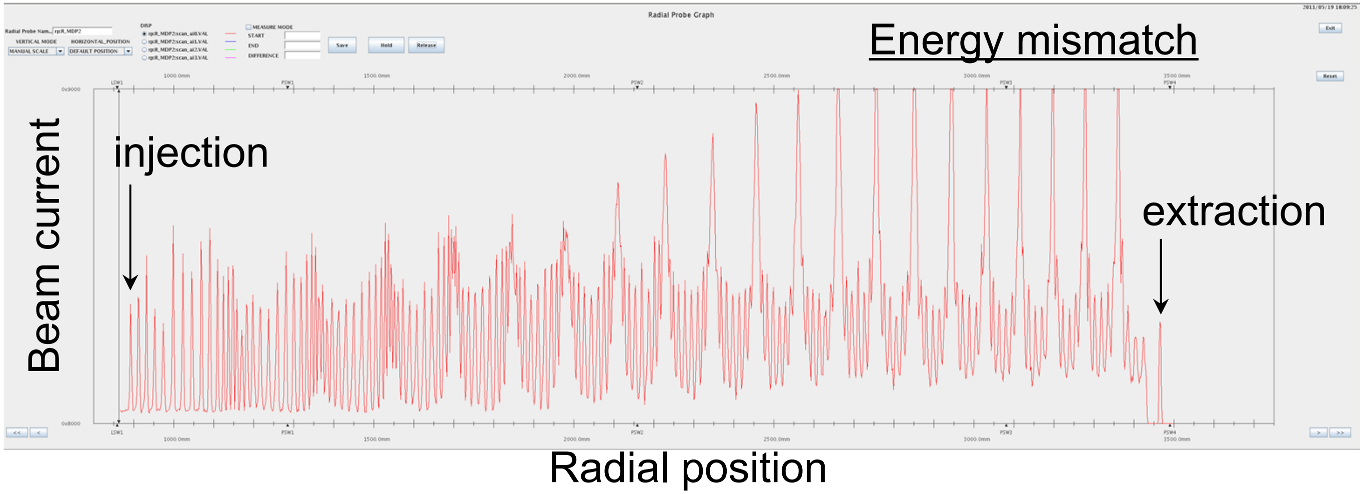


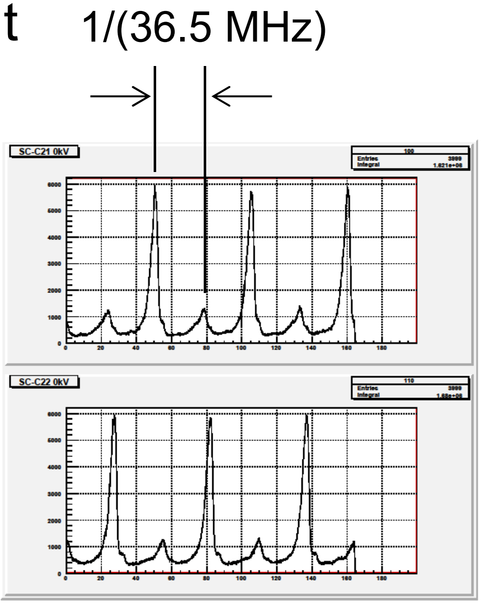
Beam energy matching

Fine tuning of injection energy to RRC is required.

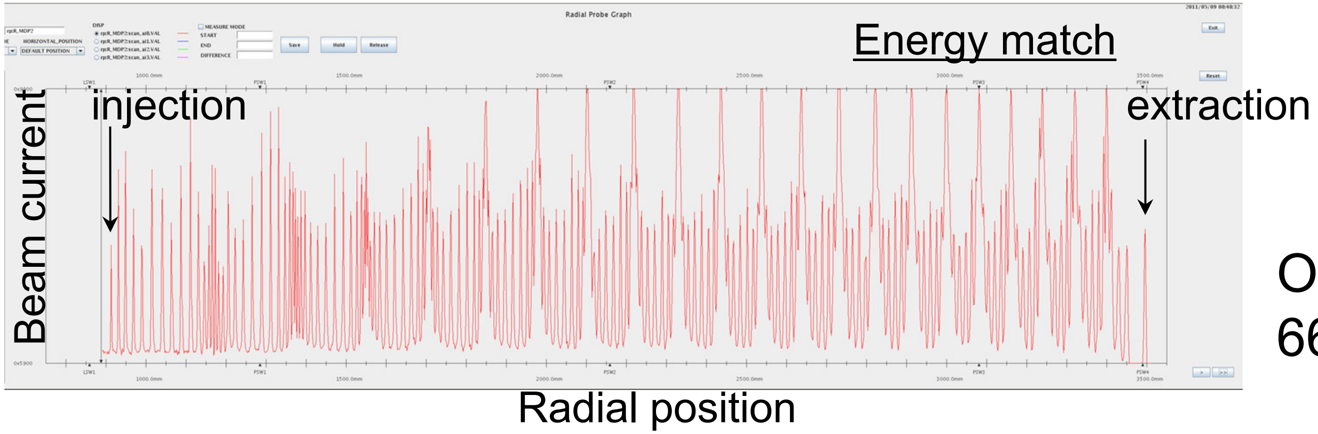
Beam energy from RILAC2 was decided by time-of-flight measurement and adjusted so as to obtain an optimal turn pattern of RRC.

RRC turn pattern, ^{124}Xe beam (2011/05)





Timing spectra measured by plastic scintillators



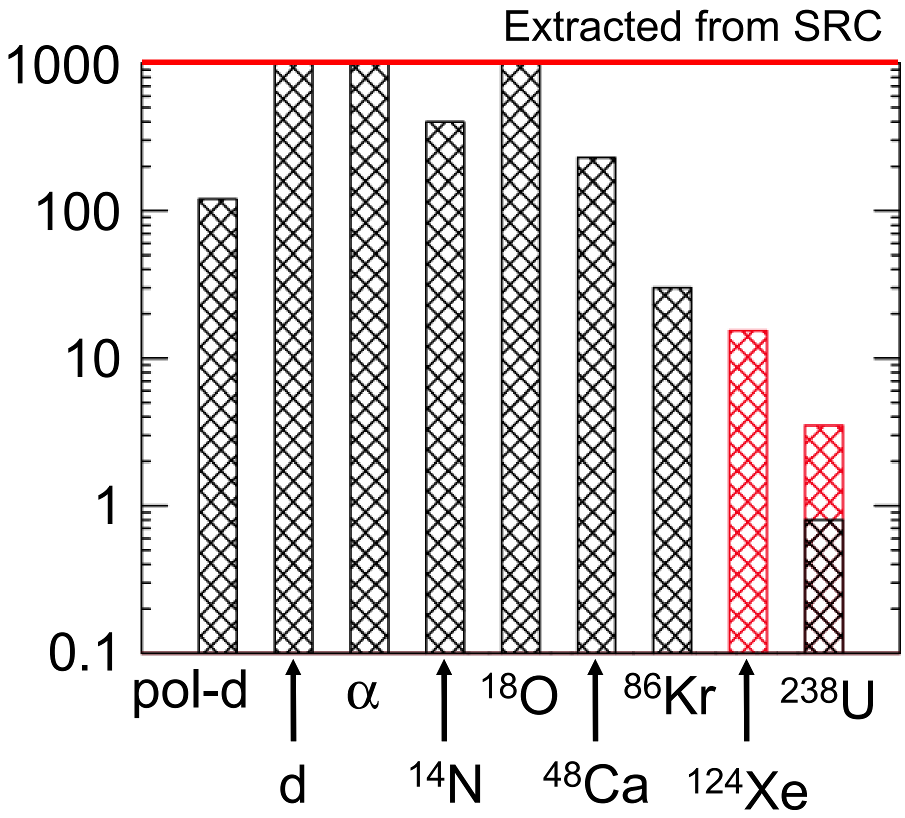
Optimal energy
669 keV/u

Deployment of RILAC2 for RIBF experiment

RILAC2 successfully started supplying beams from October 2011.

- 2011/10/5 ~10/6 : First experiment using RILAC2 (^{238}U 10.75 MeV/u)
- 2011/10/9 ~12/8 : First RIBF experiment (^{238}U 345 MeV/u)
- 2011/12/8 ~12/19 : RIBF experiment (^{124}Xe 345 MeV/u)

Maximum beam intensity (pnA)



^{238}U beam (~25 μA@IS)

0.8 pnA ⟹ 3.5 pnA

^{124}Xe beam (~60 μA@IS)

15.4 pnA

Much higher intensity are expected

Beam break time resulting from downtime of RILAC2

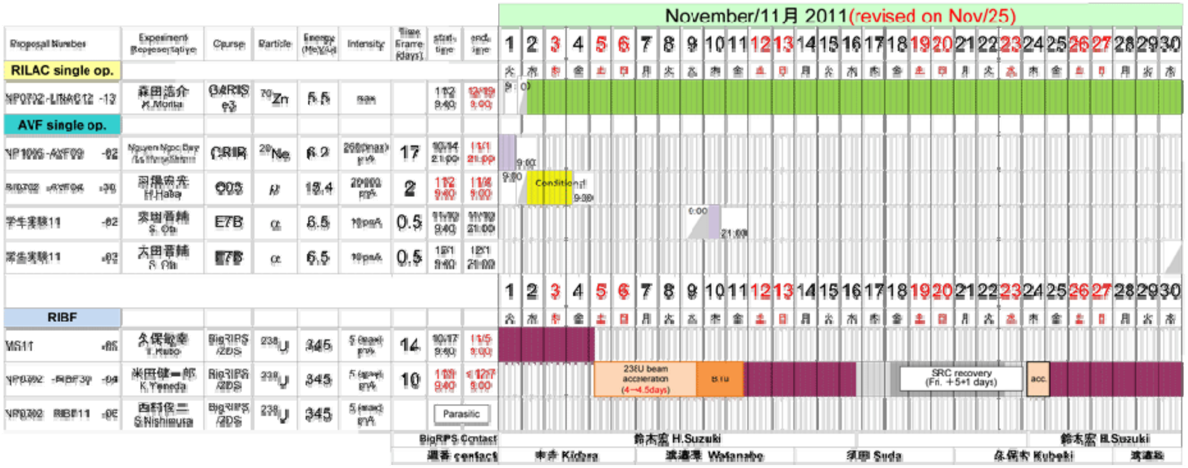
⇨ < 0.3% of the total scheduled beam time

Summary

- New linac injector RILAC2 has been successfully commissioned in 2011.

