CYCLOTRON TECHNOLOGY AND BEAM DYNAMICS FOR MICROBEAM APPLICATIONS

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National Institutes for Quantum and Radiological Science and Technology (QST)

Takasaki Advanced Radiation Research Institute

OUTLINE

1. Introduction
2. Microbeam Application
3. Microbeam Formation Technique
4. Cyclotron Development
   - 4. 1 Control of Beam Phase
   - 4. 2 Magnetic Field Stabilization
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6. Quick Change of Ion Species
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1. Introduction

About QST

Established in April 2016 by merging National Institute of Radiological Sciences (NIRS) with a few research institutes of Japan Atomic Energy Agency (JAEA).

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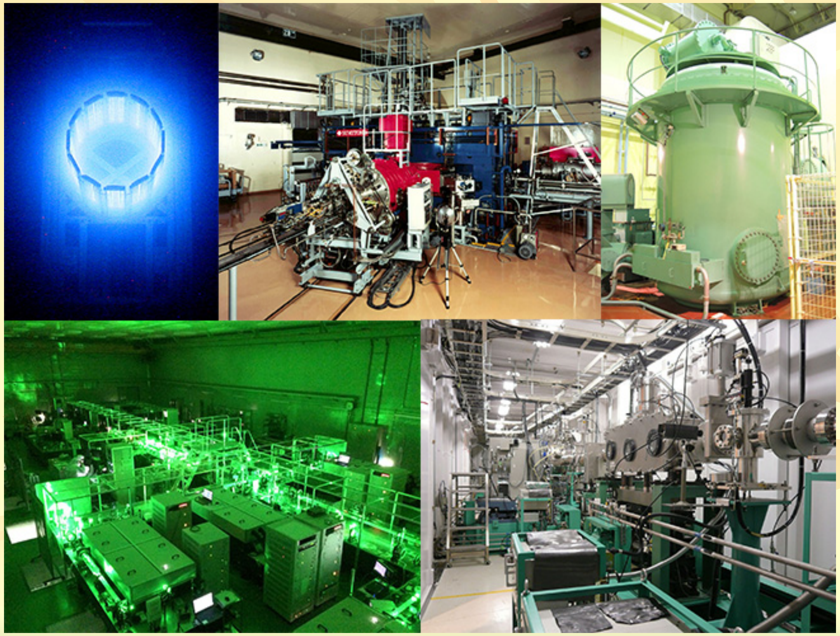

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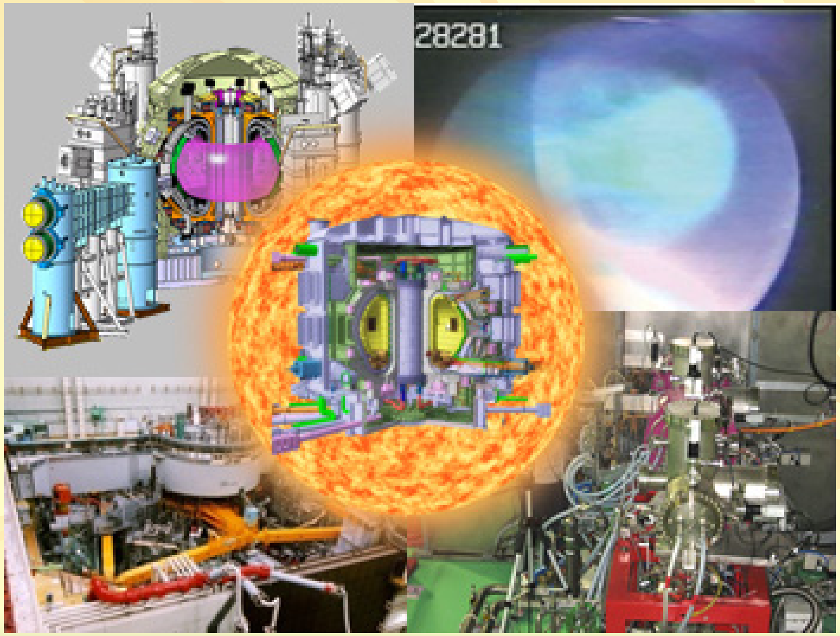

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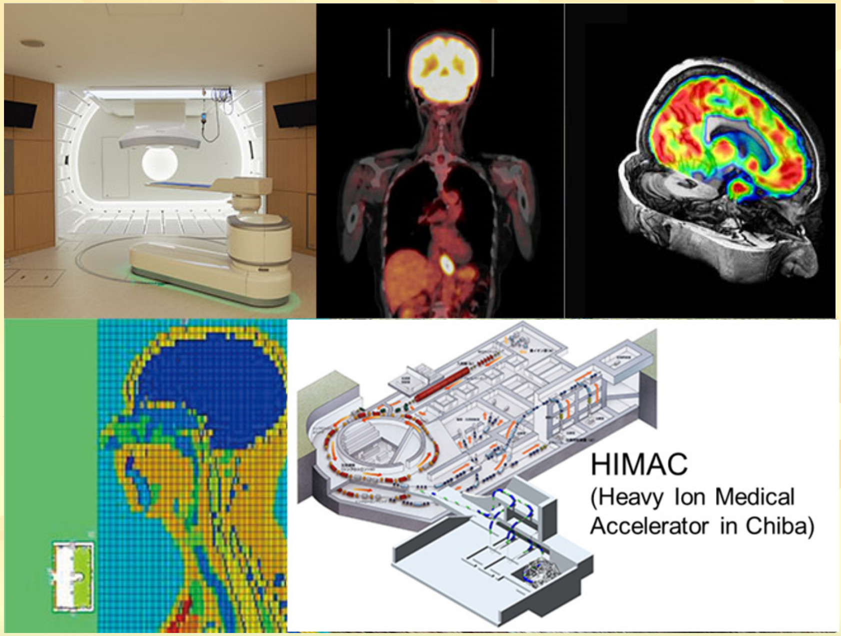

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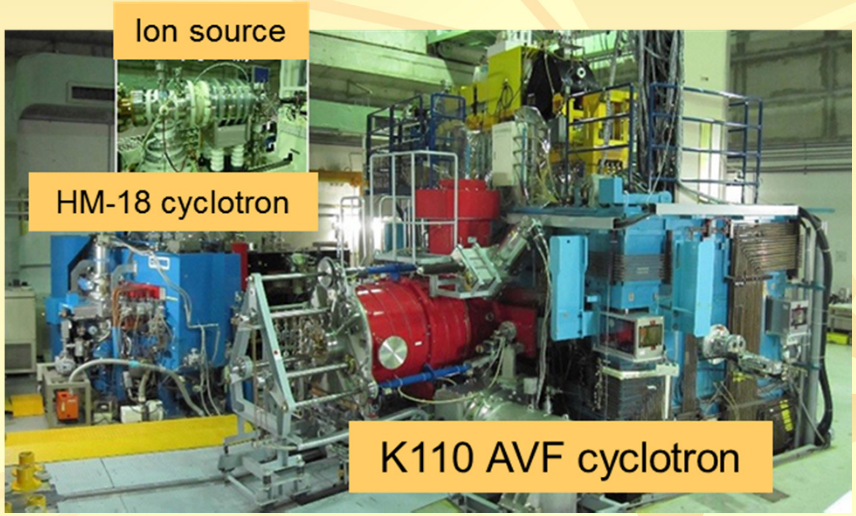

1. Introduction

About TIARA

Takasaki Ion accelerators for Advanced Radiation Application (TIARA) facility was constructed to provide high-energy ion beams mainly for research in biotechnology and materials science, and started full operation in 1993.

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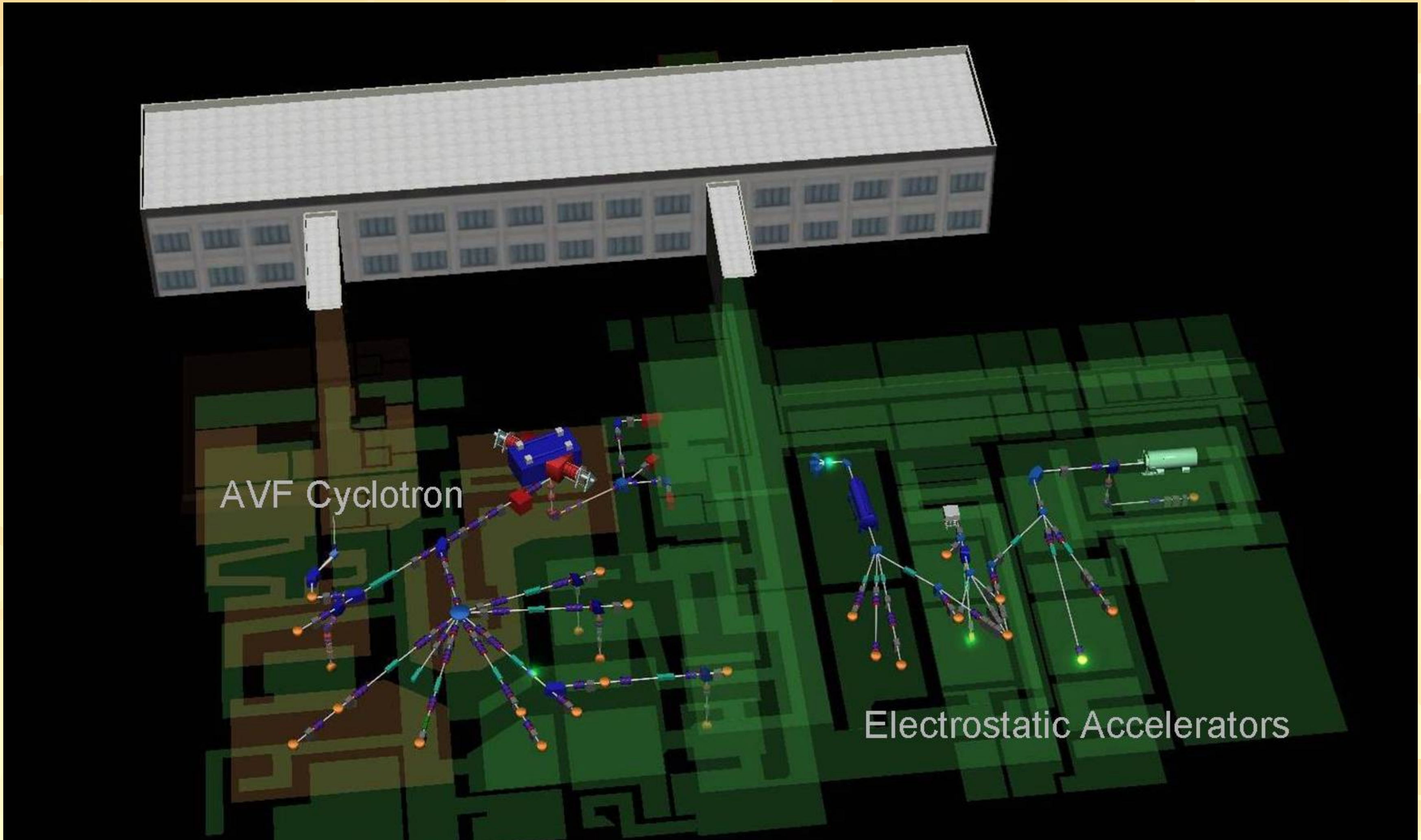

Takasaki Ion accelerators for Advanced Radiation Application: TIARA

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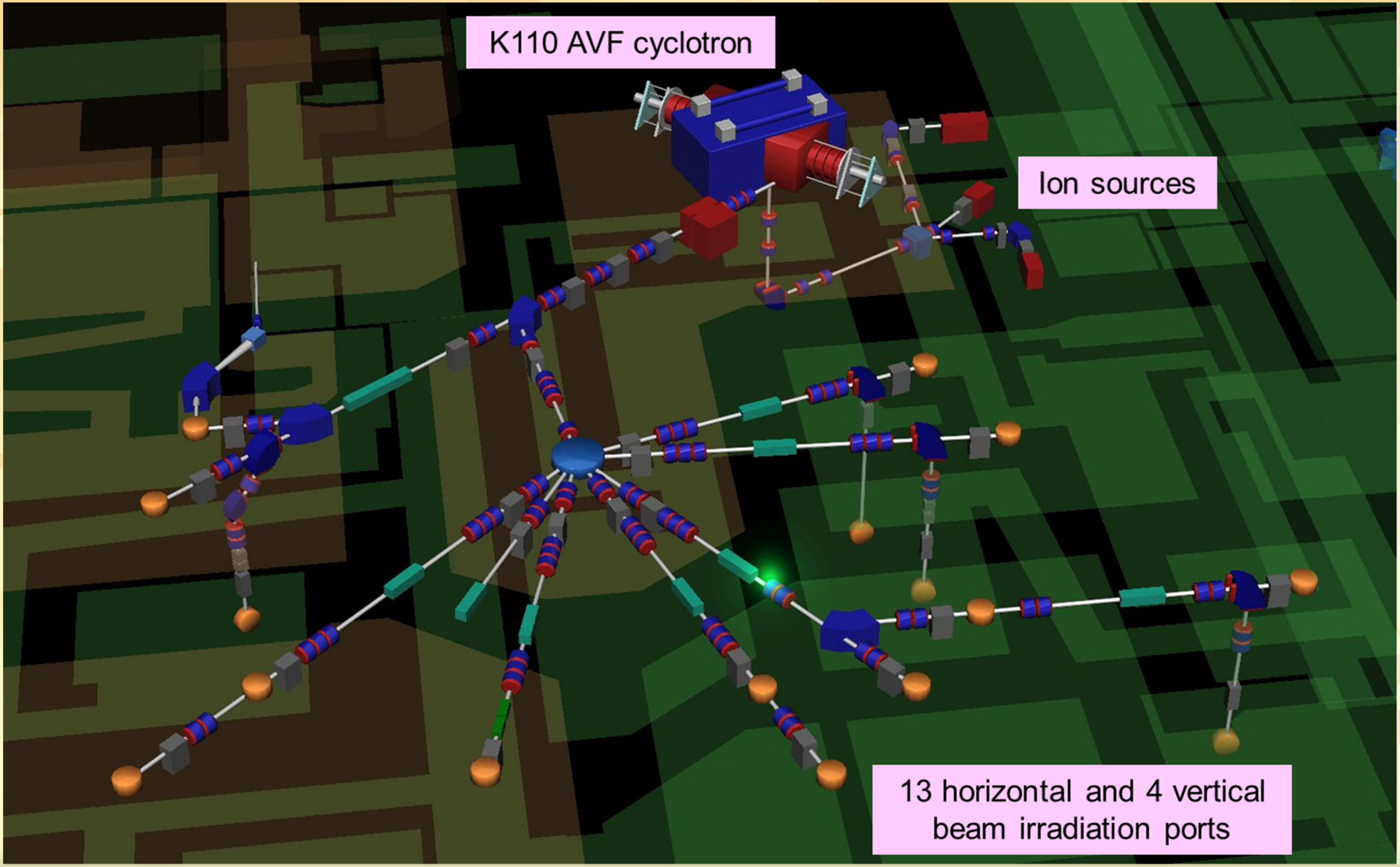

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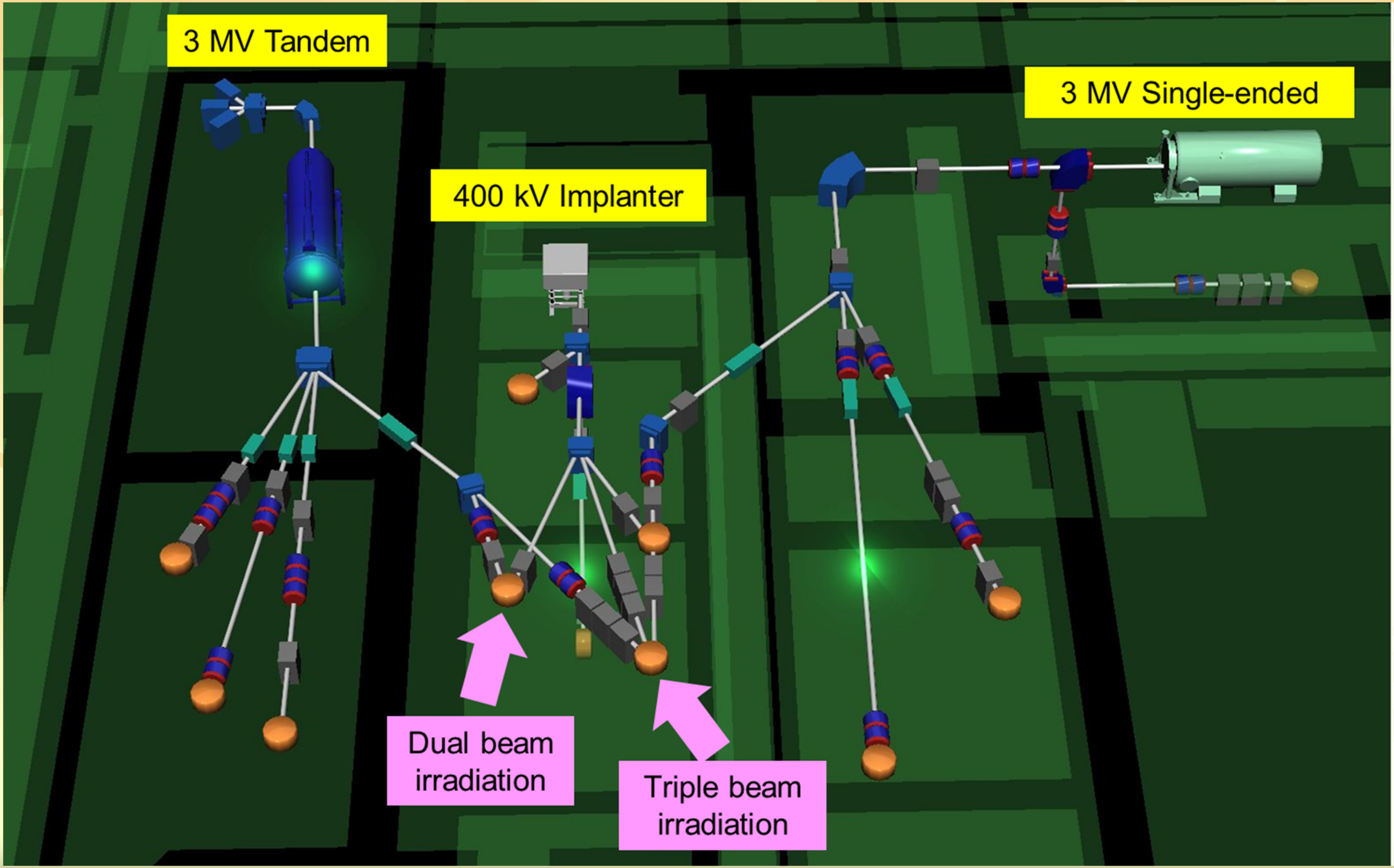

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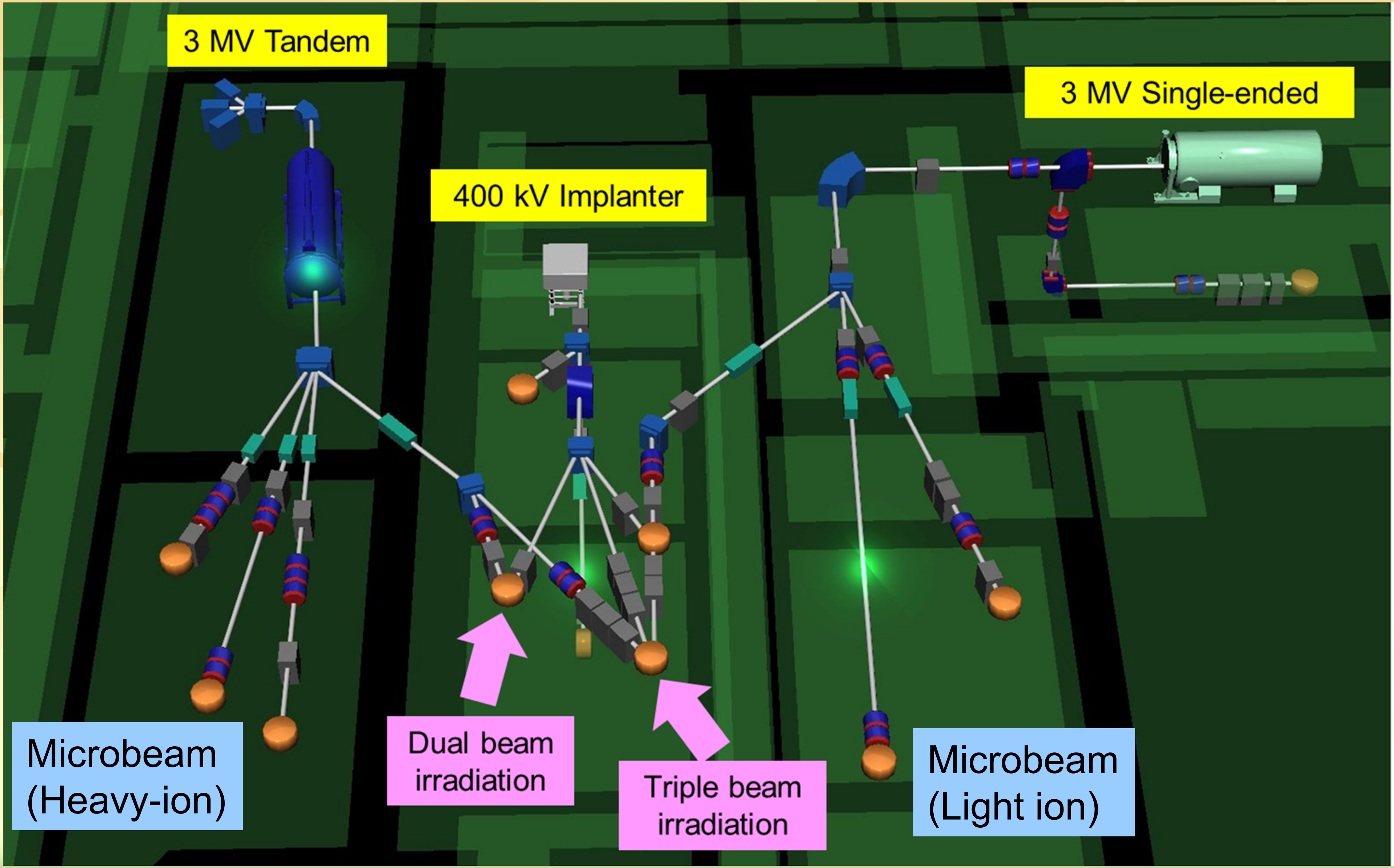
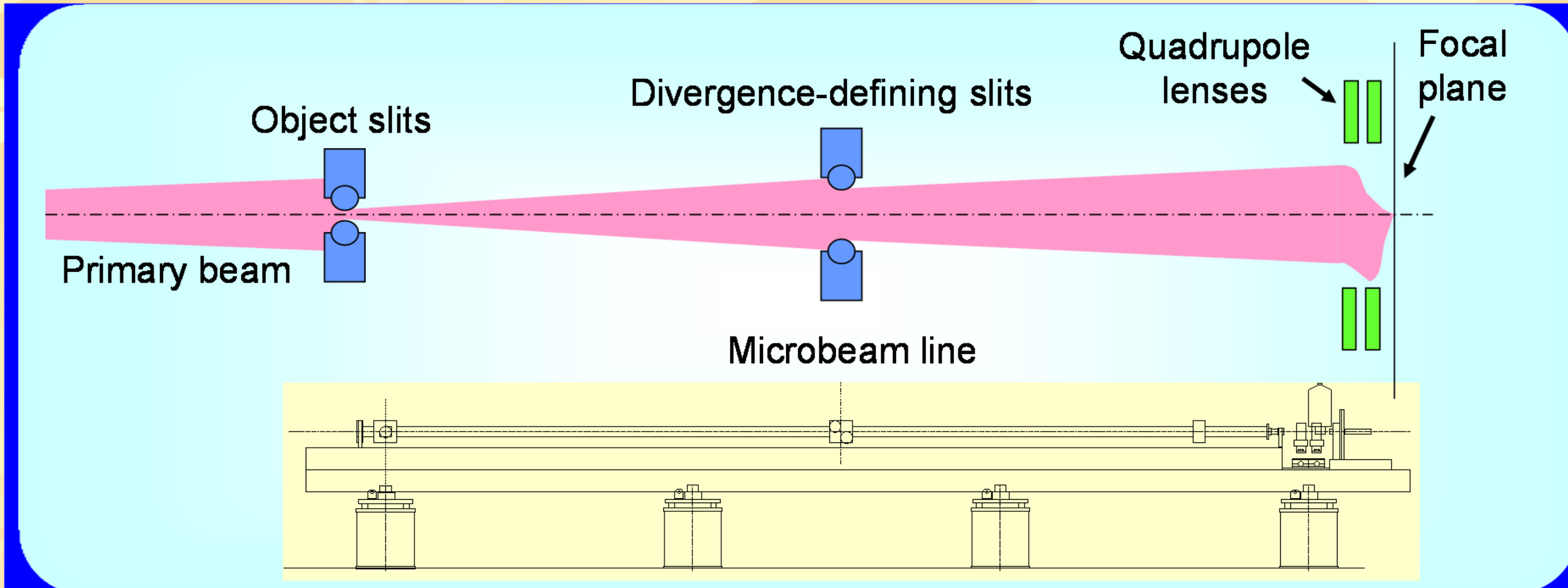


2. Microbeam Application (ESA)

A microbeam with a spot size about 1 μm is a powerful tool to analyze and/or irradiate a microscopic area.



