Production of metallic ion beams with inductive heating oven at IMP

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OUTLINE

- Background
- Standard-Inductive Oven-2019

  Uranium ion beams production with UO2

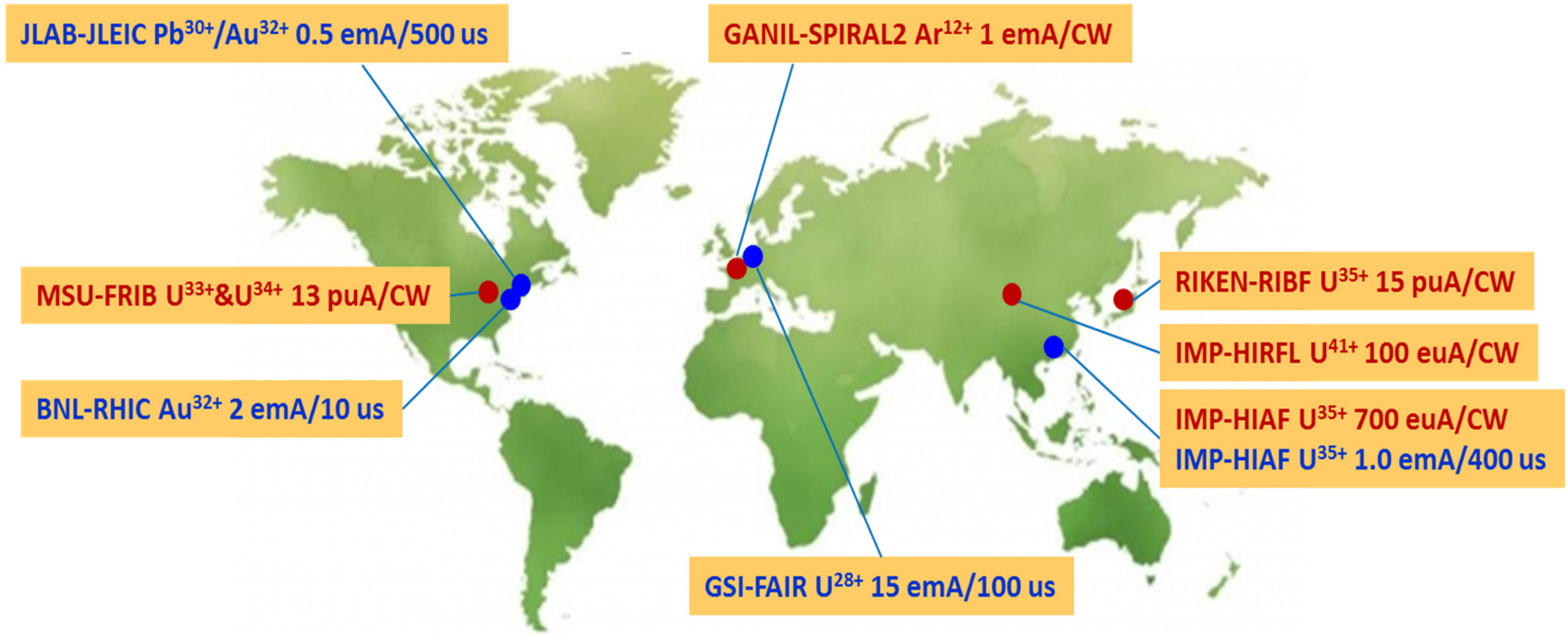
  Aluminum & Iron beams routine operation

- Mini-Inductive Oven-2020

  Calcium ion beams production with CaO

- Summary

Typical ion beams requirement for heavy ion accelerators in the world



● Intense highly charged CW-heavy-ion beams requested by accelerators

● Intense highly charged Pulsed-heavy-ion beams requested by accelerators

Methods to produce metal vapor in ECRIS

- → Plasma Heating
- → MIVOC
- → Sputtering

  RIKEN, MSU, IMP
- → Metal oven (Resistance oven, Inductive oven, etc)

  LBNL, MSU, RIKEN, GSI, IMP, JYFL…
- → Laser Ablation

…

Background-Sputtering

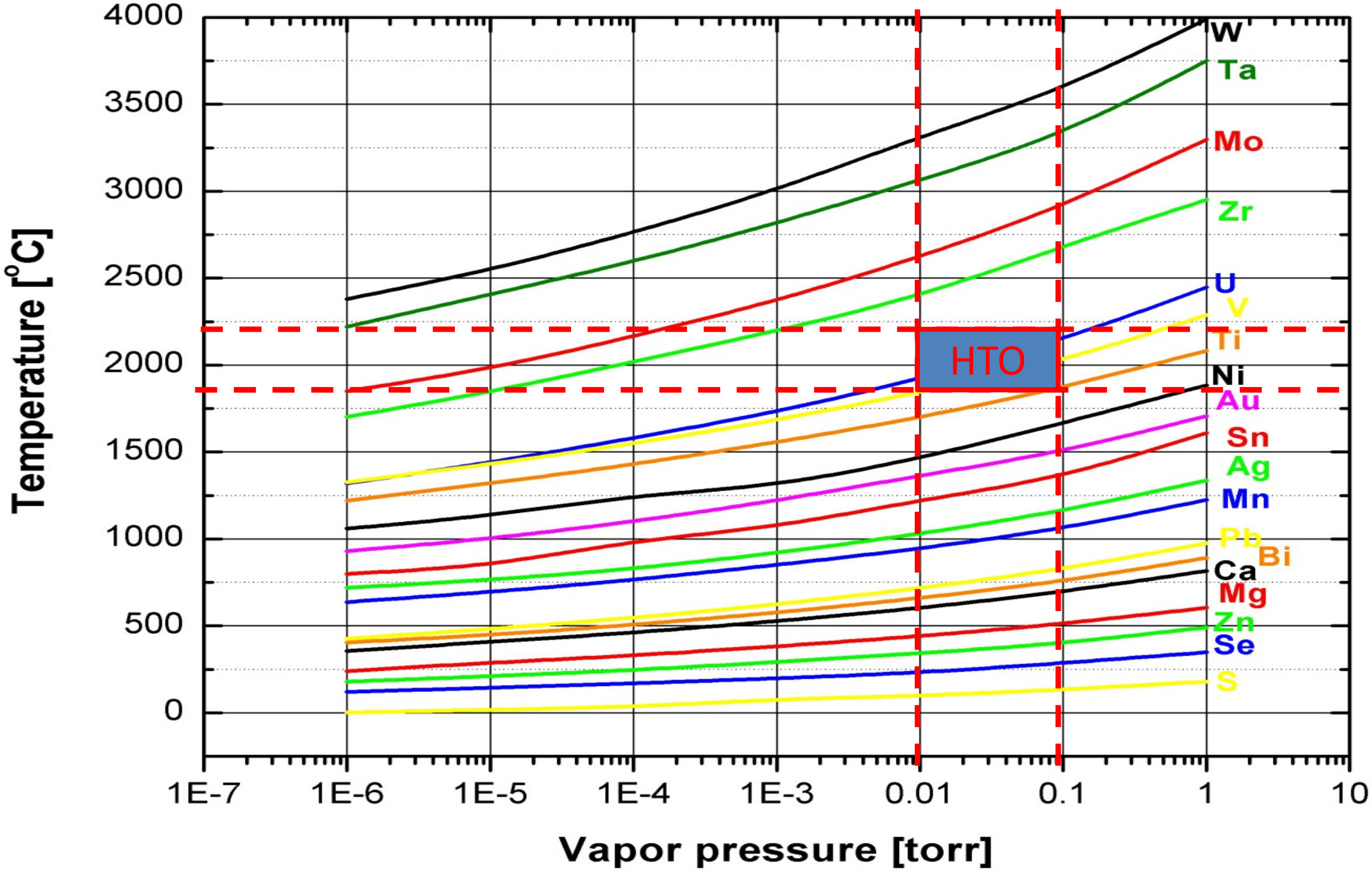
Ion Species	Source	Rf Power (kW)	Sputtering Voltage (kV)	Ion Beam intensity (euA)
$^{238}U^{33+}$	RIKEN-28	4.0	-5.5	225 [1]
$^{238}U^{35+}$	RIKEN-28	4.0	-5.5	180 [1]
$^{238}U^{33+}$	SECRAL	3.8	-3.1	202 [2]
$^{238}U^{33+}$	SuSI	2.9	-3.9	85 [3]
…				

Pros	Simple Structure; Suitable for long-time operation;
Cons	Need a lot of supporting gas; Difficult to get very high charge state;

At present, metal oven is still the best way to produce intense highly charged metallic ion beams.

