Improvement of Beam Intensities for Ion Beams with Charge-to-Mass Ratio of 1/3 with Two-Frequency Heating Technique

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1. Status of Carbon Ion Radiotherapy

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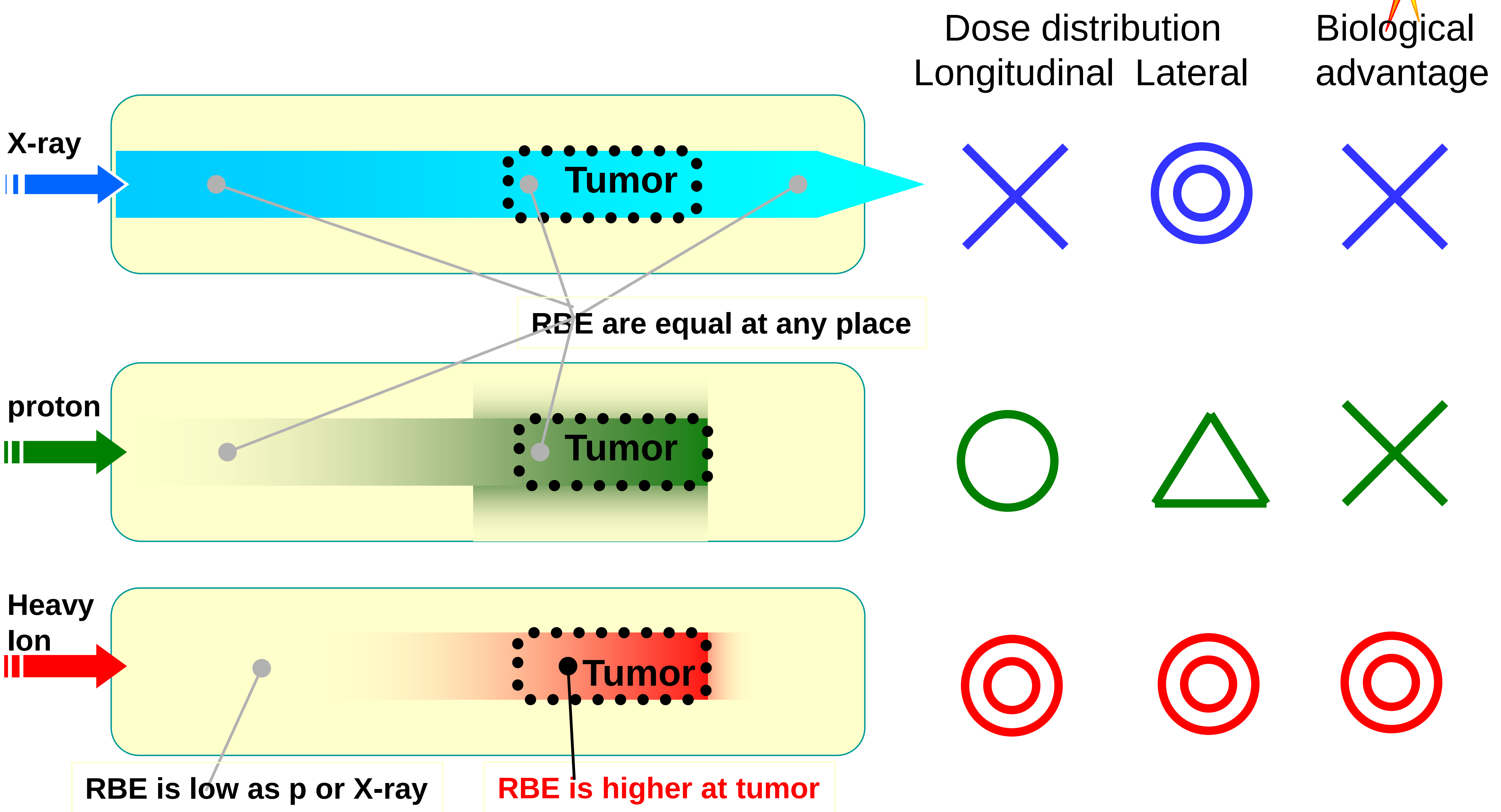
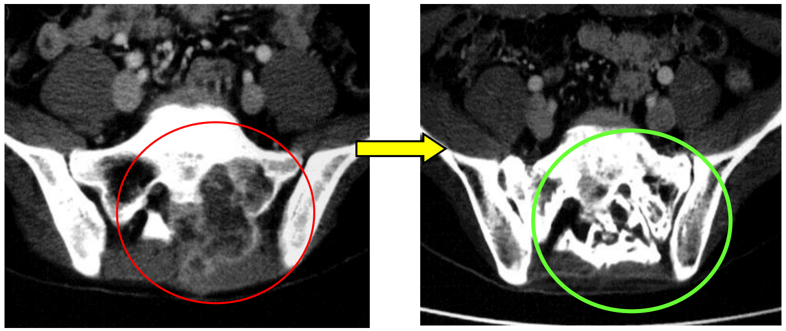
Comparison between heavy ion and other radiotherapy



Summary of present clinical results

Carbon ion radiotherapy has 3 large advantage,

Better local control / survival ratios



before **5 years after**

5 years overall survival ratio in inresectable cases

46% (<500cc), 19% (>500cc)

Hypo-fractionation:The treatment period can be shorten

<u>1 day treatment</u>

1 fraction ~<u>50.0</u>GyE

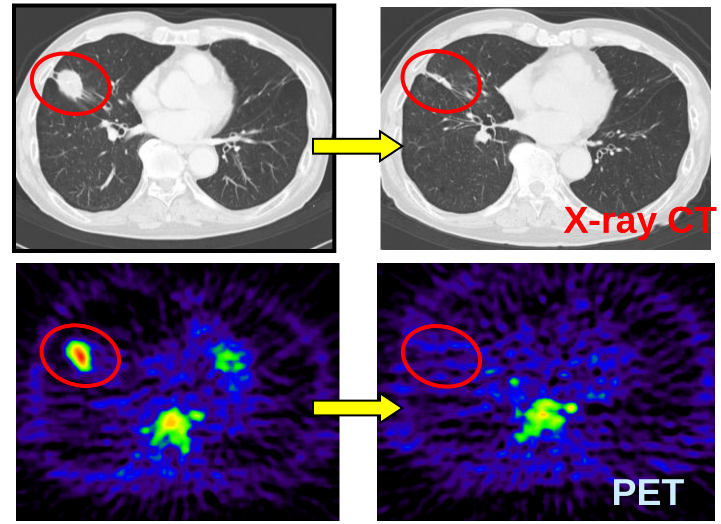
in 1 day

3 year Local control
83%

5 years survival
55%

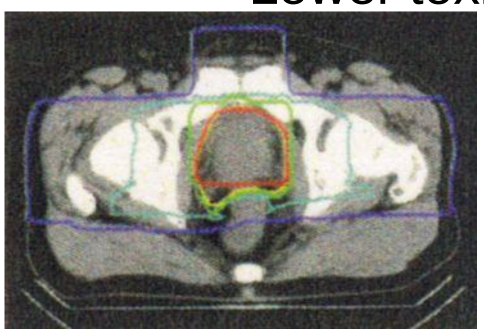
(mean age=73.9)

cause specific survival
73%



before **1 year after**

Lower toxicities



Delayed adverse reaction (>=G2)
0.3% (Rectum)
2.4% (Genitourinary system)

<u>Recent clinical results</u>
http://www.nirs.go.jp/ENG/publication/

<u>Publications</u>
D. Schulz-Ertner and H. Tsujii, Journal of Clinical Oncology, 2, 953 (2007).
H. Tsujii *et al.*, New Journal of Physics 10, 075009 (2008).
H. Tsujii and T. Kamada, Jpn. J. Clin. Oncol. 42, 670 (2012).

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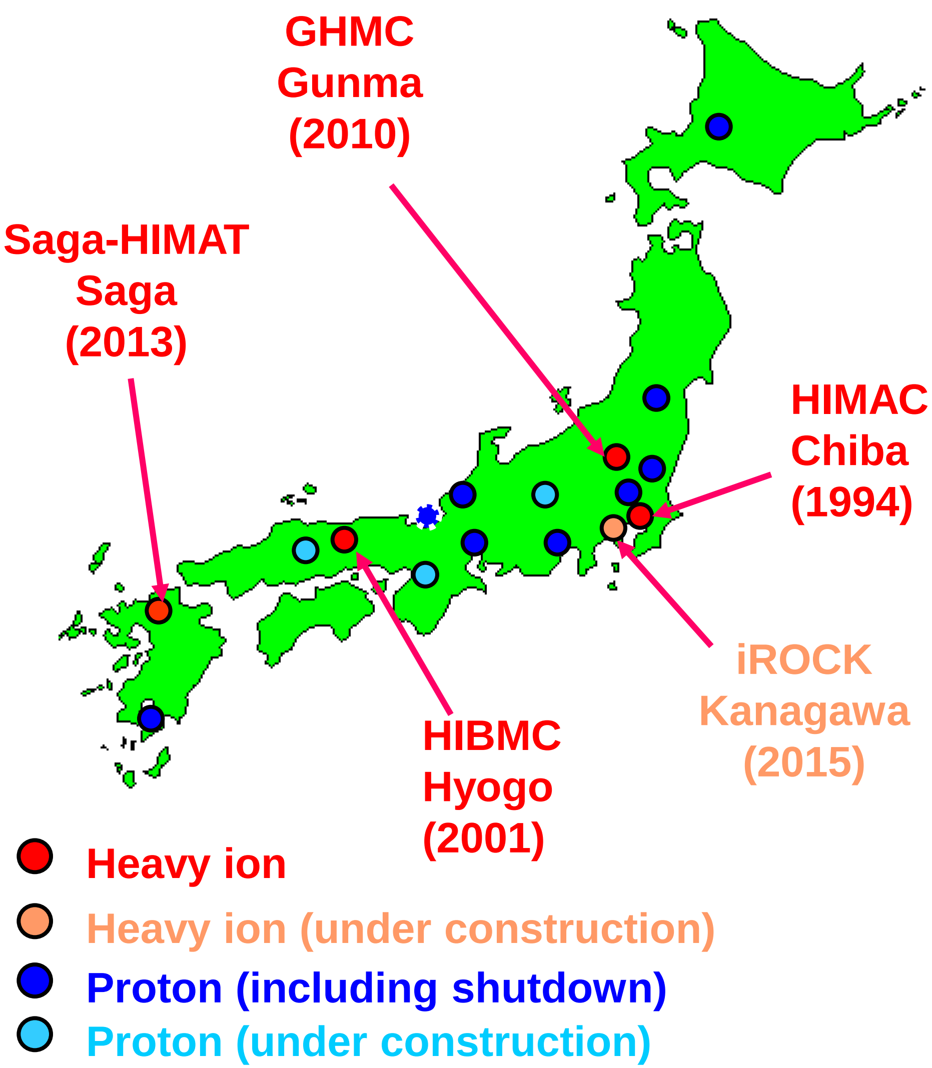
Present facilities in Japan



Operation facilities:

	Period	Patients total	(/year)
HIMAC	('94 – '14.3)	8227	(888)
HIBMC	('05 – '13.12)	1905	(249)
GHMC	('10 – '13.12)	985	(448)
Saga-HIMAT	('13.8 – '14.1)	84	(-)
	sum	11201	(1585)