Tens MeV Heavy Ion Microbeam Line

MeV Light Ion microbeam Line

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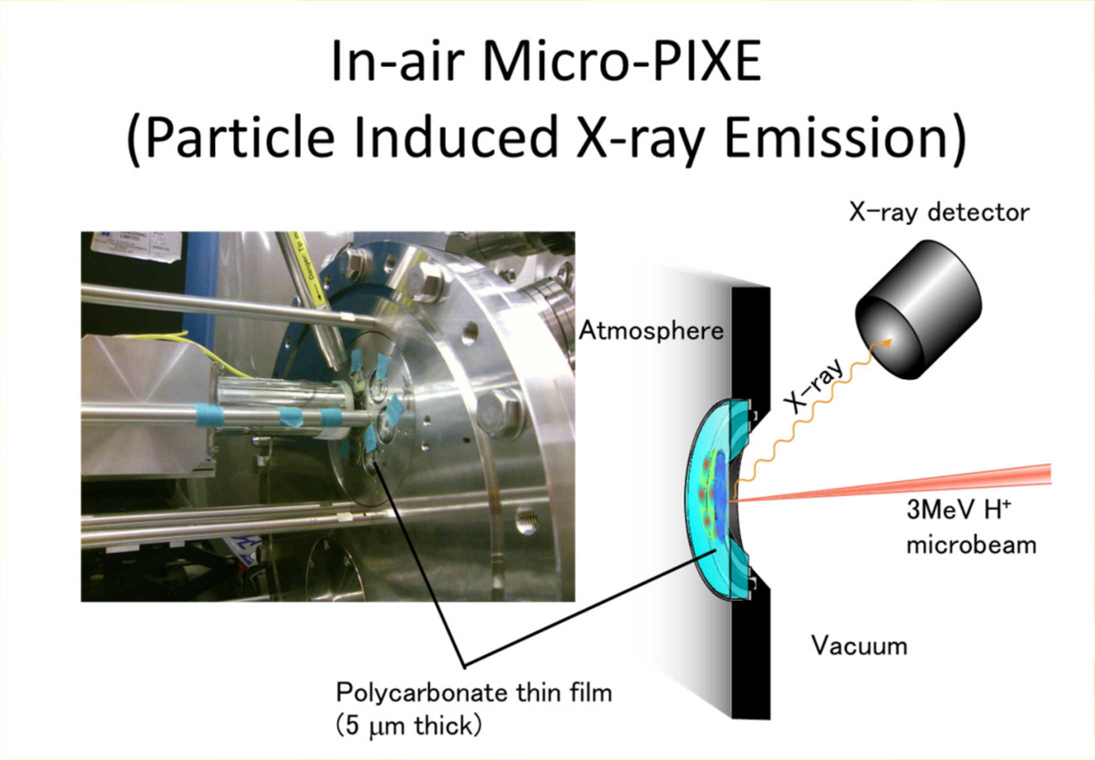

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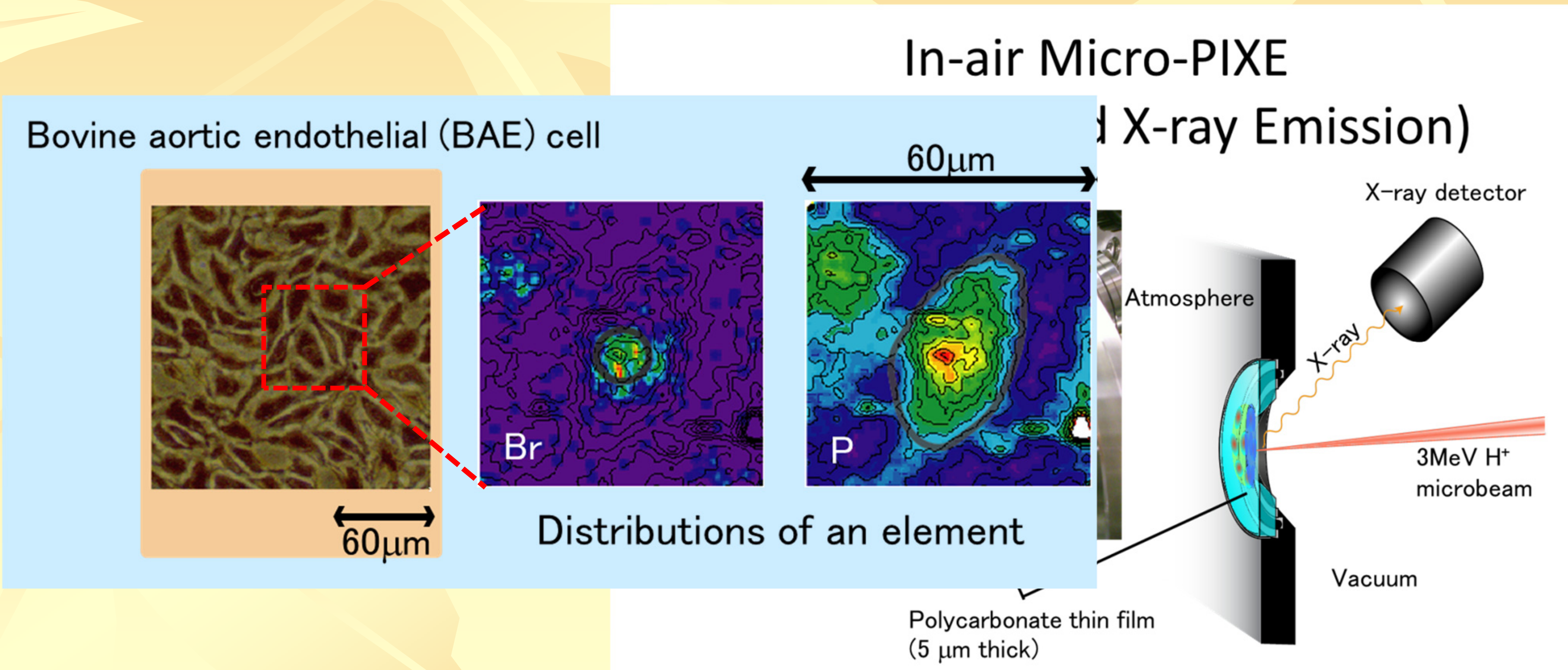
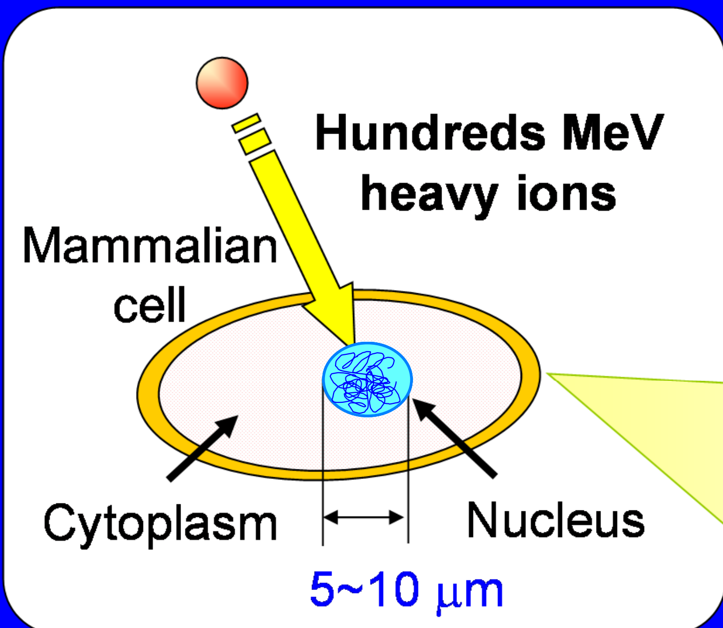


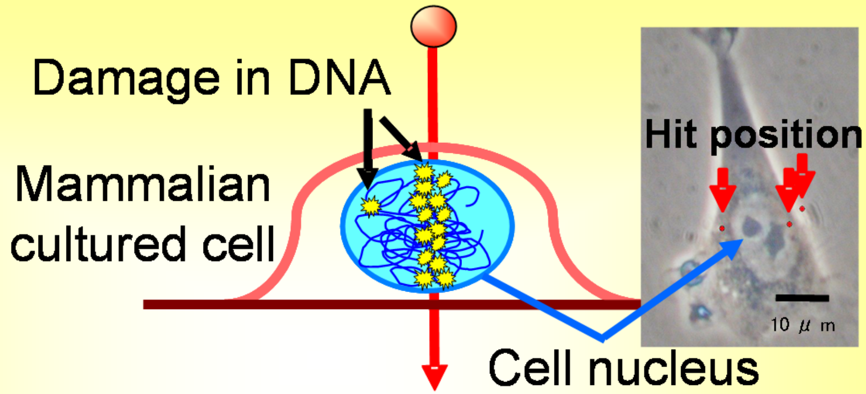
2. Microbeam Application (Cyc)

High LET (Linear Energy Transfer) heavy ion beams

Microbeam Application to biotechnology

Elucidation of Cellular Radiation Response





- Investigation of cell-to-cell communications such as “bystander effects”
- Analysis of cellular spatial sensitivity, interaction of damages, dynamics of cellular repair and intra-cellular process like apoptosis

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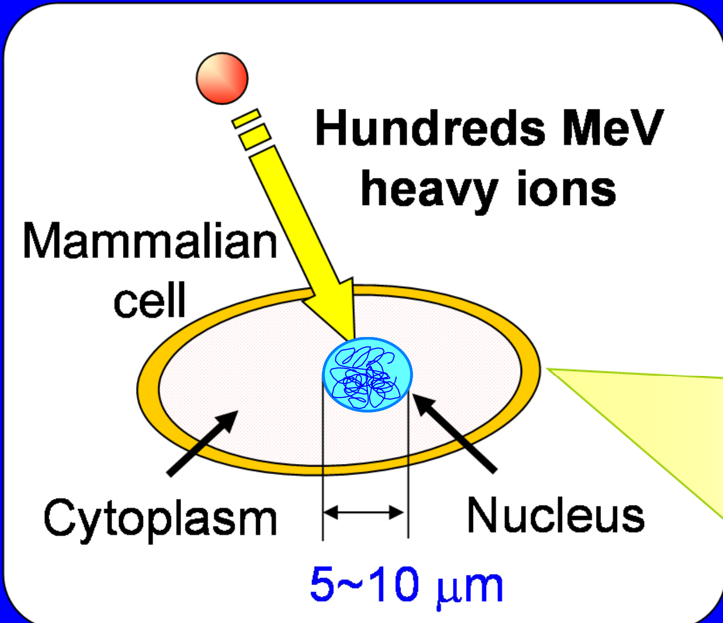
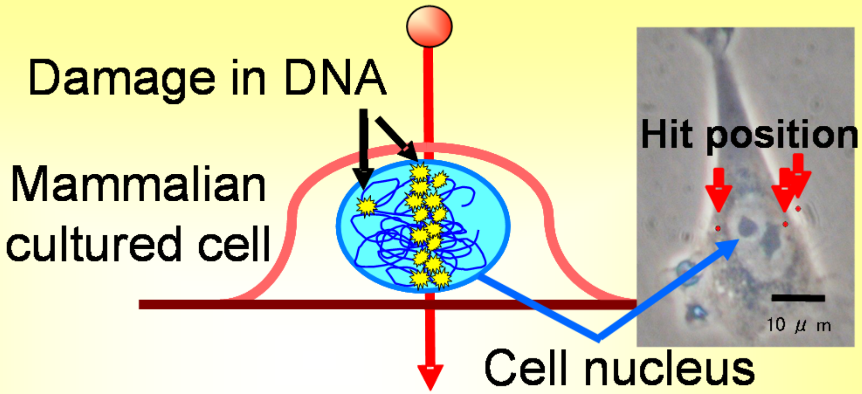
High LET (Linear Energy Transfer) heavy ion beams

Microbeam Application to biotechnology

Elucidation of Cellular Radiation Response





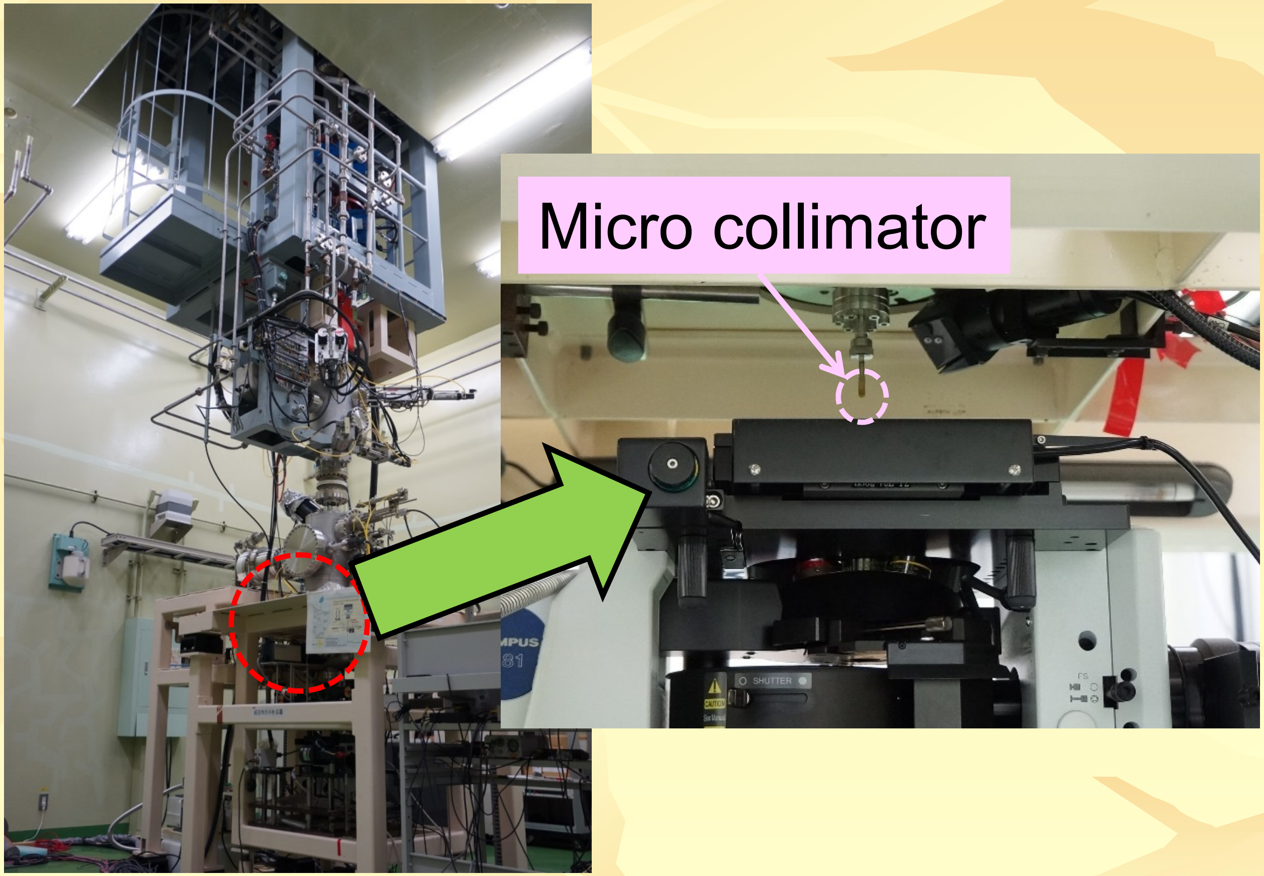
• Investigation of cell to cell communications such
as

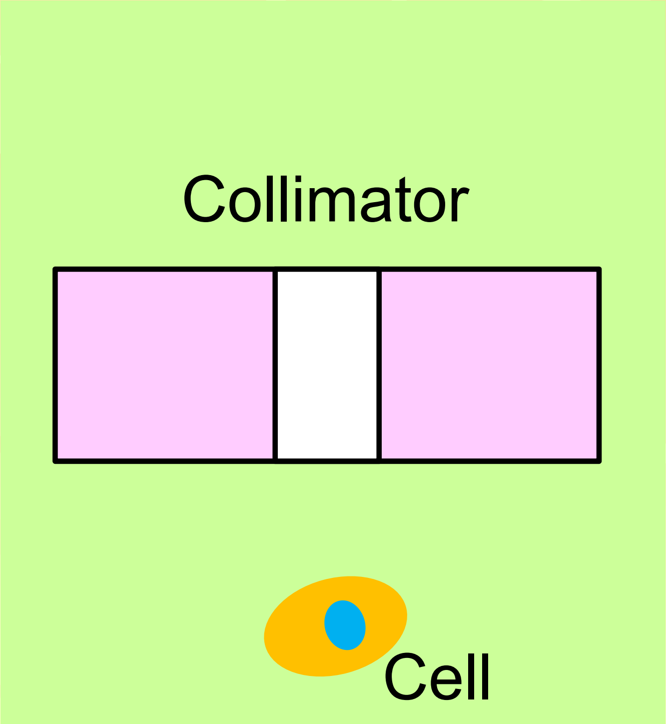
• Ana ion
of
intra-cellular process like apoptosis

Single-ion hit irradiation
with 1 µm beam

3. Microbeam Formation Technique

Microbeam formation using a collimator





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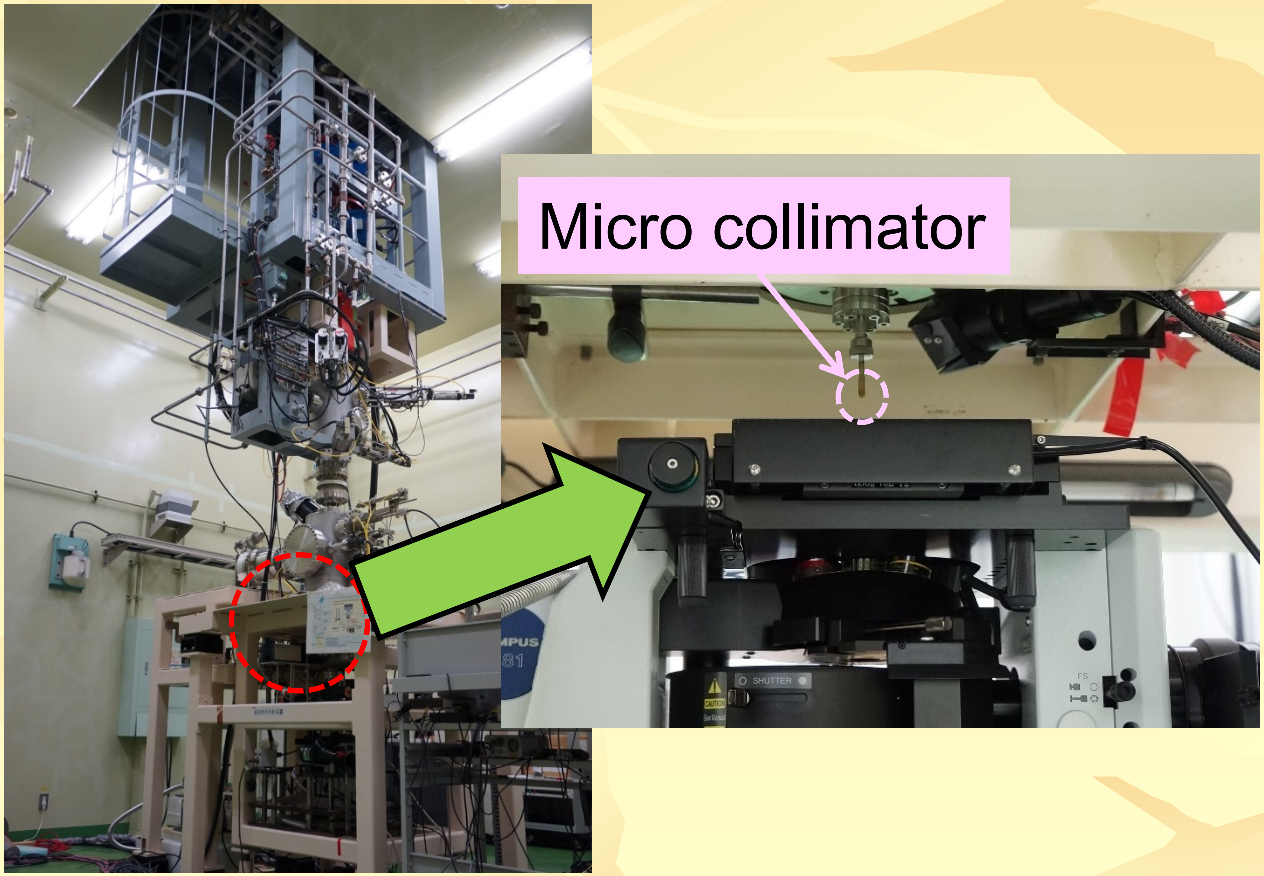

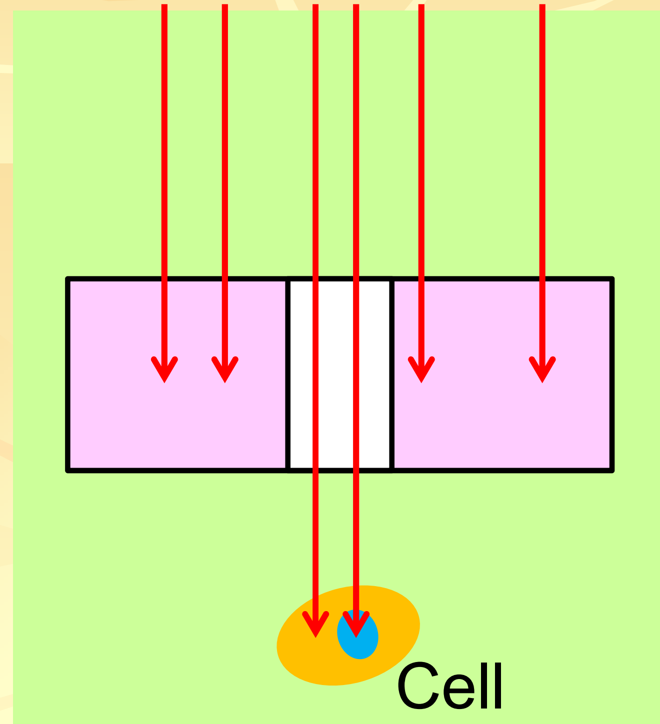

- Limitation of aperture size (20 μm for C, 5 μm for Ar)

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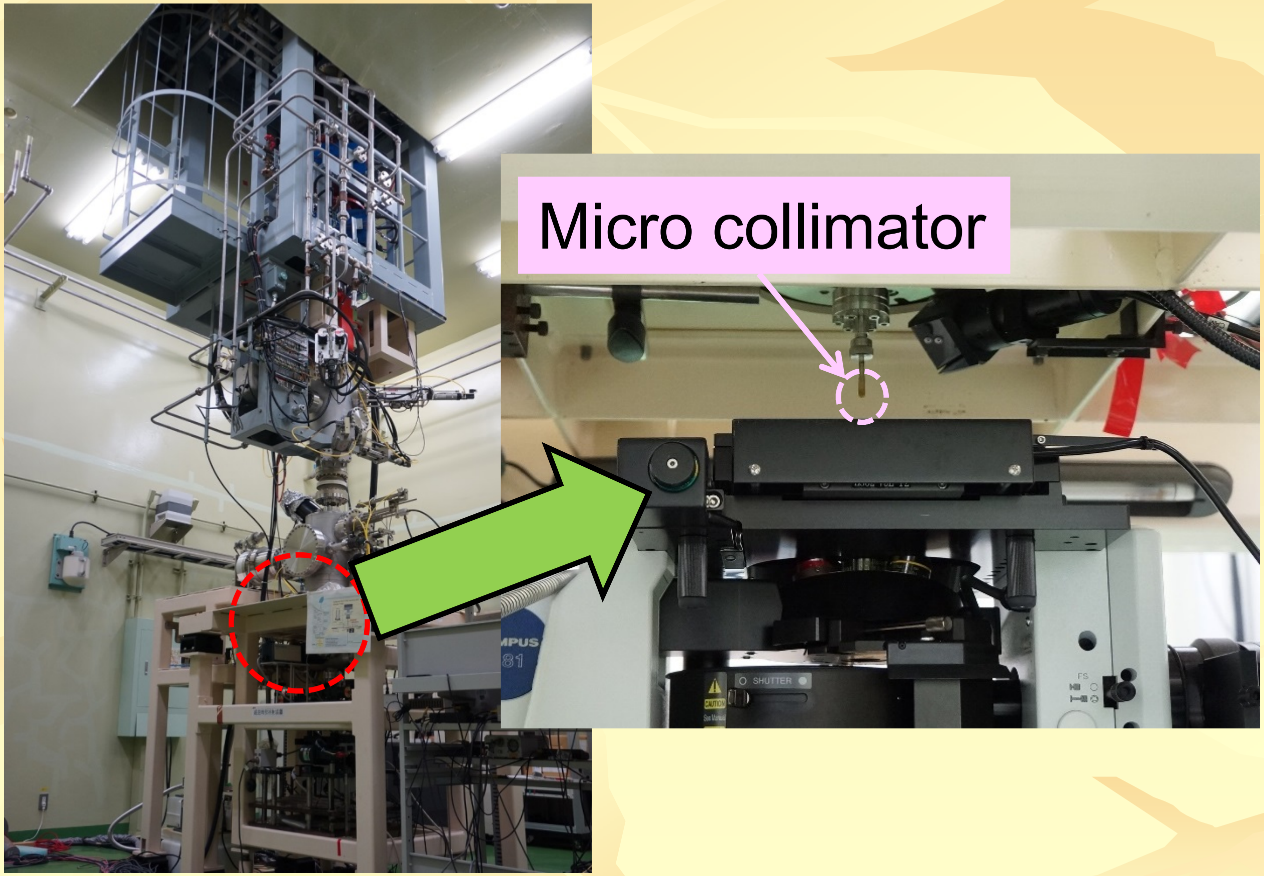

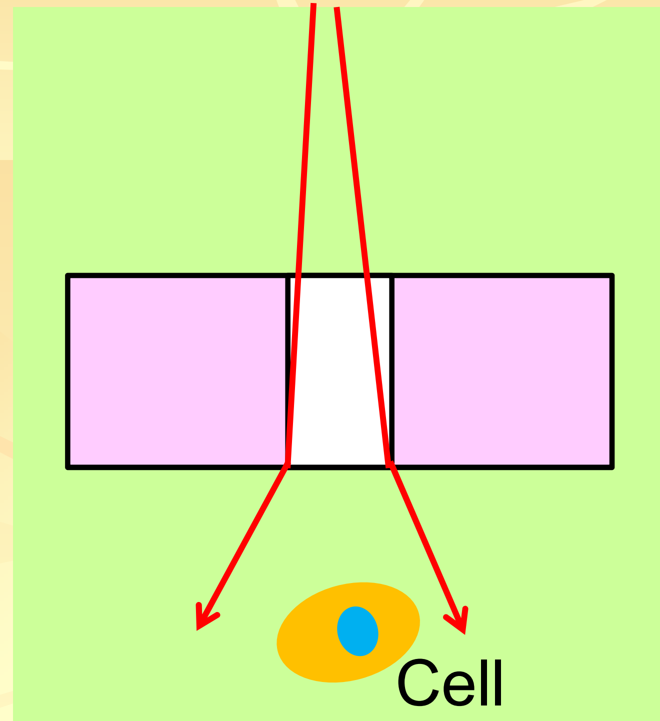

- Limitation of aperture size (20 μm for C, 5 μm for Ar)
- Scattering at the edge (20 to 30%)

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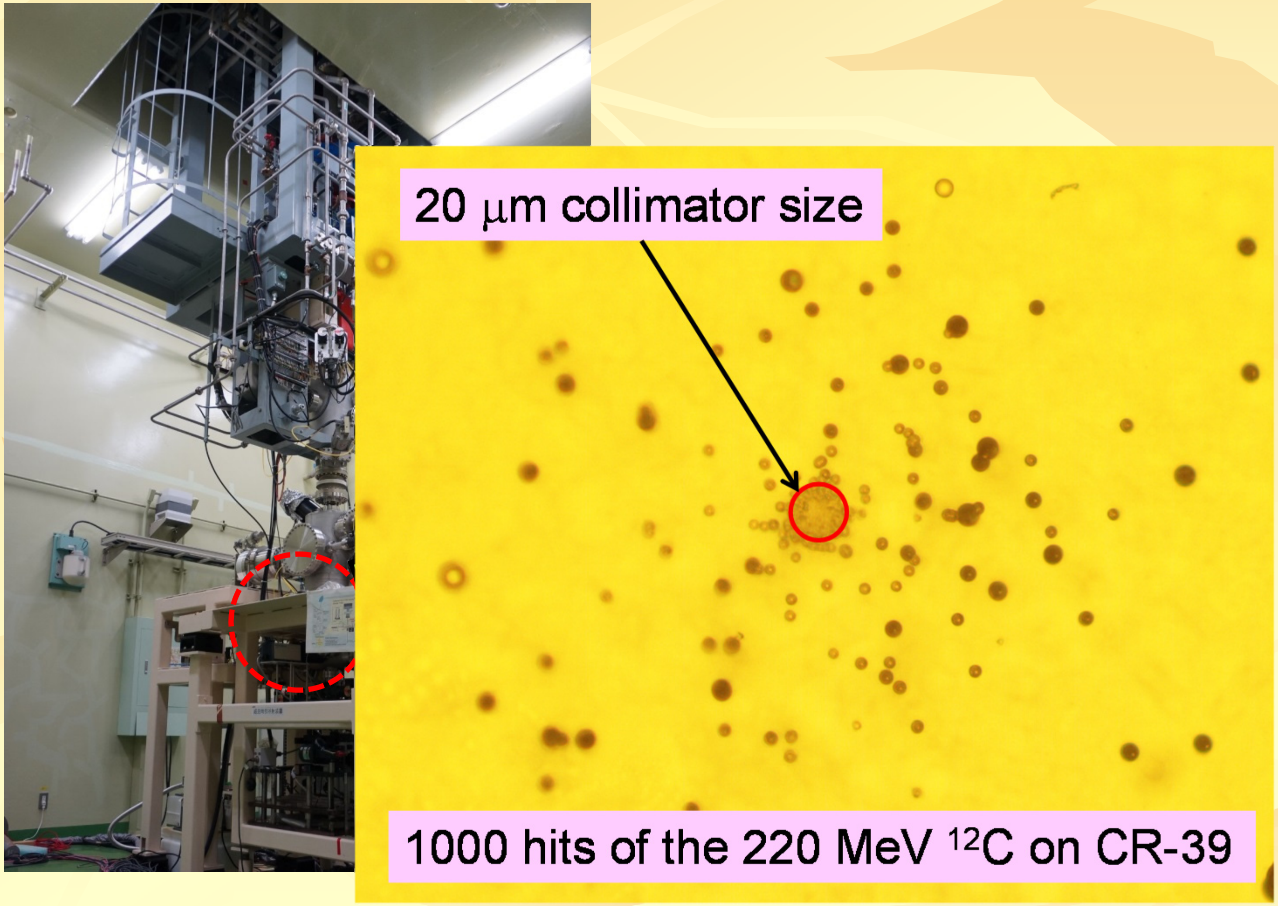