[1]. Y. Higurashi, et al. Recent development of RIKEN 28 GHz SC-ECRIS, ICIS2013, Chiba, Japan, 2013.
[2]. W. Lu, et al. SECRAL commissioning report, 2013;
[3]. L. T. Sun, et al. Intense ion beam production with SuSI., ECRIS2010, LPSC-Grenoble, France, 2010.

Vapor pressure vs crucible temperature



For refractory metals, the typical temperature to produce enough vapor (0.01-0.1 torr) in ECR ions source is 1600~2000 degree C.

Background-Resistive Heating Oven

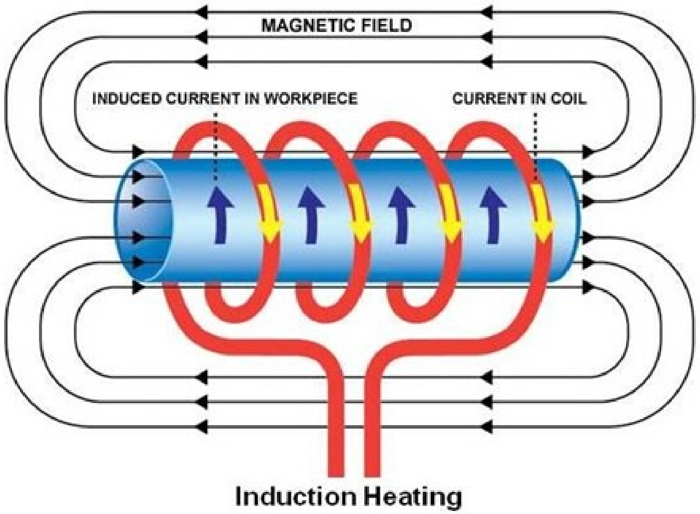
Ion Species	Source	Rf Power (kW)	Operation Time	Ion Beam Intensity (euA)
$^{238}U^{33+}$	VENUS	6.5+1.8	~10 hours	440 [4]
$^{238}U^{35+}$	VENUS	6.5+1.8	~10 hours	300 [4]
$^{238}U^{33+}$	RIKEN-28	2.2-2.6	-	~225 [5]
$^{238}U^{35+}$	RIKEN-28	2.2-2.6	-	~200 [5]
$^{238}U^{35+}$	RIKEN-28	-	~1 month	100-120 [6]
…				

Pros	Temperature up to 2000 °C; Large capacity;
Challenges	Strong Lorenz force; Crucible deformation; Especially used in the next generation ECR ion source (B_{inj}~6 T)

Inductive heating might be another choice

[4]. J. Y. Benitez, et al. Current developments of the VENUS ion source in research and operations, ECRIS2012, Sydney, Australia, 2012.
[5]. T. Nakagawa, et al. Production of intense metal ion beam with RIKEN 28 GHz SC-ECRIS, in this conference.
[6]. J. Ohnishi, et al. Practice use of high-temperature oven for 28 GHz superconducting ECR ion source at RIKEN., ECRIS2018, Catania, Italy, 2018.

Principle of inductive heating and its features



$$\delta = 5033\sqrt{\frac{\rho}{\mu_r f}}$$

δ: skin depth, cm
ρ: resistivity of heated metal, $\Omega.cm$
μ_r: Relative permeability
f: AC current frequency, Hz

Pros:

- **Lorenz force free** when work in high magnetic field environment (B>3-6 T);
- Fast temperature respond to the heating power;

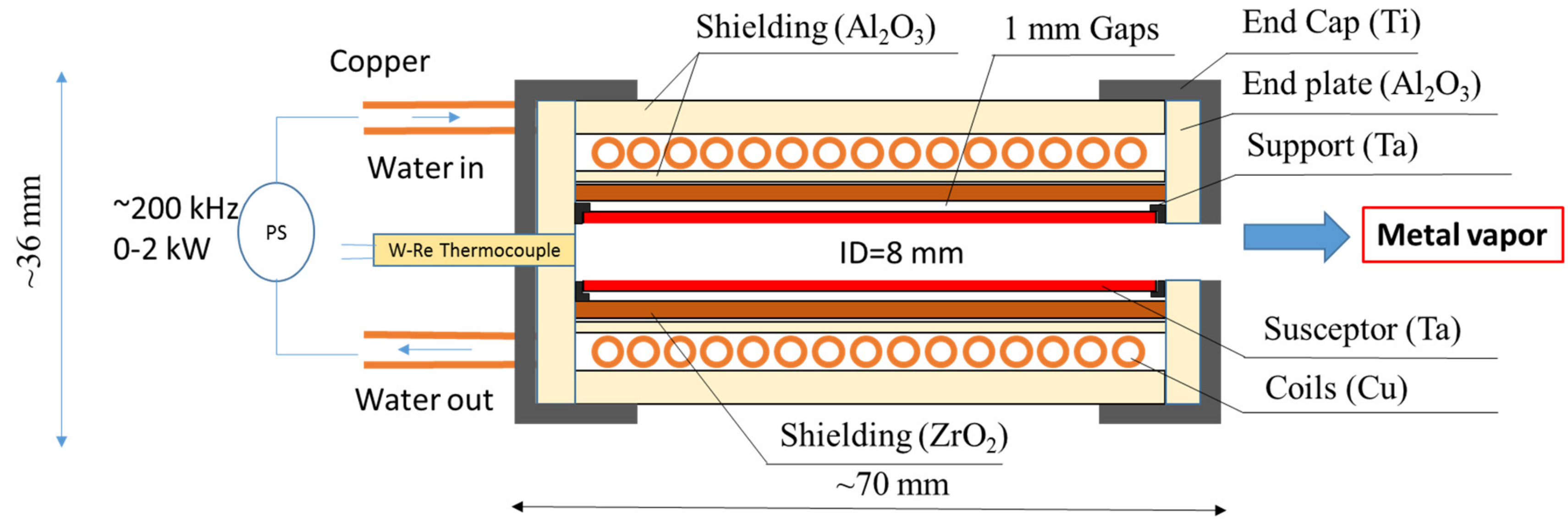
Challenges:

- **Material compatibility** under high temperature;
- Thermal radiation and thermal conduction shielding;

With inductive heating oven, MSU got ~200 euA of U^{33+} in 2012. But the performance of oven degrades quickly!

Standard Inductive Oven-2019

The layout of inductive oven at IMP (2019)



- Design temperature: 1800 -2100 ^{0}C ;
- Design working life: >200 hours;
- Control mode: Close loop (open loop at the first step);
- Capacity: Ø 8 mm × 50 mm crucible;
- Main features: **Add gap between crucible and ZrO_2;**

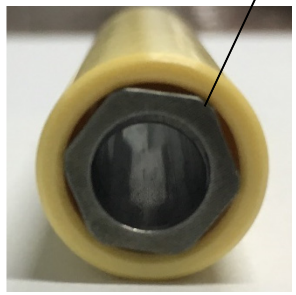
Idea from MSU

Inductive oven assembling

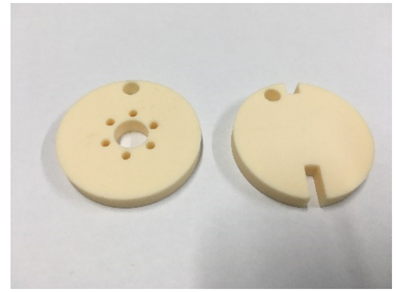
Ta support

For pumping

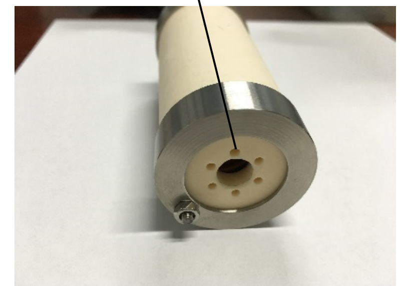
1 mm of Susceptor (Ta)



