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Upgrade of the RCNP AVF Cyclotron

Upgrade

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1. Introduction

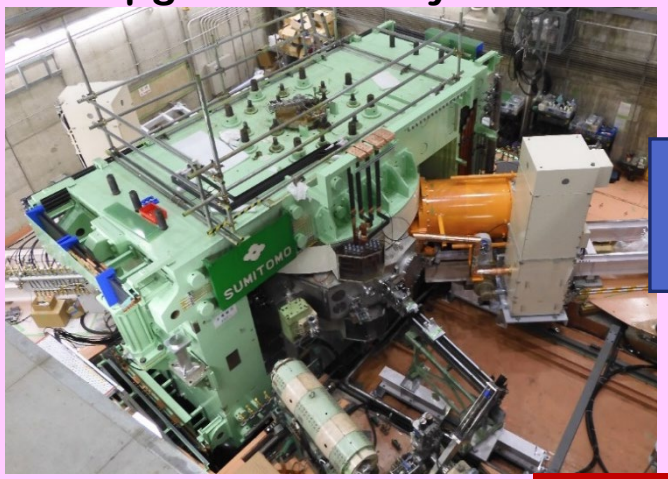
History of RCNP

1971	Foundation of RCNP
1973	Completion of the AVF cyclotron (K=140MeV) construction
1976	Start of experiments
1987	Start of the ring cyclotron (K=400MeV) construction
1991	Completion of the ring cyclotron
2005	Partial upgrade of the AVF cyclotron and beam lines
2014	Partial upgrade of the AVF and ring cyclotrons, beam lines
2019	Renovation and reinforcement of the accelerator facility
2020	Upgrade of the AVF cyclotron
2021	Adjustment of the AVF cyclotron
2022	Beam commissioning and start of beam supply
2023	Full operation for experiments

RCNP Cyclotron Facility

*Aim of the Upgrade Program

Upgraded AVF cyclotron

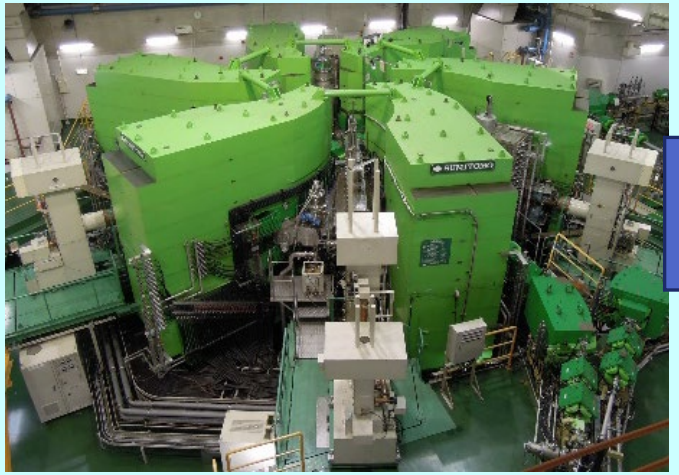


Stand alone mode

Injector mode

High-intensity
High-quality

Ring cyclotron



1. Production of RIs — Several tens to 100 μA
   - Increase of proton and deuteron beam intensity
     → Short-lived RI supply platform
   - Increase of helium beam intensity
     → Targeted alpha-particle therapy
     (Trial treatment started in March 2022)

2. Production of secondary particle beam — > 10 μA
   - Increase of 400 MeV proton beam intensity
     → Muons produced by MuSIC
     → White neutrons for soft-error-rate testing
     → Mono-energetic neutrons

3. High quality beam — $\Delta E/E \sim 10^{-4}$
   - Increase of high-quality light ion beam intensity
     → Hyper-quality, halo-free beam
     → highly-polarized beam

4. Unstable heavy ion beam
   - Increase of heavy ion beam intensity
     → Unstable nuclear beam
     → CAGRA + Grand-RAIDEN