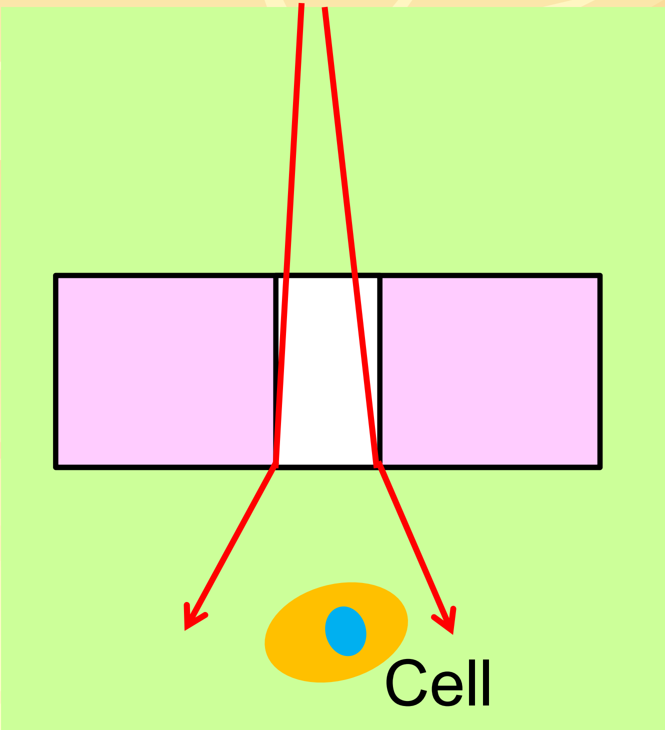

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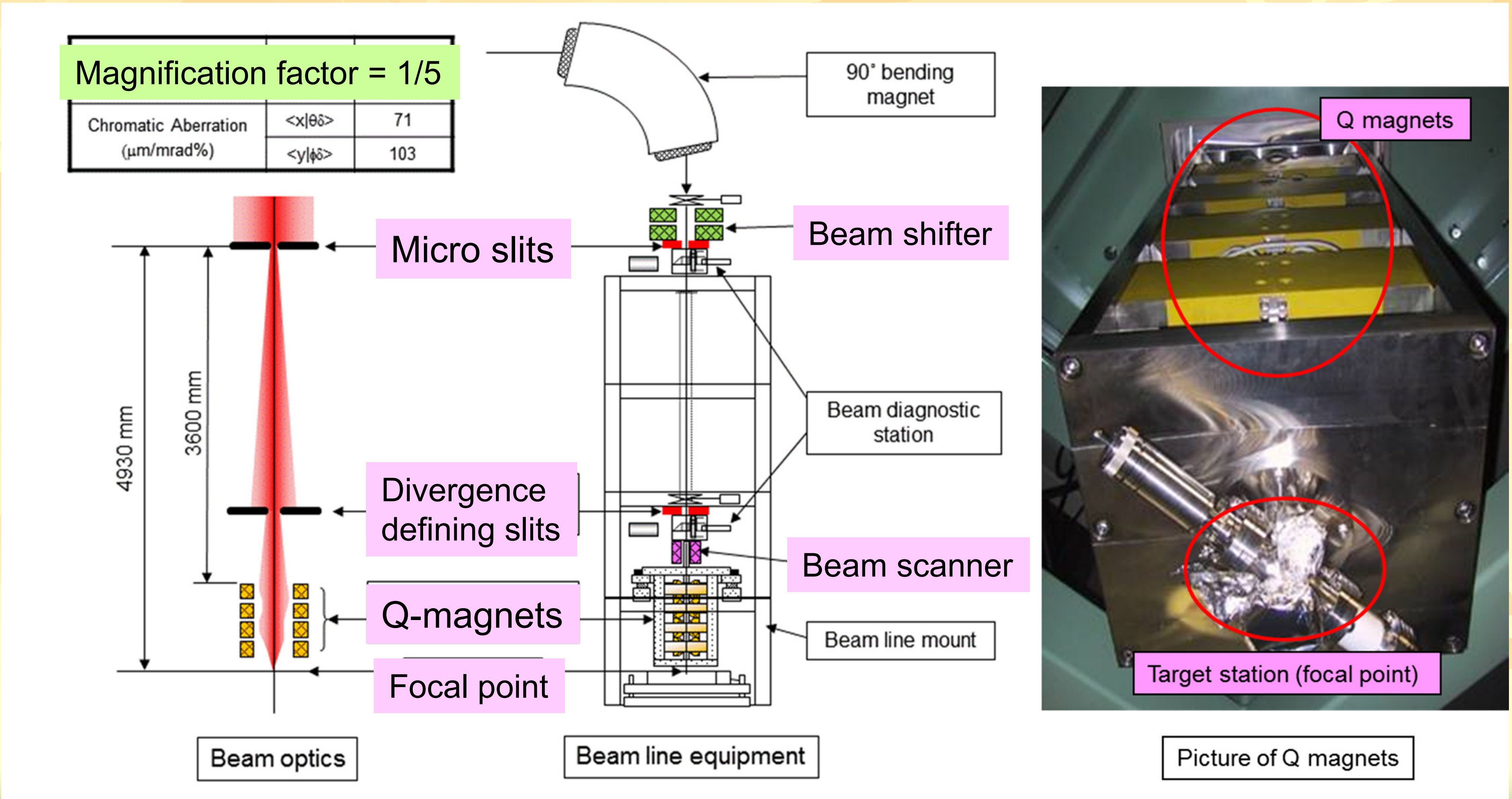
3. Microbeam Formation Technique

Microbeam formation using focusing magnets



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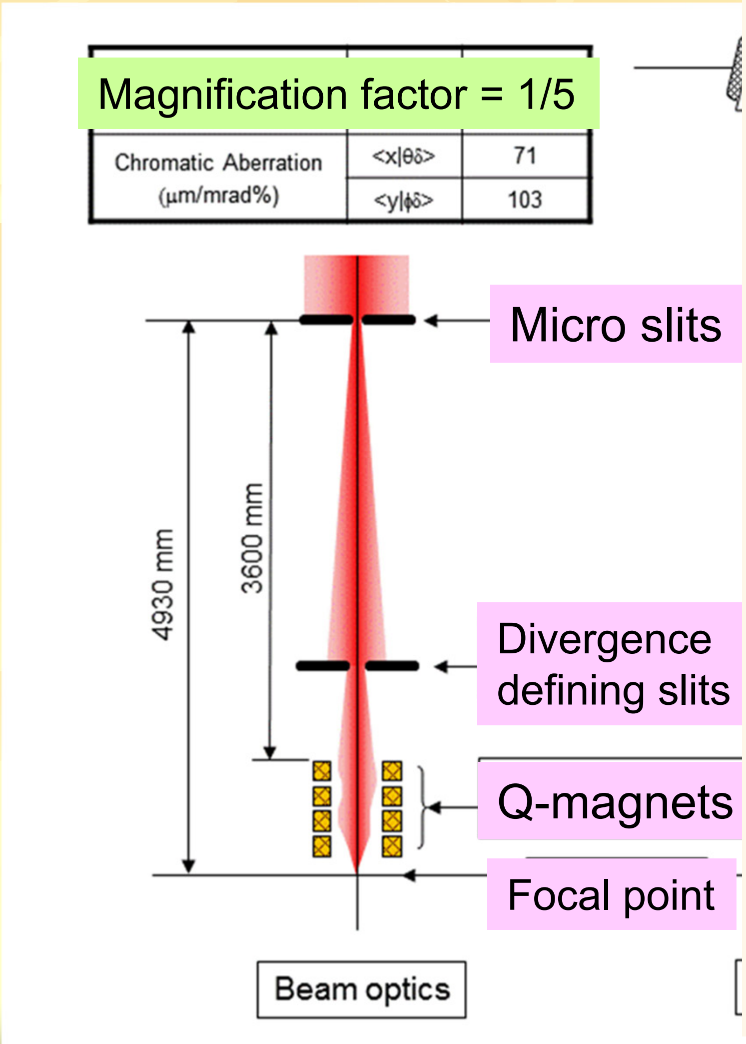

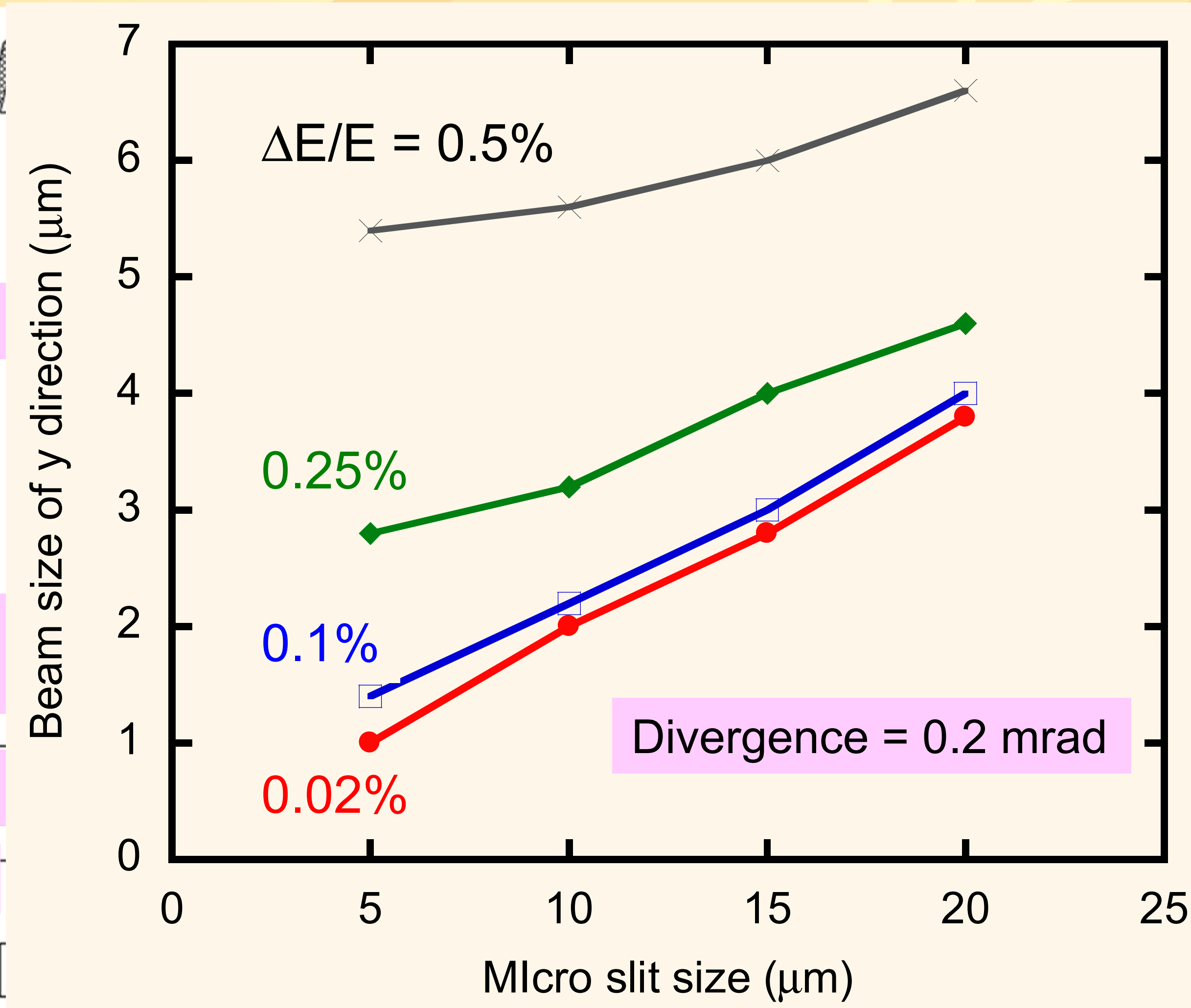

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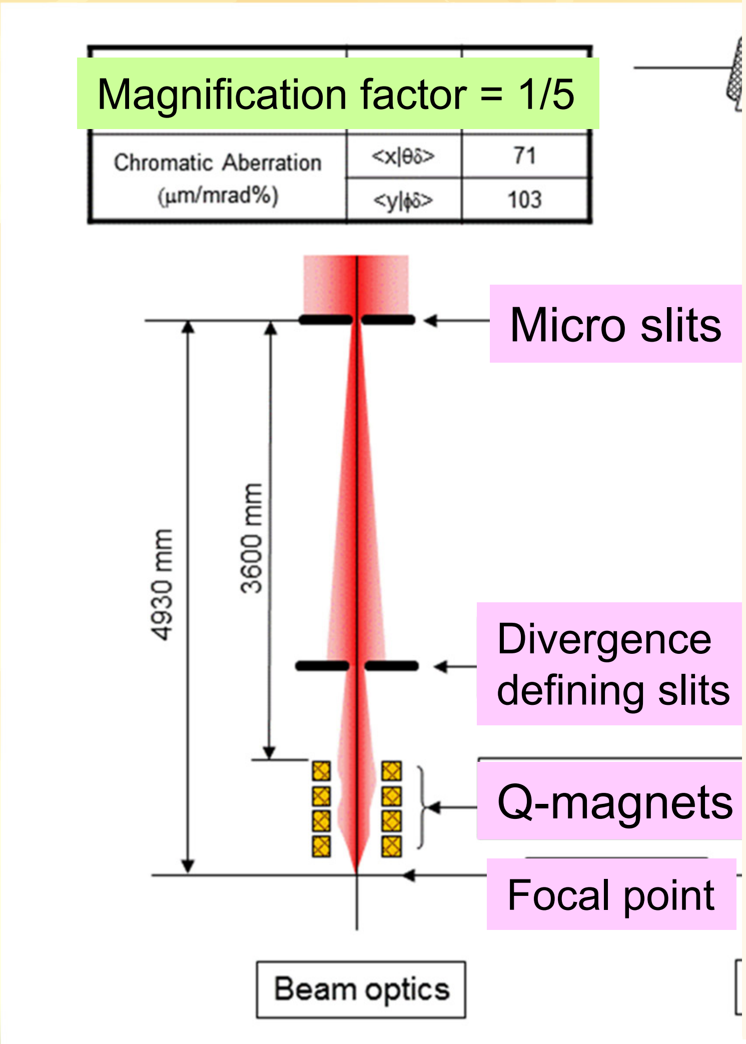
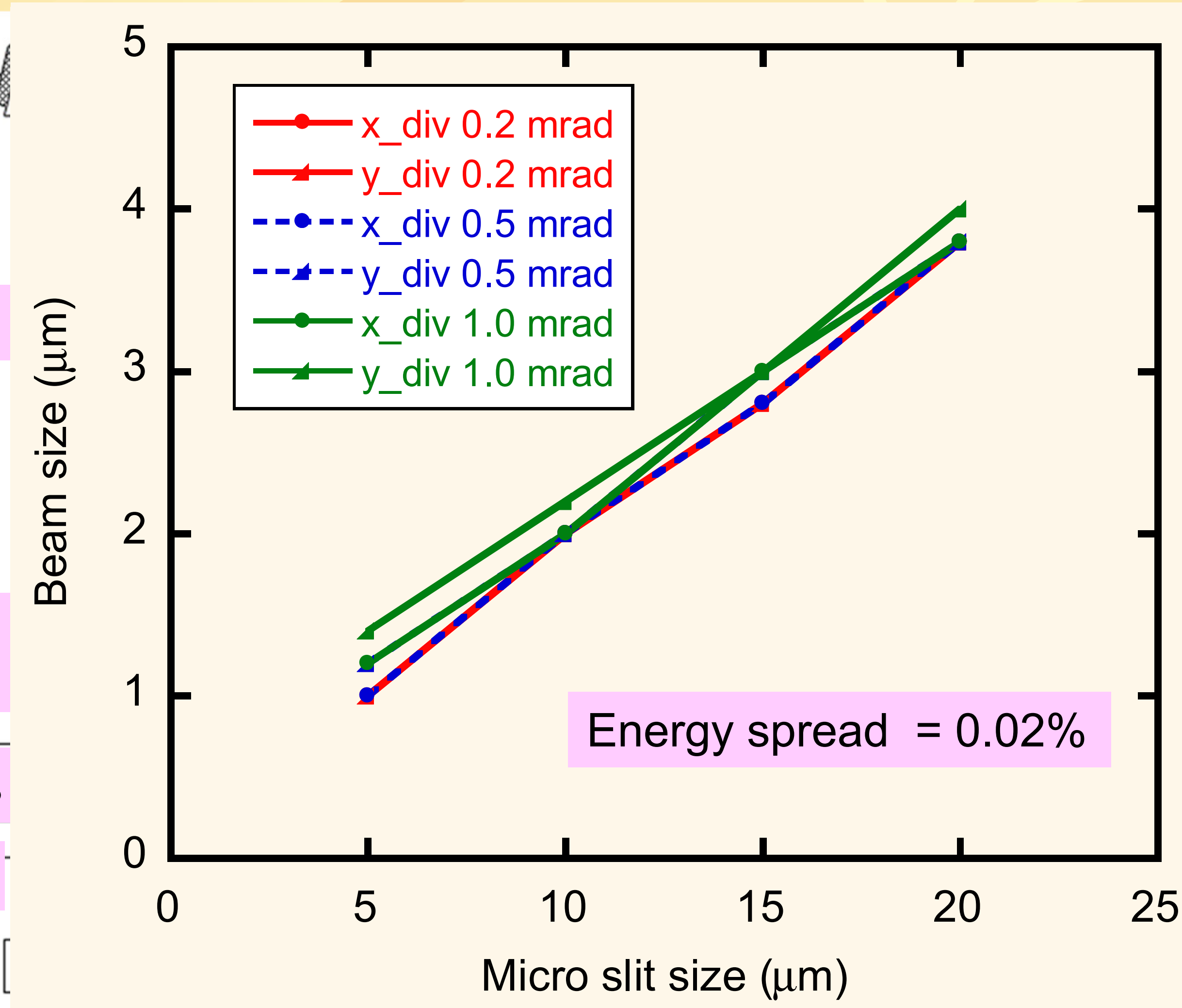
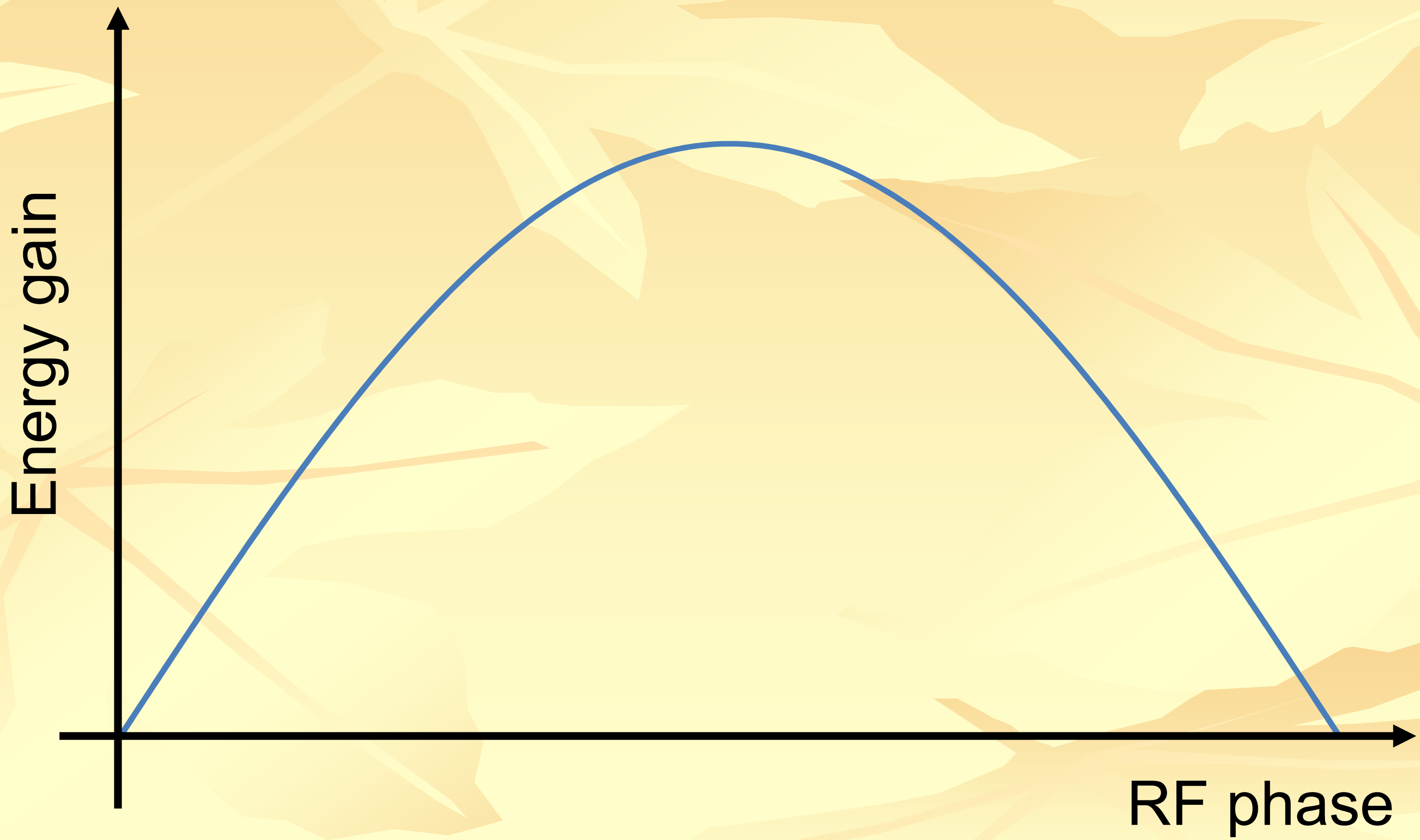




4. Cyclotron Development

Energy spread $\Delta E/E = 2 \times 10^{-3}$
(30 MeV proton, for example)

On the order of 10^{-4}



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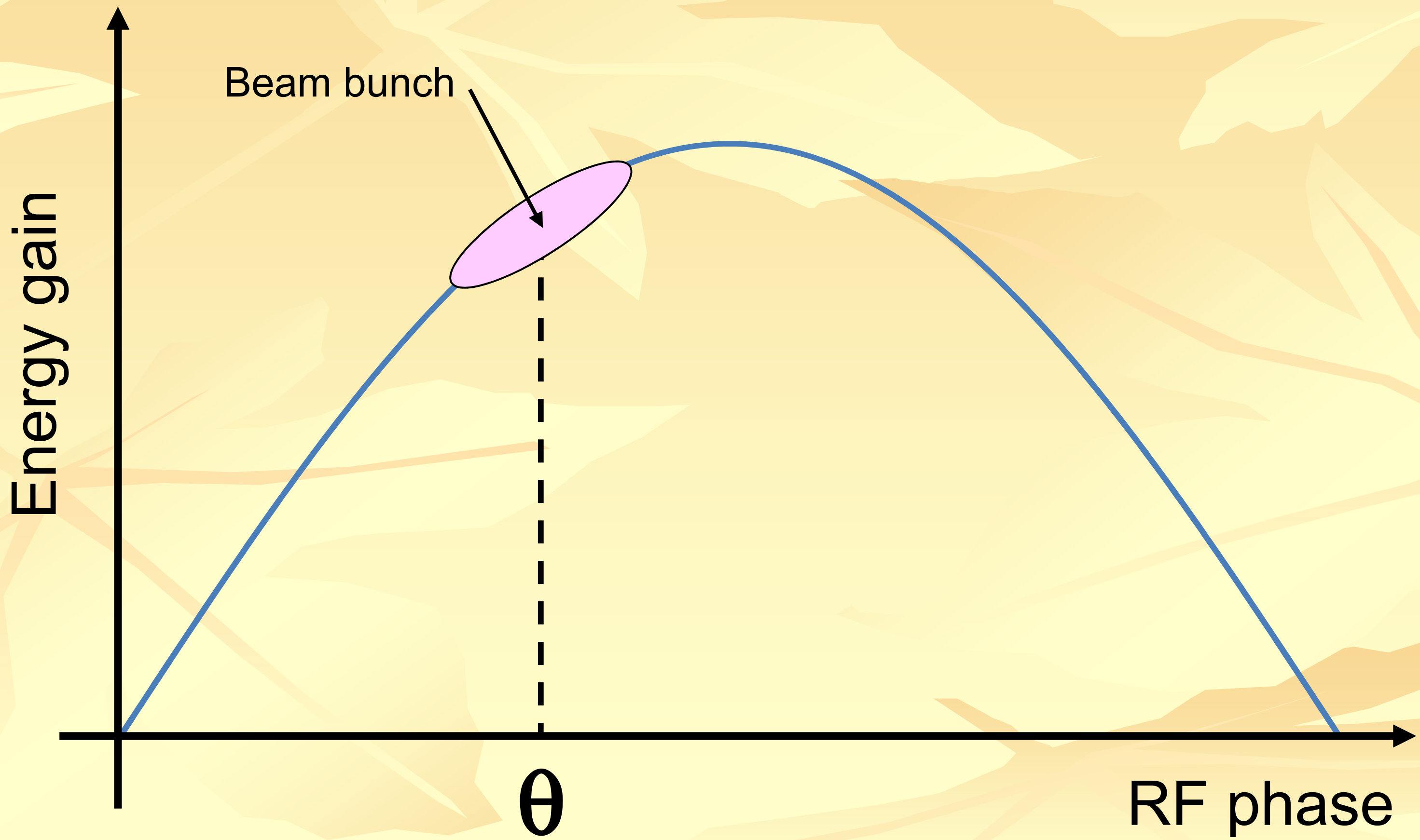

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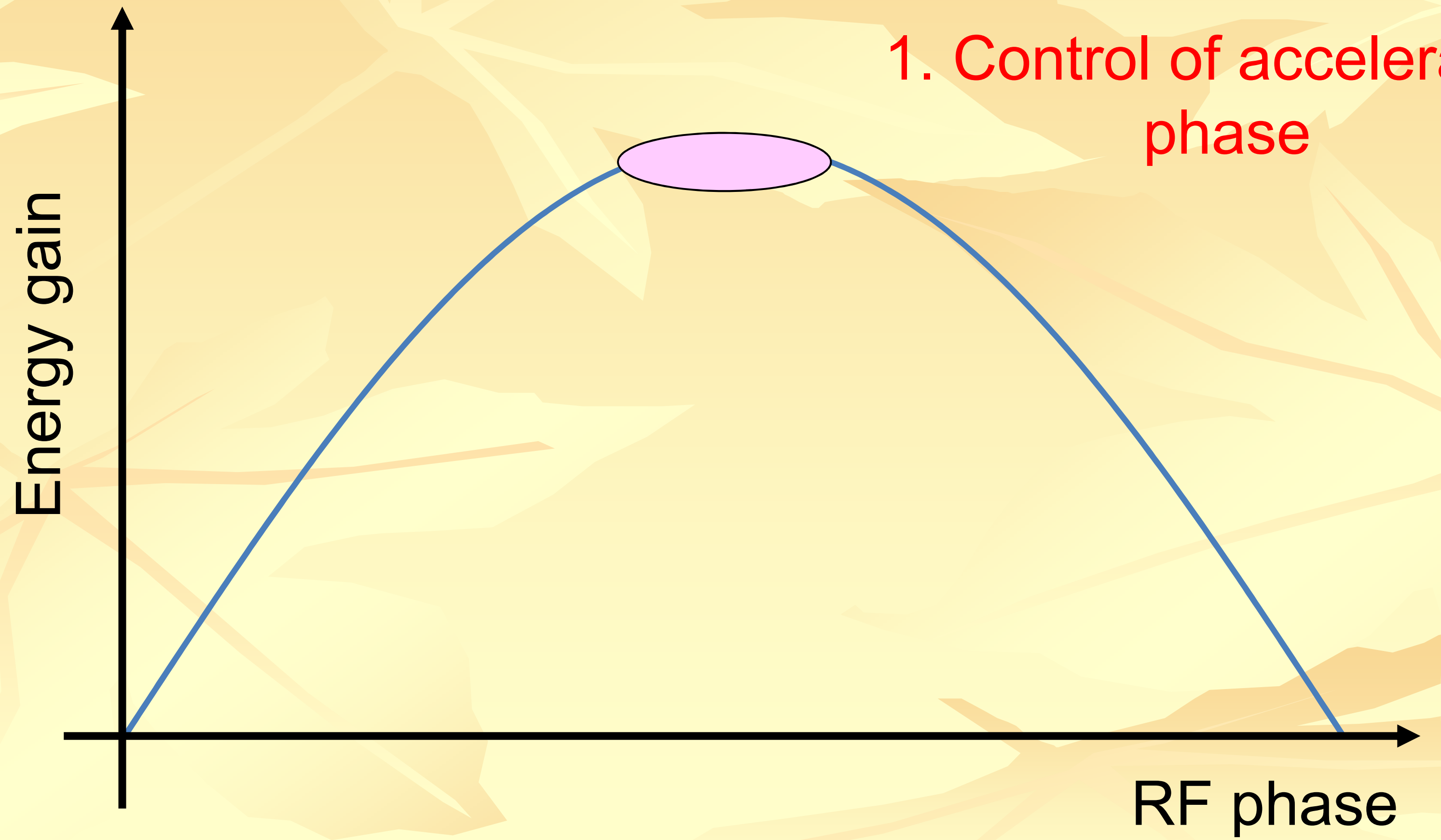
1. Control of acceleration phase