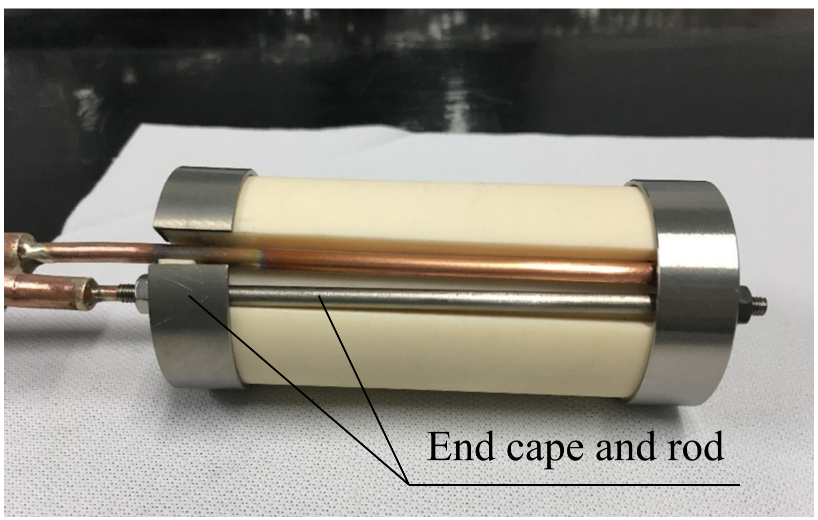
2 mm of ZrO2



Al_2O_3 End plate



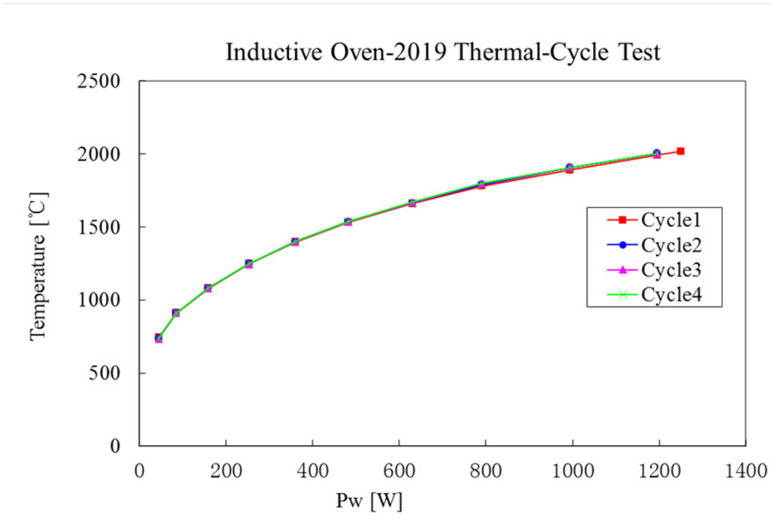
Inductive oven-2019

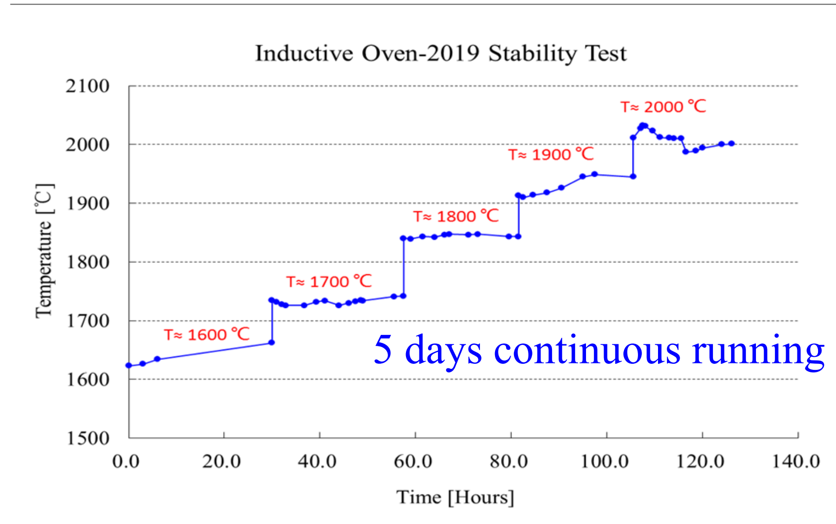


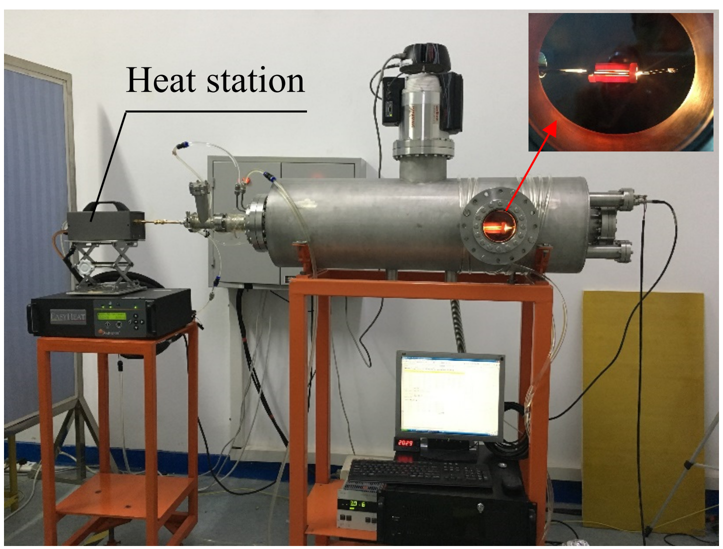
Inductive oven after assembling

RF power generator (0-2 kW, 200 kHz)