Under construction:

iROCK (plan '15 –)

Other plans:

Osaka, Yamagata, Okinawa, …

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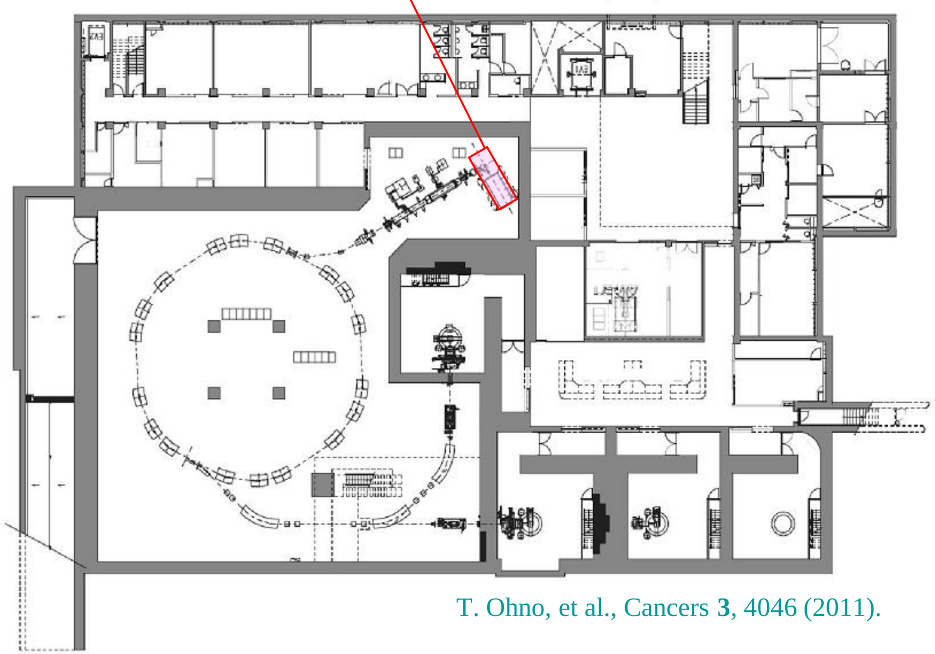
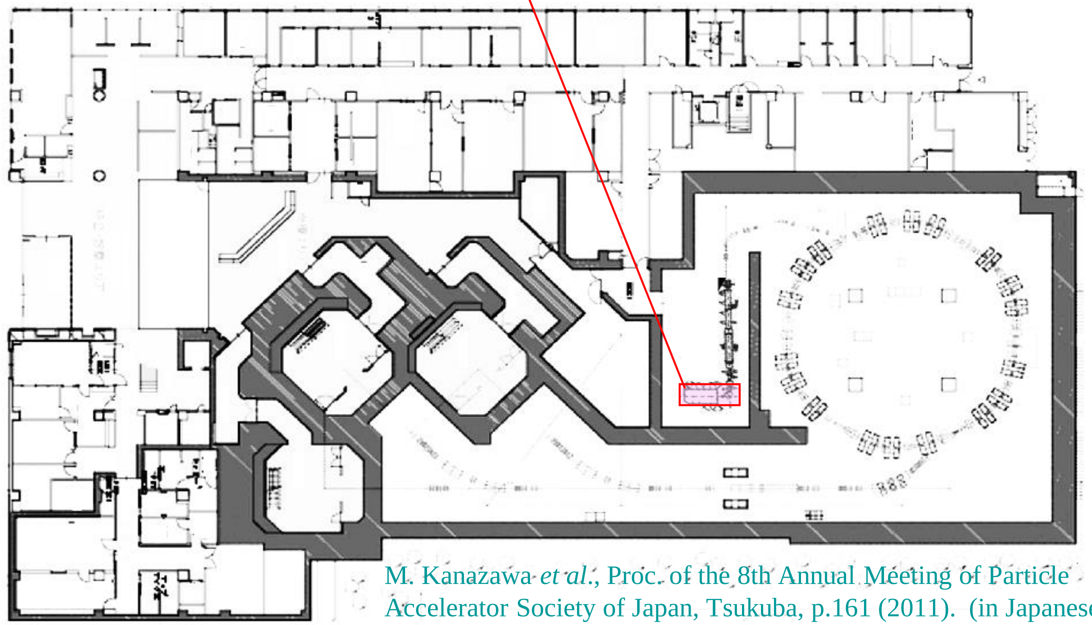
ECRIS dedicated for carton ion radiotherapy

KeiGM1 GHMC



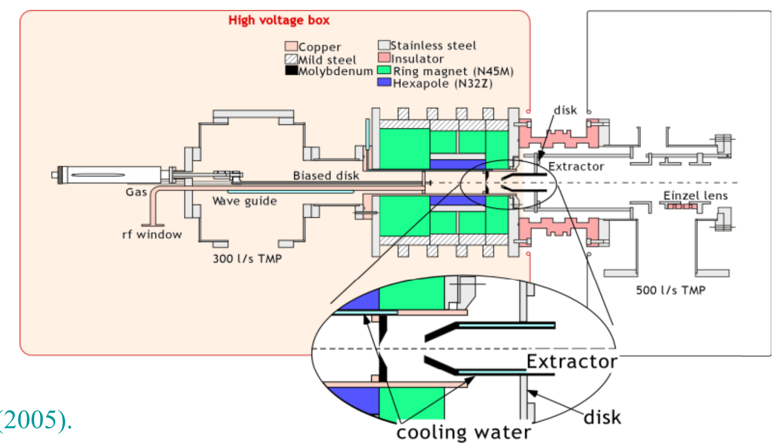
T. Ohno, et al., Cancers **3**, 4046 (2011).

KeiSA Saga-HIMAT



M. Kanazawa *et al.*, Proc. of the 8th Annual Meeting of Particle Accelerator Society of Japan, Tsukuba, p.161 (2011). (in Japanese)

M. Muramatsu, et al., Rev. Sci. Instrum. **76**, 113304 (2005).



	Kei2
Mirror magnetic field	
material	Permanet (NdFeB)
Injection field	0.87 T (fixed)
Minimum B field	0.25 T (fixed)
Extraction field	0.59 T (fixed)
Axial magnetic field	
material	Permanent (NdFeB)
Surface field	0.75
Effective chamber size	
Length	105
Diameter	55
Microwave	
Frequency	8 – 11 GHz
Power	300 W
Extraction	
Voltage	30 kV

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Operation status of Kei-series

Ion source	Facility	Launch	Operation time (hours)	Failures*1 during treatment
Kei2	HIMAC	2010*2	-	-*3
KeiGM1	GHMC	2009	20130	3
KeiGM2	(stand alone)	2011	1813	-*3
KeiSA	SagaHIMAT	2012	7200*4	0
KeiGM3	i-ROCK	2014(plan)	-	-

*1 Failures interrupted the patient treatment

*2 Relocation from the test bench into the accelerator

*3 Utilized for the development or experiments only

*4 Including commissioning in the factory

From PTCOG53 report in June 2014 by Hikaru Souda, Satoru Yamada (GHMC), and Mitsutaka Kanazawa (SagaHIMAT)

2. Requirement for life science research

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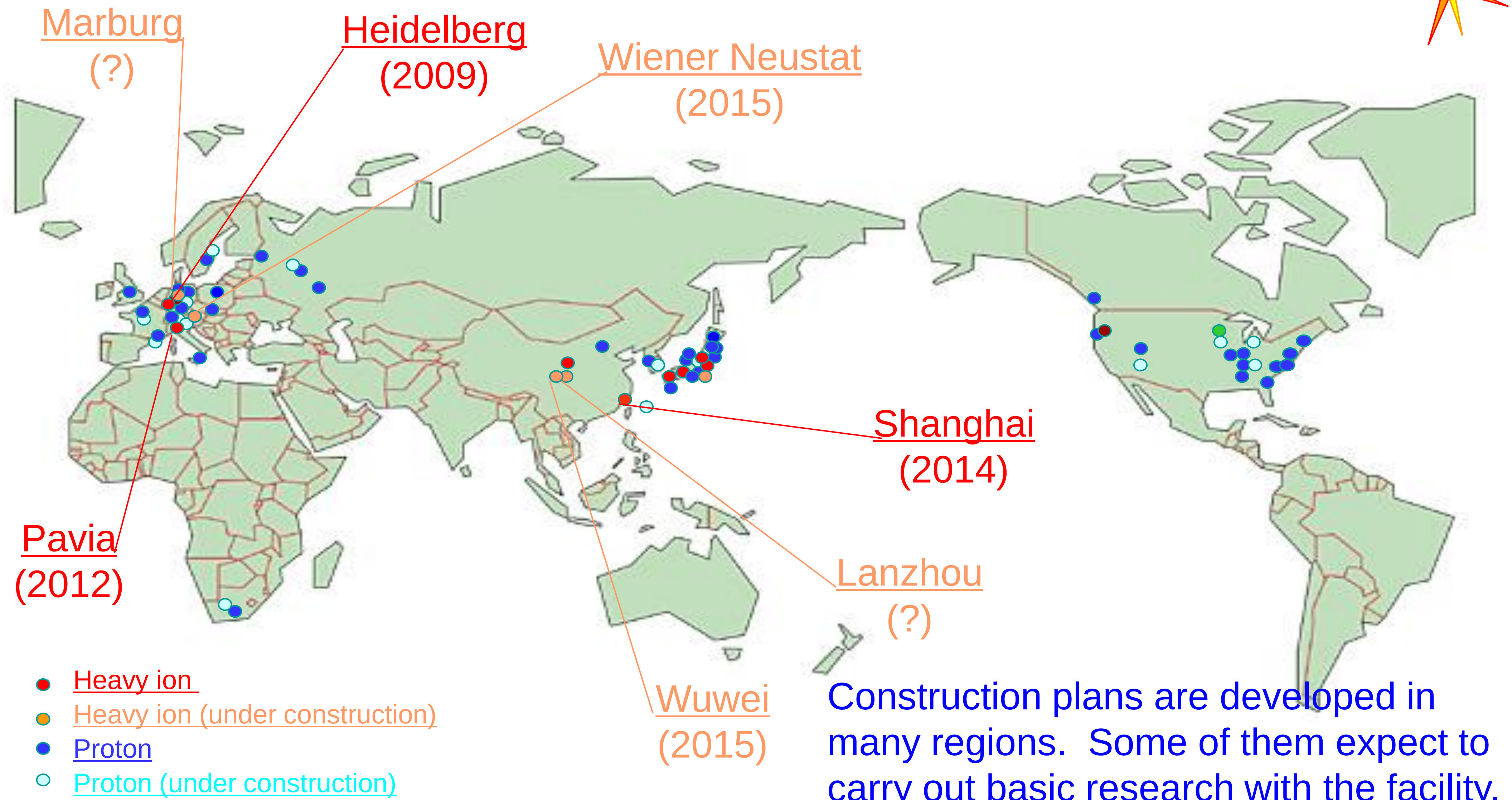
Charged particle radiotherapy worldwide



Construction plans are developed in many regions. Some of them expect to carry out basic research with the facility.