- Independent operation of RIBF experiments and the SHEs research becomes possible.

Beam time schedule



November/11月 2011(revised on Nov/25)

Proposal Number	Experiment Representative	Course	Particle	Energy (MeV/u)	Intensity	Time Frame (days)	start time	end time
RILAC single op.								
NP0702-LINAC12 -13	森田浩介 K.Morita	GARIS e3	^{70}Zn	5.5	max		11/2 9:40	12/19 9:00
AVF single op.								
NP1006-AVF09 -02	Nguyen Ngoc Duy / [illegible]	CRIB	^{20}Ne	6.2	250(max) pnA	17	10/14 21:00	11/1 21:00
[illegible] -AVF04 -30	羽場宏光 H.Haba	C03	d	[illegible]	[illegible] pnA	2	11/2 9:40	11/4 9:00
学生実験11 -02	大田晋輔 S. Ota	E7B	α	6.5	10pnA	0.5	11/10 9:40	11/10 21:00
学生実験11 -03	大田晋輔 S. Ota	E7B	α	6.5	10pnA	0.5	12/1 9:40	12/1 21:00
RIBF								
MS11 -05	久保敏幸 T. Kubo	BigRIPS /ZDS	^{238}U	345	5 (max) pnA	14	10/17 9:40	11/5 9:00
NP0702 -RIBF30 -04	米田健一郎 K.Yoneda	BigRIPS /ZDS	^{238}U	345	5 (max) pnA	10	11/8 9:40	12/7 9:00
NP0702 -RIBF11 -0E	西村俊二 S.Nishimura	BigRIPS /ZDS	^{238}U	345	5 (max) pnA		Parasitic	

BigRIPS Contact: 鈴木宏 H.Suzuki … 鈴木宏 H.Suzuki

週番 contact: 木寺 Kidera … 渡邉 Watanabe … 須田 Suda … 久保木 Kuboki … 渡邉

← SHEs research

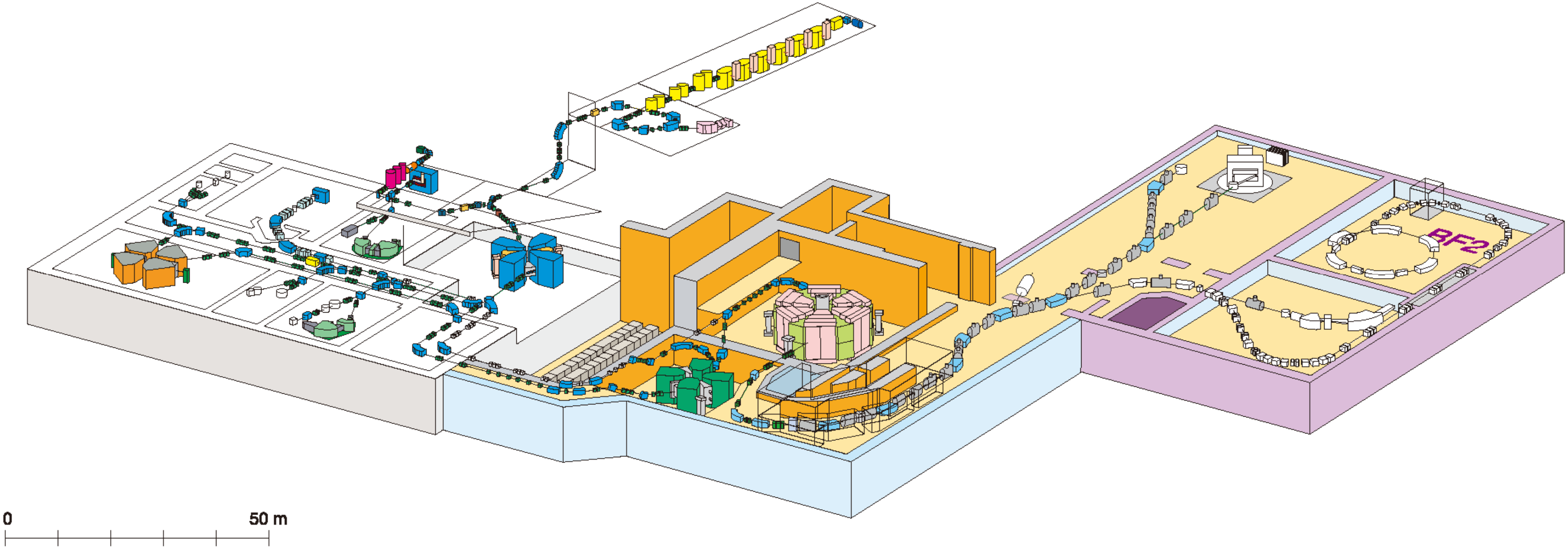
← RIBF experiments

- Intensity of very heavy ions such as U and Xe are increasing reliably.

Refs

RI beam factory (RIBF)

- To produce the world’s most intense RI beams over the entire range of atomic masses using heavy ion beam accelerated up to *v*/c ≈ 0.7

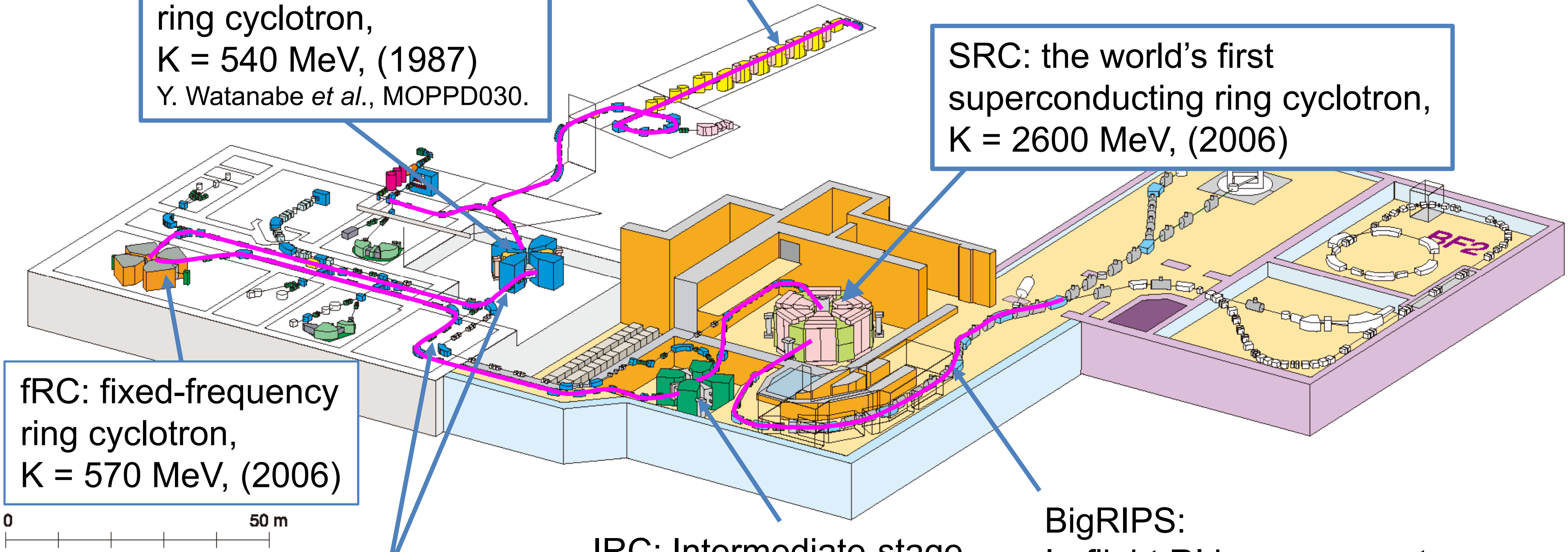


Entire view of RIBF

RI beam factory (RIBF)

- To produce the world's most intense RI beams over the entire range of atomic masses using heavy ion beam accelerated up to *v*/c ≈ 0.7

U, Xe acceleration mode : E = 345 MeV/u



RILAC: RIKEN heavy ion linac, (1981)

RRC: RIKEN ring cyclotron,
K = 540 MeV, (1987)
Y. Watanabe *et al*., MOPPD030.

SRC: the world's first superconducting ring cyclotron,
K = 2600 MeV, (2006)

fRC: fixed-frequency ring cyclotron,
K = 570 MeV, (2006)

Charge strippers
H. Imao *et al*., THPPP084.

