Kyushu University 2011
100th Anniversary

Current Status of Beam Commissioning of FFAG Accelerator at Kyushu University

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KYUSHU UNIVERSITY

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2. Development of RF acceleration system
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    - 3.1. COD measurement
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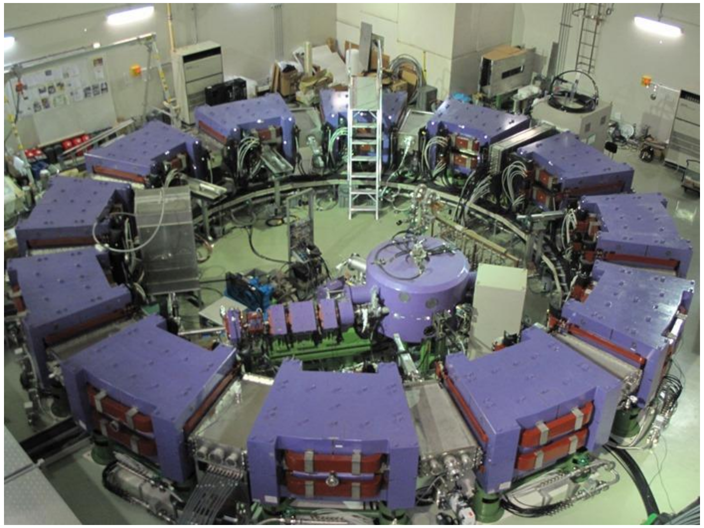
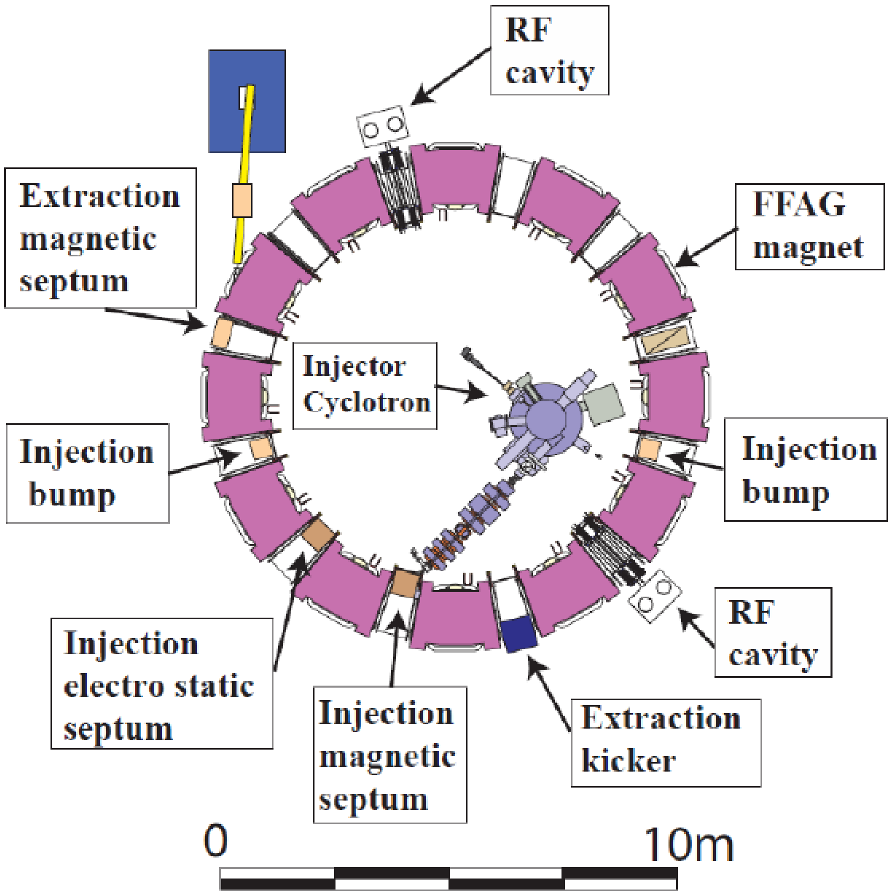
4. Summary



Overview of 150 MeV FFAG Accelerator



magnet	Radial sector type (DFD-triplet)
Cell	12
K-value	7.62
Beam energy	10 ⇒125 MeV (12 ⇒ 150 MeV)
Radius	4.47 ⇒ 5.20 m
Betatron tune	H: 3.69～3.80 V: 1.14～1.30
Max. field	F-field: 1.63 T
(along orbit)	D-field: 0.78 T
Circ. freq.	1.55～4.56 MHz
Repetition	100 Hz
Mean current	1.5 nA

150 MeV FFAG accelerator has been developed for various applications, such as nuclear physics ,nuclear engineering and medical science.

Injector cyclotron

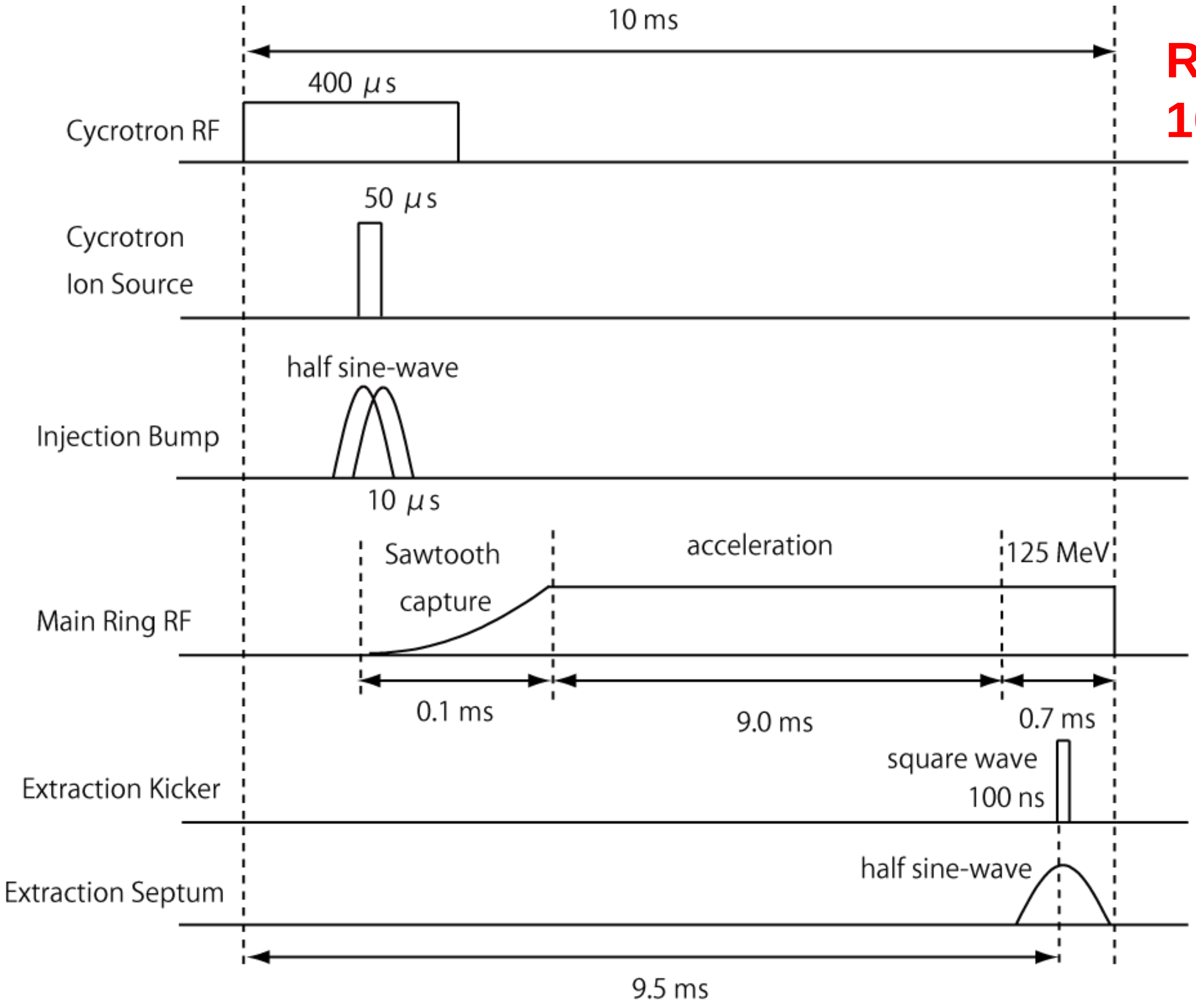
Design parameters of Baby-Cyclotron

Energy	10 MeV (proton)
Type	AVF Cyclotron
Ion Source	Internal PIG (LaB6 cathode)
RF Dee Voltage	40 kV
Extraction Radius	300 mm
Magnetic field	Max. 1.54 T
RF Frequency	47 MHz (2^{nd} harmonic)
Beam Current	15 μA

JSW Baby-Cyclotron

We are planning the irradiation experiments for low energy physics

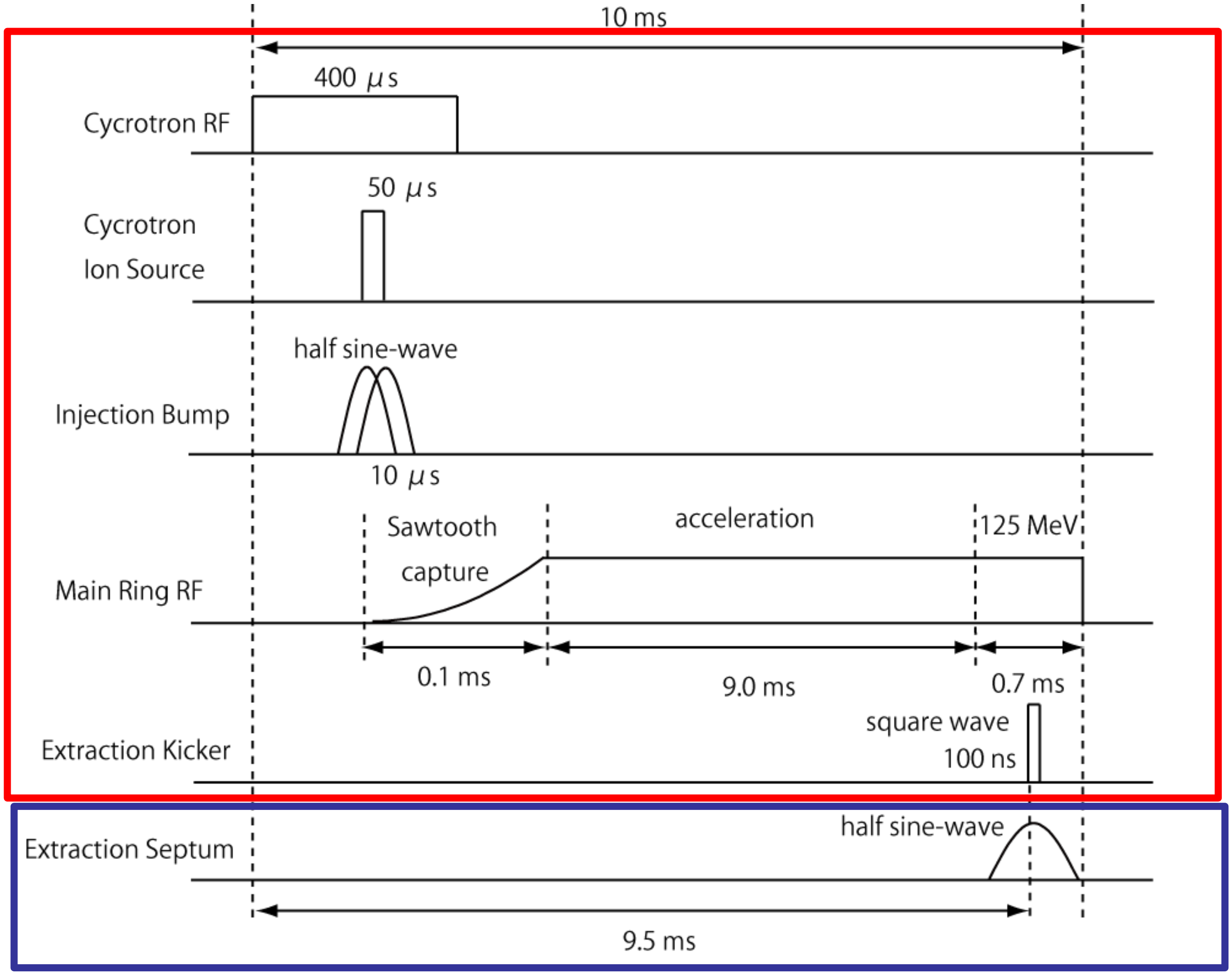
Timing Chart of injector and FFAG



Repetition rate 100Hz

Timing Chart

Preparation has been completed



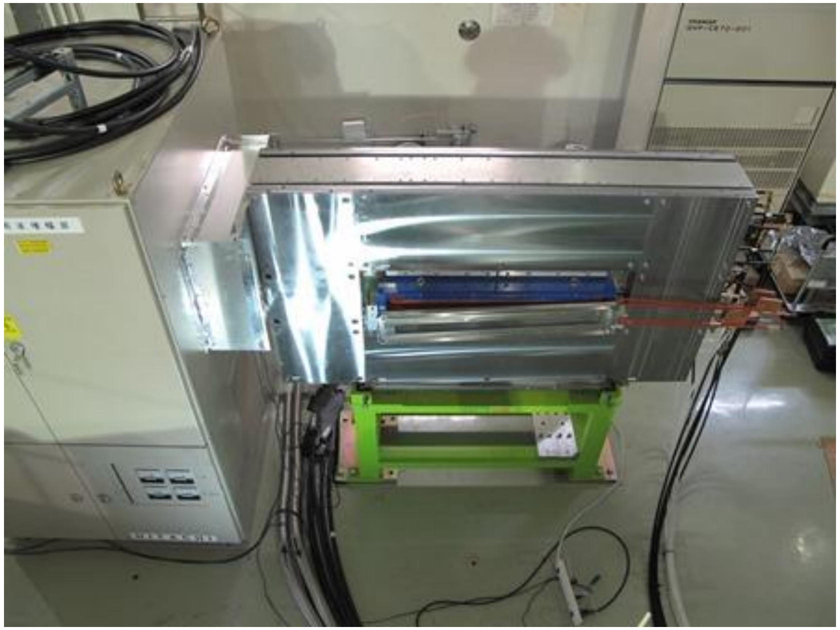
In preparation

Beam commissioning log

2012	Jan.	The 1st turn was observed
	Feb.	Circulating beam was observed
	Apr. – Jun.	Maintenance period (Saving electricity)
	Jul. – Sep.	Assembling of the RF cavity Low power test of RF amplifiers
	Nov. – Dec.	Beam study of multi-turn injection
2013	Jan. – Mar.	Maintenance period (repair of power sources and vacuum system)
	Apr. – Jun.	High power test of RF amplifiers Installation of the RF cavity, High power test
	Jul.	Beam acceleration was demonstrated (~80MeV)
	Jul. – Aug.	Study of beam acceleration has been performed