Off-line test



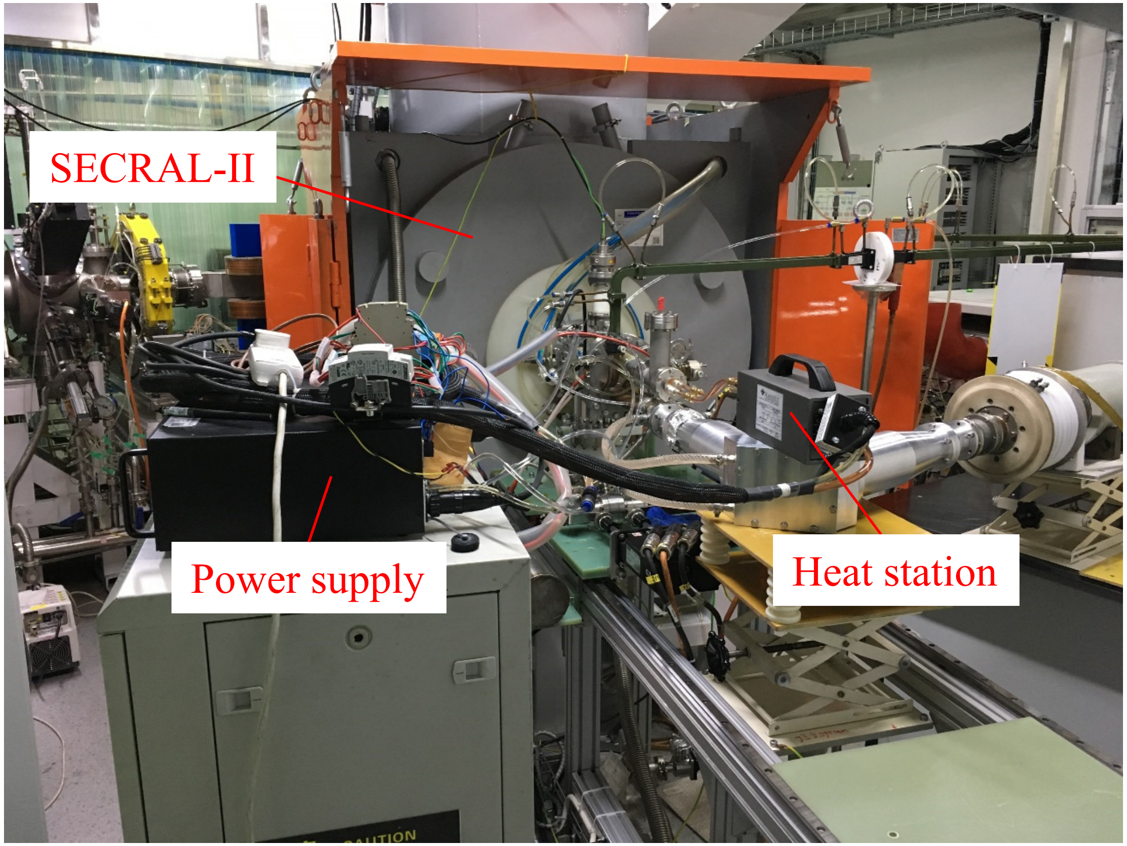




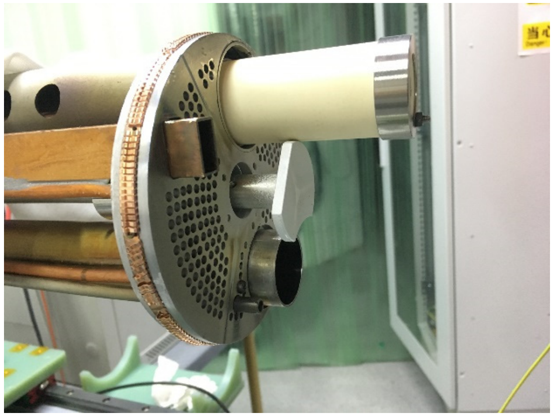
Coil ZrO_2 Ta crucible

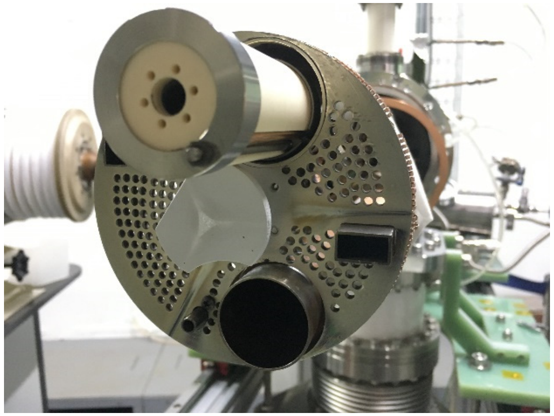
- **ZrO2 and Ta crucible survived;**
- **Similar performance in thermal-cycle test**

The On-line Test on SECRAL-II platform



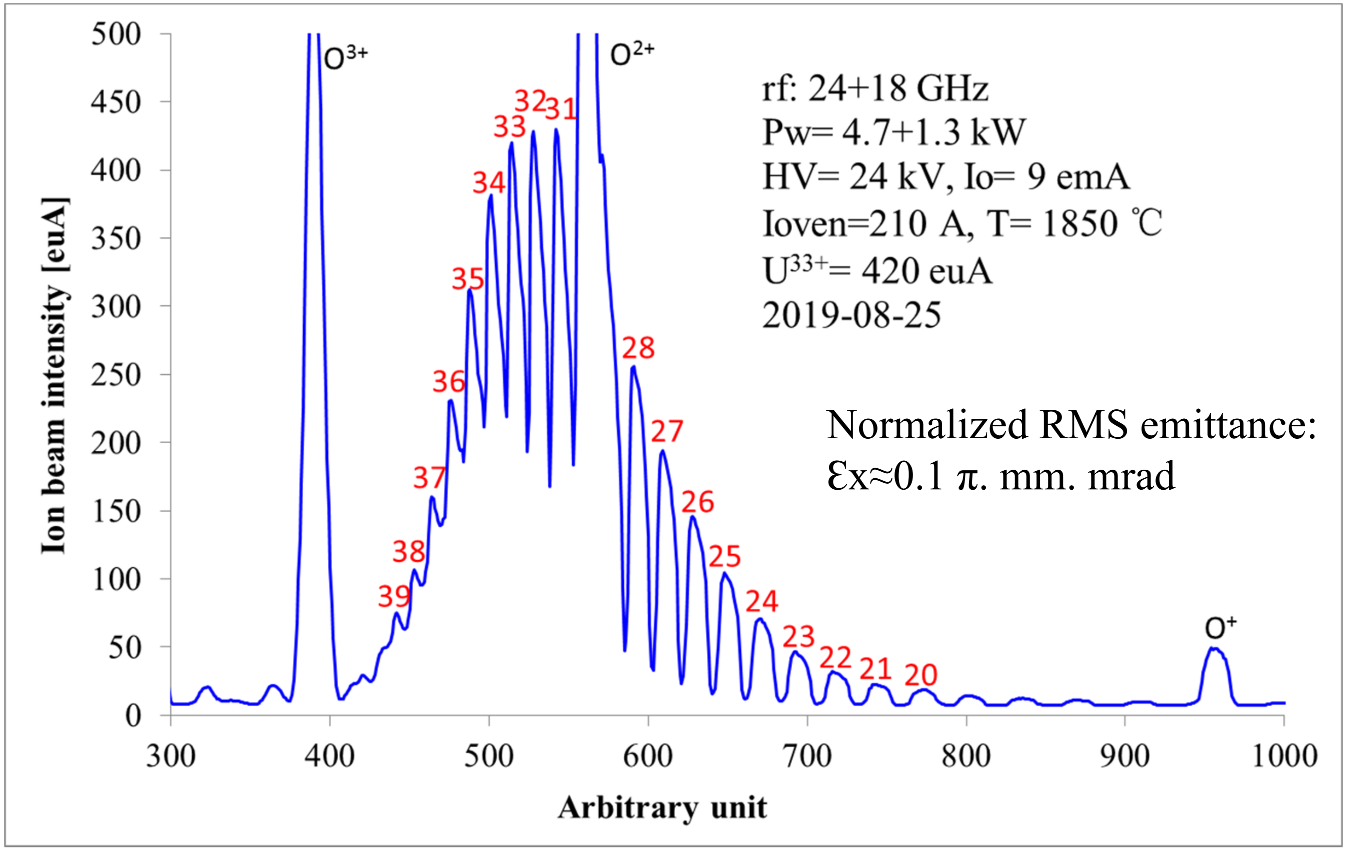
SECRAL-II platform

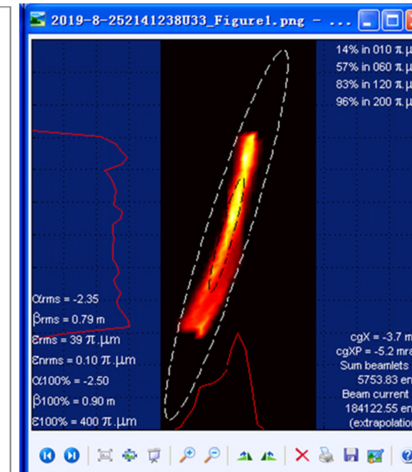


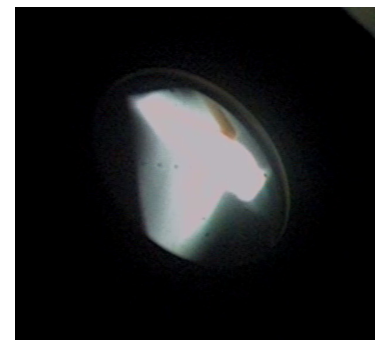


Injection component (SECRAL-II)