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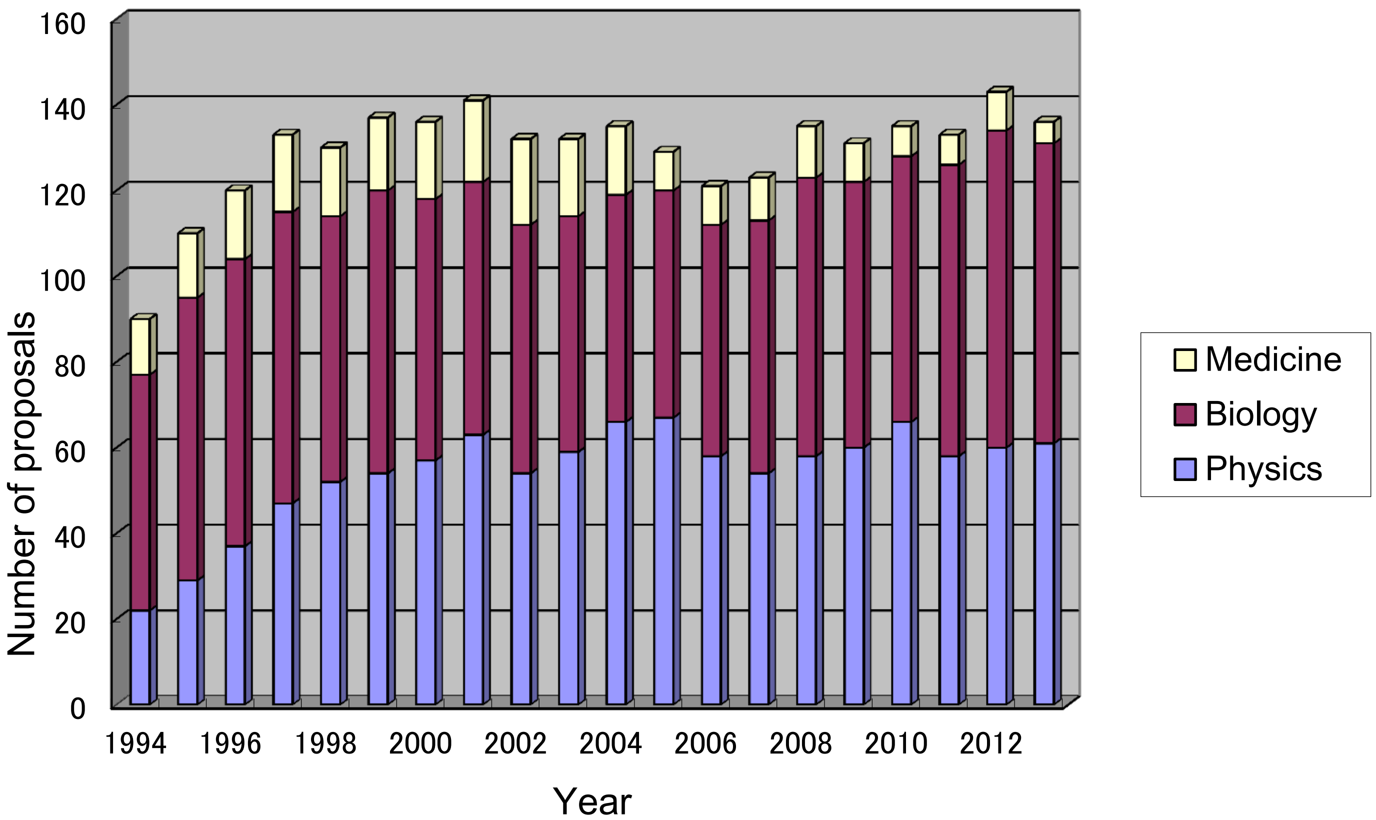
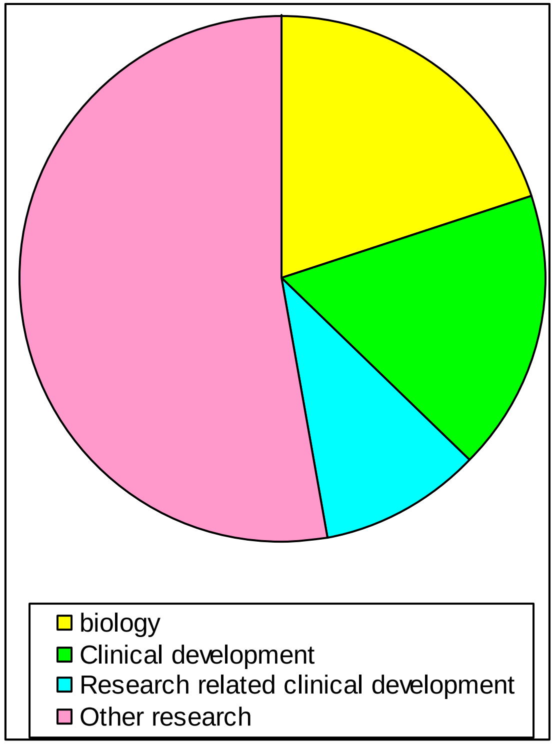
Proposals of basic sciences at HIMAC



Rough breakdown of beam time



Beam time ~ 5000 hours / year

Life science uses a half of beam time

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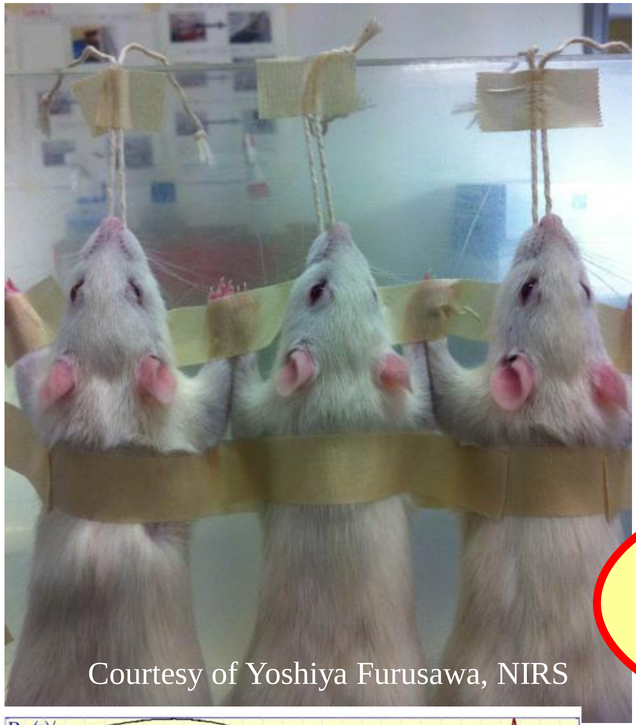
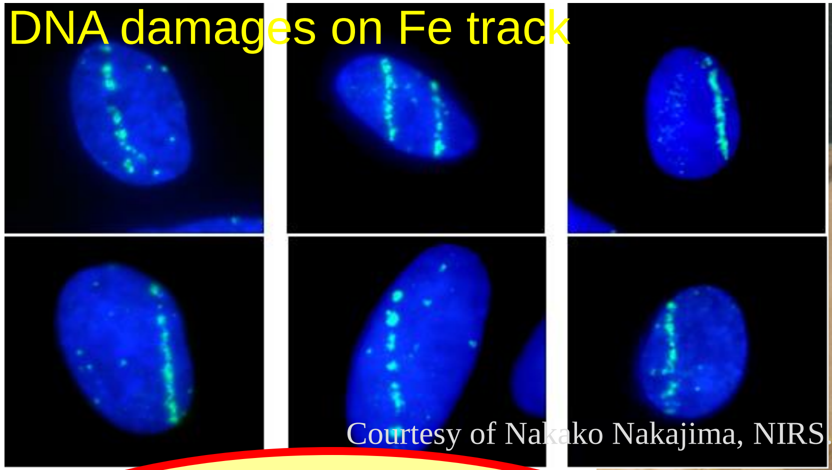
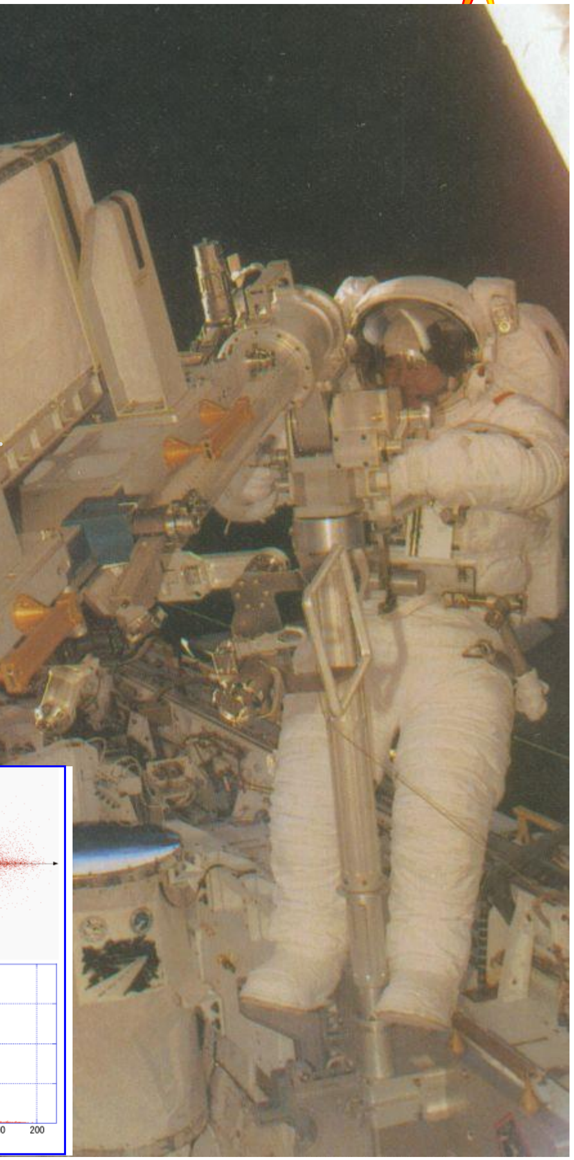
Life science experiments

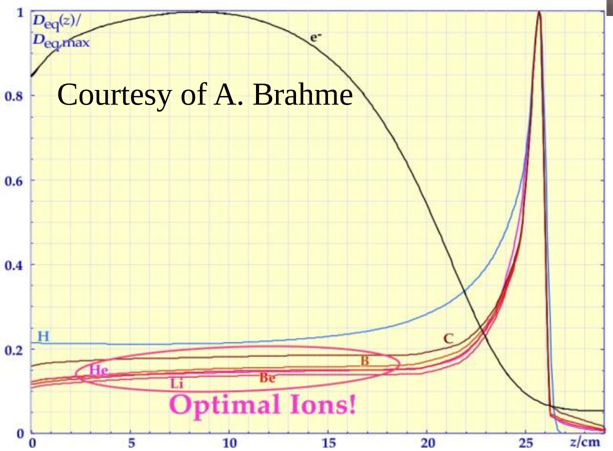

Courtesy of Yoshiya Furusawa, NIRS

DNA damages on Fe track


Courtesy of Nakako Nakajima, NIRS.