Contents

1. Overview of 150 MeV FFAG Accelerator
2. Development of RF acceleration system
3. Measurements of COD and tune
4. Demonstration of Beam acceleration
5. Summary



Power amplifier and RF cavity

Requirements of RF acceleration system

To achieve a rapid cycling acceleration of 100 Hz,

RF voltage	3 kV / 1 cavity
Number of RF cavities	2
Frequency range	1.5 – 4.2 MHz

Power dissipation of an RF cavity

$$P = \frac{V^2}{2R} = \frac{3000^2}{2 \times 200} = 25\ \mathrm{kW} \rightarrow 12.5\ \mathrm{kW}/1\mathrm{core}$$

⇒ Effective Cooling system

Strong fringing field of FFAG magnets at the straight sections

⇒ Magnetic Shield of RF cavity
COD correction magnets

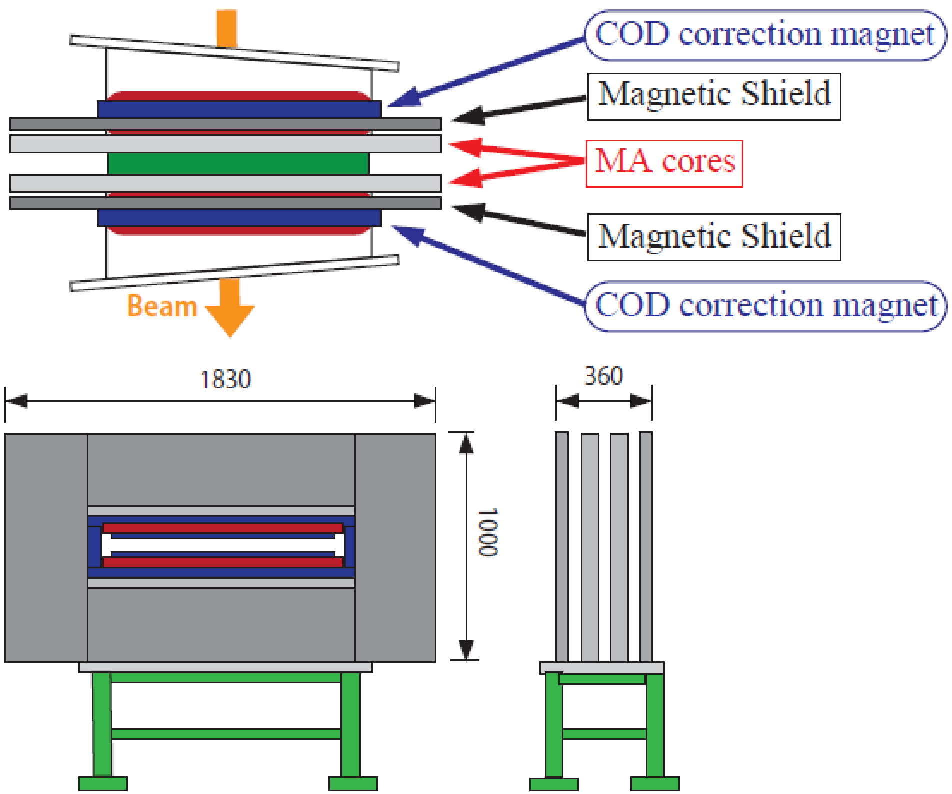
Overview of RF acceleration system

Function Generator → Transistor Power Amplifier → Main RF Amplifier → MA Cavity

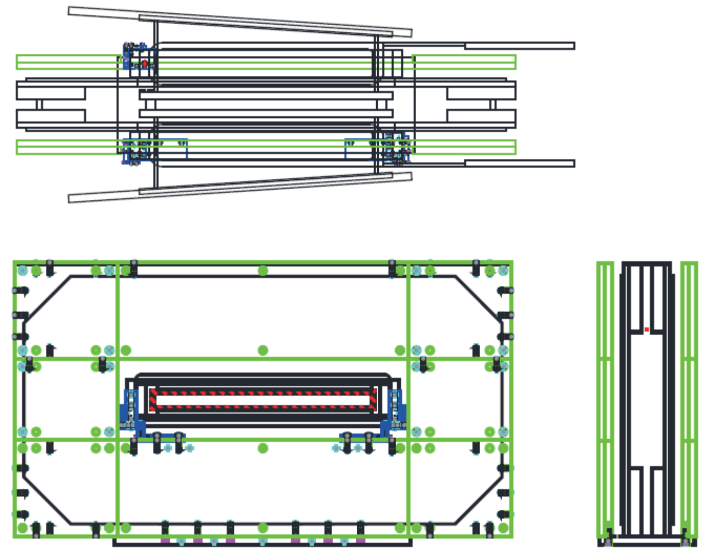
Experimental setup for a power test

Gap Voltage	3 .0 kV/cavity
RF frequency	1.5 – 4.2 MHz
Power tube	4CW15000E × 2
Class	B class, Push-pull
Core material	FINEMET (FT-3M)
RF output power	200 kW

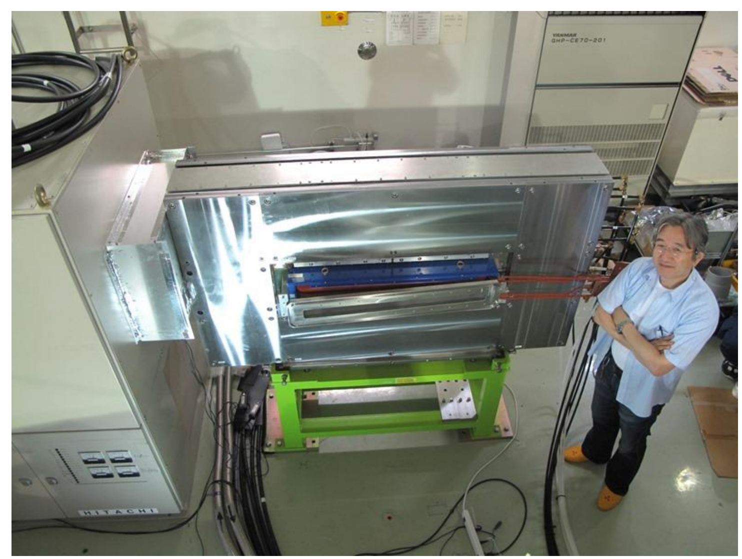
Overview of RF cavity



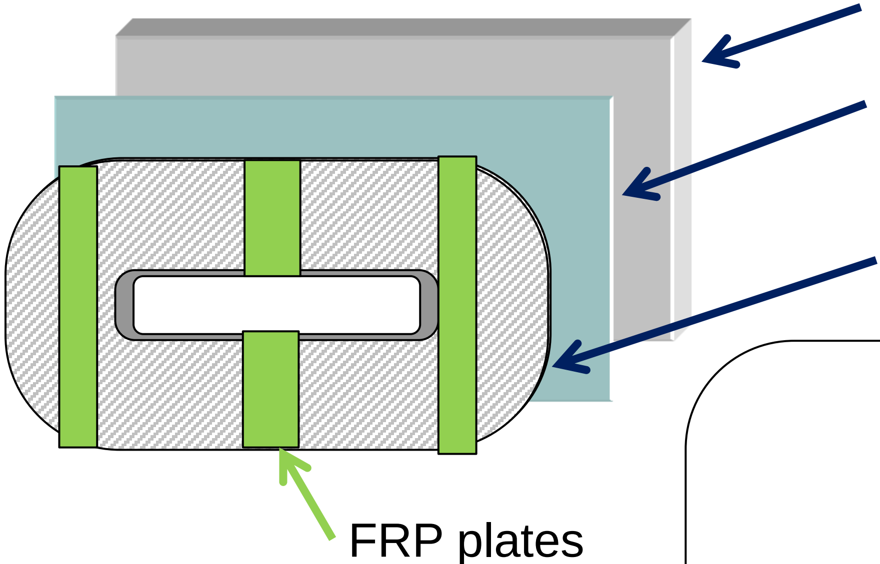
Schematic drawing of the RF cavity

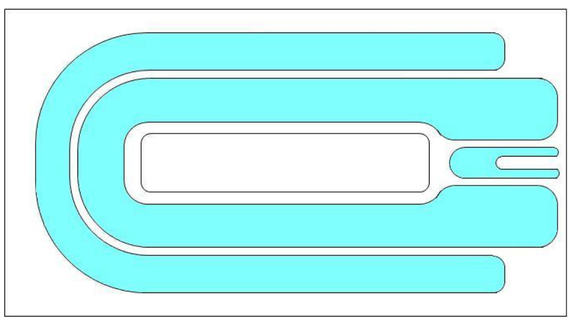


Mechanical drawing



Indirect water cooling system





Cross sectional view
of the cooling plate

Temperature difference between
core and cooling plate

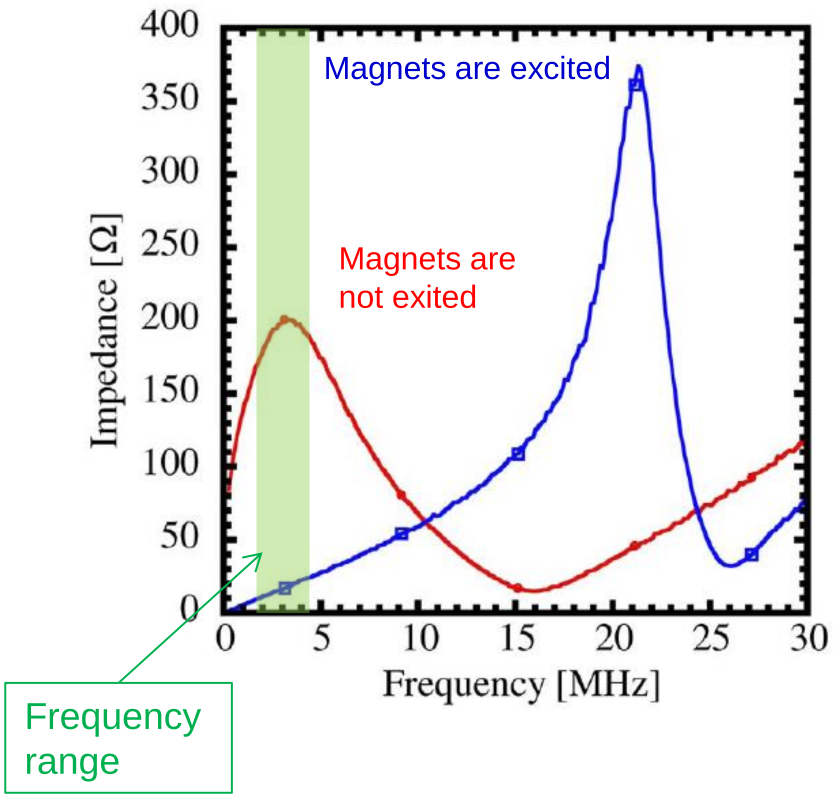
$$\Delta T = \frac{q}{A}\left(\frac{\Delta x_1}{k_1} + \frac{\Delta x_2}{k_2}\right)$$

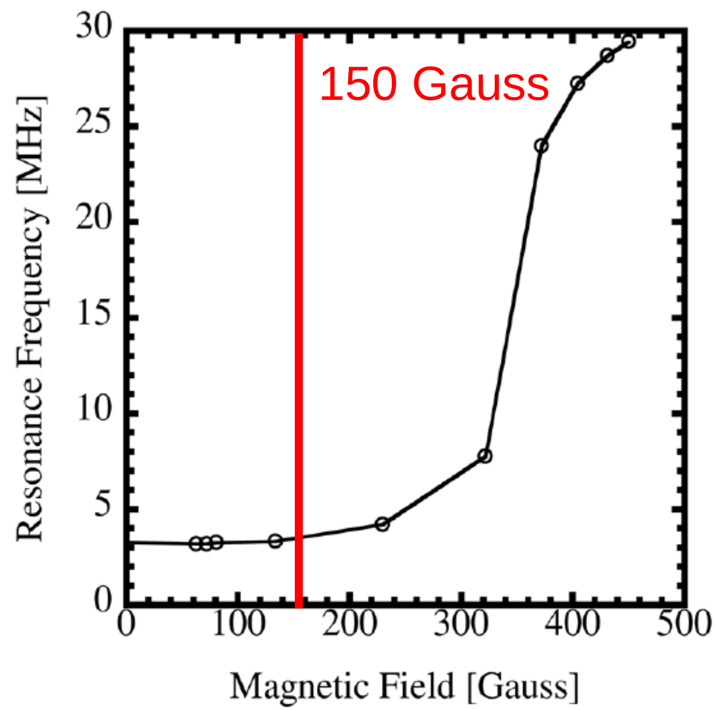
k_1 : Coefficient of thermal conductivity of core (20 W/m K)
k_2 : Coefficient of thermal conductivity of spacer (3 W/m k)
Δx_1 : Thickness of MA core (35 mm)
Δx_2 : Thickness of spacer (1 mm)
q : Power dissipation of 1 core (25 kW)
A : Area of cooling plate (1.36 m^2)

→ ΔT = 38 degree

Magnetic Shield of RF cavity

The RF cavity should be magnetically shielded

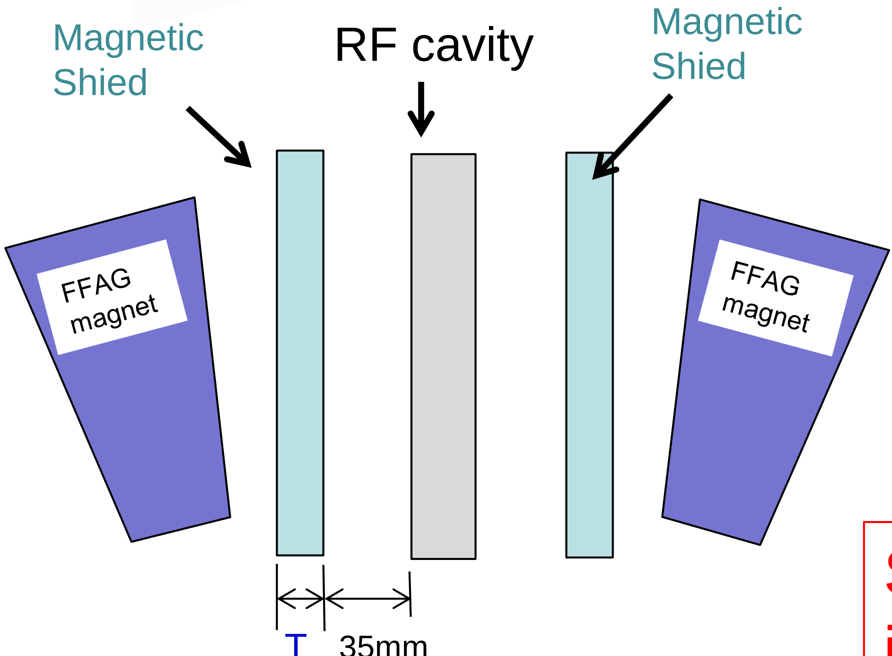




The measured resonance frequency varied
when the fringing field was greater than 150 Gauss.