IRC: Intermediate-stage ring cyclotron,
K = 980 MeV, (2006)

BigRIPS:
In-flight RI beam separator

Entire view of RIBF

RI beam factory (RIBF)

- To produce the world’s most intense RI beams over the entire range of atomic masses using heavy ion beam accelerated up to *v*/c ≈ 0.7

Mode for synthesis of super-heavy elements (SHEs)

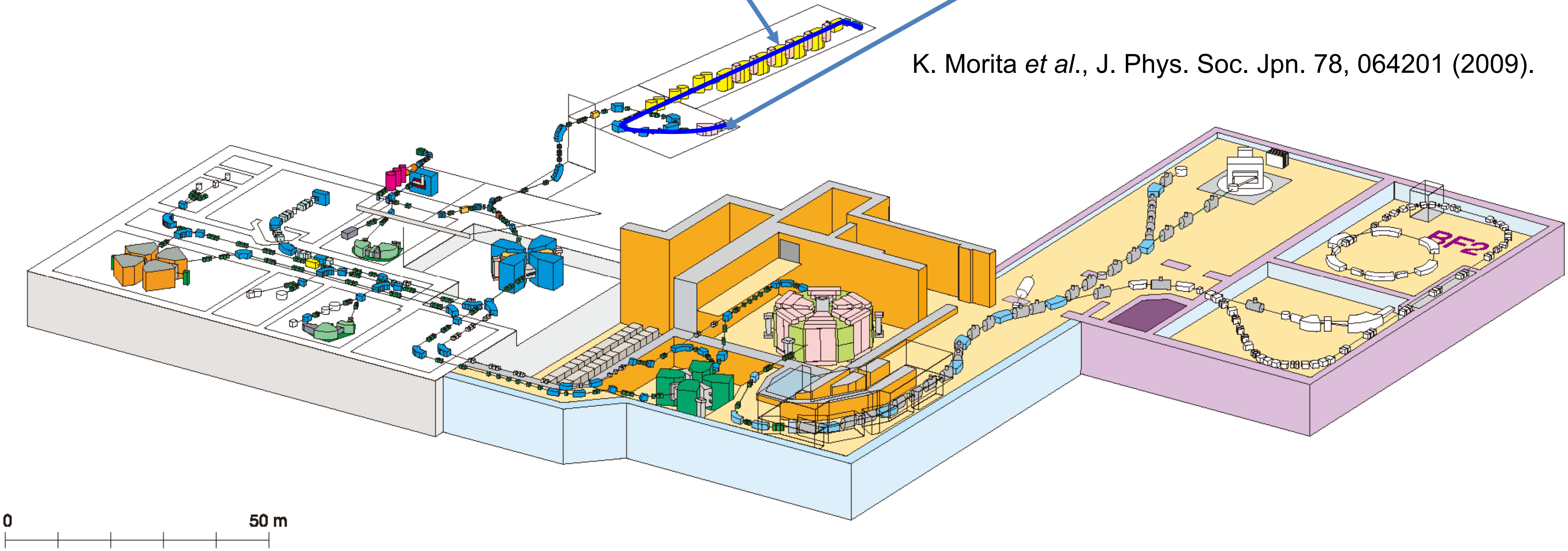
M. Kase *et al*., THPPP040.

RILAC: RIKEN heavy ion linac, (1981)

RIBF injector
GARIS
} shared

GARIS spectrometer for SHE research

K. Morita *et al*., J. Phys. Soc. Jpn. 78, 064201 (2009).



H. Imao *et al*., THPPP084.

Entire view of RIBF

RI beam factory (RIBF)

- To produce the world's most intense RI beams over the entire range of atomic masses using heavy ion beam accelerated up to *v*/c ≈ 0.7

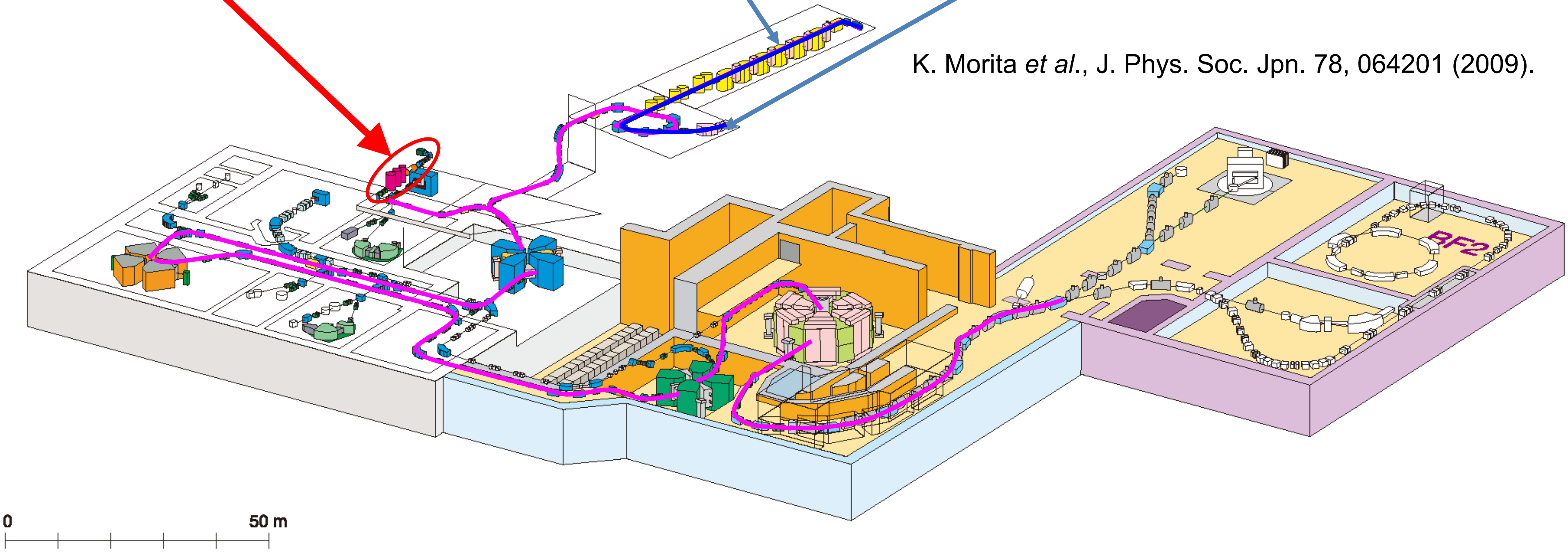
Independent operation of RIBF experiments and SHE research

RILAC2: New linac injector for RIBF

RILAC: RIKEN heavy ion linac, (1981)

RIBF injector
GARIS
} shared

GARIS spectrometer for SHE research



K. Morita *et al*., J. Phys. Soc. Jpn. 78, 064201 (2009).

H. Imao *et al*., THPPP084.

Entire view of RIBF

Ring cyclotrons

fRC

IRC

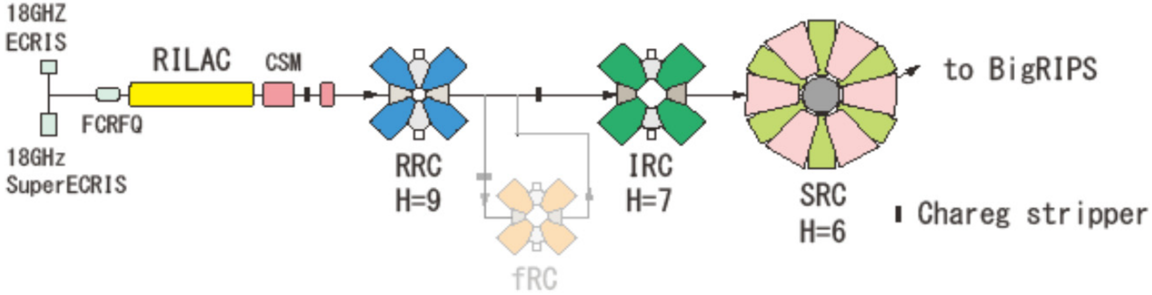
SRC

	RRC	fRC	IRC	SRC
K-number (MeV)	540	570	980	2600
Sector magnets	4	4	4	6
Velocity gain	4.0	2.1	1.5	1.5
Trim coils (/sector)	26	10	20	4(SC) 22(NC)
RF resonators	2	2+FT	2+FT	4+FT
Frequency range (MHz)	18-38	54.75	18-38	18-38

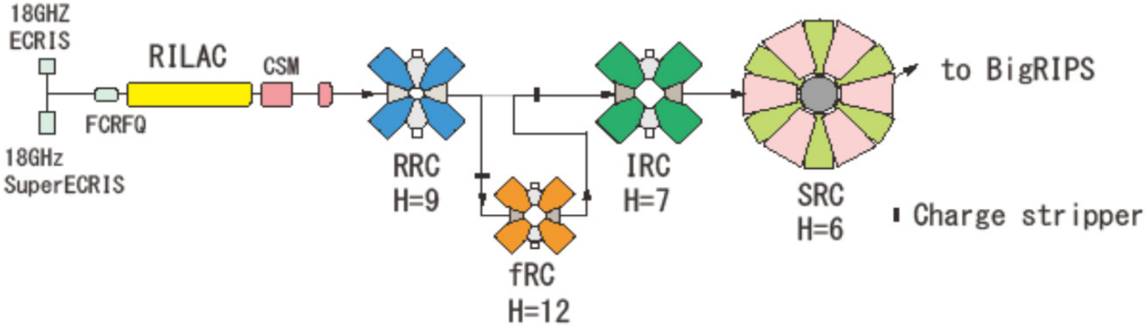
SC = superconducting
NC = normal conducting
FT = flat-top resonator

