Practical Comparison of Two-Frequency Heating Phenomena in Different ECRISs

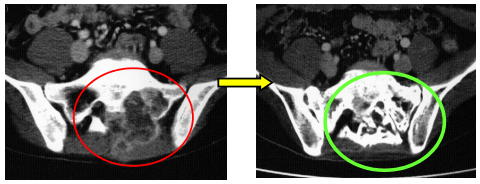
Contents:

1. Introduction
2. Previous experiments at HIMAC
3. Present experiments at ATOMKI
4. Comparison between two experimental results
5. Prospective goal

A. Kitagawa, M. Muramatsu, NIRS, QST, Chiba, Japan
S. Biri, R. Racz, ATOMKI, Debrecen, Hungary
Y. Kato, Osaka Univ., Osaka, Japan
W. Takasugi, AEC, Chiba, Japan

Introduction of
National Institutes for Quantum and Radiological Science and Technology (QST)
since April 2016

- President
  - Headquarters
  - National Institute of Radiological Sciences (NIRS)
  - Quantum Beam Science Research Directorate
    - Takasaki Advanced Radiation Research Institute
    - Kansai Photon Science Institute
  - Fusion Energy Research and Development Directorate
    - Naka Fusion Institute
    - Rokkasho Fusion Institute

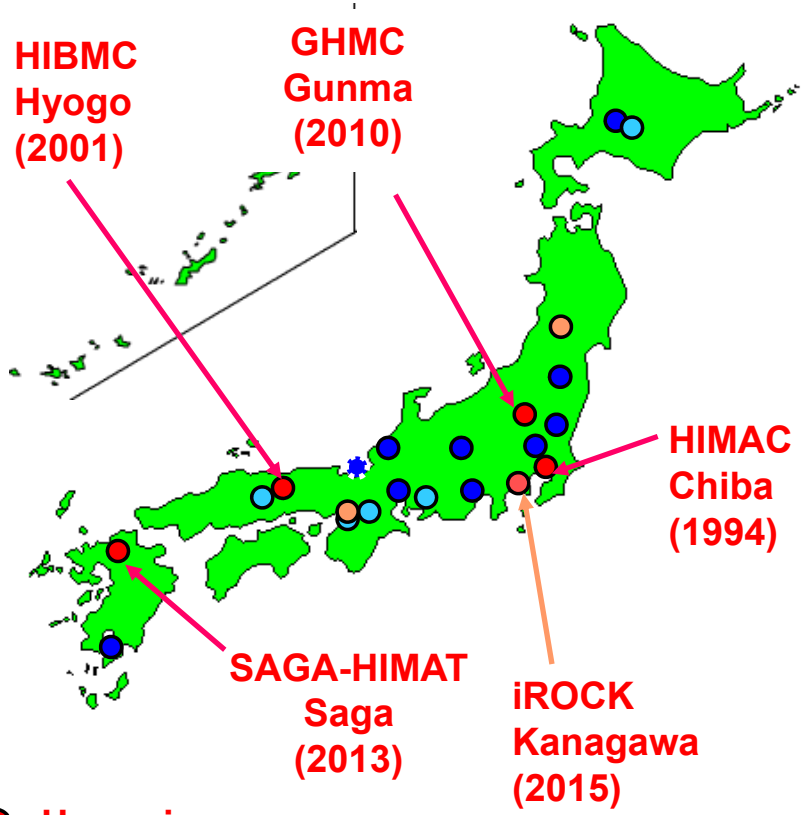


before　　5 years after

1. Introduction

NIRS
HIMAC

Carbon-ion radiotherapy in Japan



Operation facilities:

	Period	Patients total	Patients (in 2014)
HIMAC	(1994 – 2016.8)	10031	(794*)
HIBMC	(2005 – 2016.3)	2263	(241)
GHMC	(2010 – 2016.6)	2087	(501)
Saga-HIMAT	(2013 – 2016.7)	1492	(503)
iROCK	(2015.12 –)	-	(-)
	sum	15873	(2039)

*from Apr. to Mar.

Under construction:

Osaka (plan 2018 –)

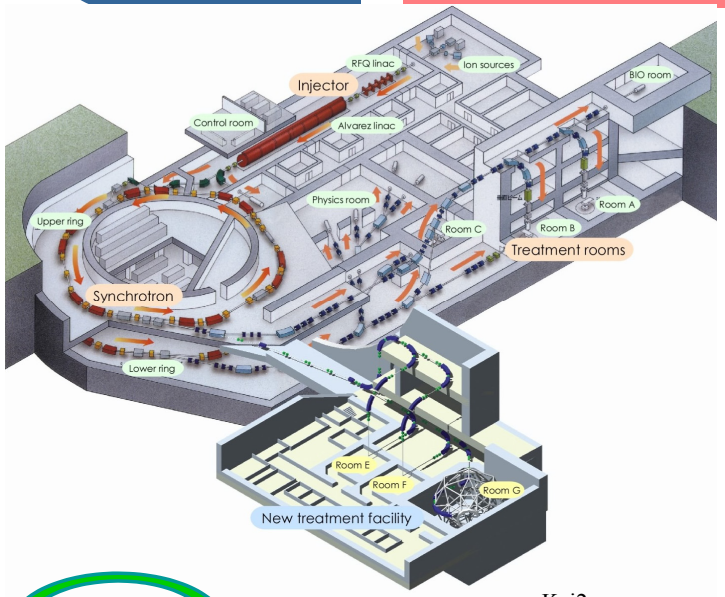
Yamagata (plan 2019 –)