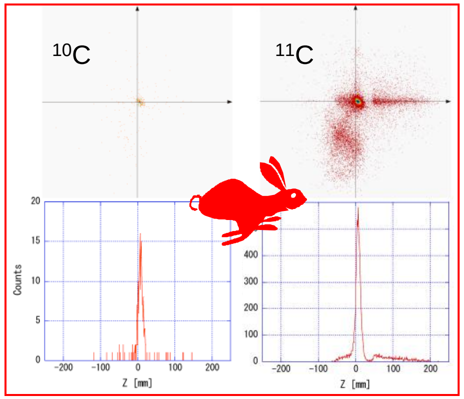


Requirements of ion species with several Gy/min

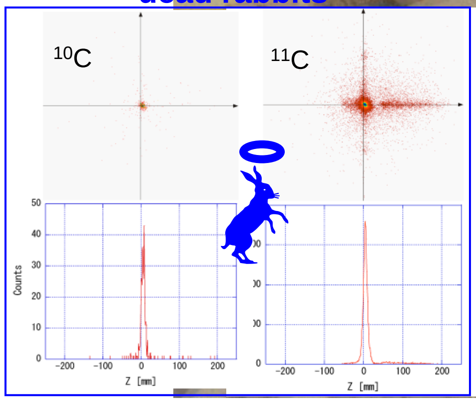


Courtesy of A. Brahme

alive rabbits



dead rabbits



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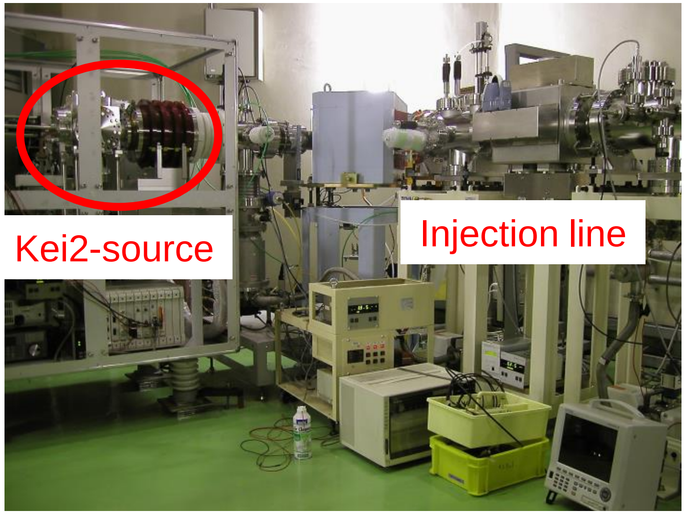
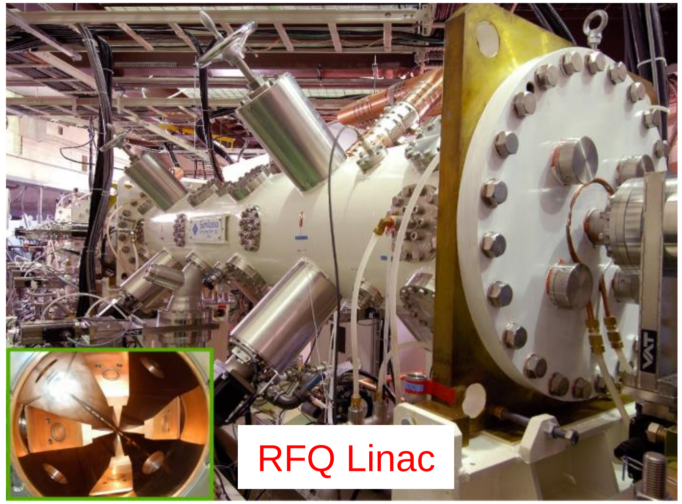
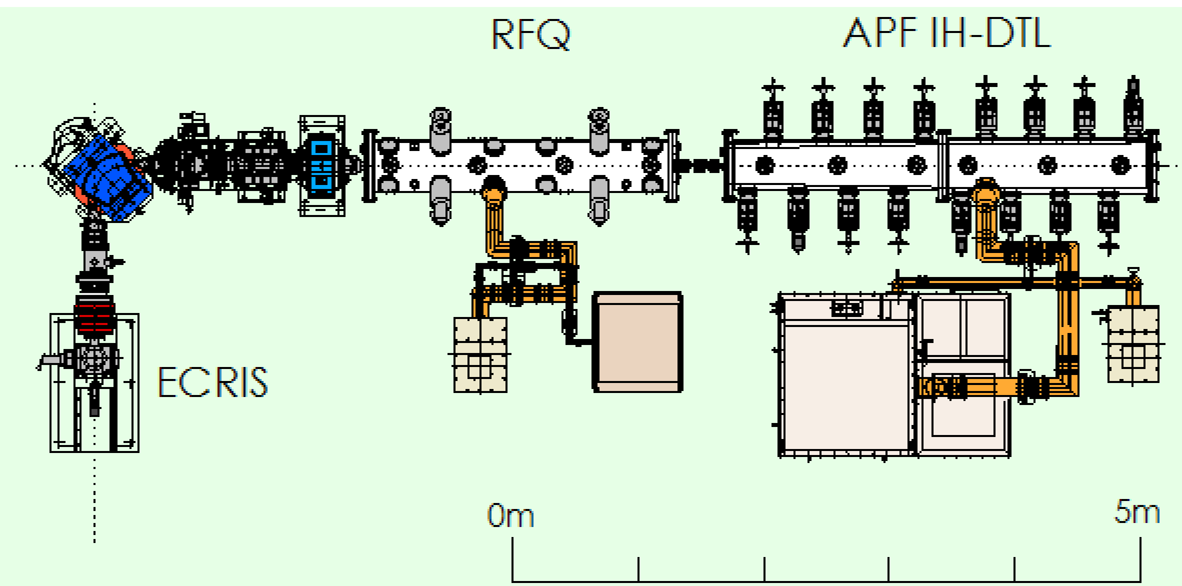
Hospital specified injector design







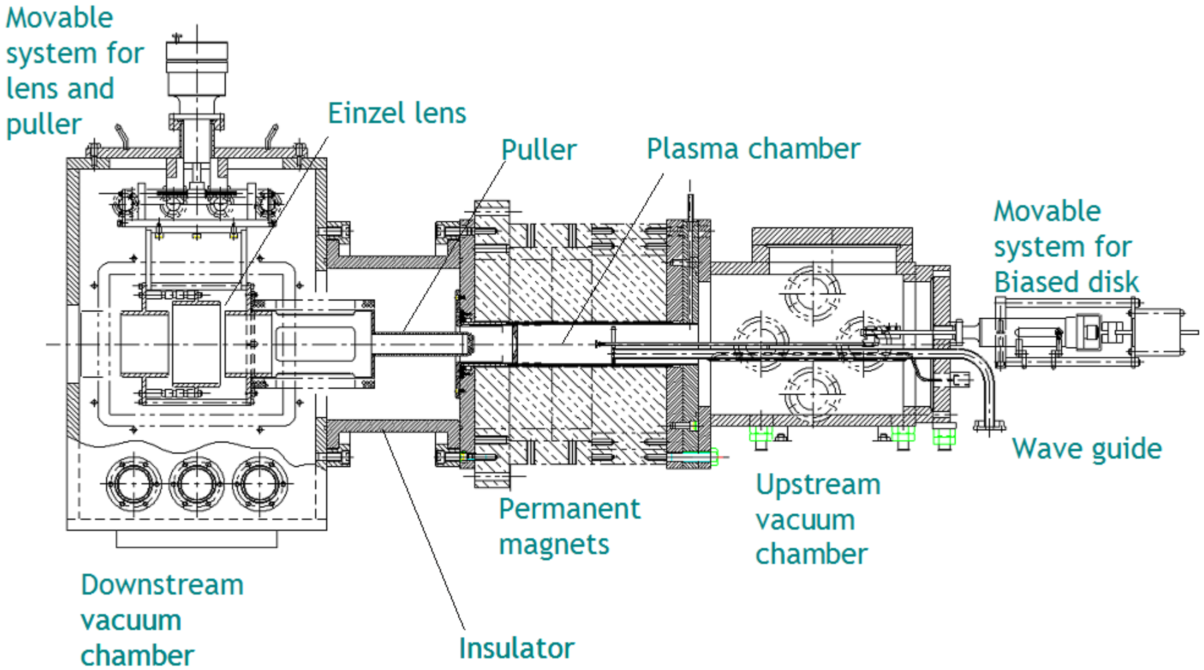
Major parameter of the compact linacs

Parameters	RFQ	IH-DTL	units
Injection energy	**0.01**	0.61	MeV/n
Extraction energy	0.61	4.0	MeV/n
Frequency	200	200	MHz
q/m	**1/3**	1/3	-
Cavity length	2.5	3.4	m
Outer diameter	0.42	0.44	m

Y. Iwata *et al.*, Nucl. Instrum.Meth. A572, 1007 (2007).

Development of Kei3

Charge-to-mass ratio: about 1/3 (margin is 10%)
Target ion species: He ~ Ne (if possible ~ Si)
Magnet:
Microwave: } ……………… same as previous Kei-series



M. Muramatsu, et al., ECRIS2012, Sydney, September 2012, p.49 (2012).

This will be not sufficient for ion species heavier than Si, like Fe.

3. Technical Method

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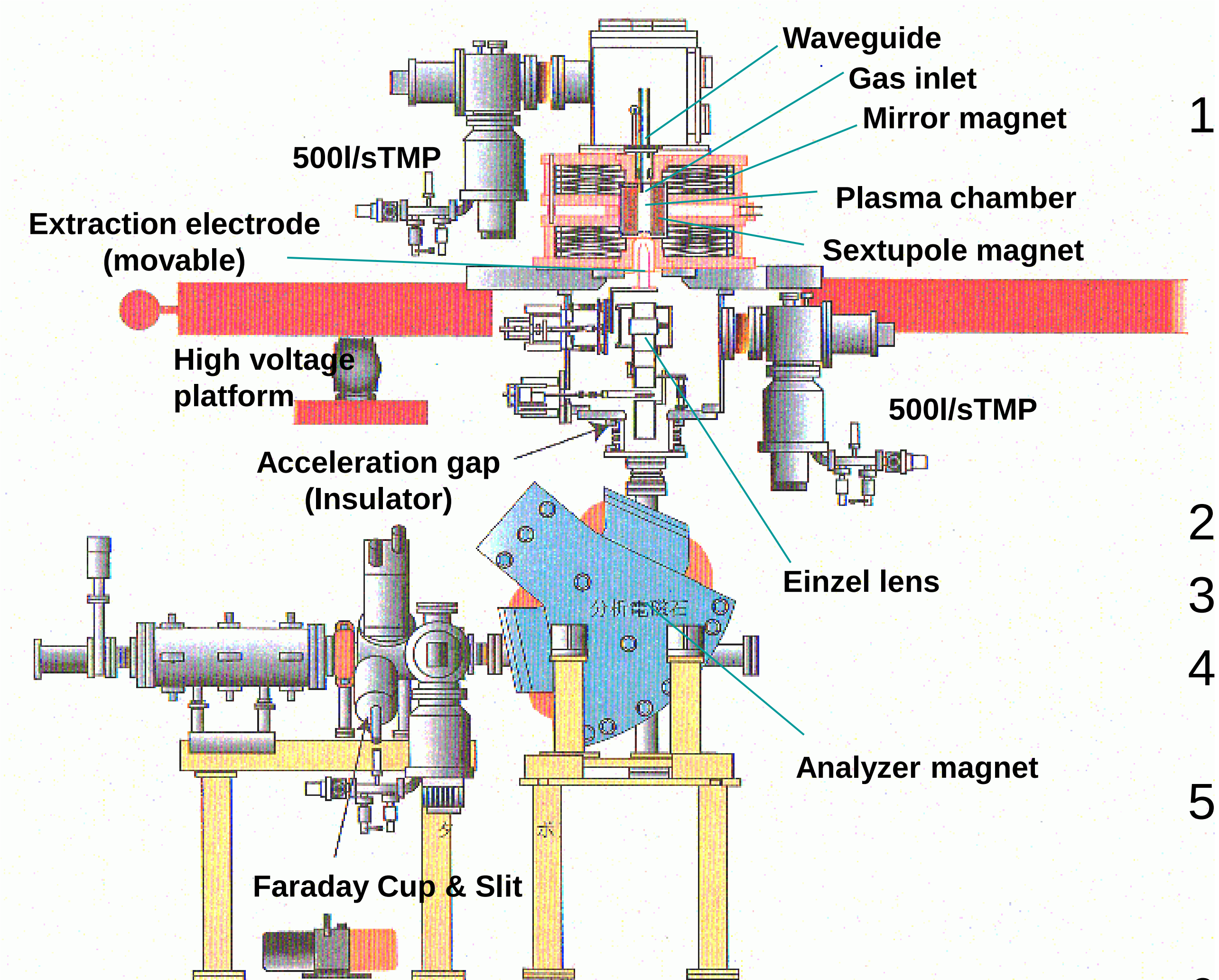
18GHz NIRS-HEC