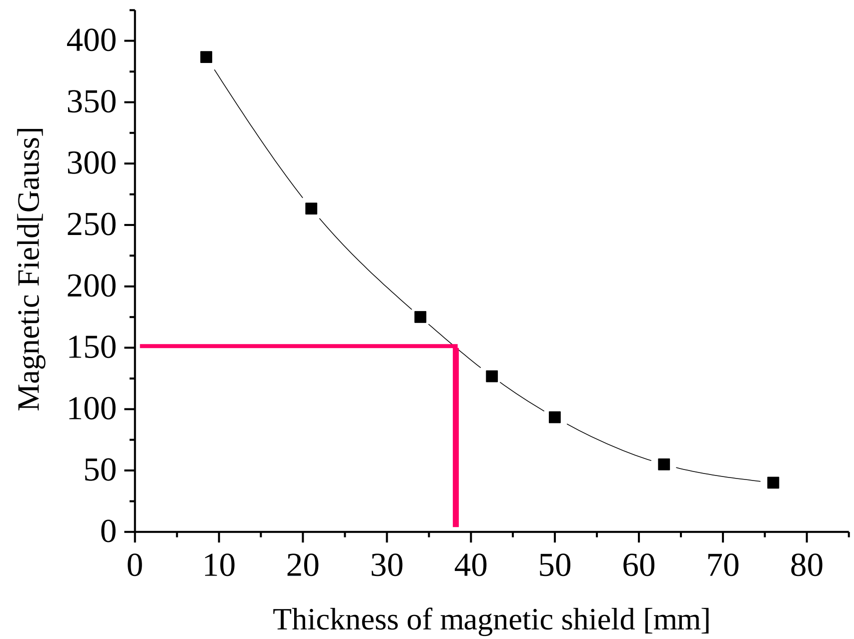
Design of Magnetic Shield

Calculation model of Opera-3d



T = 8 ~ 76 mm

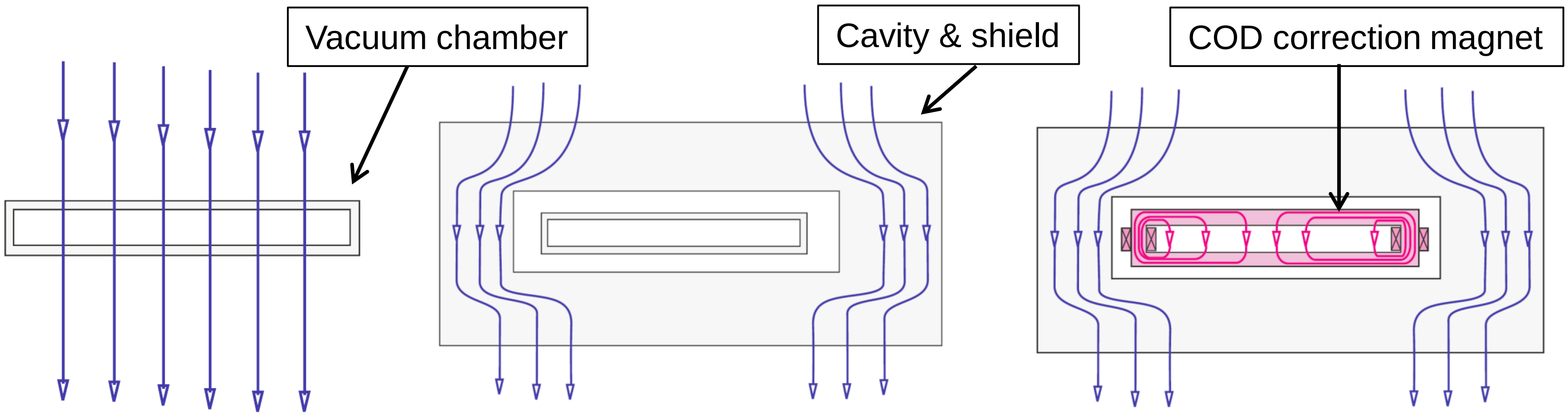
Optimization of thickness of magnetic shield



The required thickness of the shield is about 40 mm or more

Shield with a thickness of 50 mm is employed for the RF cavity

COD correction magnets

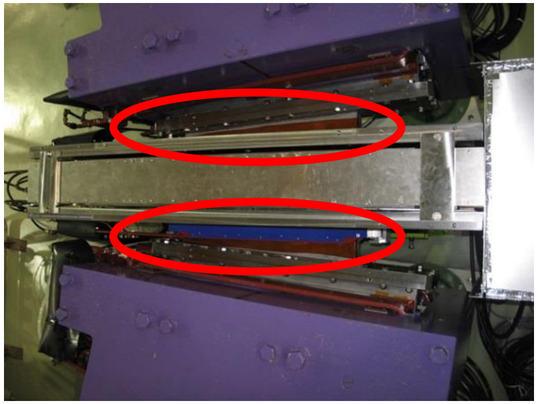


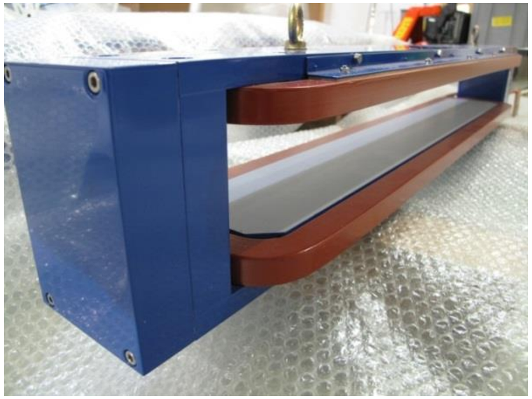
Straight section
(Bz = 400 Gauss)

Cavity & Shield

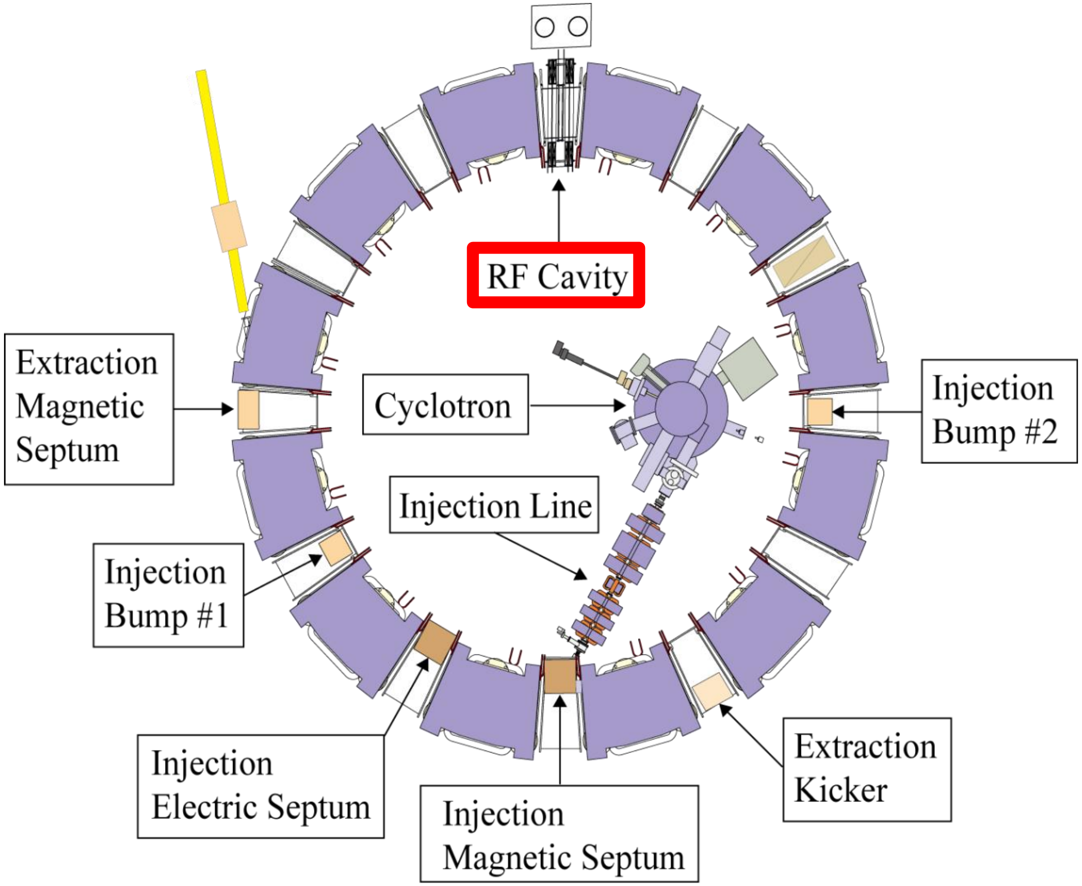
Cavity & Shield
+ COD correction magnet

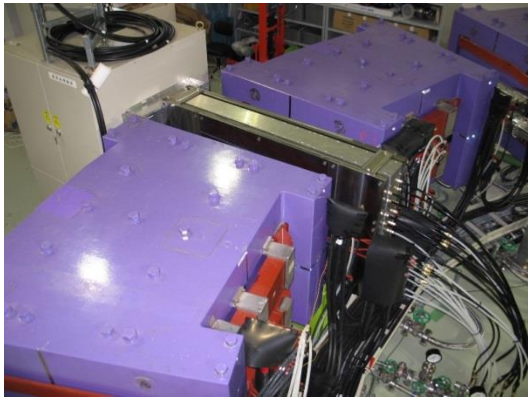
Current of coil	max. 980 A
Magnetic field	970 Gauss
Length	100 mm
Gap	76 mm





Installation of RF cavities

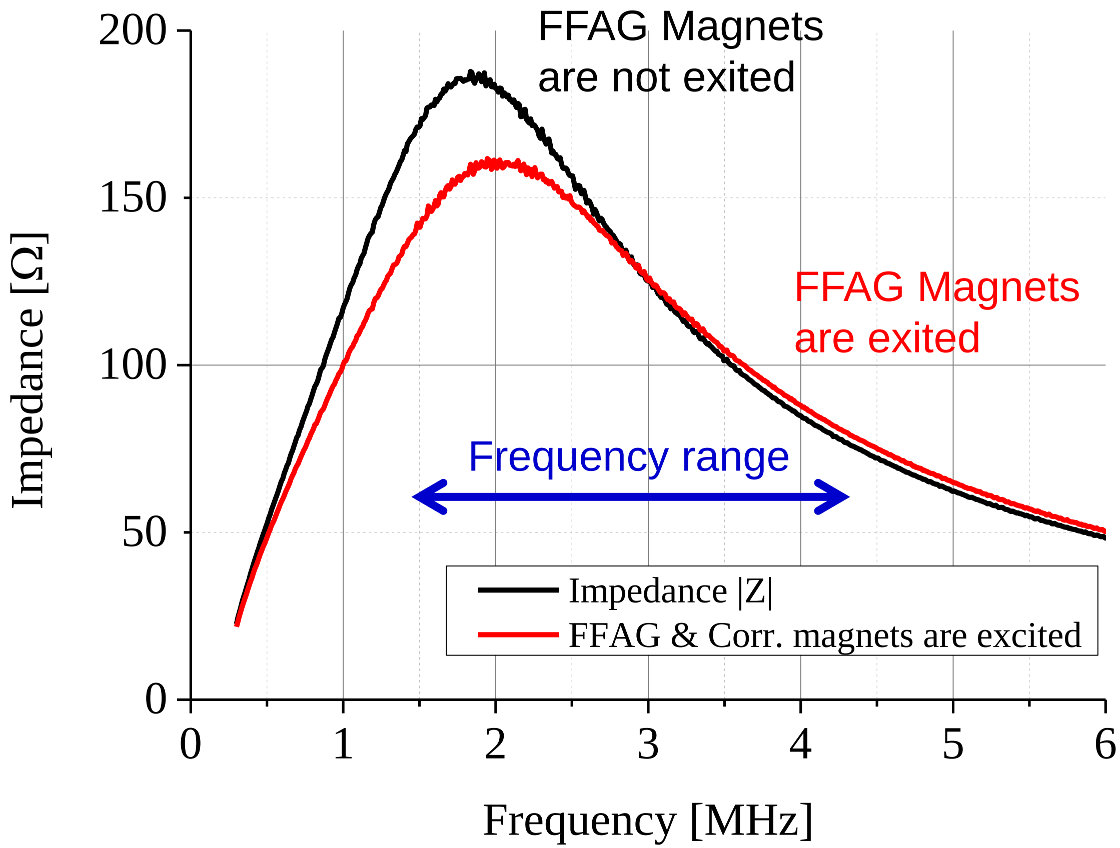




The second RF cavity will be installed in 2014.