2. Dismantling of the former AVF cyclotron

* Former K140 AVF Cyclotron

1973 Completed

1991 Mainly used as an injector of the ring cyclotron

- Energy of ions with M/Q≦5

proton	≦ 80 MeV
D^+, $^4He^{2+}$	≦ 35 MeV/n
$^3He^{2+}$	≦ 180 MeV
Heavy Ion	≦ $140 \times (Q/A)^2$

Magnet

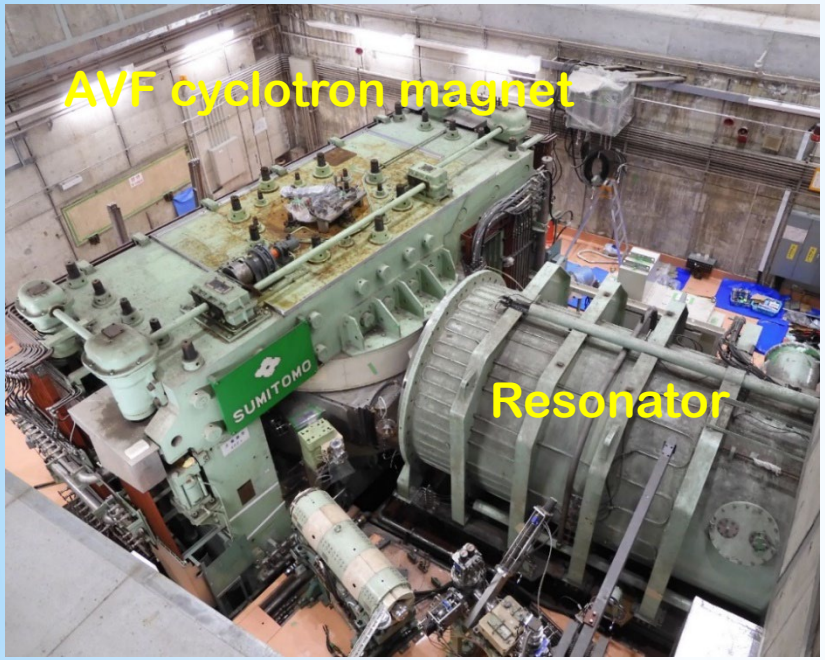
- Pole diameter : 3300 mm
- Pole gap : 206 ~ 347 mm
- Averaged field : 1.6 T
- Extraction radius : 1000 mm
- Trim coils : 16 pairs
- Valley coils : 2 sets
- Weight : 400 tons