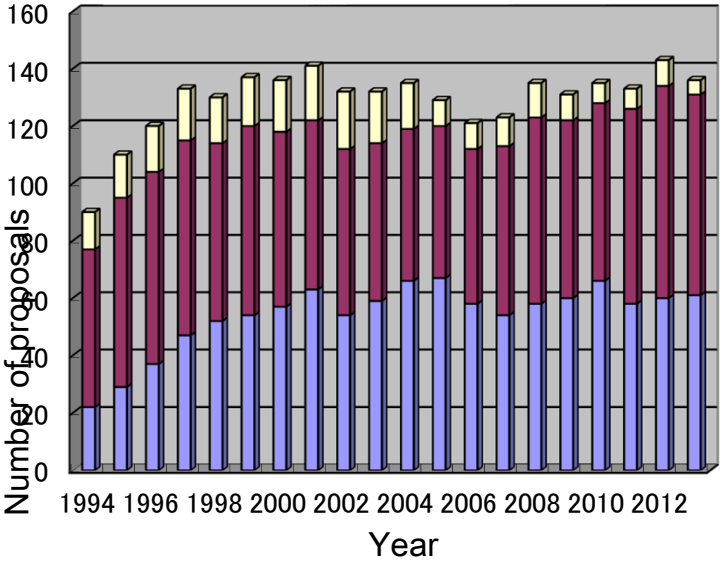
See, Muramatsu's WEBO02

NIRS

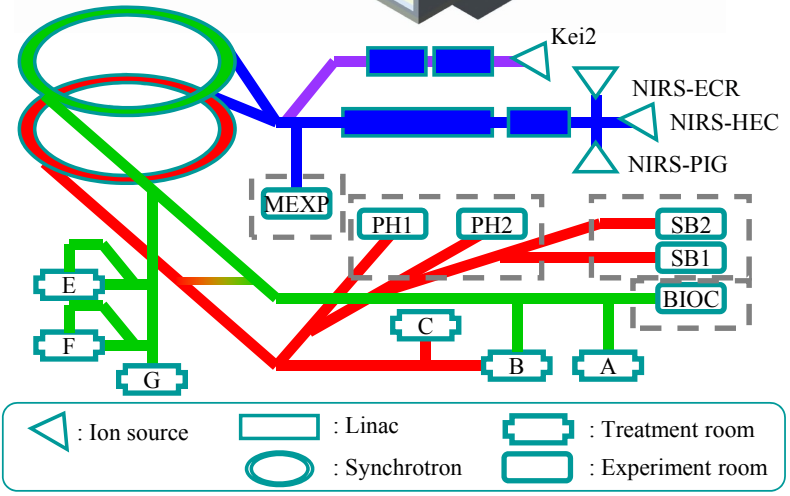
HIMAC

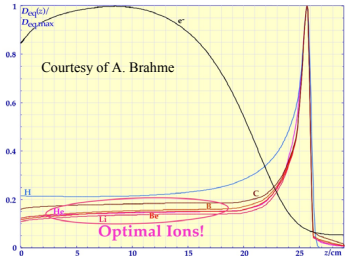
Basic experiments at HIMAC

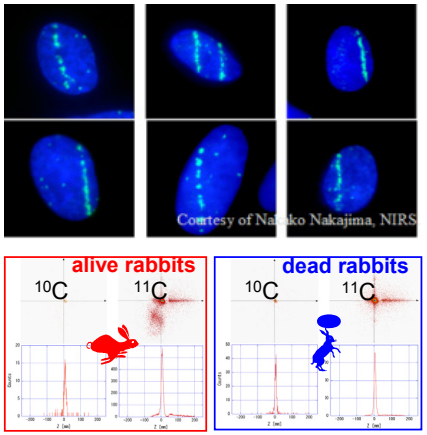




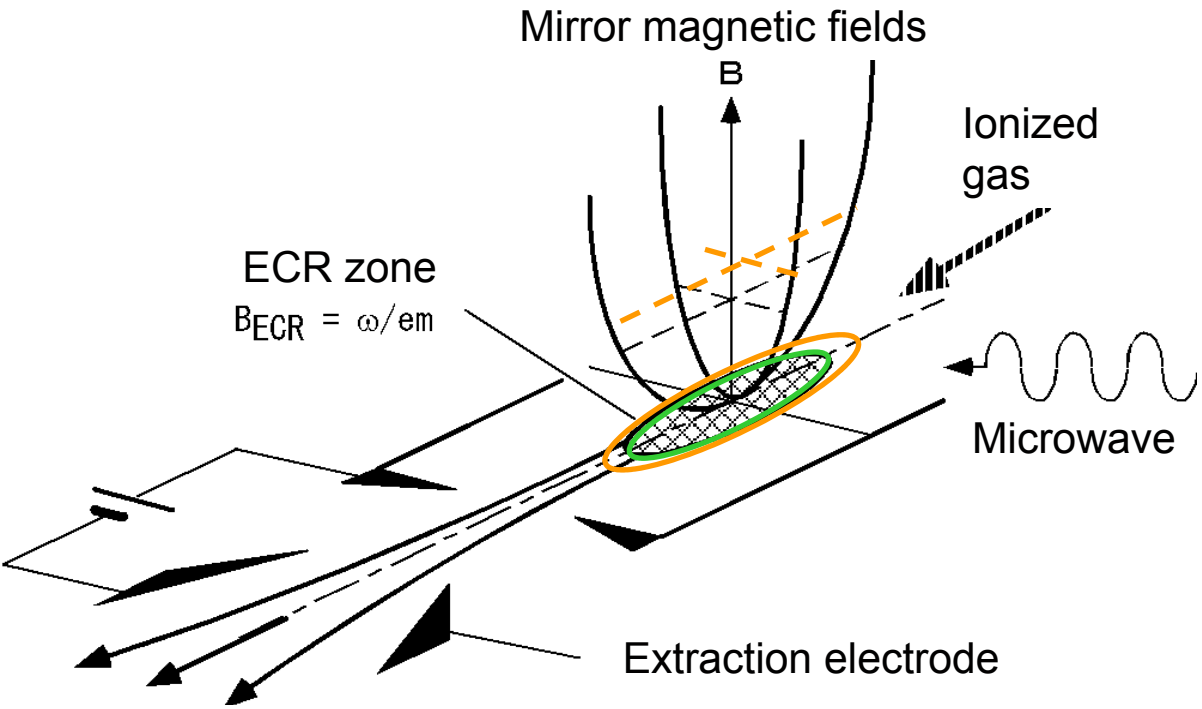
Beam time
~ 5000 hours / year

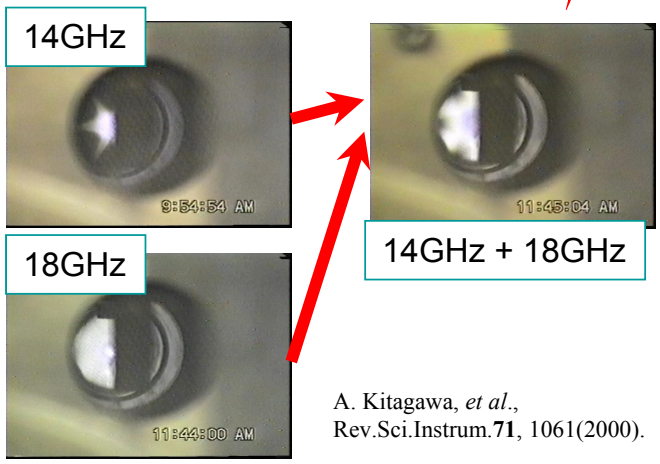




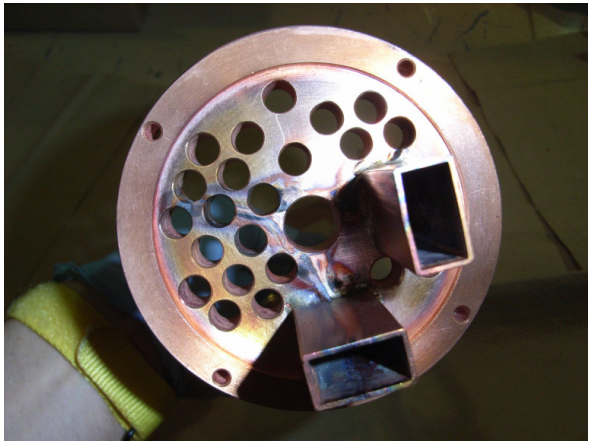


Two-frequency heating





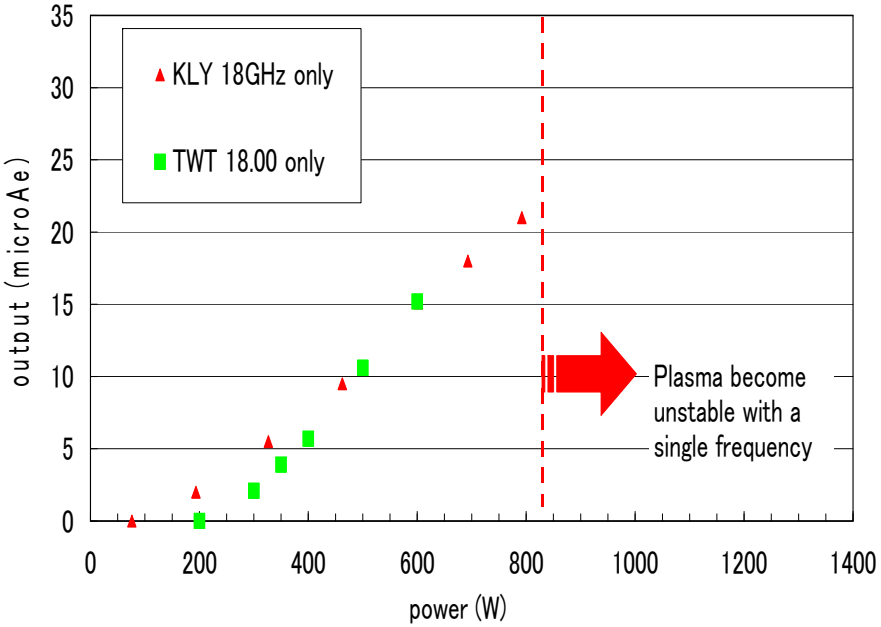
A. Kitagawa, *et al.*,
Rev.Sci.Instrum.**71**, 1061(2000).



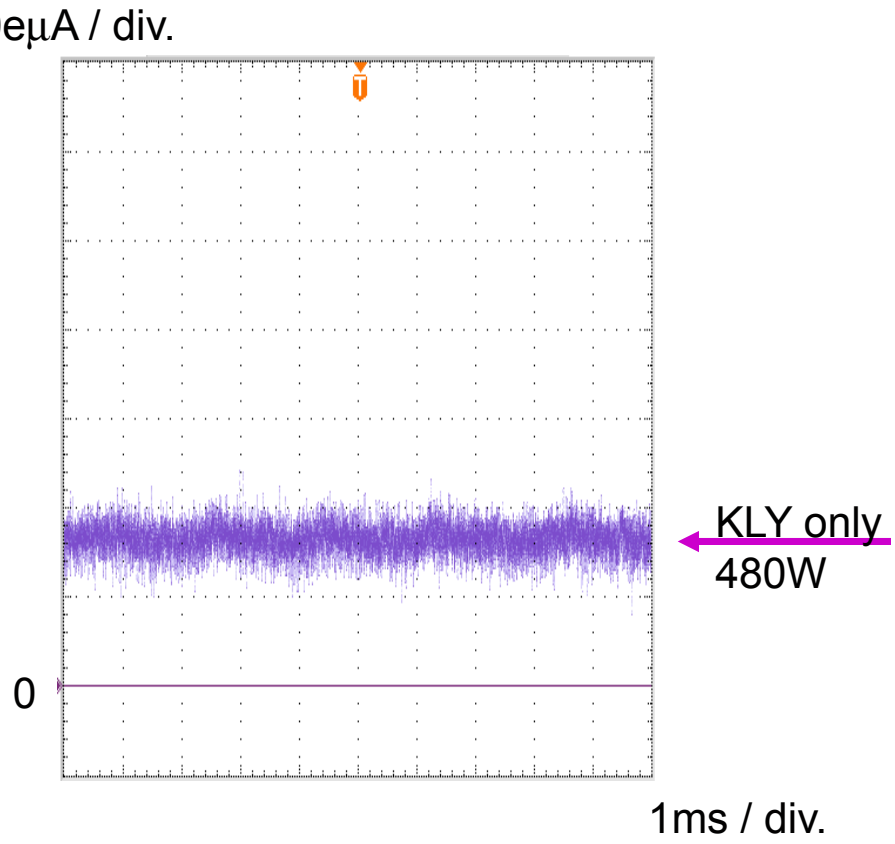
In order to increase the beam intensities of various ions, a technique to feed multiple microwaves with different frequencies, the so-called two-frequency heating technique, has been studied.

2. Previous experiments at HIMAC

Power dependence and instability

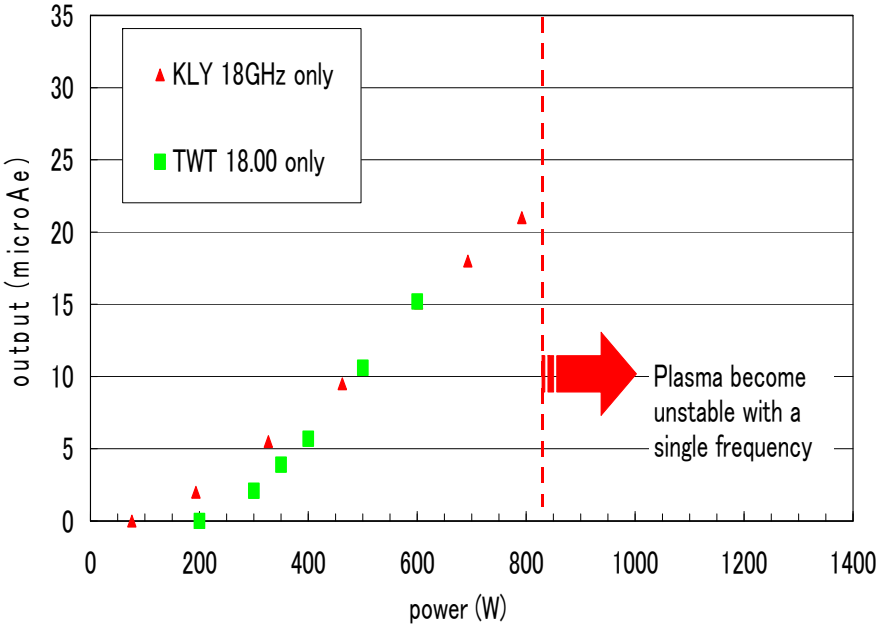


Microwave power dependence

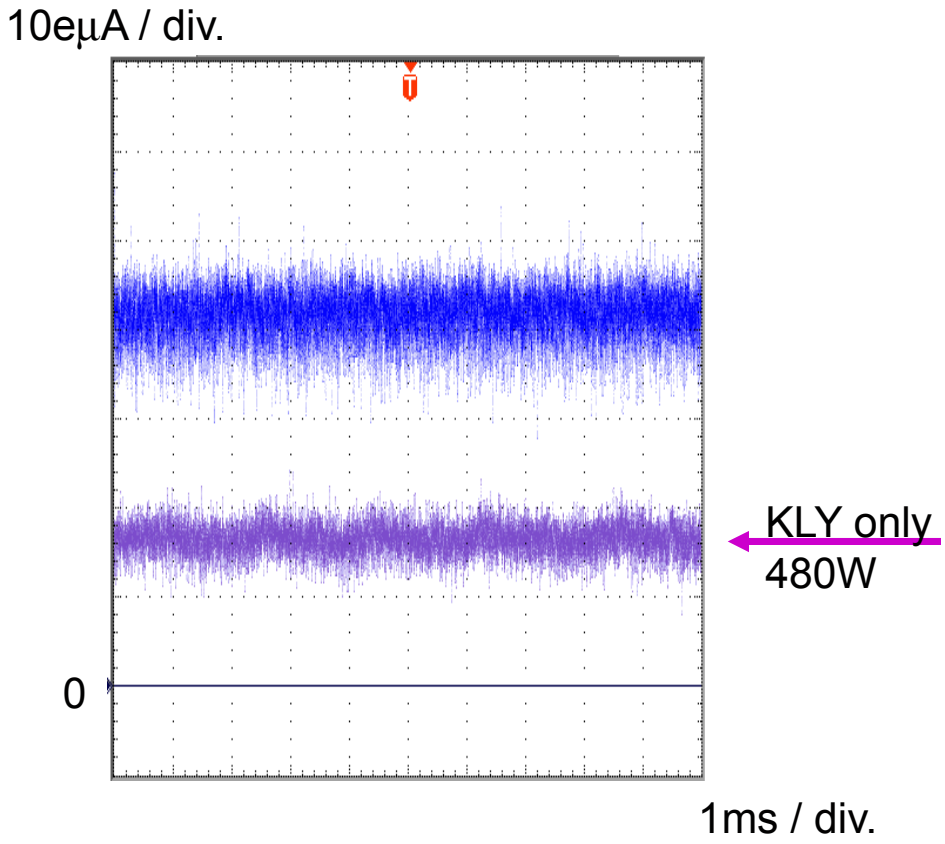


Example of time structures (Xe^{21+})