Production of intense uranium beams



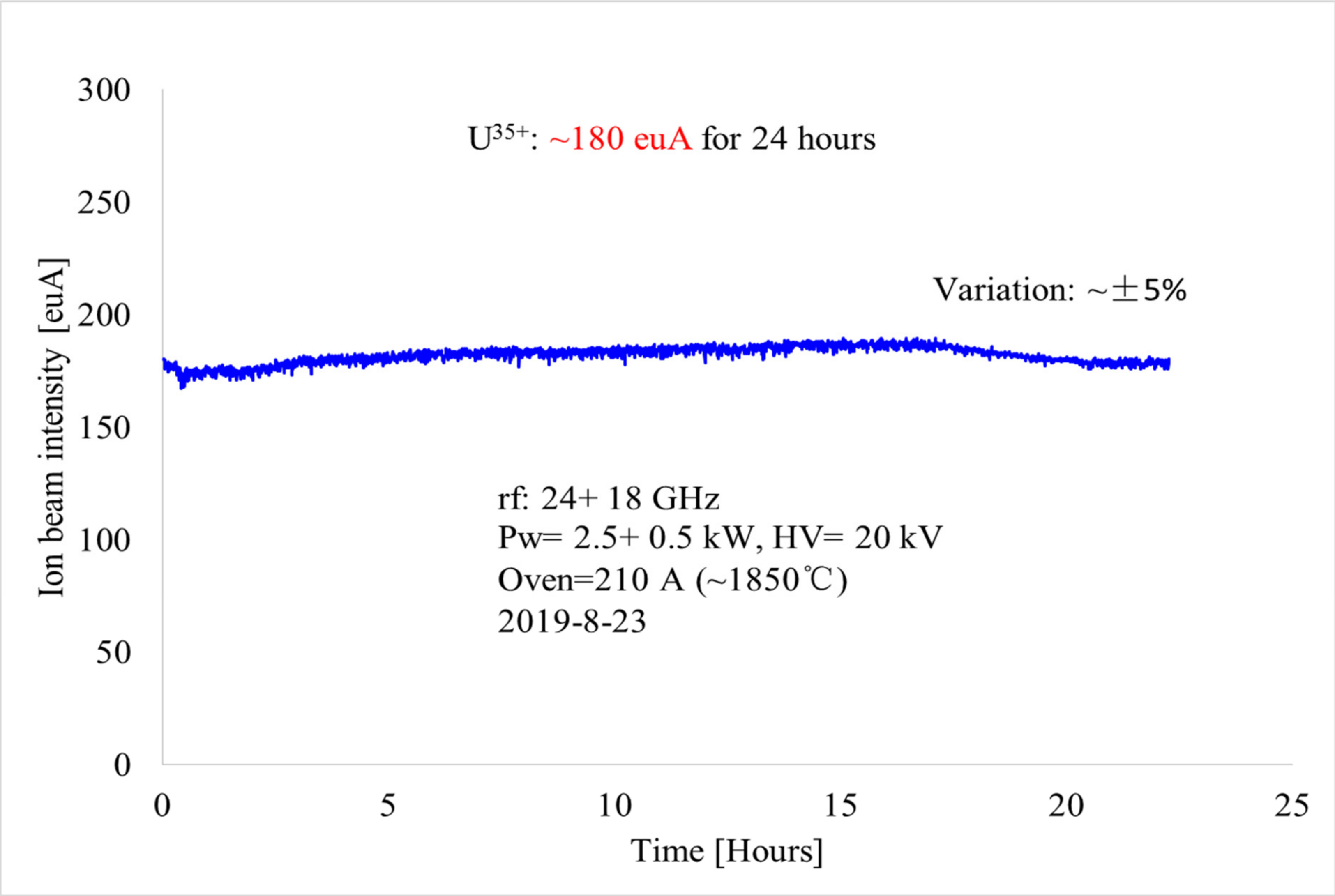




Total maximum rf power ~6.0 kW, some preliminary but very promising intense uranium ions were produced, such as:

450 euA of U^{33+}, 380 euA of U^{34+}, 310 euA of U^{35+}, etc

$^{238}U^{35+}$ stability test



Uranium beam latest results

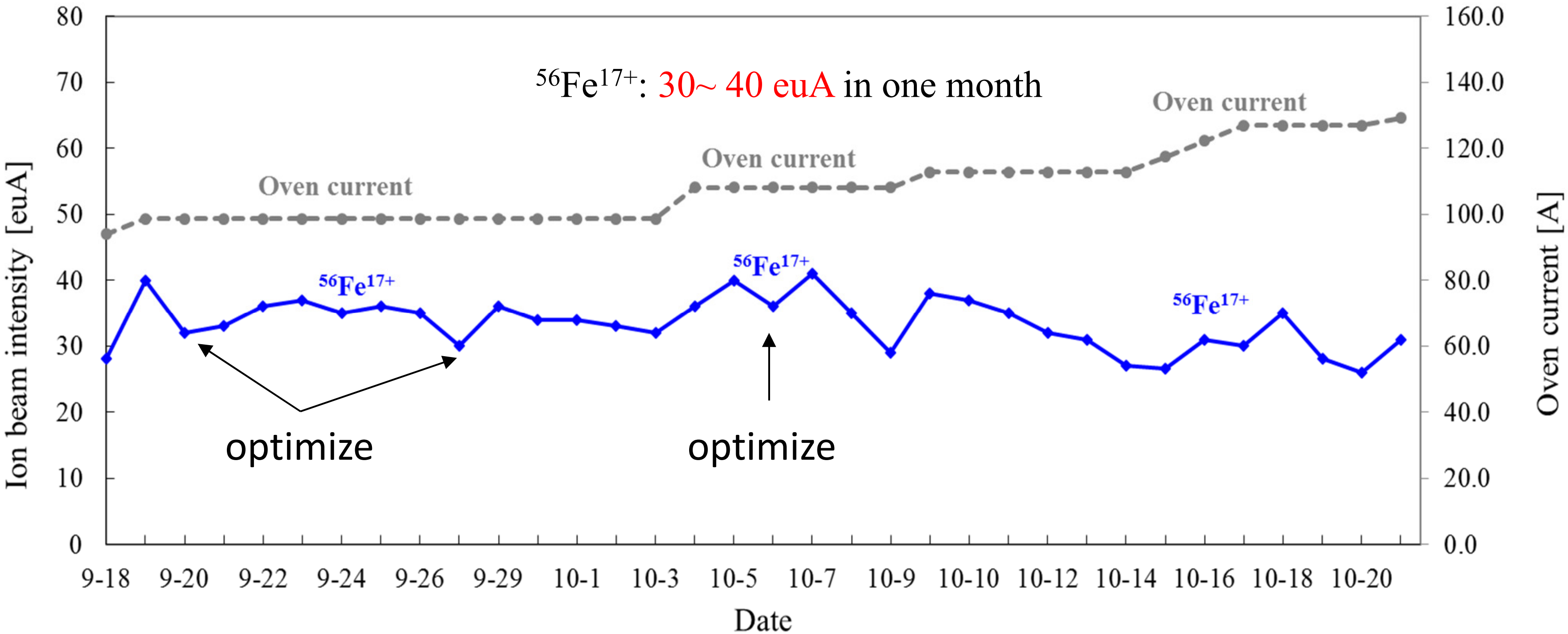
Ion Species	Source	Rf Power (kW)	Ion Beam Intensity (euA)
$^{238}U^{33+}$	SuSI	3.4	180
$^{238}U^{35+}$	SuSI	3.4	135
$^{238}U^{33+}$	SECRAL-II	6.0	450
$^{238}U^{35+}$	SECRAL-II	5.8	310
$^{238}U^{42+}$	SECRAL-II	5.8	60
$^{238}U^{46+}$	SECRAL-II	5.8	26
$^{238}U^{50+}$	SECRAL-II	5.8	9
$^{238}U^{54+}$	SECRAL-II	5.8	2.6
$^{238}U^{56+}$	SECRAL-II	5.8	0.9

