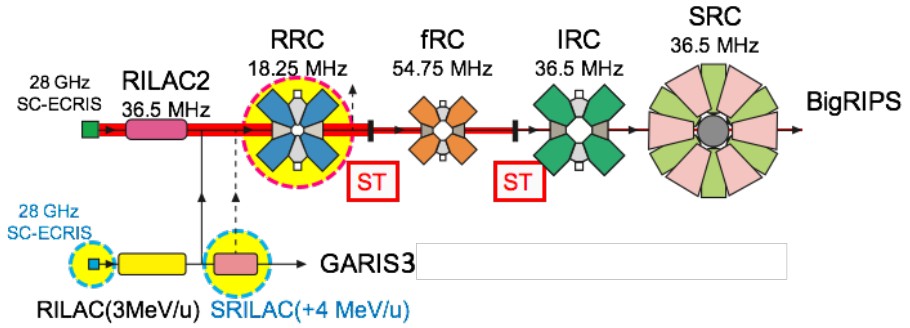
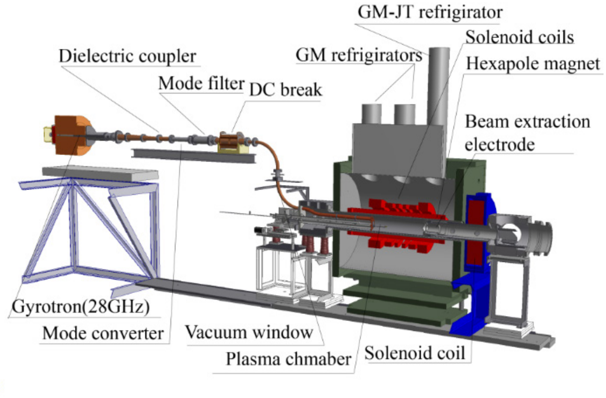
High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

T. Nakagawa (Nishina center for accelerator based science, RIKEN)

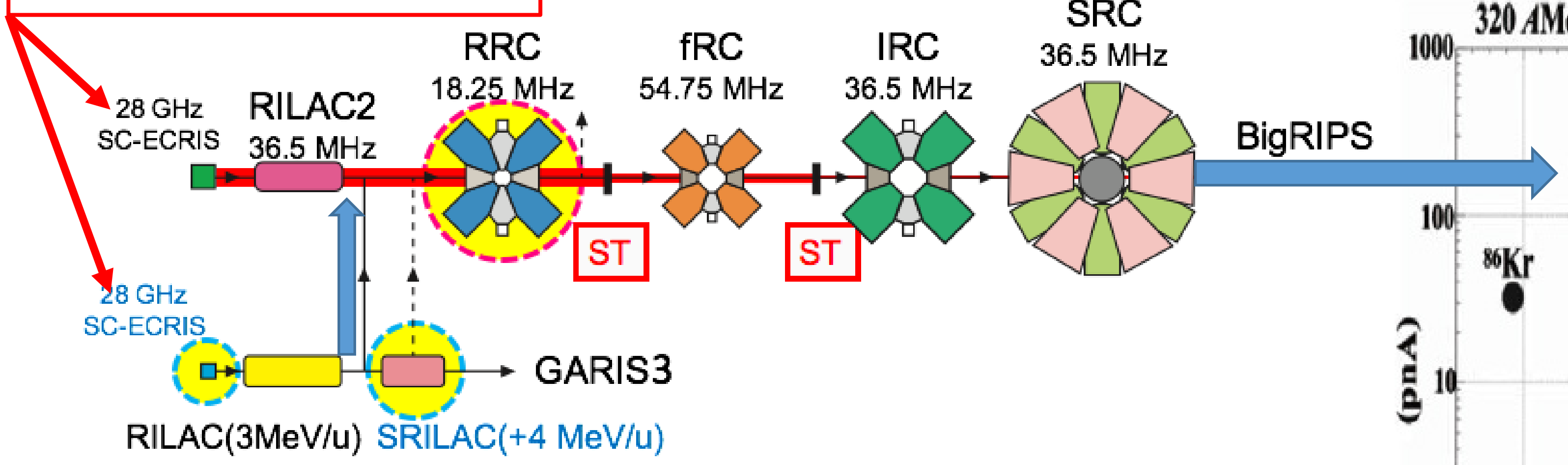




Cyclotron 2022 (Dec. 5-9, 2022, Beijing, China)

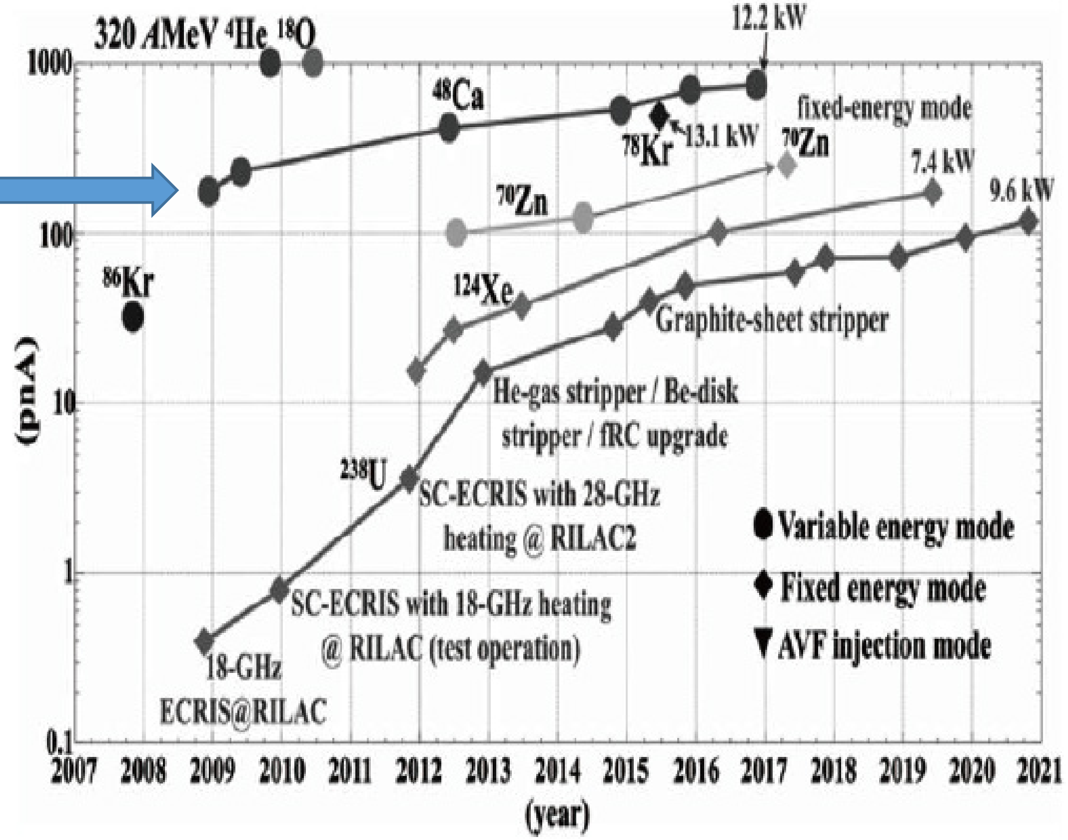
I. RIKEN Radioactive Ion Beam Facility

Two 28GHz SC-ECRISs



(II)RIKEN RIBF (P------ U)

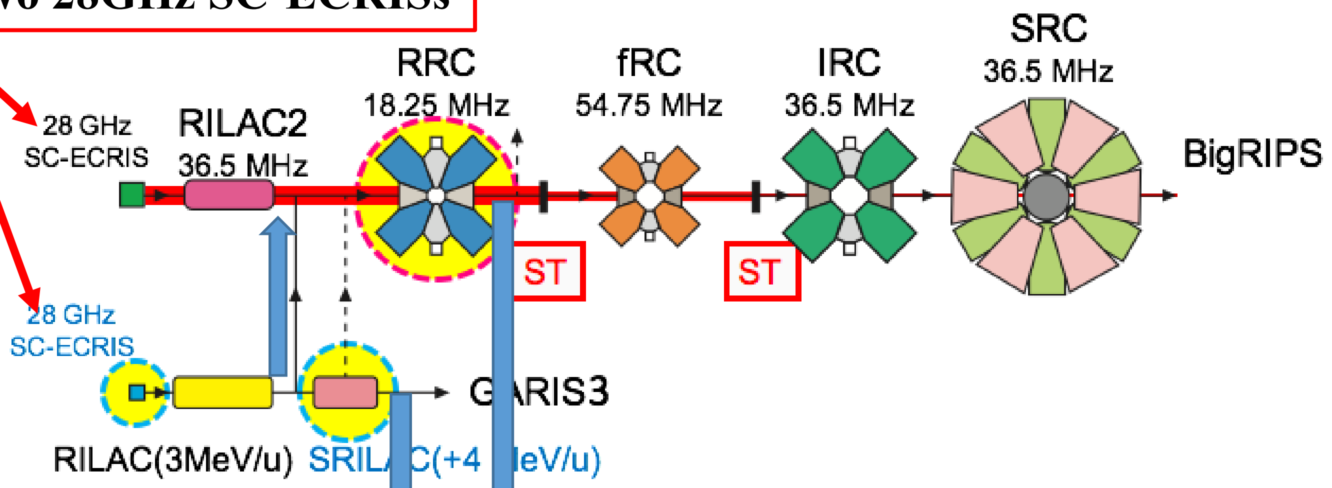
2009~2018,U beam (X100)



N. Fukunishi, JPASJ 17 (2020)236

II. Synthesis of Super-heavy elements

Two 28GHz SC-ECRISs



Metallic ion beam

(Ti, V, Cr…..)

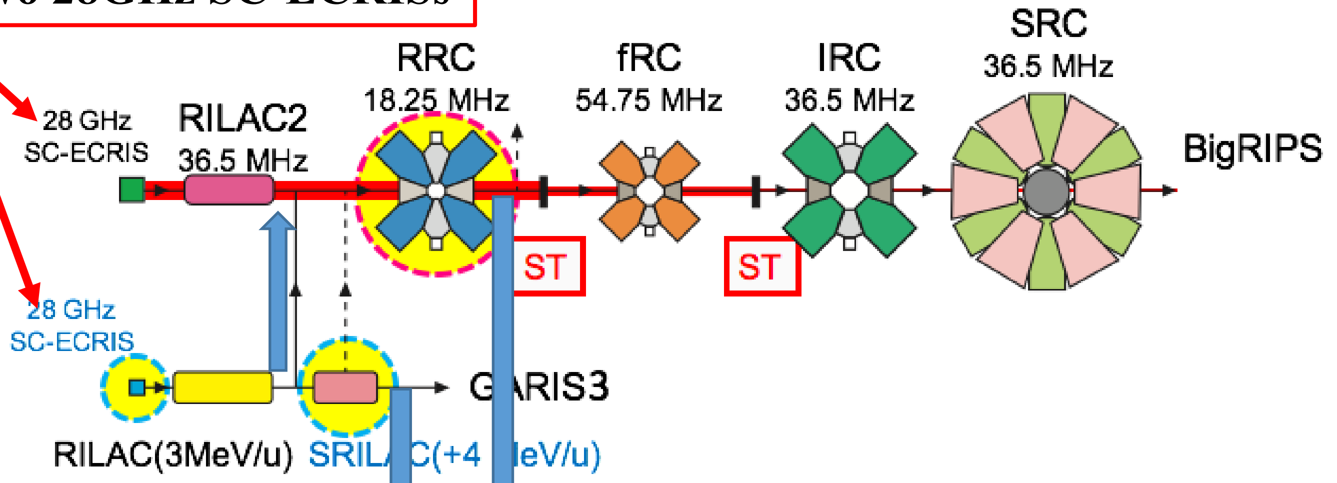
(I)Synthesizing new elements(Z=119,120….)

$^{48}Ca^{16+}$ for RIKEN RIBF

$^{50}Ti^{13+}$, $^{51}V^{13+}$, etc for synthesis of super-heavy elements

II. Synthesis of Super-heavy elements

Two 28GHz SC-ECRISs



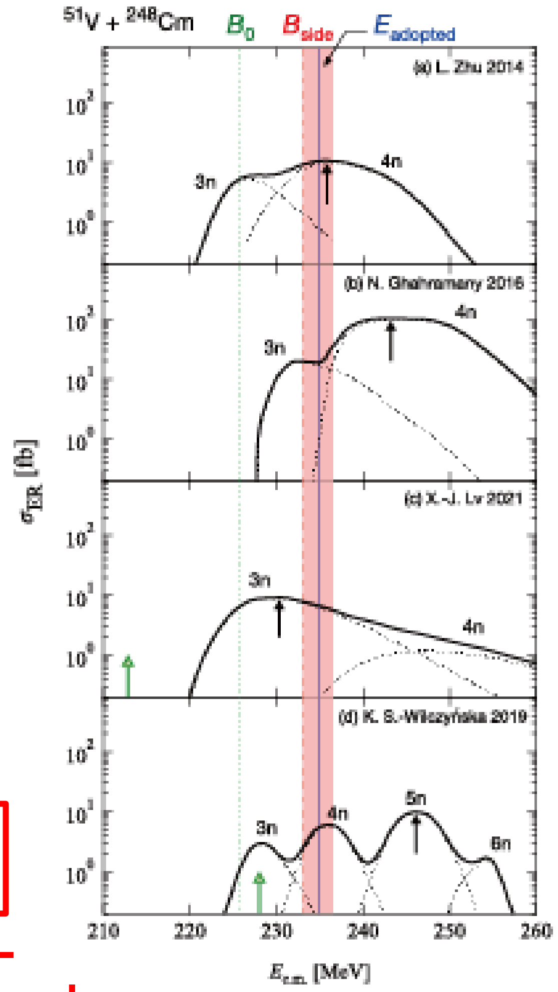
Metallic ion beam

(Ti, V, Cr…..)

(I)Synthesizing new elements(Z=119,120….)

$^{48}Ca^{16+}$ for RIKEN RIBF

$^{50}Ti^{13+}$, $^{51}V^{13+}$, etc for synthesis of super-heavy elements



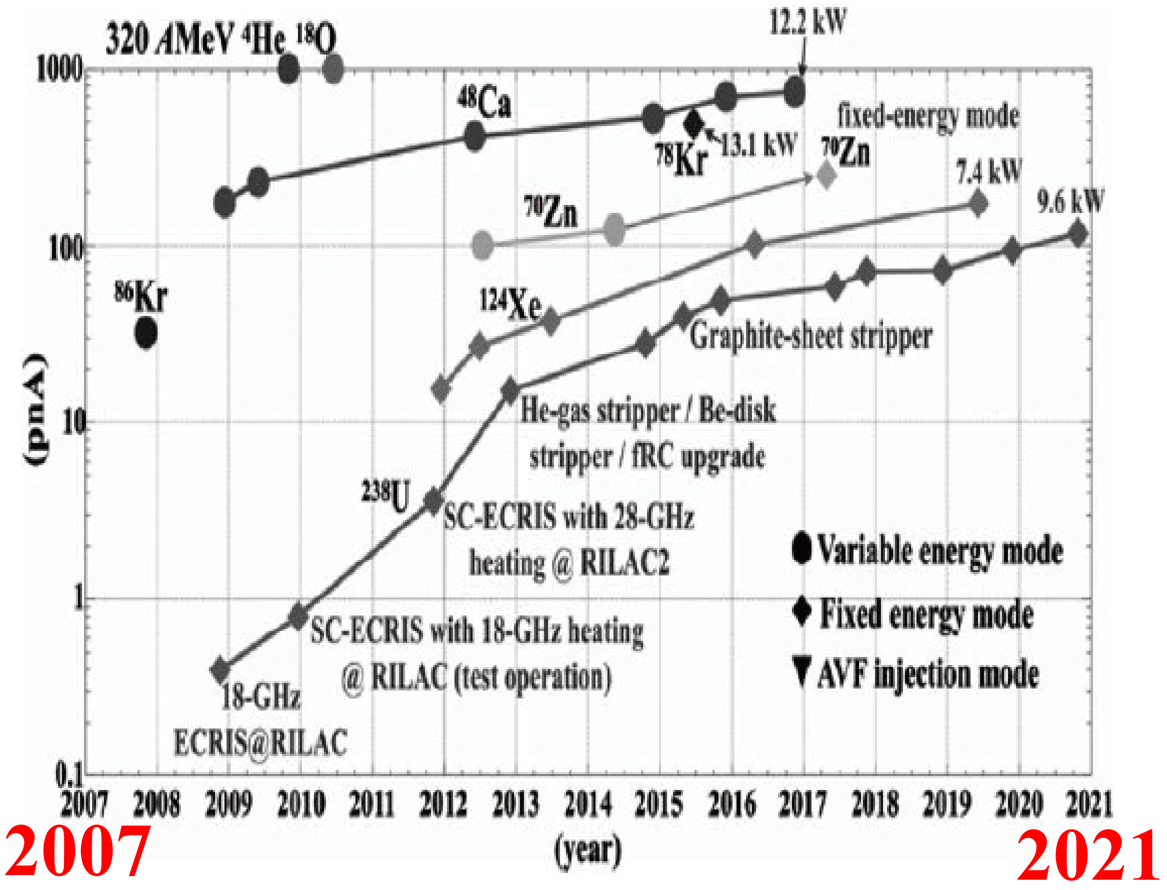
M. Tanaka et al, JPSJ 91, 084201(2022)

V+Cm→Z=119(Super heavy element)

Small production cross section

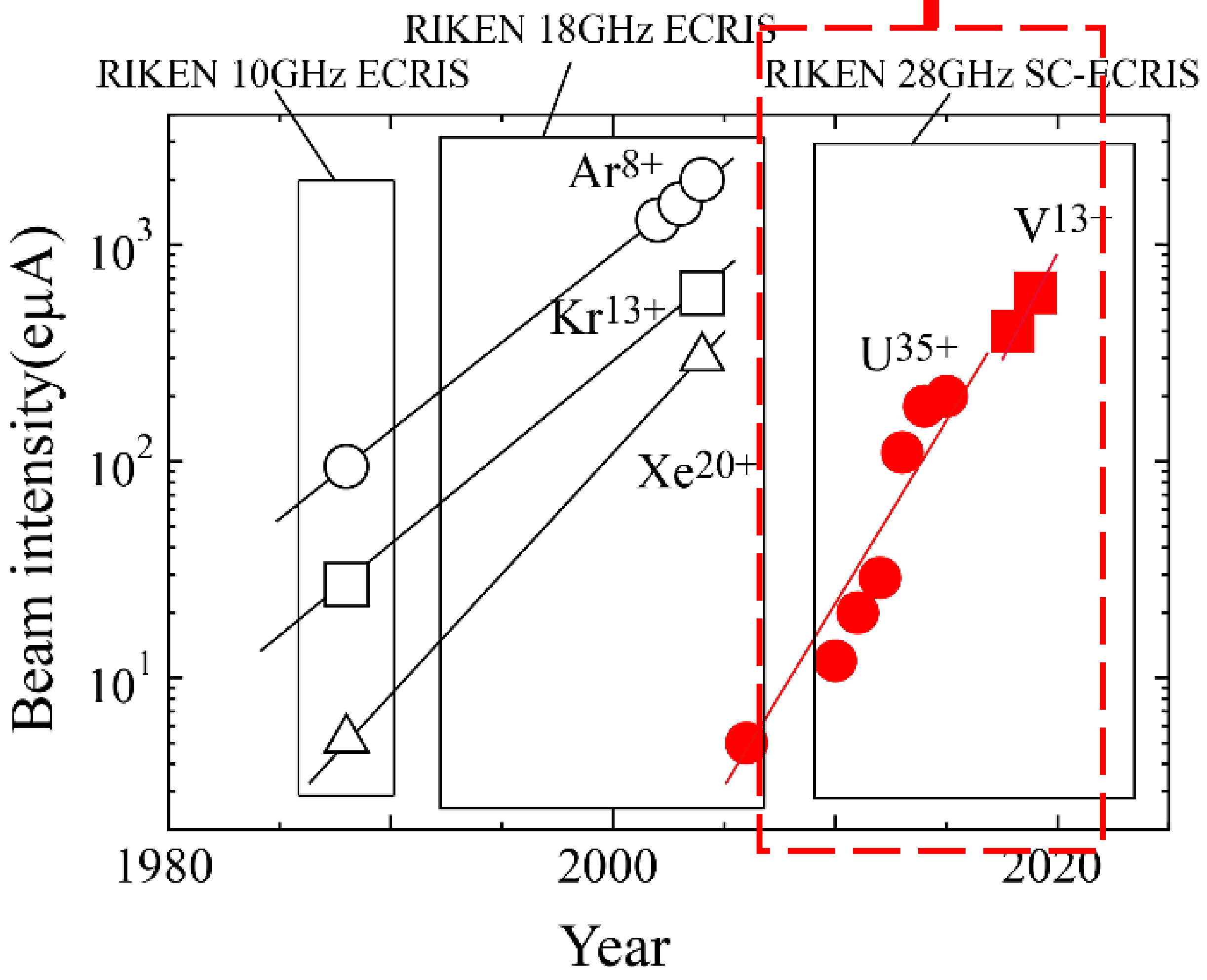
Need intense beam

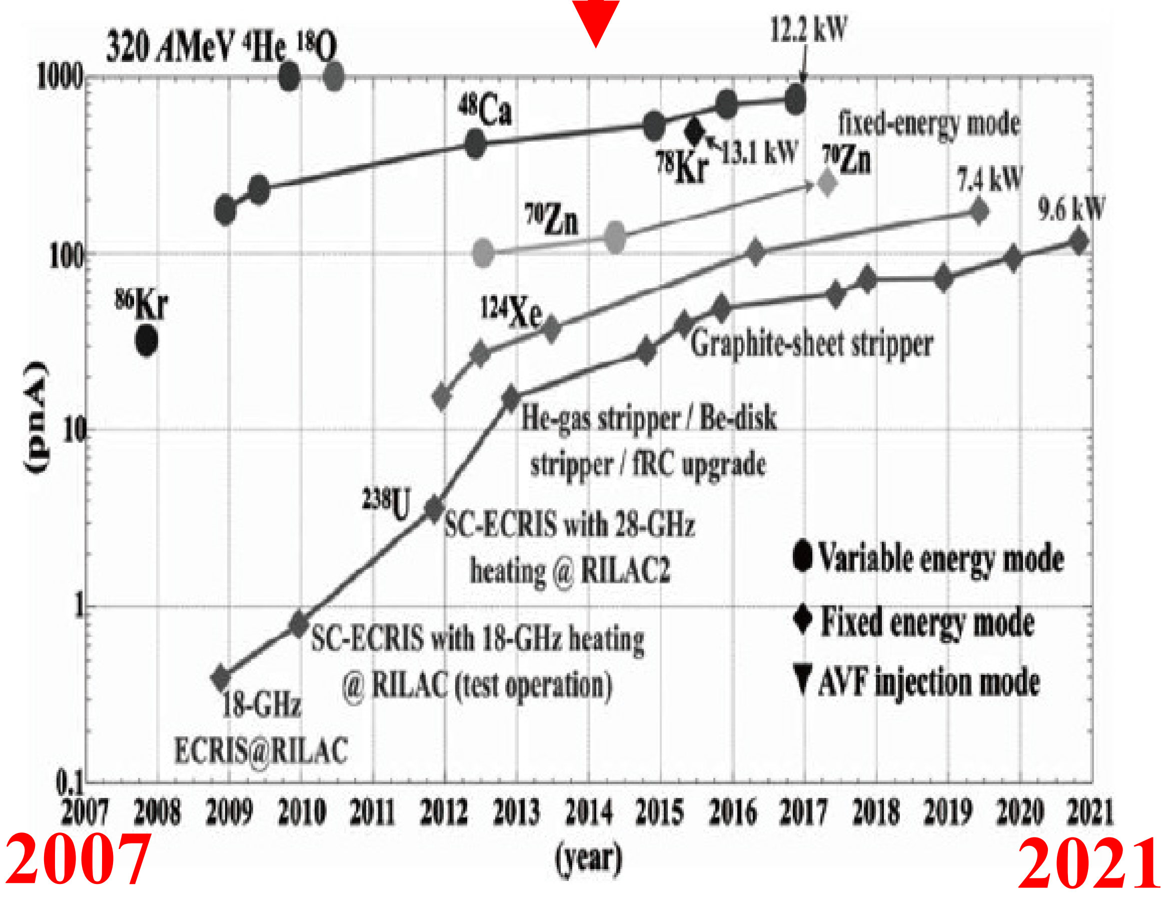
Brief history (time revolution of beam intensity)