Power dependence and instability

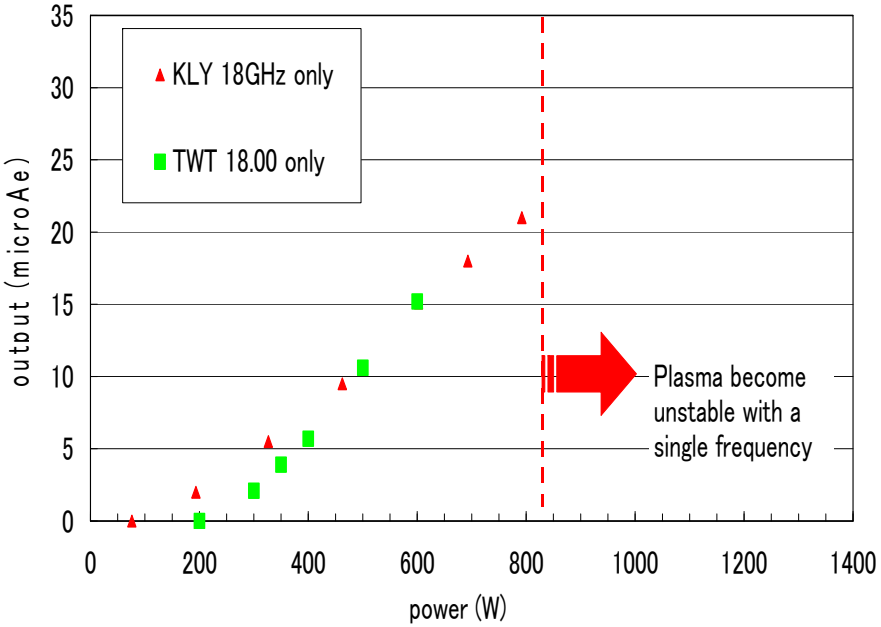


Microwave power dependence

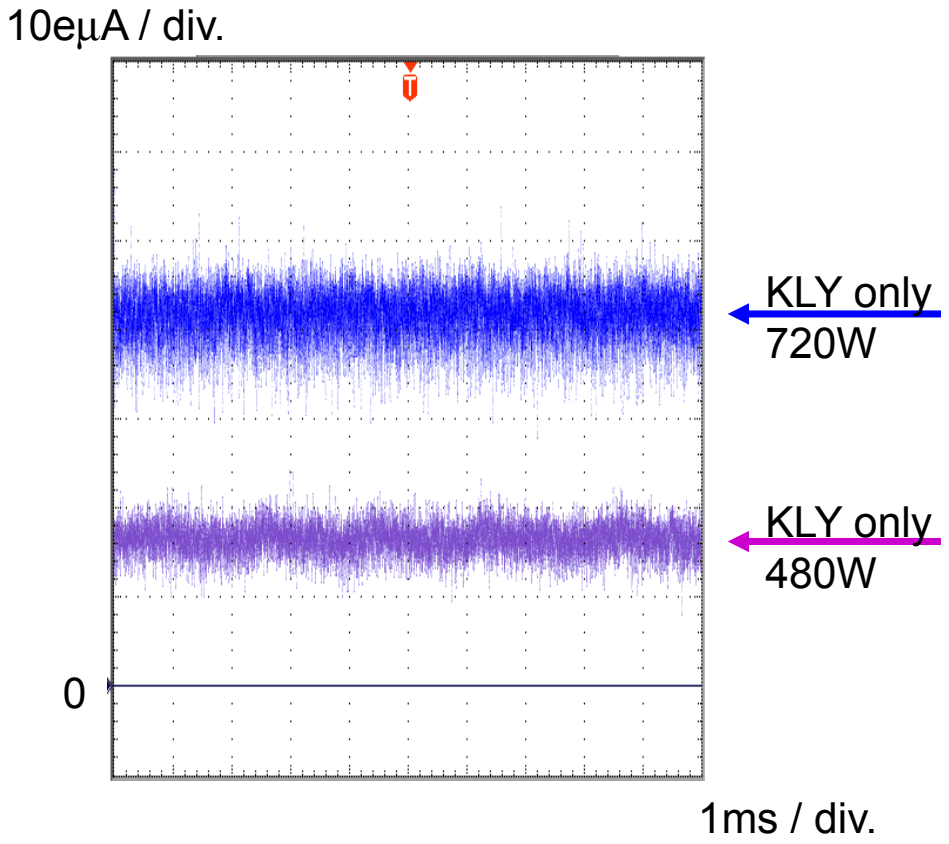


Example of time structures (Xe^{21+})

Power dependence and instability

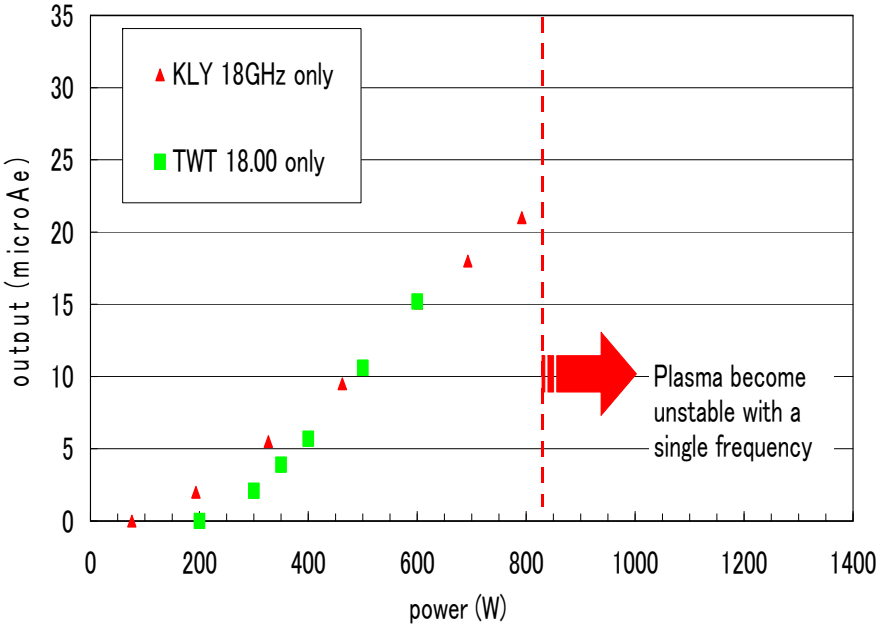


Microwave power dependence

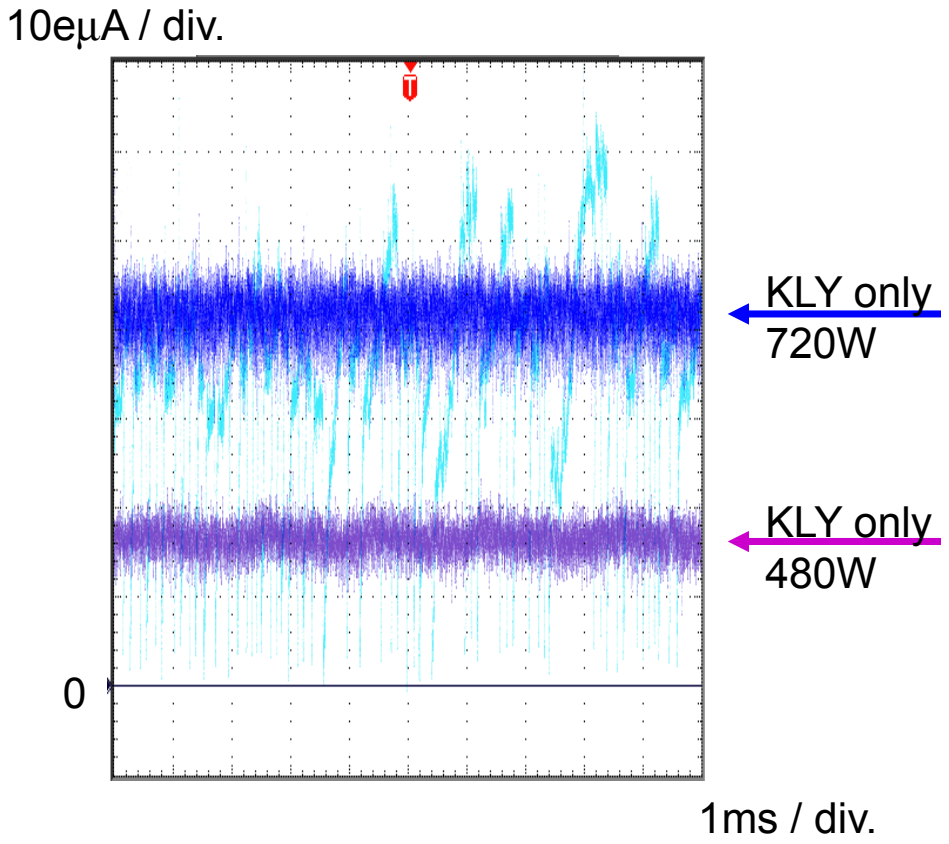


Example of time structures (Xe^{21+})

Power dependence and instability

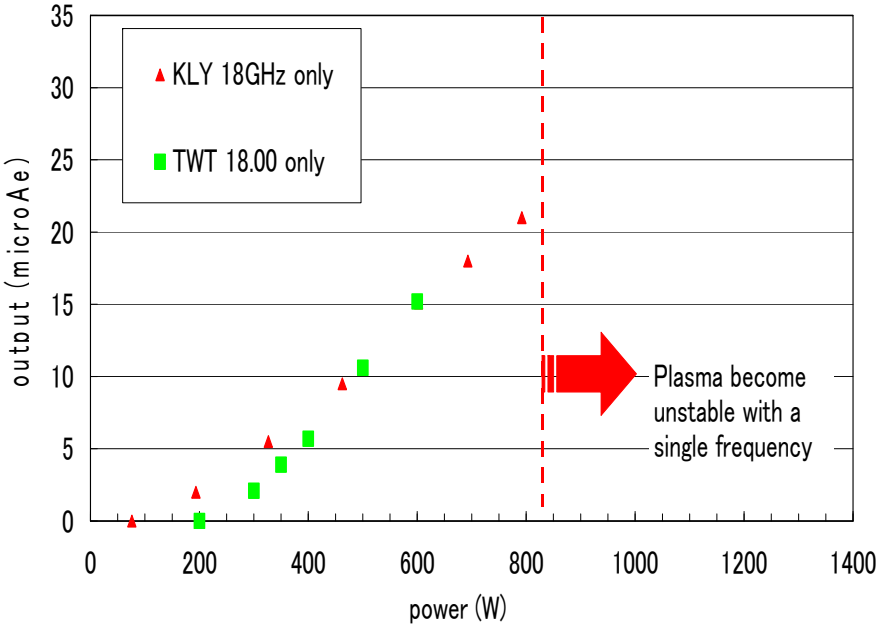


Microwave power dependence

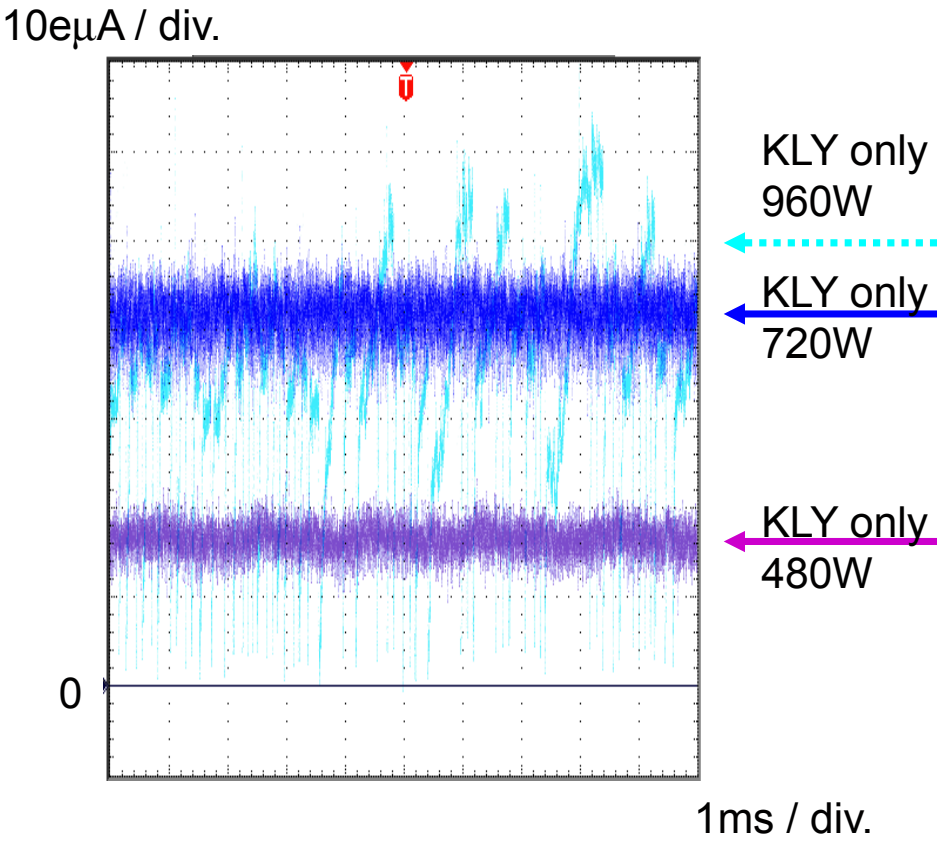


Example of time structures (Xe^{21+})