Acceleration mode at RIBF

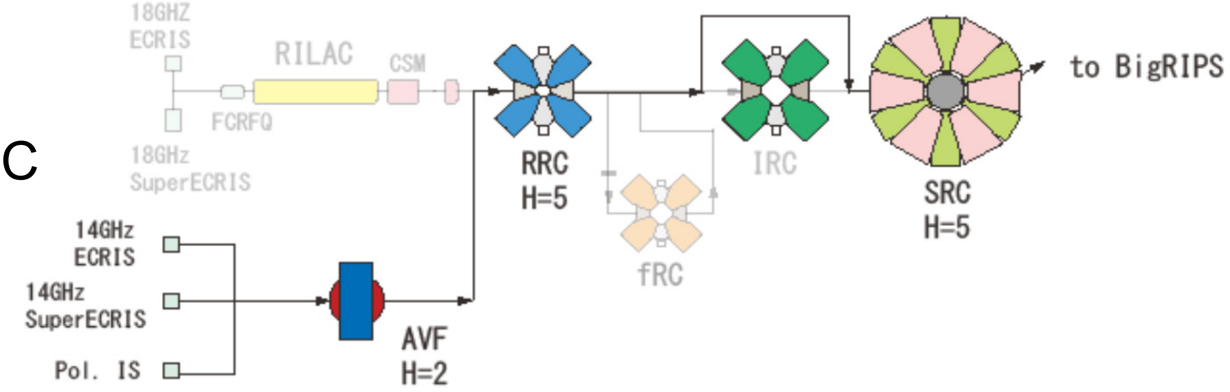
Variable-energy mode :
α, ^{18}O, ^{48}Ca, ^{86}Kr
up to 400 MeV/u @SRC



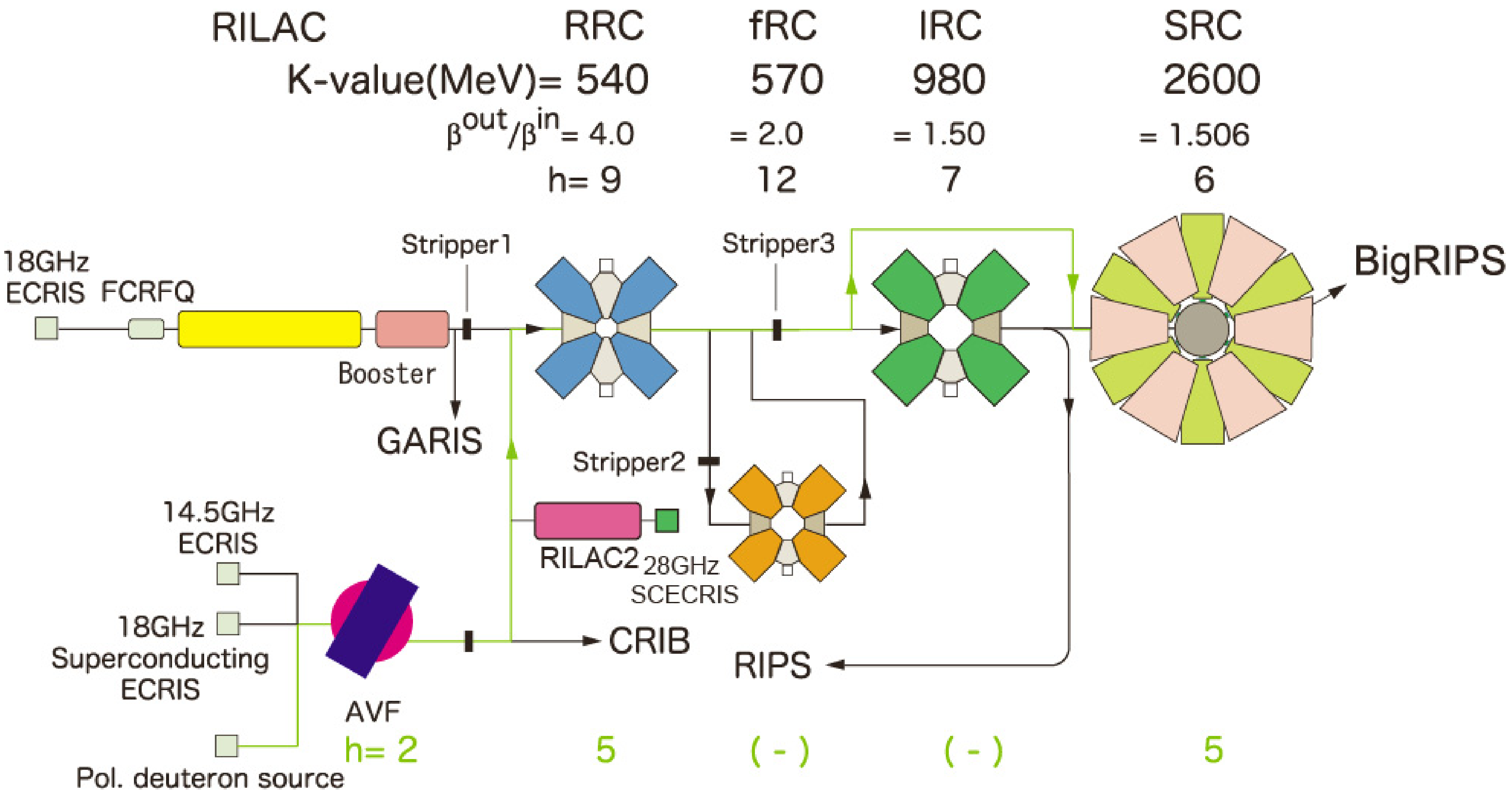
Fixed-energy mode :
^{238}U, ^{124}Xe
345 MeV/u @SRC



Light ion mode :
Pol-d, ^{14}N
250-440 MeV/u @SRC



Present acceleration mode at RIBF



Influence of RF instability

0.1° phase difference on DTL3 ⇨ 0.08% voltage difference on DTL3

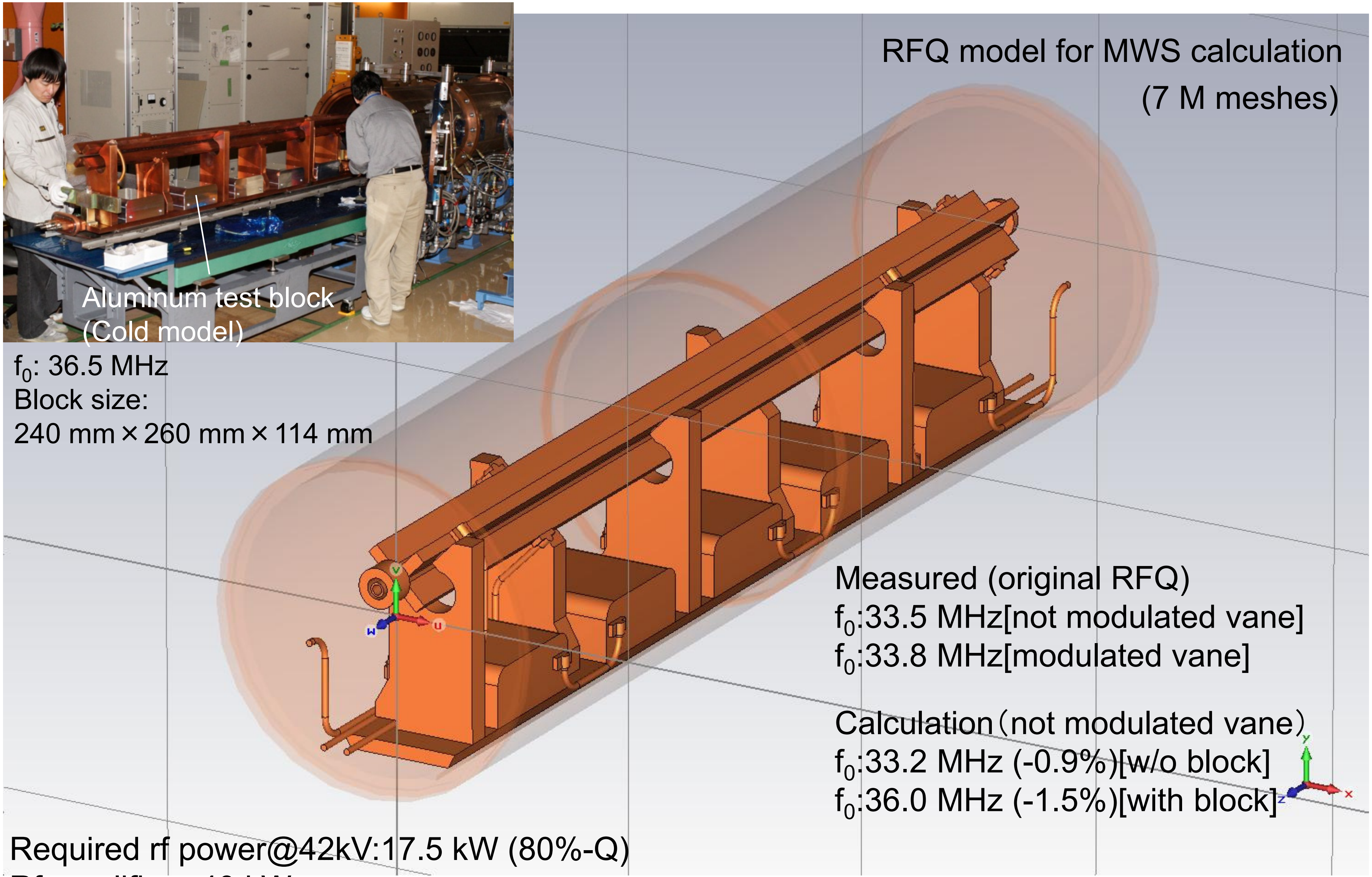
ΔV 0.1% on DTL3
→ $\Delta\phi$ ~4° @ injection of RRC
→ Δr ~ 3.7 mm @ extraction of RRC
(Turn separation @ extraction of RRC : 6.7 mm)