N. Fukunishi, JPASJ 17 (2020)236

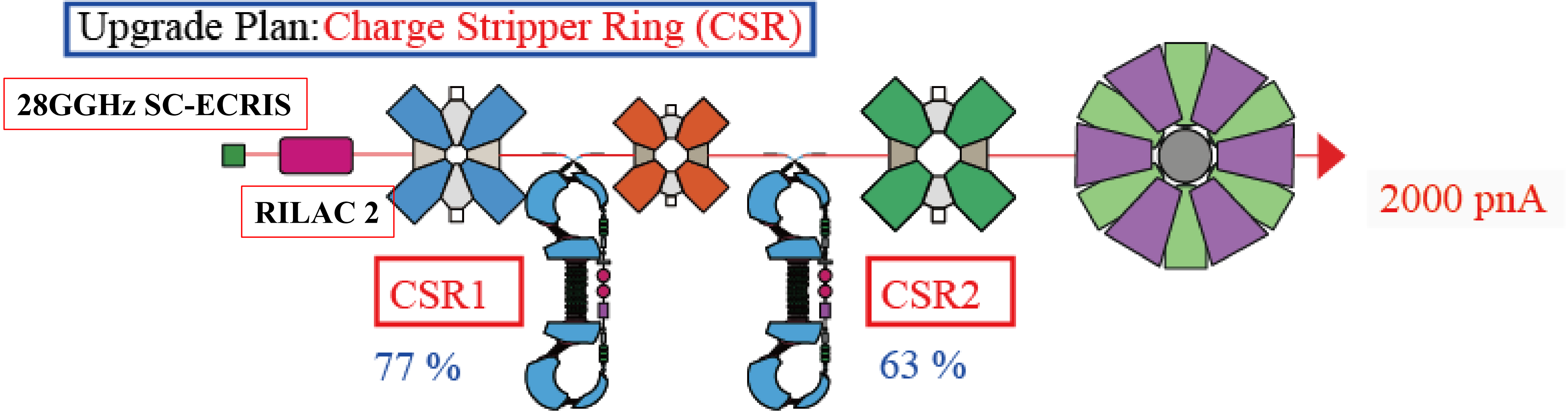
Brief history (time revolution of beam intensity)





N. Fukunishi, JPASJ 17 (2020)236

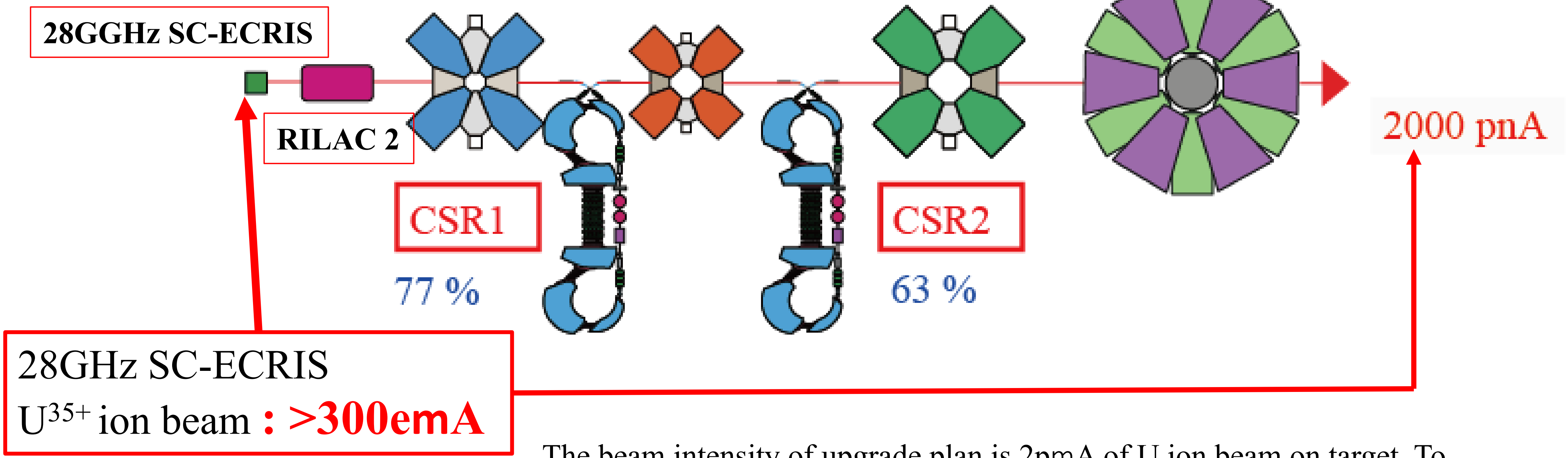
Upgrade plan (increase of the beam intensity)



O. Kamigaito et al, Cylotron 2019, Cape Town, South Africa, MOB01

Upgrade plan (increase of the beam intensity)

Upgrade Plan: Charge Stripper Ring (CSR)



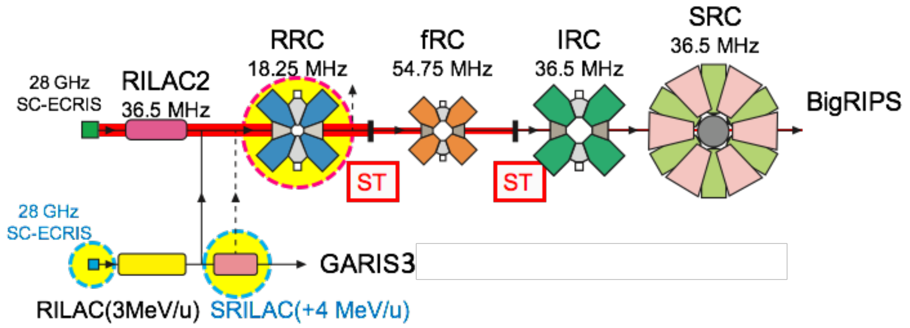
The beam intensity of upgrade plan is 2pmA of U ion beam on target. To obtain this bema intensity, we need to produce at least 300 emA of U^{35+} ion beam from the ion source.

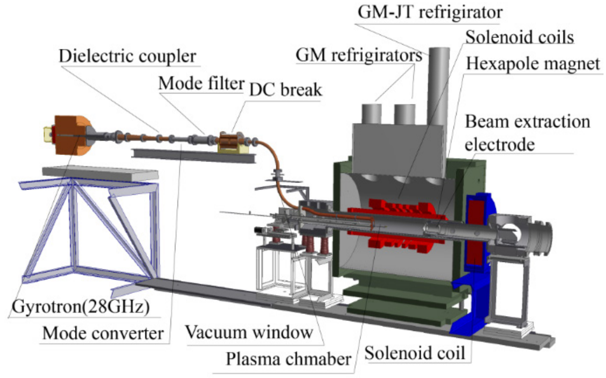
O. Kamigaito et al, Cylotron 2019, Cape Town, South Africa, MOB01

High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

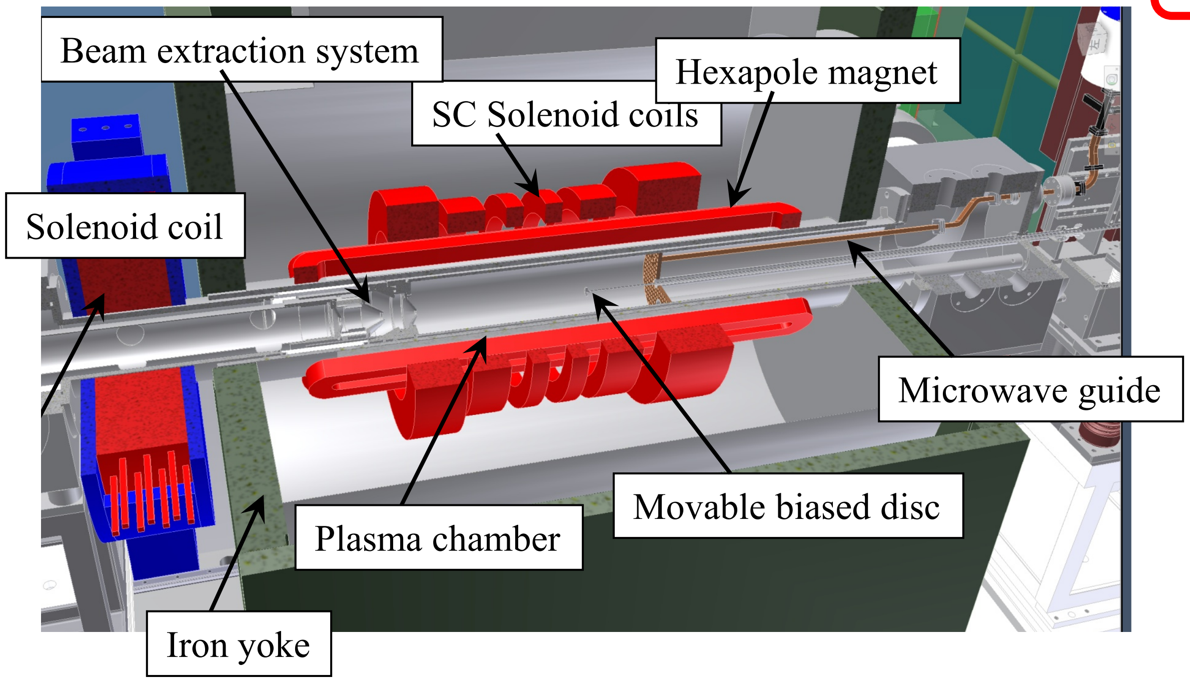
T. Nakagawa (Nishina center for accelerator based science, RIKEN)

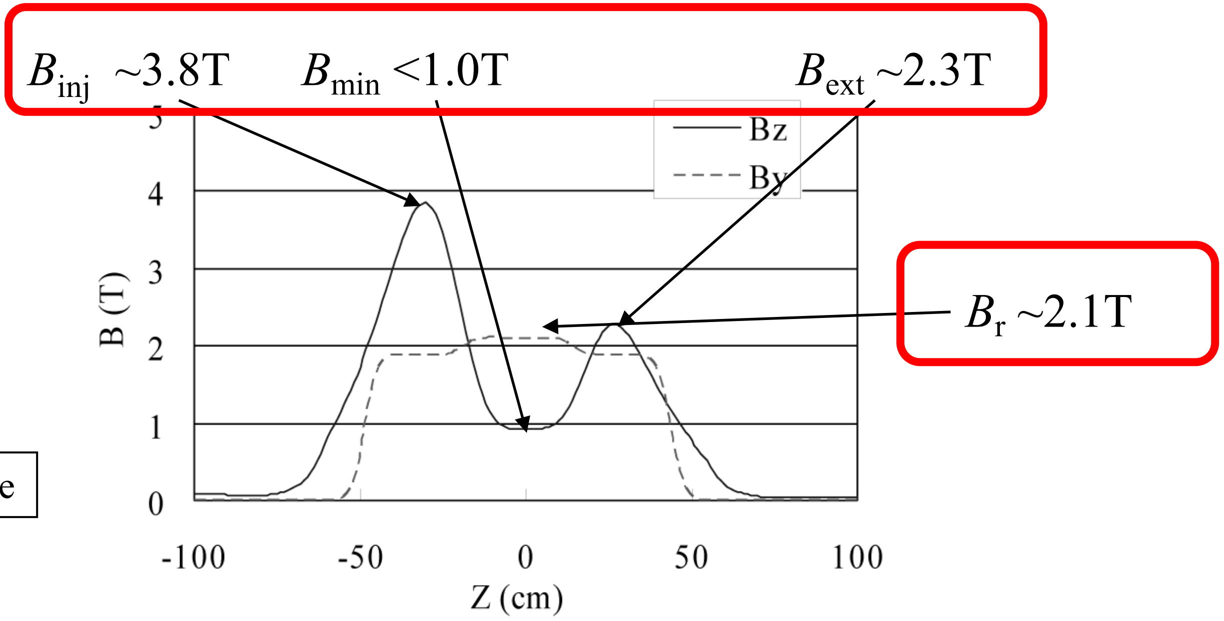
1. Introduction
    1. RIBF and SHE search exp.
    2. Brief history
    3. Upgrade plan
2. Ion source
    1. Structure
    2. High temp. oven
3. Production of U ion beam(RIBF)
    1. Beam intensity (Consumption rate of material)
    2. Emittance (Space charge effect)
4. Production of V ion beam(SHE)
    1. Beam intensity(consumption rate)
    2. Emittance and emittance slit
5. Conclusion and Next step





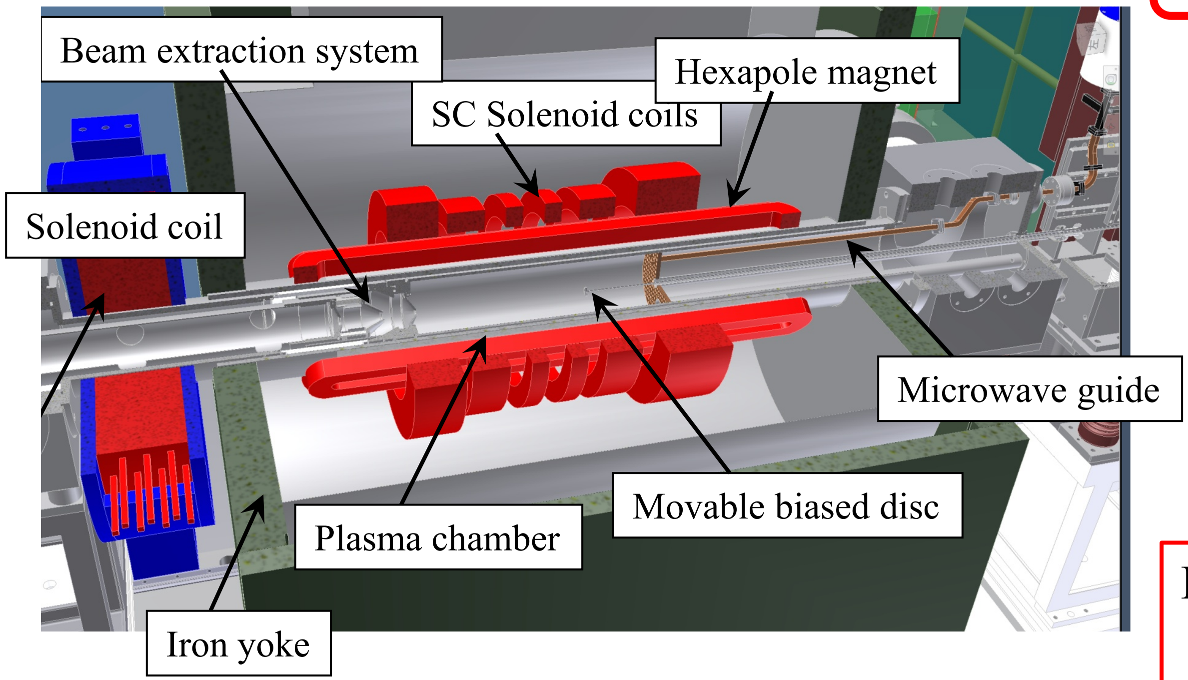
Magnetic field and plasma chamber

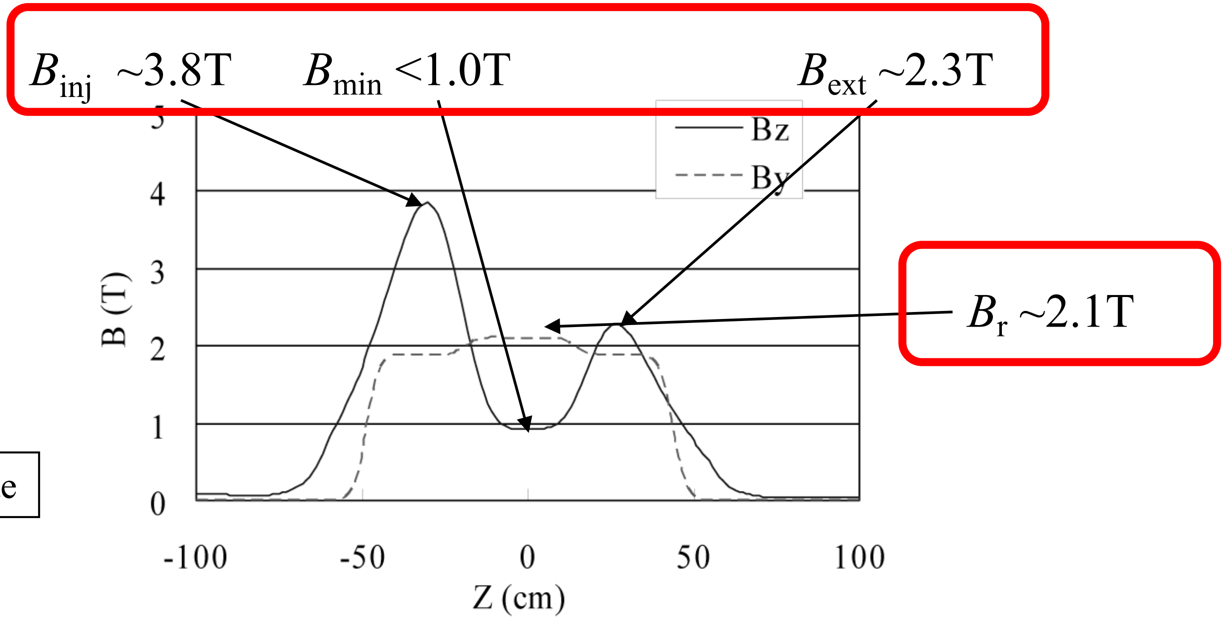




T. Nakagawa et al., RSI vol. 81, 02A320(1994).
G. D. Alton and D. N. Smithe, RSI vol. 65, 775(1994).

Magnetic field and plasma chamber

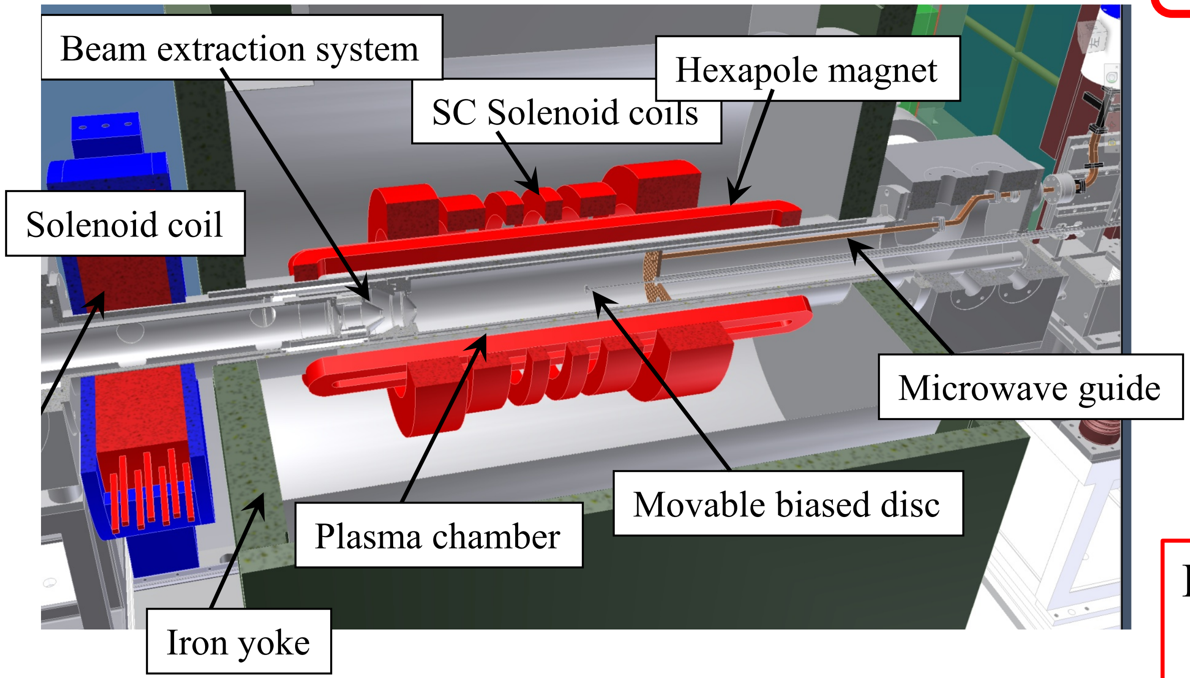


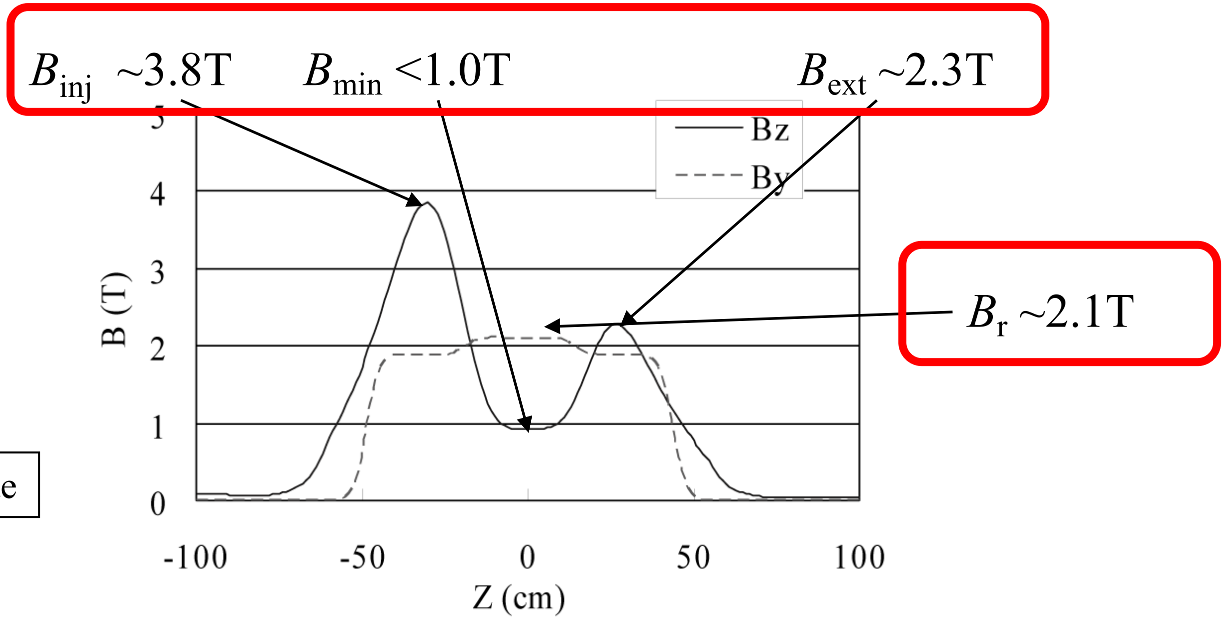


Plasma chamber :	15 cm (diameter)
	50 cm (length)
Vacuum:	2x1100l/sec turbo pumps
	(10^{-6}~10^{-5} Pa)
V_{ext}:	<22kV
RF(18+28GHz):	28GHz(10kWmax)
	18 GHz (~600W)

T. Nakagawa et al., RSI vol. 81, 02A320(1994).
G. D. Alton and D. N. Smithe, RSI vol. 65, 775(1994).

Magnetic field and plasma chamber





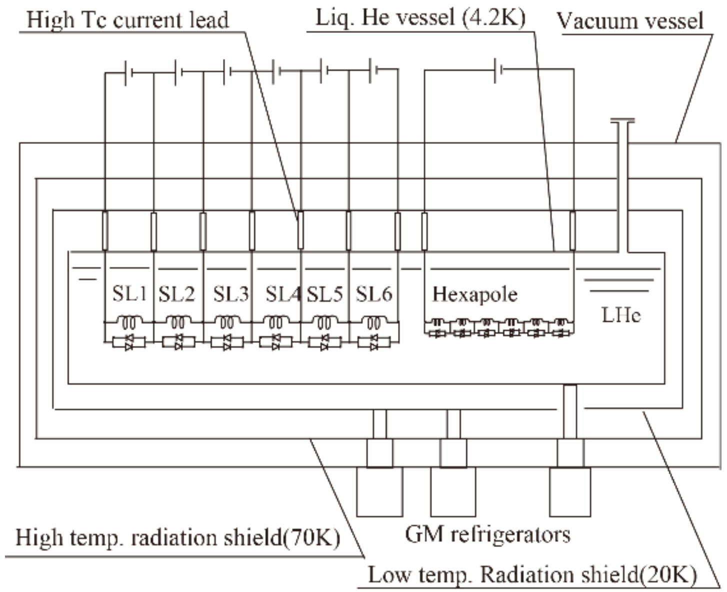
1. Movable biased disc
2. Movable extraction electrode
3. Solenoid coil (focusing element)