Power dependence and instability



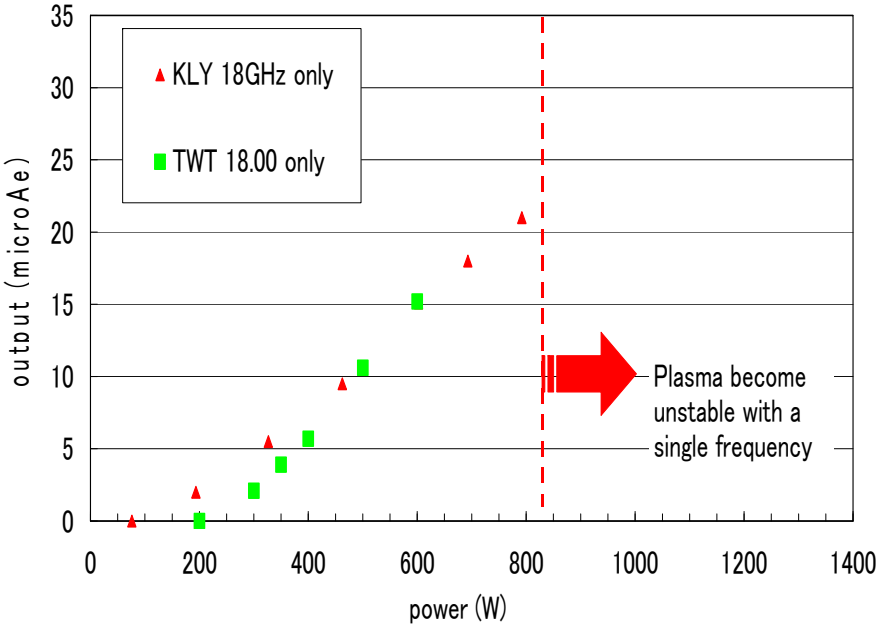
Microwave power dependence



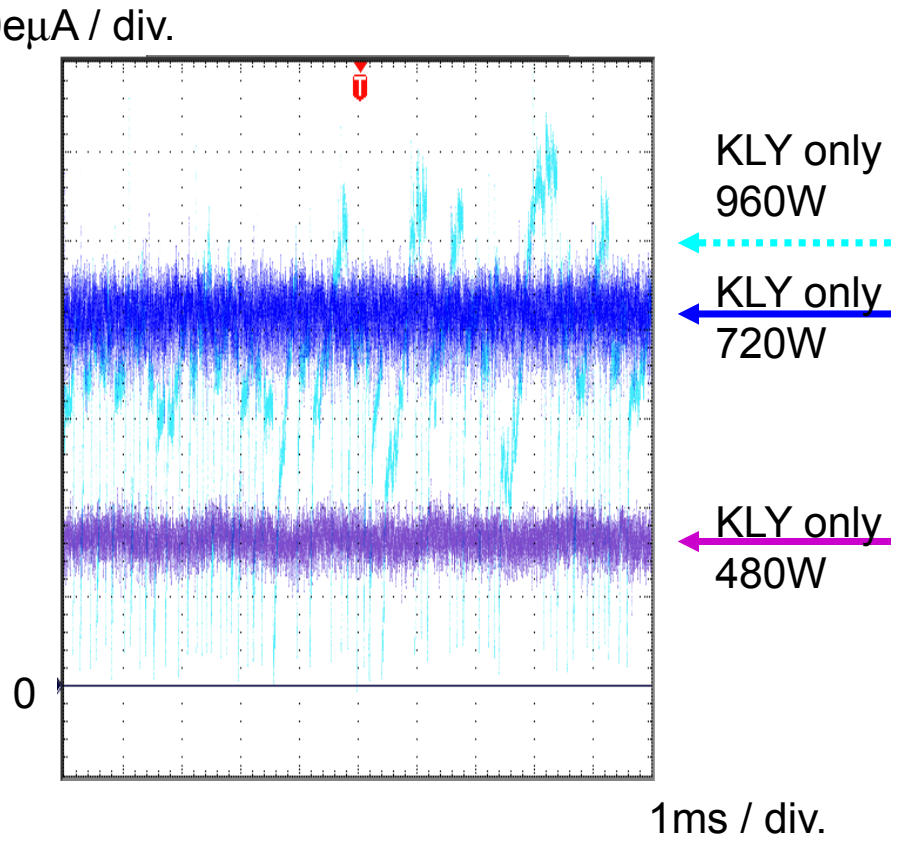
Example of time structures (Xe^{21+})

Power dependence and instability

- When the microwave power increases, the plasma shows instability, and it is difficult to keep.

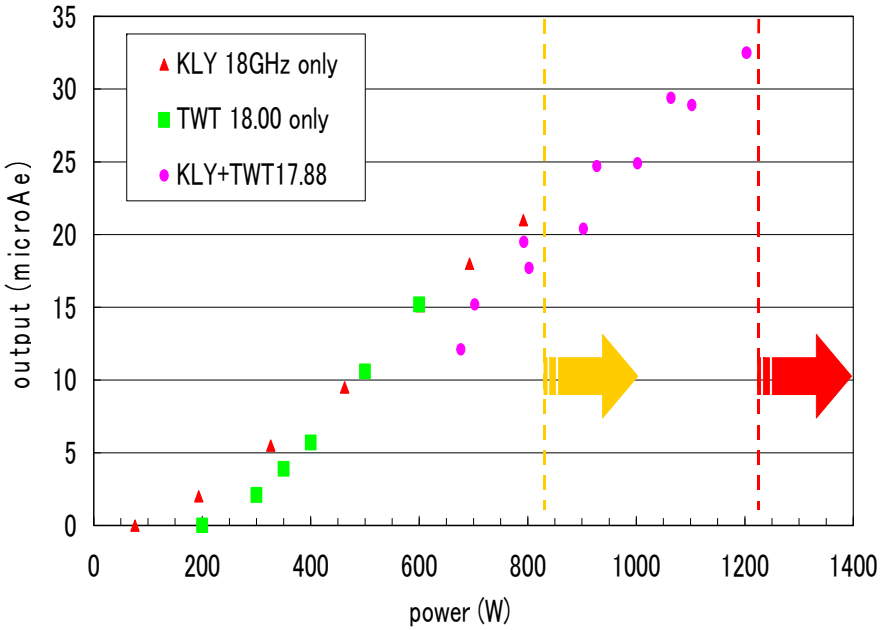


Microwave power dependence

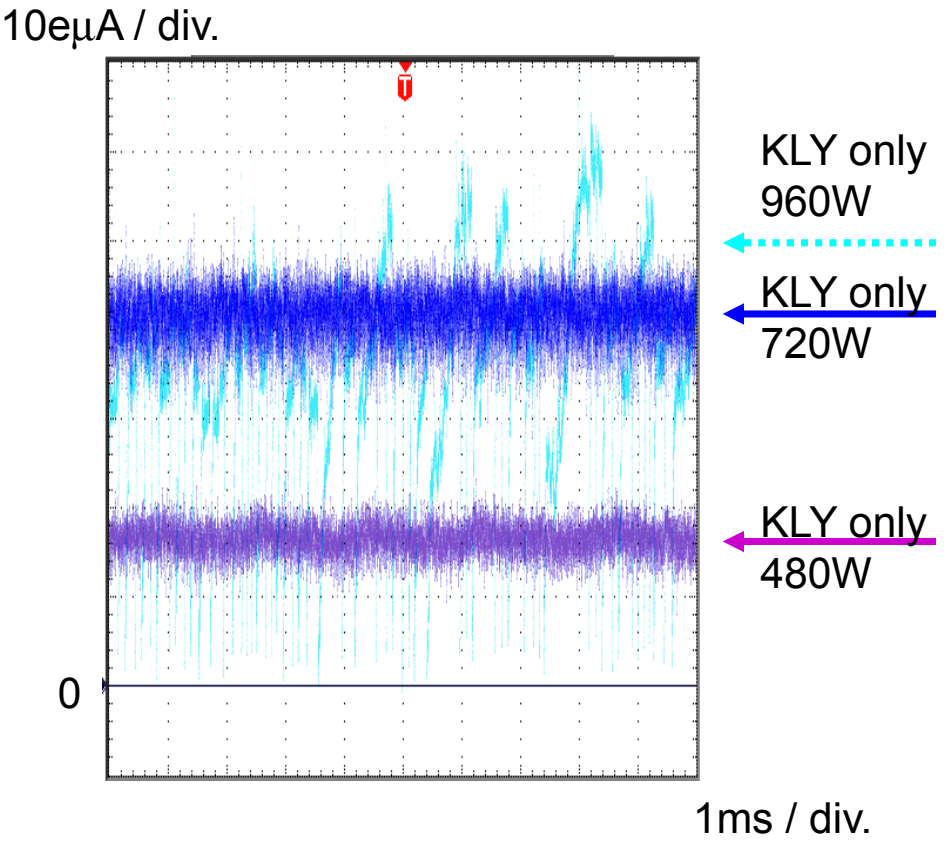


Example of time structures (Xe^{21+})

Power dependence and instability



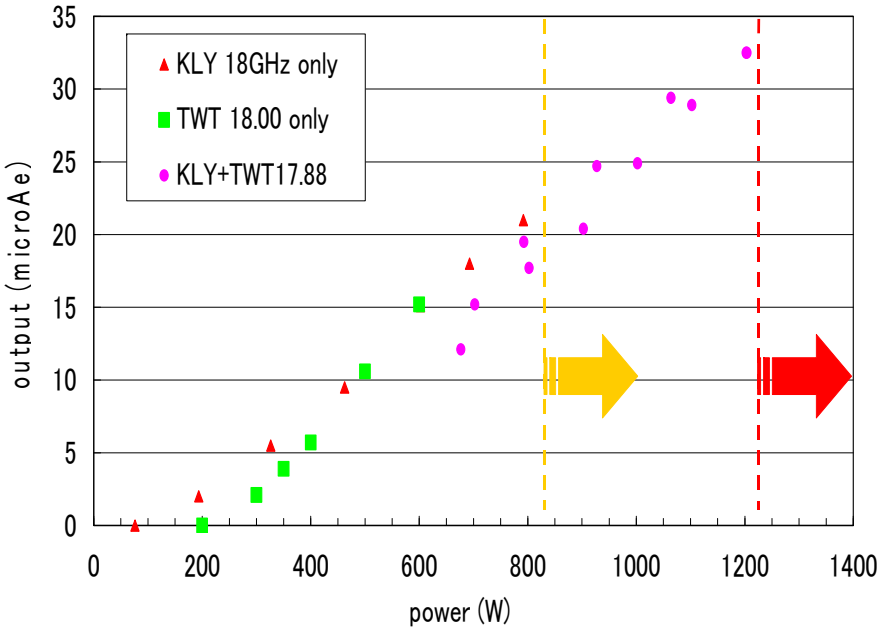
Microwave power dependence



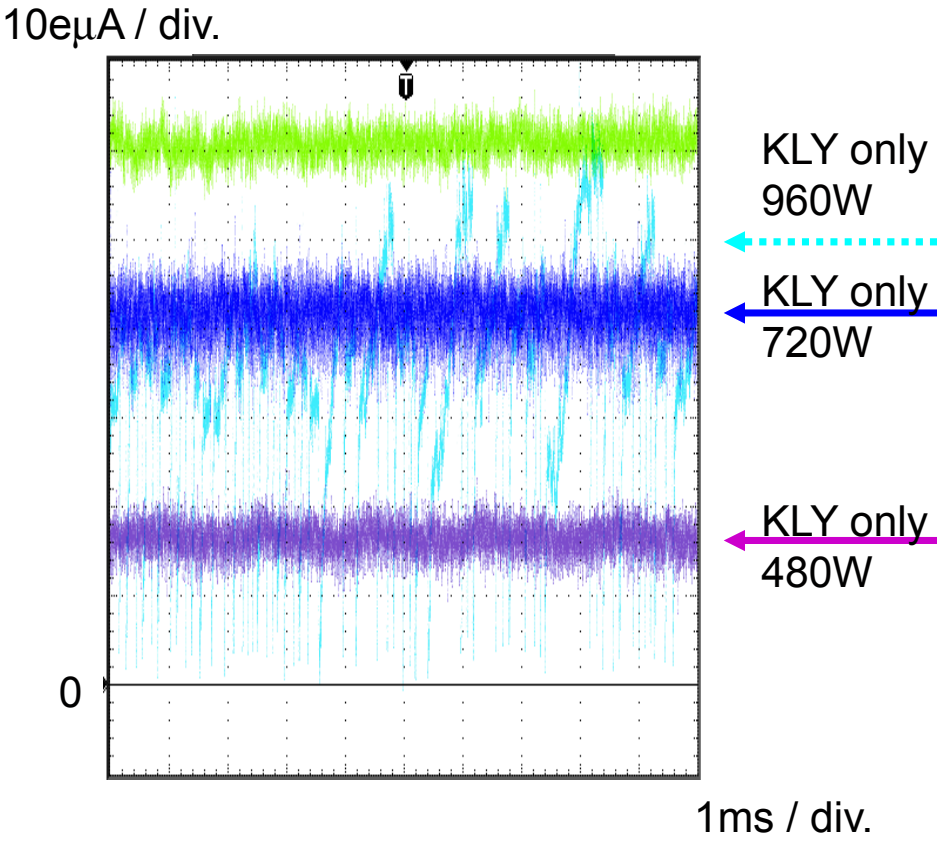
Example of time structures (Xe^{21+})