⇩

Critical degradation of extraction efficiency

Modification of RFQ

Put a block tuner into every gap between the posts
→ Size of block was optimized by 3D EM calculation (MWS) and cold-model test



RFQ model for MWS calculation
(7 M meshes)

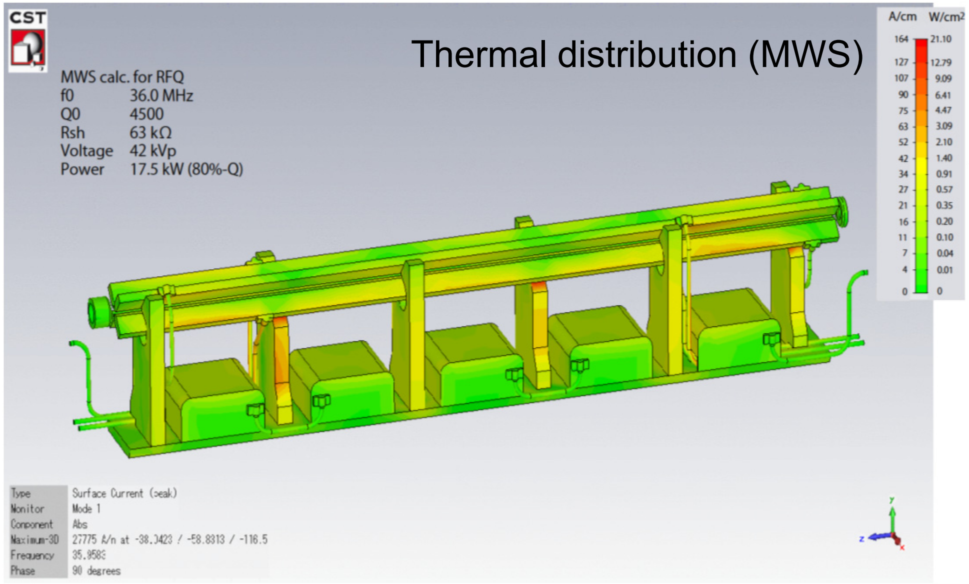
f_0: 36.5 MHz
Block size:
240 mm × 260 mm × 114 mm

Measured (original RFQ)
f_0:33.5 MHz[not modulated vane]
f_0:33.8 MHz[modulated vane]

Calculation（not modulated vane）
f_0:33.2 MHz (-0.9%)[w/o block]
f_0:36.0 MHz (-1.5%)[with block]

Required rf power@42kV:17.5 kW (80%-Q)
Rf amplifier : 40 kW max.

Detailed design of block tuner

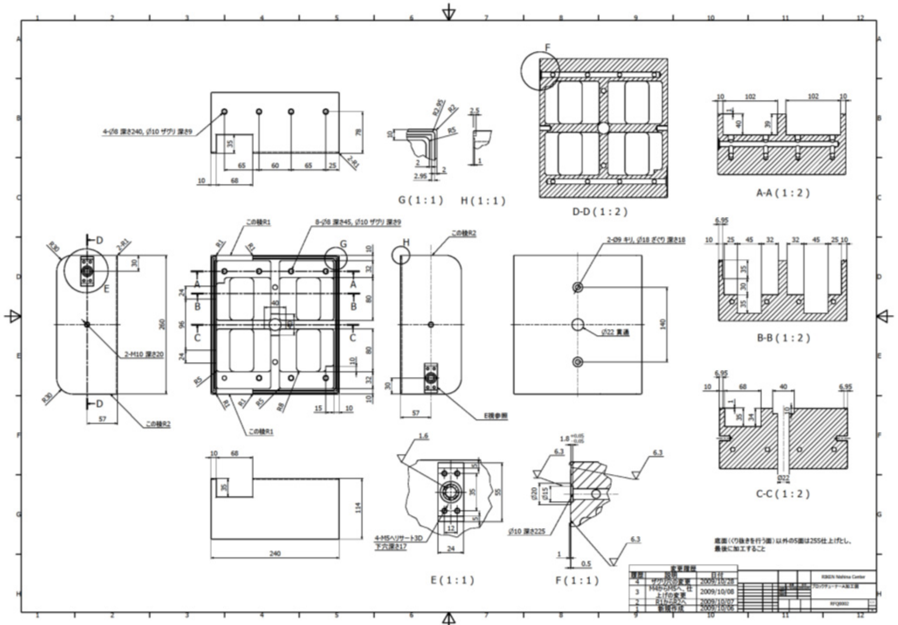


Thermal distribution (MWS)

MWS calc. for RFQ

f0	36.0 MHz
Q0	4500
Rsh	63 kΩ
Voltage	42 kVp
Power	17.5 kW (80%-Q)

Type	Surface Current (peak)
Monitor	Mode 1
Component	Abs
Maximum-3D	27775 A/m at -38.0423 / -58.8313 / -116.5
Frequency	35.9583
Phase	90 degrees

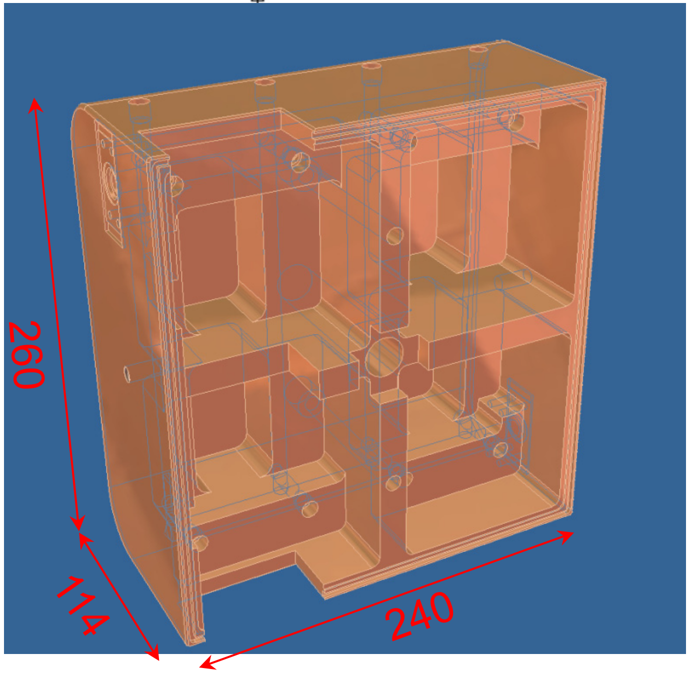


- Heat load of five block tuners：～2.1 kW@42 kV

- Cooling of block (assumed as φ11.6 mm, 4.85 m, 50 bend)
  Cooling water 18 L/min(inlet 0.5 MPa, outlet 0.2 MPa)
  Water temp. ～2 ℃ up、inner surface temp. ～1 ℃ up

- Weight saving : 64 kg→33 kg

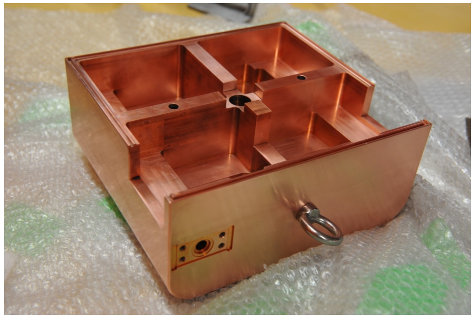
- 3D CAD drawing (Autodesk inventor)