Plasma chamber :	15 cm (diameter)
	50 cm (length)
Vacuum:	2x1100l/sec turbo pumps
	(10^{-6}~10^{-5} Pa)
V_{ext}:	<22kV
RF(18+28GHz):	28GHz(10kWmax)
	18 GHz (~600W)

T. Nakagawa et al., RSI vol. 81, 02A320(1994).
G. D. Alton and D. N. Smithe, RSI vol. 65, 775(1994).

SC-magnet and cryostat

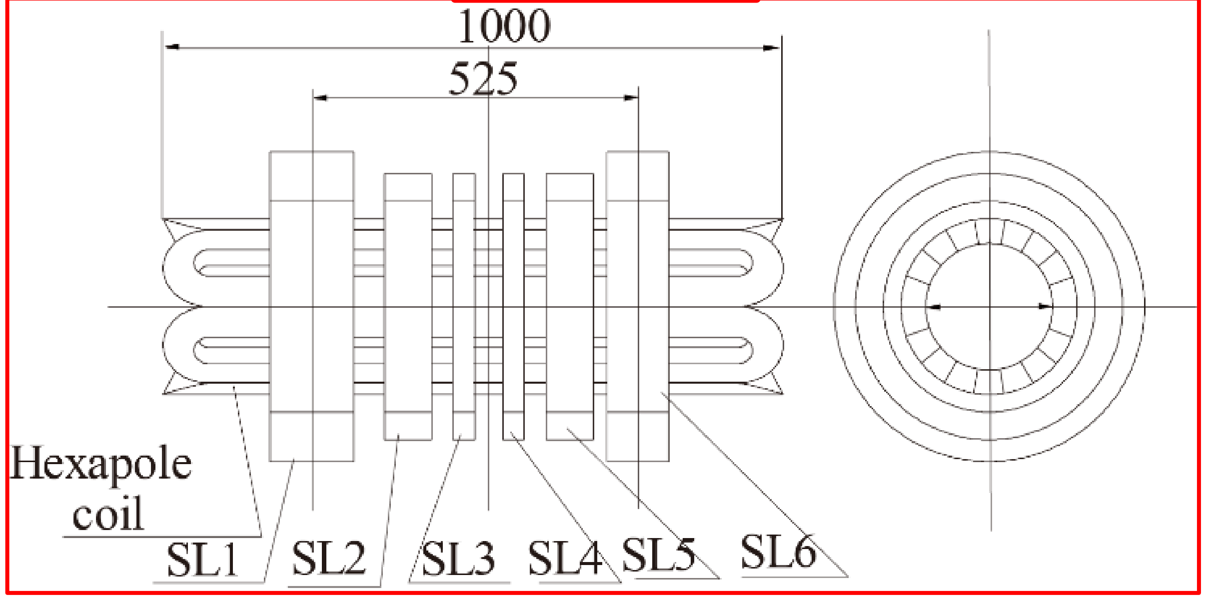
Cryostat



(W)

Item	Helium vessel	Low temp. radiation shield	High temp. radiation shield
Design temp.	4.2 K	20 K	70K
Radiation	0.005	5.5	40
Conduction			
Support	0.005	0.3	4
Port	0.06	1.5	20
Current lead	0.07	10	64
Total heat load	0.14	17.3	128

SC-Magnet



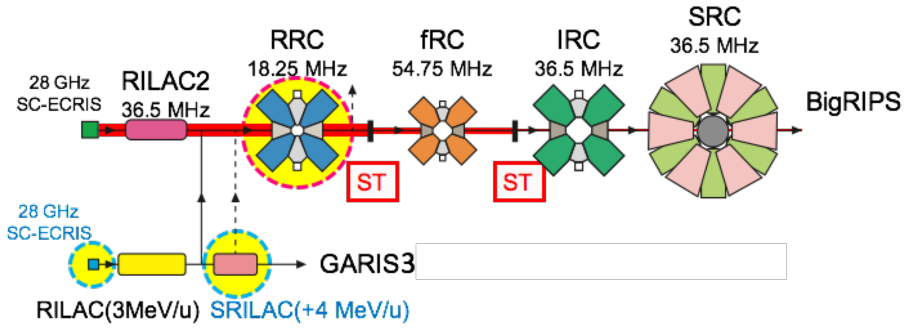
Against the X-ray heat load produced in plasma

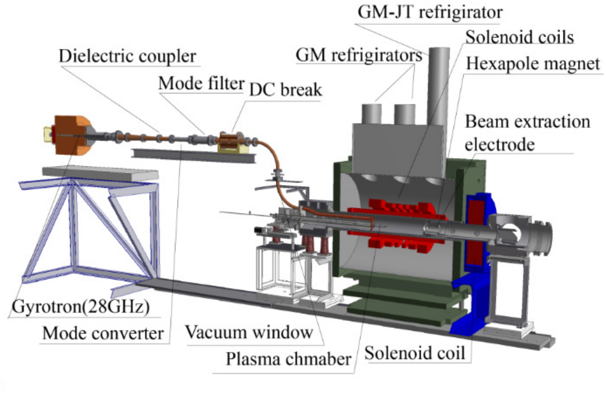
RILAC2 and RILAC:GM (~1.2 W at 4.2 K)
Additional ref.:
RILAC 2:GM-JT ref. (~4 W at 4.4 K)x2 **~8W**
RILAC: GM-JT ref. (~4W at 4.2K) **~4W**

High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

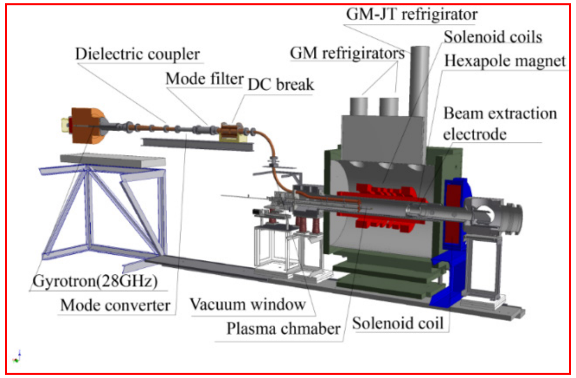
T. Nakagawa (Nishina center for accelerator based science, RIKEN)

1. Introduction
    1. RIBF and SHE search exp.
    2. Brief history
    3. Upgrade plan
2. **Ion source**
    1. Structure
    2. **High temp. oven**
3. Production of U ion beam(RIBF)
    1. Beam intensity (Consumption rate of material)
    2. Emittance (Space charge effect)
4. Production of V ion beam(SHE)
    1. Beam intensity(consumption rate)
    2. Emittance and emittance slit
5. Conclusion and Next step





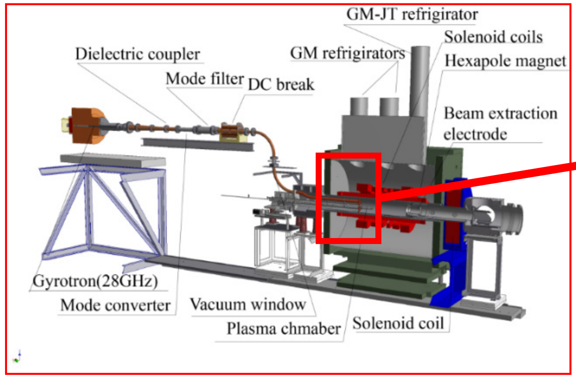
High temperature oven



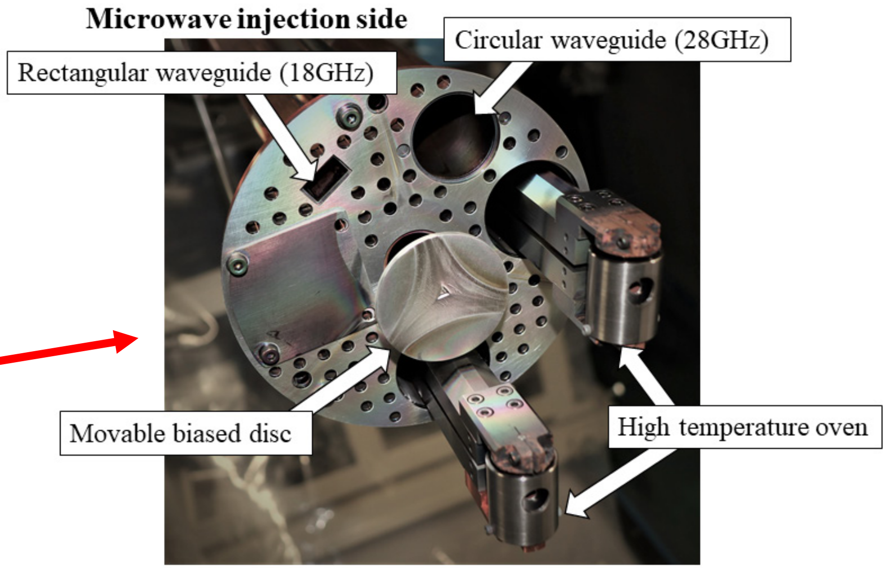
RIKEN 28 GHz SC-ECRIS

For production of the V and U vapour, we used the high temperature oven. To obtain enough temperature for evaporating the materials, the detailed simulation was carefully done and successfully obtained high enough temperature to produce the vapour.

High temperature oven



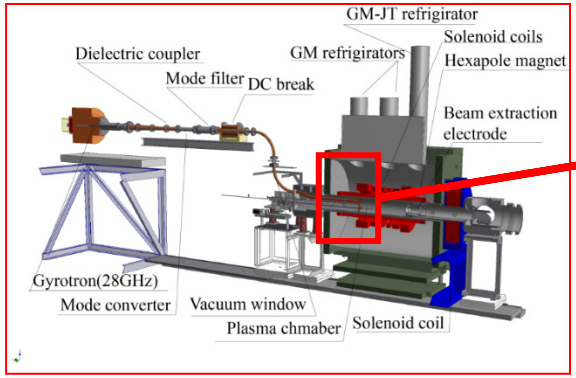
RIKEN 28 GHz SC-ECRIS



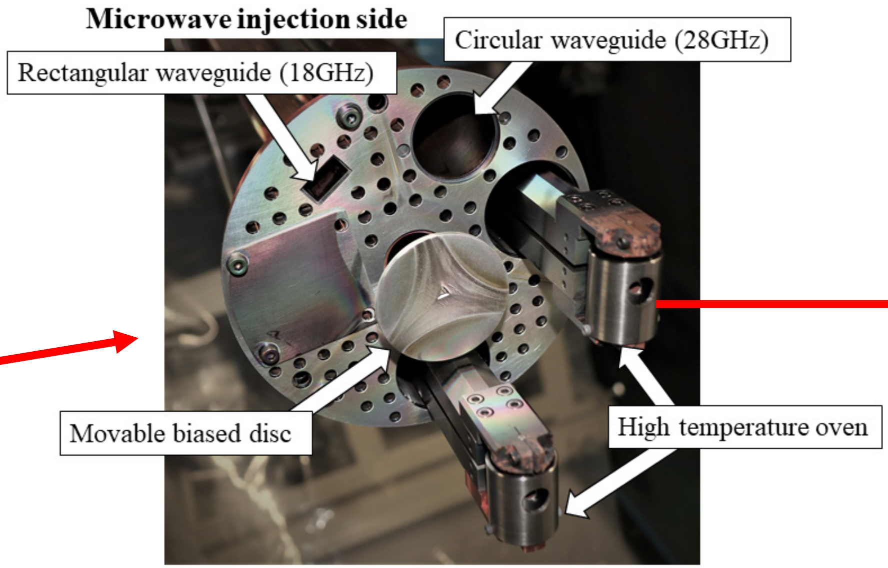
RF injection side

For production of the V and U vapour, we used the high temperature oven. To obtain enough temperature for evaporating the materials, the detailed simulation was carefully done and successfully obtained high enough temperature to produce the vapour.

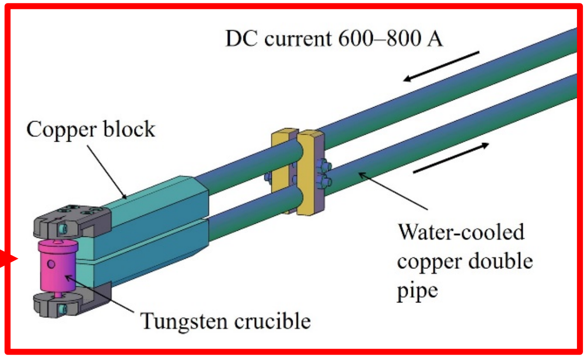
High temperature oven



RIKEN 28 GHz SC-ECRIS



RF injection side

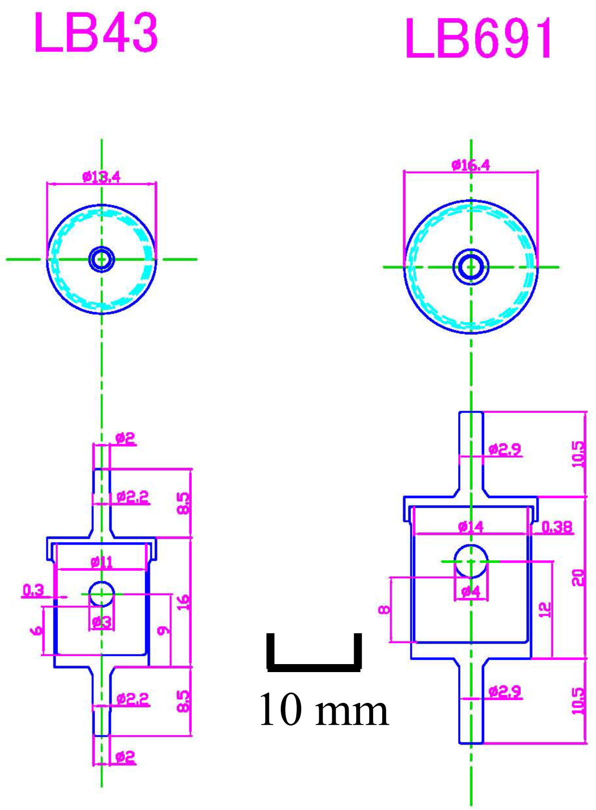


High temperature oven

For production of the V and U vapour, we used the high temperature oven. To obtain enough temperature for evaporating the materials, the detailed simulation was carefully done and successfully obtained high enough temperature to produce the vapour.

Crucible (High temperature oven)

Old crucible　　New crucible

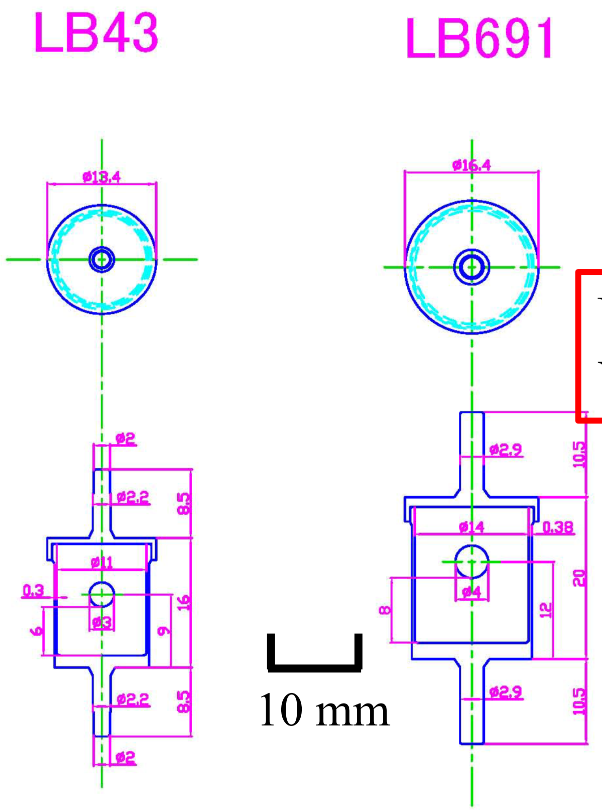


Old crucible : J. Ohnishi et al, Rev. Sci. Instrum. 87, 02A709 (2016)
New crucible: J. Ohnishi et al, in the proceedings of ECRIS2018

For long term operation, we fabricated new crucible, which has almost two times larger volume than the old one.

Crucible (High temperature oven)

Old crucible New crucible



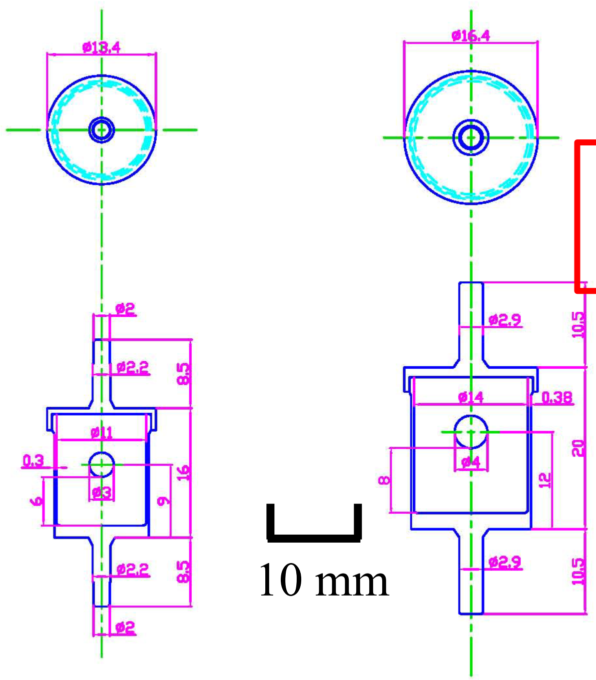
UO_2 ~4gr
V ~2gr

For long term operation, we fabricated new crucible, which has almost two times larger volume than the old one.

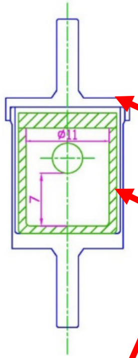
Old crucible : J. Ohnishi et al, Rev. Sci. Instrum. 87, 02A709 (2016)
New crucible: J. Ohnishi et al, in the proceedings of ECRIS2018

Crucible (High temperature oven)

Old crucible	New crucible
LB43	LB691

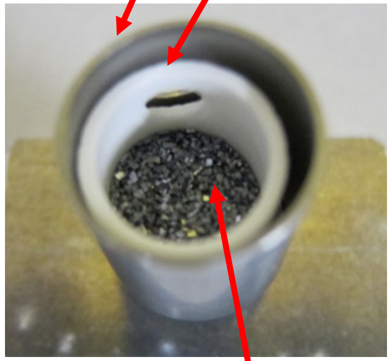


UO_2 ~4gr
V ~2gr



W crucible

Ceramic crucible
(Y_2O_3 or Al_2O_3)



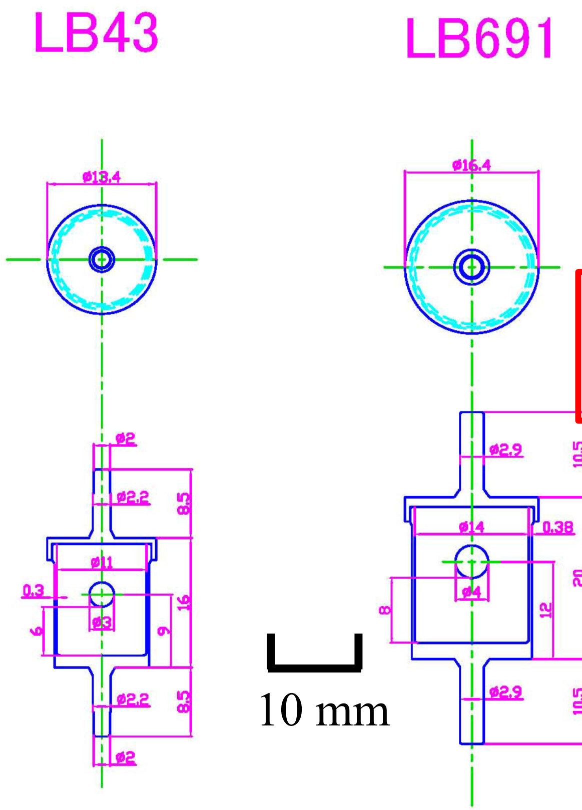
Vanadium powder

For long term operation, we fabricated new crucible, which has almost two times larger volume than the old one.

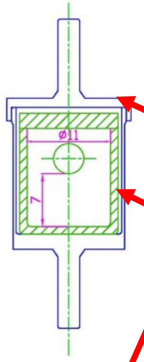
Old crucible : J. Ohnishi et al, Rev. Sci. Instrum. 87, 02A709 (2016)
New crucible: J. Ohnishi et al, in the proceedings of ECRIS2018

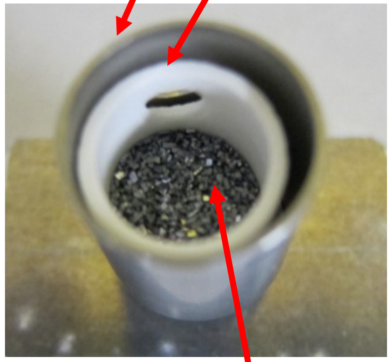
Crucible (High temperature oven)

Old crucible New crucible



UO_2 ~4gr
V ~2gr

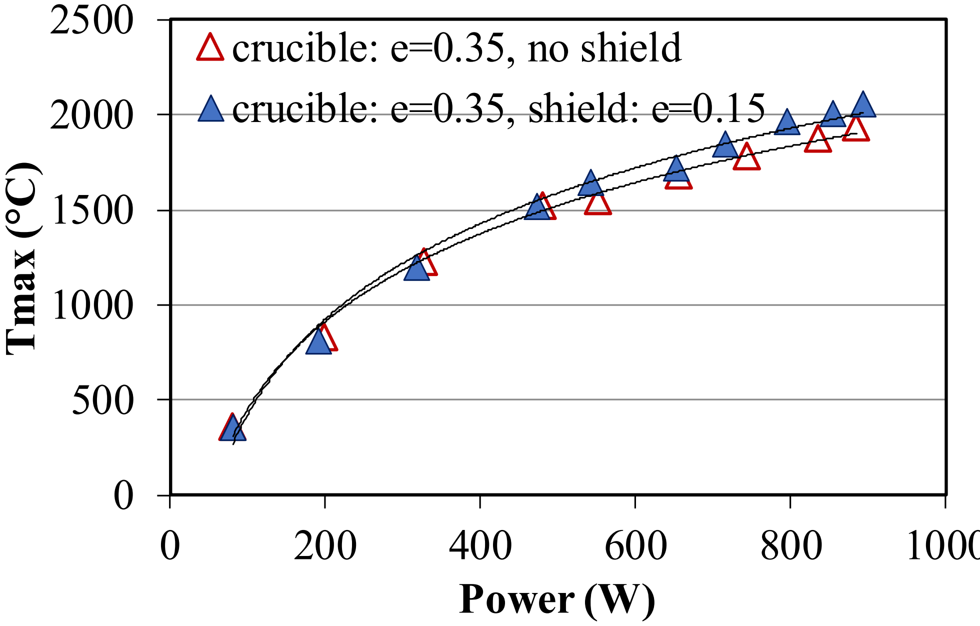




W crucible

Ceramic crucible (Y_2O_3 or Al_2O_3)

Vanadium powder



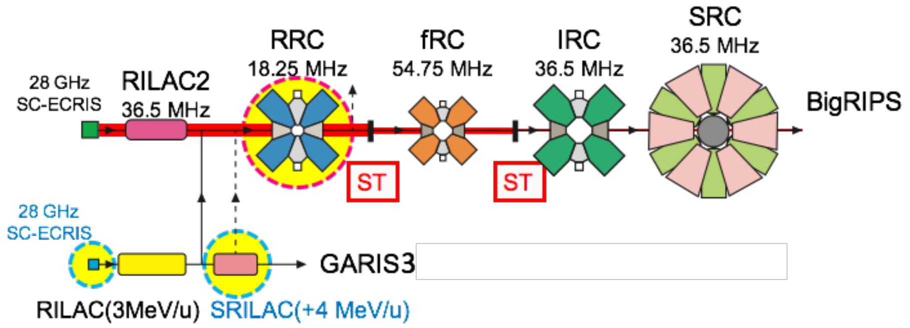
For long term operation, we fabricated new crucible, which has almost two times larger volume than the old one.