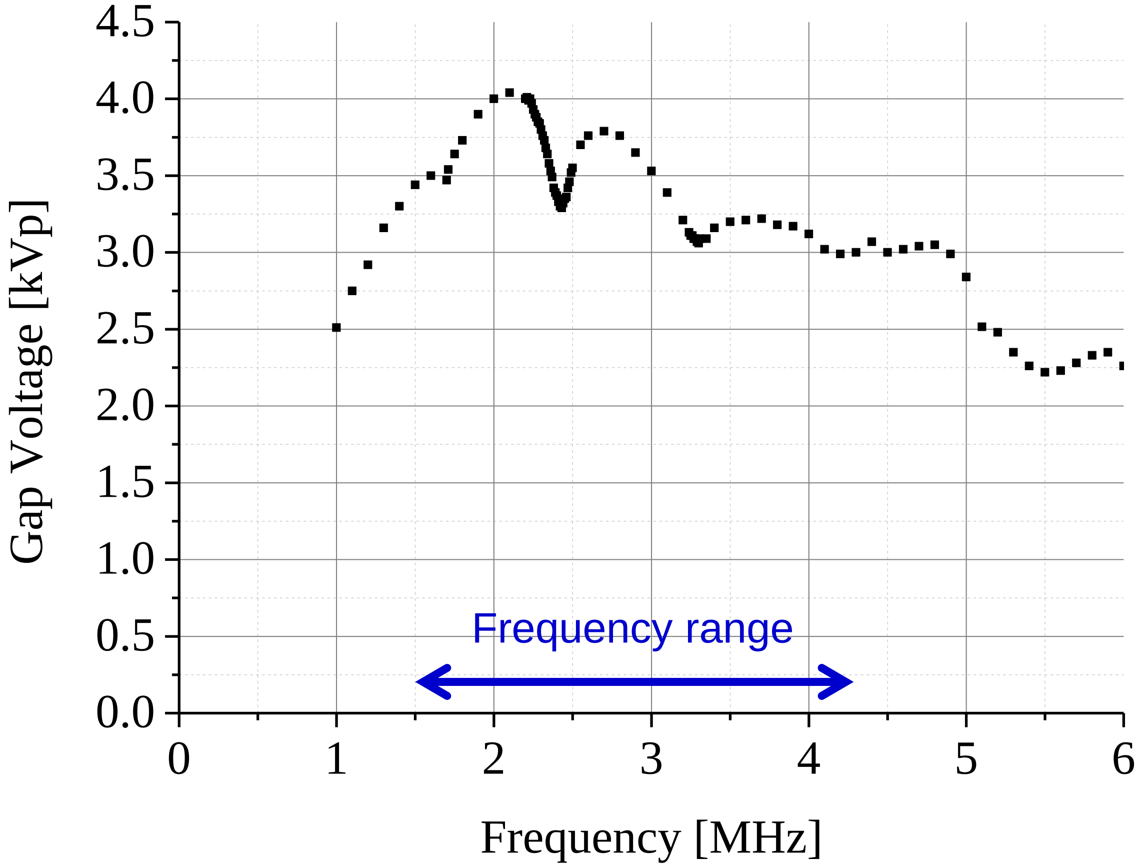
Measured Impedance of RF cavity

To confirm the shielding effect, the impedance of the cavity was measured



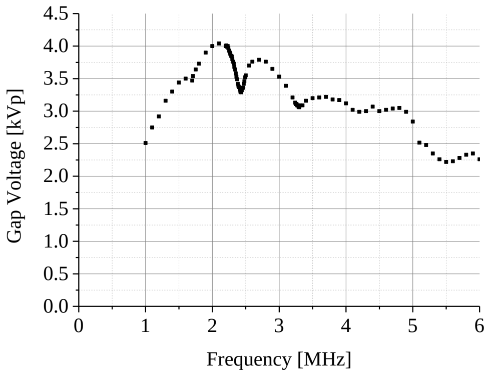
The resonance frequency increase slightly
The shunt impedance decreased by about 10 %

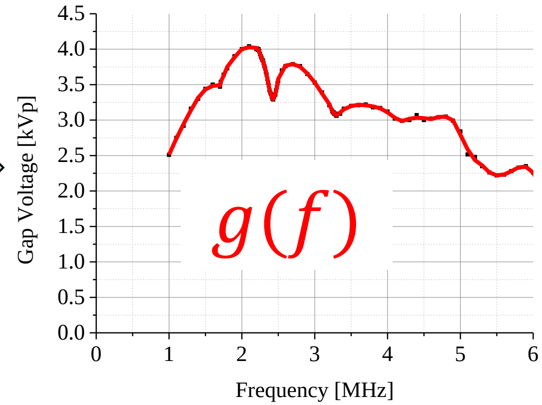
Measurement of Gap voltage



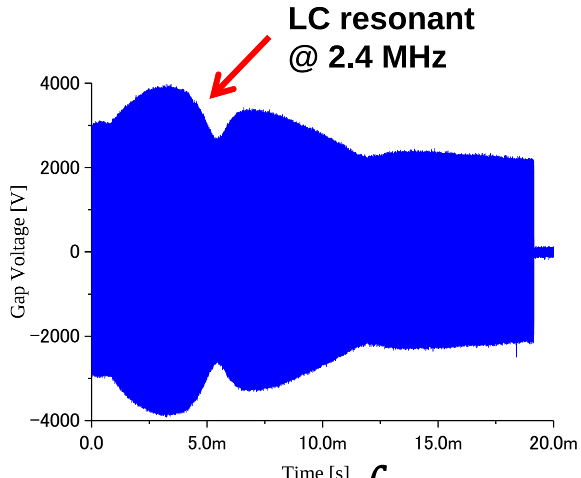
The drop of the gap voltage causes the beam loss during acceleration.

Acceleration voltage with amplitude modulation

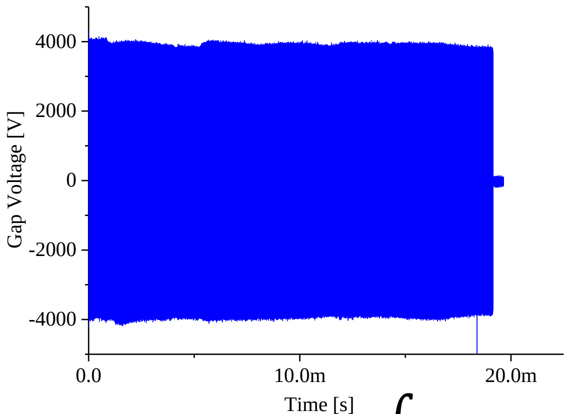




$$\frac{1}{g(f)} = h(f)$$



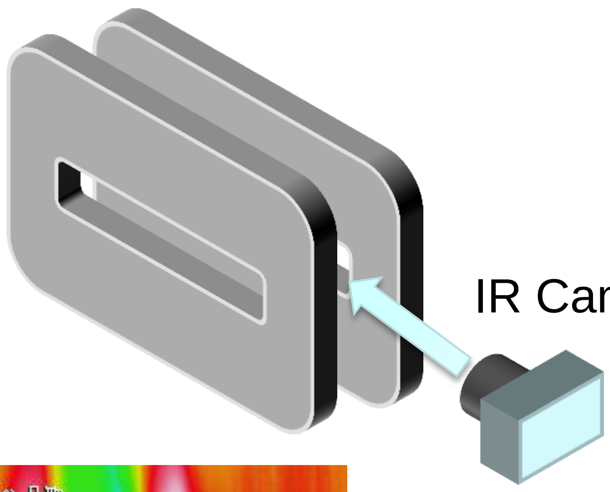
$$V(t) = \sin(\int f(t)dt)$$

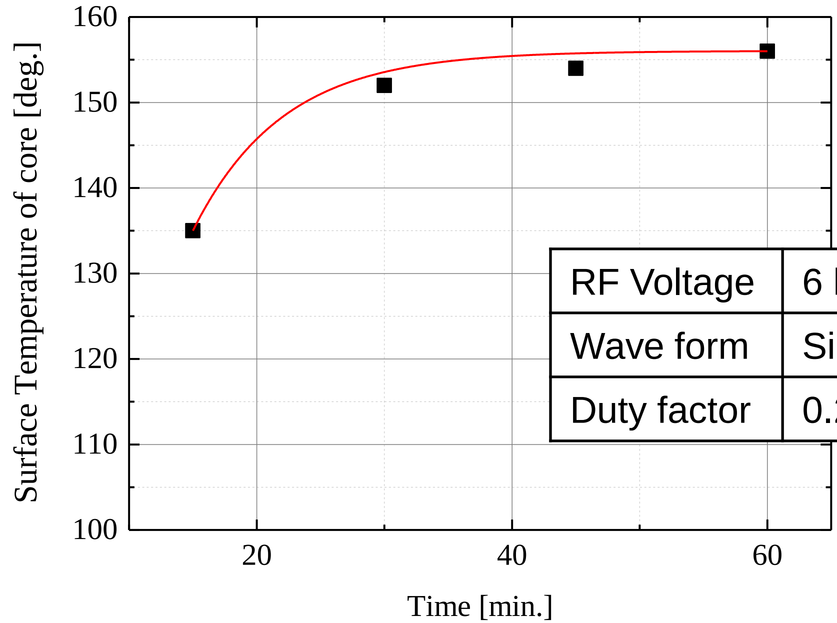


$$V(t) = h(f)\sin(\int f(t)dt)$$

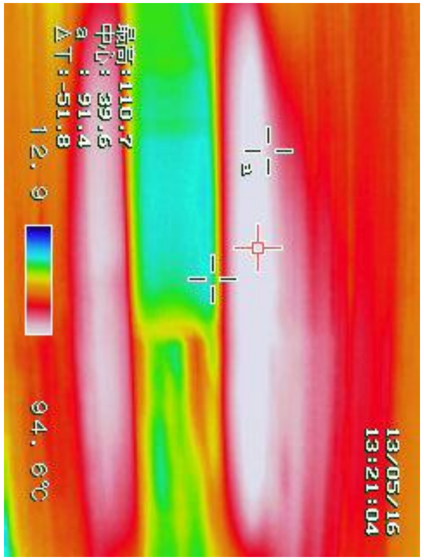
the variation of the RF voltage has been reduced.

High power test





RF Voltage	6 kV
Wave form	Sin wave
Duty factor	0.2



$$\Delta T = \frac{q}{A}\left(\frac{\Delta x_1}{k_1} + \frac{\Delta x_2}{k_2}\right)$$

Coefficient of thermal conductivity of core

~~20 W/m K~~ ➔ 5 W/m K

Cooling Capability

$$P = \frac{V^2}{2R} \times duty = \frac{6000^2}{2 \times 180} \times 0.2 = 20\ kW$$

Requirements for 100Hz operation ⇒ 25 kW

➔ An additional cooling system is required

Summary of Development of RF acceleration system

Requirements

RF voltage	3 kV / 1 cavity
Frequency range	1.5 – 4.2 MHz
Magnetic shielding	< 150 Gauss
Cooling Capability	25 kW

Achieved !

> 20 kW (insufficient)

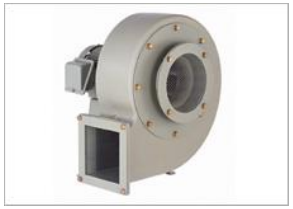
An additional forced-air cooling system (5 kW) is required.

Q: required amount of air

$$Q = \frac{P}{\gamma C \Delta T} = \frac{5kW}{1150\times(60-25)} = 7.5\ m^3/\text{min}$$

γ:specific gravity of air
C: specific heat of air
ΔT: specific heat of air
P: heat generation

=



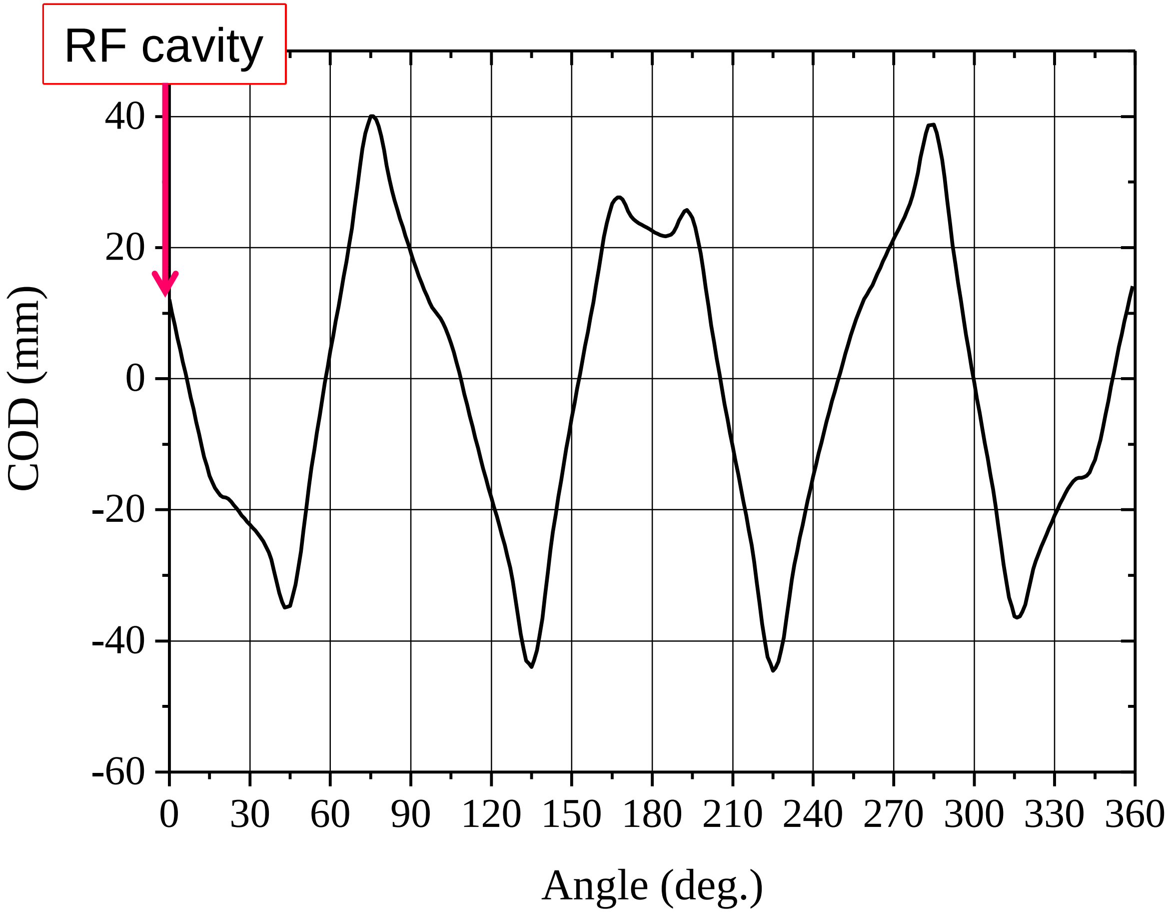
tow air blowers

The Preparation of the forced-air cooling system has been completed.
High Power test of the cooling system will be started.