A. Kitagawa, et al, ECRIS2012, Sydney, September 2012, p. 10 (2012).

Power dependence and instability



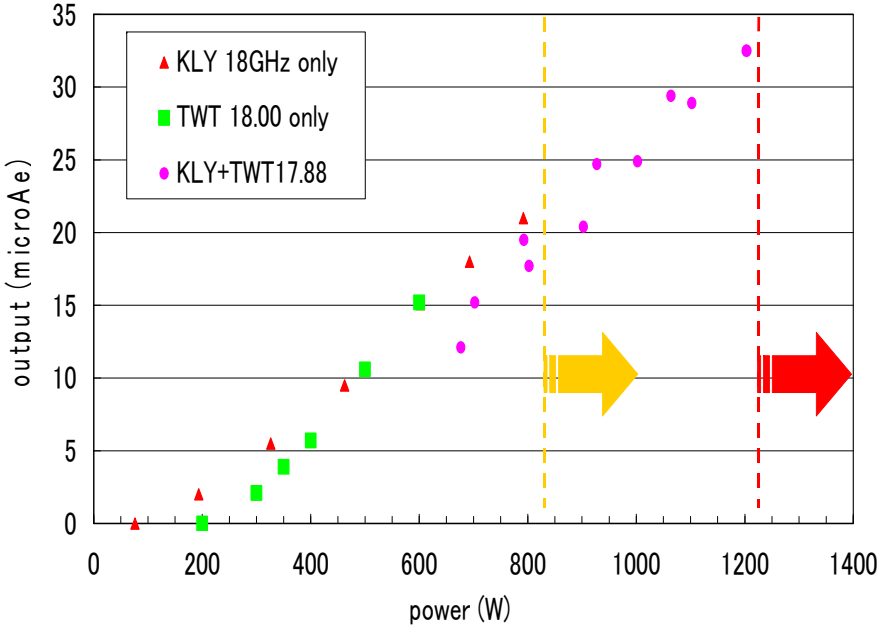
Microwave power dependence



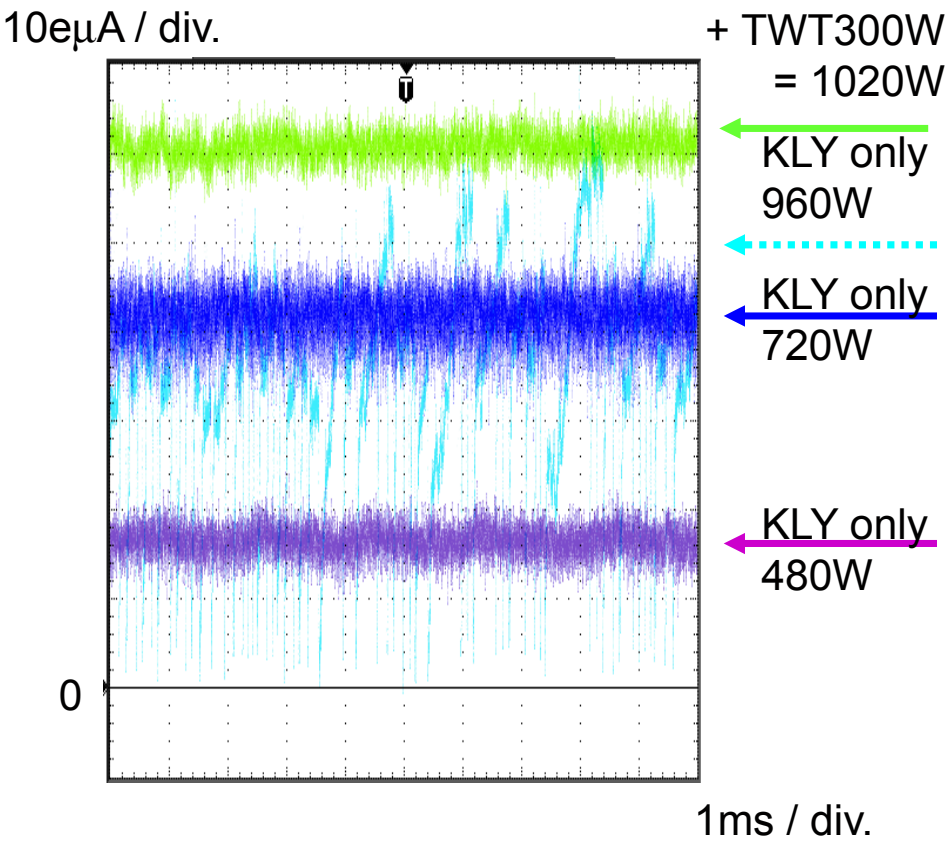
Example of time structures (Xe^{21+})

A. Kitagawa, et al, ECRIS2012, Sydney, September 2012, p. 10 (2012).

Power dependence and instability



Microwave power dependence

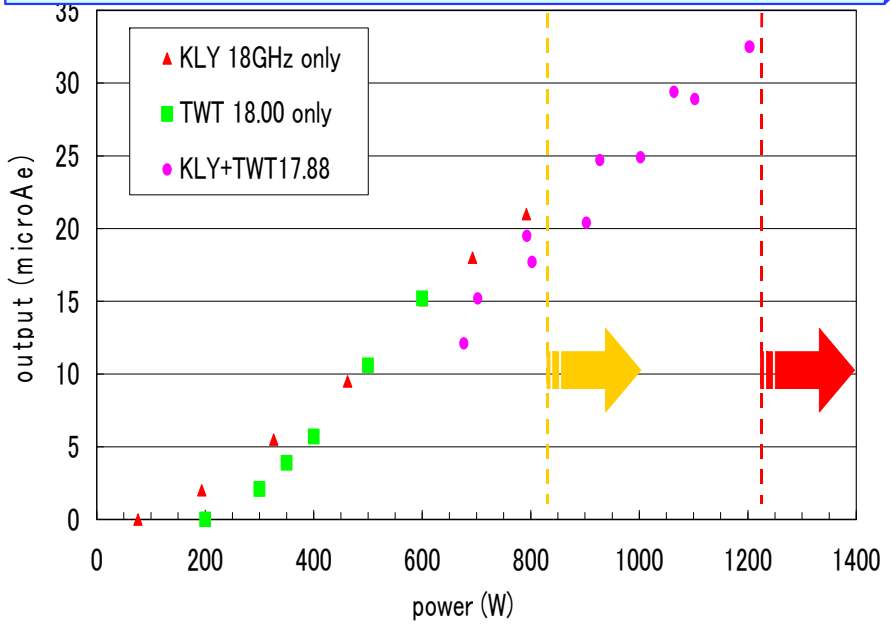


Example of time structures (Xe^{21+})

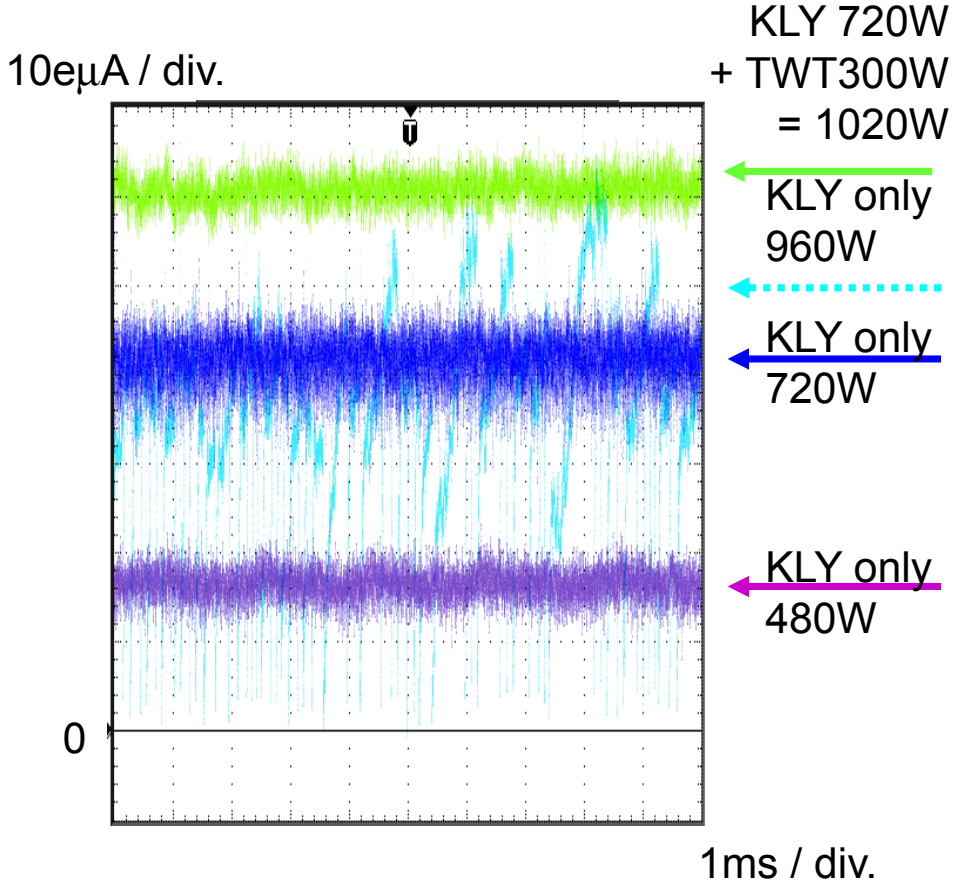
A. Kitagawa, et al, ECRIS2012, Sydney, September 2012, p. 10 (2012).

Power dependence and instability

- When an additional microwave with a different frequency is added, the plasma stability is improved at greater microwave power.



Microwave power dependence



Example of time structures (Xe^{21+})

A. Kitagawa, et al, ECRIS2012, Sydney, September 2012, p. 10 (2012).

Our previous conclusion

- An additional microwave with a different frequency improves the plasma stability at greater microwave power.
- The output current of the highly charged ion beam is proportional to the total power of both microwaves.
- It was guessed that the additional frequency controls the anisotropy of the electrons' velocity distribution which may affect the plasma instability. Two frequencies are each close together ("close 2f") are capable for this purpose at NIRS.
- The dependence on the additional frequency showed fine structure. This structure depended on the parameters (magnetic field, vacuum pressure, and so on).

Frequency dependence

Large power 18.0 GHz Krystron

+ Small power TWT

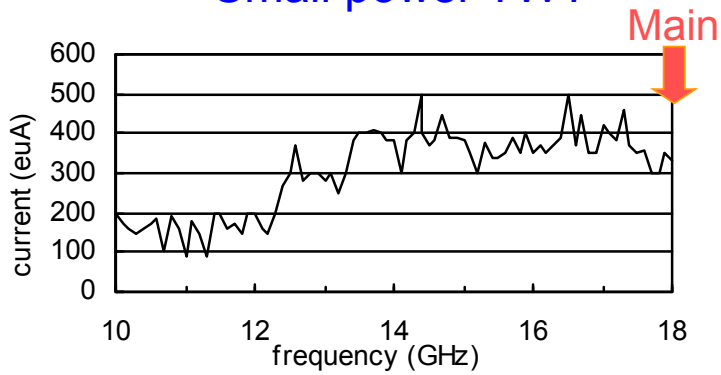


Fig.5. Output currents of Ar^{8+} as a function of the frequency of the additional microwave.

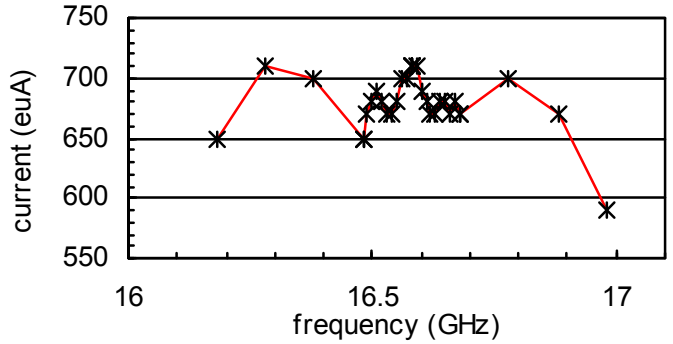
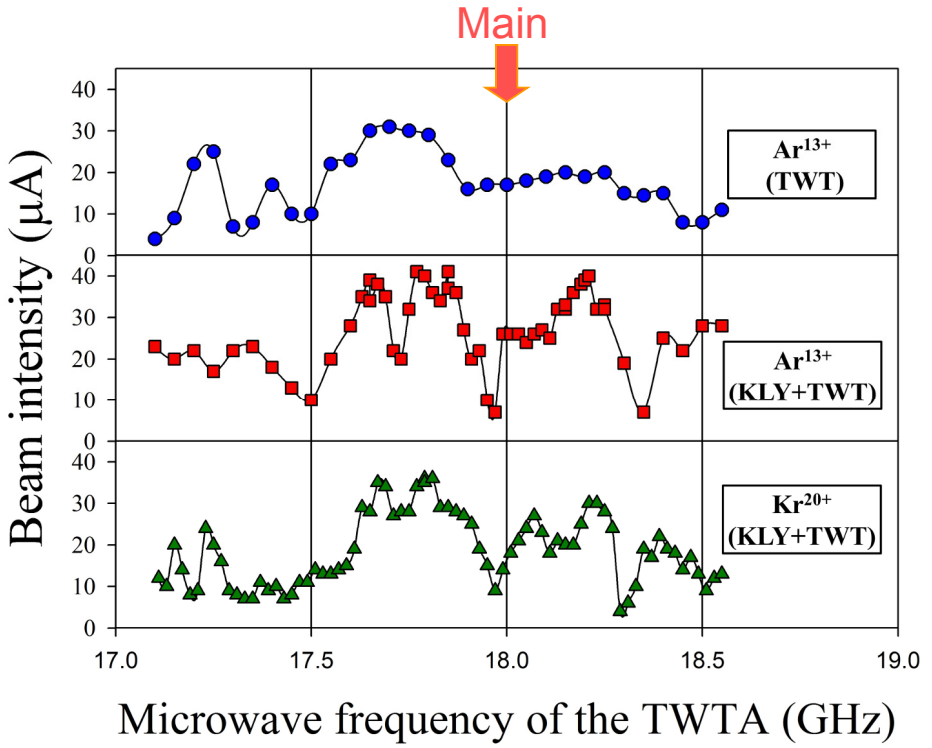


Fig.6. Output currents of Ar^{8+} as a function of the frequency of the additional microwave.