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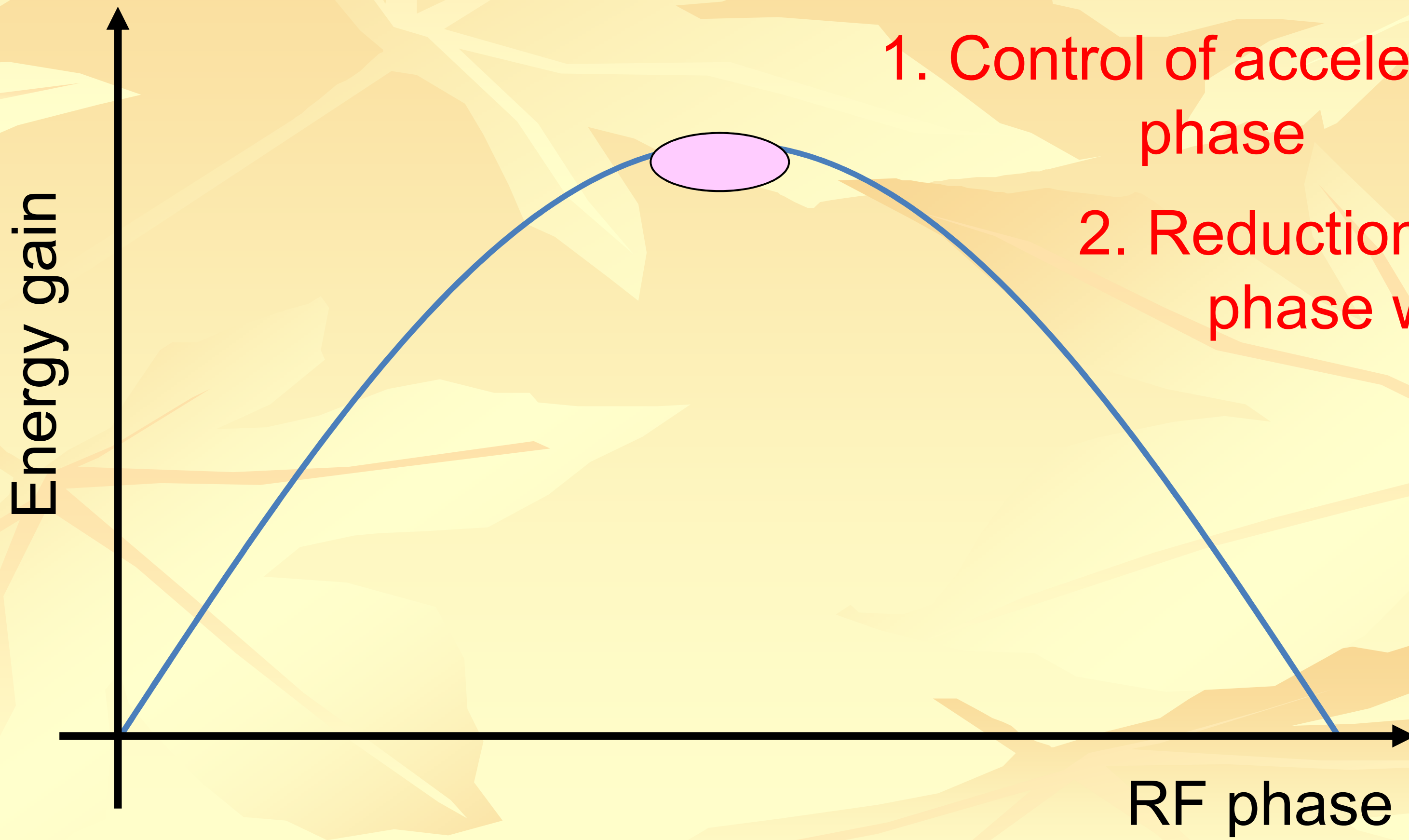

1. Control of acceleration phase
2. Reduction of beam phase width

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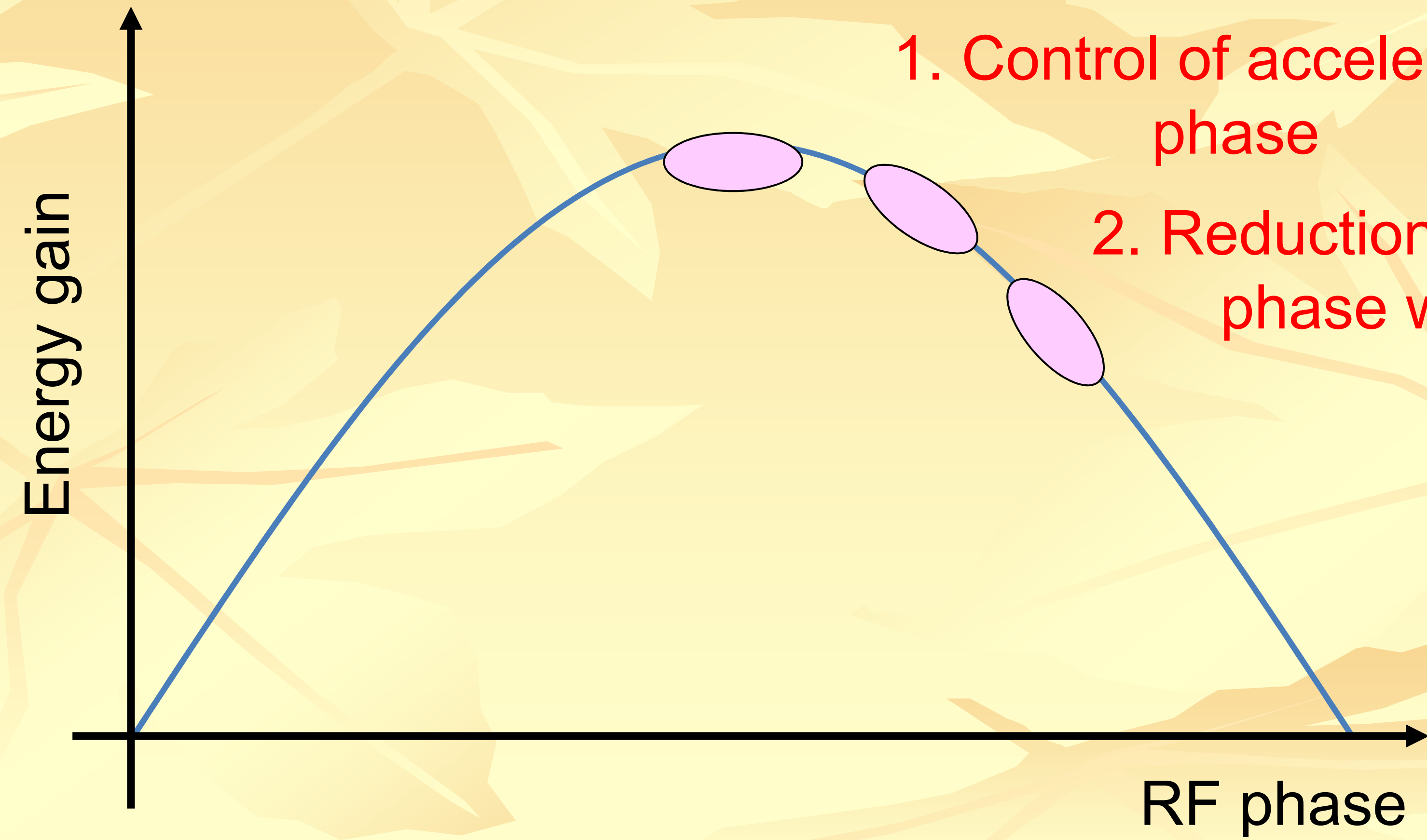

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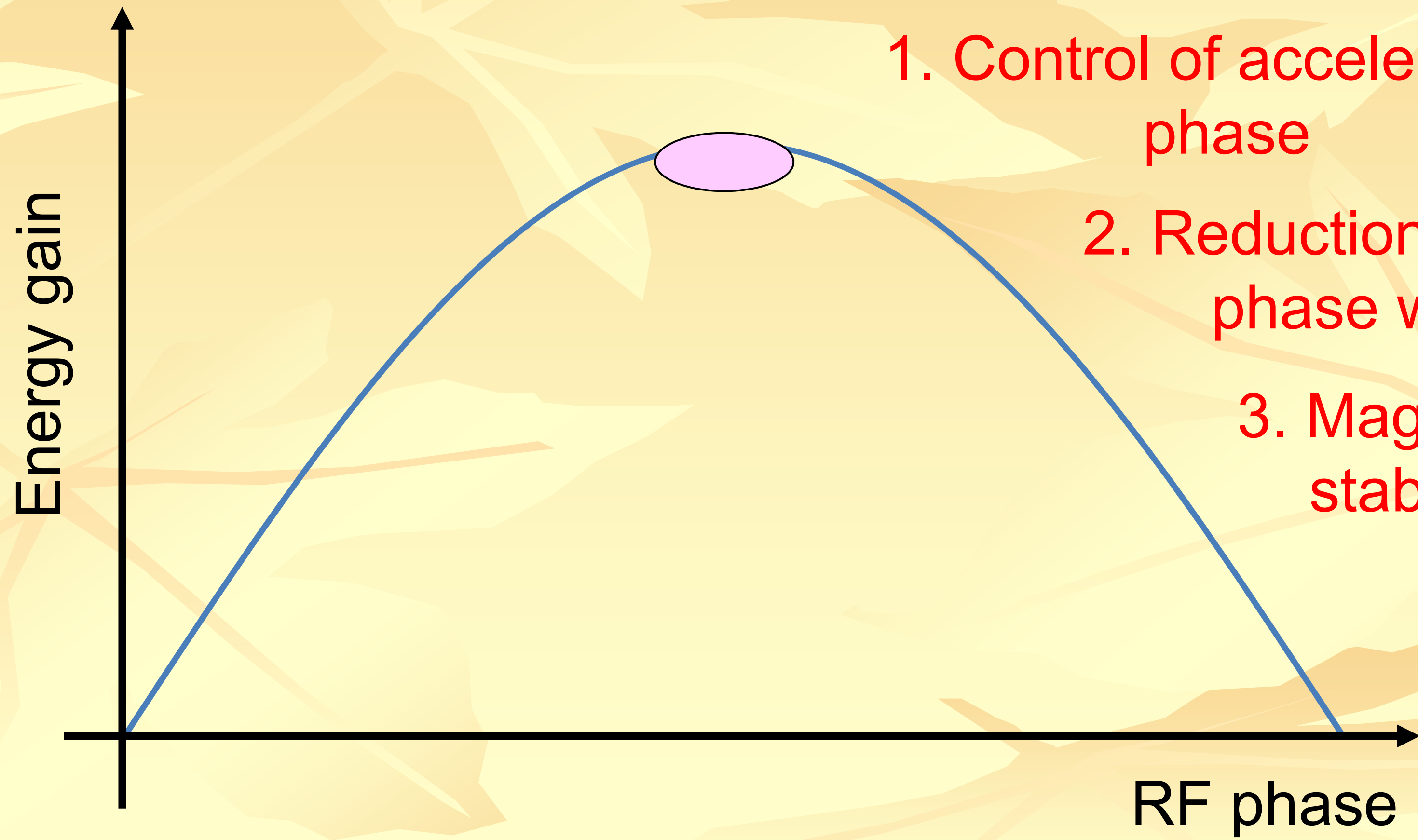

1. Control of acceleration phase
2. Reduction of beam phase width
3. Magnetic field stabilization

4. Cyclotron Development

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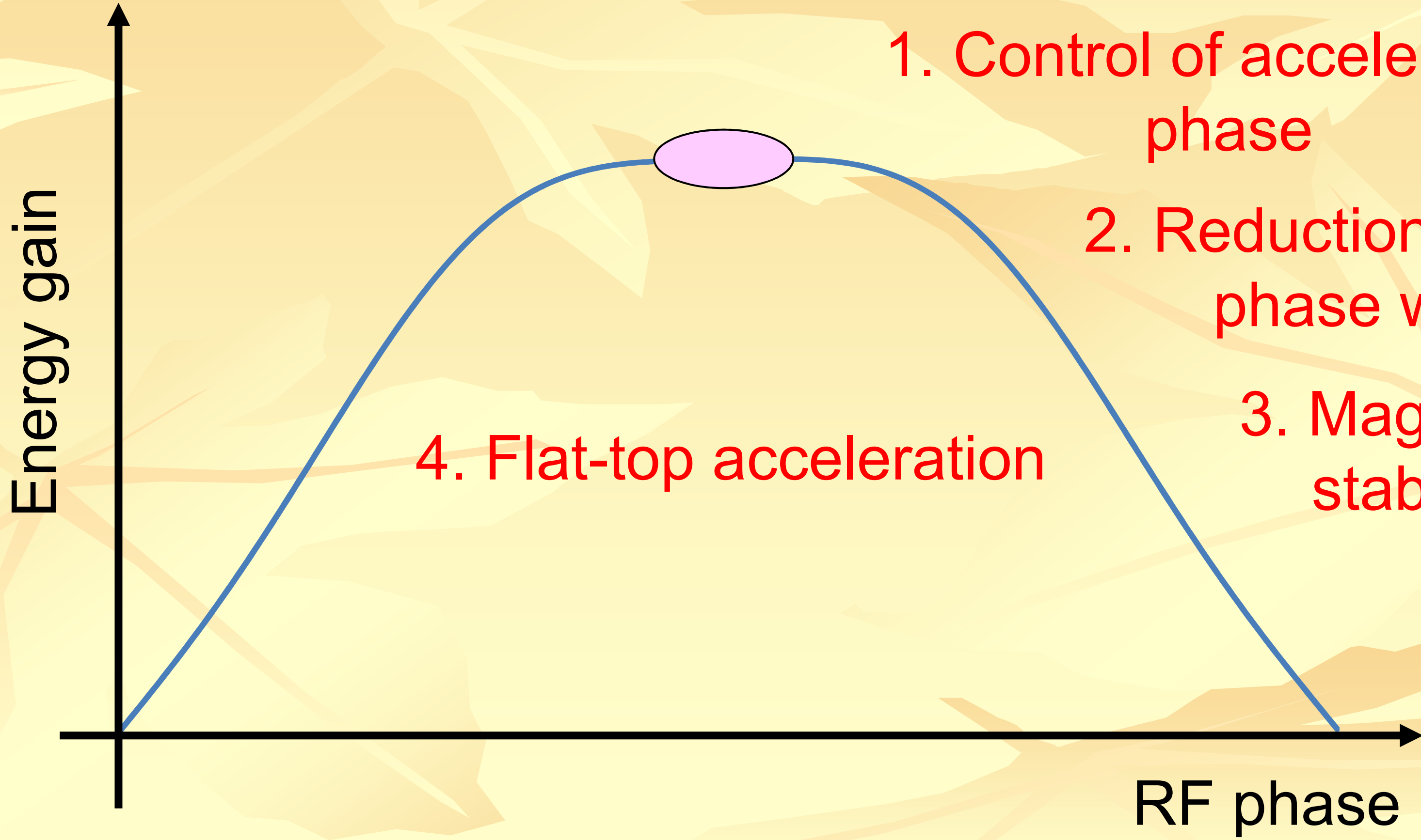

1. Control of acceleration phase
2. Reduction of beam phase width
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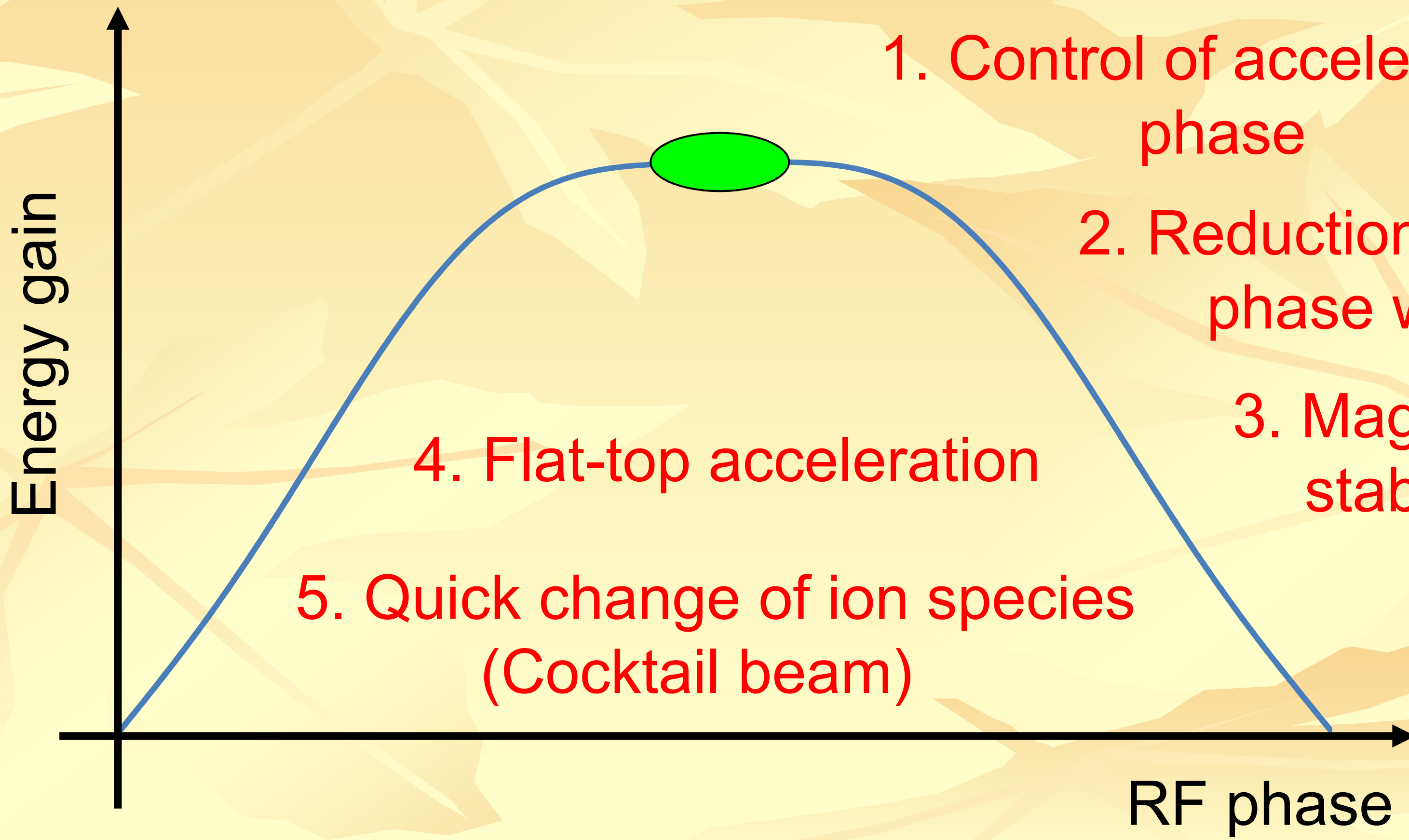
→ **On the order of 10^{-4}**

1. Control of acceleration phase
2. Reduction of beam phase width
3. Magnetic field stabilization
4. Flat-top acceleration
5. Quick change of ion species (Cocktail beam)



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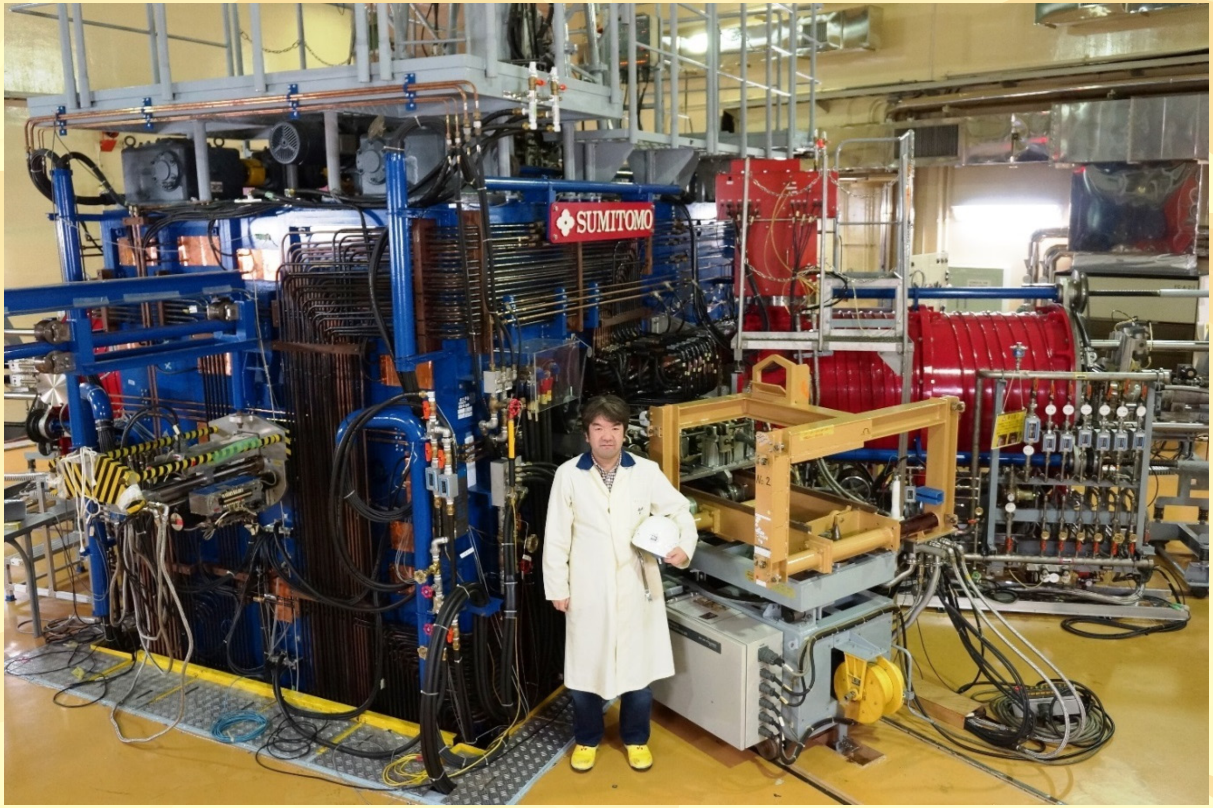

Spec. of the Cyclotron

Kb	110
Kf	95
Extraction radius (m)	0.923
Max. Average Field (T)	1.64
RF (MHz)	11-22
Acceleration Harmonics	1, 2 and 3
Span Angle of Dee (deg.)	86
Maximum Dee Voltage (kV)	60
Proton Energy (MeV)	10 to 90
Heavy-ion Energy (MeV/n)	2.5 to 27

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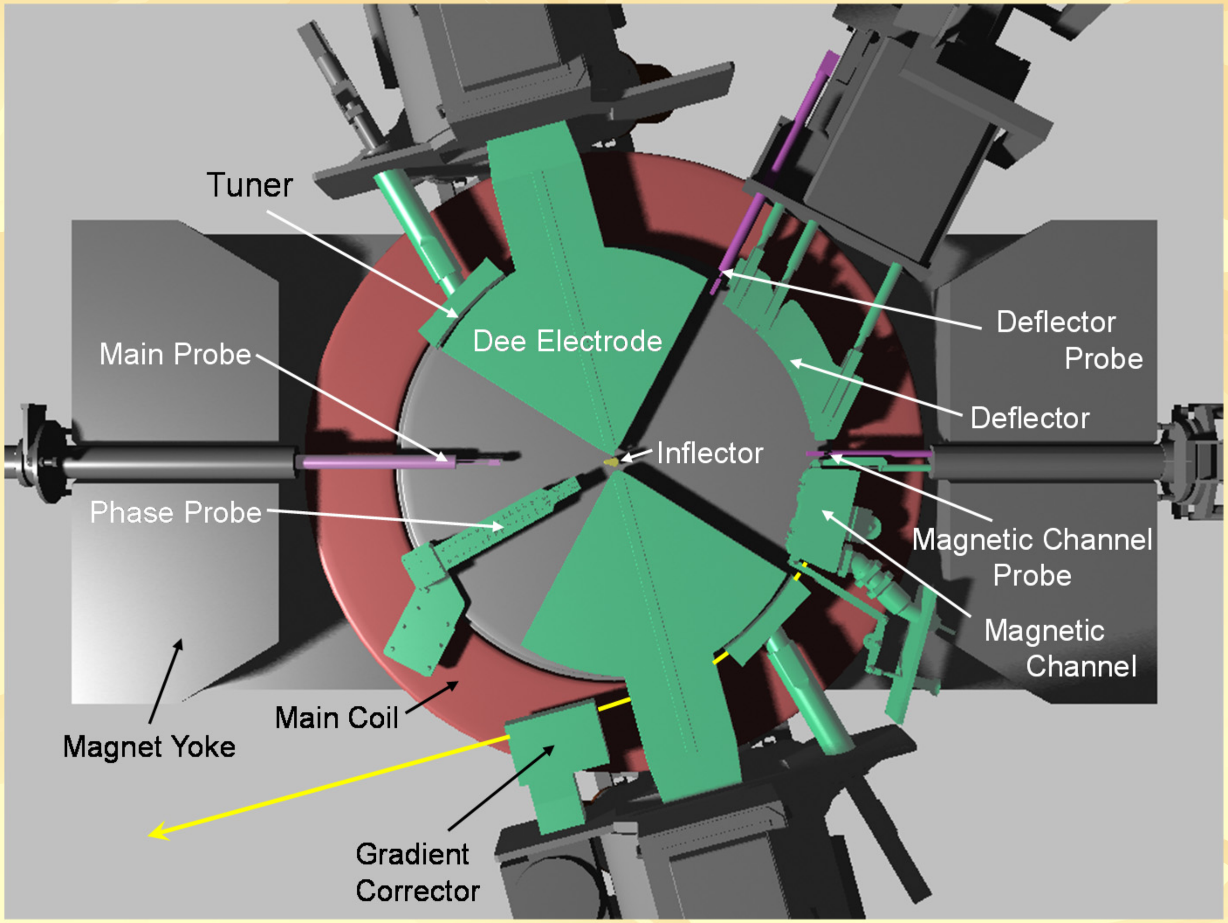

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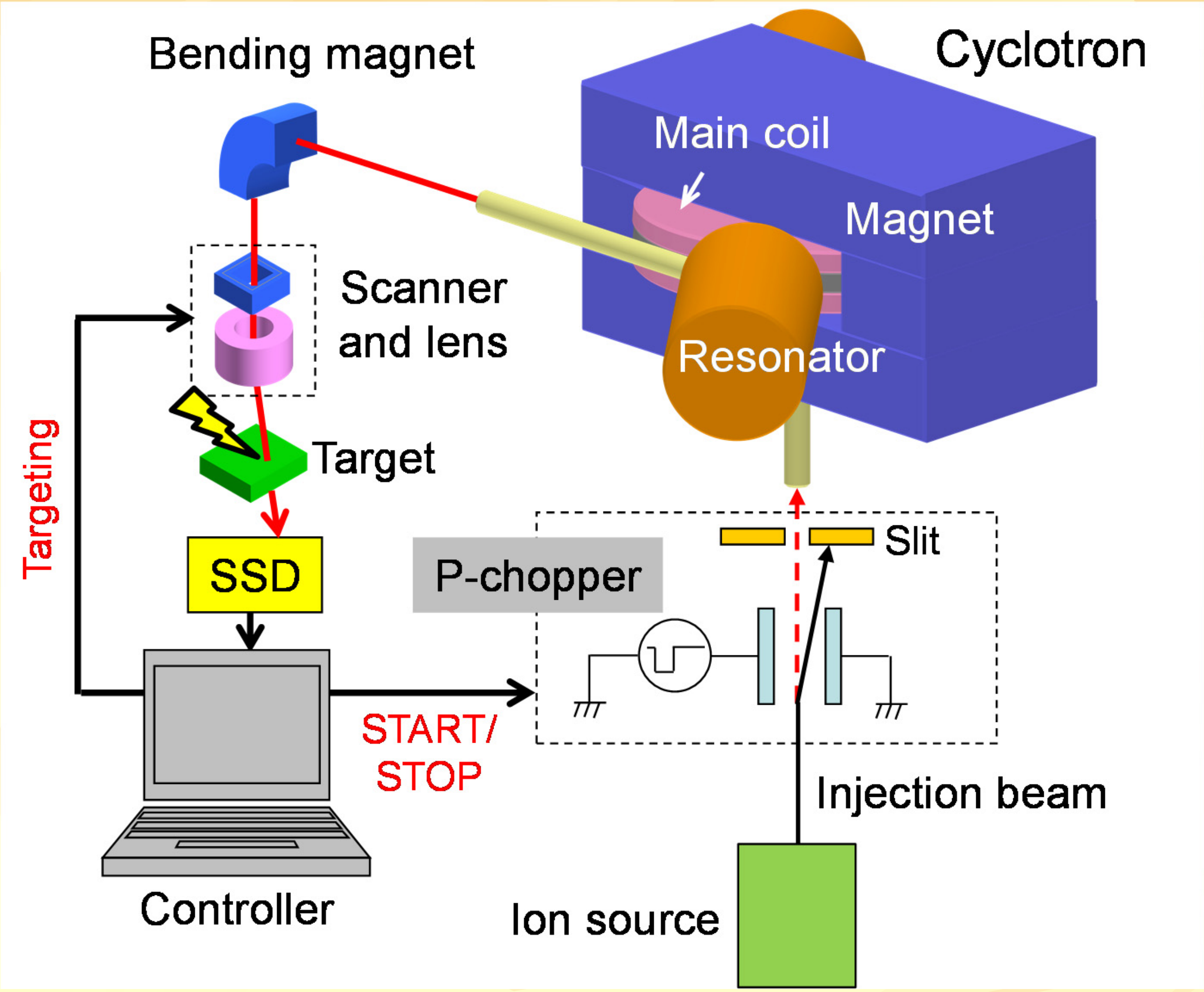