A. Kitagawa et al., Rev.Sci.Instrum. **71**, 981 (2000).

NIRS-HEC is operating mainly for basic experiments since 1996.

Features

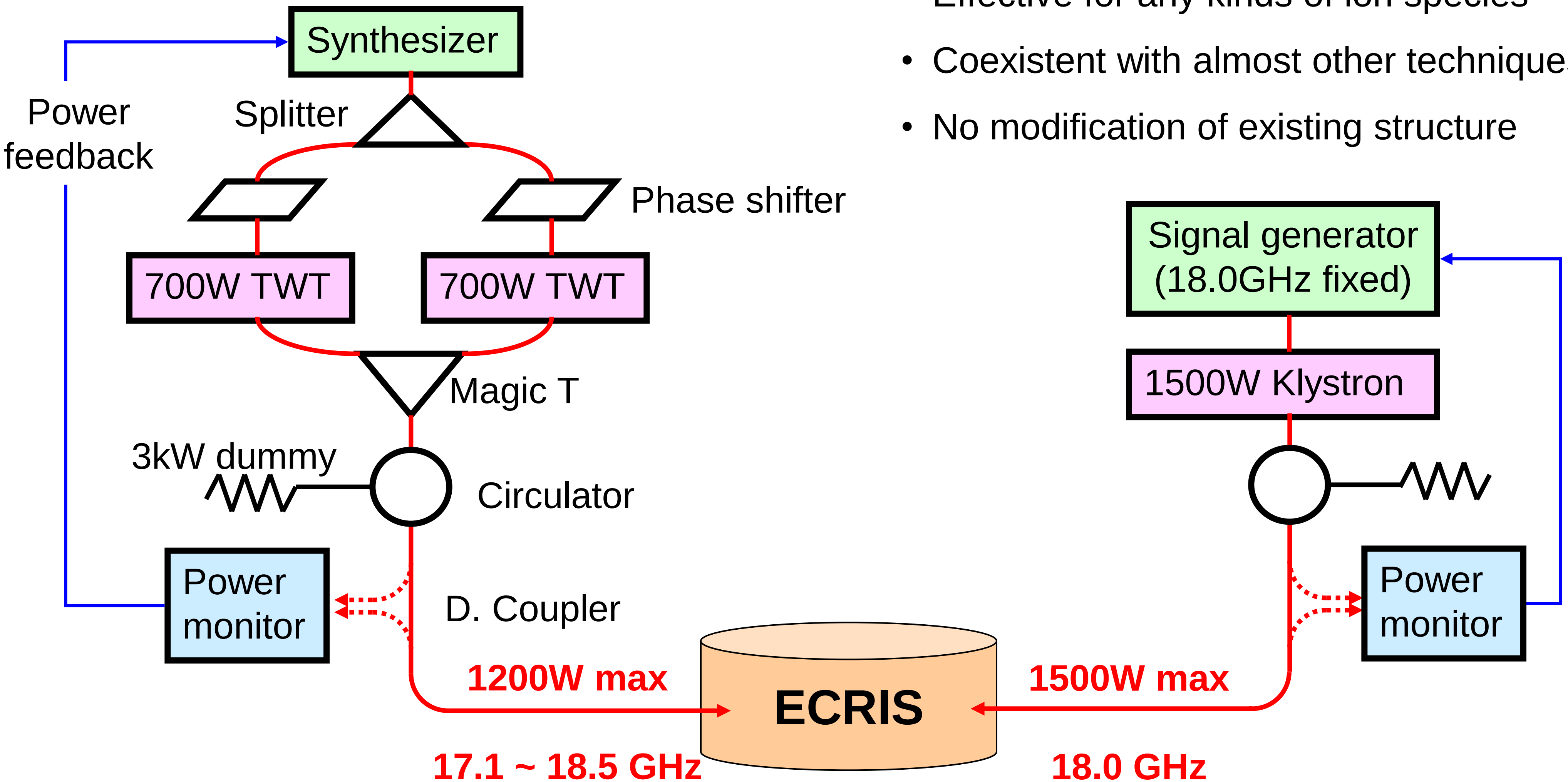
1. Max. 60kV extraction voltage (A high voltage power supply on the source potential safely applies the extraction voltage between the plasma electrode and the extraction electrode independent of the source potential.)
2. Room temperature coils
3. Vertical beam extraction
4. For production of ions with charge-to-mass ratio of 1/7
5. Long lifetime with the minimum maintenance under dirty conditions
6. Good reproducibility for easy operation

Two-Frequency Heating Technique

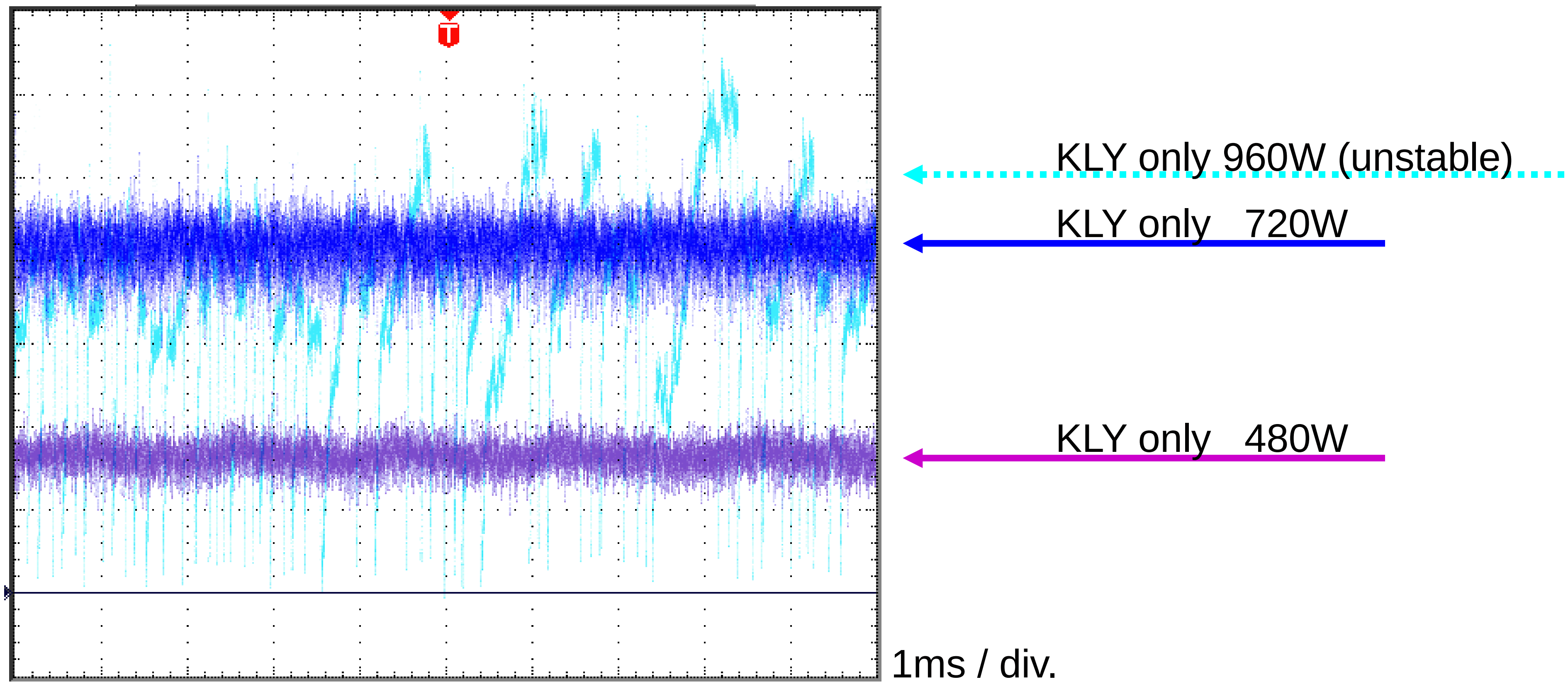
In order to improve the intensity, we tested the two-frequency heating technique.