A. Kitagawa et al., EPAC'00, Wien, June 2000, p.1607 (2000)

+ Large power TWT

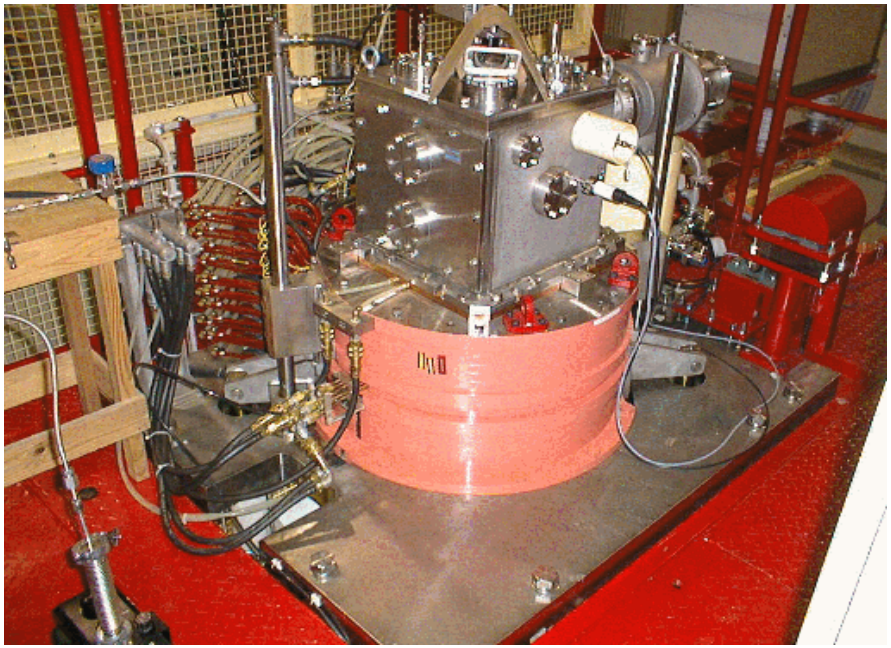


S. Biri et al., Rev.Sci.Instrum. **85**, 02A931 (2014).

2. Previous experiments at HIMAC

Only NIRS-HEC ?

An interest has arisen as to whether the fore mentioned phenomenon can be demonstrated using a different ion source where the two frequencies are even far apart from each other (“far 2f”).



NIRS-HEC designed for 18GHz

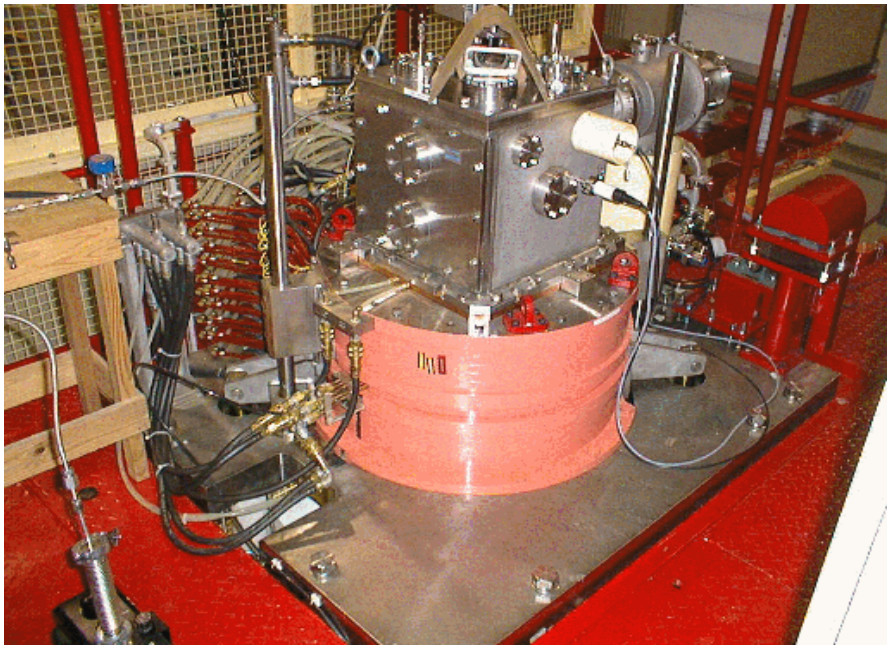
?

NIRS

HIMAC

Only NIRS-HEC ?

An interest has arisen as to whether the fore mentioned phenomenon can be demonstrated using a different ion source where the two frequencies are even far apart from each other (“far 2f”).



NIRS-HEC designed for 18GHz

Various previous works:

1. large power, fixed frequency
   +
   large power, fixed far frequency

2. large power, fixed frequency
   +
   small power, flexible frequency

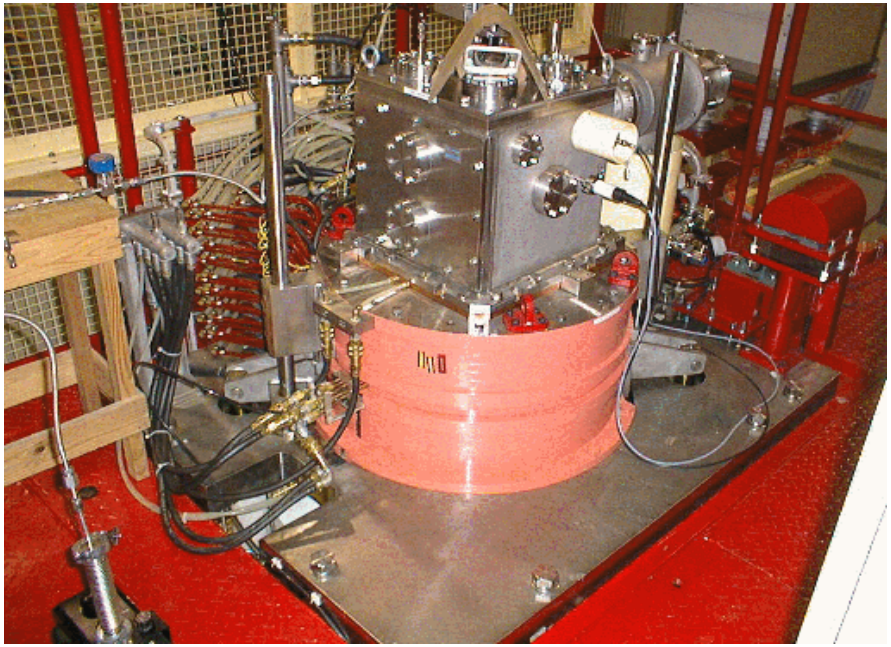
? large power, fixed frequency
   +
   large power, flexible frequency

3. Present experiments at ATOMKI

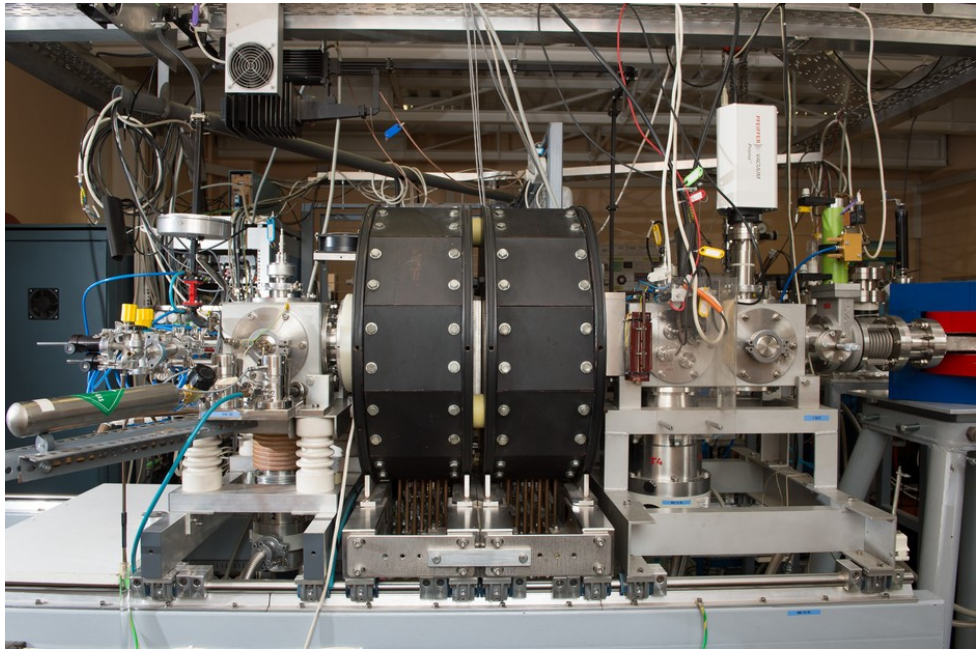
3. Present experiments at ATOMKI

ATOMKI-ECR

In order to obtain data at large power and flexible “far 2f”, we installed a 17.75-18.25 GHz TWT microwave system in addition to the 14.3 GHz klystron amplifier of the ATOMKI ECRIS.