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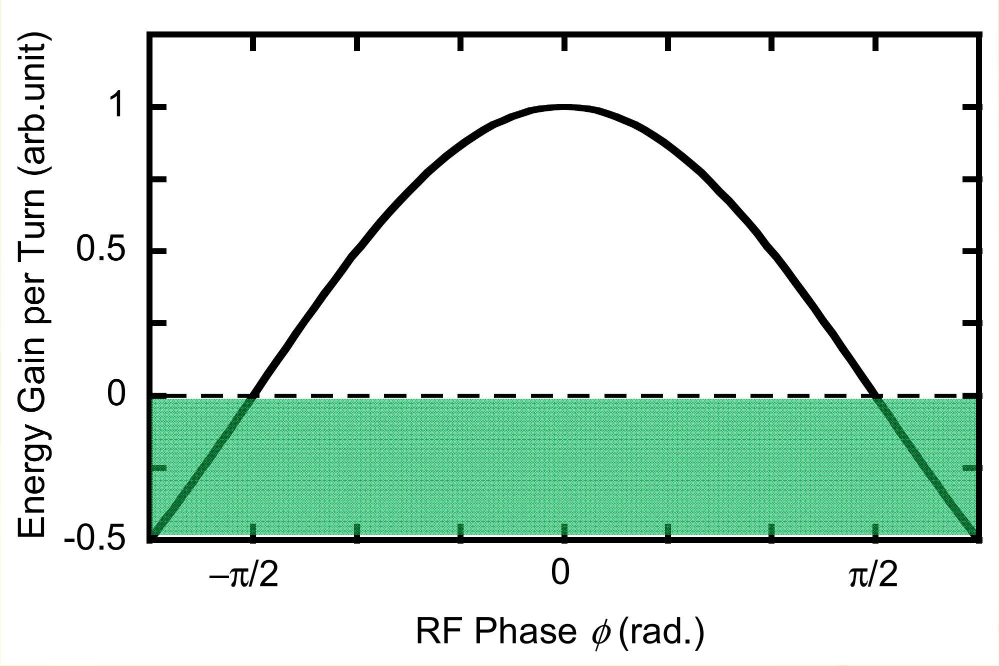
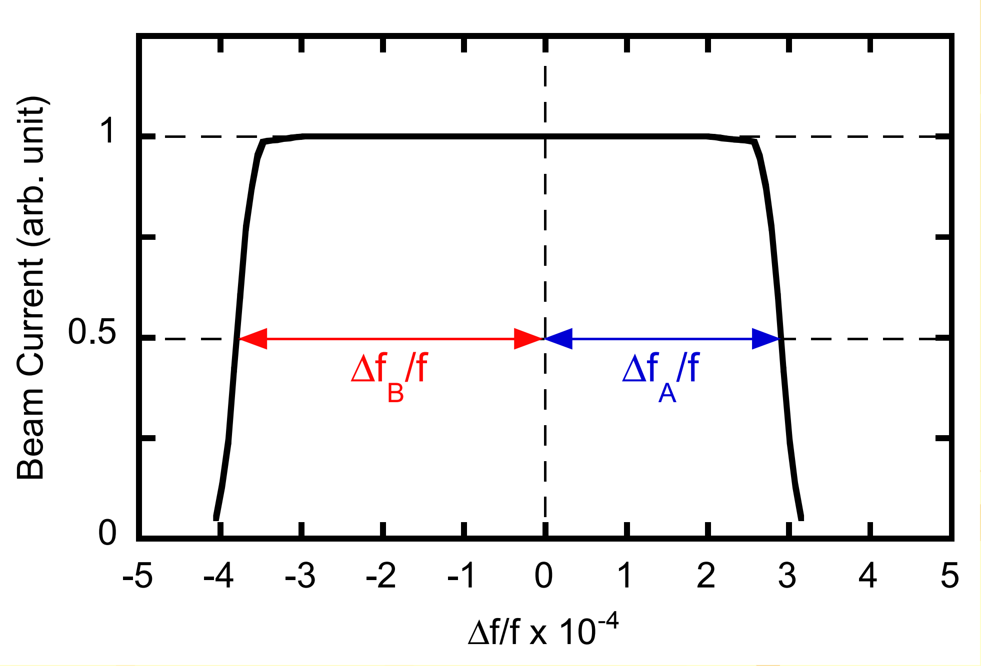
4. 1 Control of Beam Phase

Measurement of acceleration phase

- Good isochronous field (within 5 deg.)
- Negligible voltage distribution along the acceleration gap

Measure the beam current in the cyclotron changing the RF by Δf/f.





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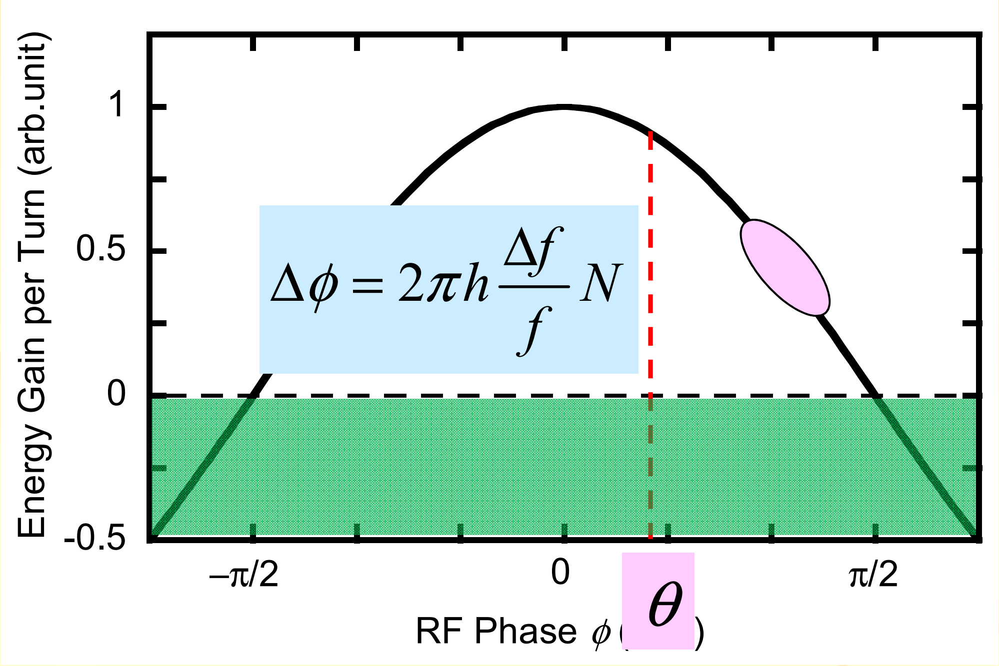

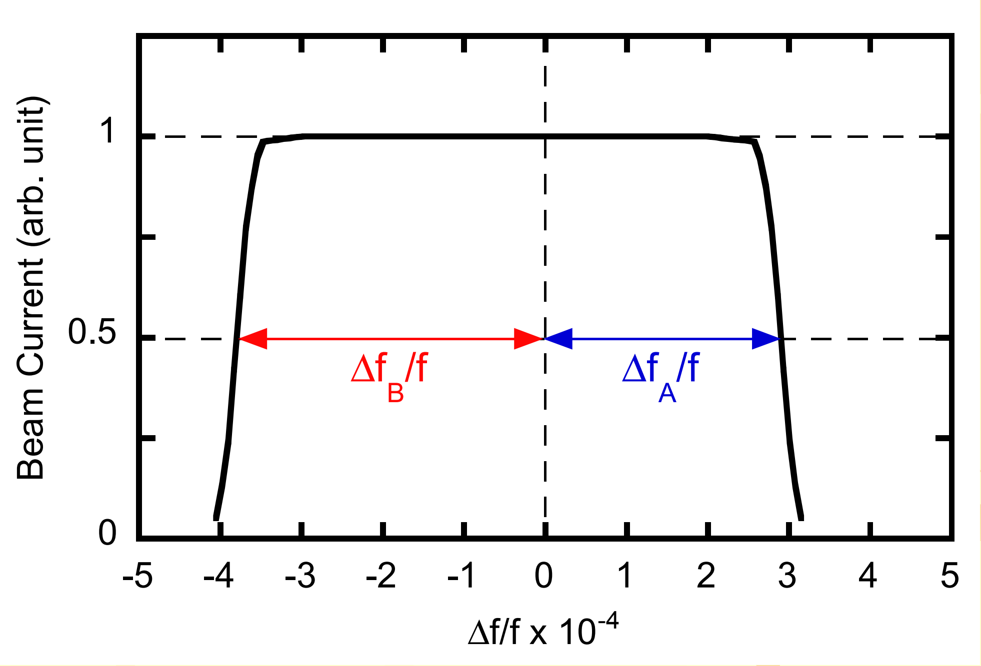

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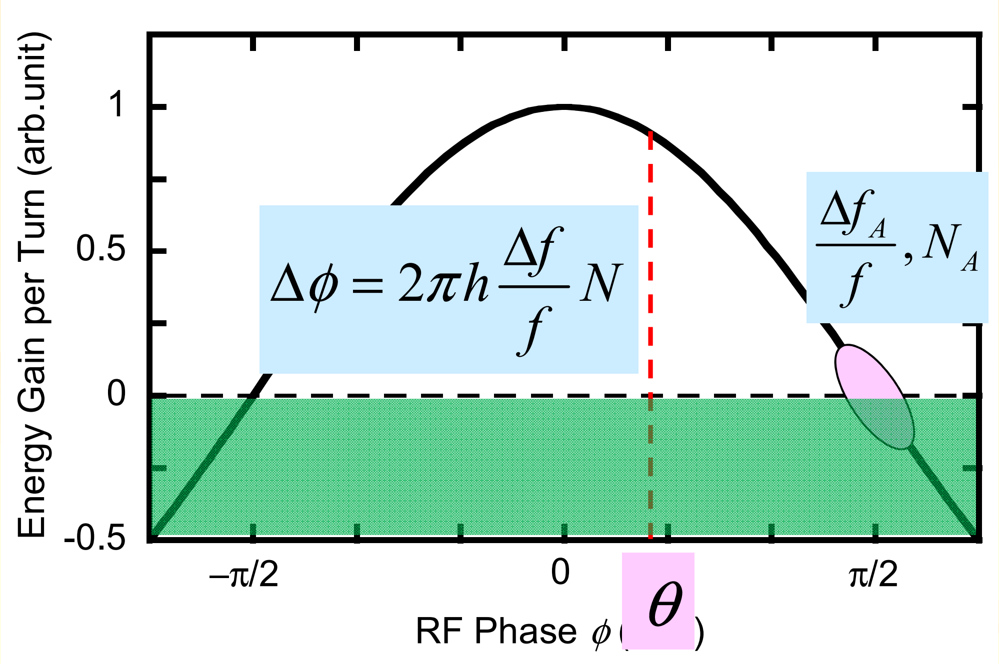

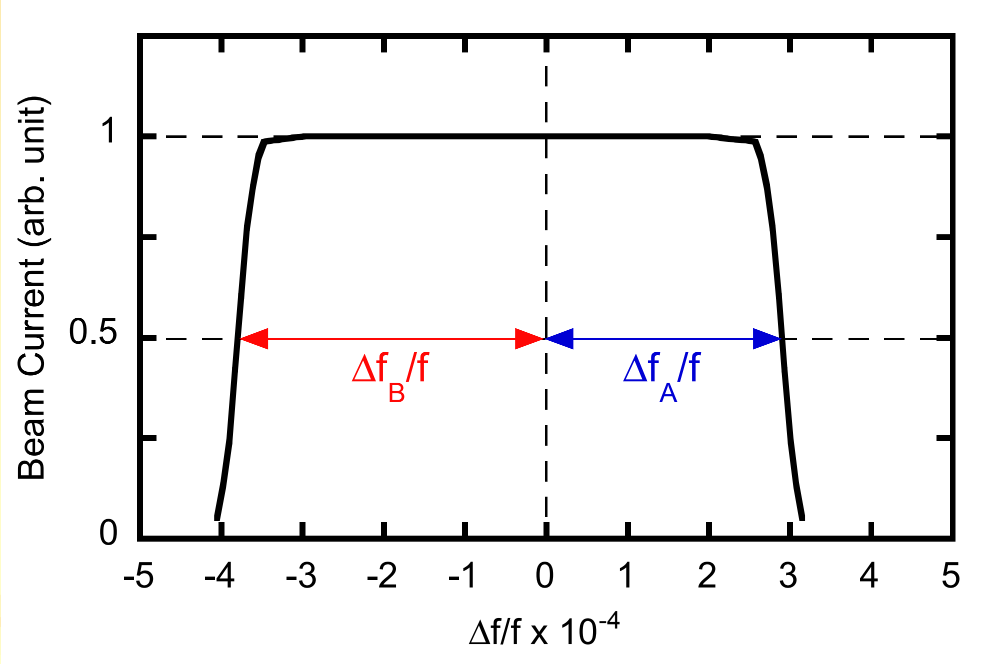

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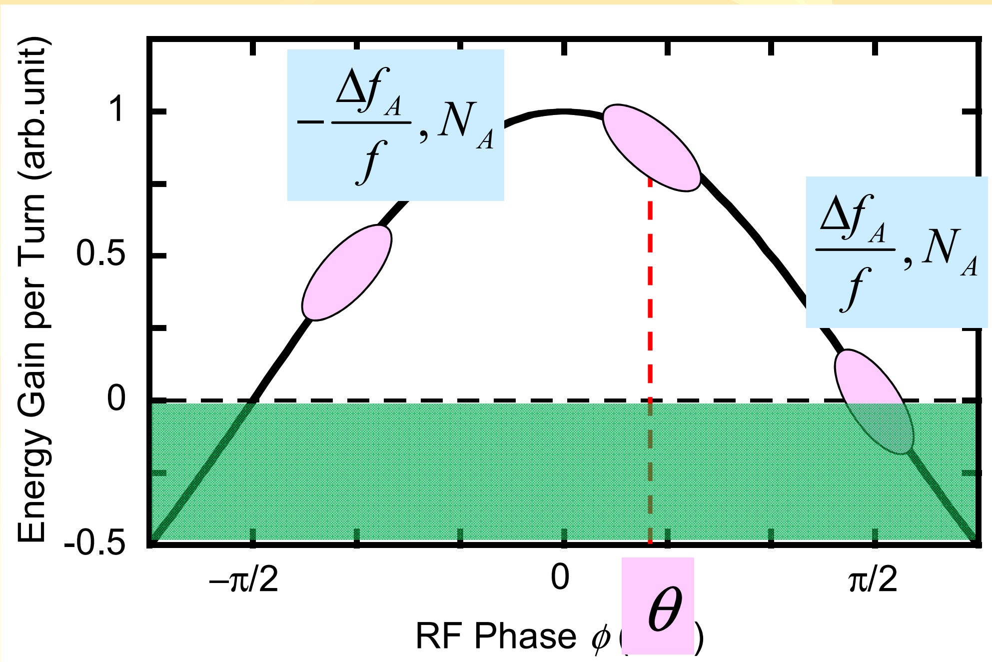

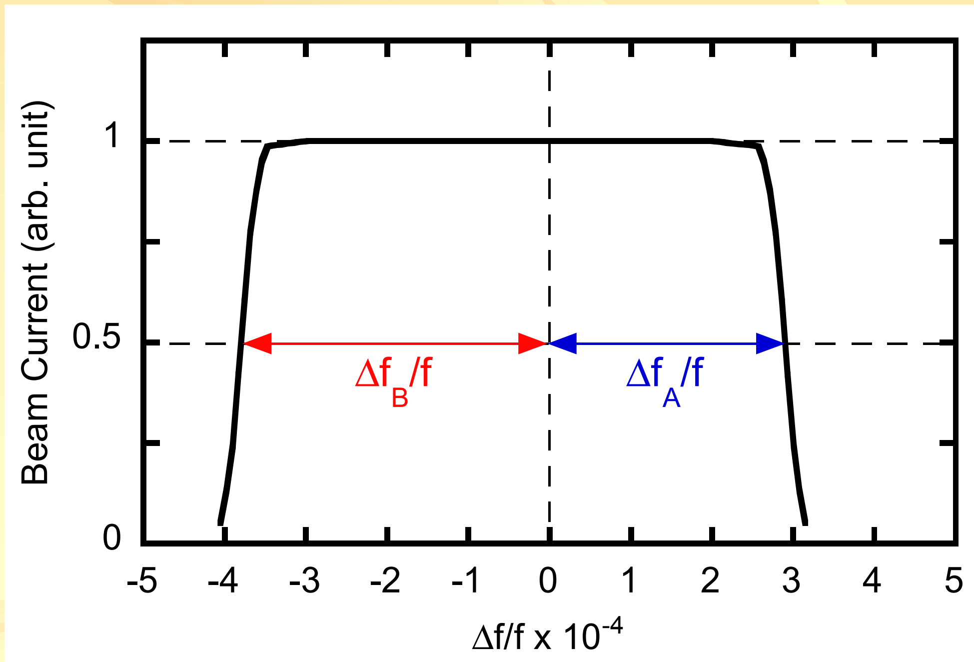

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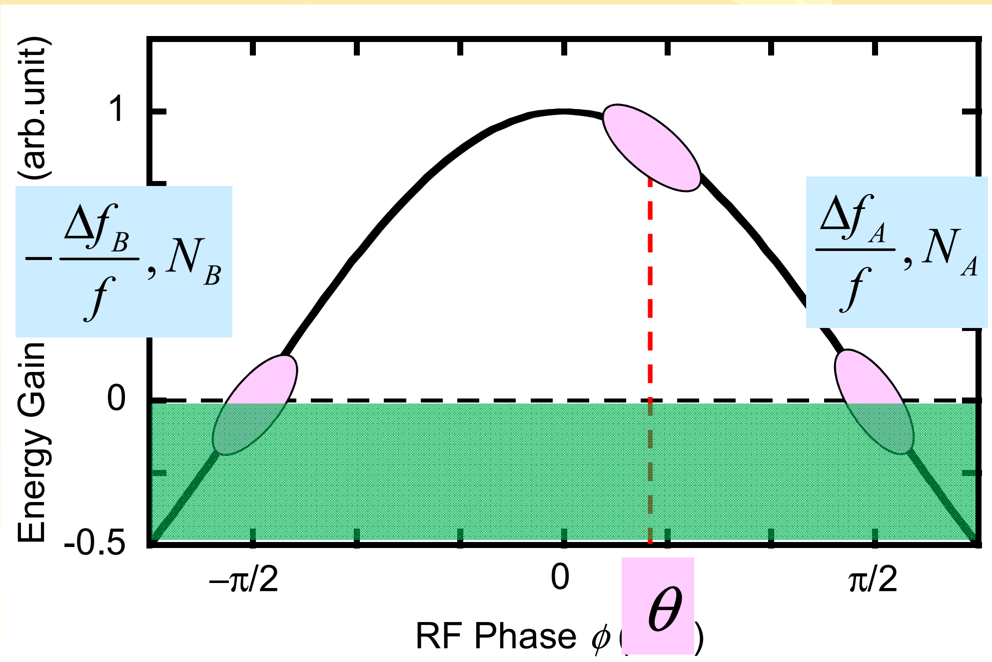

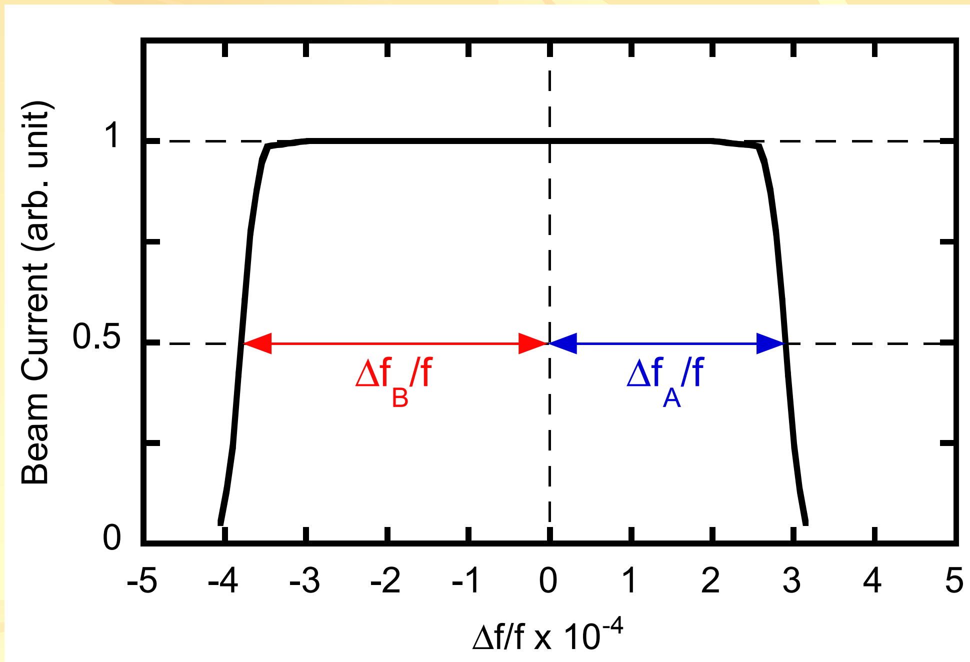

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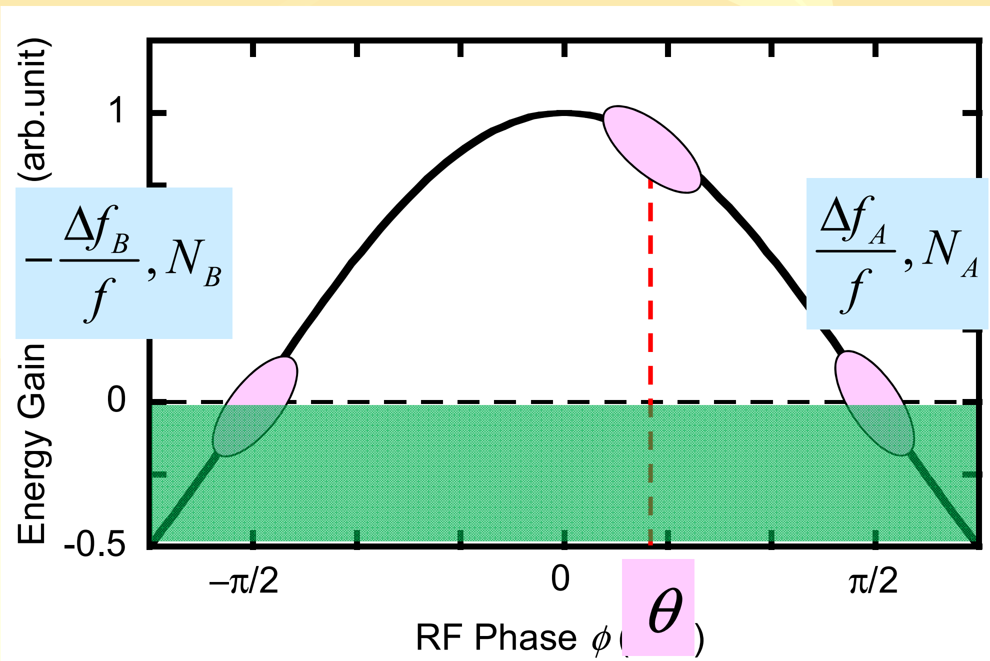

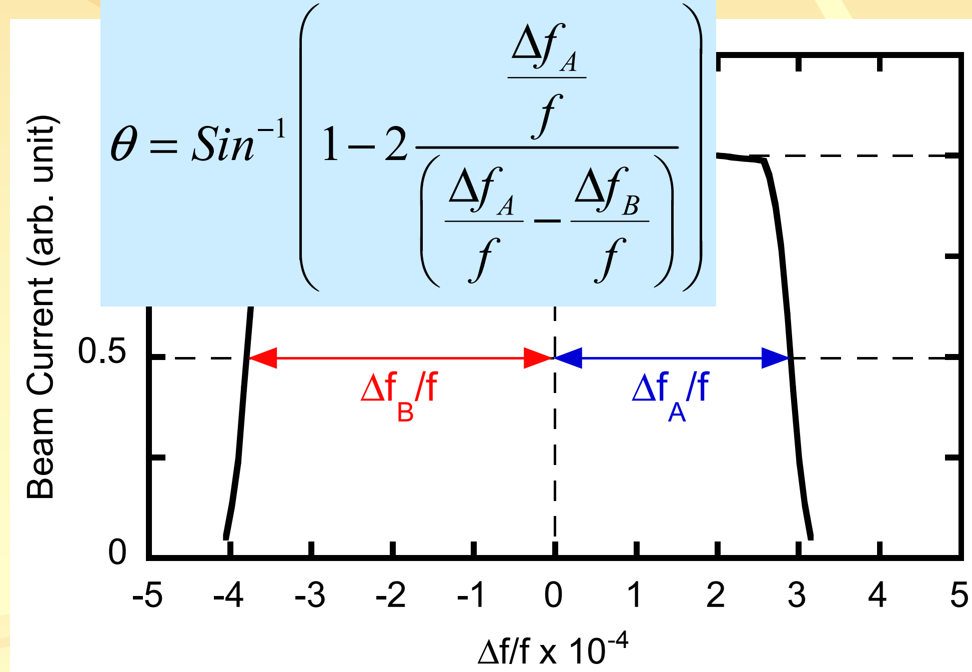

$$\theta = Sin^{-1}\left(1 - 2\frac{\frac{\Delta f_A}{f}}{\left(\frac{\Delta f_A}{f} - \frac{\Delta f_B}{f}\right)}\right)$$

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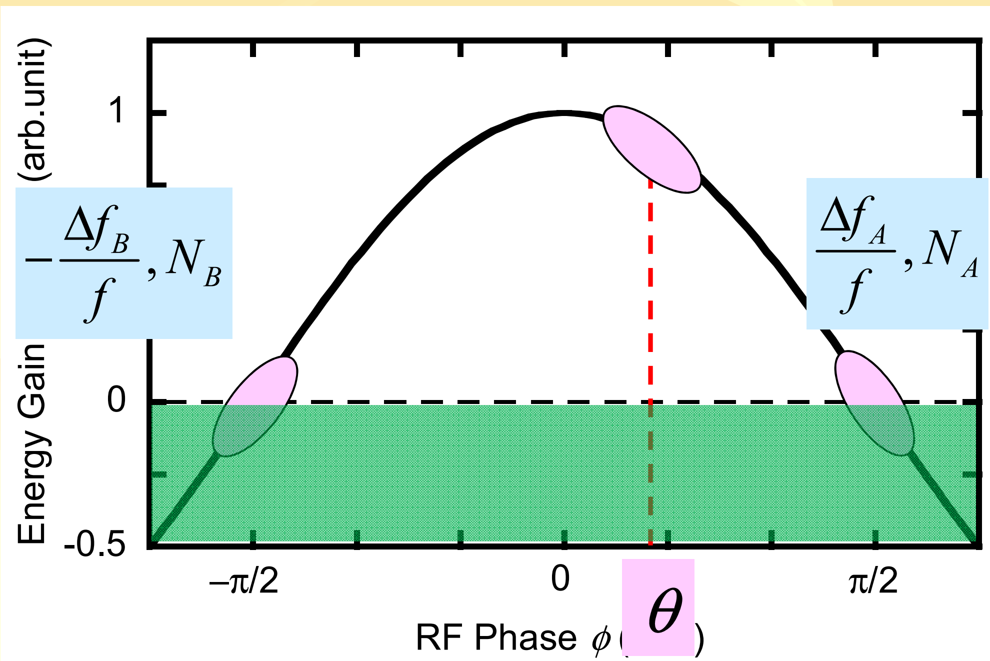