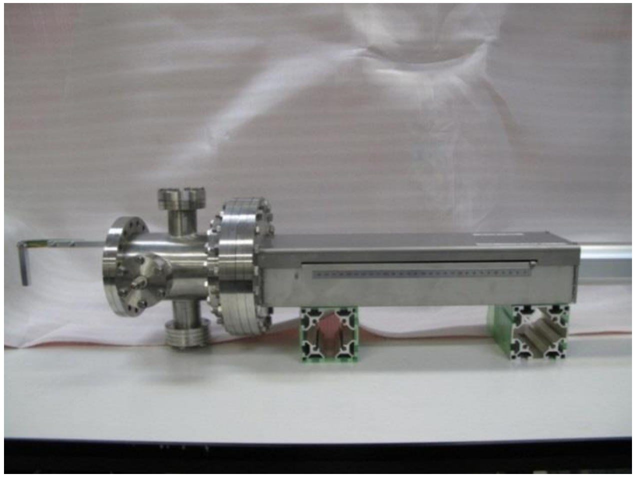
Contents

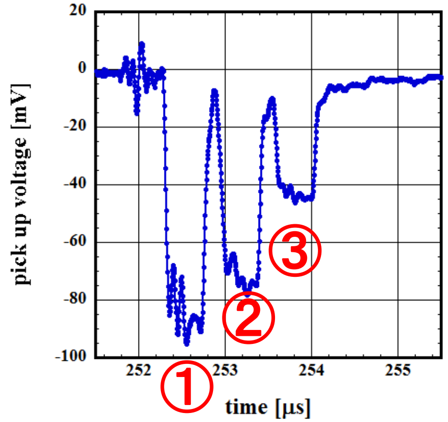
COD measurement

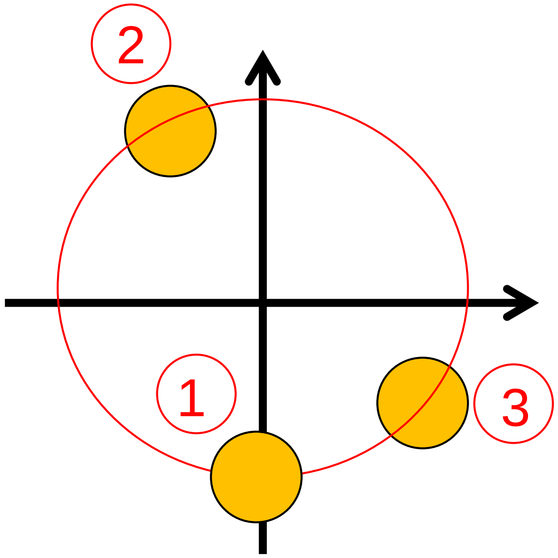
Because of the strong fringing filed at straight sections,
the RF cavity is large source of COD.

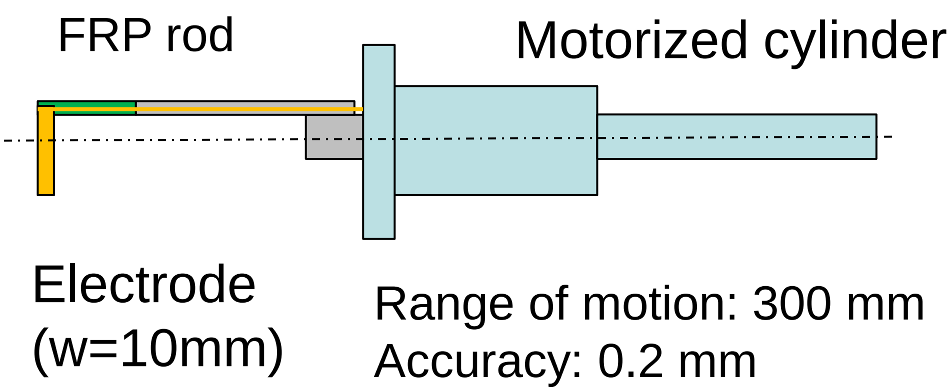


Beam profile monitor

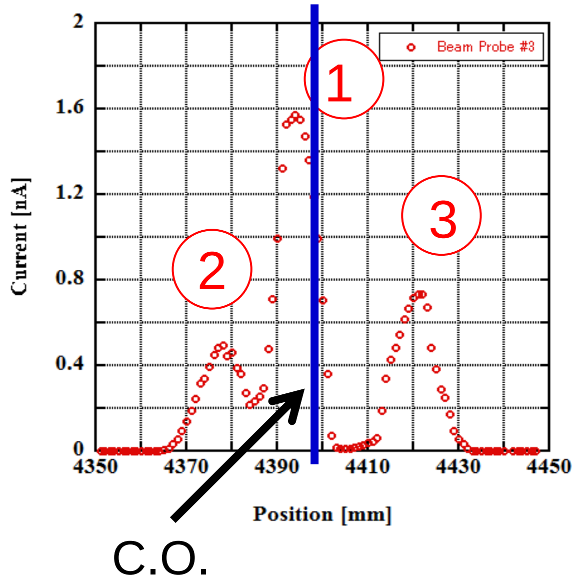






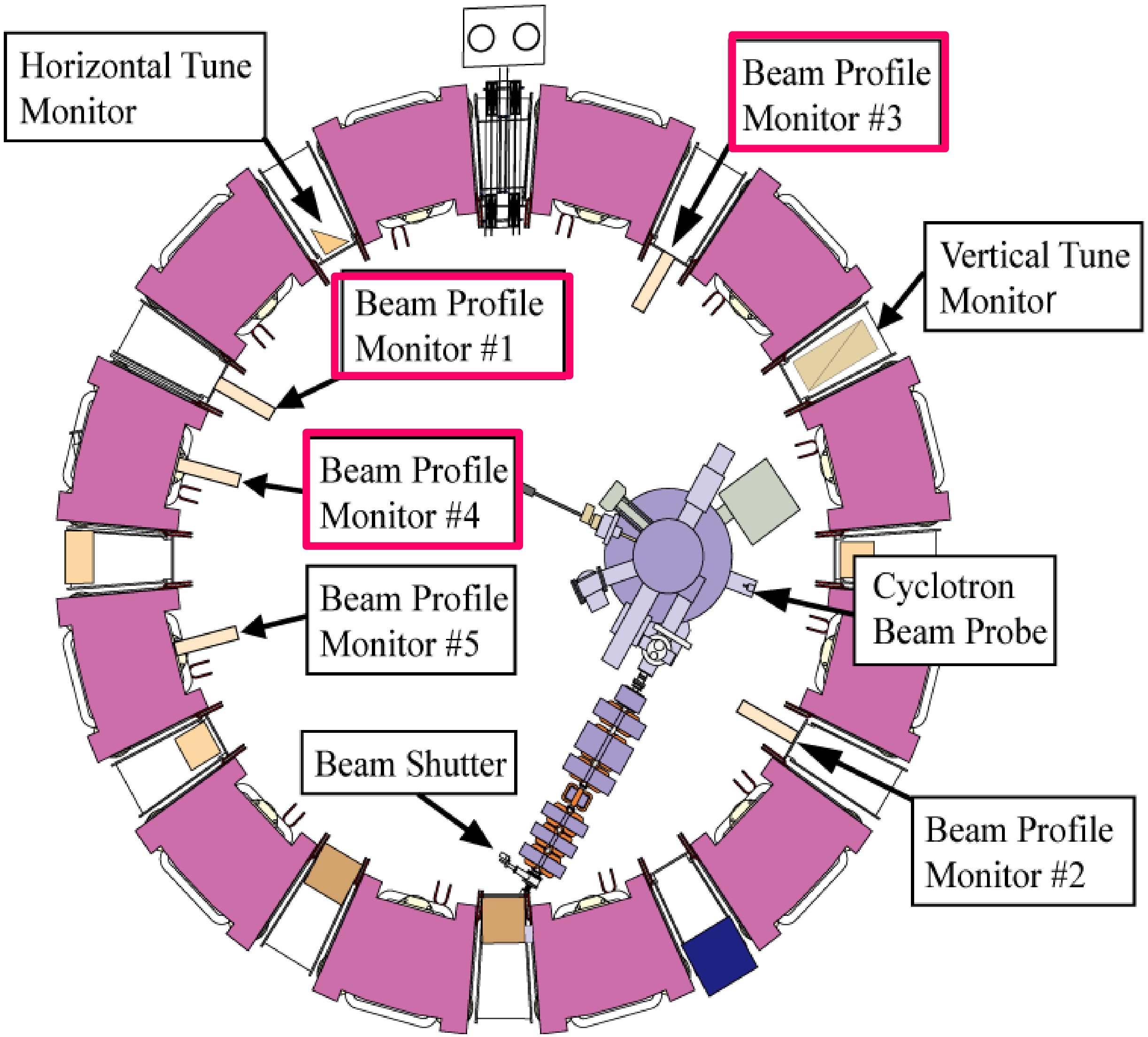


Range of motion: 300 mm
Accuracy: 0.2 mm
Control system: PLC + LabView

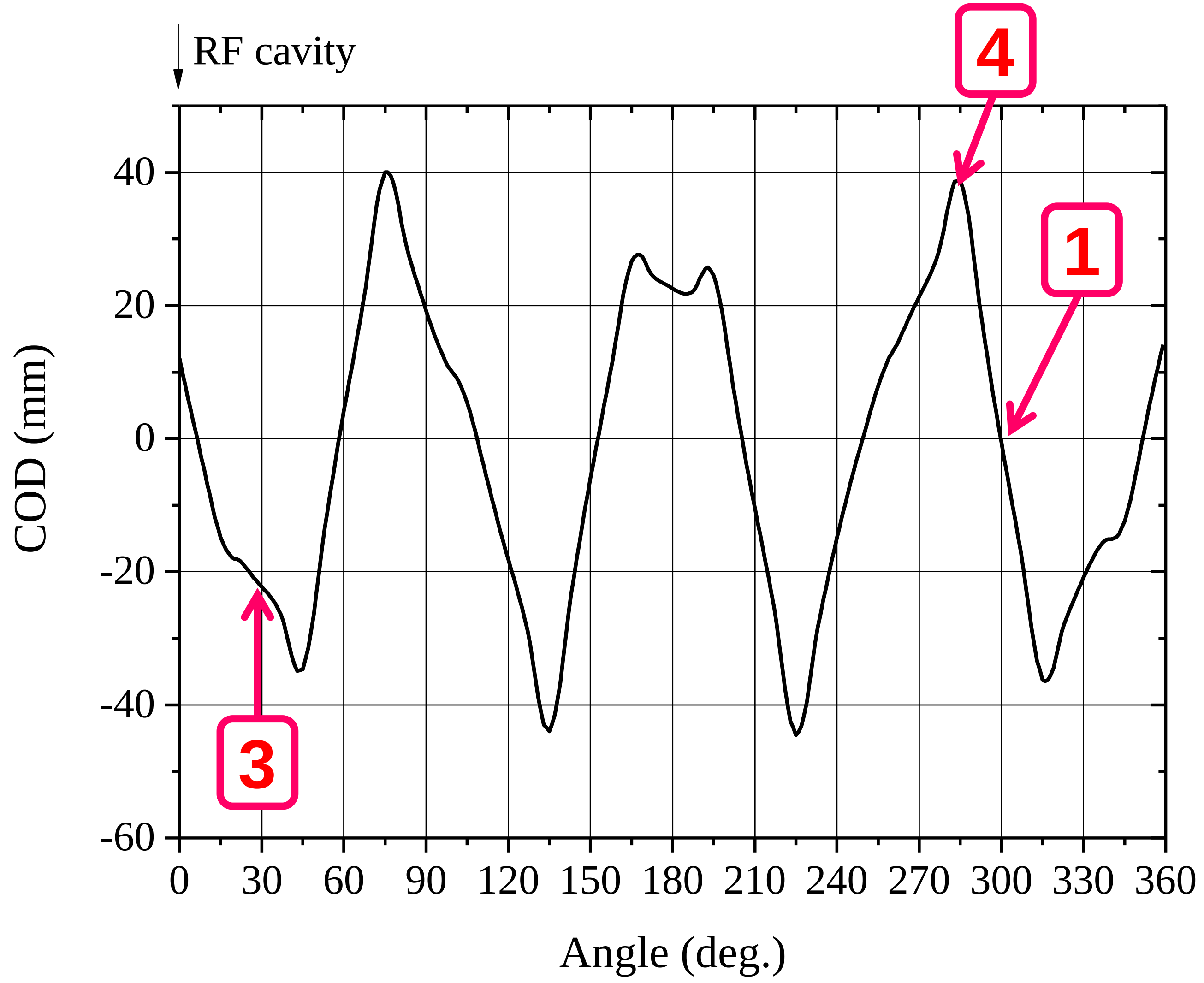


A position of closed orbit was obtained by analyzing beam profiles.