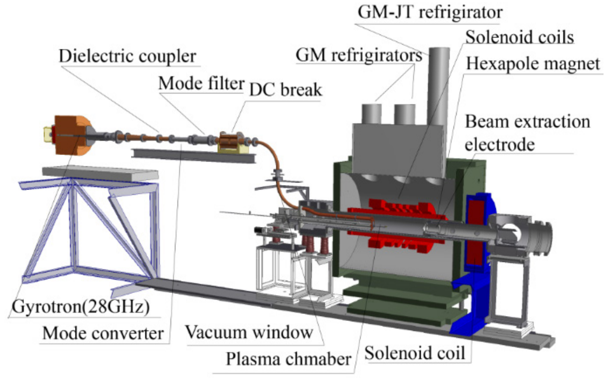
Old crucible : J. Ohnishi et al, Rev. Sci. Instrum. 87, 02A709 (2016)
New crucible: J. Ohnishi et al, in the proceedings of ECRIS2018

High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

T. Nakagawa (Nishina center for accelerator based science, RIKEN)

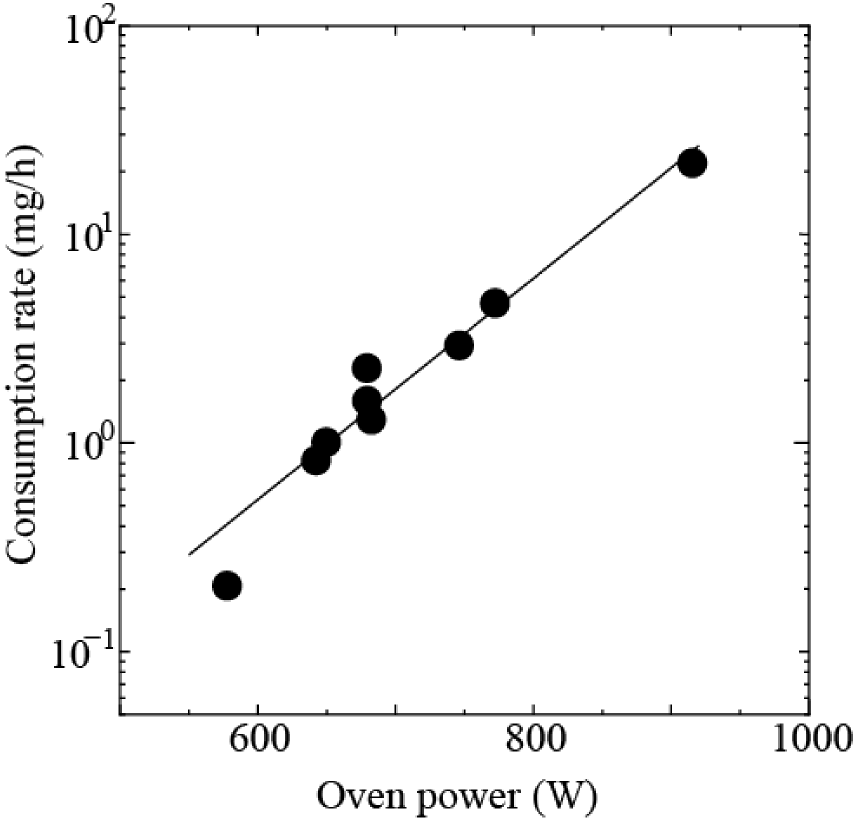
1. Introduction
    1. RIBF and SHE search exp.
    2. Brief history
    3. Upgrade plan
2. Ion source
    1. Structure
    2. High temp. oven
3. **Production of U ion beam(RIBF)**
    1. **Beam intensity (Consumption rate of material)**
    2. Emittance (Space charge effect)
4. Production of V ion beam(SHE)
    1. Beam intensity(consumption rate)
    2. Emittance and emittance slit
5. Conclusion and Next step



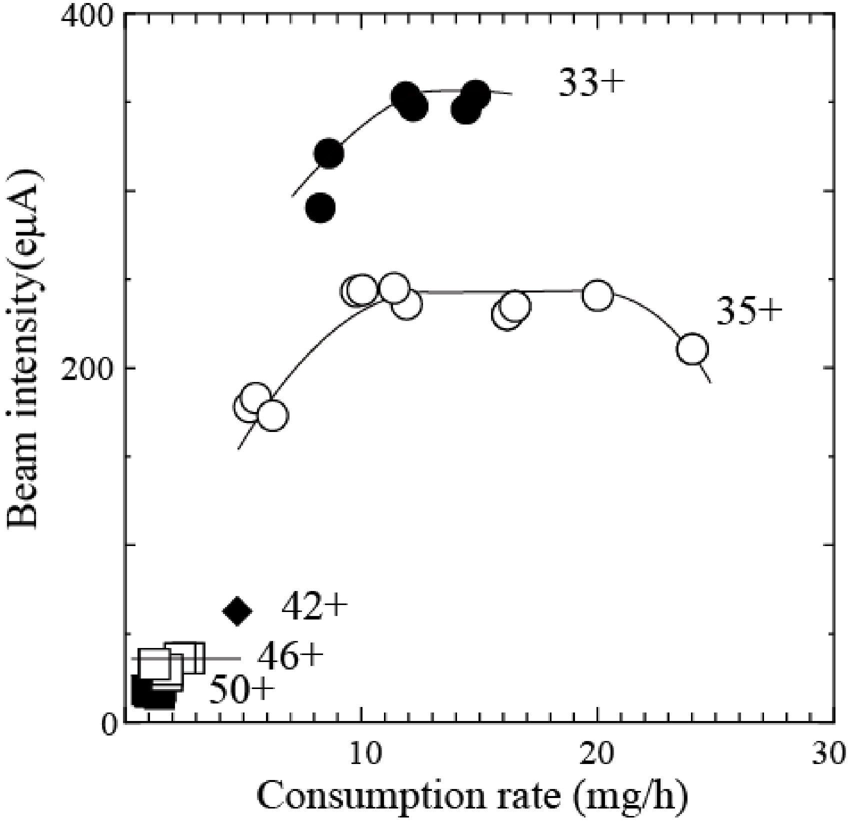


Consumption rate

Consumption rate vs. Oven power



Beam intensity as a function of consumption rate at ~3 kW

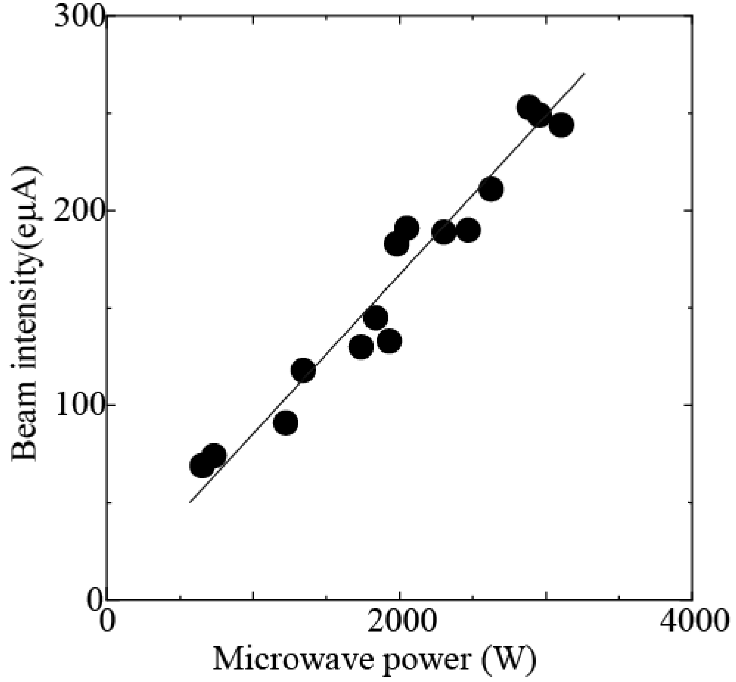


The consumption rate increases exponentially with increasing the oven power from 600 to 900 W

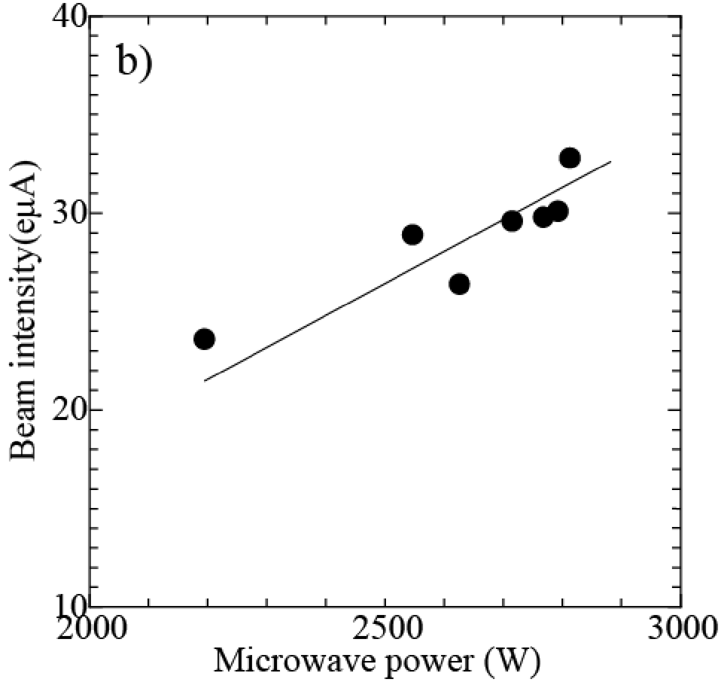
The beam intensity of U^{35+} increases with increasing the consumption rate up to ~10 mg/h and than saturated at ~3 kW of microwave power. The beam intensity decreases with increasing the consumption rate above 20 mg/h

Beam intensity of highly charged U ions as a function of microwave power

U^{35+}



U^{46+}



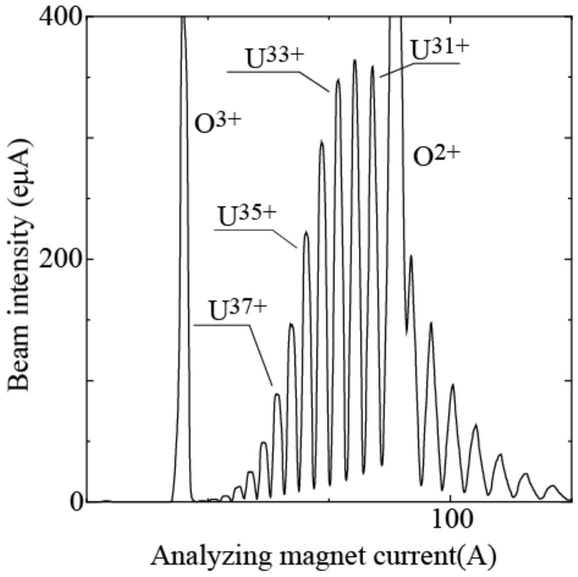
The beam intensity of highly charged U ions linearly increases with increasing the microwave power up to 3.5 kW. It is noted that the beam intensity is not saturated at highest power in this experiments.

We have possibility to further increase the beam intensity with higher microwave power.

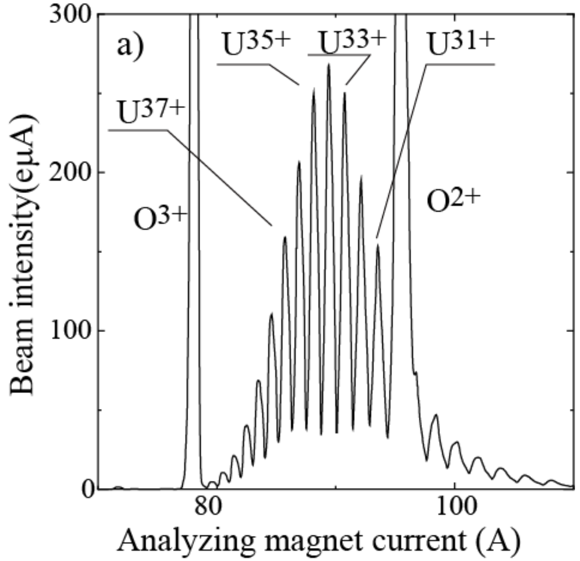
Charge state distribution

Microwave power ~3 kW

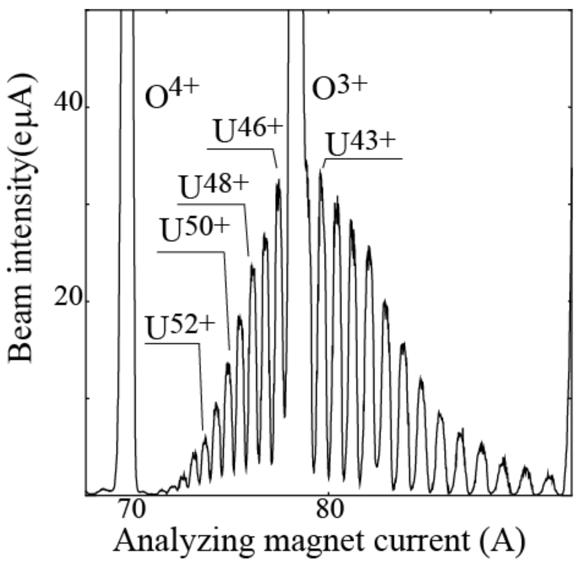
U^{33+}



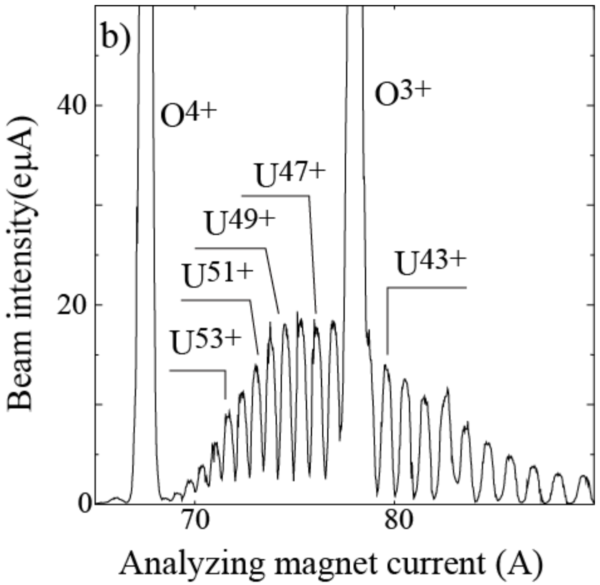
U^{35+}



U^{46+}

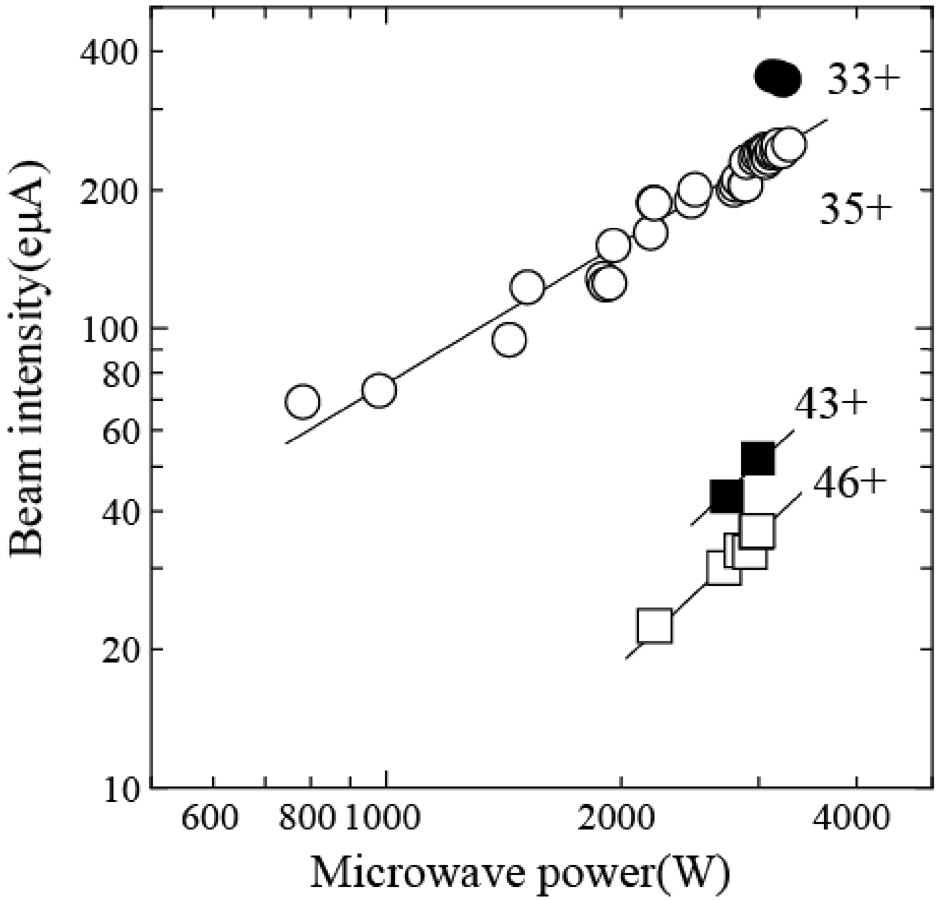


U^{50+}



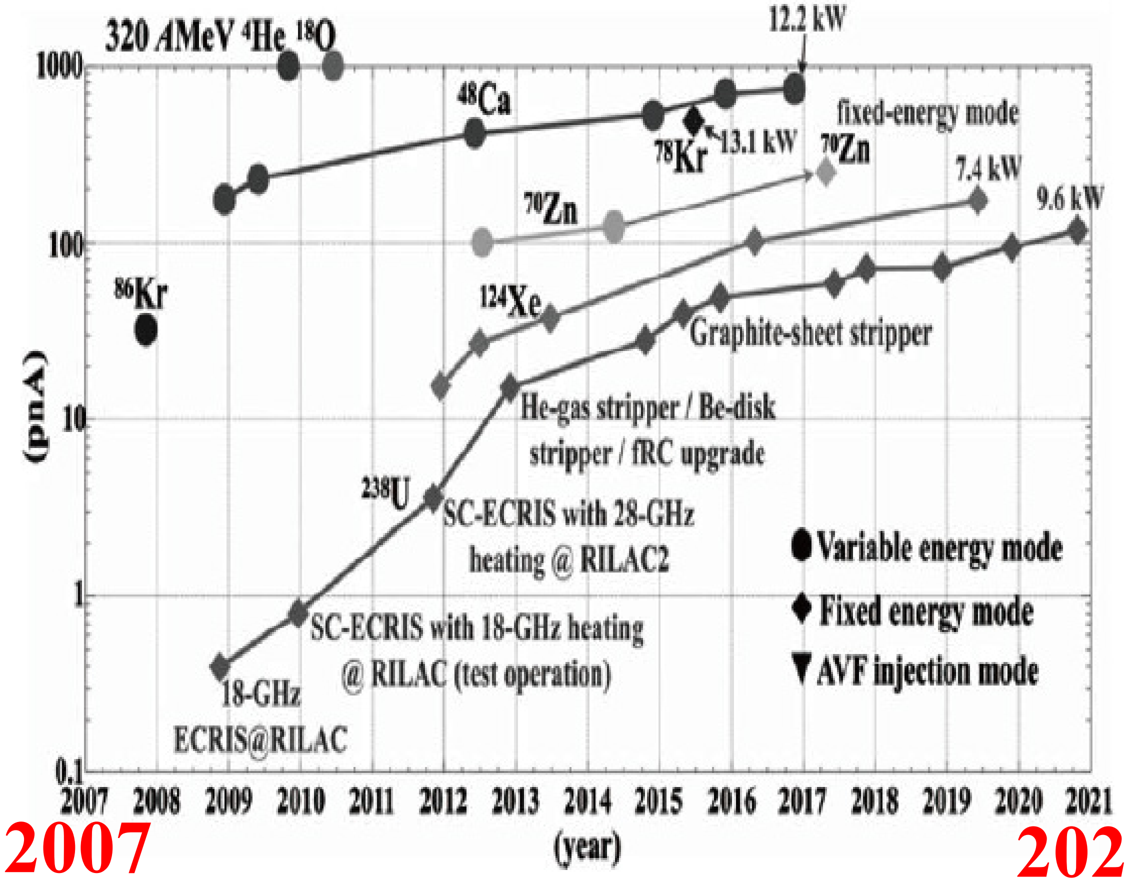
Microwave power dependence

Beam intensity of highly charged U ions as a function of microwave power



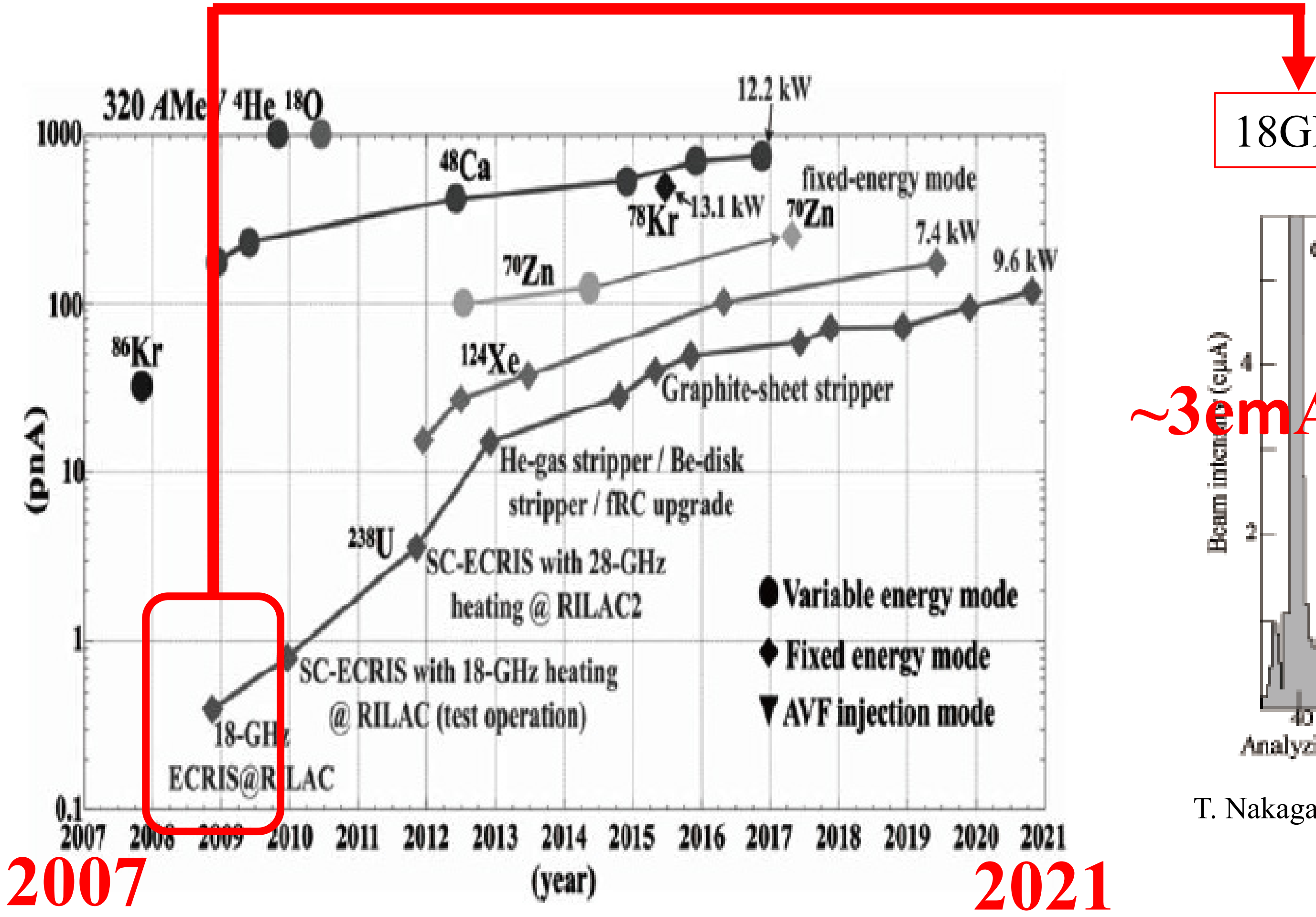
Charge state	I (eμA)	Microwave power (W)	Consumption rate (mg/h)
33	346	3240	12.2
35	250	3170	10.9
42	62.6	3000	4.74
46	36.2	2990	2.68
50	20.1	2980	1.48
54	10.4	3000	0.78