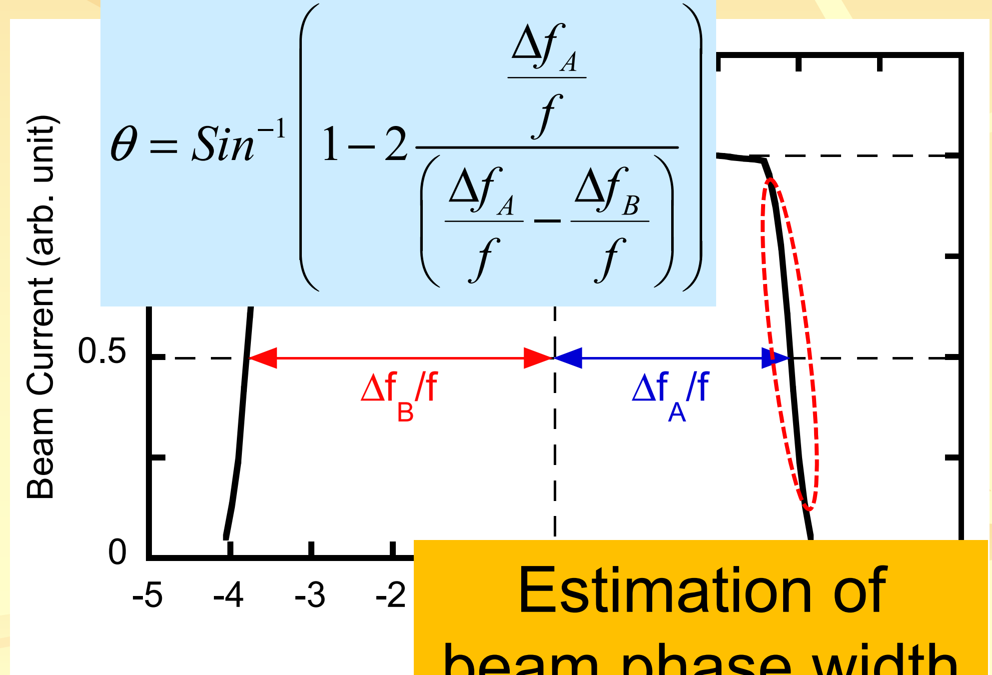

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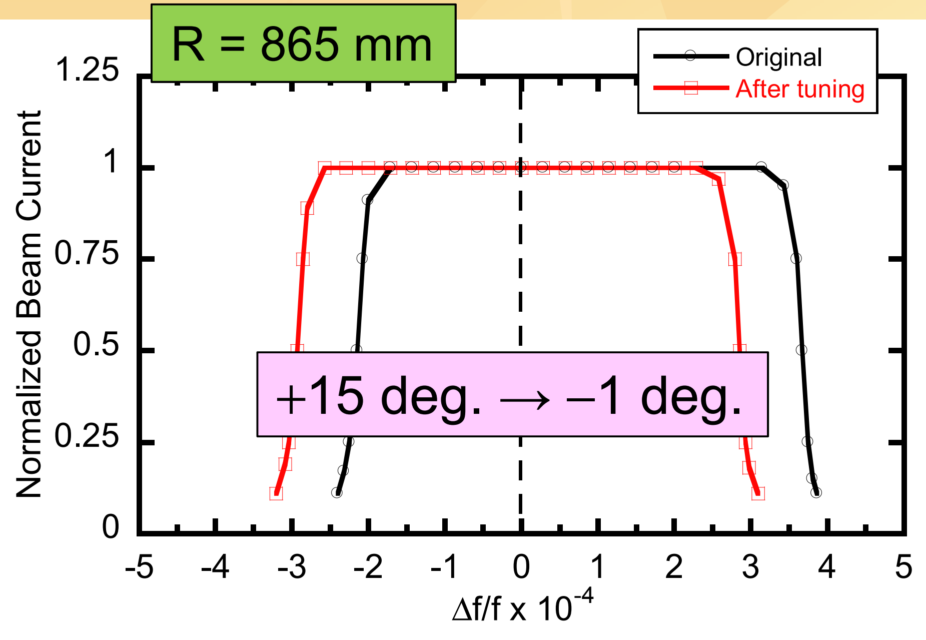
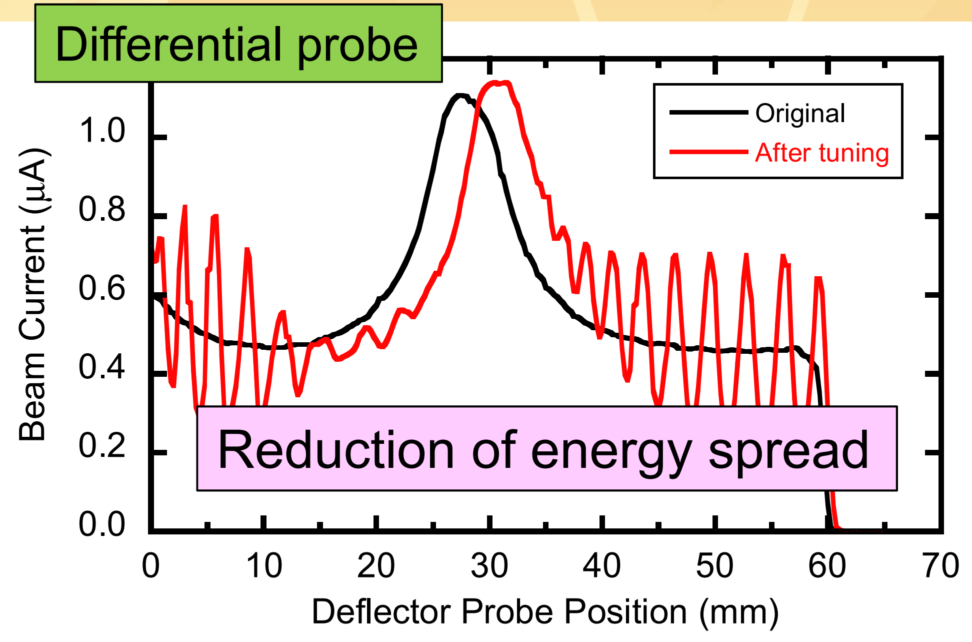
Estimation of beam phase width

4. 1 Control of Beam Phase





Estimation of beam phase width $\Delta\theta$

	h = 1		h = 2	
	45 MeV H^{+}	108 MeV $^{4}He^{2+}$	220 MeV $^{12}C^{5+}$	260 MeV $^{20}Ne^{7+}$
Δθ with buncher (deg.)	27	19	8	6
Δθ without buncher (deg.)	57	50	25	20

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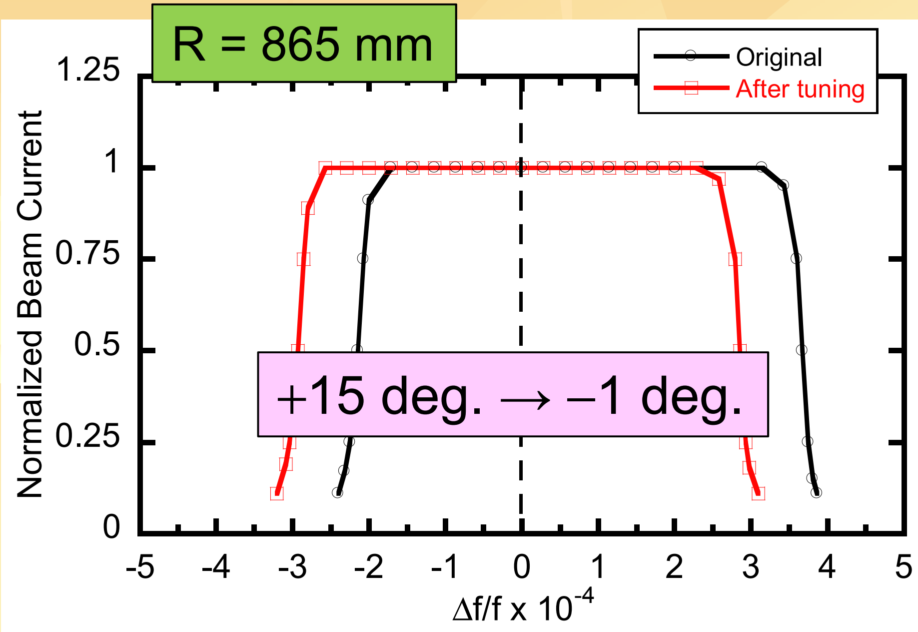

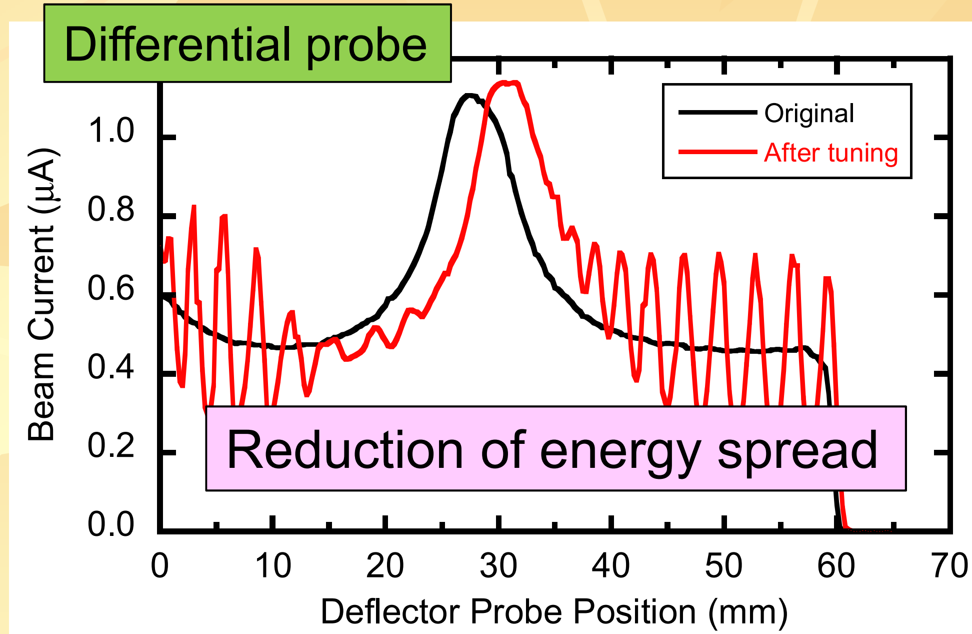

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	$h = 2$	
	220 MeV $^{12}C^{5+}$	260 MeV $^{20}Ne^{7+}$
Δθ with buncher (deg.)	8	6
Δθ without buncher (deg.)	25	20

“Phase compression” in the central region.

N. Miyawaki, et al., NIM-A 636 (2011) 41.

4. 2 Magnetic Field Stabilization

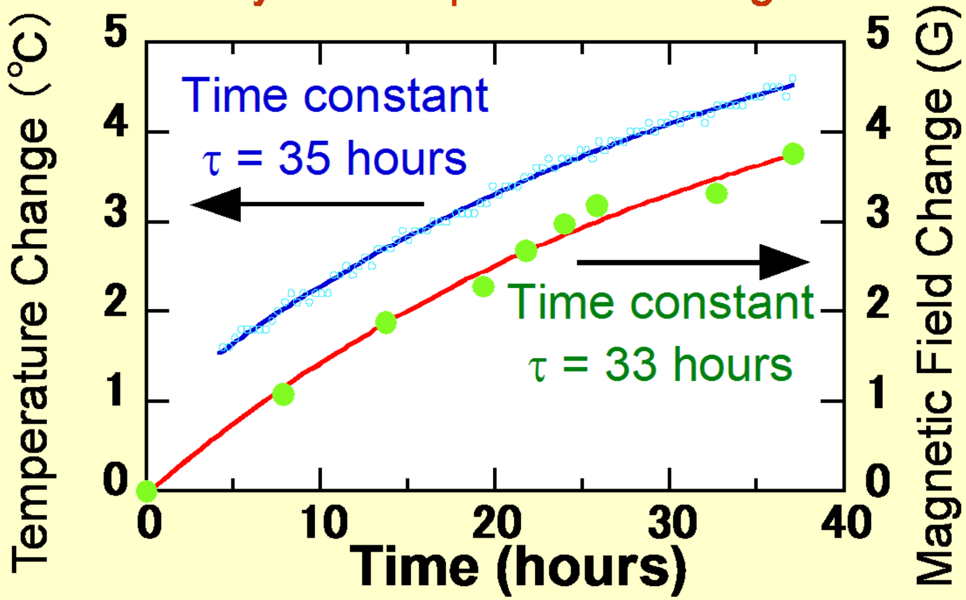
Unstable phenomena :

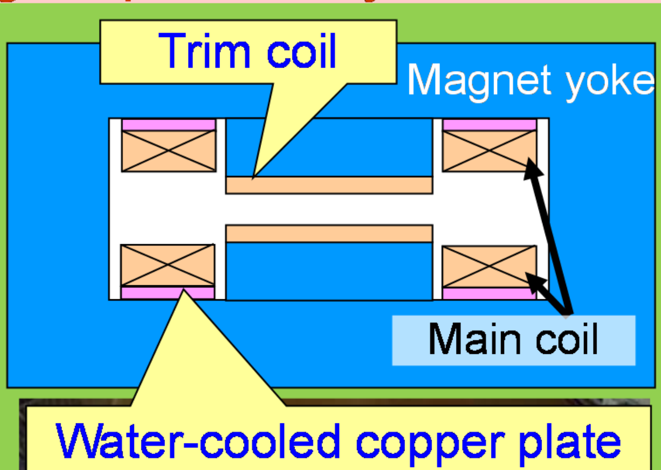
A beam current decreased by half several hours after magnet excitation

Measures

- Cutting off thermal conduction
- Stabilizing temperature of the magnet pole and yoke

Correlation between the magnetic field and yoke temperature changes





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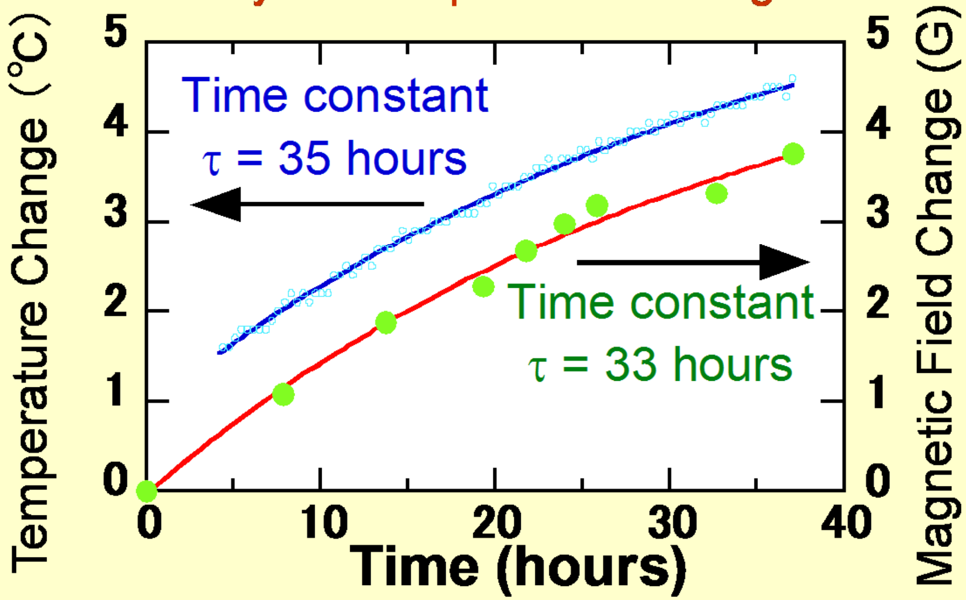

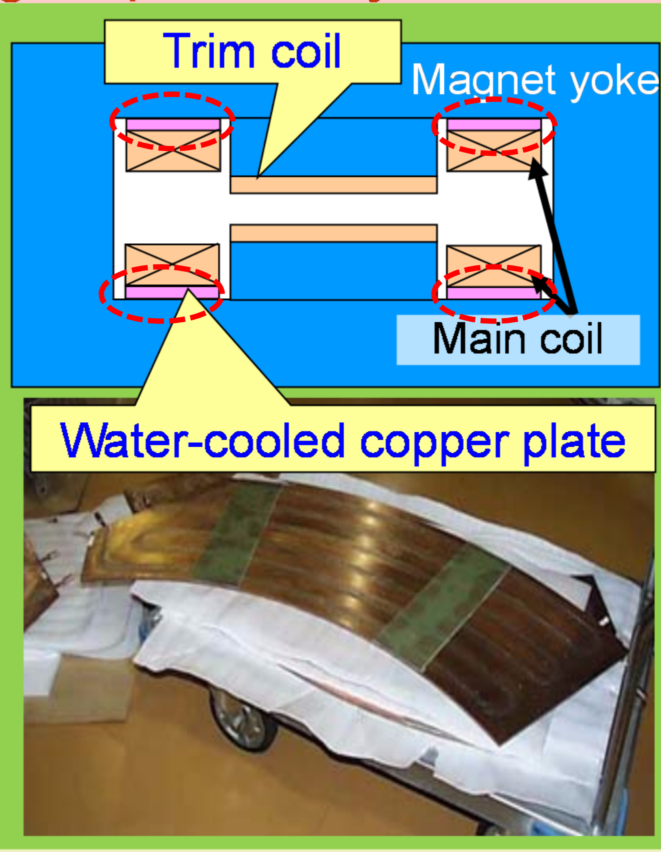

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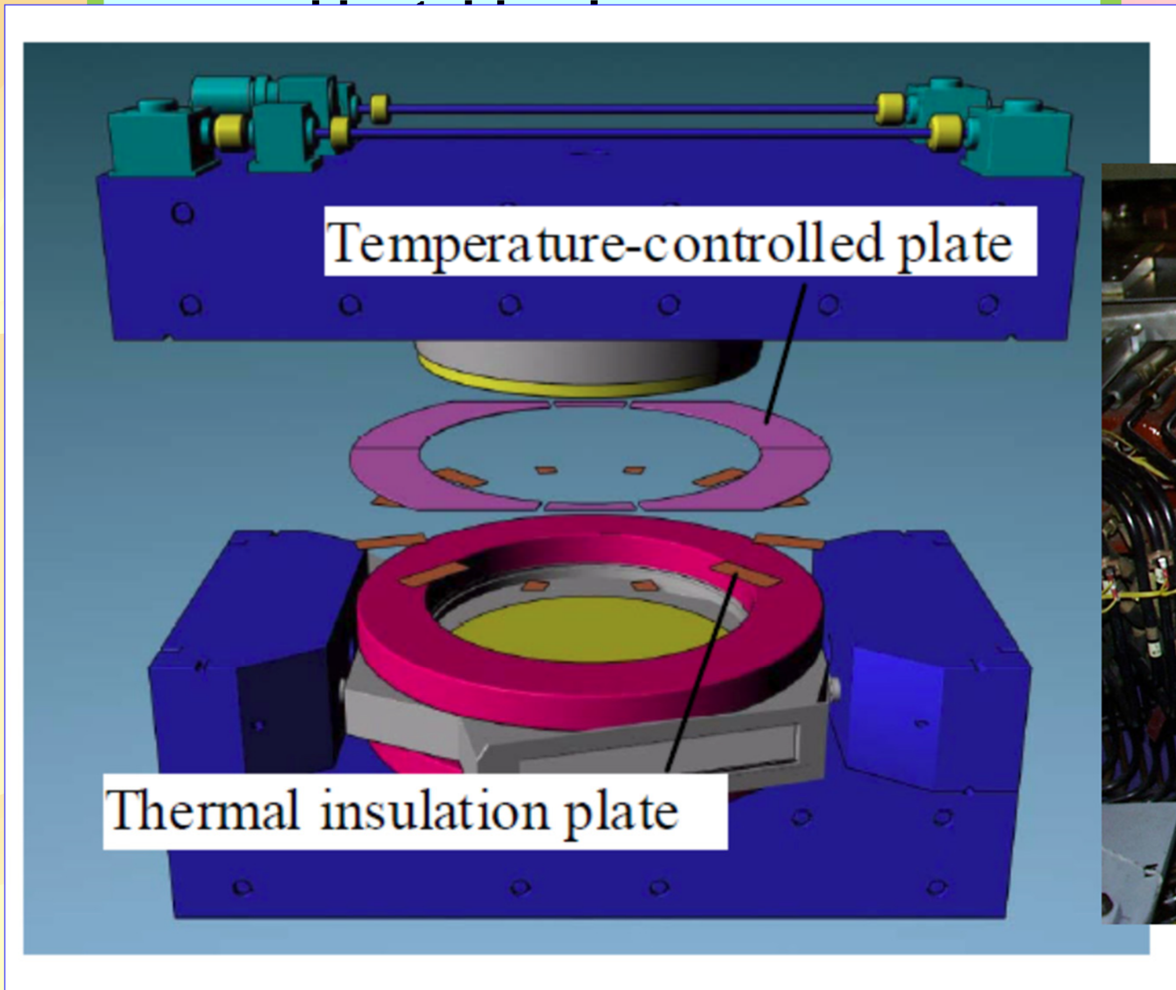

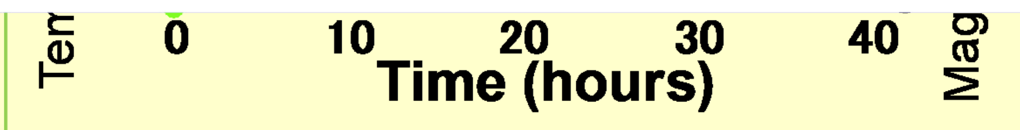

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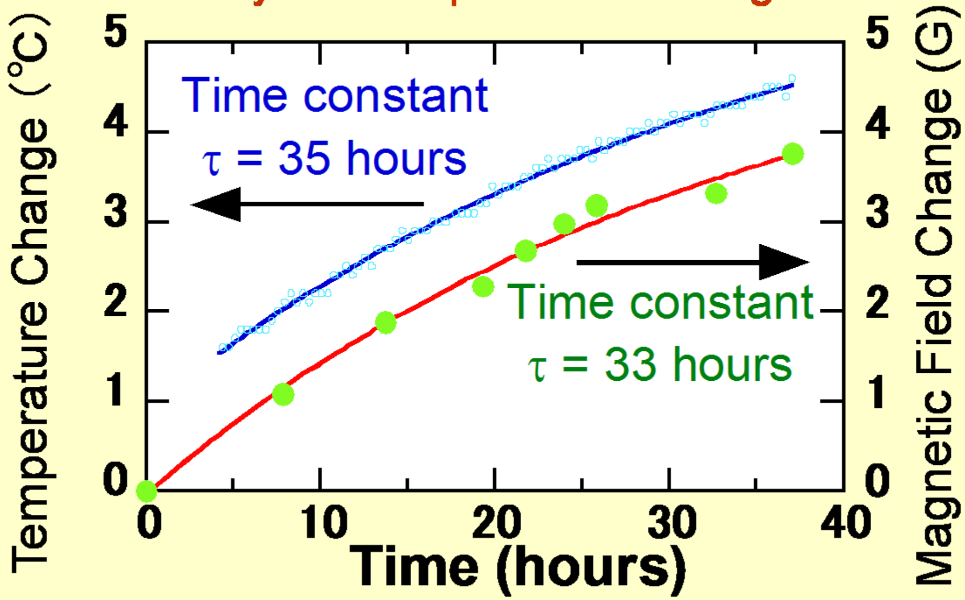

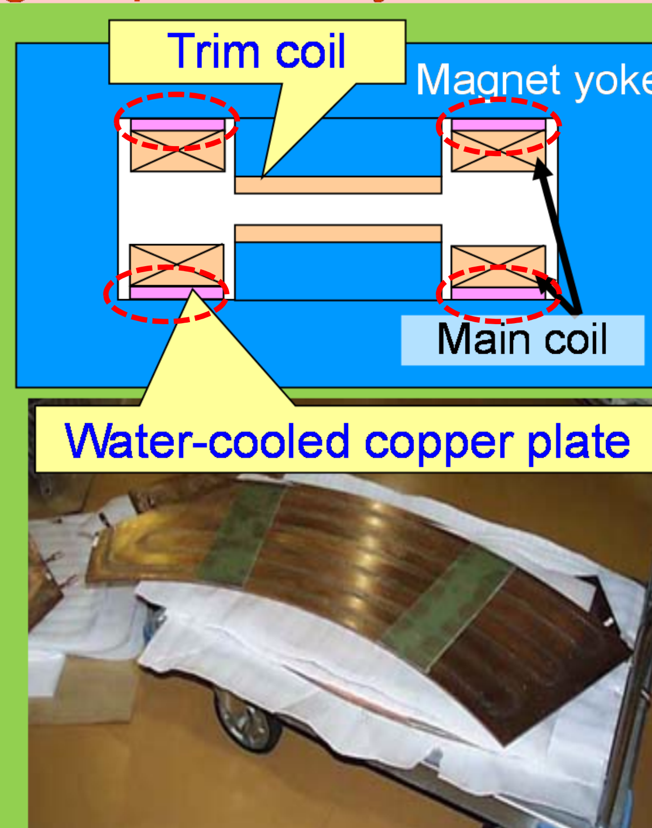

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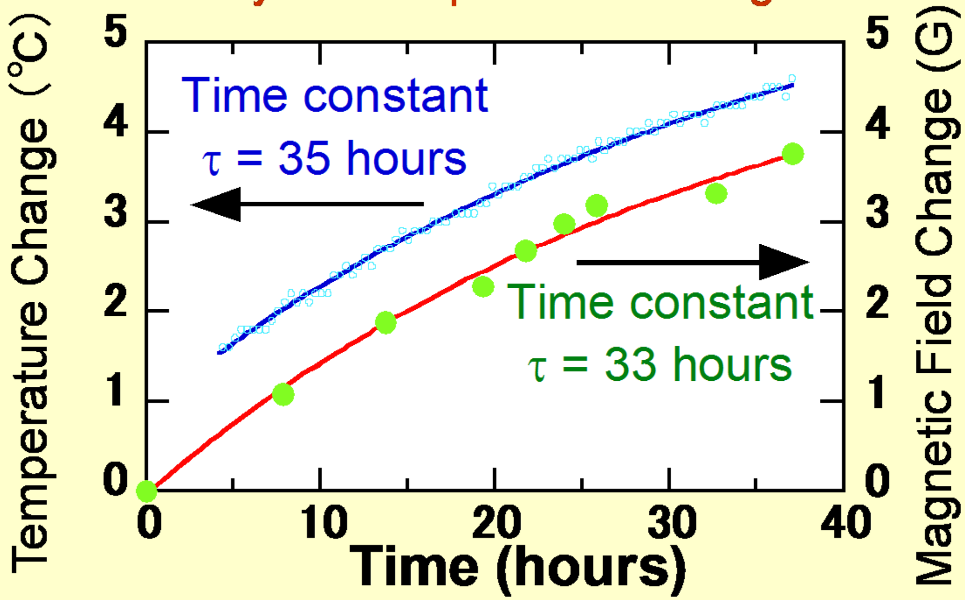
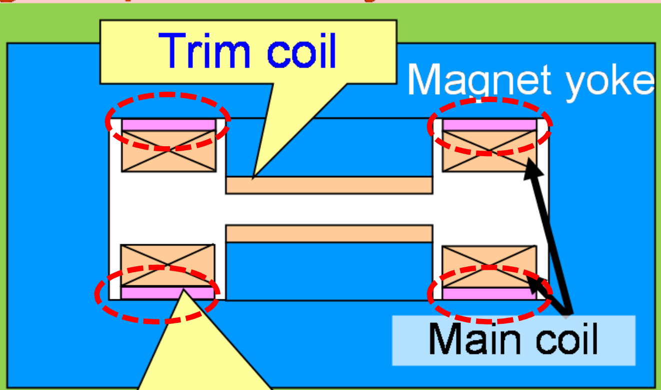
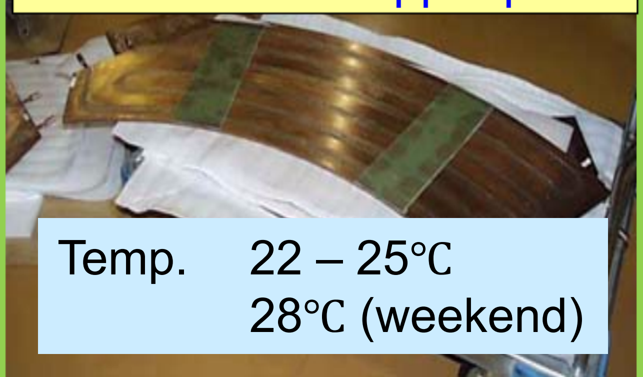
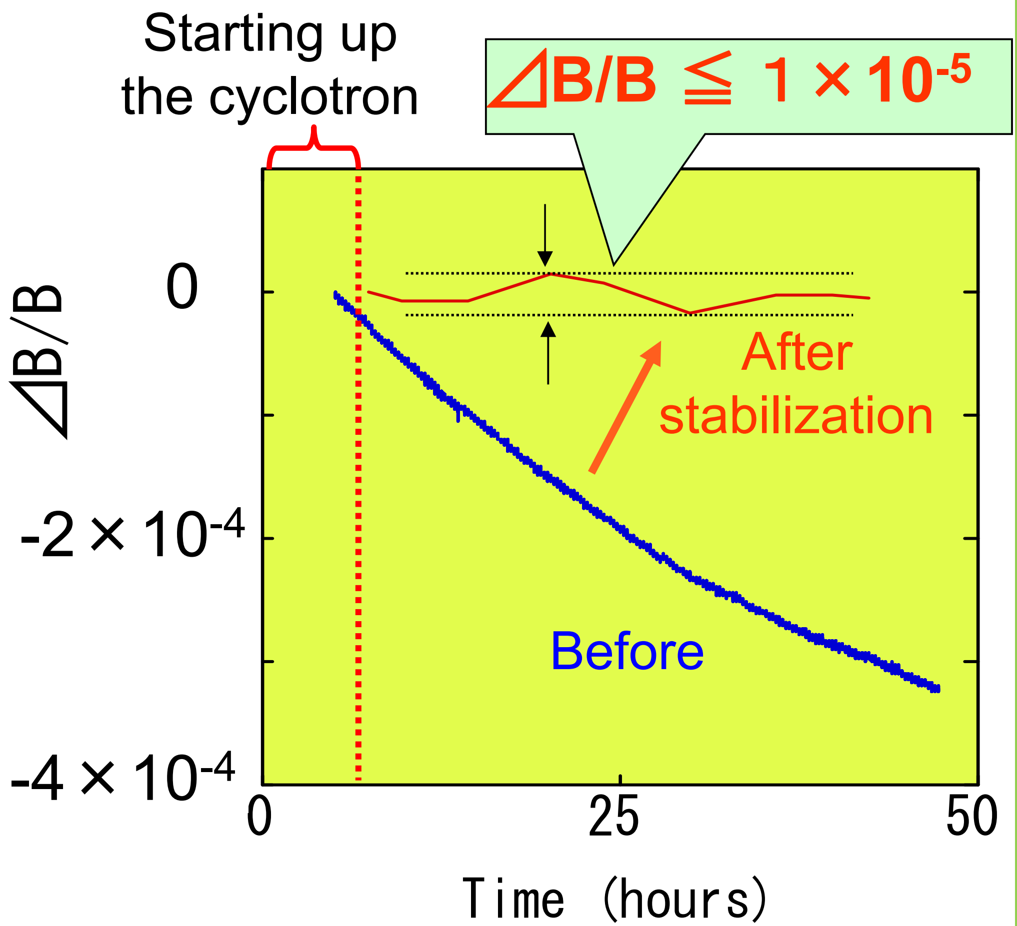