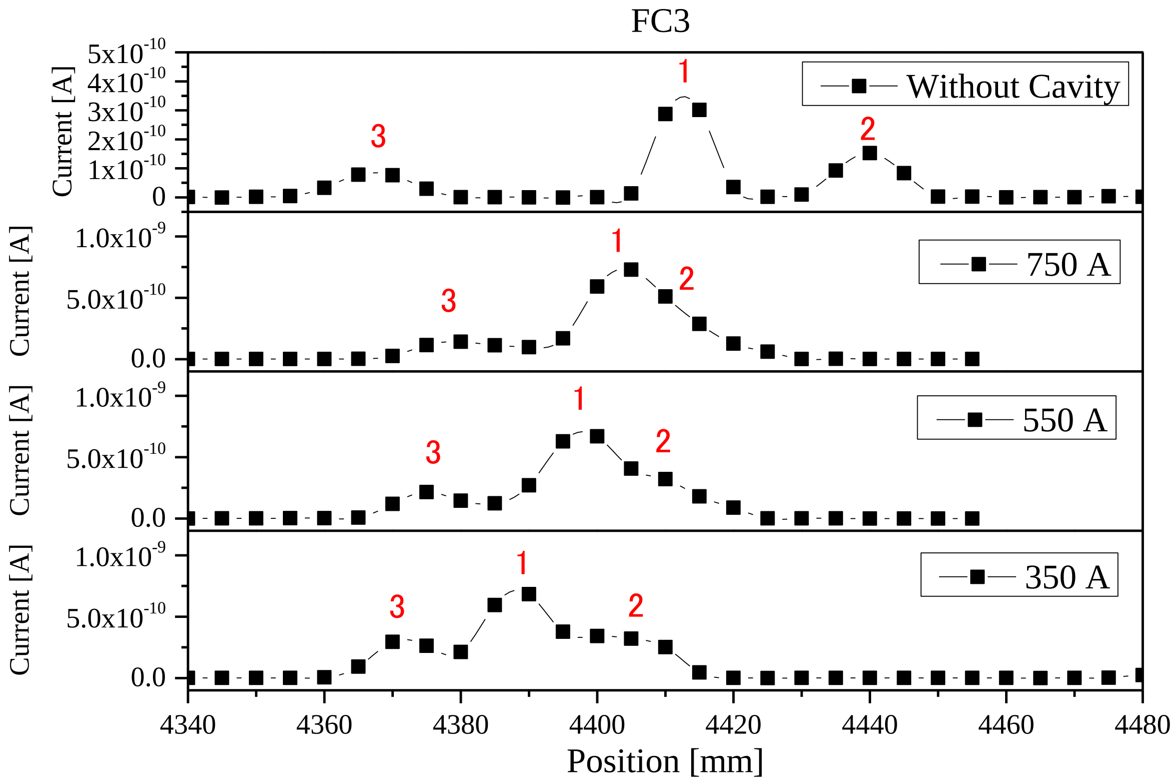
Layout of beam monitors

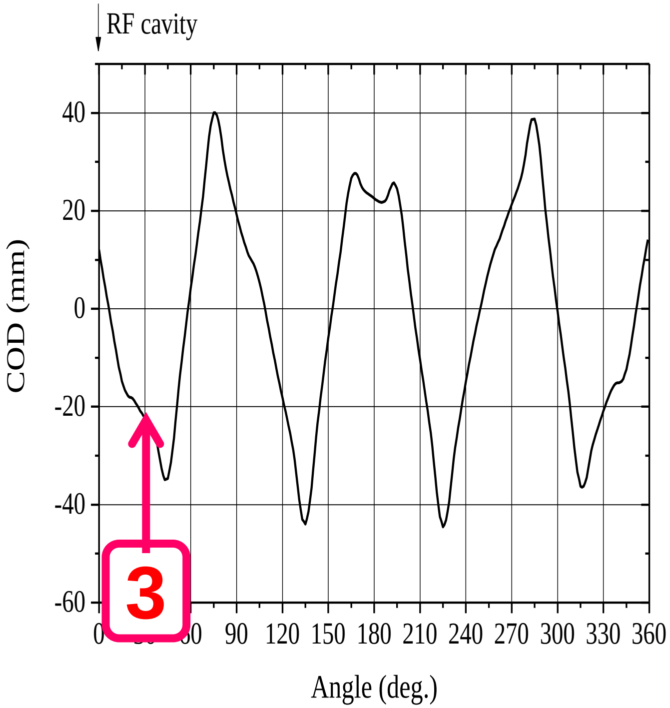


Position of beam profile monitors



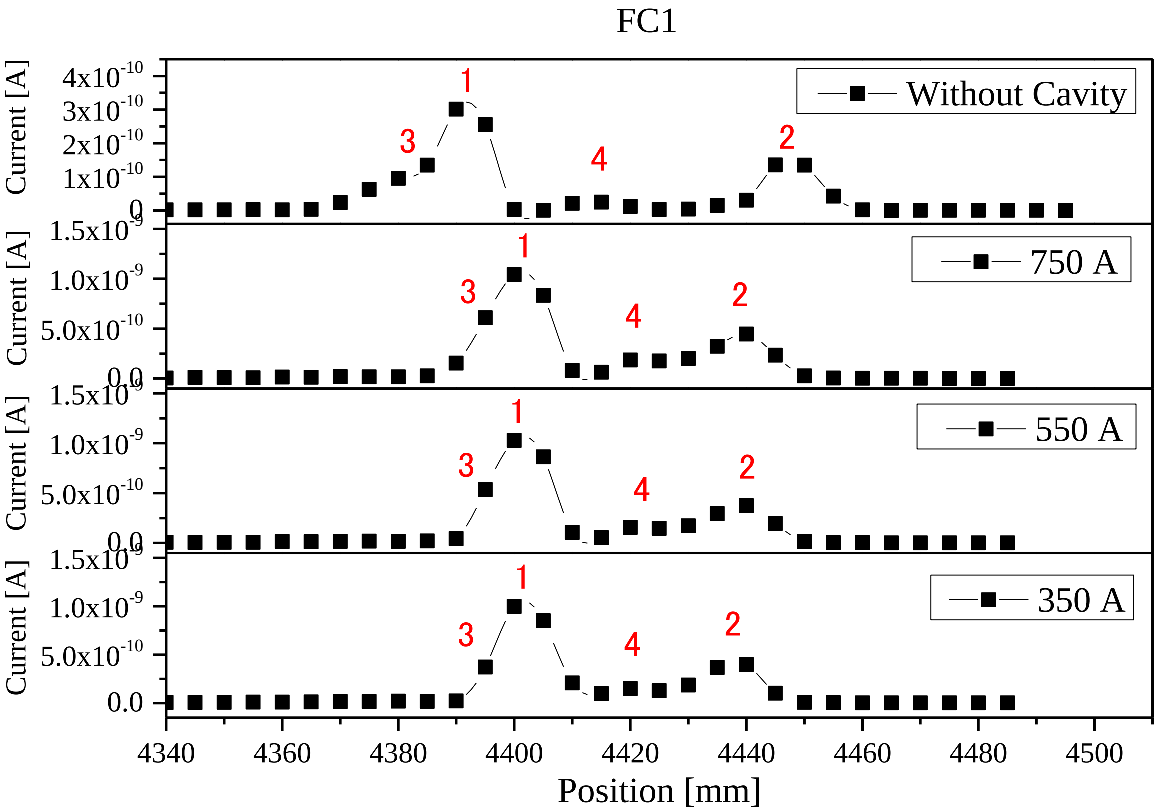
COD Measurement (1)

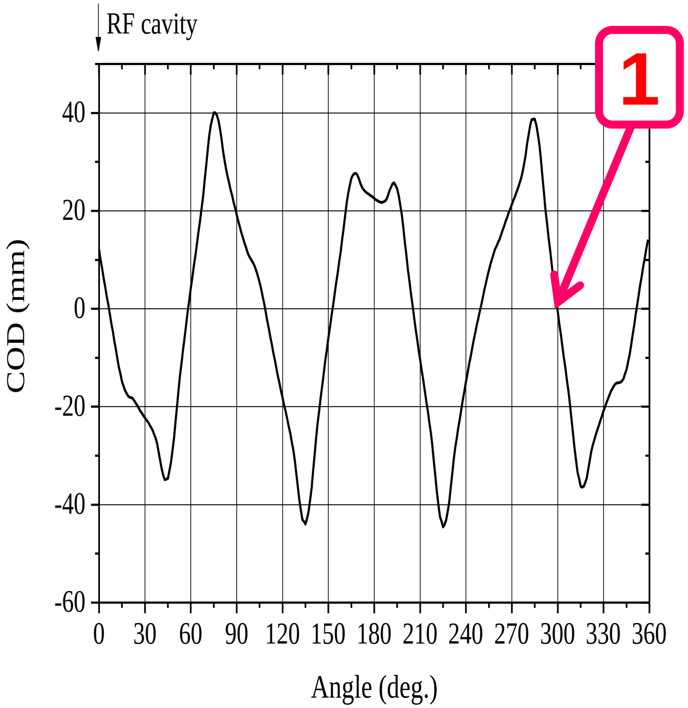




Center of beam profile shifted to inner side.

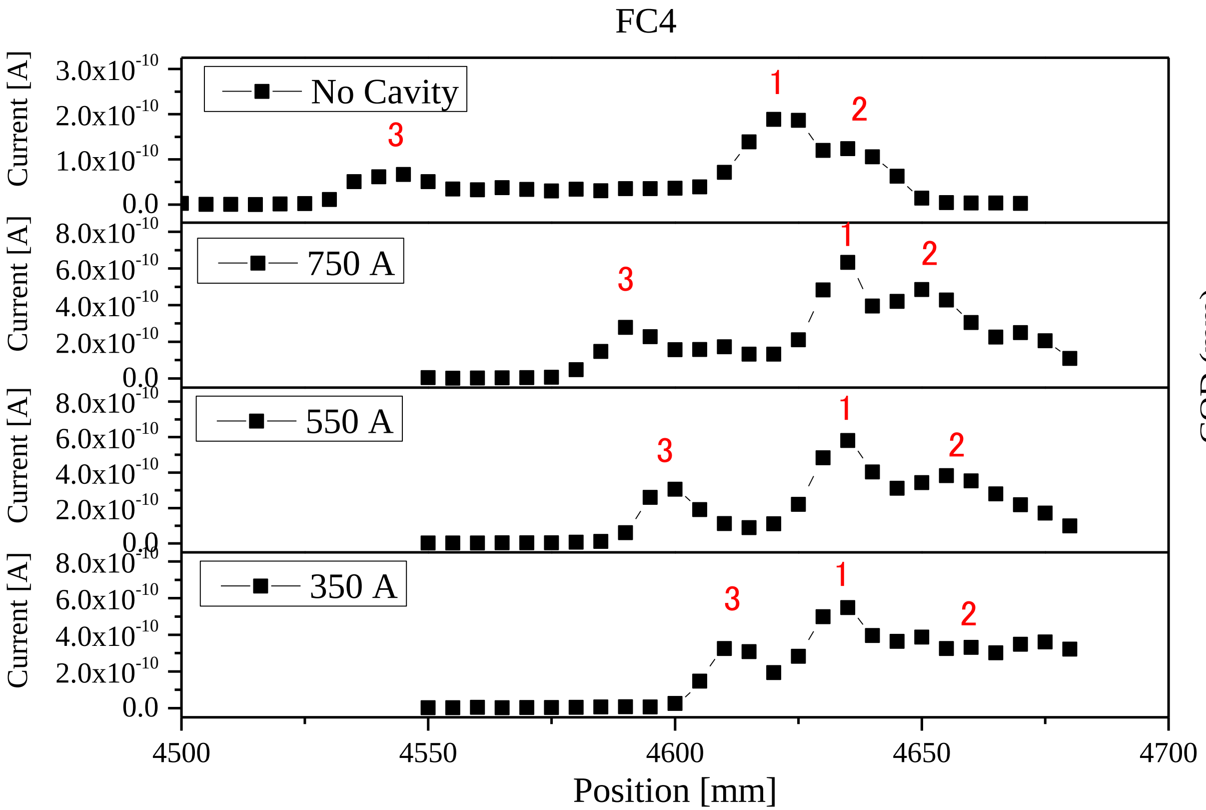
COD Measurement (2)

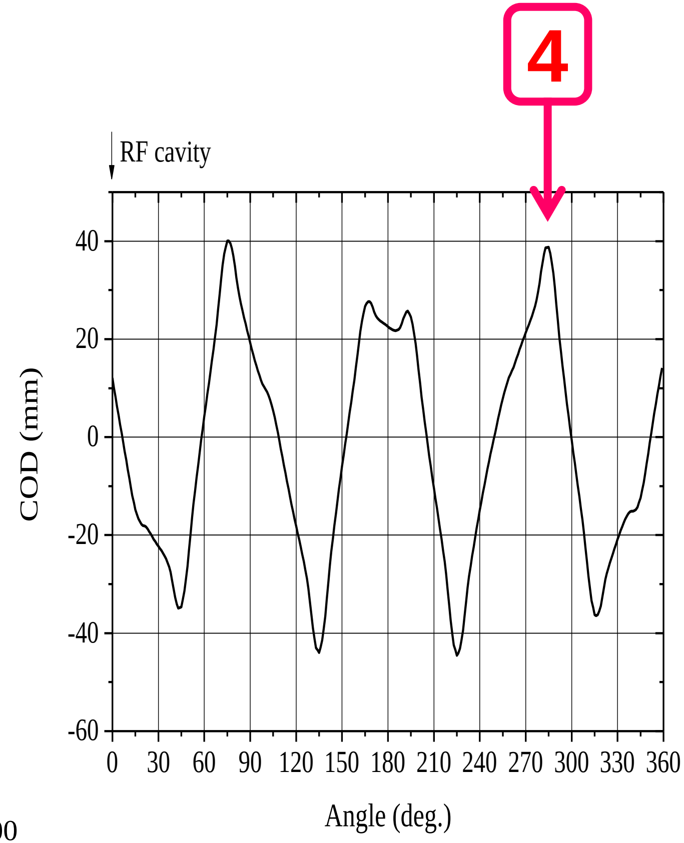




Positions of the beam profile are constant.
Closed orbit = 4.42 m

COD Measurements (3)