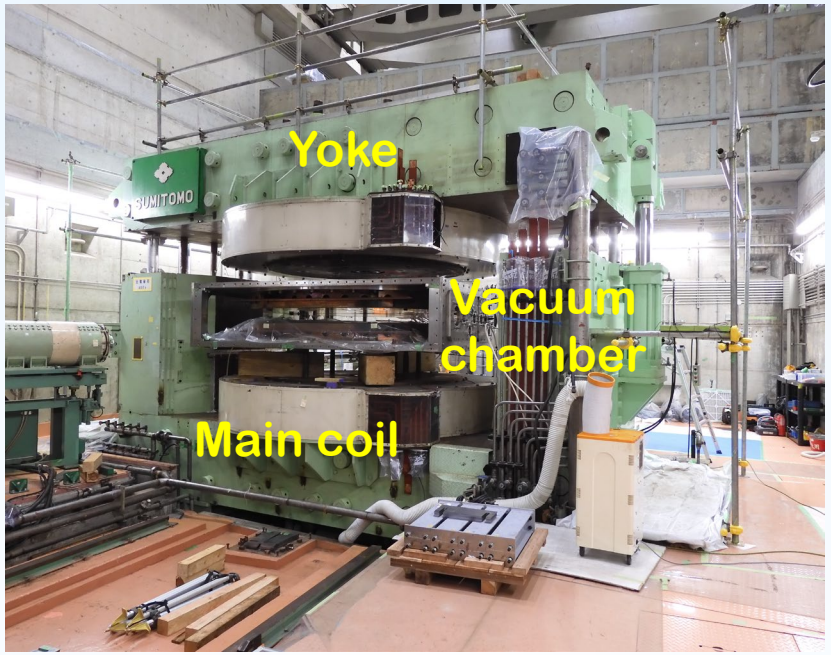
Acceleration system

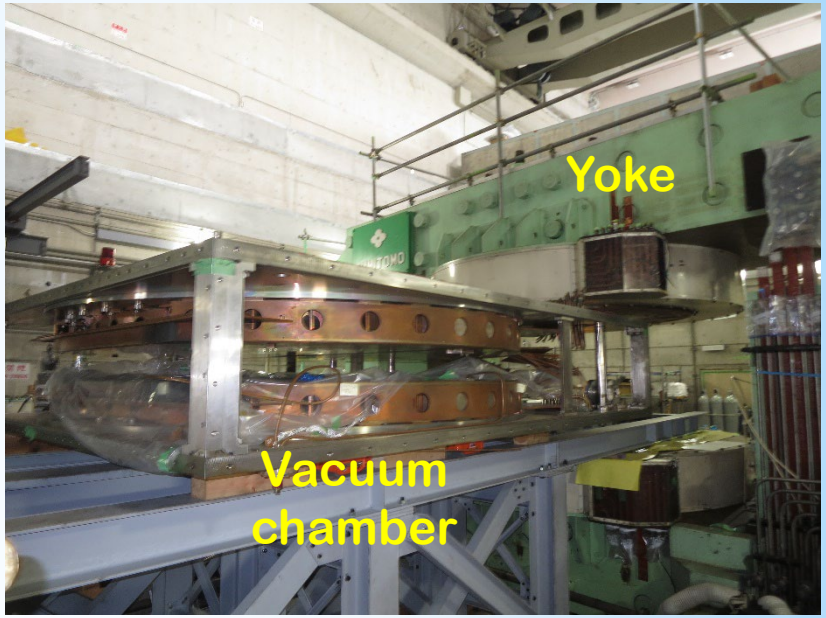
replaced

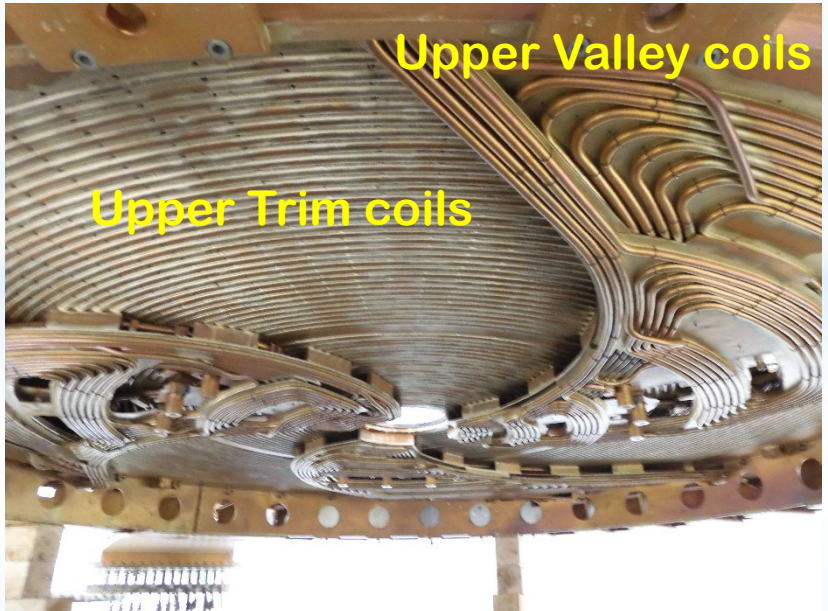
- Dee : Single electrode with 180 degree spanning angle
- Resonator : Coaxial type with a movable short
- Frequency : 6 ~ 19 MHz
- Max. Dee voltage : 60 kV
- Acceleration harmonics : 1, 3
- Injection : Inflector of spiral type
- Extraction system : Deflector, Gradient corrector