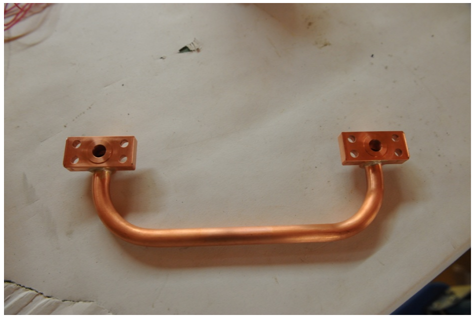
Block tuner made of oxygen free copper

Test of RFQ linac

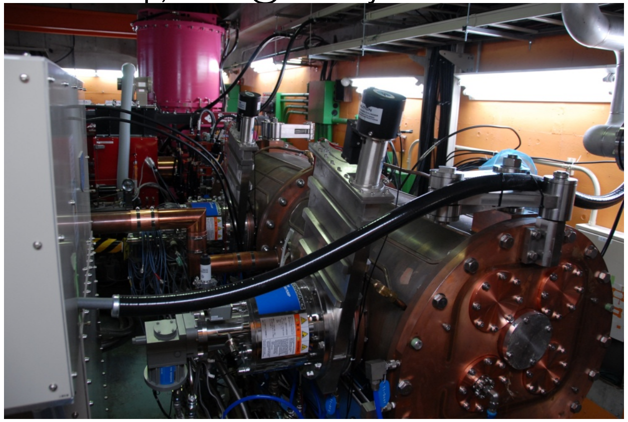
Block tuner



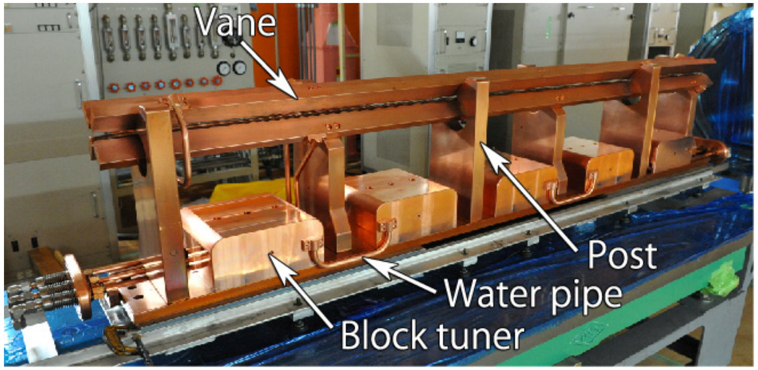
Connection pipe for cooling water



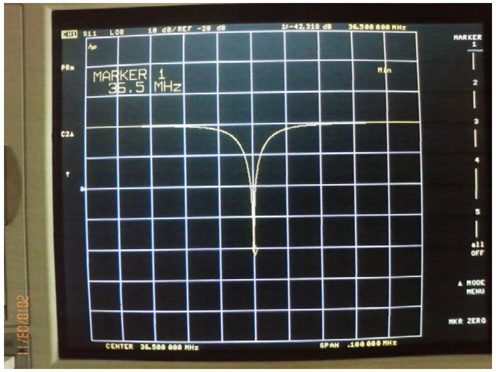
02 Sep, 2010 @ AVF cyclotron vault



Inner construct of RFQ linac

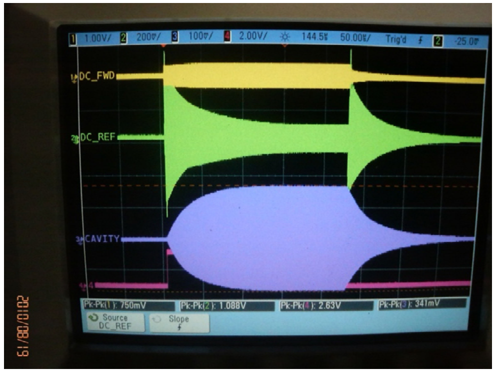


S11 result of RFQ

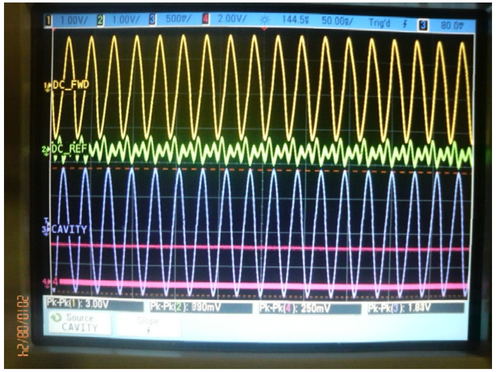


Frequency : 36.5 MHz
Loaded-Q : 2500 (S21)

High power test (pulse)



High power test (CW)

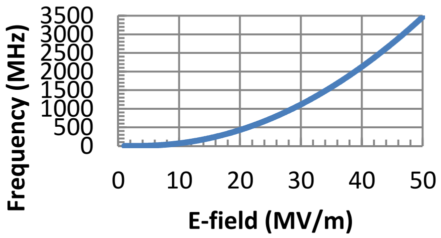


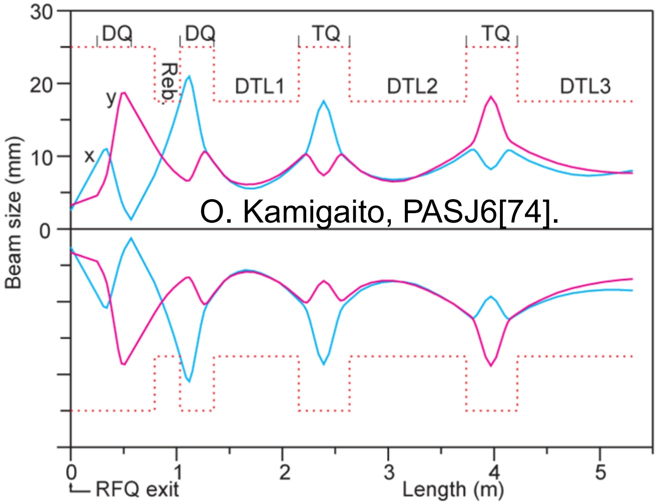
- Assembly : performed in March 2010
- Vacuum test : acceptable (< 8×10^{-6} Pa)
- Resonant frequency : corresponds to 36.5 MHz
- Low-level circuits & rf amplifier : ready
- High power test : achieved the rated voltage of 42 kV!!

Drift tube linac

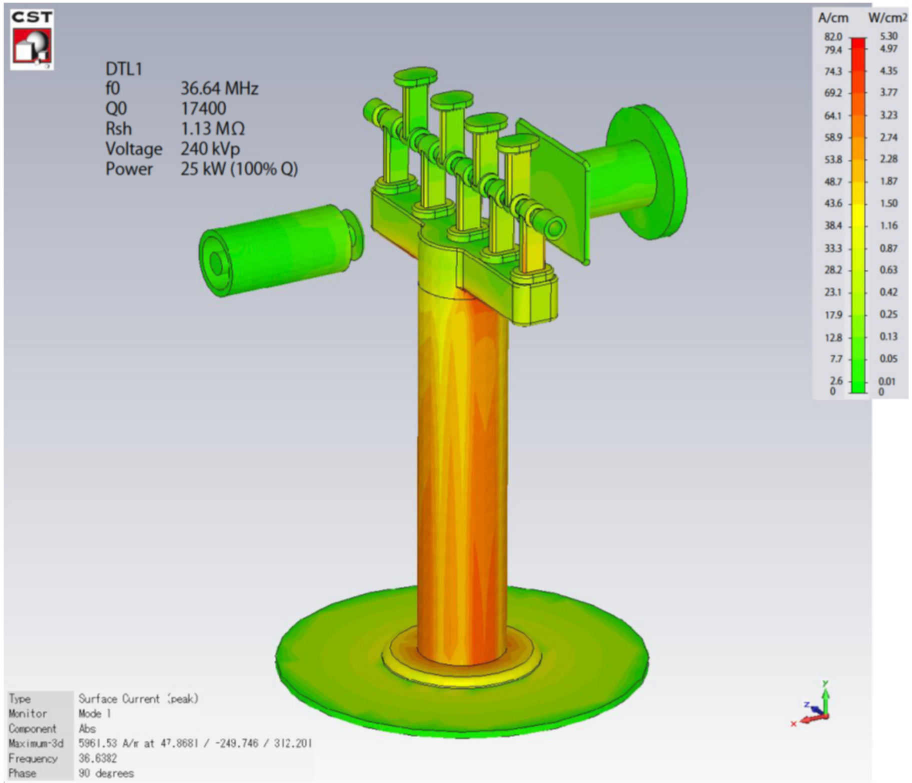
- DTL1, 2 : new fabrication
- DTL3 : modify CSM-D1 tank
- CW-QWR
- Low-β : 0.015～0.038
- 1.1 ～1.2 Kilpatrick
- Direct coupling scheme for saving cost and space

Kilpatrick limit at tens MHz





O. Kamigaito, PASJ6[74].



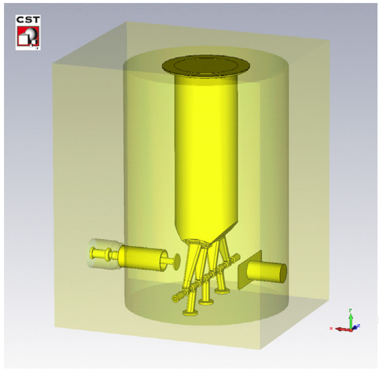
DTL1
f0 36.64 MHz
Q0 17400
Rsh 1.13 MΩ
Voltage 240 kVp
Power 25 kW (100% Q)

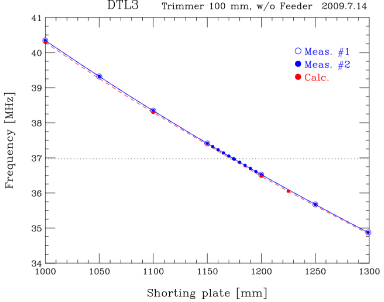
Type Surface Current (peak)
Monitor Mode 1
Component Abs
Maximum-3d 5961.53 A/m at 47.8681 / -249.746 / 312.201
Frequency 36.6382
Phase 90 degrees

Surface current of DTL1 (MWS : 10M meshes)

	DTL1	DTL2	DLT3
Frequency (MHz)	36.5	36.5	36.5
Duty (%)	100	100	100
m/q ratio	7	7	7
Input energy (keV/u)	100	220	450
Output energy (keV/u)	220	450	680
Length (cm)	80	110	130
Height (mm)	1320	1429	1890
Gap number	10	10	8
Gap length (mm)	20	50	65
Gap voltage (kV)	110	210	260
Drift tube aperture (mm)	17.5	17.5	17.5
Peak surface field (MV/m)	8.9	9.4	9.7
Synchronous phase (deg.)	-25	-25	-25