Average consumption rate in a week: ~4.5 mg/h

Standard Inductive Oven-2019

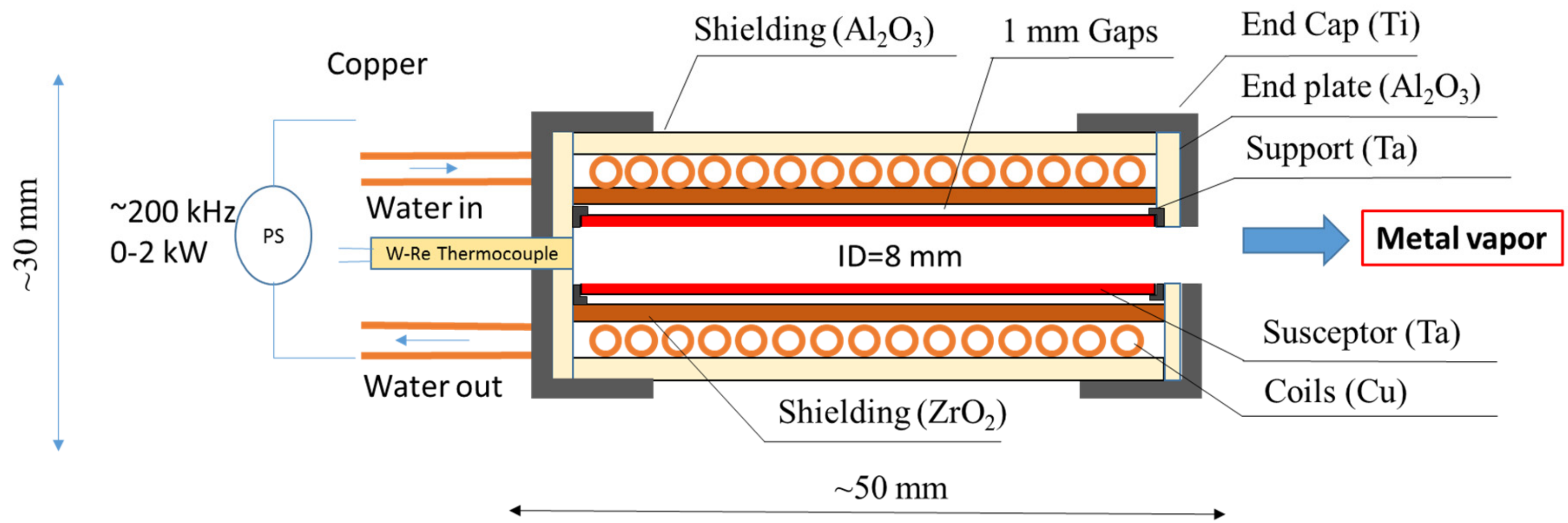
Al^{8+} & Fe^{17+} Routine Operation for HIRFL-CSR

	IHO temperature (℃)	Beam current (euA)	Continuous operation time (days)
$^{27}Al^{8+}$	1300-1400	20-30	7
$^{56}Fe^{17+}$	1400-1500	30-40	32



Long-term reliability of standard inductive oven-2019 is reasonable!

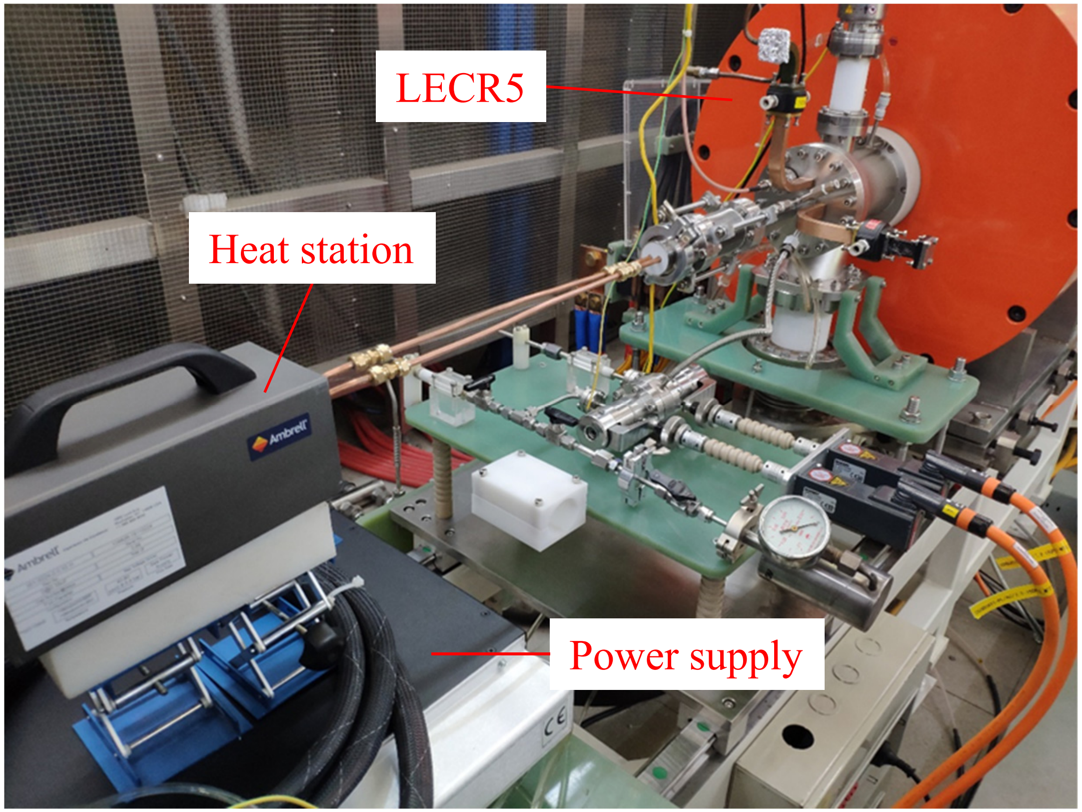
The layout of Mini-Inductive Oven (2020)



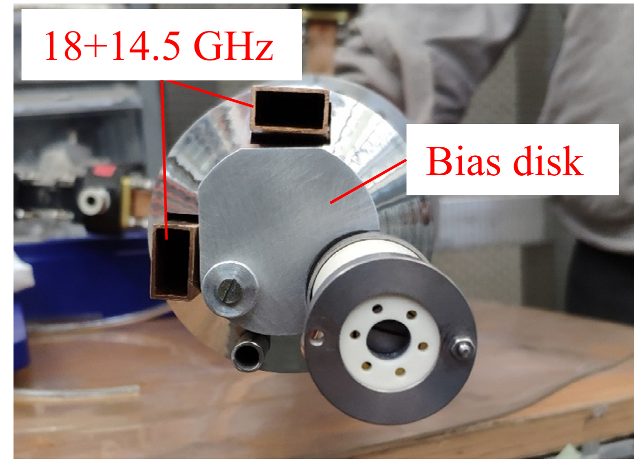
- Design temperature: 1800 -2100 ^{0}**C ;**
- Design working life: >200 hours;
- Control mode: Close loop (open loop at the first step);
- Capacity: Ø 8 mm×40 mm crucible;
- Main features: **Smaller & Shorter, but similar crucible diameter;**

Mini-Inductive Oven-2020

The On-line Test on LECR5 platform



LECR5 platform



Injection component (LECR5)