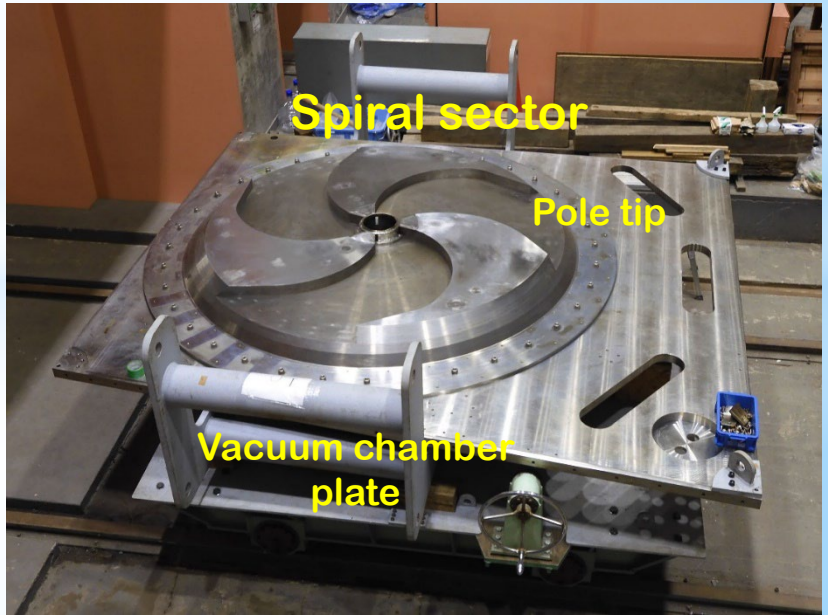
Dismantling of the vacuum chamber



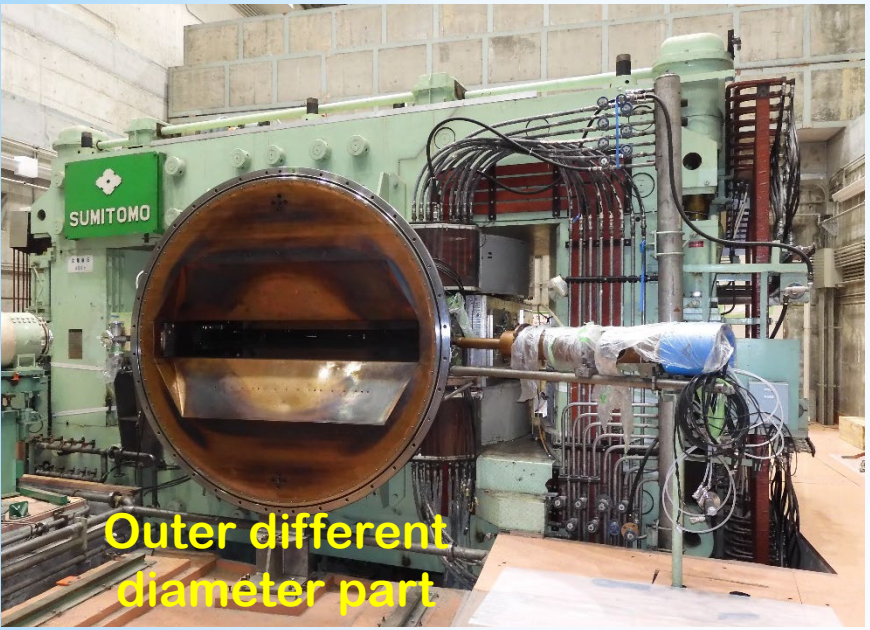


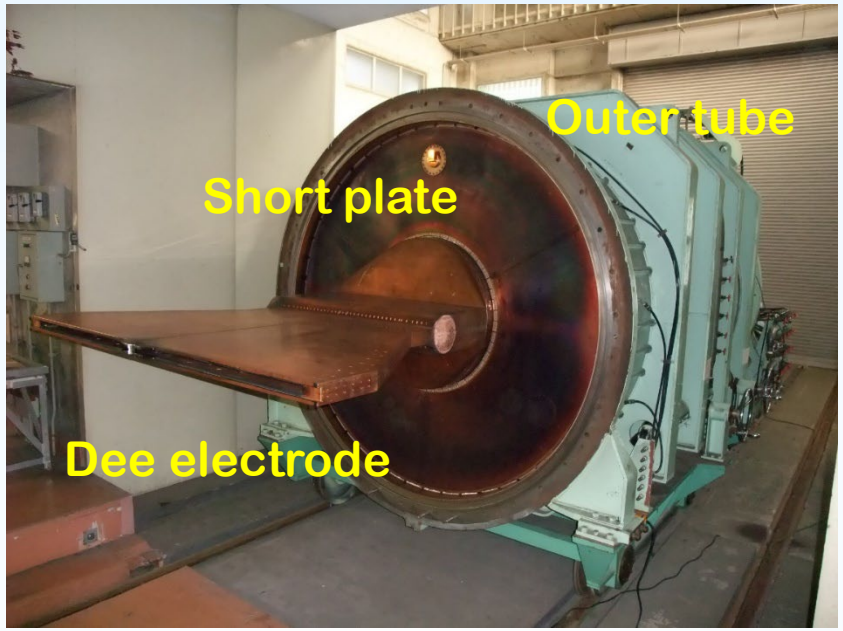






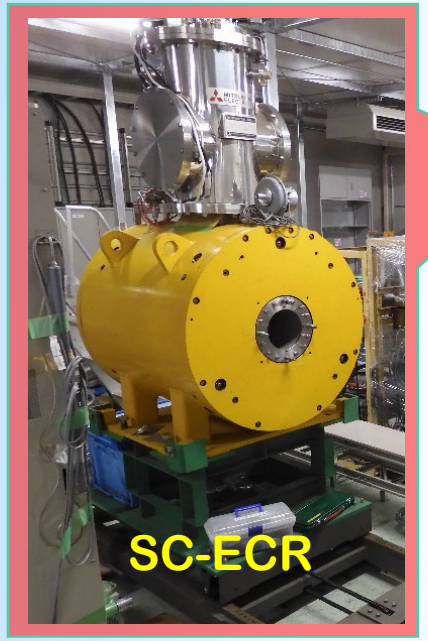