Time evolution of the U^{35+} ion beam intensity

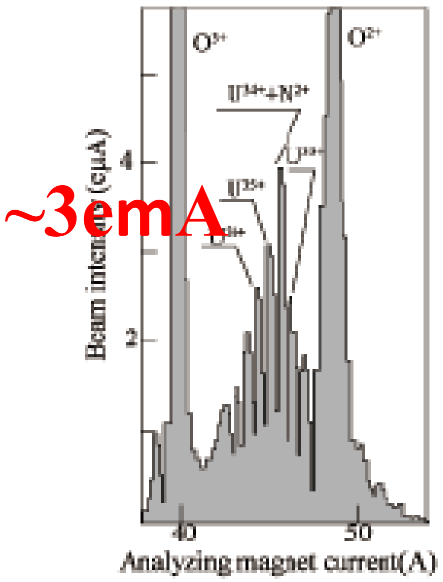


2007 **2021**

Time evolution of the U^{35+} ion beam intensity

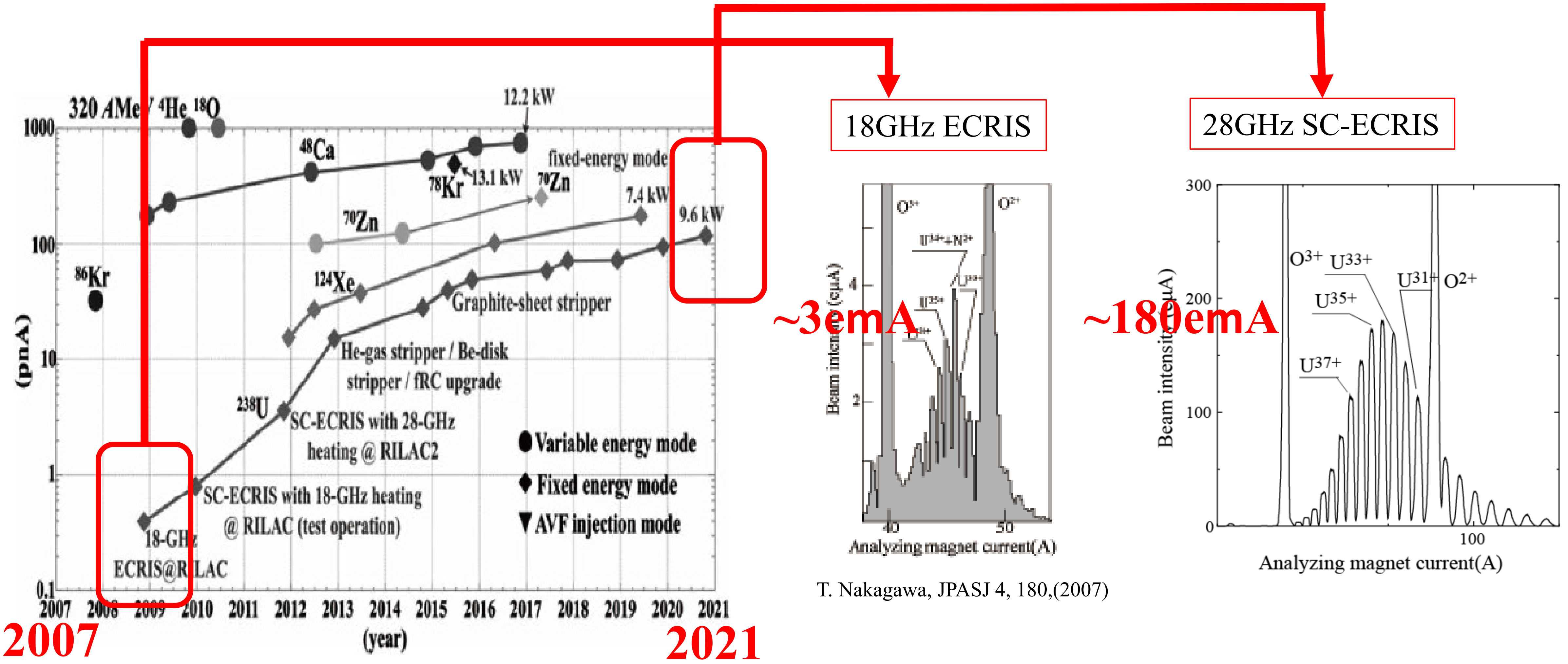


18GHz ECRIS



T. Nakagawa, JPASJ 4, 180,(2007)

Time evolution of the U^{35+} ion beam intensity

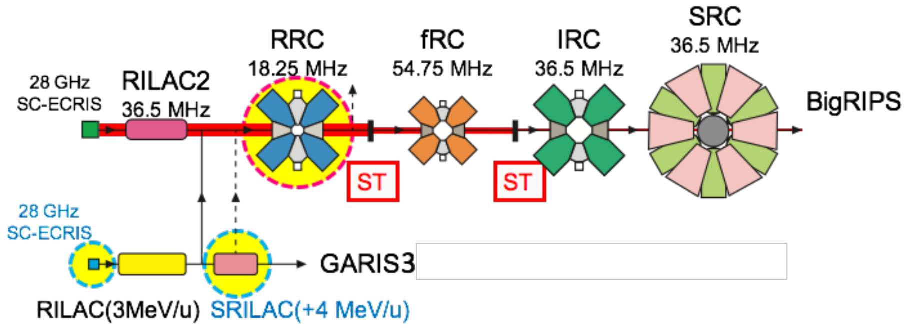


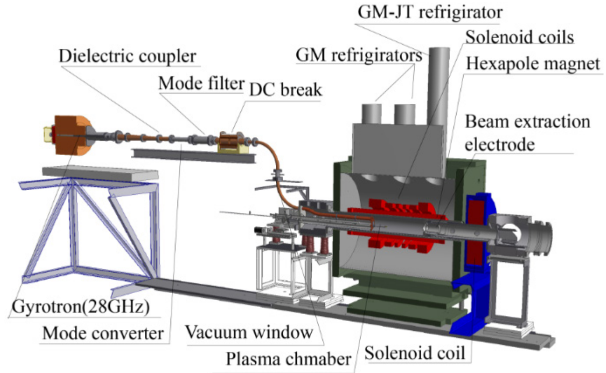
T. Nakagawa, JPASJ 4, 180,(2007)

High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

T. Nakagawa (Nishina center for accelerator based science, RIKEN)

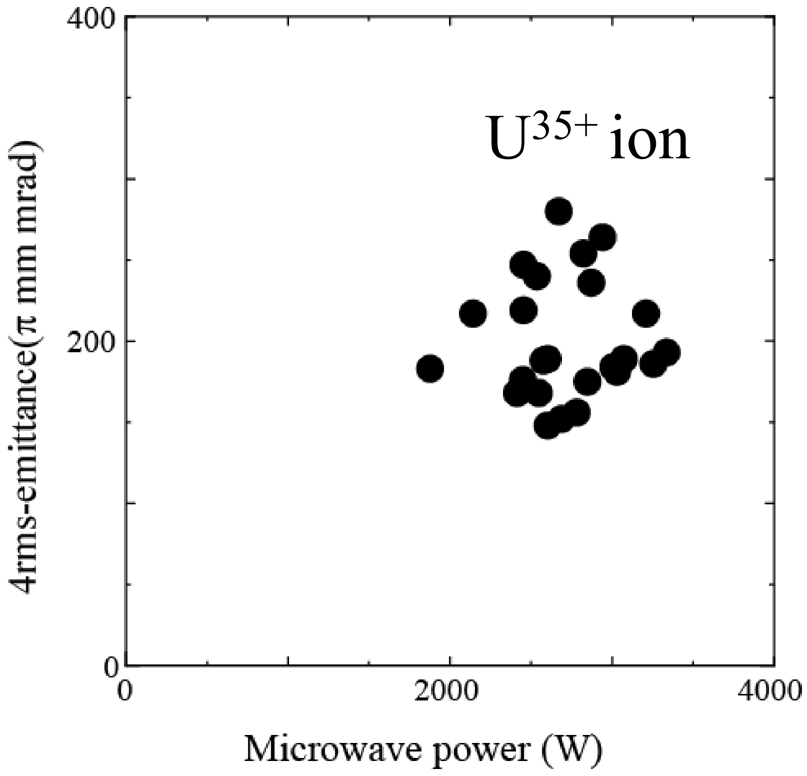
1. Introduction
    1. RIBF and SHE search exp.
    2. Brief history
    3. Upgrade plan
2. Ion source
    1. Structure
    2. High temp. oven
3. **Production of U ion beam(RIBF)**
    1. Beam intensity (Consumption rate of material)
    2. **Emittance (Space charge effect)**
4. Production of V ion beam(SHE)
    1. Beam intensity(consumption rate)
    2. Emittance and emittance slit
5. Conclusion and Next step





Emittance

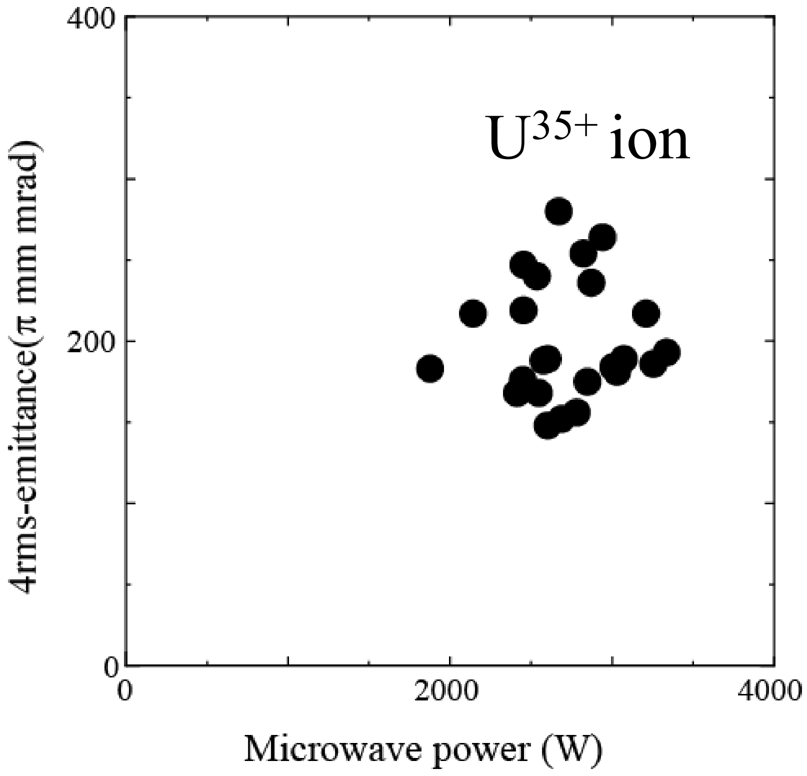
Emittance vs. microwave power



It seems that the no relevance between the emittance and the microwave power

Emittance

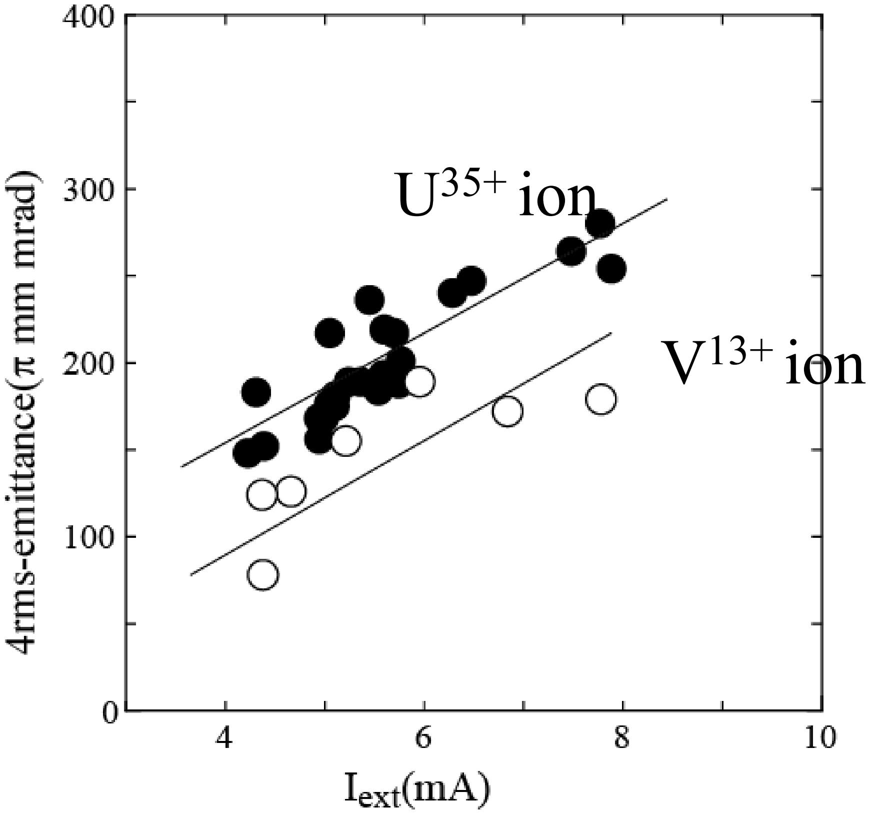
Emittance vs. microwave power



It seems that the no relevance between the emittance and the microwave power

The emittance becomes larger with increasing the extraction current
(space charge effect?)

Emittance vs. extraction current



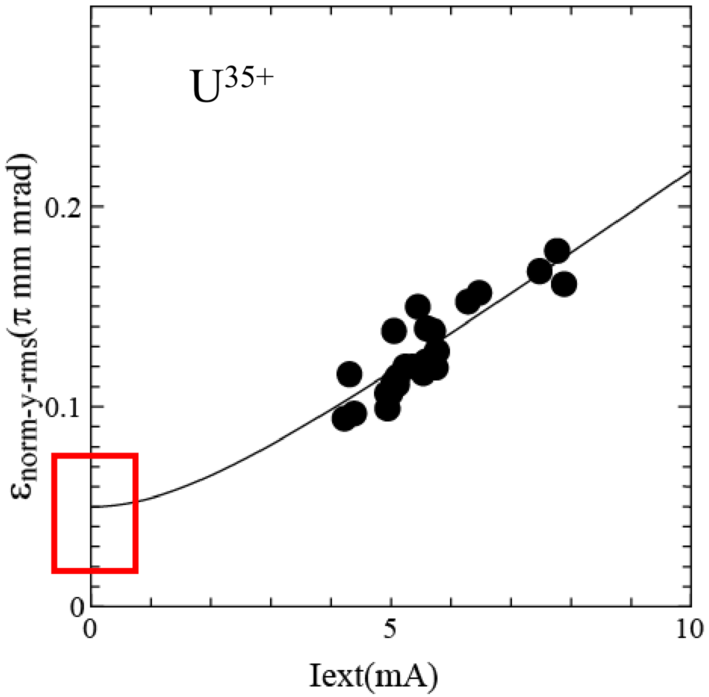
Space charge effect

$$\varepsilon_{eff}=\sqrt{\varepsilon^2+K\left(\frac{I_z}{I_c(\beta\gamma)}\right)^2}$$

Y. K. Batygin, NIMA **539**, 455 (2005).

$$\varepsilon_{eff}=\sqrt{\varepsilon^2+CI_{ext}^2}$$

Ion source emittance



Space charge effect

U^{35+} emittance <0.1 p mm mrad ?

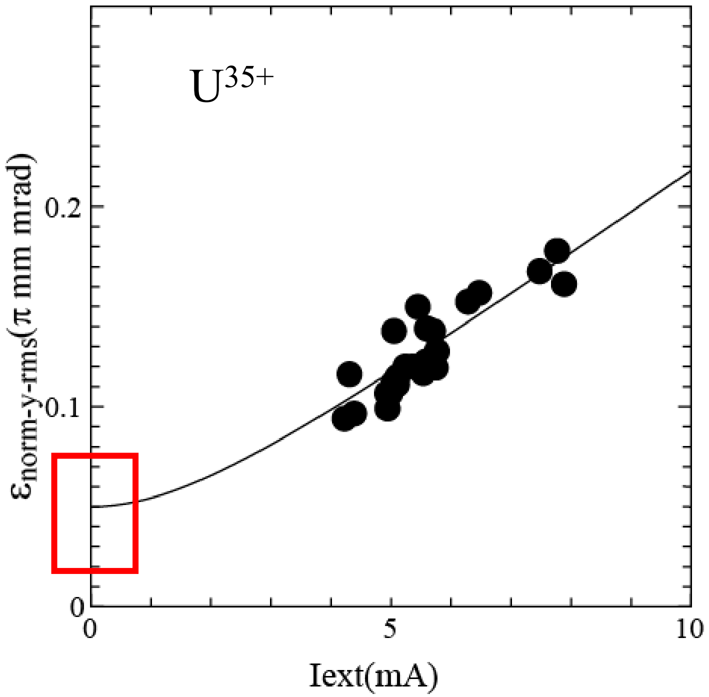
Space charge effect

$$\varepsilon_{eff}=\sqrt{\varepsilon^2+K(\frac{I_z}{I_c(\beta\gamma)})^2}$$

Y. K. Batygin, NIMA **539**, 455 (2005).

$$\varepsilon_{eff}=\sqrt{\varepsilon^2+CI_{ext}^2}$$

Ion source emittance



To obtain more accurate value, we need the measured emittance at lower extraction current

Space charge effect

U^{35+} emittance <0.1 p mm mrad ?

Space charge effect

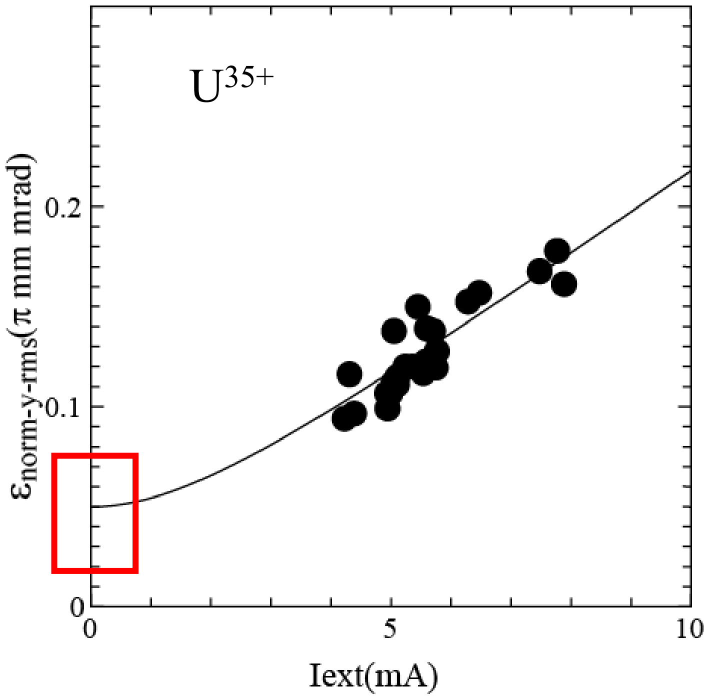
$$\varepsilon_{eff}=\sqrt{\varepsilon^2+K\left(\frac{I_z}{I_c(\beta\gamma)}\right)^2}$$

Y. K. Batygin, NIMA **539**, 455 (2005).

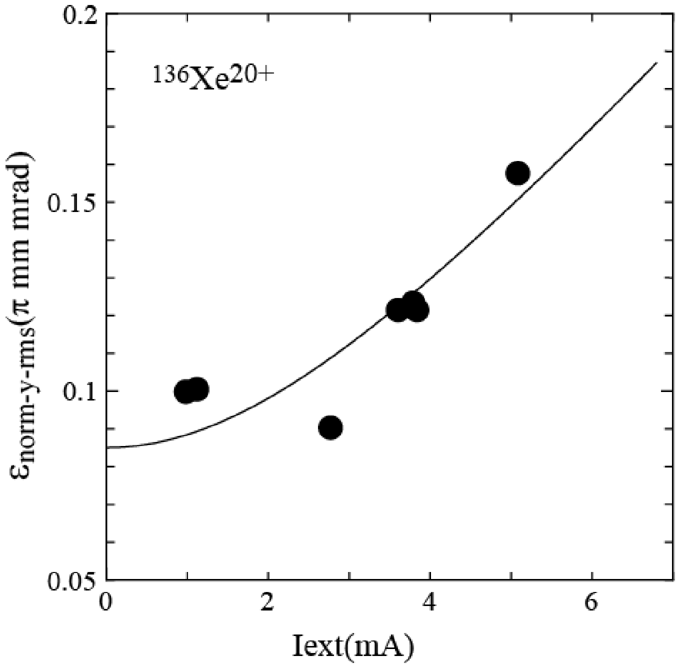
$$\varepsilon_{eff}=\sqrt{\varepsilon^2+CI_{ext}^2}$$

Ion source emittance

Test experiments (Xe^{20+}) for lower extraction current
Beam intensity of Xe^{20+} ~30emA



To obtain more accurate value, we need the measured emittance at lower extraction current



Space charge effect
U^{35+} emittance <0.1 p mm mrad ?

Space charge effect

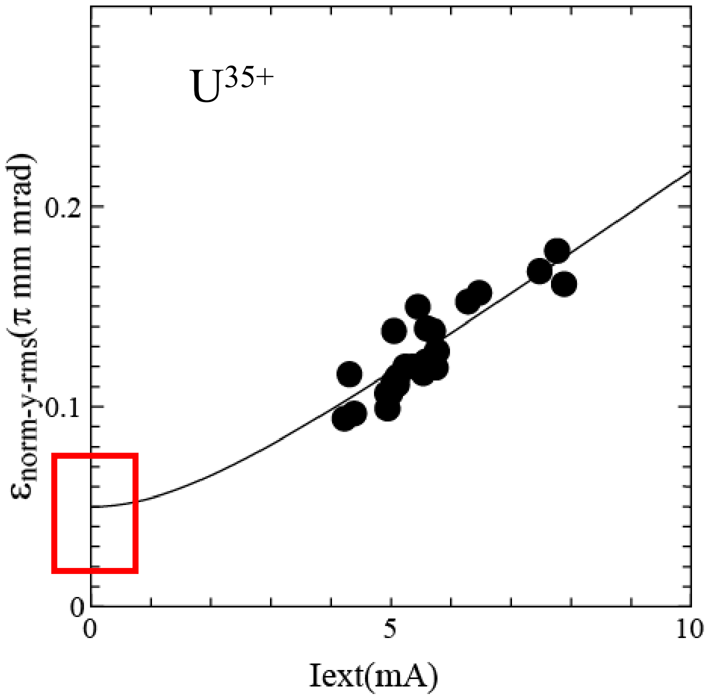
$$\varepsilon_{eff}=\sqrt{\varepsilon^2+K(\frac{I_z}{I_c(\beta\gamma)})^2}$$

Y. K. Batygin, NIMA **539**, 455 (2005).

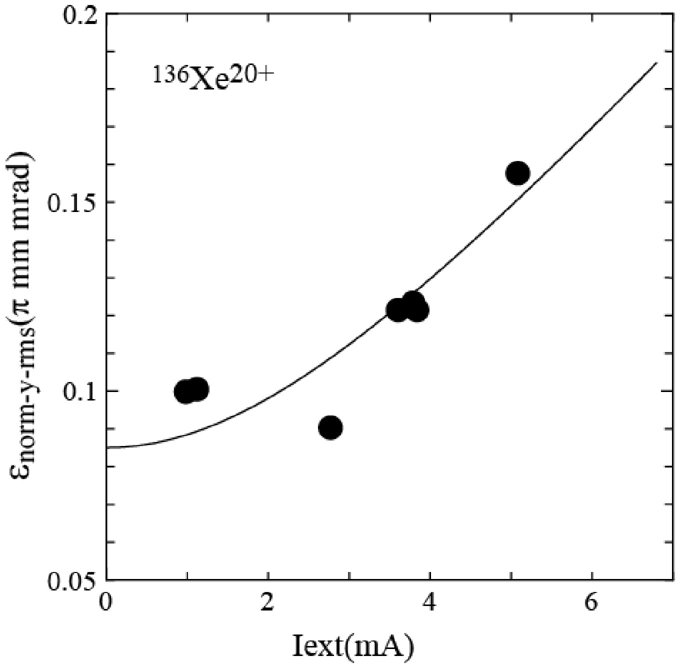
$$\varepsilon_{eff}=\sqrt{\varepsilon^2+CI_{ext}^2}$$

Ion source emittance

Test experiments (Xe^{20+}) for lower extraction current
Beam intensity of Xe^{20+} ~30emA



To obtain more accurate value, we need the measured emittance at lower extraction current



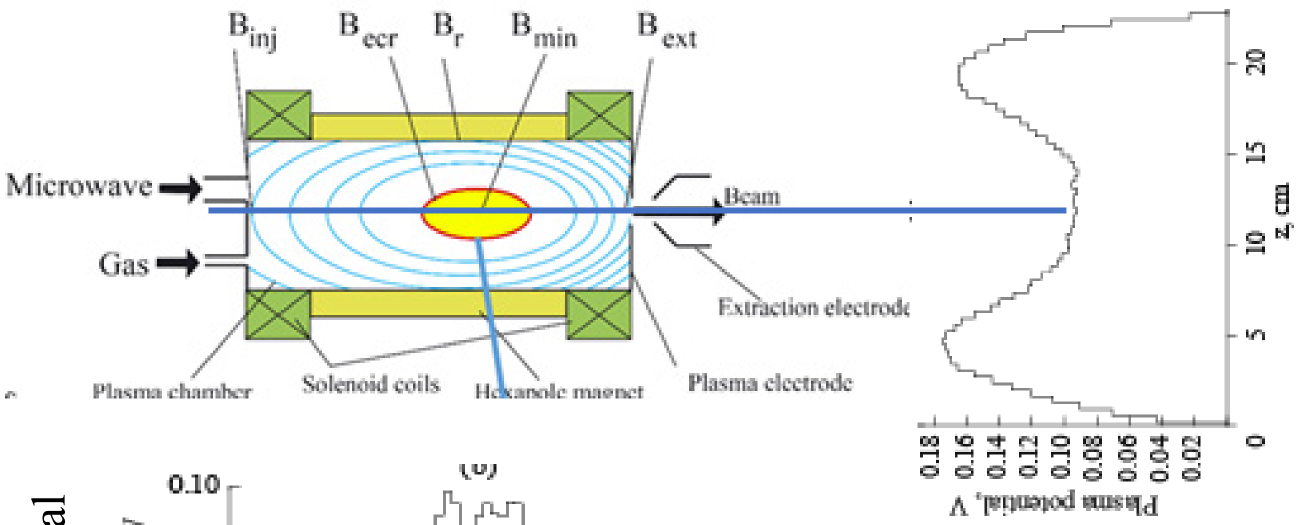
Space charge effect
U^{35+} emittance <0.1 p mm mrad ?