NIRS-HEC designed for 18GHz

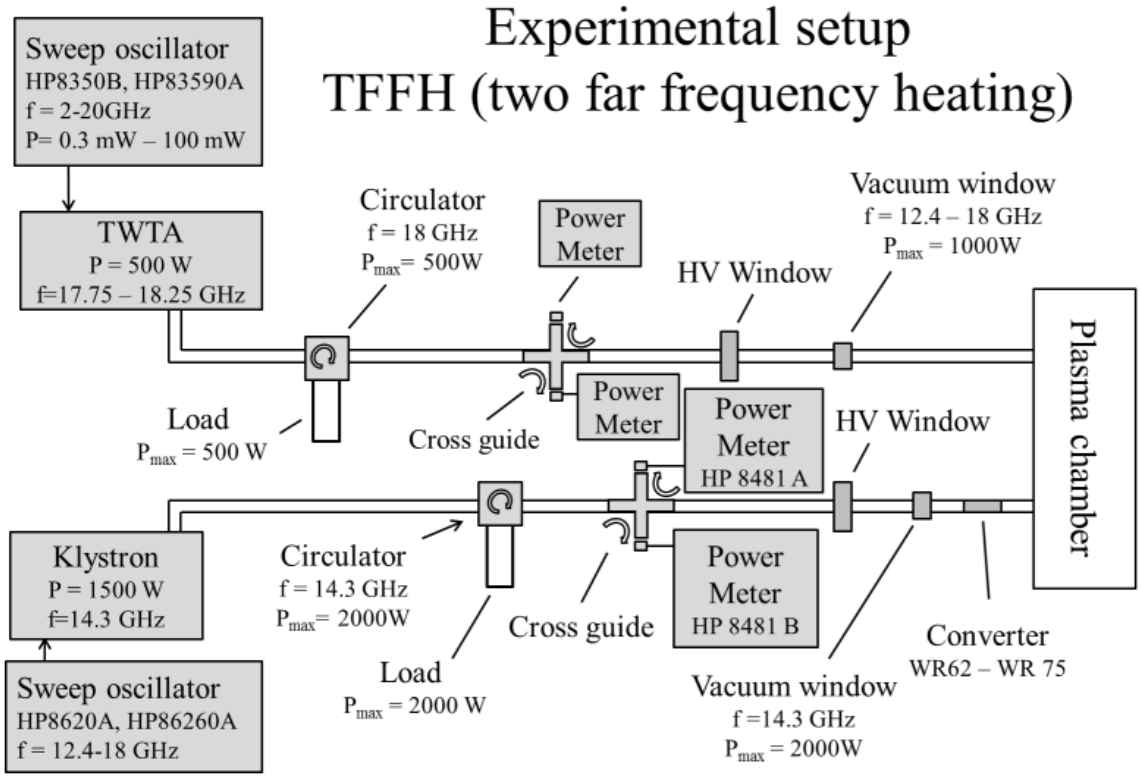


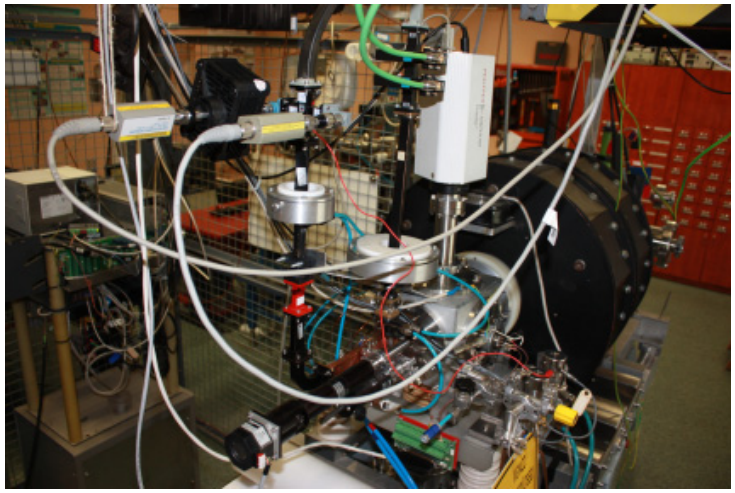
ATOMKI-ECR designed for 14GHz

Specifications

	NIRS-HEC	ATOMKI-ECR
Main microwave frequency (GHz)	18.0	14.3
Maximum power (kW)	1.5	1.4
Additional microwave frequency (GHz)	17.10 – 18.55	17.75 – 18.25
Maximum power (kW)	1.2	0.5
Maximum mirror magnetic field at injection side(T)	1.3	1.2
at extraction side (T)	1.2	0.95
Mirror field peak-peak distance (mm)	165	235
Radial magnetic field on the surface of chamber (T)	1.1	1.1
Hexapole magnet length (mm)	200	200
Plasma chamber length (mm)	200	210
Plasma chamber diameter (mm)	61	58
Maximum extraction voltage (kV)	56	30

Setup at ATOMKI-ECR

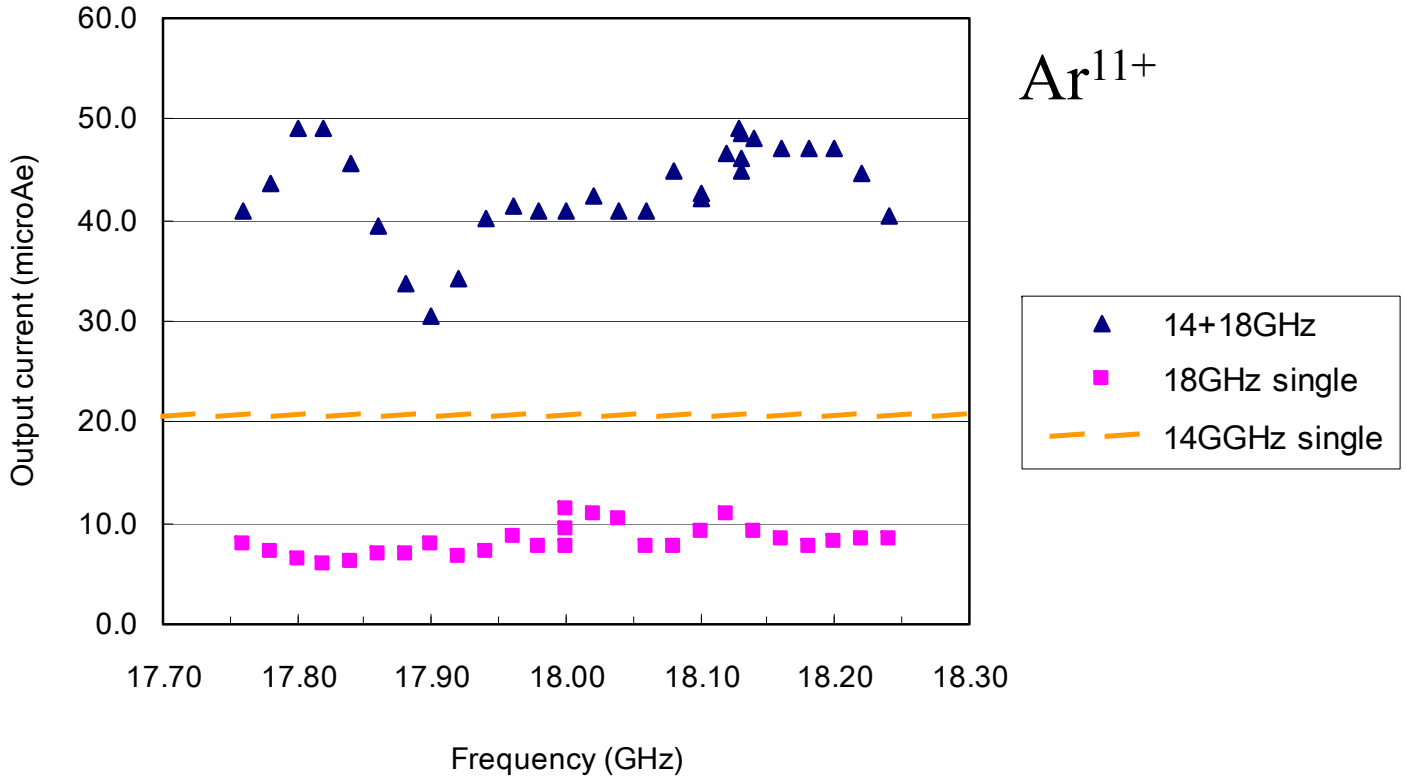




Limitation at the present experiment:

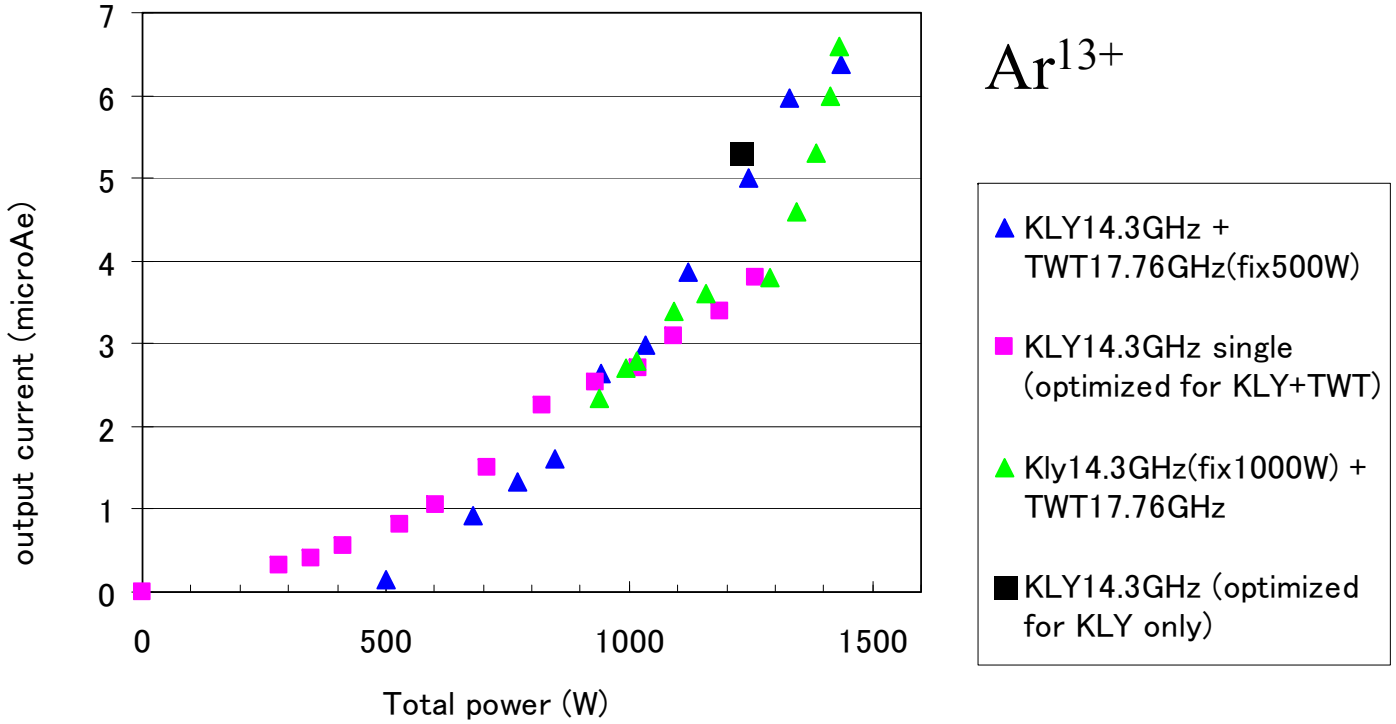
- Cooling capacity at the plasma chamber ≤ 1.5 kW
- Extraction voltage ≤ 10 kV
- Horizontal slit for good analyzing resolution = narrow

Frequency dependence



- The typical frequency dependence in this “far 2f” experiment at ATOMKI-ECR shows the fine structure similar to the case of the “close 2f” experiments at NIRS-HEC.

Power dependence



- The output currents of Ar^{11+} and Ar^{13+} were almost proportional to the power. (The dependence of Ar^{7+} and Ar^{1+} were saturated at lower powers.)
- Since the maximum total power was limited to bellow 1.5 kW (due to the limited cooling capacity), no plasma instability appeared during this measurement.

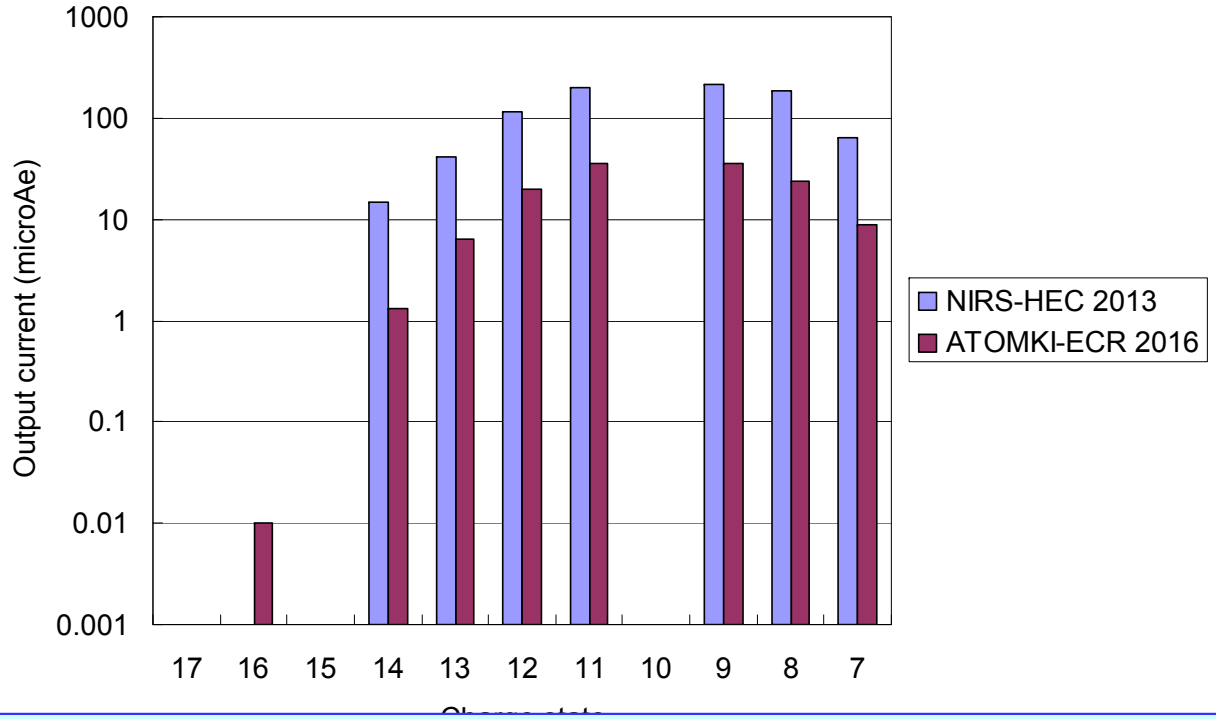
4. Comparison between two experimental results