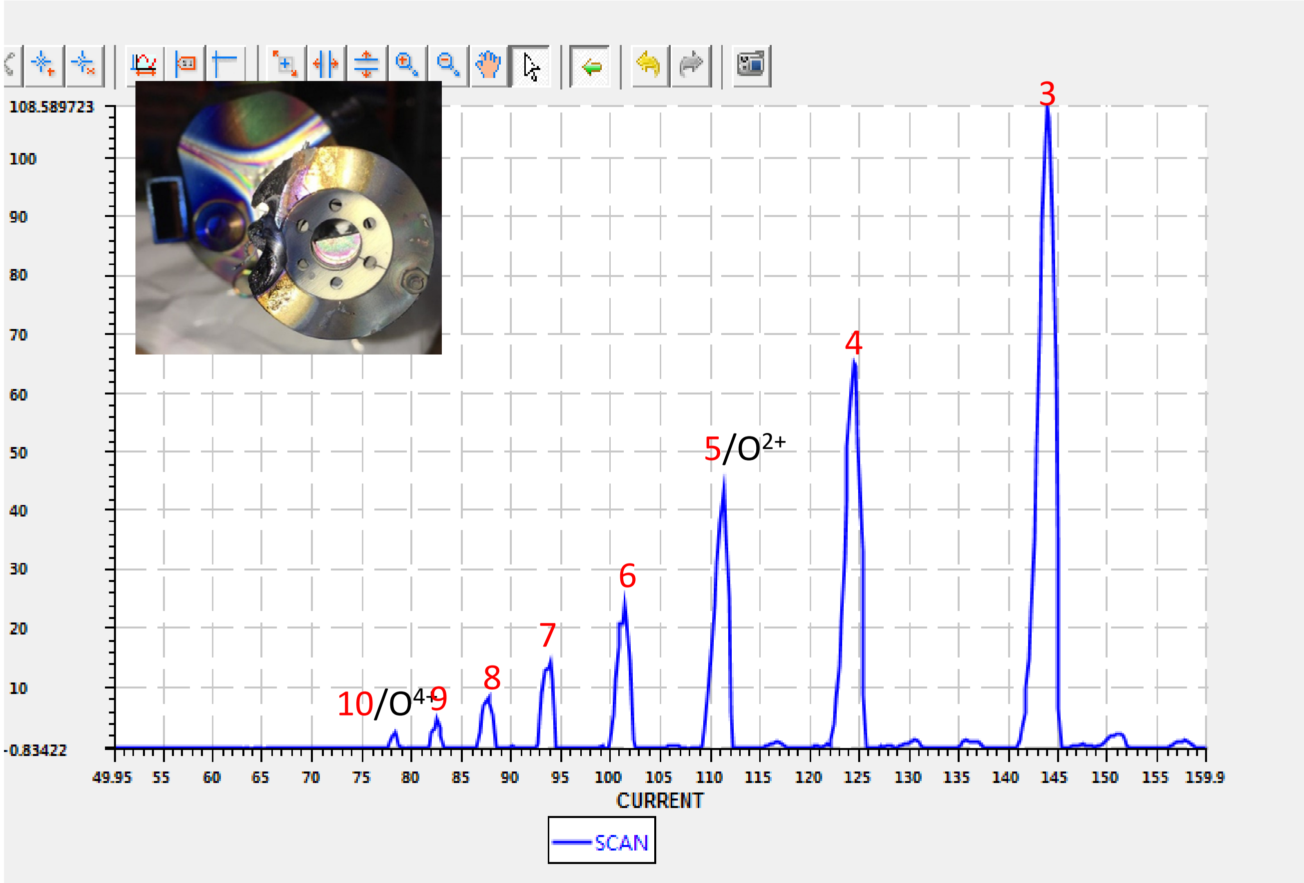
Mini-Inductive Oven-2020

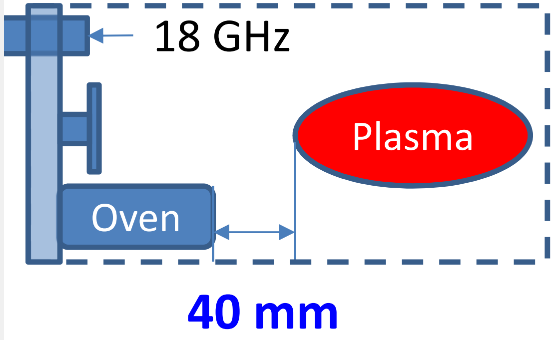
To produce calcium beams with CaO & Mini-Inductive Oven-2020

Ion source group at RIKEN has produced ~50 euA of $^{40}Ca^{11+}$ with CaO & high temperature oven in 2019*

* Private communication

Production of calcium beams with CaO-1st test





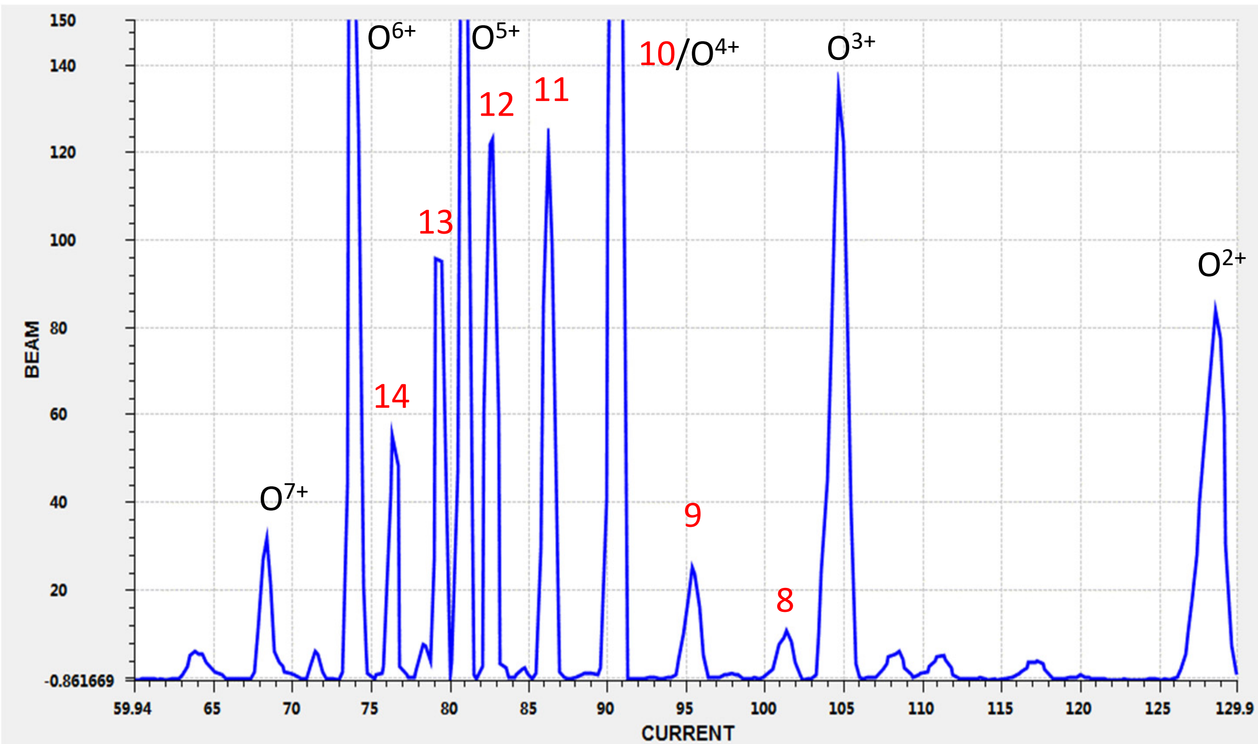
rf: 18 GHz
Pw= 0.4 kW, HV= 15 kV
Io= 1.4 emA, $^{40}Ca^{3+}$= 110 euA
OVEN: 195 A (1800 °C)
Pinj= 3.8×10^{-7} mbar
Pext= 1.0×10^{-7} mbar
2020-7-27

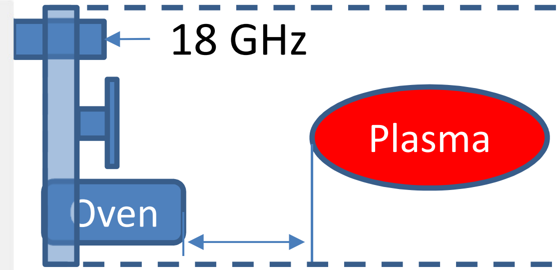
Plasma heating contributes too much, that leads to serious outgassing and instability.

Only low charge state ion beams produced, like:

110 euA of Ca^{3+}, 60 euA of Ca^{4+}, etc

Production of calcium beams with CaO-2nd test





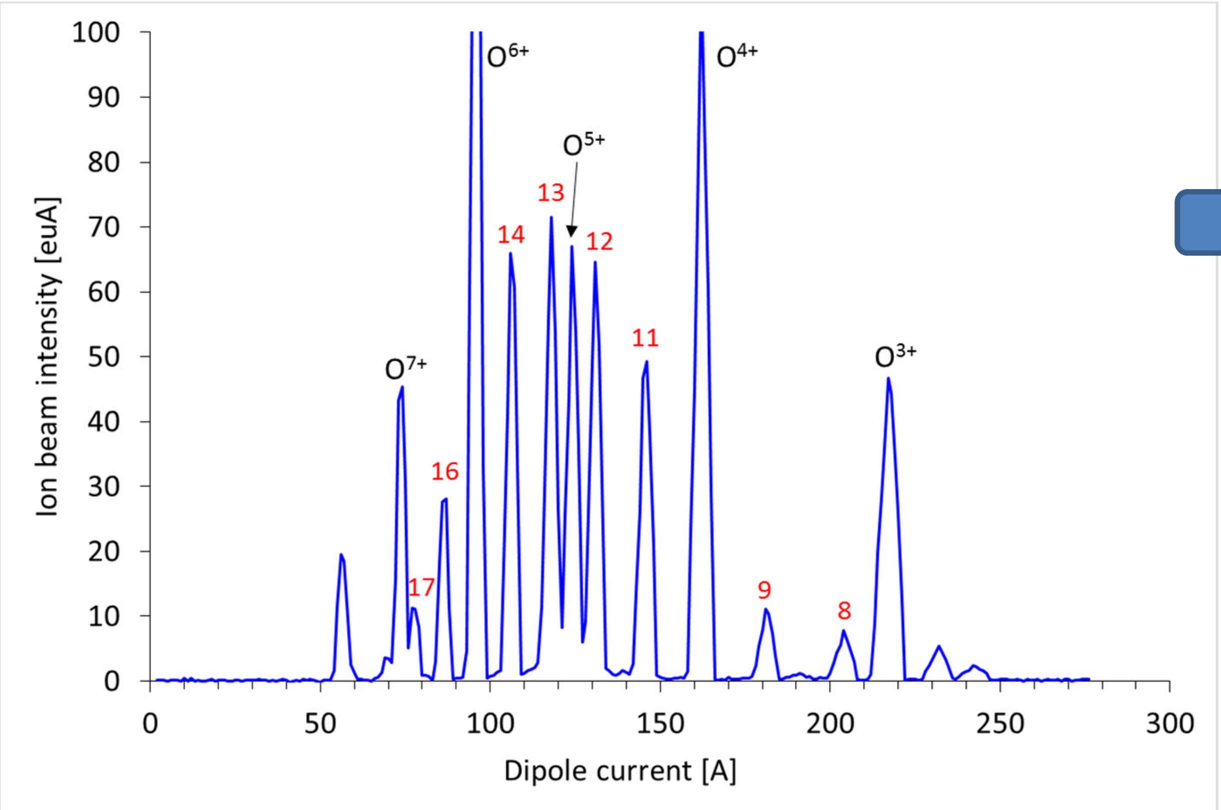
60 mm

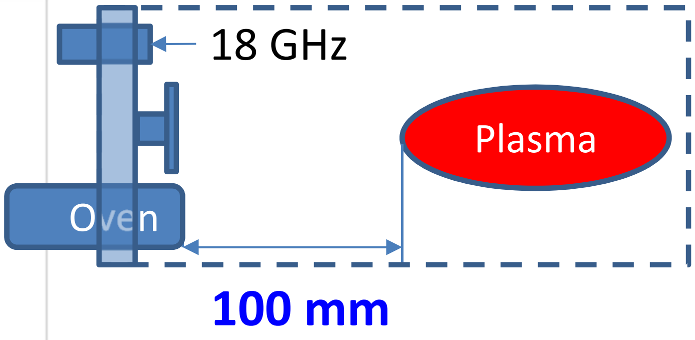
rf: 18 GHz
Pw= 1.0+0.2 kW, HV= 20 kV
Io= 2.0 emA, $^{40}Ca^{12+}$= 120 euA
OVEN: 180 A (1700 °C)
Pinj= 3.6×10^{-7} mbar
Pext= 9.2×10^{-8} mbar
2020-8-4

Plasma heating influence still obvious, but much lower, some medium charge state ion beams can been produced:

120 euA of Ca^{12+}, 50 euA of Ca^{14+}, etc

Production of calcium beams with CaO-3rd test



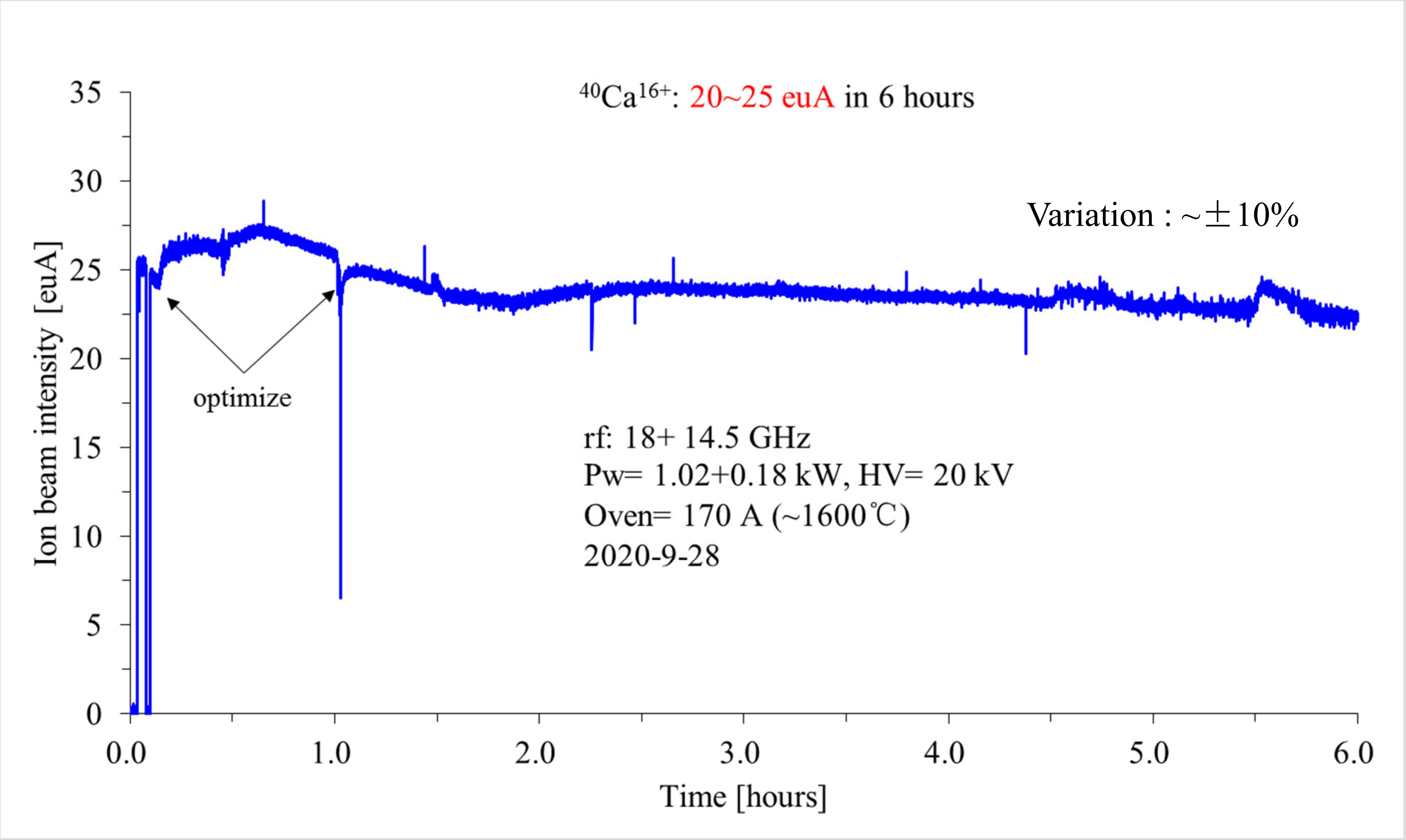


rf: 18 GHz
Pw= 1.02+0.18 kW, HV= 20 kV
Io= 1.1 emA, $^{40}Ca^{16+}$= 28 euA
OVEN: 170 A (1600 °C)
Pinj= 2.5×10^{-7} mbar
Pext= 5.4×10^{-8} mbar
2020-9-27

Plasma heating influence can be well controlled, and very high charge state ion beams produced:

30 euA of Ca^{16+}, 10 euA of Ca^{17+}, etc

$^{40}Ca^{16+}$ stability test



Summary

- Standard and Mini inductive heating ovens have been developed at IMP and they can reach up to 2000 °C with 1.2 kW of AC power.
- Some good results of uranium beams have been achieved on SECRAL-II superconducting ECR ion source platform with about 6 kW of rf power, like 450 euA of U^{33+}, 310 euA of U^{35+}, 60 euA of U^{42+}, and so on.
- Intense high-charge-state calcium ion beams can be produced on LECR5 room temperature ECR ion source with CaO and inductive heating oven.

Acknowledgement

- Thanks for you attention!