Design of DTL tanks

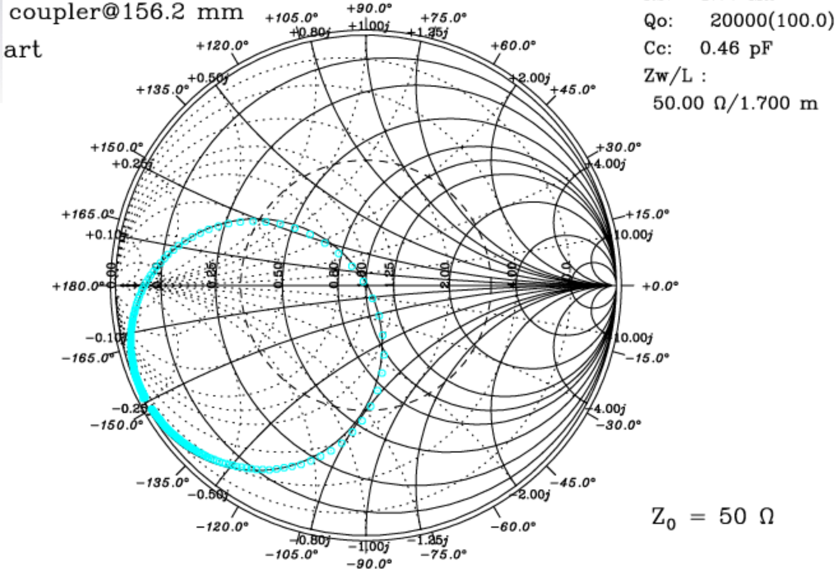

DTL3 model for MWS

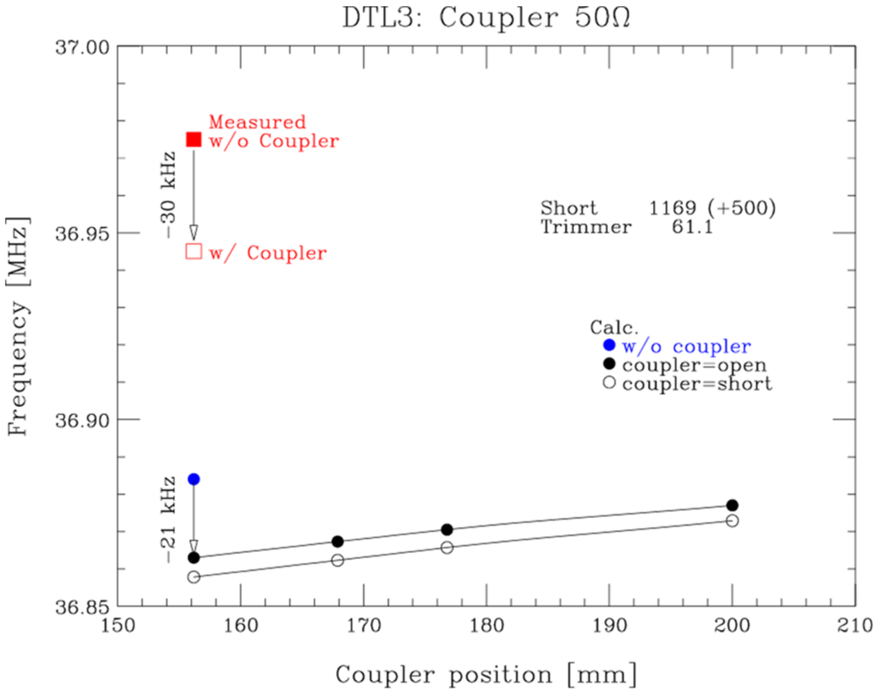


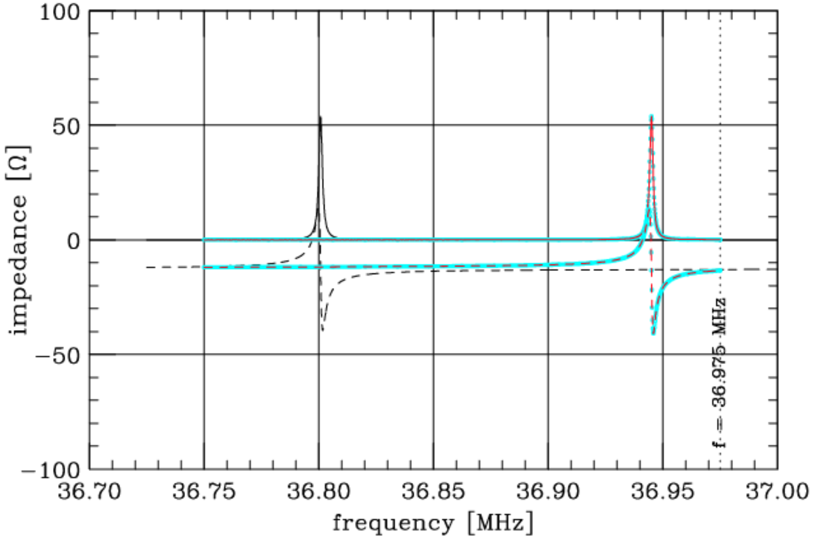
- Direct coupling scheme

→ resonant frequency decreases
because of their series/parallel
capacitance

- Target frequency was adopted
such that this decrease was compensated
- The decrease was estimated to be -225 kHz
by comparing measurement and MWS calculation





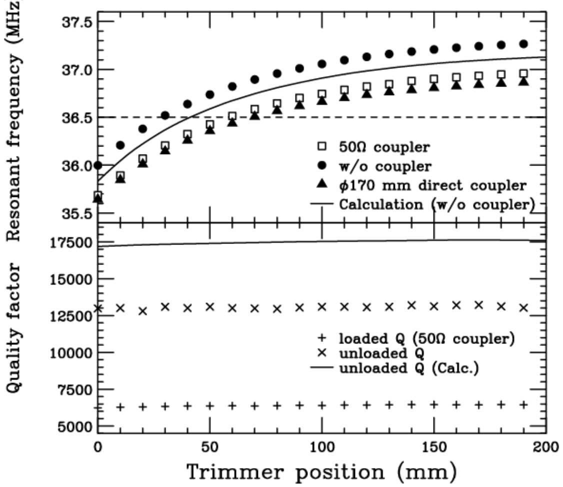


Test result of DTL tanks

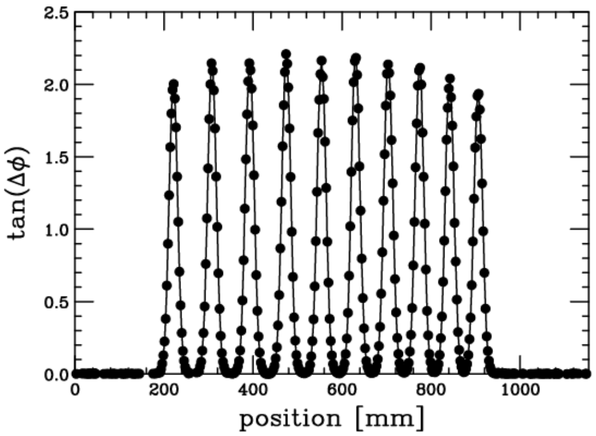
For three tanks

- Resonant frequency : conformable to designed value 36.5 MHz
- High power test : achieved the rated voltage

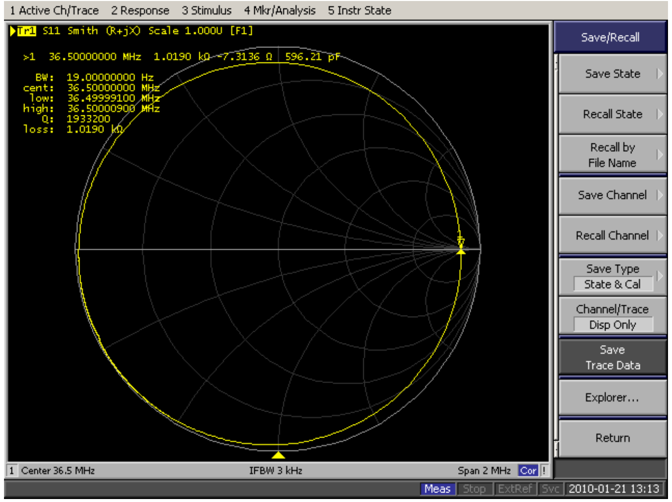
Frequency response of DTL1



Field distribution of DTL1



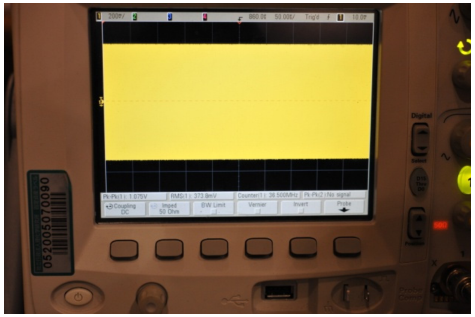
Coupling of DTL1 (φ170mm coupler)



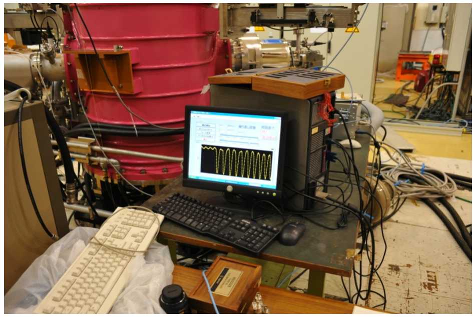
```
Tr1 S11 Smith (R+jX) Scale 1.000U [F1]

>1  36.50000000 MHz  1.0190 kΩ -7.3136 Ω  596.21 pF

  BW:  19.00000000 Hz
cent:  36.50000000 MHz
 low:  36.49999100 MHz
high:  36.50000900 MHz
   Q:  1933200
loss:  1.0190 kΩ

1  Center 36.5 MHz          IFBW 3 kHz          Span 2 MHz
2010-01-21 13:13
```