4. 2 Magnetic Field Stabilization

Magnetic field variation measured by an NMR probe



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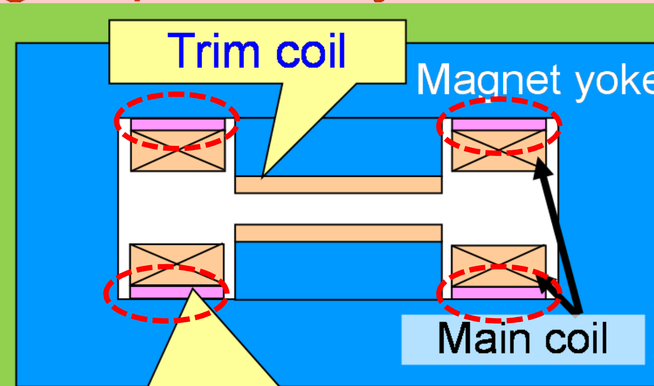
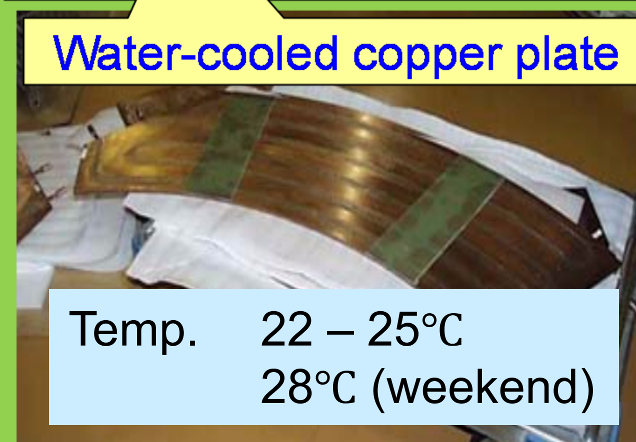


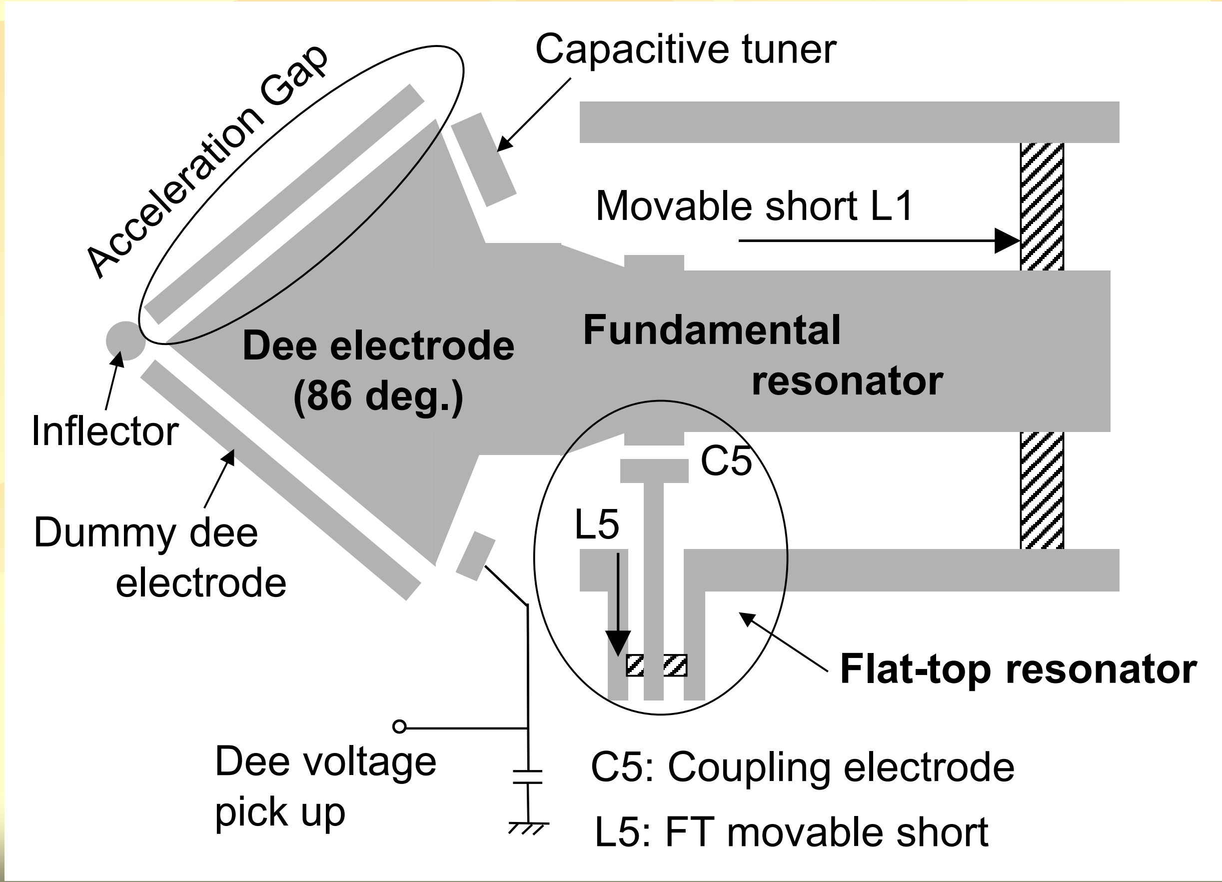


4. 3 Flat-top Acceleration

Flat-top (FT) acceleration using 5th harmonic frequency → Low power dissipation, Compact resonator

$$V_1 : V_{n\text{-th FT}} = 1 : 1/n^2$$

$$V_{5th} = V_1/25$$



C5: Coupling electrode

L5: FT movable short

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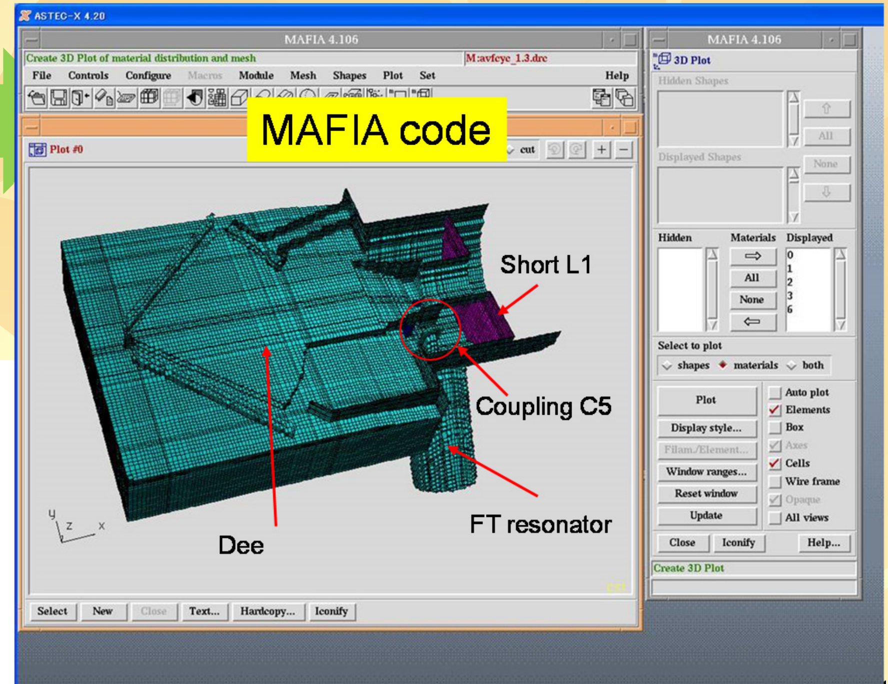

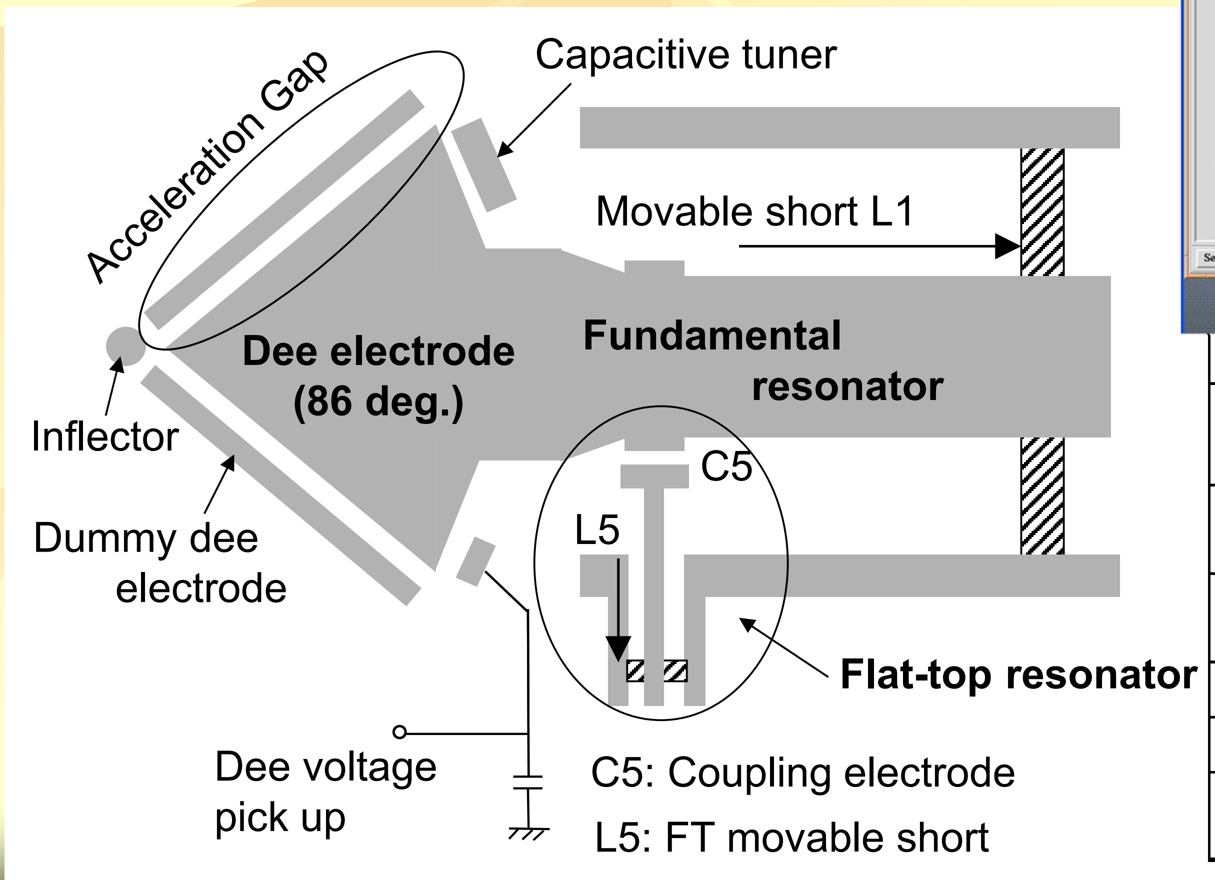

Resonance frequency	55 - 110 MHz
Movable gap range of the coupling capacitor (C5)	6 - 50 mm
Size of the electrode of the coupling capacitor	130 mm x 150 mm
Movable range of the shorting plate (L5)	250 mm
Inner tube diameter	70 mm
Inside diameter of outer tube	300 mm
Maximum output power of amplifier	3 kW (50 ohm)

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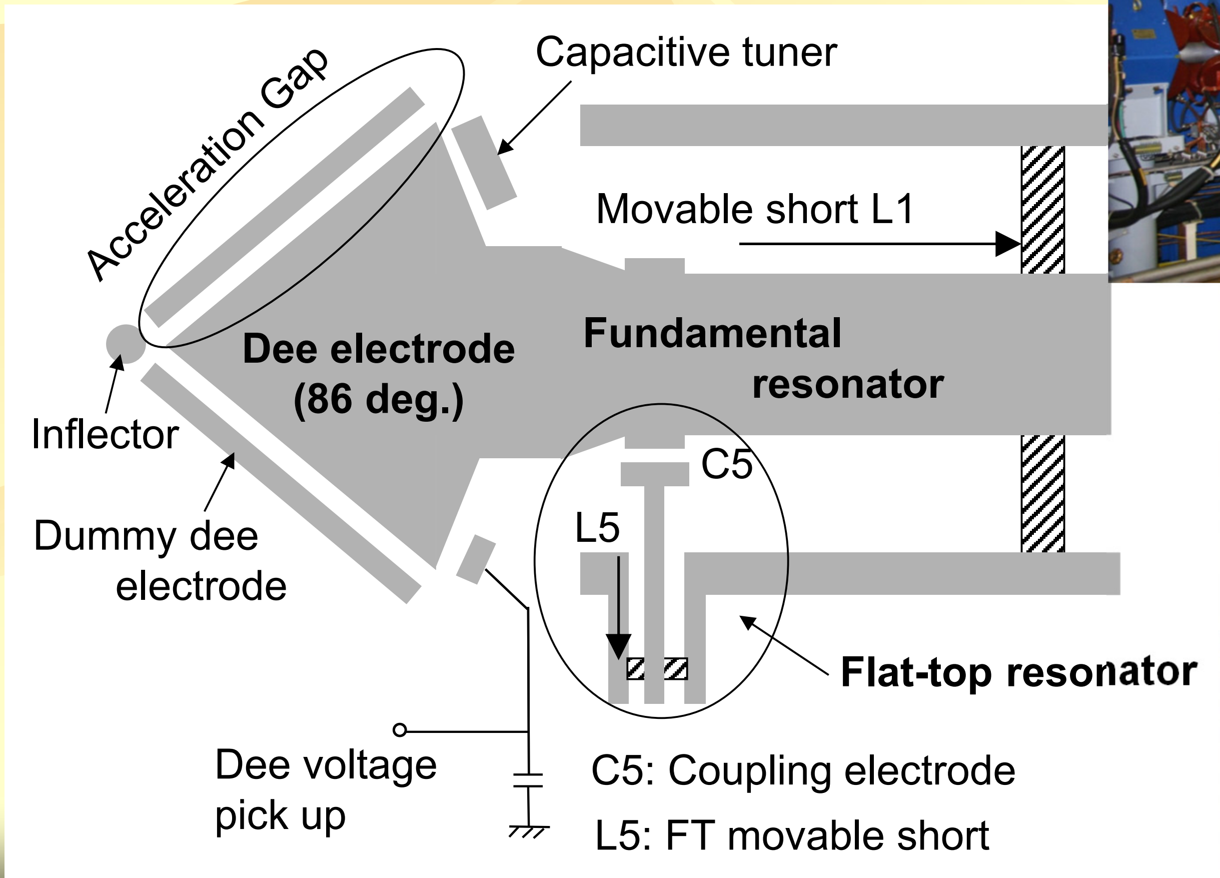
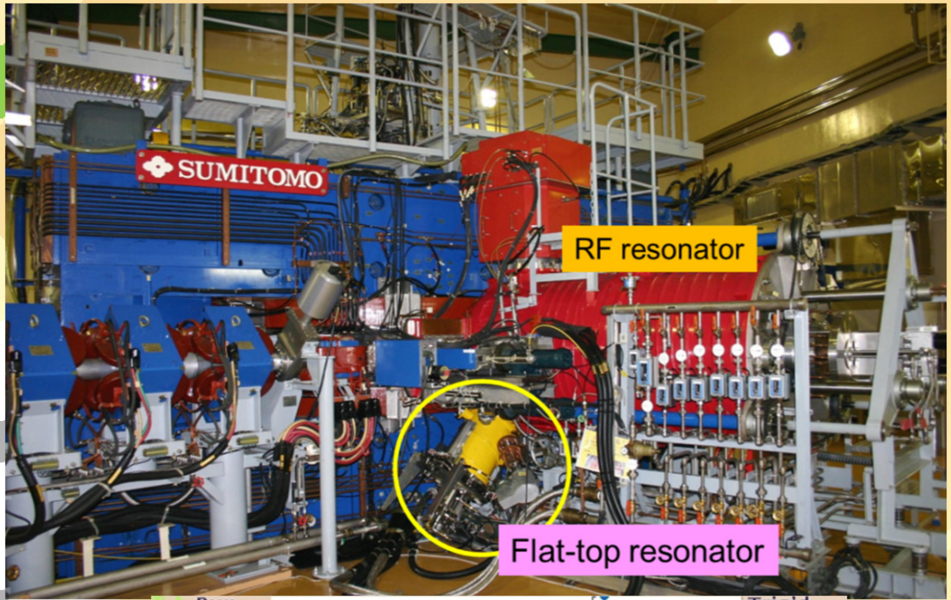
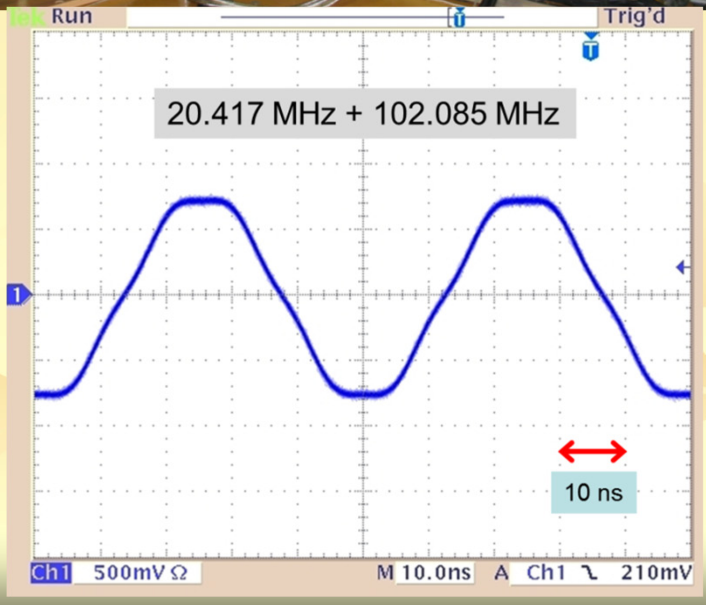
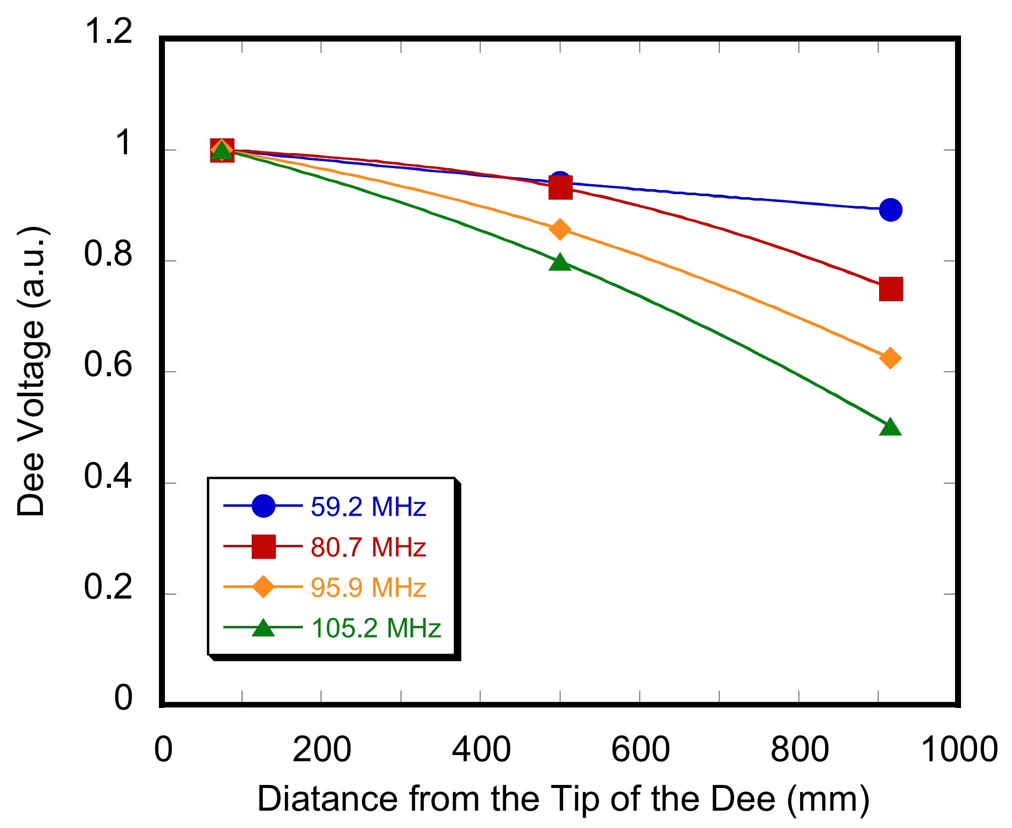




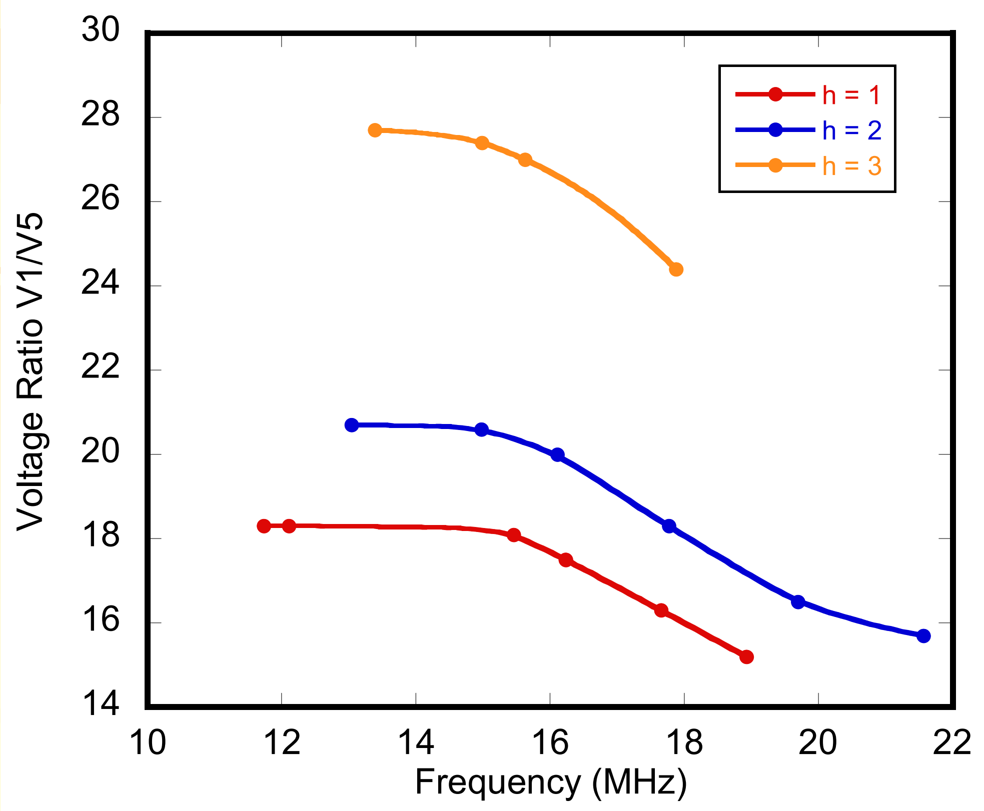


4. 3 Flat-top Acceleration

Voltage distributions along the dee gap



Optimum voltage ratio at the tip of dee



The fifth-harmonic voltage needs to be optimized at each frequency to uniform the overall energy gain of the beam bunch just before extraction.

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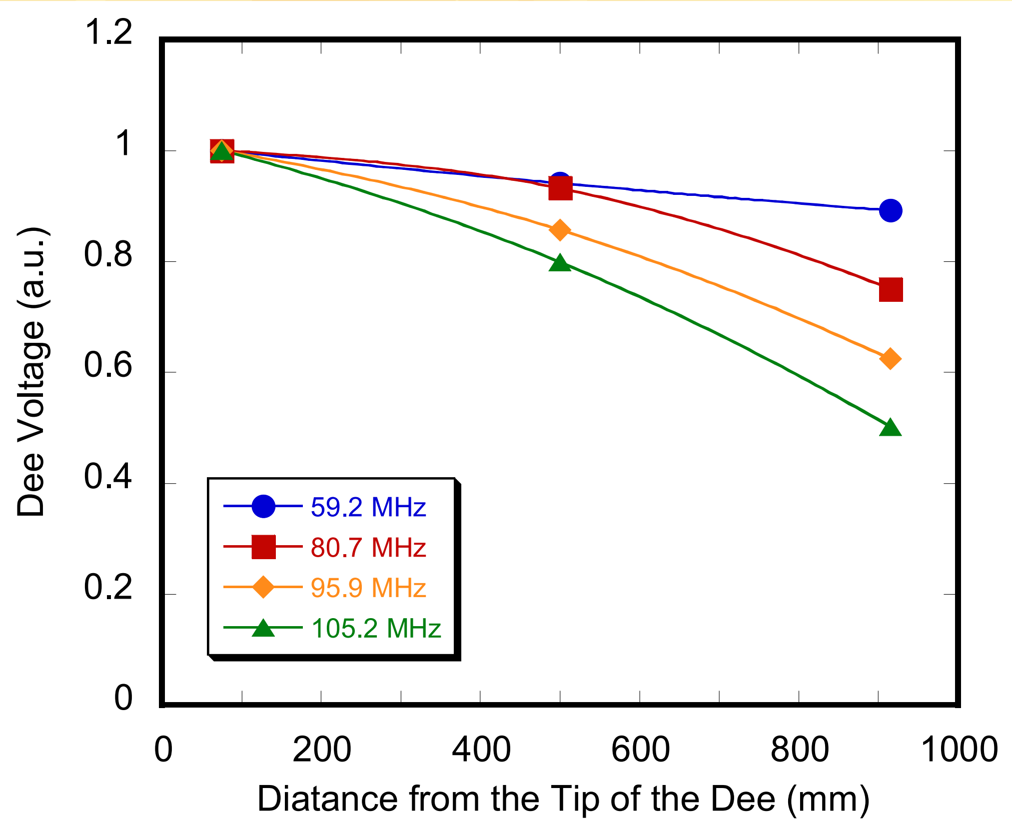

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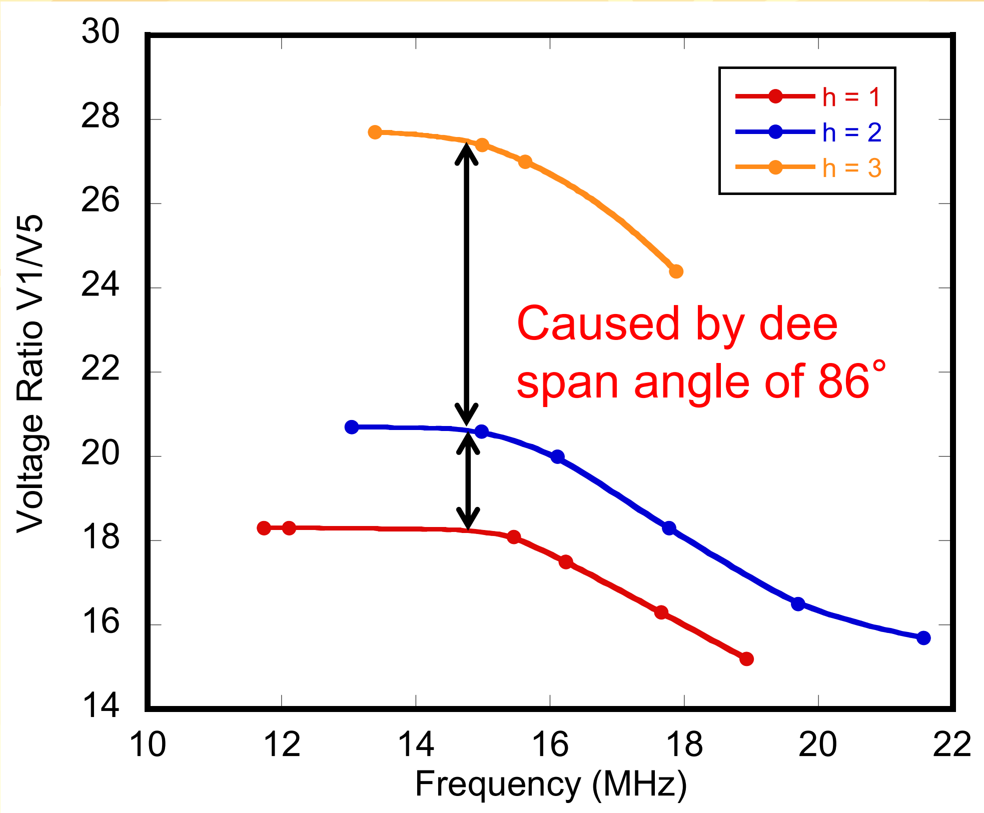
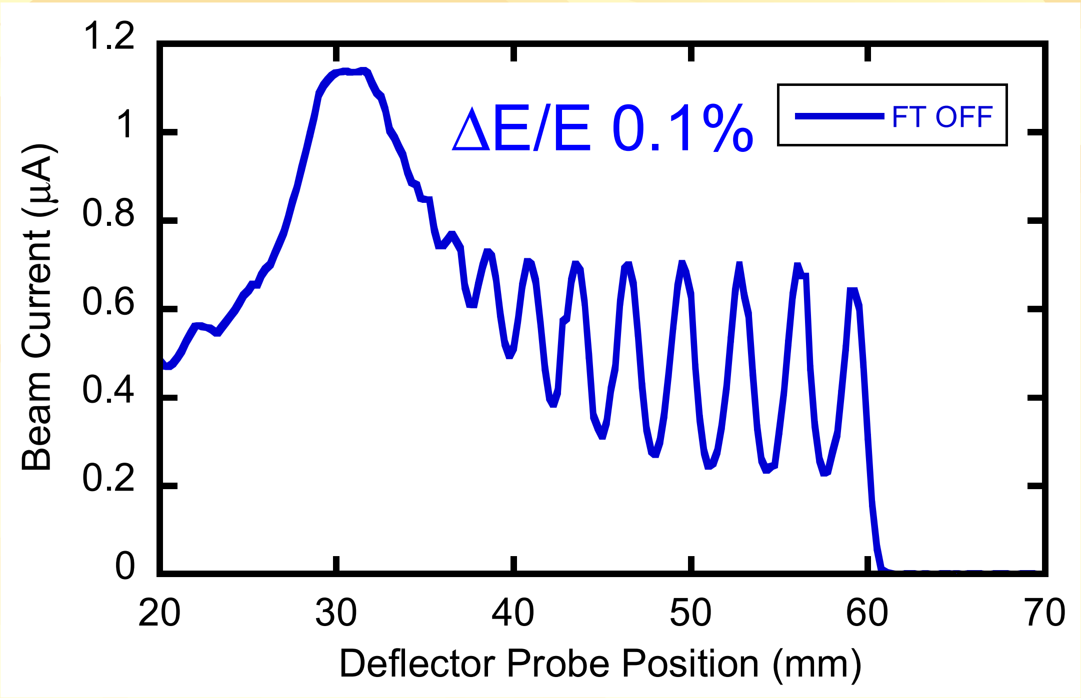


The fifth-harmonic voltage needs to be optimized at each frequency to uniform the overall energy gain of the beam bunch just before extraction.