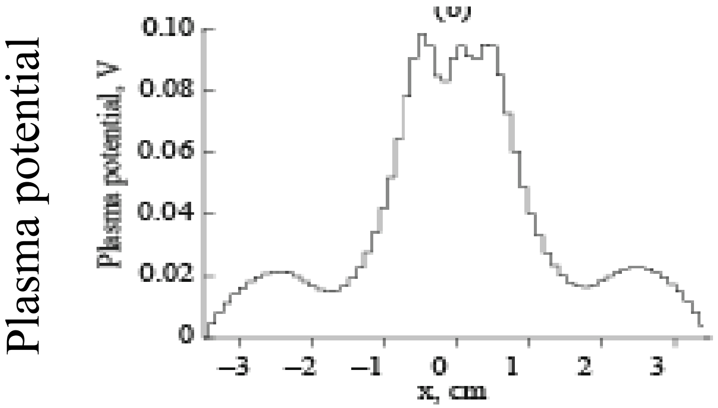
To obtain smaller emittance, we need lower extraction current

Reduction of extraction beam current (smaller emittance)

Existence of plasma potential dip

Plasma potential



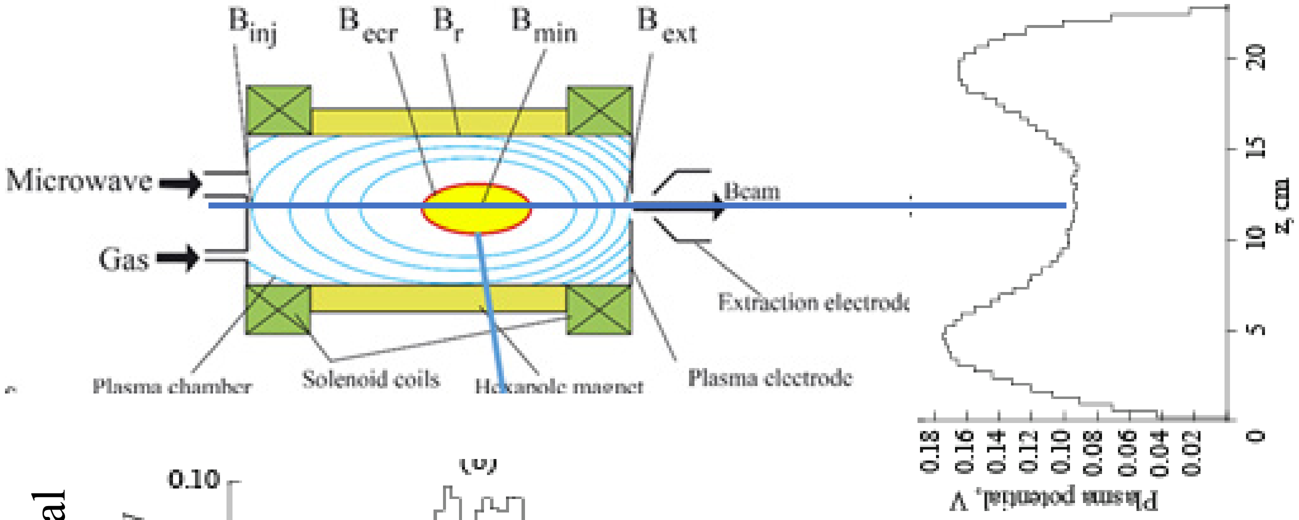


Physics of Particles and Nuclei Letters, 2021, Vol. 18, No. 3, pp. 370–377
V. Mironov et al.,

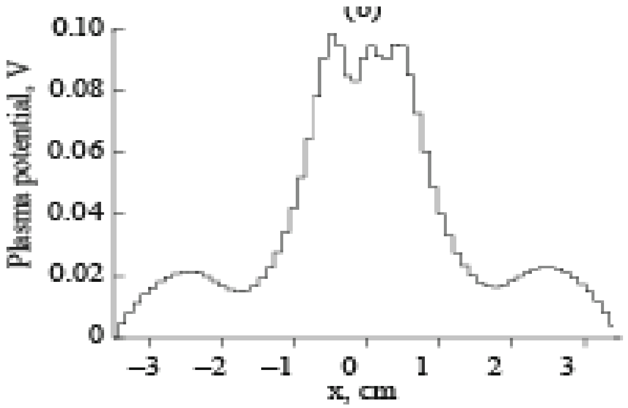
Reduction of extraction beam current (smaller emittance)

Existence of plasma potential dip

Plasma potential



Plasma potential



Ion trap
qV (charge state x potential dip)

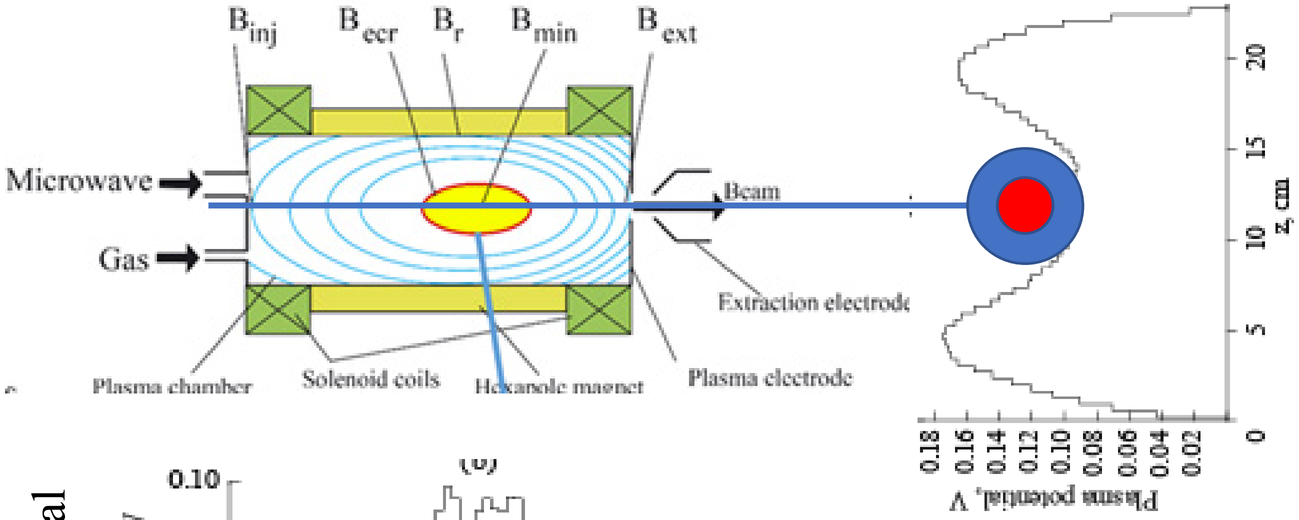
Larger q ➡ strong trap ➡ central region

Physics of Particles and Nuclei Letters, 2021, Vol. 18, No. 3, pp. 370–377
V. Mironov et al.,

Reduction of extraction beam current (smaller emittance)

Existence of plasma potential dip

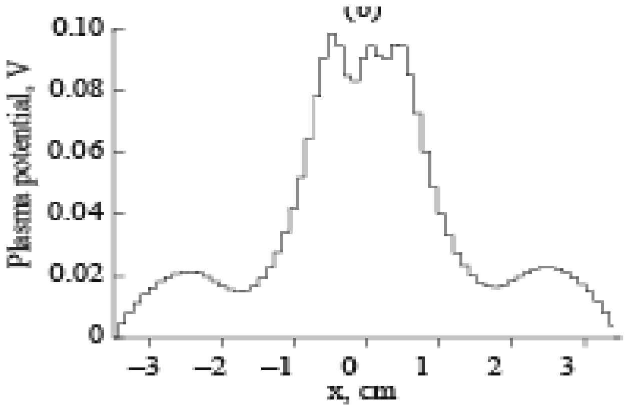
Plasma potential

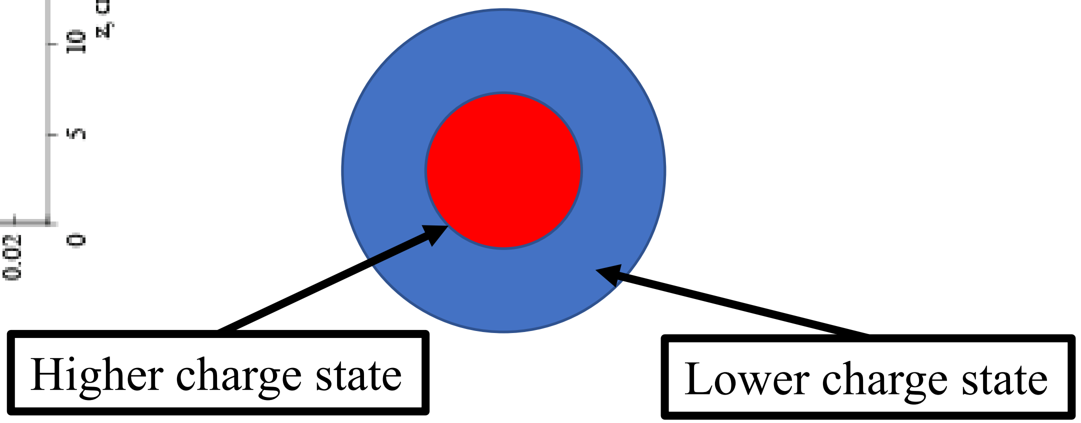


Ion trap
qV (charge state x potential dip)

Larger q ➡ strong trap ➡ central region

Plasma potential

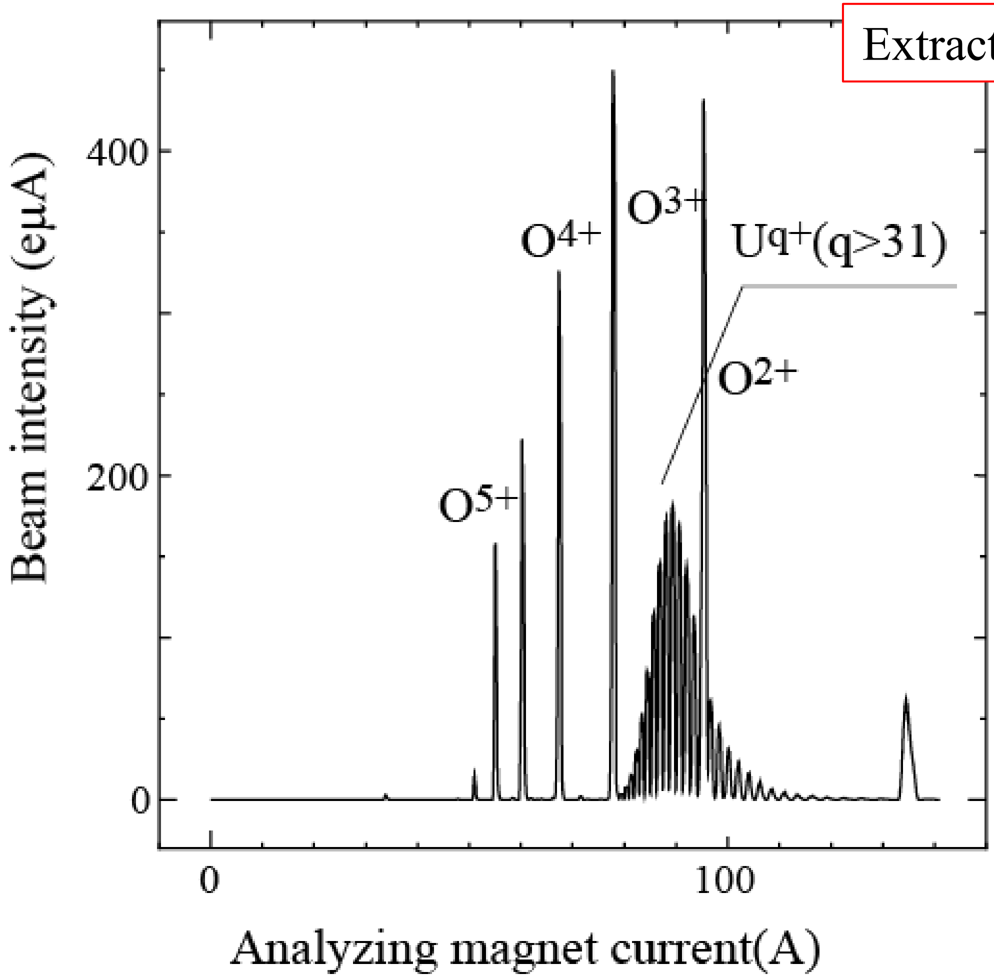




Beam size

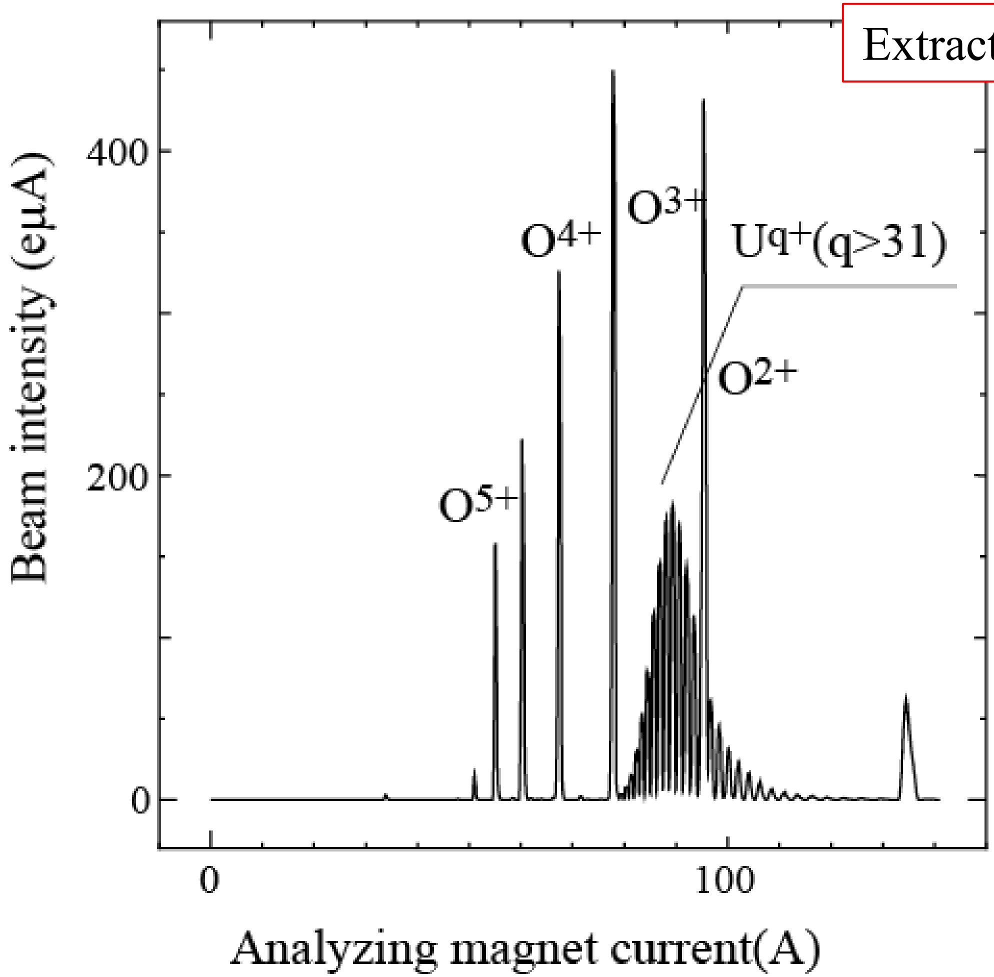
Physics of Particles and Nuclei Letters, 2021, Vol. 18, No. 3, pp. 370–377
V. Mironov et al.,

Extraction hole (10 mm in diameter)



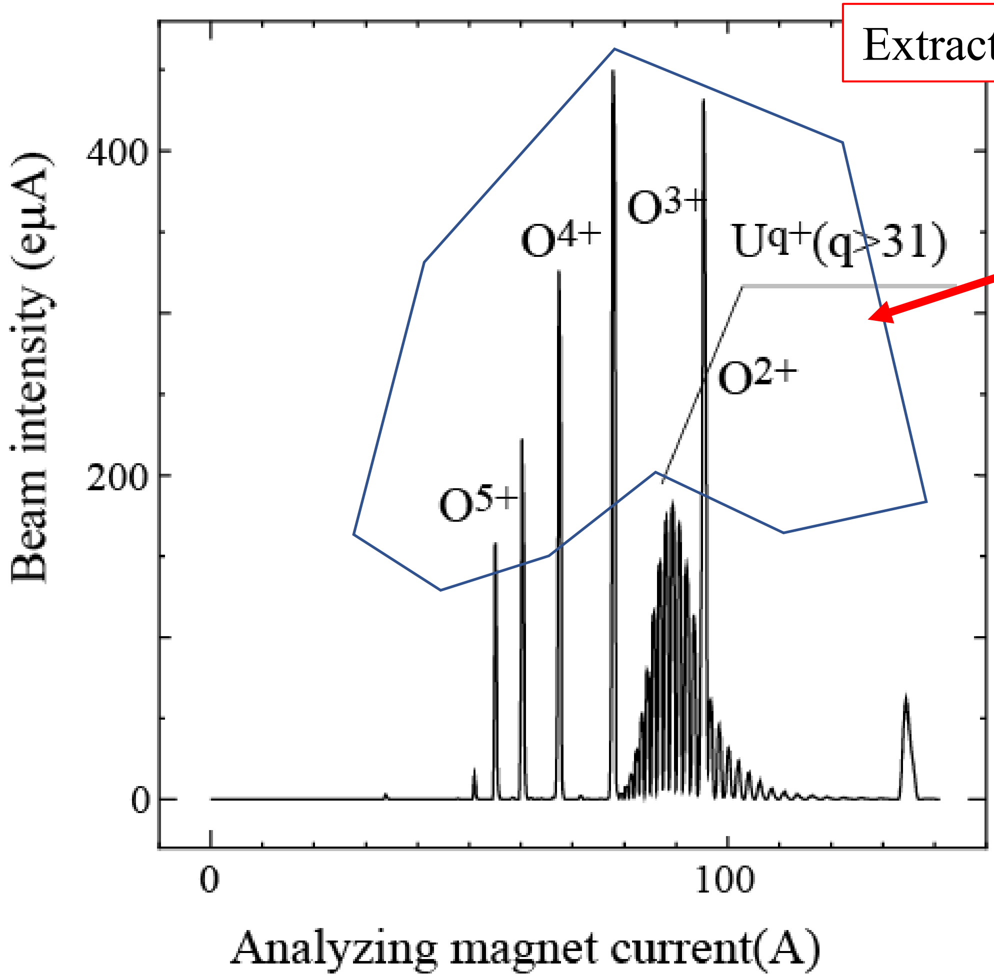
Extraction beam is mainly O ions (lower charge state)
We may reduce the extraction beam using smaller extraction hole

Extraction hole (10 mm in diameter)



Extraction beam is mainly O ions (lower charge state)
We may reduce the extraction beam using smaller extraction hole

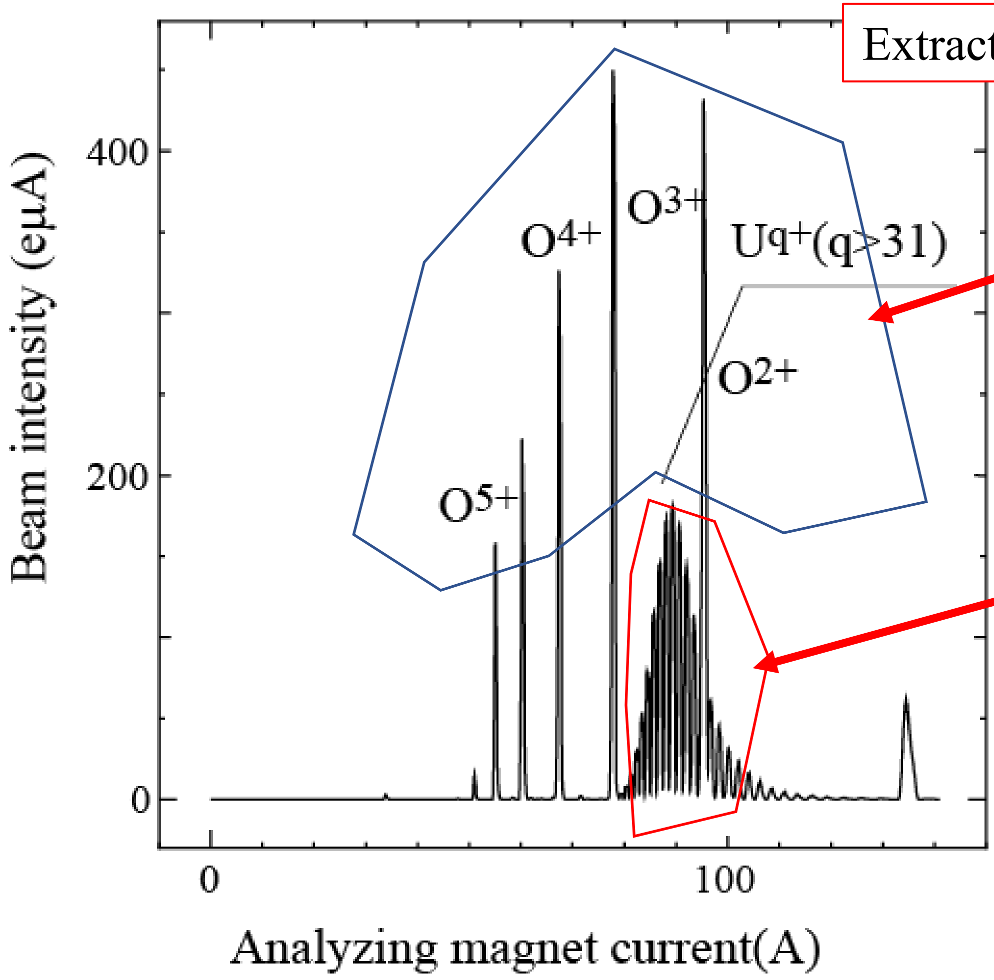
Extraction hole (10 mm in diameter)



O ions (2+~5+) Larger beam size

Extraction beam is mainly O ions (lower charge state)
We may reduce the extraction beam using smaller extraction hole

Extraction hole (10 mm in diameter)