<u>Advantages</u>

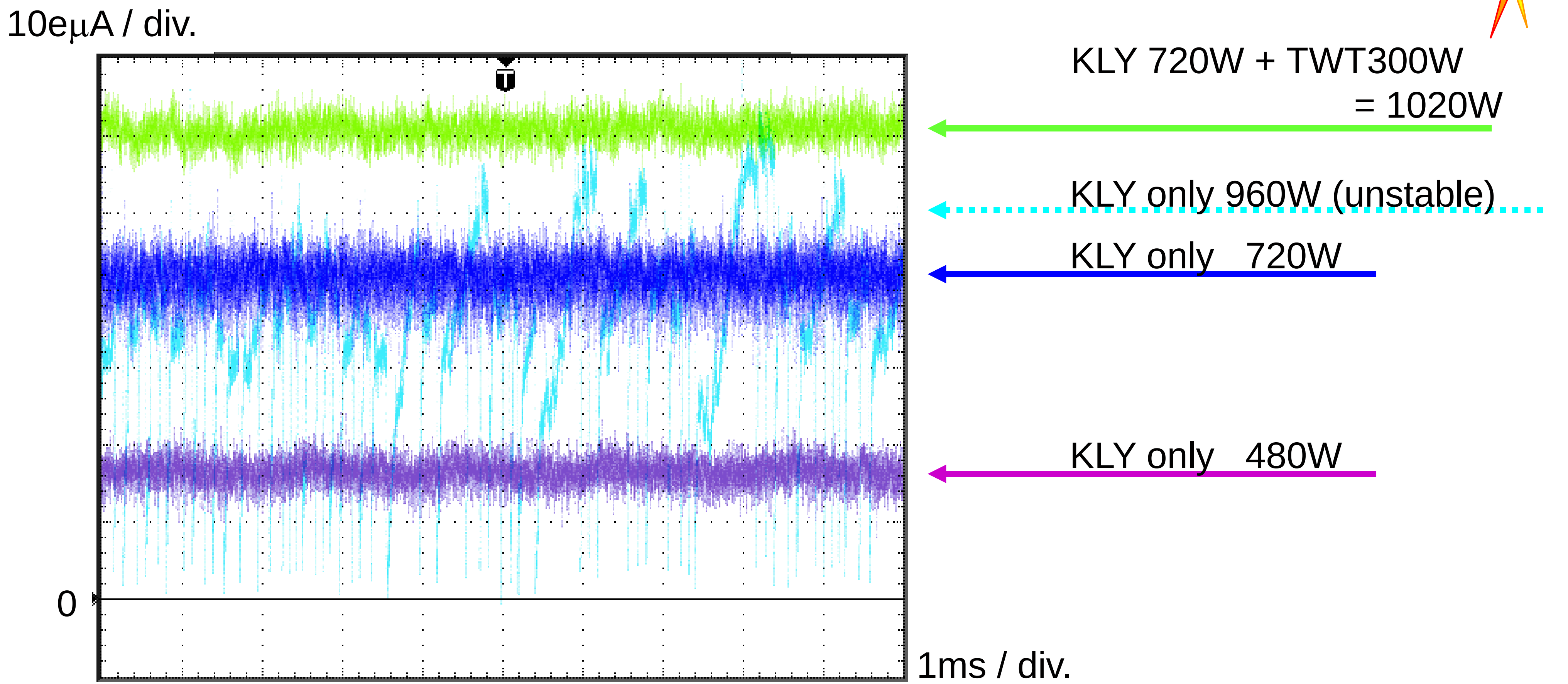
- Effective for any kinds of ion species
- Coexistent with almost other techniques
- No modification of existing structure



Improvement of plasma instability



Improvement of plasma instability



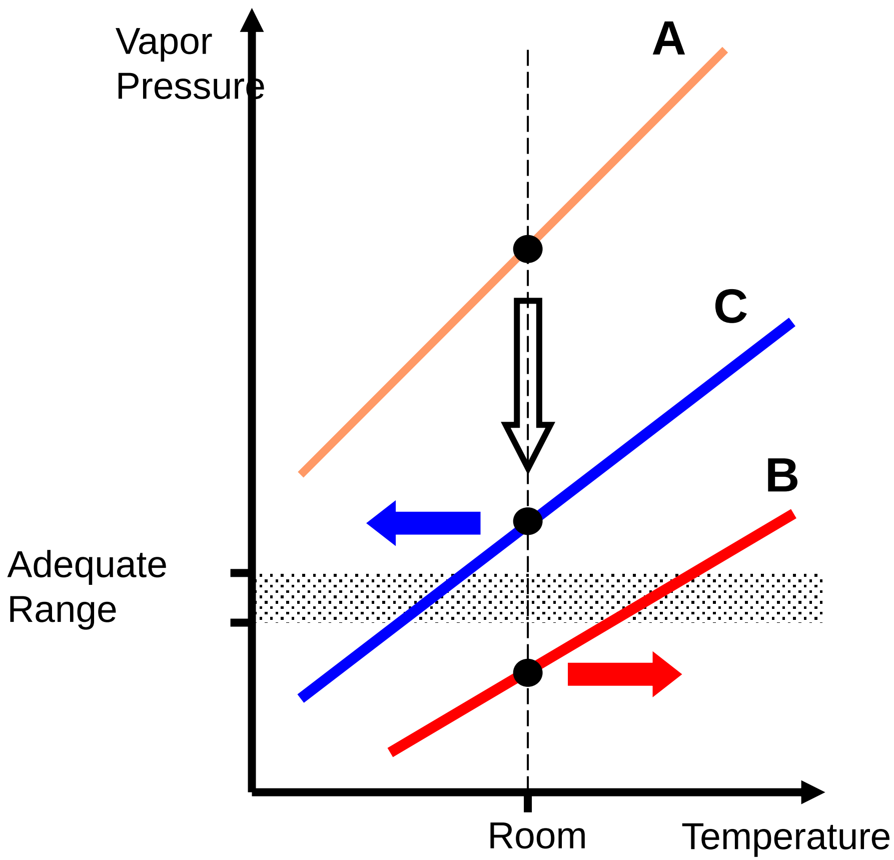
Important points for better outputs

- To supply enough power for both microwaves.
- To precisely adjust the additional frequency. The best frequency depends on other parameters, magnetic configuration, vacuum pressure, and so on.

Metal Ions from Volatile Compound (MIVOC) method

The two-frequency heating technique requires the precise pressure control. MIVOC with thermal control system is suitable for Fe, Ni, and Co.

Schematic diagram of the gas-flow control

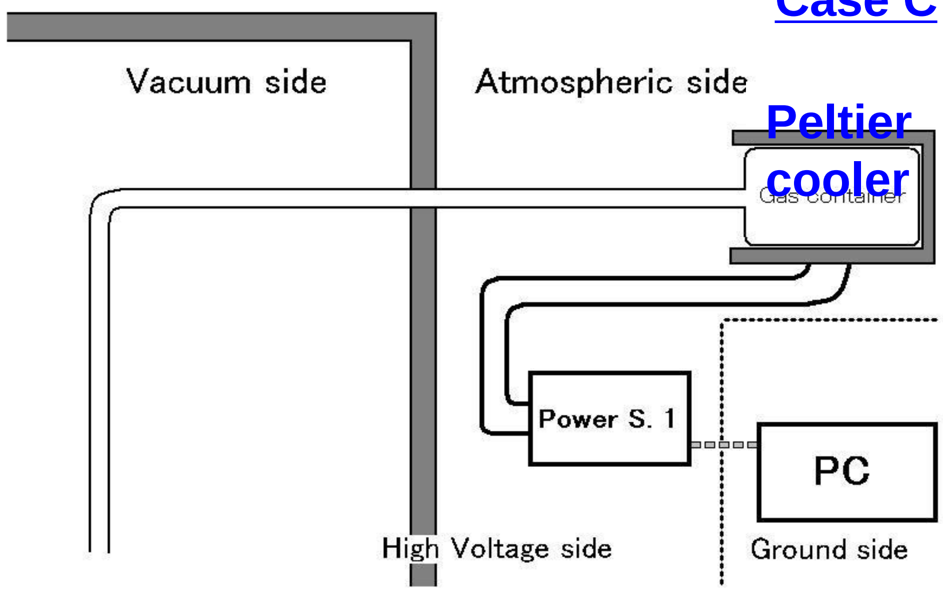


W. Takasugi, et al., Rev. Sci. Instrum. **81**, 02A329 (2010).

Merits of MIVOC

1. The material consumption rate is very low.
2. The equipment is small and easy.
3. The ion species can be changed without exposing the vacuum chamber to atmosphere.

Case C



Block diagram of the cooling MIVOC system

4. Experimental Results

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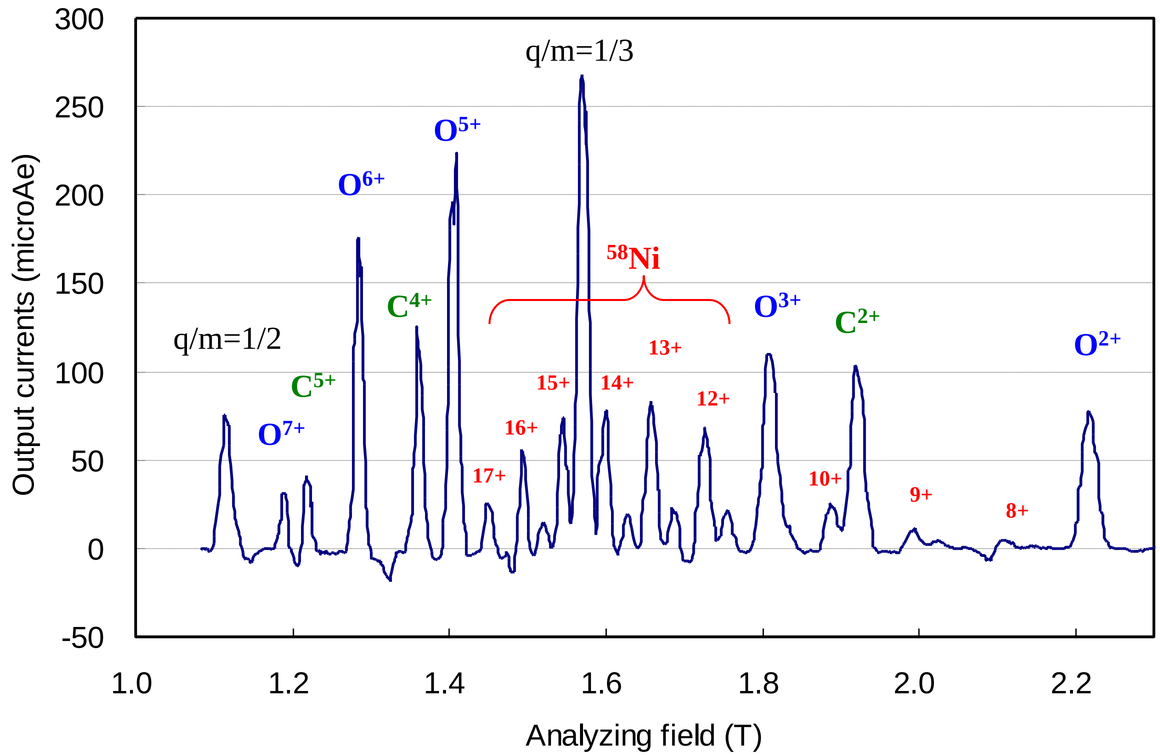
Typical Spectrum of Ni