Dismantling of the resonator



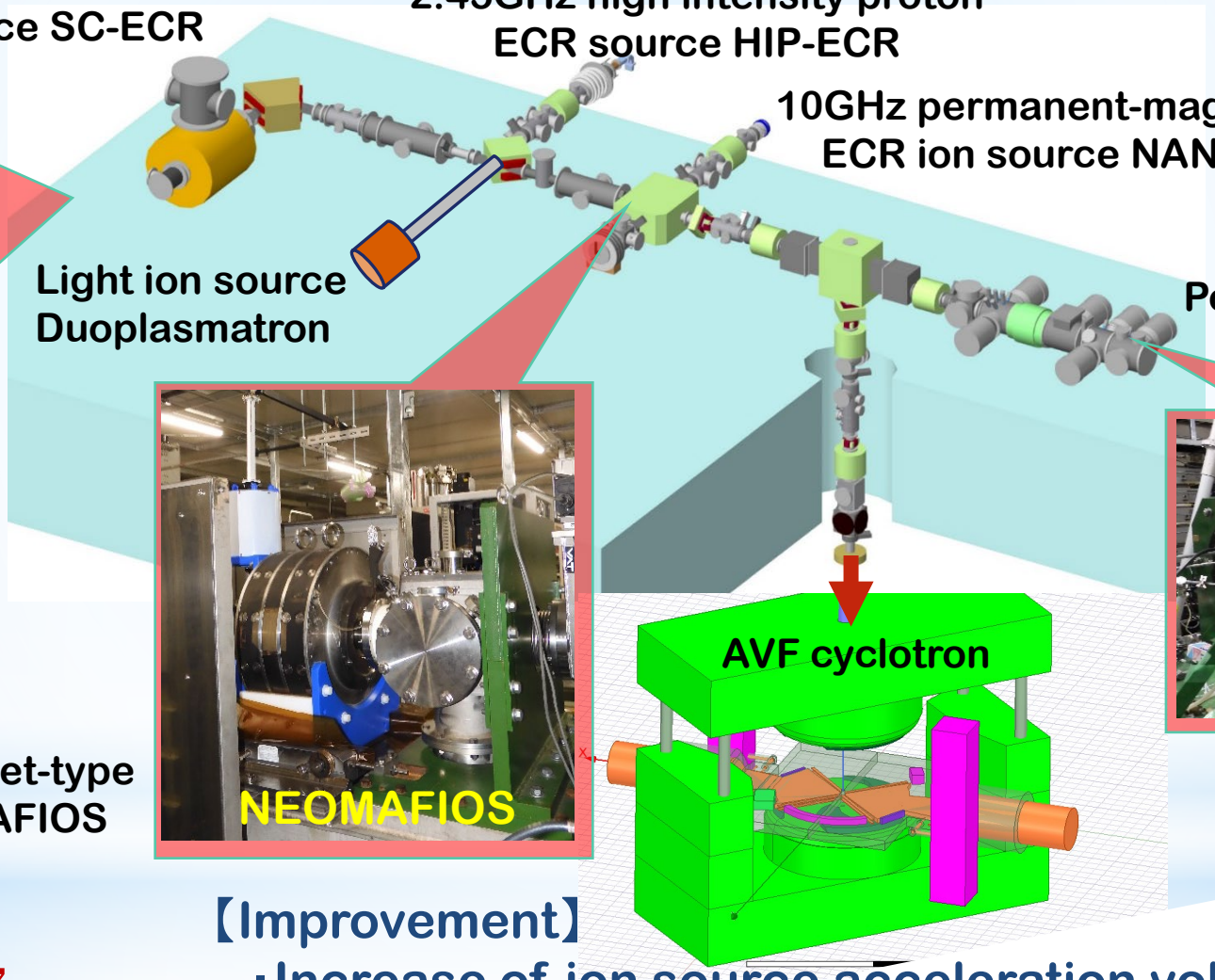


3. Upgrade of the AVF cyclotron

Upgrade of ion sources and LEBT system



18GHz superconducting
ECR ion source SC-ECR