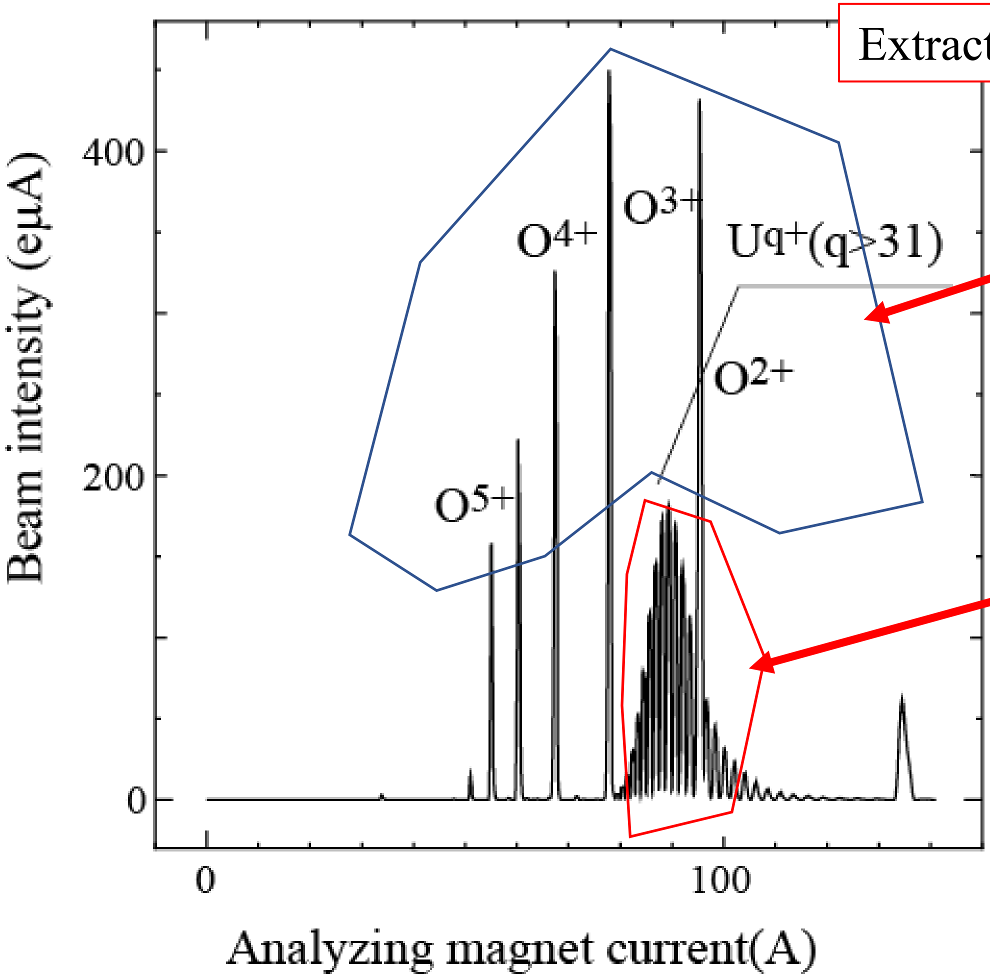


O ions (2+~5+) Larger beam size

U ions (31+~40+) Smaller beam size

Extraction beam is mainly O ions (lower charge state)
We may reduce the extraction beam using smaller extraction hole

Extraction hole (10 mm in diameter)



O ions (2+~5+) Larger beam size

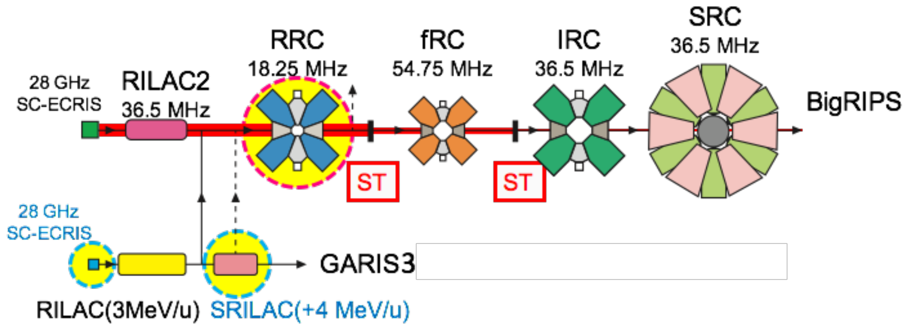
U ions (31+~40+) Smaller beam size

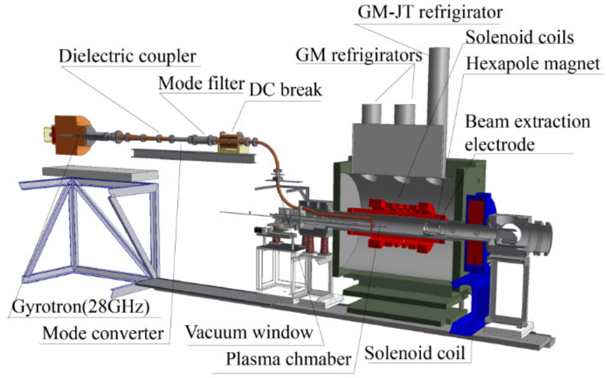
If we use smaller extraction hole, the total extraction current may be reduced while keeping the beam intensity of U^{35+}

High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

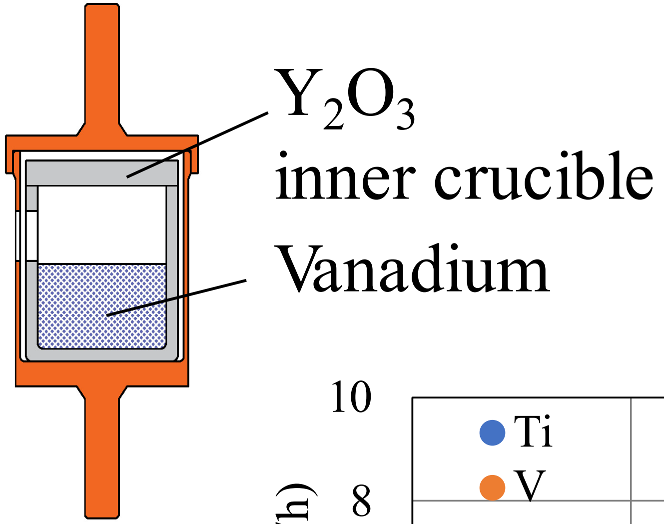
T. Nakagawa (Nishina center for accelerator based science, RIKEN)

1. Introduction
    1. RIBF and SHE search exp.
    2. Brief history
    3. Upgrade plan
2. Ion source
    1. Structure
    2. High temp. oven
3. Production of U ion beam(RIBF)
    1. Beam intensity (Consumption rate of material)
    2. Emittance (Space charge effect)
4. **Production of V ion beam(SHE)**
    1. **Beam intensity(consumption rate)**
    2. Emittance and emittance slit
5. Conclusion and Next step

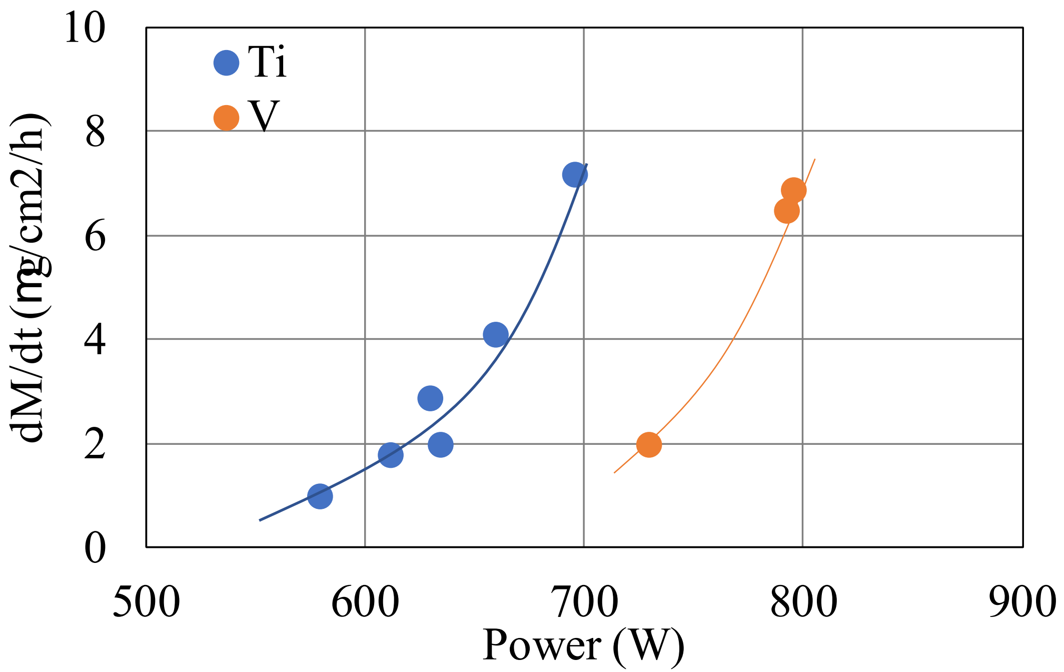




Consumption rate of V and Ti (High temperature oven)



To obtain metal vapor (Ti and V), we used the High temp. oven. To avoid the chemical reaction between the crucible and material (Ti and V), we used the Y_2O_3 inner crucible.

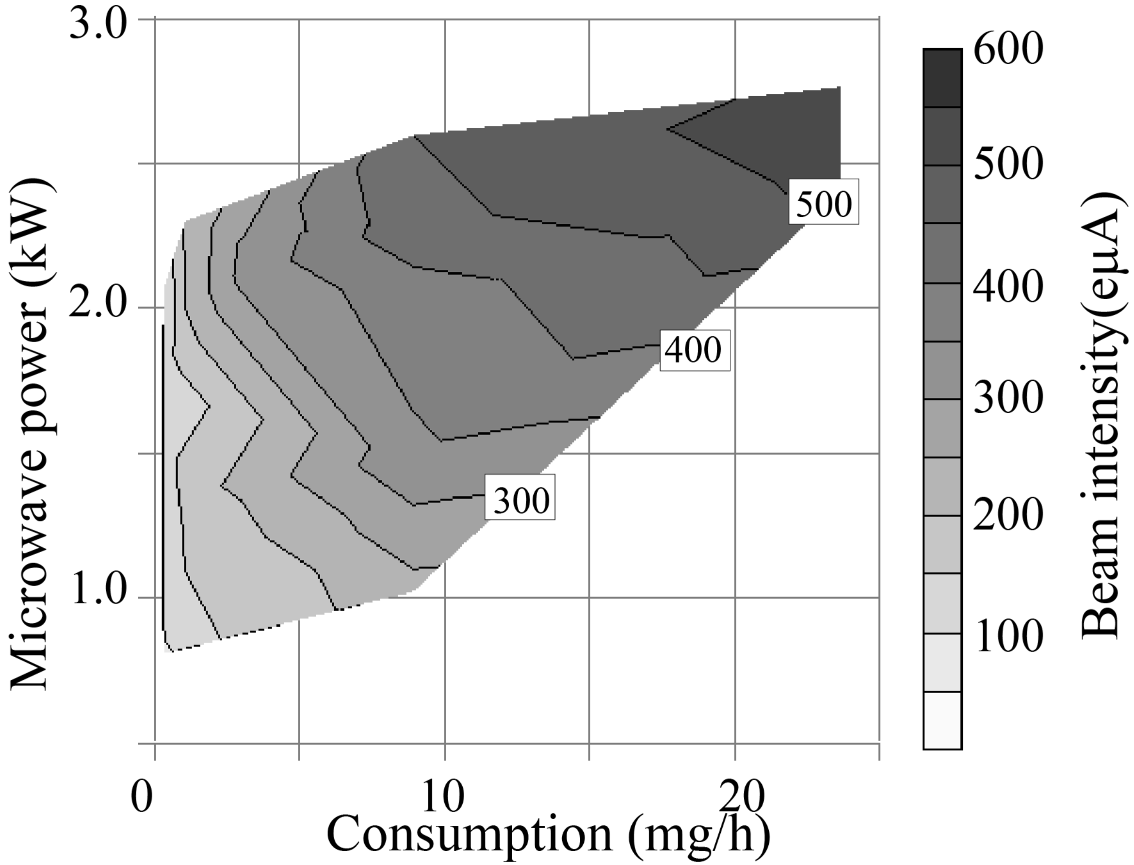


J. Ohnishi et al, ECRIS2018, Catania, Italy, WEB4

The consumption rate increases exponentially with increasing the oven power. The consumption rate of Ti is much higher than that for V. it is due to the difference of the melting point.

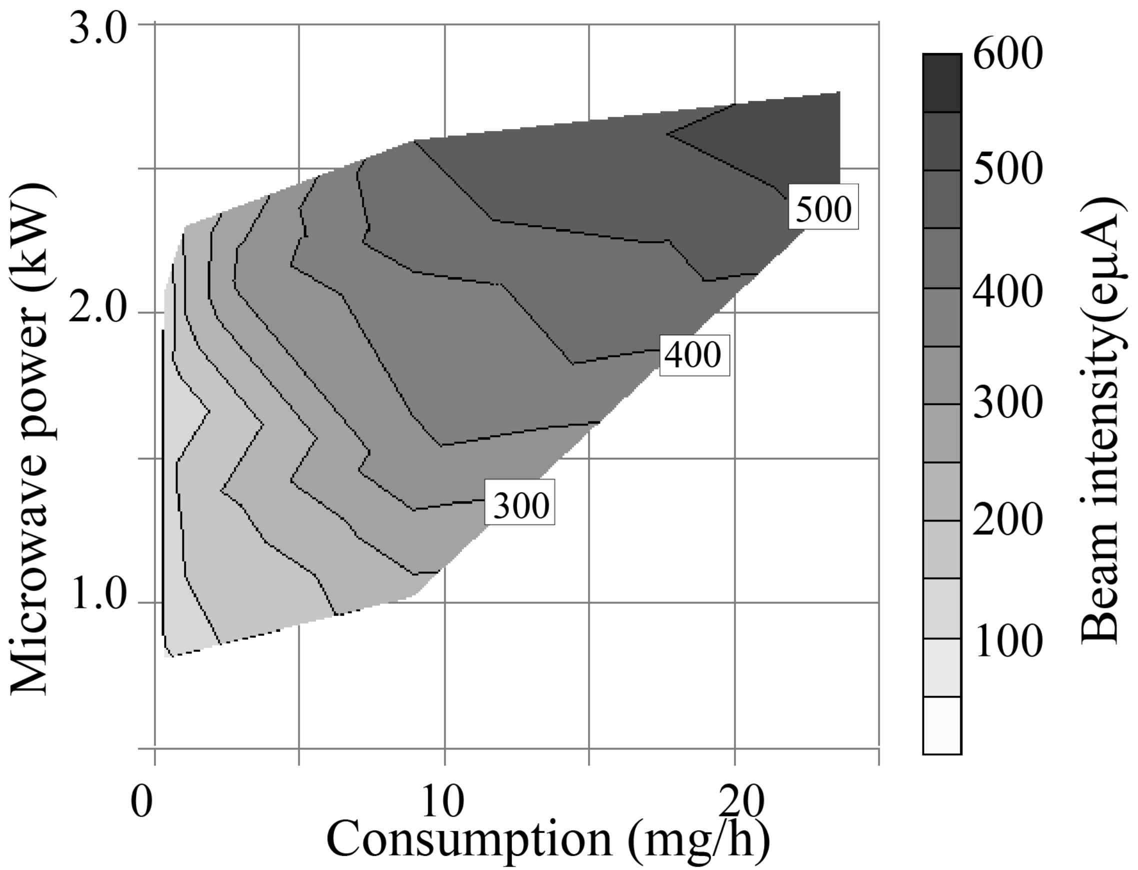
Melting point of Ti: ~1670 K
Melting point of V: ~1940 K

V^{13+} intensity(consumption rate vs. microwave power)



T. Nagatomo et al, RSI 91, 023318(2020)

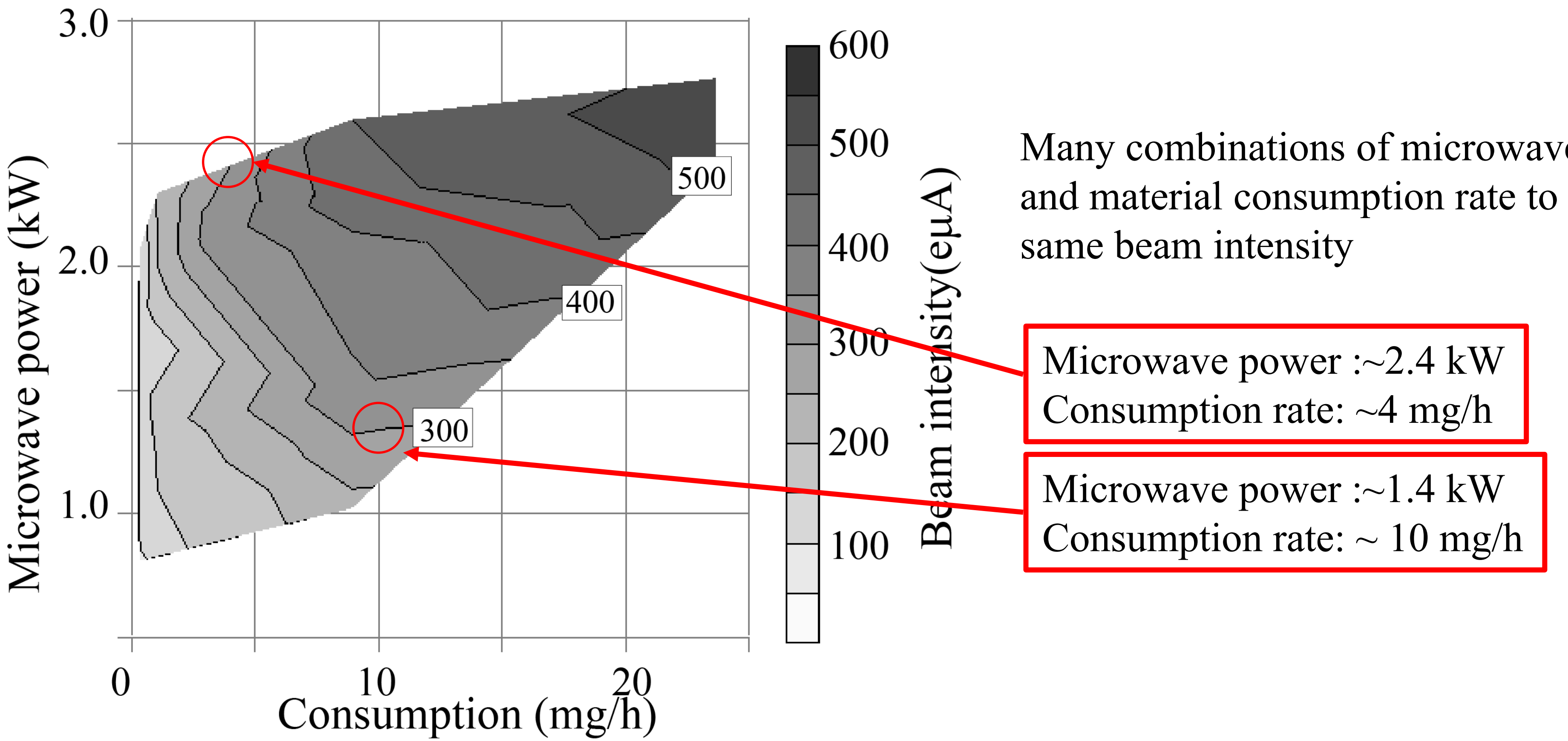
V^{13+} intensity(consumption rate vs. microwave power)



T. Nagatomo et al, RSI 91, 023318(2020)

Many combinations of microwave power and material consumption rate to produce same beam intensity

V^{13+} intensity(consumption rate vs. microwave power)

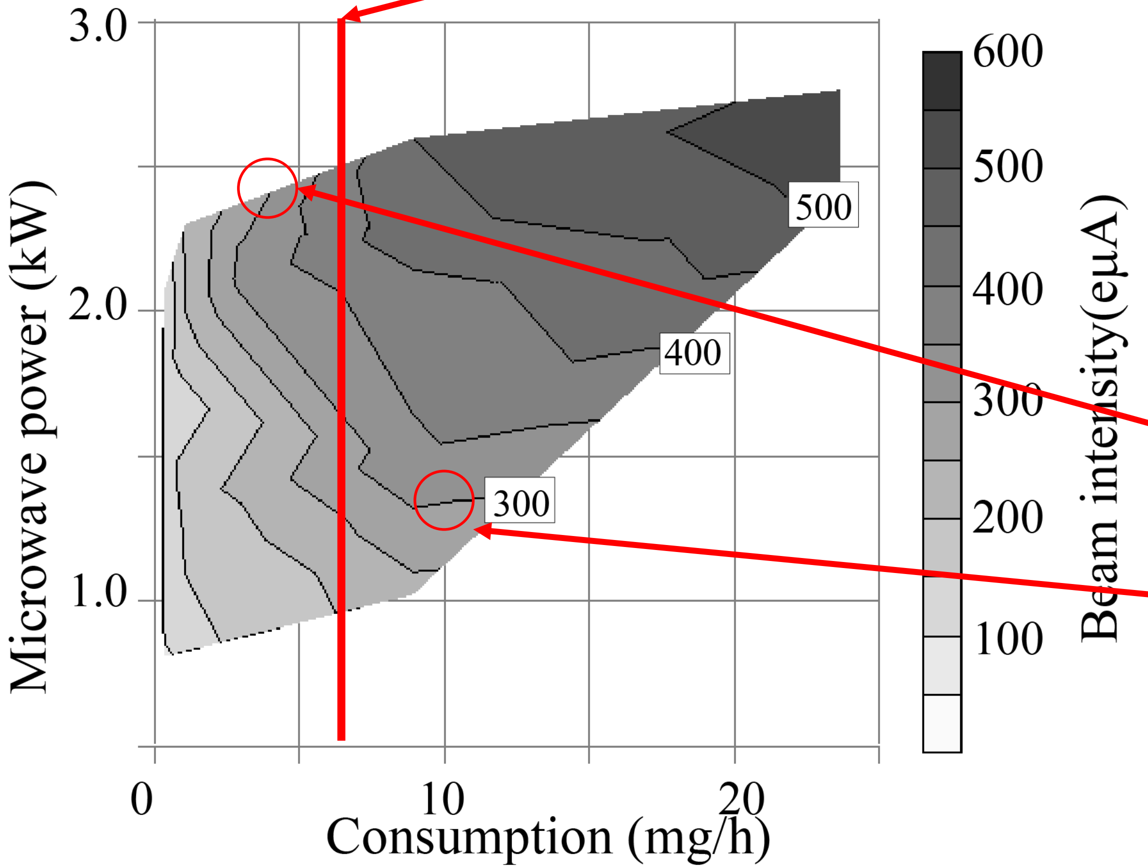


Many combinations of microwave power and material consumption rate to produce same beam intensity

T. Nagatomo et al, RSI 91, 023318(2020)

V^{13+} intensity(consumption rate vs. microwave power)

Double oven system (metal V: 4 gr max)
One month operation without break



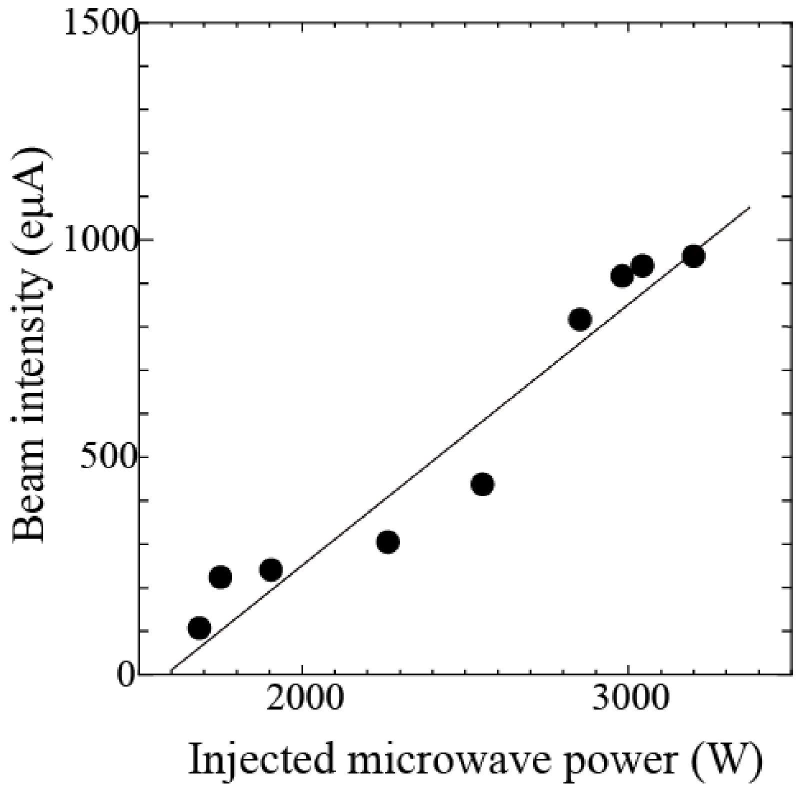
T. Nagatomo et al, RSI 91, 023318(2020)

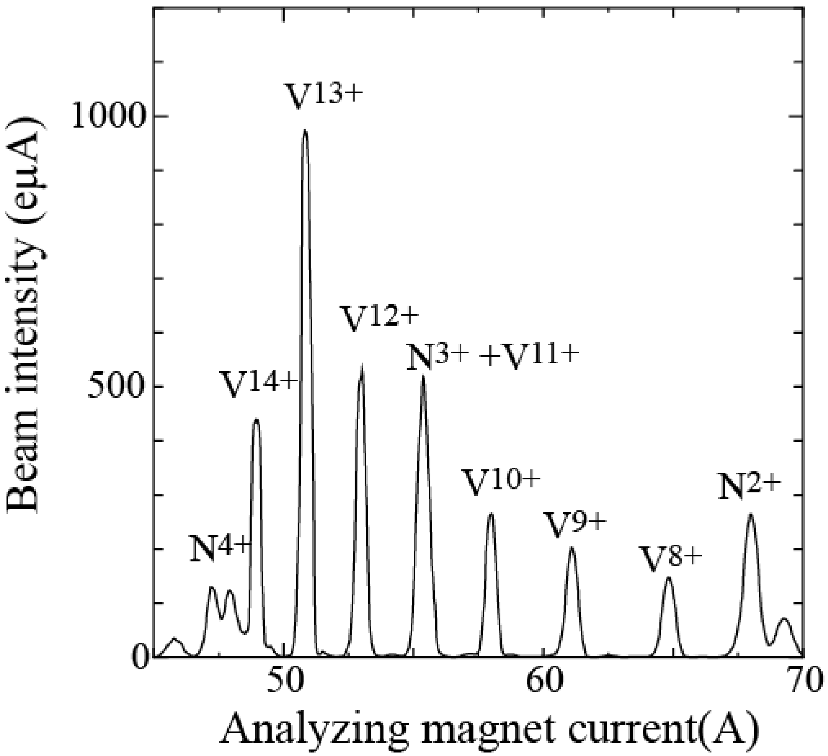
Many combinations of microwave power and material consumption rate to produce same beam intensity

Microwave power :~2.4 kW
Consumption rate: ~4 mg/h

Microwave power :~1.4 kW
Consumption rate: ~ 10 mg/h

V^{13+} ion beam – microwave power dependence, charge distribution-





The beam intensity linearly increases with increasing the microwave power up to ~3.5 kW. It should be stressed that the beam intensity is not saturated at highest power. Therefore we have possibility to obtain higher beam intensity at higher power.