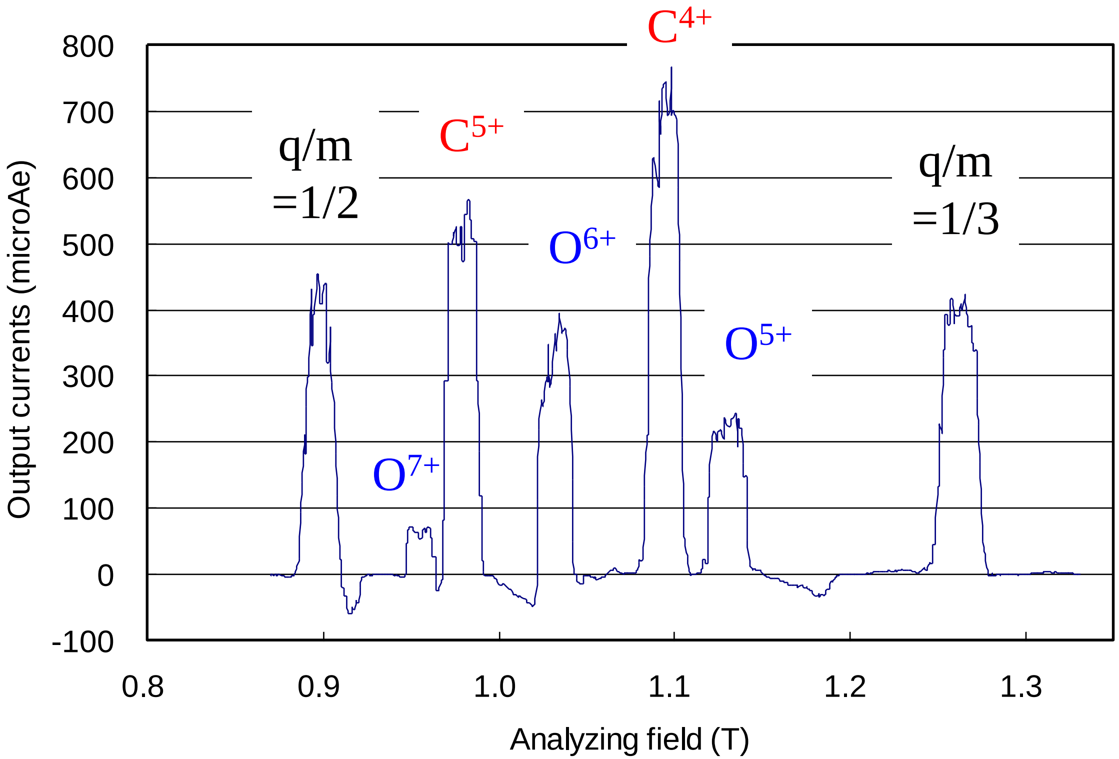


Operation parameters
optimized $^{58}Ni^{17+}$ at after-grow

$t_{\mu w}$ =30ms
f_1=18.00GHz, P_1=630W
f_2=17.87GHz, P_2=1100W
B_{inj}=1.21T, B_{ext}=0.74T
V_{ext}=31kV, d_{ext}=20mm
T_{Ni}=23C°
S_{O2}=0.024cc/min atom
$P_{inj}=3.3x10^{-5}$Pa

The intensity of $^{58}Ni^{17+}$ was 26 eμA.
The peak of $^{58}Ni^{18+}$ was coverd by the peak of O5+.
The peak of $^{60}Ni^{18+}$ was appeared.
The intensity of $^{58}Ni^{18+}$ was estimated about 12 eμA.
Although the peak of $^{58}Ni^{19+}$ and $^{60}Ni^{19+}$ were covered,
we expected an output current for $^{58}Ni^{19+}$ of a few eμA.

Typical Spectrum of C



Operation parameters

optimized C^{5+} at after-grow

$t_{\mu w}$ =20ms

f_1=18.00GHz, P_1=1050W

f_2=17.843GHz, P_2=1200W

B_{inj}=1.21T, B_{ext}=0.72T

V_{ext}=30kV, d_{ext}=18mm

S_{CH4}=0.070cc/min atom

P_{inj}=5.0x10^{-5}Pa

Peaks of oxygen appeared due to residual gas from the previous measurement. This was not suitable condition for highly charged carbon ions.

Improvement of Beam Currents

	H	He	B	B	C	N	O	Ne	Si	Cl	Ar	Ti	Fe	Ni	Co	Cu	Ge	Kr	In	Sn	Xe
q+/m	2	4	10	11	12	14	16	20	28	35	40	48	56	58	59	63	74	84	115	120	132
1+	**800**	**4000**																			
2+		**550**	**150**		**650**	**1240**	**1420**														
3+						**1050**	**930**	**1200**													
4+				**250**	**870**	**1000**		**1050**													
5+					**550**	**920**	**900**	**1160**	**250**												
6+						**150**	**770**	**750**		**400**	**320**										
7+							**165**	**300**			**650**										
8+								**100**		**190**	**1100**		**35**								
9+										**60**	**650**		**200**		**160**						
													400								
10+		Red:										**8**	**160**	**165**		**50**					
11+		after-glow technique									**200**		**130**	**125**			**50**	**210**			
12+		Green:									**116**		**130**	**110**				**254**			
13+		two-frequency heating									**42**		**120**	**83**				**260**			
14+		Purple: both									**15**			**78**							
15+													**70**	**75**				**250**			
																		200			
16+		**New records**											**41**	**56**							
17+		**in 2014**											**12**	**26**				**153**			
18+													**2**	**12**				**110**		**20**	**185**
19+														**a few**				**80**			**170**
20+																		**44**			**168**
																			140		
21+																					**155**
																					200
22+																		**11**			
23+																		**5**			**115**
24+																					**91**
25+																					
26+																					**37**
27+																					**11**

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Estimation of possibility to use

Charge state	5+	12+	13+	14+	15+	16+	17+	18+	19+
C	550								
Ar		116	42	15					
Fe		130	120		70	41	12	2	
Ni		110	83	78	75	56	26	12	a few

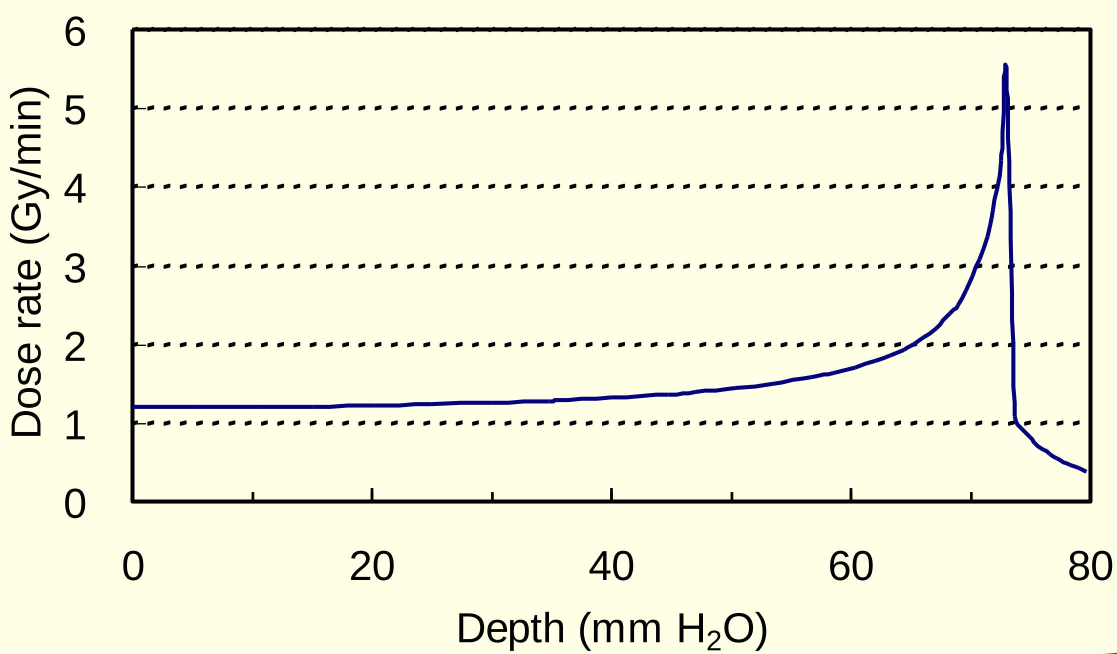
Estimation of possibility to use

Charge state	5+	12+	13+	14+	15+	16+	17+	18+	19+
C	550								
Ar		116	42	15					
Fe		130	120		70	41	12	2	
Ni		110	83	78	75	56	26	12	a few

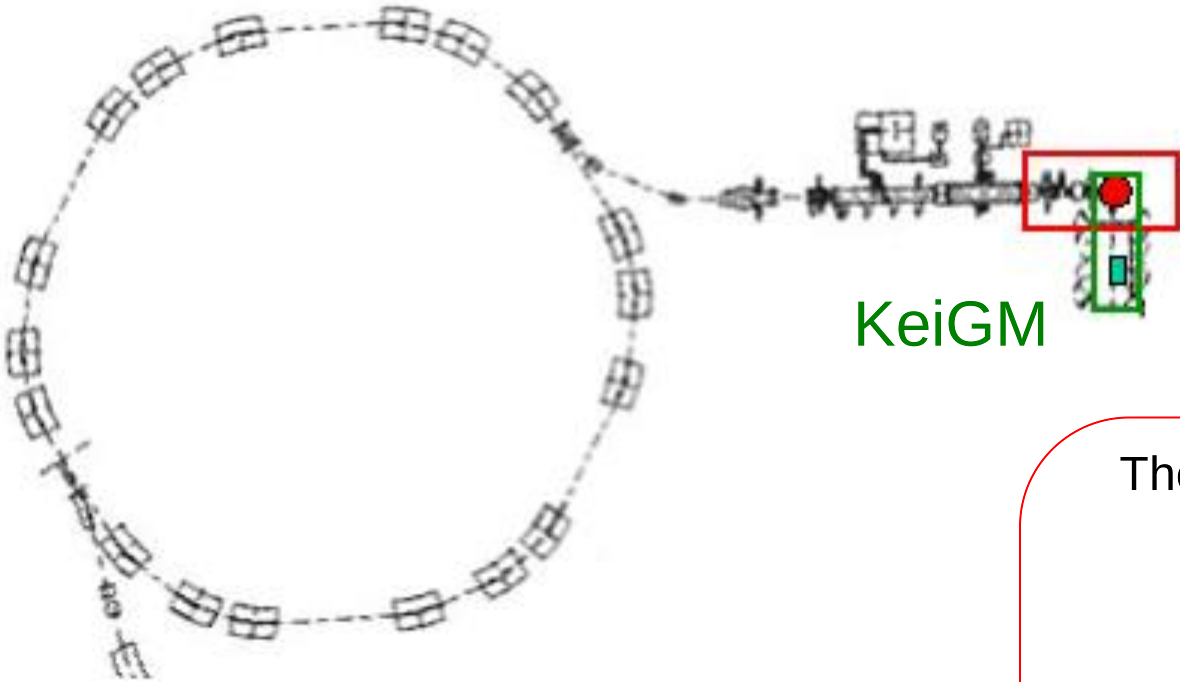
Depth dose distribution at biology experiment room

Uniform field size: 2 cmϕ

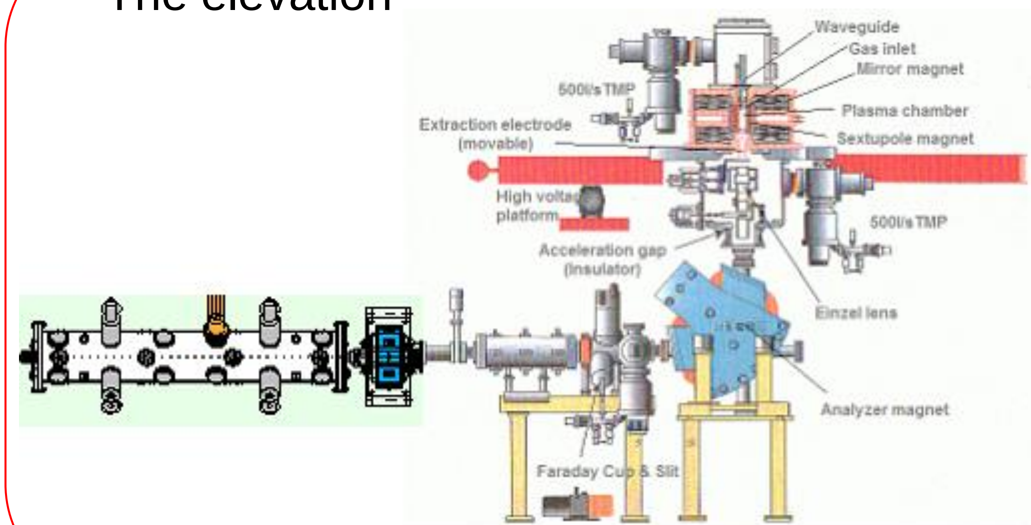
It is enough for cell experiments, but more intensity is better for animal experiments.