NIRS

HIMAC

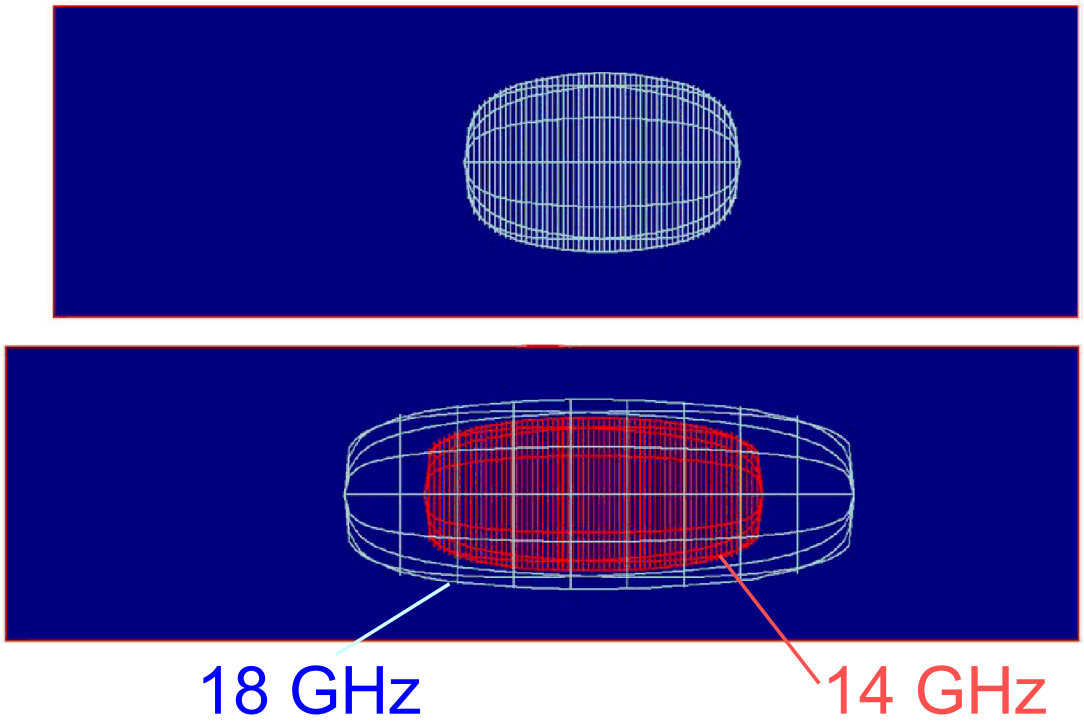
4. Comparison between two experimental results

Output currents of Ar



- The output currents at ATOMKI-ECR in 2016 were 10-20 % of NIRS-HEC in 2013 due to several experimental conditions like the extraction voltage (10kV at ATOMKI and 20kV at NIRS), analyzing slit width, and so on.
- The charge-state distribution at ATOMKI-ECR was relatively lower.
- The other differences were the geometry of ECR zone.

Size comparison of both ECR zones



	ATOMKI-ECR		NIRS-HEC
Frequency (GHz)	18	14	18
Diameter (cm)	3.8	3.1	3.5
Length (cm)	10.0	6.6	5.0
Volume (cm^3)	85	36	35
Surface (cm^2)	112	61	51

- The surface area and volume of ECR zone at NIRS-HEC is similar to that of 14 GHz's at ATOMKI-ECR; however 18 GHz's one at ATOMKI-ECR is roughly twice as them.

Present conclusion

- It has not been confirmed that the mixture of two frequencies suppresses the plasma instability and improves the output currents of highly charged ions with “far 2f”. However, there is no disproof.
- The other tendencies of the observed phenomena in the “far 2f” experiment are very similar to the “close 2f” experiments.
- From a practical point of view, at both cases large improvement was observable. If the cooling capacity is improved, it is expected the output currents increases with increasing the total power.

5. Prospective goal

Goal of research

How to obtain more intense beam for highly charged ions?

NIRS

HIMAC

Goal of research

How to obtain more intense beam for highly charged ions?

Increasing the power of microwave and decreasing the vacuum pressure together.

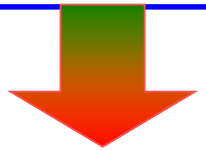
NIRS

HIMAC

Goal of research

How to obtain more intense beam for highly charged ions?

Increasing the power of microwave and decreasing the vacuum pressure together.



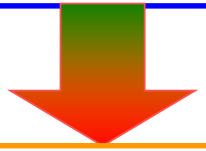
NIRS

HIMAC

Goal of research

How to obtain more intense beam for highly charged ions?

Increasing the power of microwave and decreasing the vacuum pressure together.



It usually causes the plasma instability

NIRS

HIMAC

5. Prospective goal

Goal of research

How to obtain more intense beam for highly charged ions?

Increasing the power of microwave and decreasing the vacuum pressure together.

It usually causes the plasma instability

Apply two frequency
to control the anisotropy of the electrons' velocity distribution
for decreasing the plasma instability

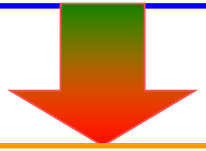
NIRS

HIMAC

Goal of research

How to obtain more intense beam for highly charged ions?

Increasing the power of microwave and
decreasing the vacuum pressure together.



It usually causes the plasma instability

Apply two frequency
to control the anisotropy of the electrons' velocity distribution
for decreasing the plasma instability

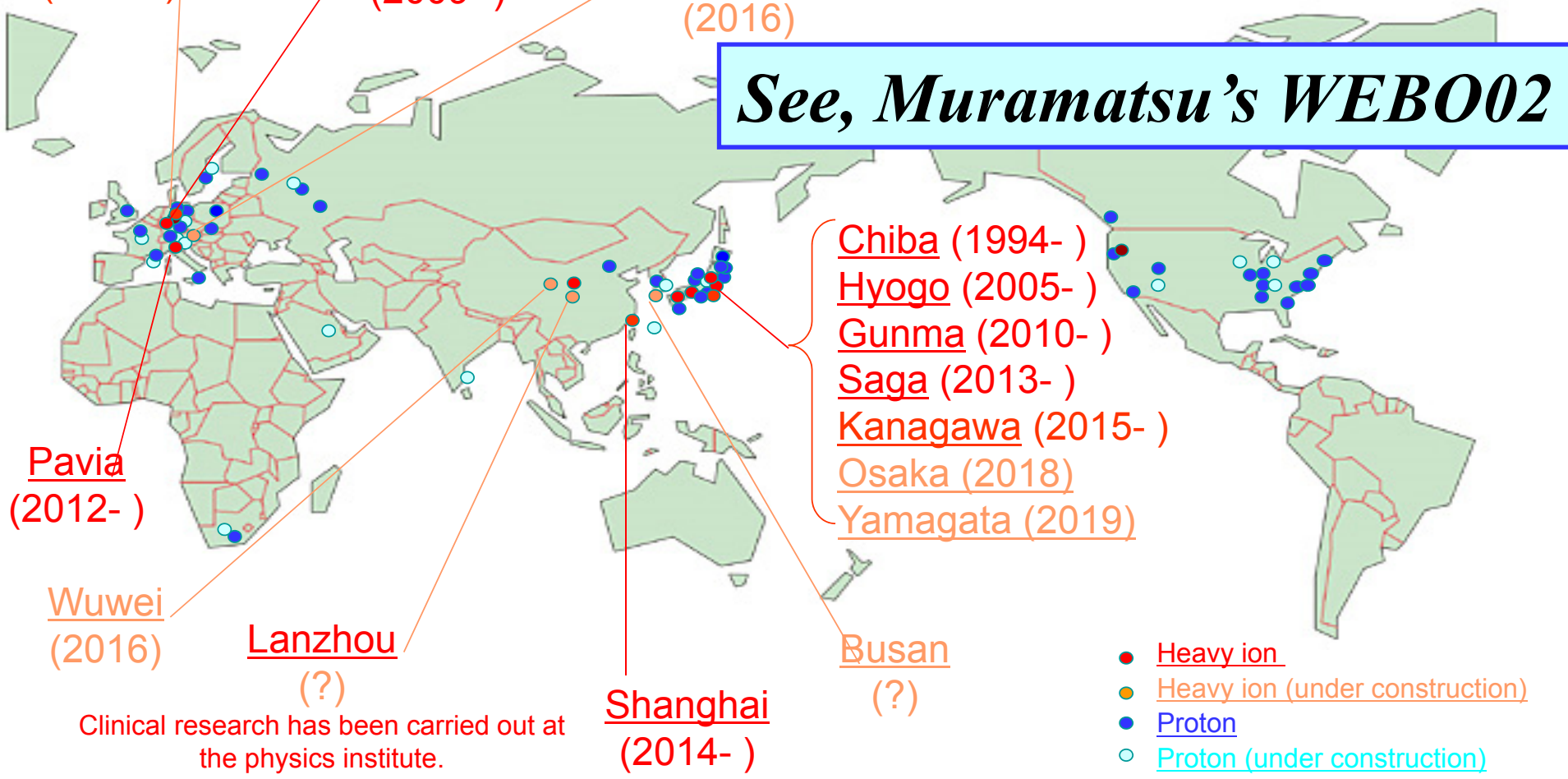
How to adapt or to design a source suitable for 2-f system?
- necessary frequency width, power, feeding, etc…

NIRS

HIMAC

5. Prospective goal

Charged particle radiotherapy worldwide



NIRS

HIMAC

5. Prospective goal

Improvement of Intensities with q/m=1/3

C^{4+} injector requires q/m = 1/3 ions

Technique		Charge state of Ar ions				
Frequency	Afterglow	11+	12+	13+	14+	16+
Single	No apply	130	50	21	-	-
Two	No apply	200	116	42	15	-
Two	Apply	300	242	118	47	2.3

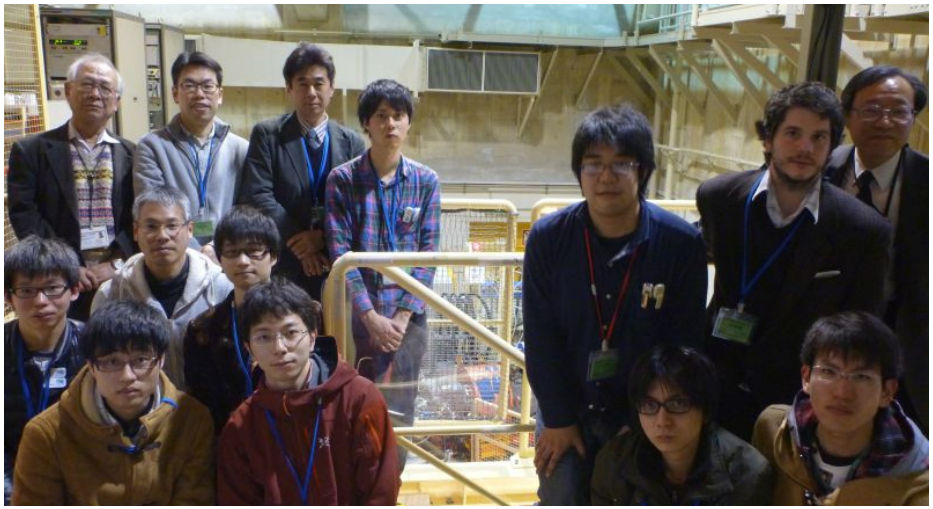
- Two-frequency heating technique gives a potential to apply various types of ions for basic life science studies even at a hospital-specified carbon-ion radiotherapy facility.

Summary

1. **Previous conclusion with “close 2f”**
   - An additional microwave with a different frequency improves the plasma stability at greater microwave power.
   - The output current of the highly charged ion beam is proportional to the total power of both microwaves.
   - The dependence on the additional frequency showed fine structure. This structure depended on the parameters (magnetic field, vacuum pressure, and so on).
2. **Present result of “far 2f” and comparison with “close 2f”**
   - The tendencies of the observed phenomena in the “far 2f” experiment are very similar to the “close 2f” experiments.
3. **Desired output**
   - It’s expected to apply for basic life science studies at a hospital-specified carbon-ion radiotherapy facility

Prof. Masayuki Sekiguchi
(27 Aug. 1938 – 2 Apr. 2016)

with his wife and Prof. Hirao at once INS.



with young colleagues at NIRS-HEC