5. Microbeam Irradiation Experiment

FT acceleration of 260 MeV $^{20}Ne^{7+}$
(h = 2, 17.475 MHz, 32 kV)



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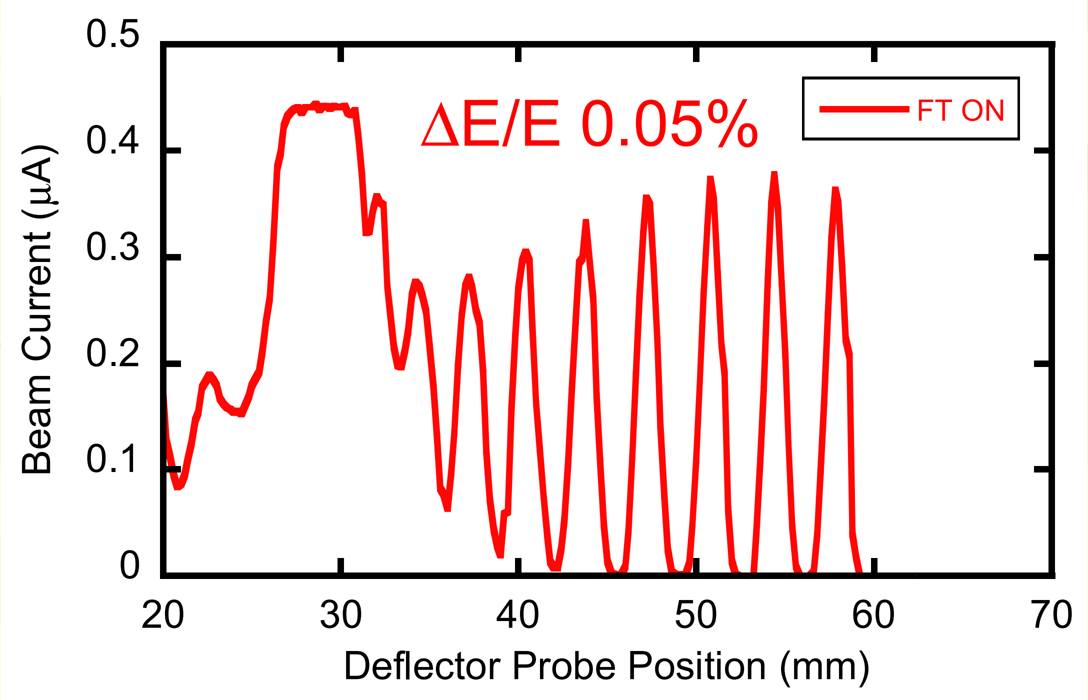

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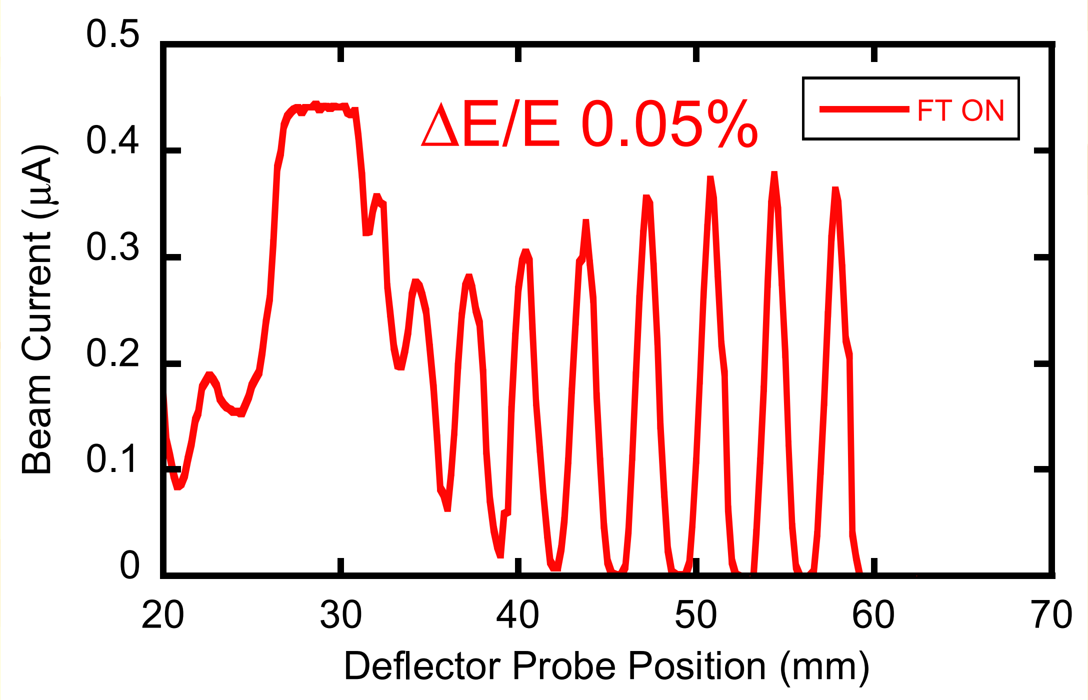
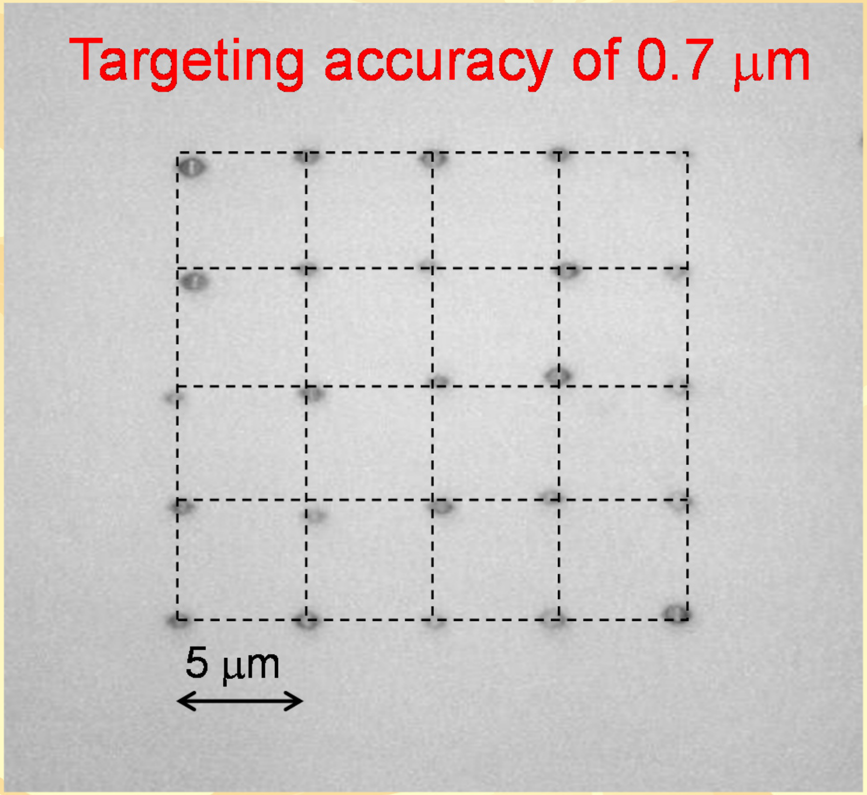


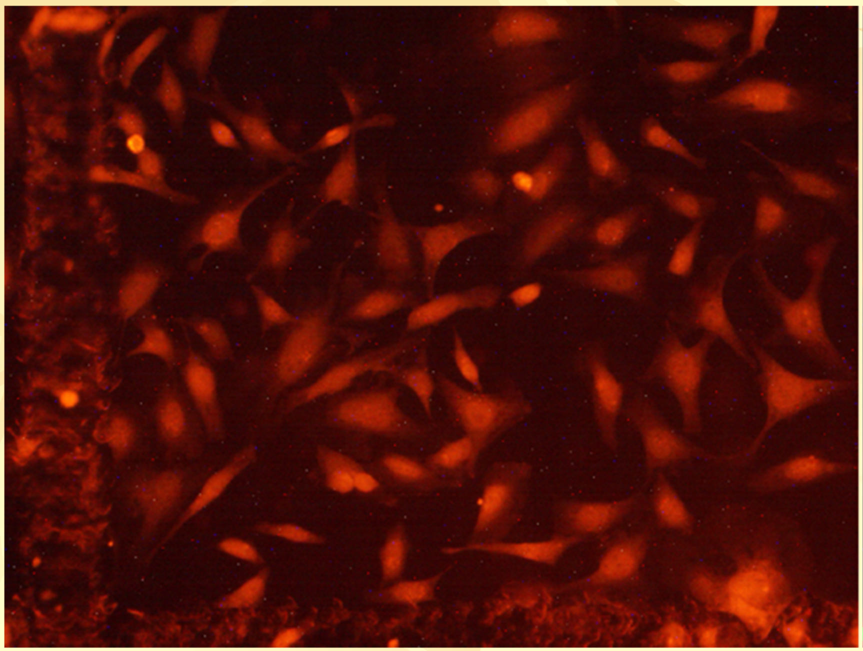


Beam spot size of 0.7 μm was formed!

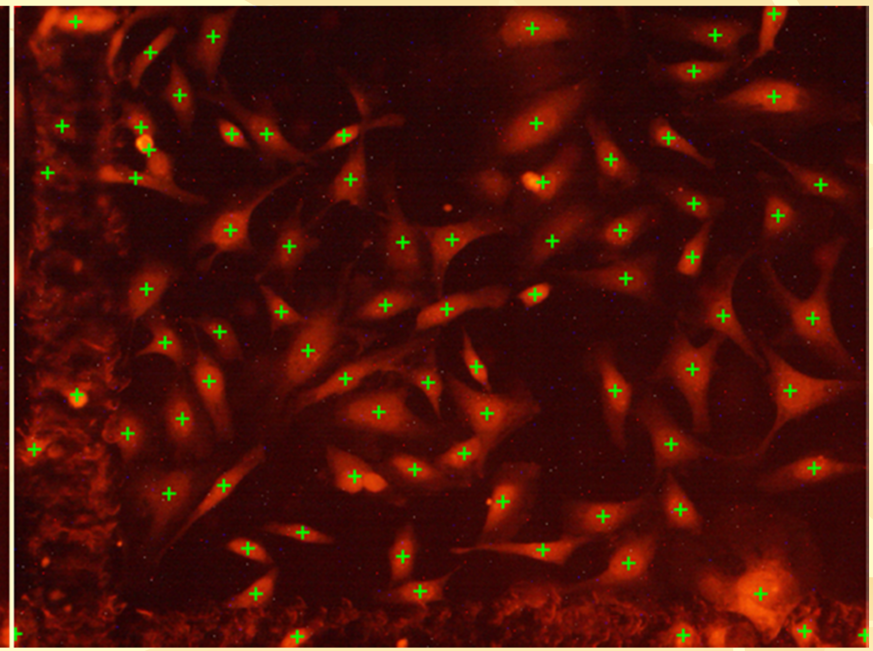
5 x 5 Single-ion Hit Pattern
on CR-39 film (after etching)

5. Microbeam Irradiation Experiment

Cell irradiation experiment in the air.
Microbeam is scattered in the air and a vacuum window (Si_3N_4, 200 nm^t) layers.



Photomicrograph of HeLa cells dyed by CellTracker Orange



Automatic detection of cell positions

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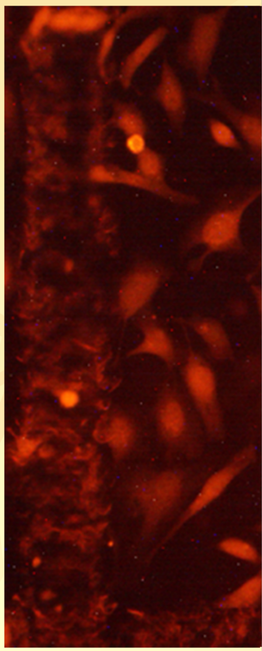
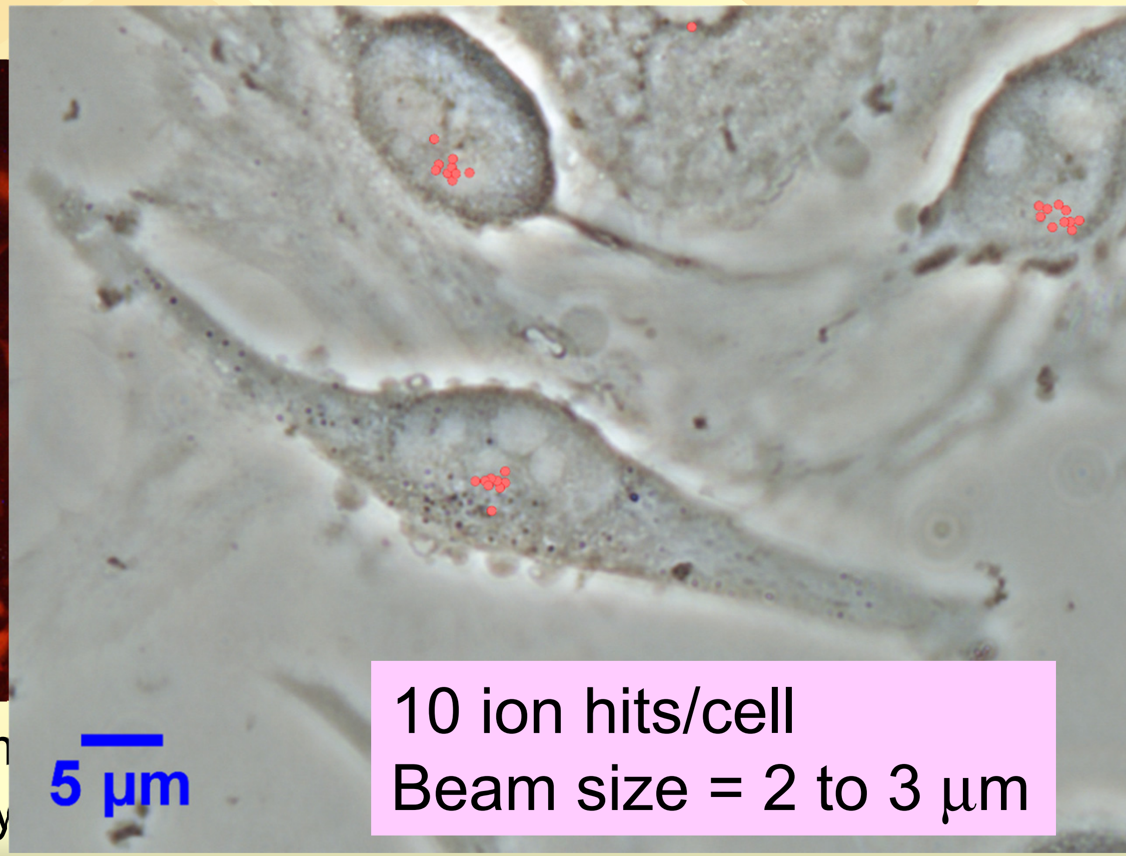
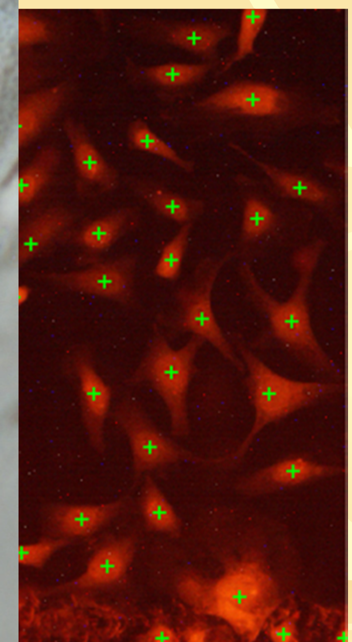






Photom
dyed by

on of cell

6. Quick Change of Ion Species

It takes about 8 h to form the microbeam. It is difficult to change the microbeam in a beam time.

↓

Cocktail beam acceleration technique was introduced to quickly change the ion species.

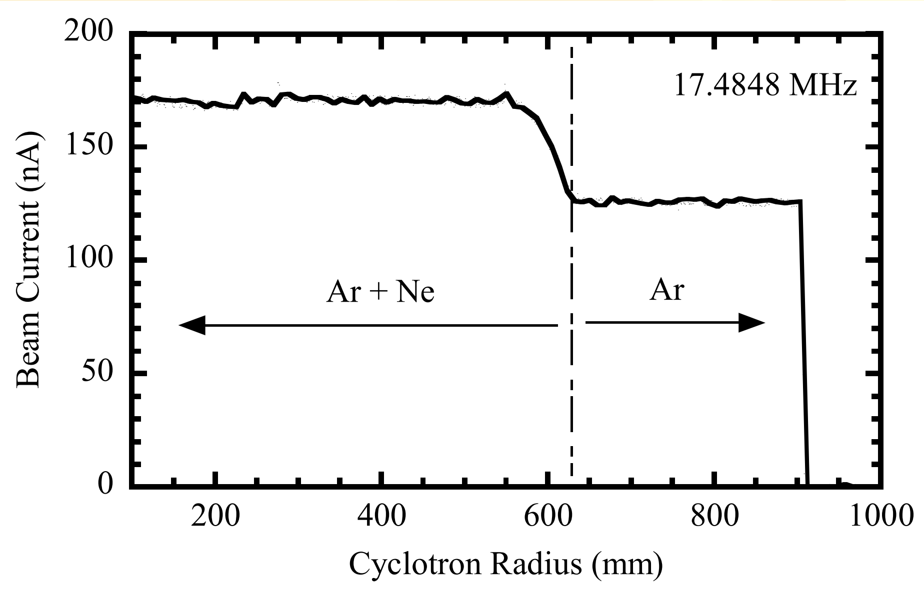
$$f_{\mathrm{RF}} = hf_{\mathrm{ion}} = \frac{h}{2\pi}\frac{eQ}{uM}B \propto \frac{Q}{M}$$

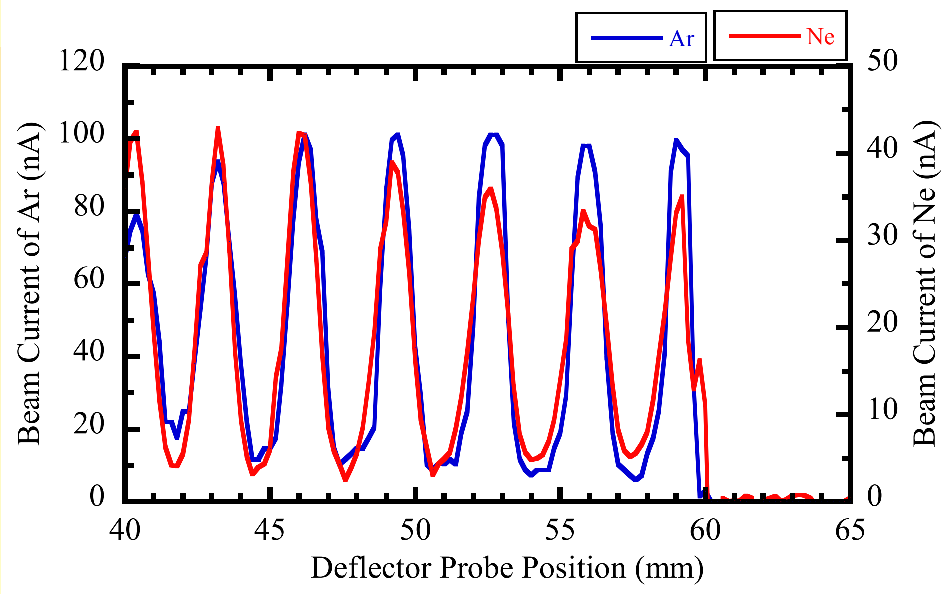
Mass resolution $R = \left|\frac{(M/Q)}{\Delta(M/Q)}\right| = \left|\frac{f_{\mathrm{RF}}}{\Delta f_{\mathrm{RF}}}\right|$

TIARA cyclotron
R = 3300

6. Quick Change of Ion Species

Ion	Mass (u)	M/Q	$\Delta(M/Q)/(M/Q)$	RF (MHz)	LET in water (keV/μm)
$^{14}N^{5+}$	14.0031	2.80007	-1.942×10^{-2}	17.8210	186.6
$^{20}Ne^{7+}$	19.9924	2.85551	0	17.4750	387.2
$^{40}Ar^{14+}$	39.9624	2.85391	-5.603×10^{-4}	17.4848	1143





Magnetic rigidities of the ion species are identical; therefore, lens parameters of the beam transport line need not to be changed.

6. Quick Change of Ion Species

Ion	Mass (u)	*M*/*Q*	Δ(*M*/*Q*)/(*M*/*Q*)	*RF* (MHz)	LET in water (keV/μm)
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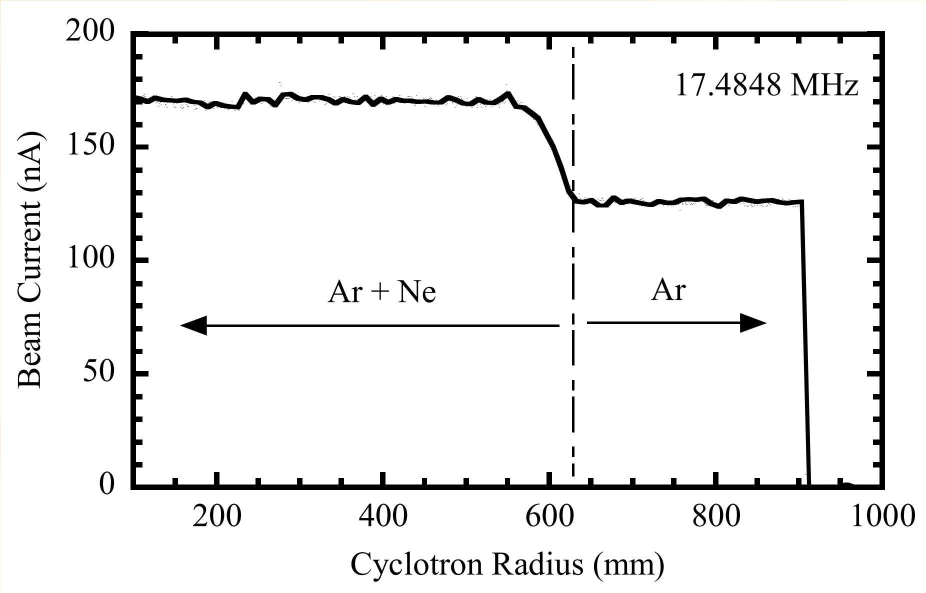

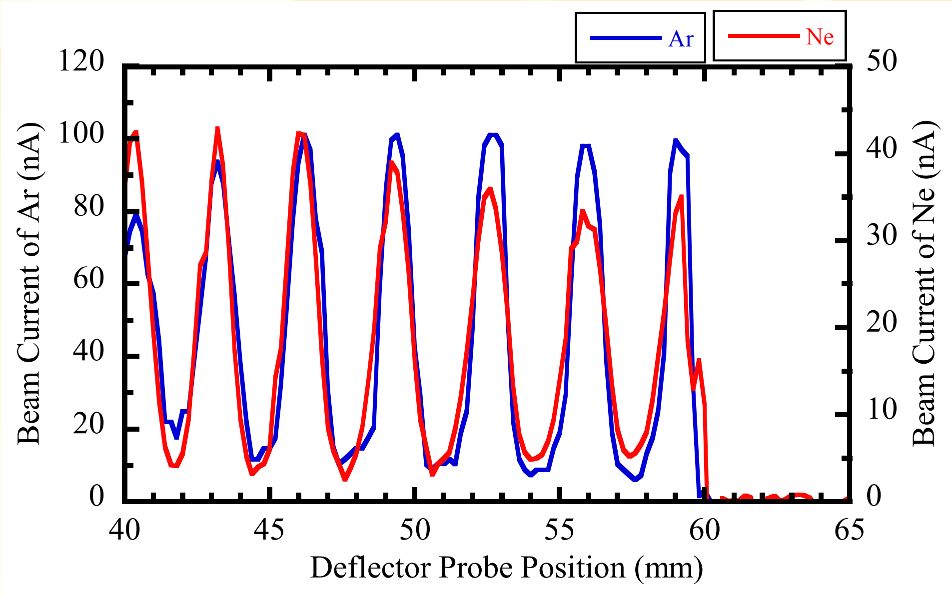

The microbeam was successfully changed in half an hour without deteriorating the beam spot size, as a result.

7. Summary

- The acceleration phase was easily controlled, and the beam phase width was effectively narrowed to about 5 deg. by phase compression in the central region (h = 2).
- The magnetic field was highly stabilized to $\Delta B/B = 1 \times 10^{-5}$ by keeping the temperature of the magnet yoke constant.
- The energy spread of the beam was reduced to $\Delta E/E = 0.05\%$ by the FT acceleration.
- Microbeam with a spot size less than 1 μm was formed and single-ion hit irradiation was successfully carried out.
- Ion species of the microbeam was quickly changed by the cocktail beam acceleration in half an hour.

Members

Cyclotron

S. Kurashima, N. Miyawaki, S. Okumura, H. Kashiwagi, K. Yoshida, T. Yuyama, T. Ishizaka, I. Ishiboiri, T. Nara, W. Yokota, M. Fukuda (Osaka Univ.)

Micobeam

T. Satoh, M. Koka, A. Kitamura (JAEA), N. Yamada, M. Oikawa, T. Kamiya, M. Suzuki, Y. Yokota, T. Sakashita, T. Funayama

Members

Thank you for your attentions!

Members

Please ask me slowly
using a simple phrase!