Footprints of NIRS-HEC and Kei-series



The elevation



Drawbacks of NIRS-HEC

- Initial construction cost is two or three times higher than Kei-series.
- Electric power consumption is huge (250kVA).

5. Discussion

Realistic possibility to use NIRS-HEC

Another important point!

Ion-source specialist is not expected in a hospital.

- The installation of gas bottles or MIVOC containers must be simple.
- The complicated operation is not acceptable. All operation parameters must be stored for the software control system. Is the one-touch operation possible?
- How to check the reproducibility by non specialists?

Interval to exchange ion species

Daily carbon operation

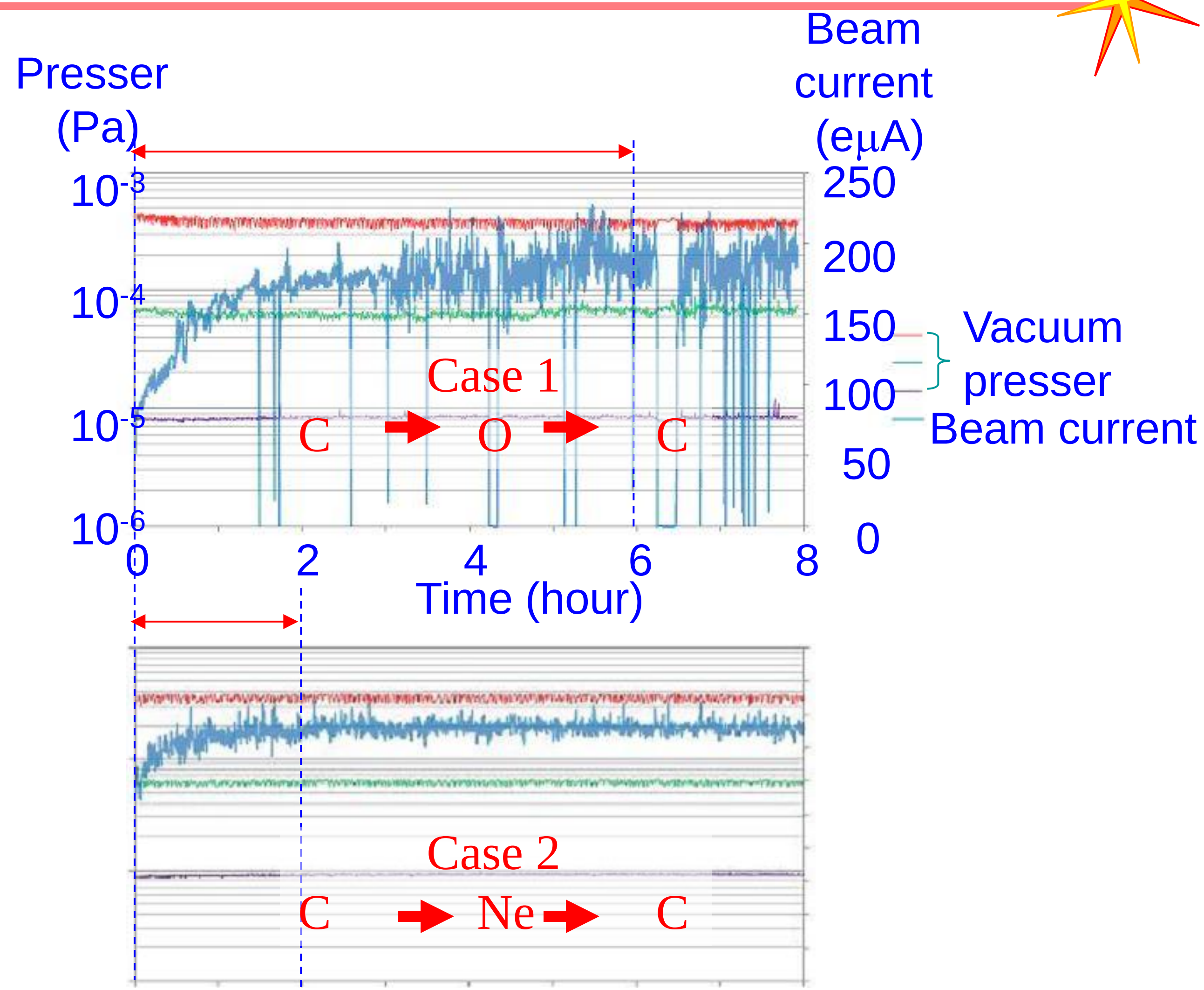
(Vacuum evacuation during one night)

Operation of other ion species, O, Ne…

(Vacuum evacuation during one night)

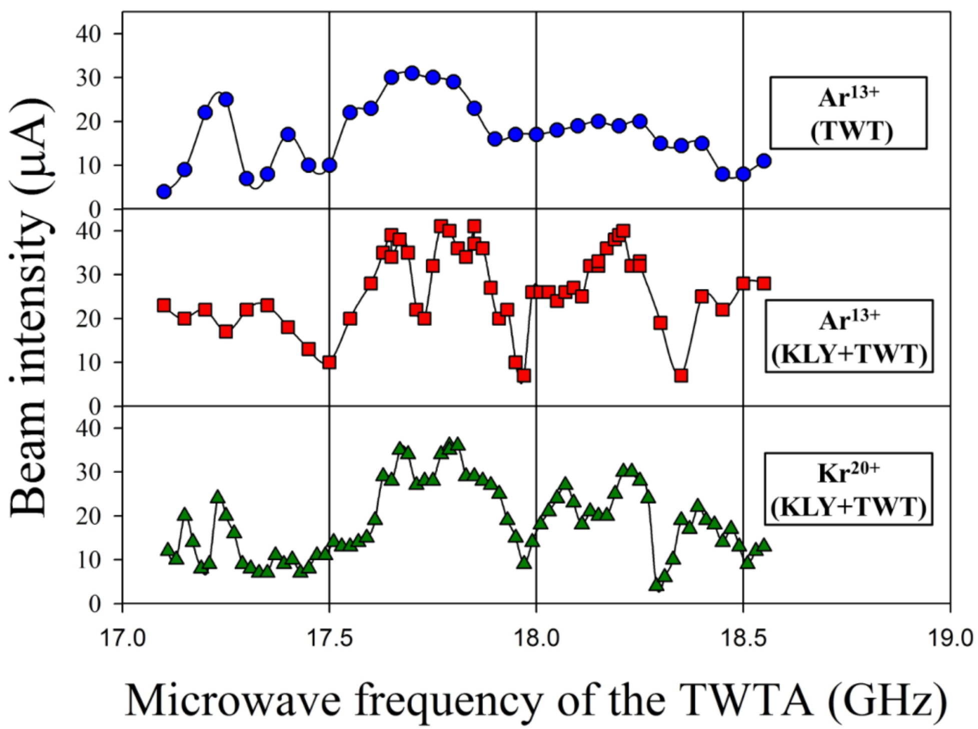
Carbon operation
- Set the previous parameter
- Measure the transient time to the stable operation

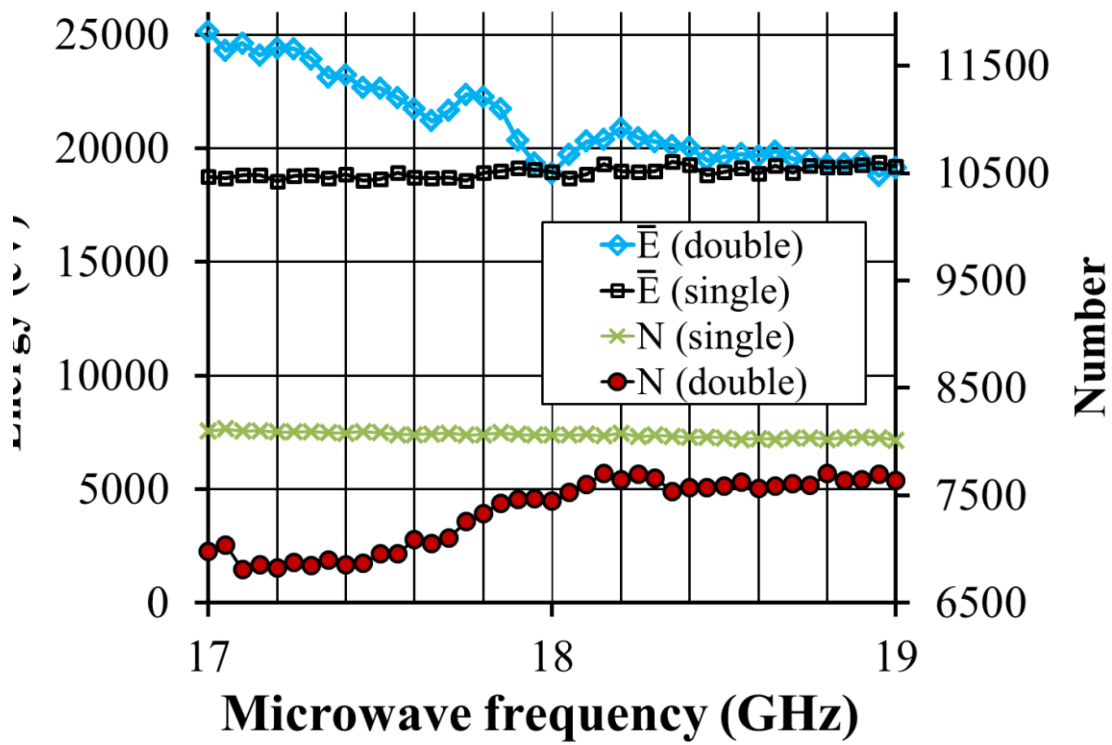
Procedure of the switching of ion species



Carbon beam currents after the switching from oxygen and neon beam by Kei2.

Understanding of mechanism





The mechanism of two-frequency heating technique is still not clear. Some recent observations of the additional frequency dependence suggested that an electron orbit effect might play some role.
One approach to verify or to reject this assumption is a computer simulation. The calculation by the TrapCAD code has continued by our collaborators.

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

Summary

1. **Status of carbon ion radiotherapy**
   - Present clinical results show enough performance.
   - ECRISs have completely satisfied the medical requirement.
   - New facilities are under construction or planned.
2. **Requirement for life science research**
   - Due to advantage to use the design for a radiotherapy dedicated facility, ions with the charge-to-mass ratio of 1/3 are necessary for life science research.
   - It is expected the range of ion species covers to Fe, Ni, or Co..
3. **Technical method**
   - 18GHz normal temperature ECRIS was tested.
   - Two-frequency heating technique has been utilized.
   - MIVOC method has been utilized for Fe and Ni.
4. **Experimental results**
   - Output currents of C^{5+}, Ar^{13+}, Fe^{18+}, and Ni^{19+} were improved.
   - Fe intensity satisfies cell biology experiments.
5. **Discussions**
   - It’s necessary to establish easy operation for a hospital.
   - The time interval is remained problem.