We do not find strong peak of highly charged N ions in the spectrum to produce ~1mA of V^{13+}

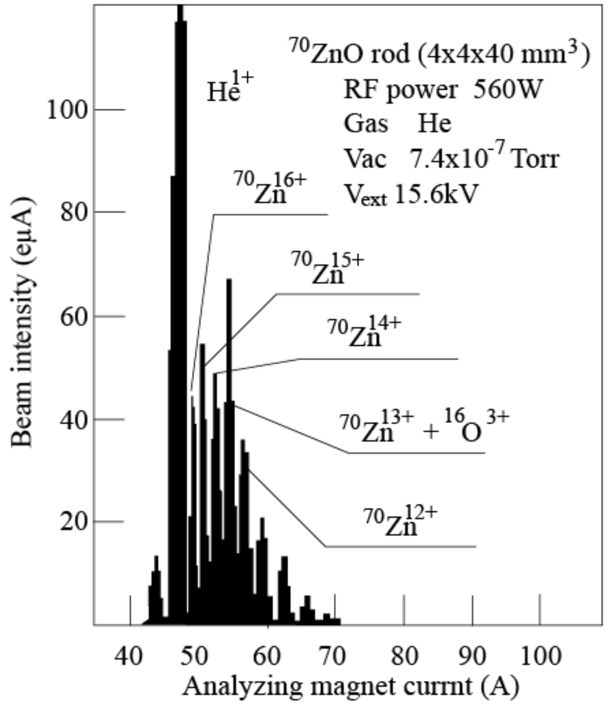
Zn ion beam(Nh production) vs.V13+ beam (Z=119 production)

$^{70}Zn^{15+,16+}$ ~50emA

~3pmA

Nh 19(+19, -10)fb (~150day/counts)

K. Morita NP A944 (2015)30



Zn ion beam(Nh production) vs.V13+ beam (Z=119 production)

$^{70}Zn^{15+,16+}$ ~50emA

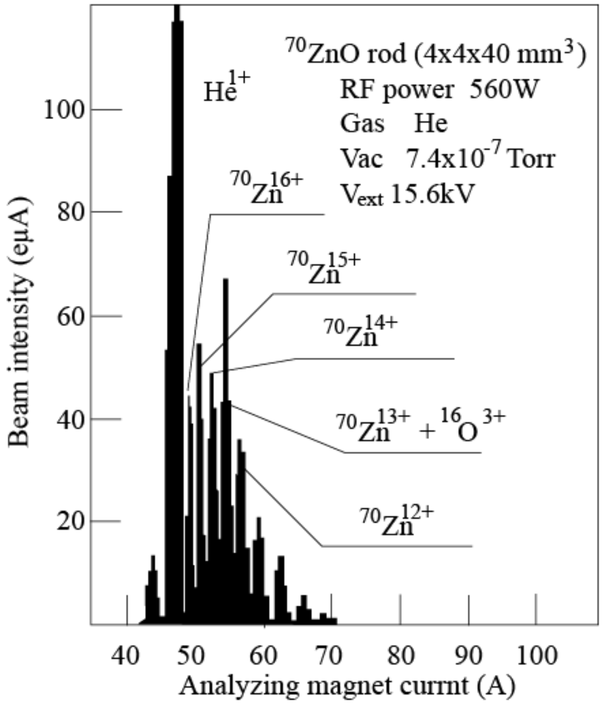
~3pmA

$^{51}V^{13+}$ ~1emA

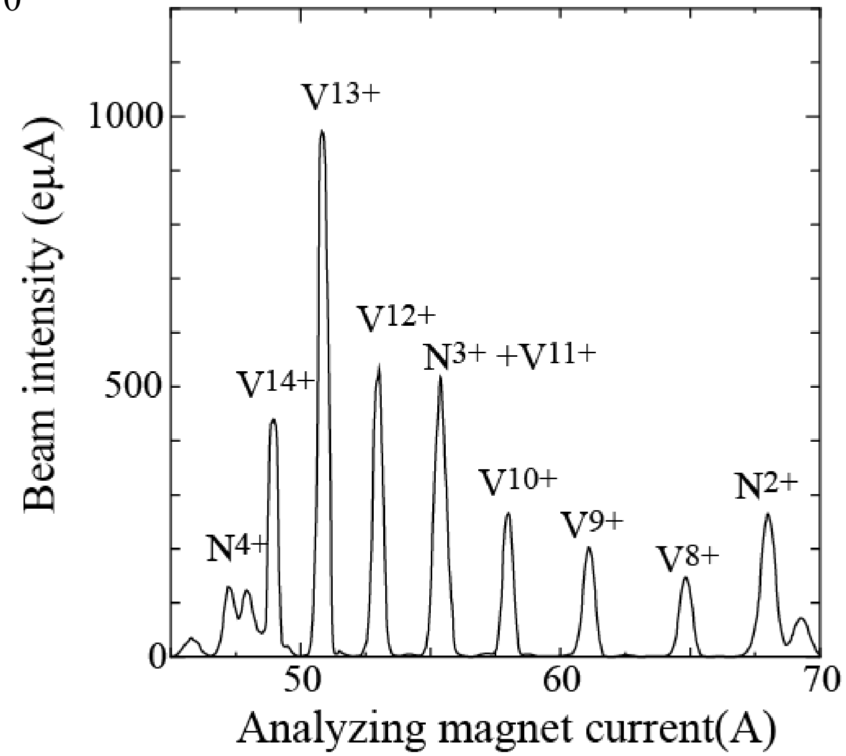
~75pmA

Nh 19(+19, -10)fb (~150day/counts)

K. Morita NP A944 (2015)30



Z=119 ? days/ counts

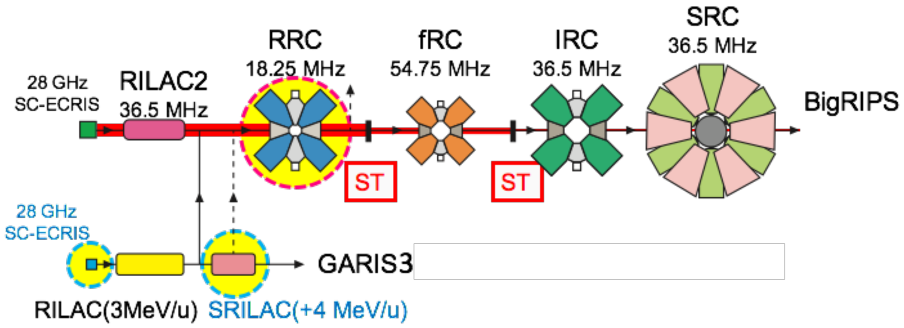


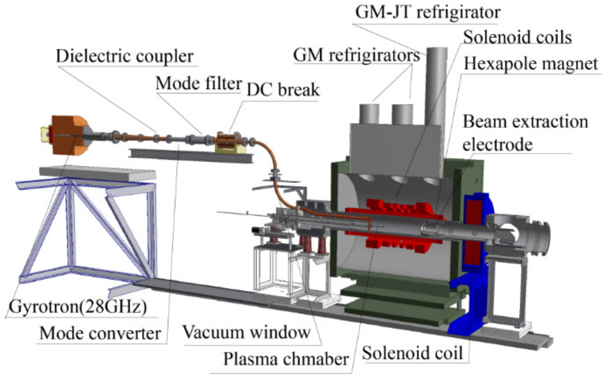
The beam intensity of V^{13+} ions is over 20 times higher than that of Zn ion beam used to produce Nh (Z=113)

High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

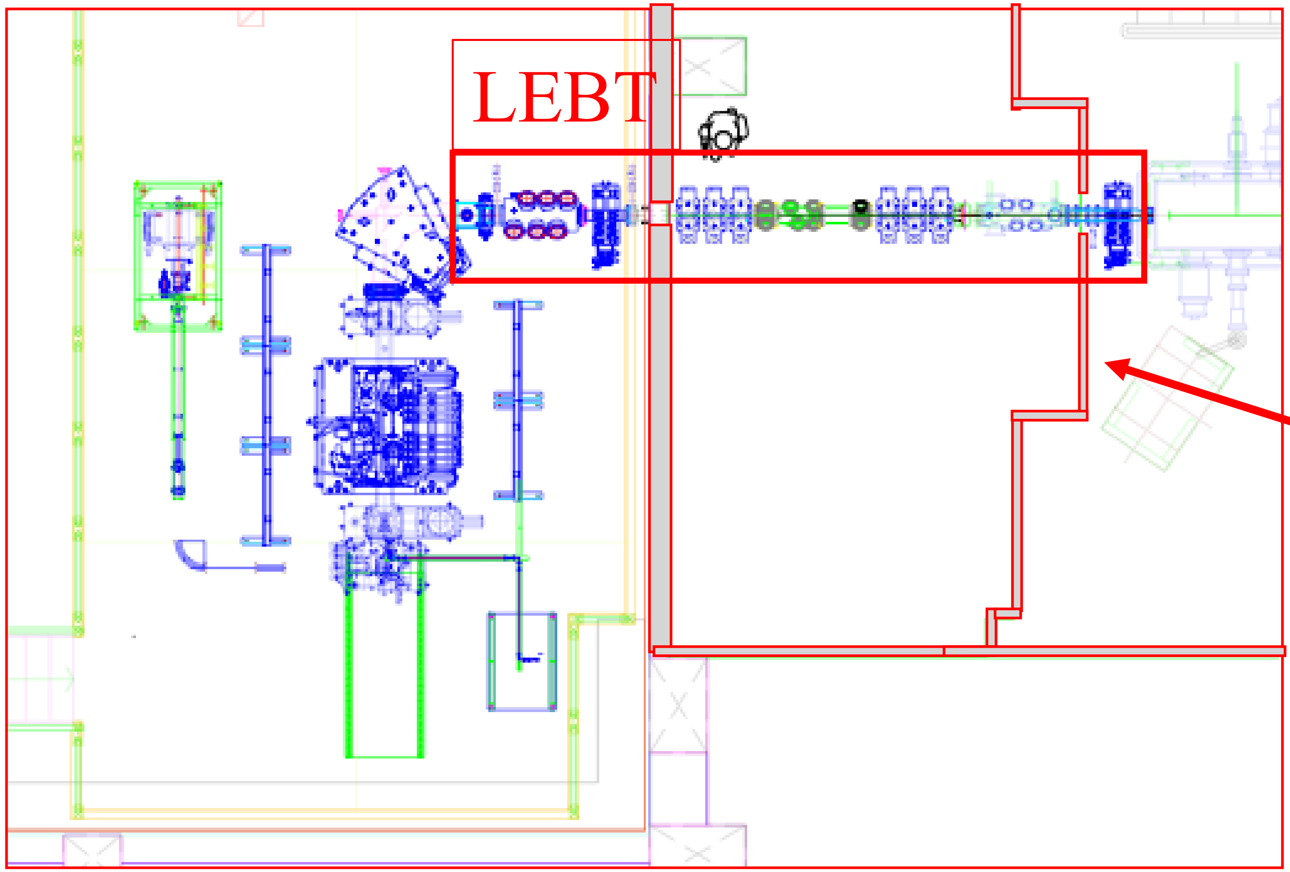
T. Nakagawa (Nishina center for accelerator based science, RIKEN)

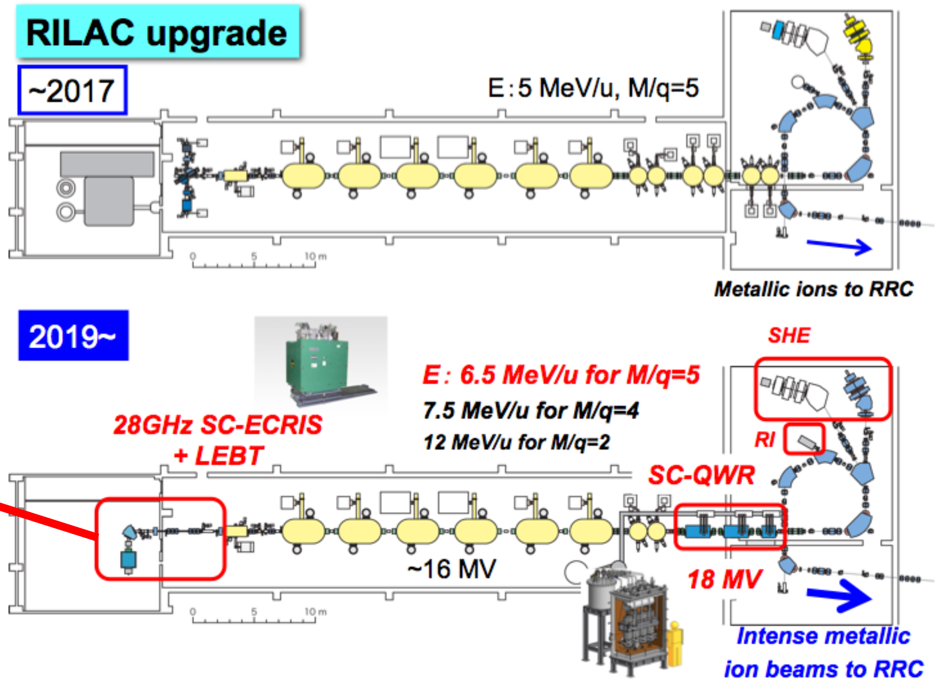
1. Introduction
    1. RIBF and SHE search exp.
    2. Brief history
    3. Upgrade plan
2. Ion source
    1. Structure
    2. High temp. oven
3. Production of U ion beam(RIBF)
    1. Beam intensity (Consumption rate of material)
    2. Emittance (Space charge effect)
4. **Production of V ion beam(SHE)**
    1. Beam intensity(consumption rate)
    2. **Emittance and emittance slit**
5. Conclusion and Next step





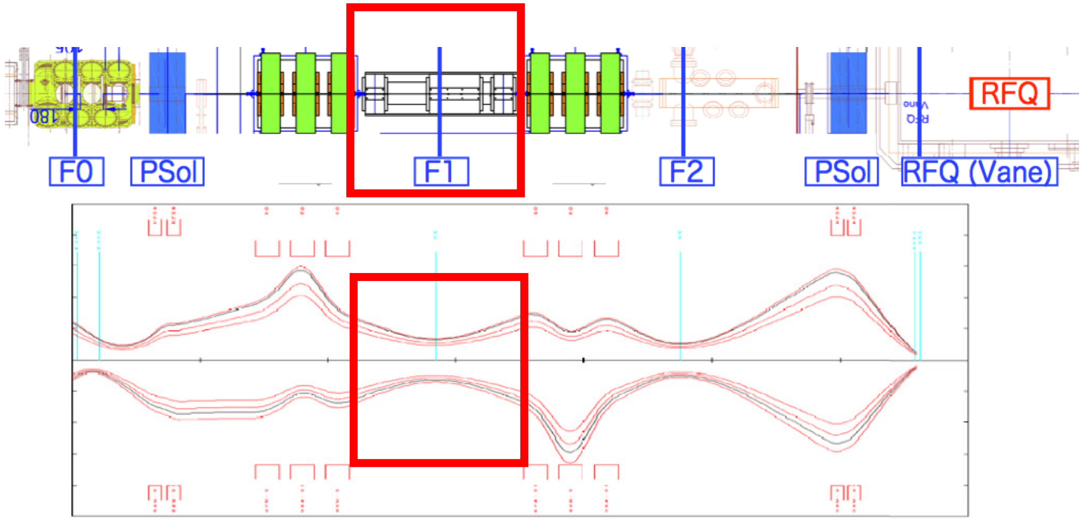
Low Energy Beam Transport (LEBT) (I)





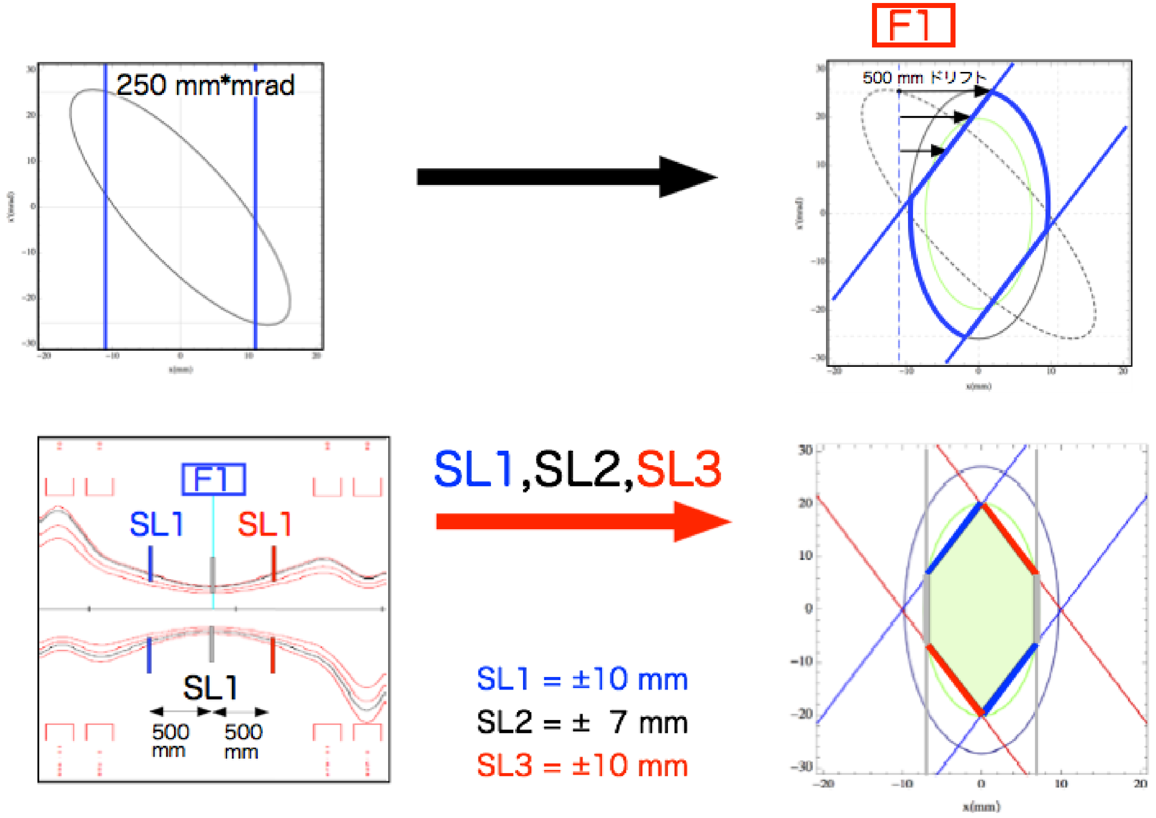
Emittance Slit

Emittance slit



Beam trajectory

For safe operation of intense beam for long term, it is important to minimize the beam loss in the accelerators. Therefore, we installed the emittance slits at the beam focus point (F1) which can cut off the beam in the phase spaces (x-x’ and y-y’)

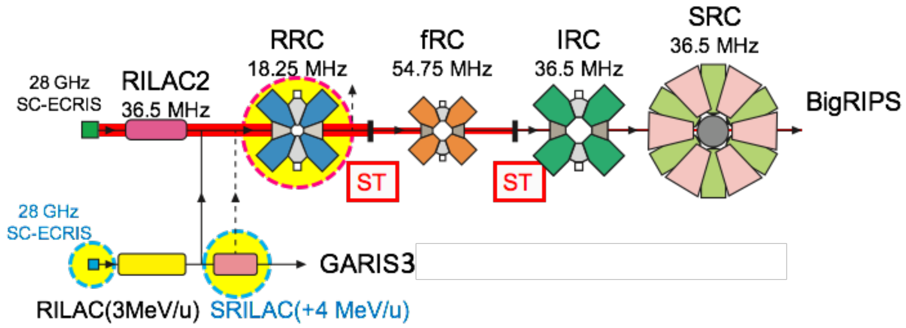


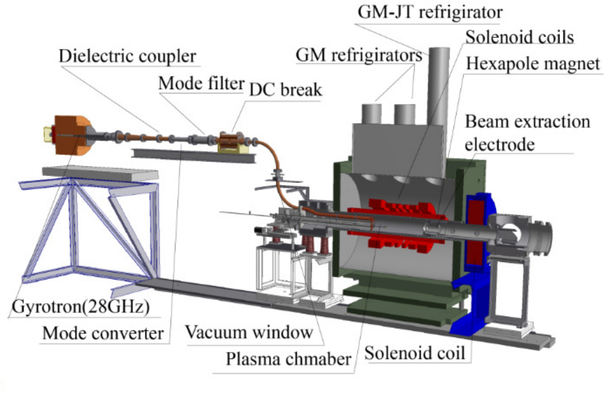
T. Nagatomo et al, RSI 91, 023318(2020)

High performance ECR ion sources development at RIKEN and their impact to heavy ion accelerators.

T. Nakagawa (Nishina center for accelerator based science, RIKEN)

1. Introduction
   1. RIBF and SHE search exp.
   2. Brief history
   3. Upgrade plan
2. Ion source
   1. Structure
   2. High temp. oven
3. Production of U ion beam(RIBF)
   1. Beam intensity (Consumption rate of material)
   2. Emittance (Space charge effect)
4. Production of V ion beam(SHE)
   1. Beam intensity(consumption rate)
   2. Emittance and emittance slit
5. **Conclusion and Next step**





Conclusions and Next step

1. Production of intense U and V ion beam with optimizing the consumption rate of the material (metal vapor)
   1. U^{33+} ~350emA
   2. U^{50+} ~20emA
   3. The beam intensity of U^{35+}(28GHz SC-ECRIS) is about 100 times higher than that with 18GHz RIKEN ECRIS
   4. $^{51}V^{13+}$ ~1emA
   5. The beam intensity of V^{13+} ions is over 20 times higher than that of Zn ion beam used to produce Nh (Z=113)

Charge state	I (eμA)	Microwave power (W)	Consumption rate (mg/h)
33	346	3240	12.2
35	250	3170	10.9
42	62.6	3000	4.74
46	36.2	2990	2.68
50	20.1	2980	1.48
54	10.4	3000	0.78

2. It is not so difficult to produce 300emA of U^{35+} at present stage. The problem is that we need to install large amount of material in the plasma chamber (3or 4 oven system ?)

3. It seems that emittance size is affected by the space charge effect, especially extracted beam of the ion source

To reduce the emittance size, it is essential to reduce the extraction current.

Use of smaller extraction hole