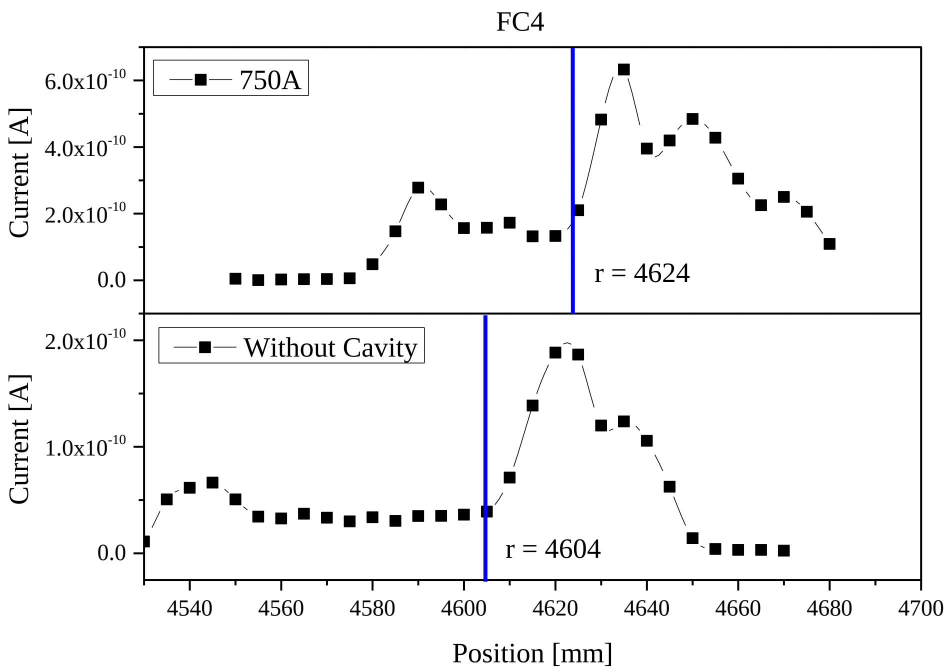


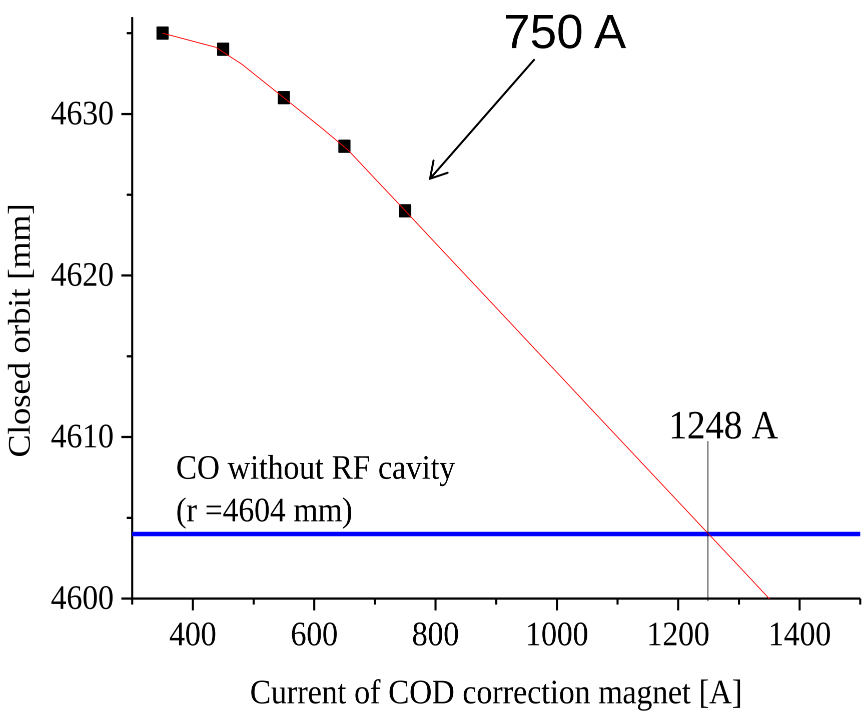
Displacements of COD is maximum

Beam profiles are employed to estimate to strength of COD correction magnets

COD measurement (4)

To estimate the strength of COD correction magnets,

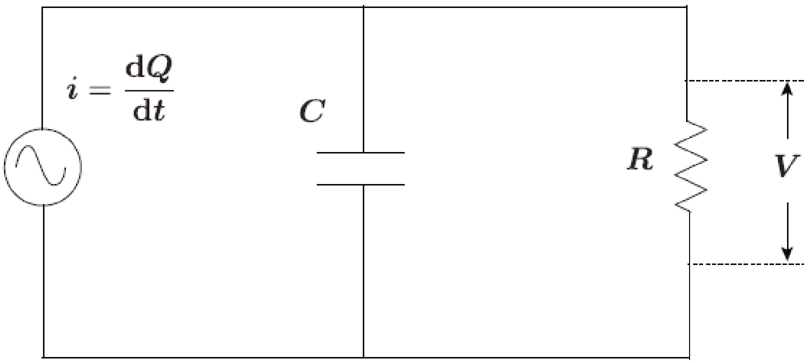




COD ~ 20 mm

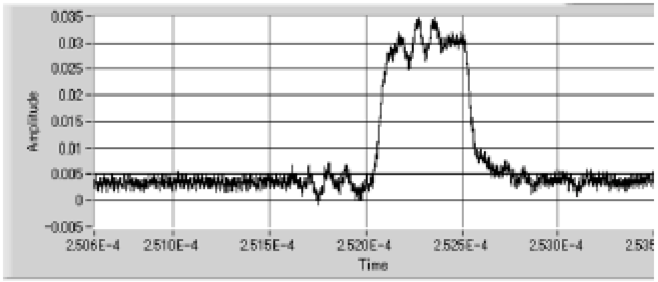
1248 A of current is required to compensate COD

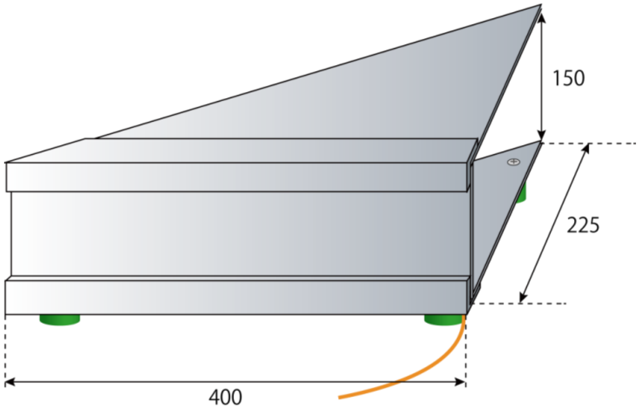
2-5. Tune monitor



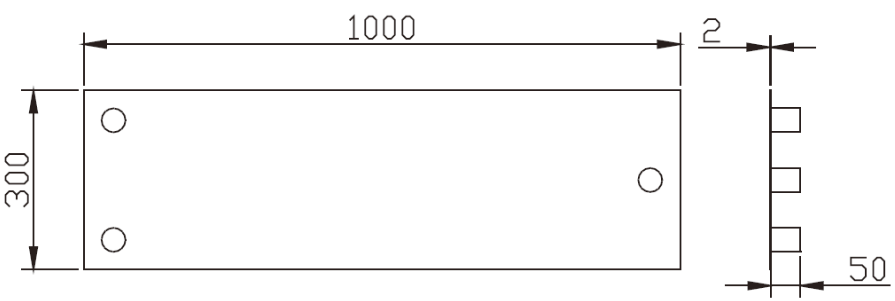
Equivalent circuit

Capacitive pickup monitor
R: Resistance 1 MΩ
C: 540 pF (horizontal monitor)
125 pF (Vertical monitor)





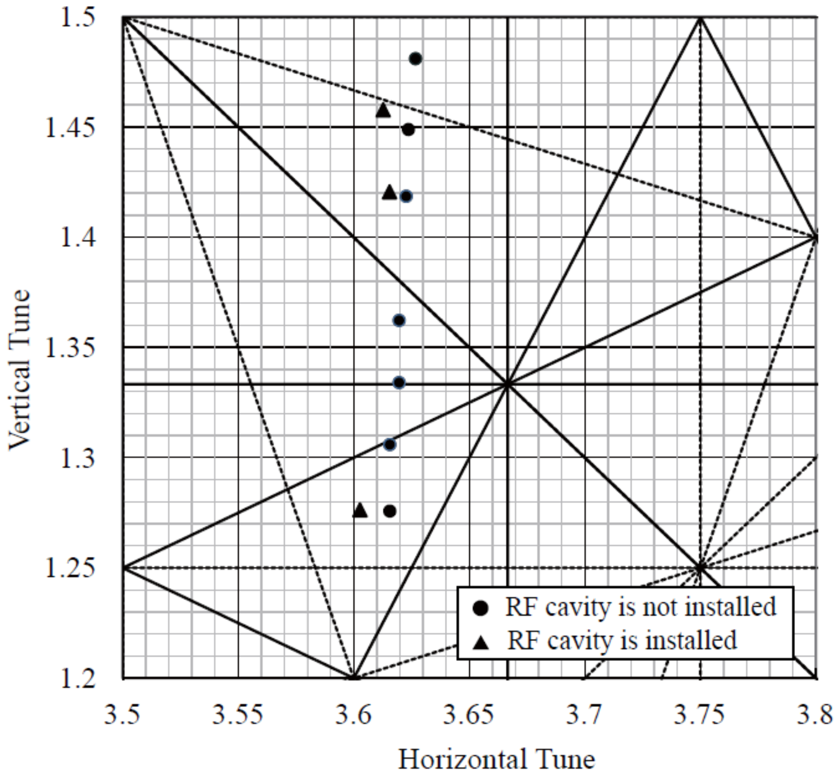
Horizontal tune monitor



Vertical tune monitor

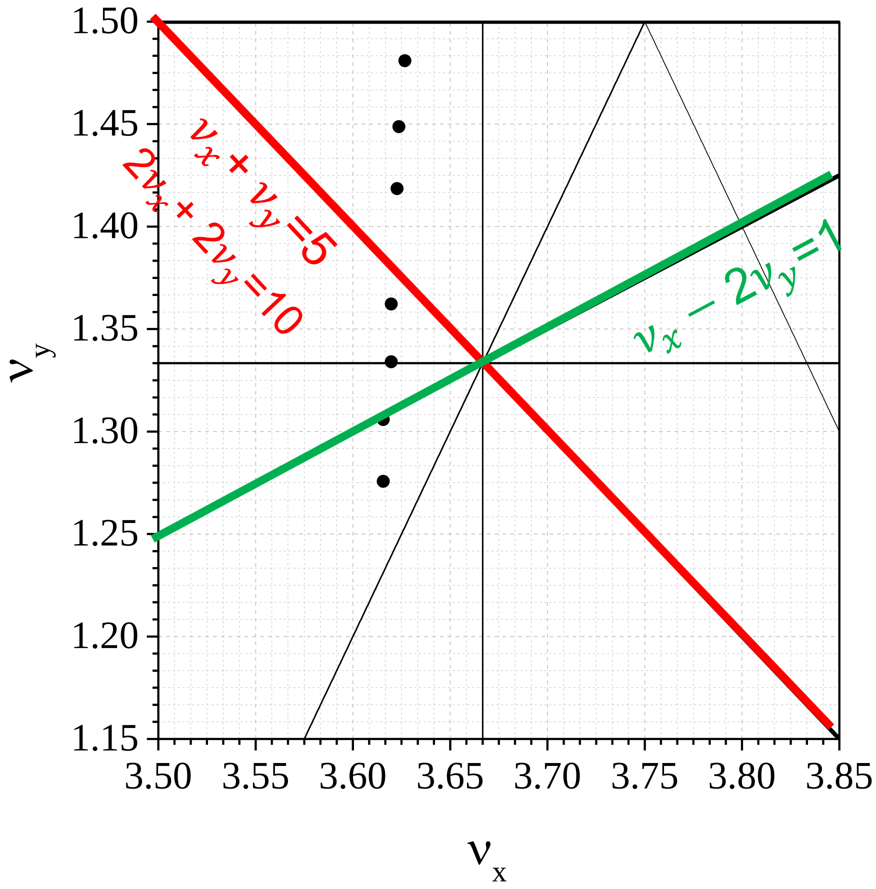
Tune measurement (1)