Measured characteristics

	DTL1	DTL2	DTL3
Frequency range (MHz)	35.64—36.87	35.5—36.8	36.25—36.69
Unloaded Q	13000	20350	22500
Shunt impedance (MΩ/gap)	0.94	1.65	1.72
Effective shunt impedance (MΩ/m)	135	176	102
Required rf power (kW)	6.5	13.4	19.6



Pick-up signal



Perturbation measurement

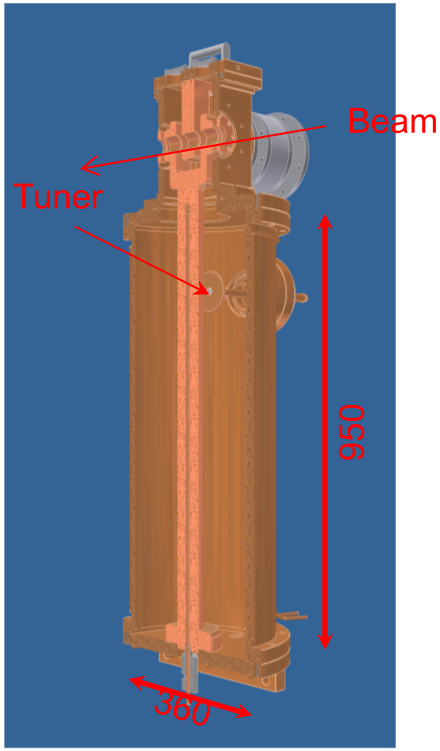
Rebunchers

REB1

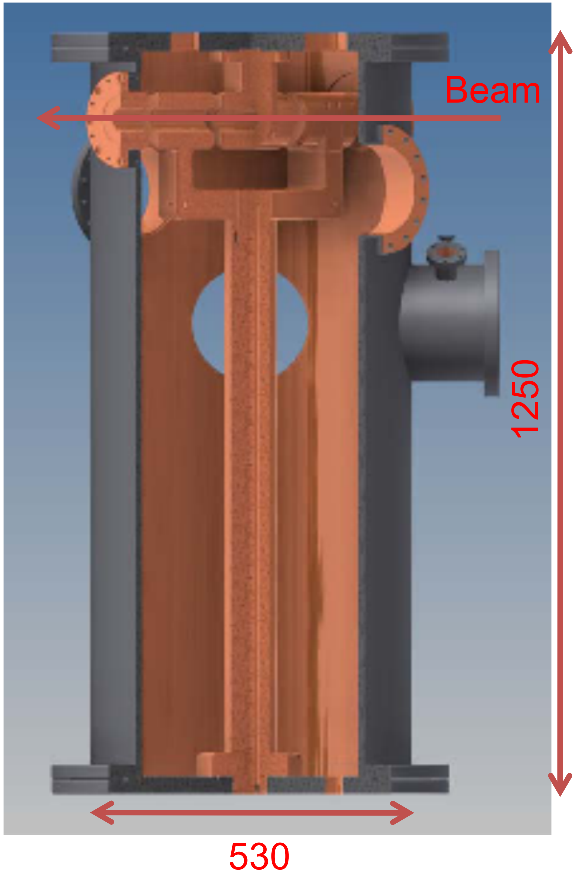
- QWR
- f_0 : 36.5 MHz
- β : 0.0147, βλ/2 : 60 mm
- Rated voltage : 100 kV total
- Gap number : 4
- Gap length : 20 mm, 10 mm
- Drift tube aperture : 17.5 mm
- Q_0 : 8500 (MWS)
- Shunt impedance : 550 kΩ (MWS)
- Required rf power : 570 W (100%-Q)
- Power amp. : 1 kW max.

REB2

- QWR
- f_0 : 36.5 MHz
- β : 0.0382, βλ/2 : 156 mm
- Rated voltage : 200 kV total
- Gap number : 4
- Gap length : 20 mm
- Drift tube aperture : 20 mm
- Q_0 : 11400 (MWS)
- Shunt impedance : 950 kΩ (MWS)
- Required rf power : 1500 W (100%-Q)
- Power amp. : 3 kW max.



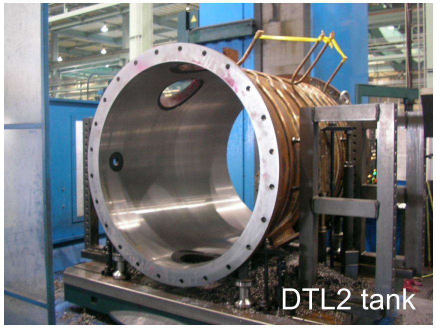
REB1 design

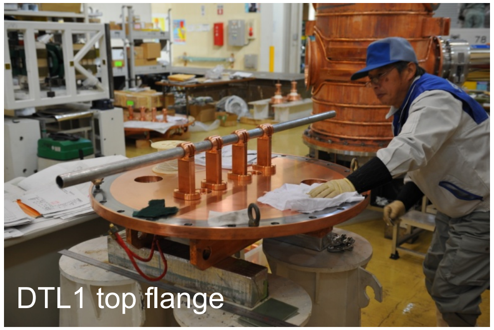


REB2 design

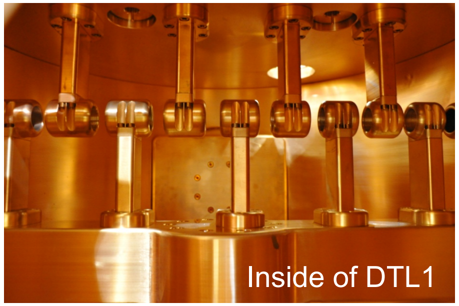
Pictures : fabrication and installation


DTL1 tank


DTL2 tank

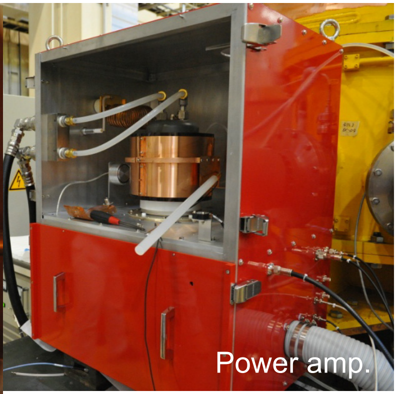

DTL1 top flange

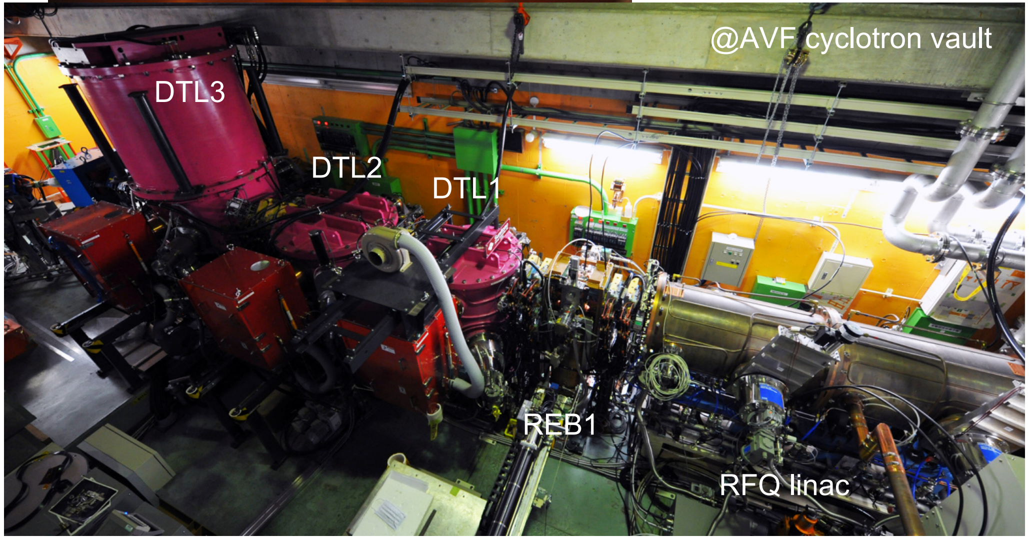

DTL1 coupler


Inside of DTL1


Inside of DTL1


Inside of DTL3


Power amp.


@AVF cyclotron vault

History of beam commissioning

RILAC2 beam commissioning

Date	Machine studies, events
Dec. 17, 2010	Construction of RILAC2 was finished.
Dec. 21, 2010	Beam commissioning was begun using $^{124}Xe^{20+}$. First beam.
Dec. 22, 2010	RILAC2 solo acceleration test using $^{124}Xe^{20+}$.
Jan. 21, 2011	RILAC2 solo acceleration test using $^{124}Xe^{20+}$.
Jan. 24 — Feb. 11, 2011	Installation and test of a rebuncher2.
Feb. 14 —16, 2011	RILAC2-RRC-fRC acceleration test using ^{124}Xe.
May. 7 — 21, 2011	RILAC2-RRC-fRC-IRC-SRC, ^{124}Xe beam was extracted from SRC.
Jun. 15 — 30, 2011	RILAC2-RRC-fRC, first acceleration test of ^{238}U. Test of charge stripper.
Aug. 26 — 29, 2011	RILAC2-RRC acceleration test using ^{238}U.
Sep. 24 — 26, 2011	RILAC2-RRC acceleration test using ^{238}U. Test of charge stripper.
Oct. 5, 2011 —	Supplying beams for experiments.