Tune shift caused by COD of the RF cavity

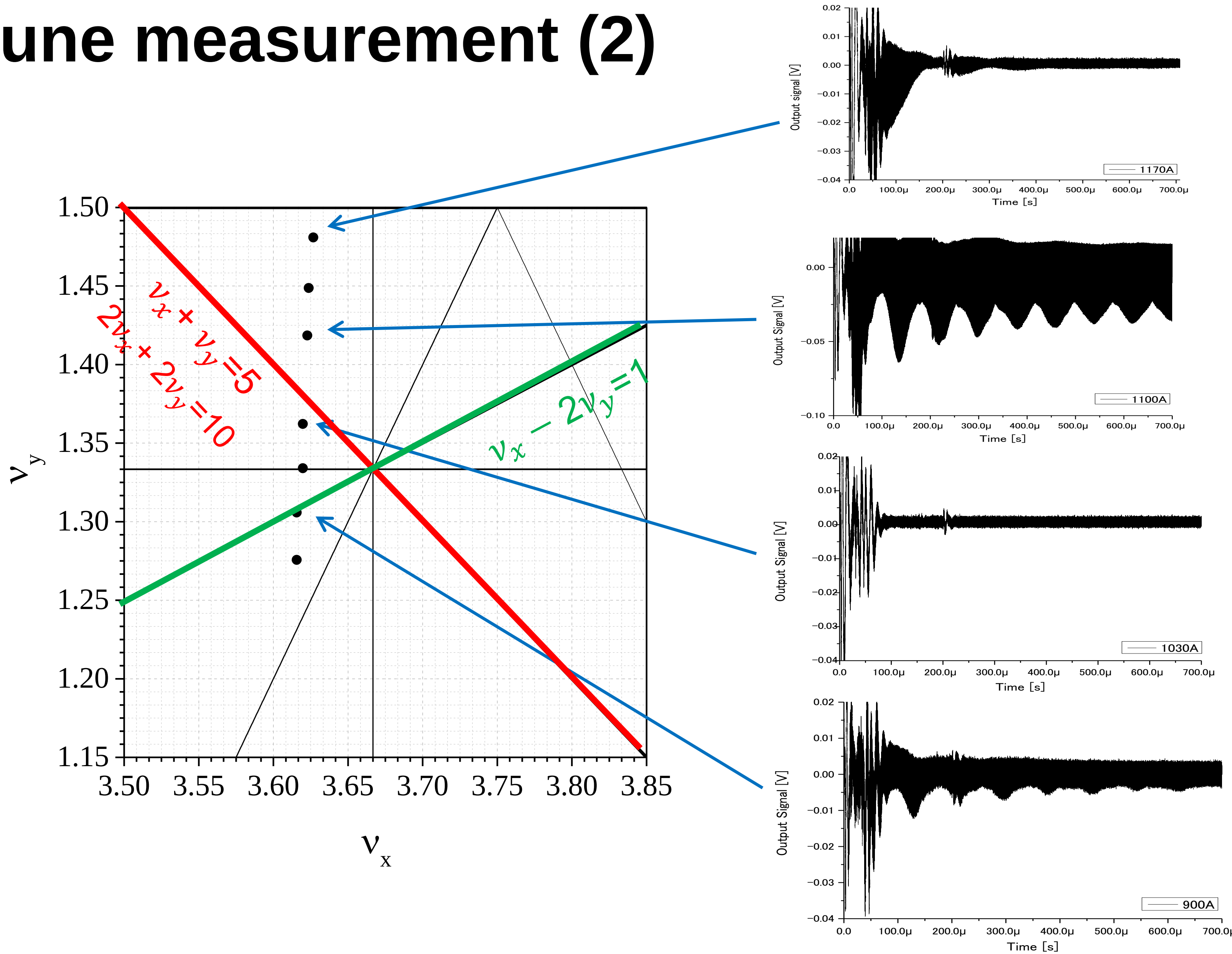


Horizontal tune has varied from 3.61 to 3.62

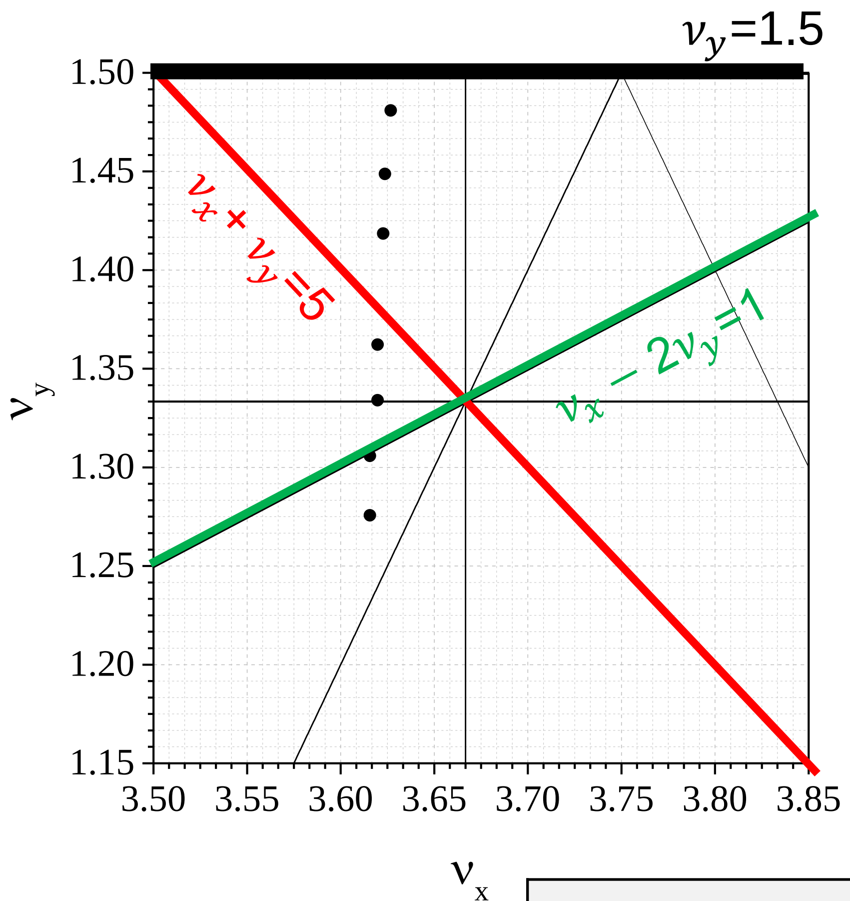
Tune measurement (2)

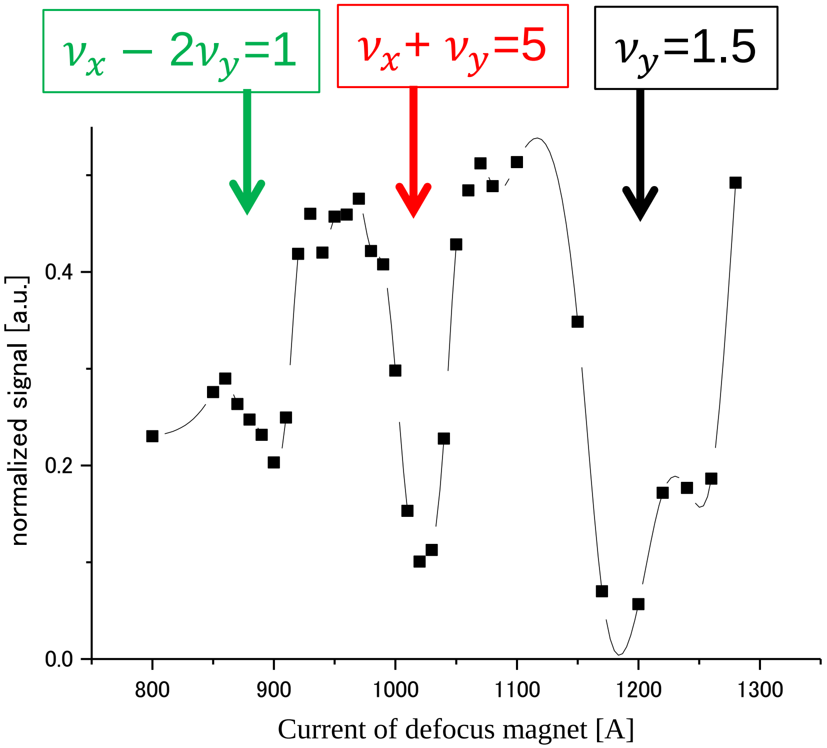


Tune measurement (2)



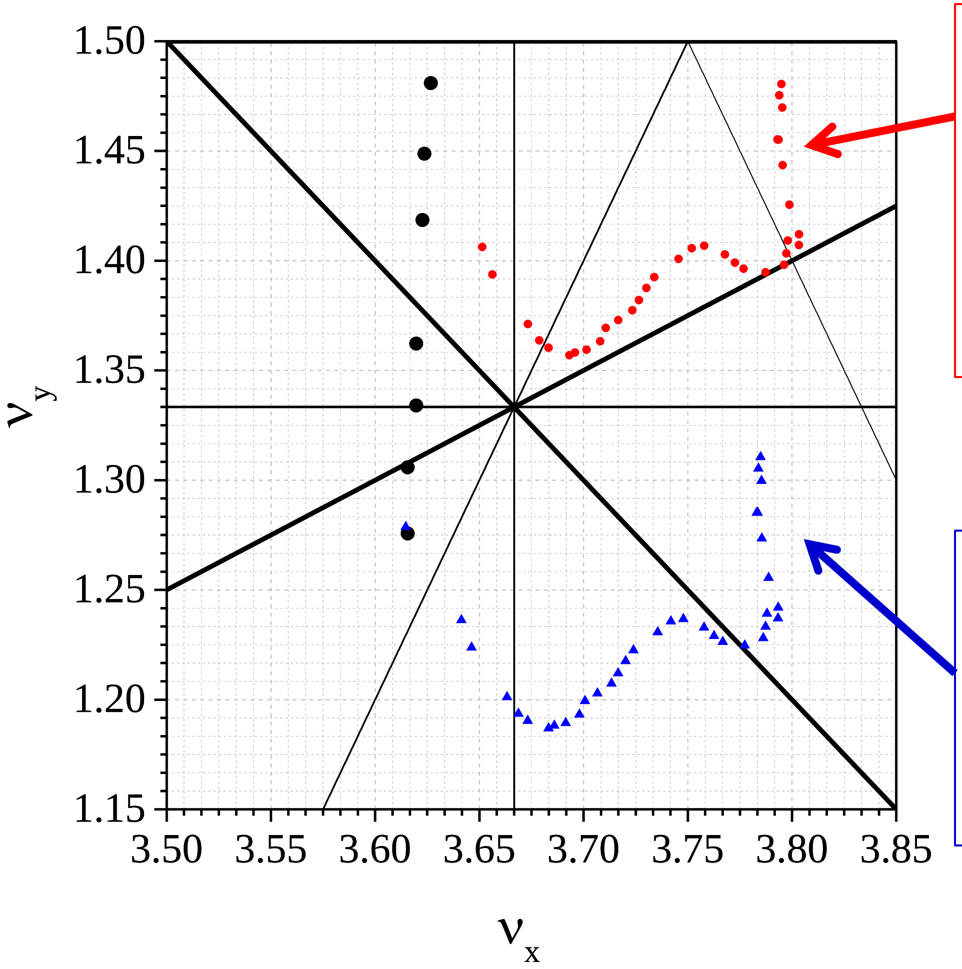
Tune measurement (3)





Resonance line	Strength
$\nu_y = 1.5$	Very Strong
$\nu_x + \nu_y = 5$ $(2\nu_x + 2\nu_y = 10)$	Strong
$\nu_x - 2\nu_y = 1$	Weak ?

Working point



Working point (1)

Advantage:
No resonance crossing

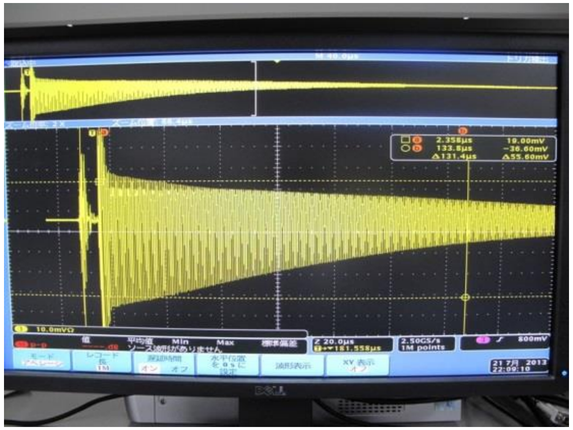
Disadvantage:
Narrow working area
between ν_y=1.5 and $\nu_x - 2\nu_y$=1

Working point (2)

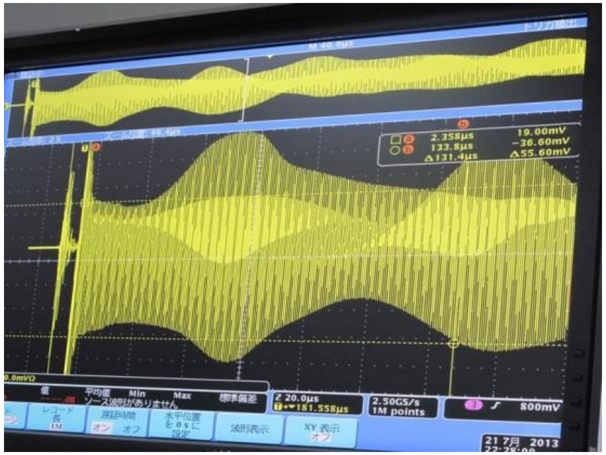
Advantage:
wide working area

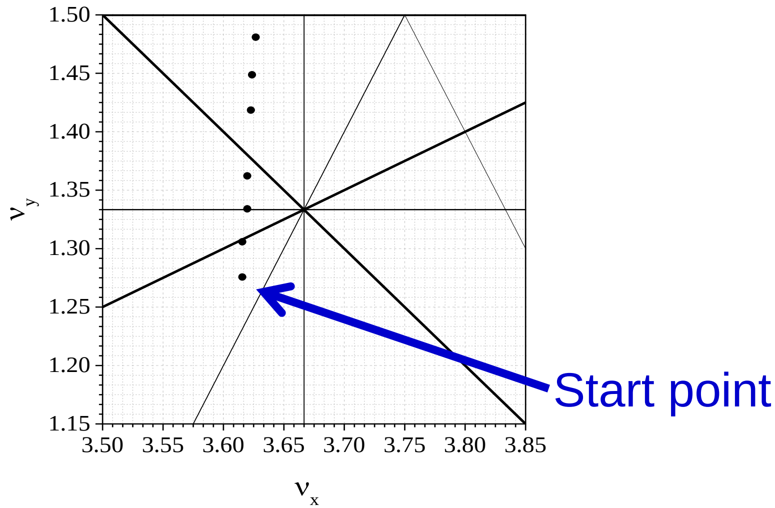
Disadvantage:
Resonance crossing of $\nu_x + \nu_y = 5$

Beam Acceleration



RF ON





22nd July 2013

The beam acceleration was successfully demonstrated. (~80MeV)

Summary

The beam commissioning of
the 150 MeV FFAG has gone smoothly.

Developed RF system satisfied almost all requirements.
The test of the air-forced cooling system will be started.

We are now in preparation for the beam acceleration up to the final energy and the beam extraction.