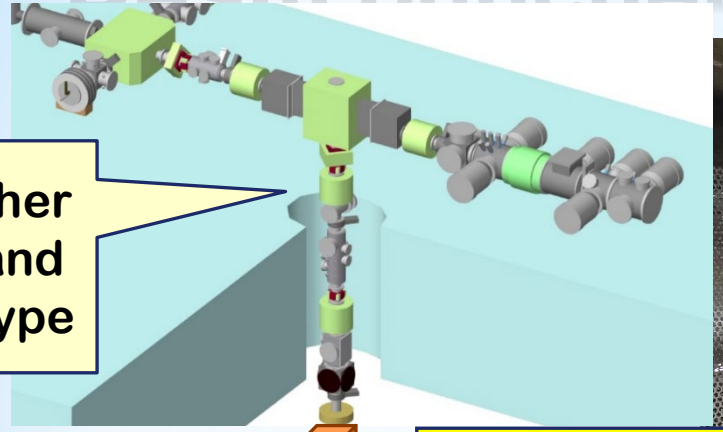
10GHz permanent-magnet-type
ECR ion source NEOMAFIOS

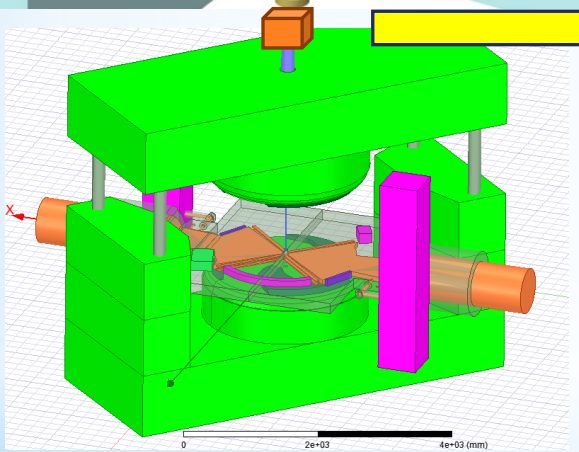
【Goal】
"High brightness"
- Increase of intensity
- low emittance

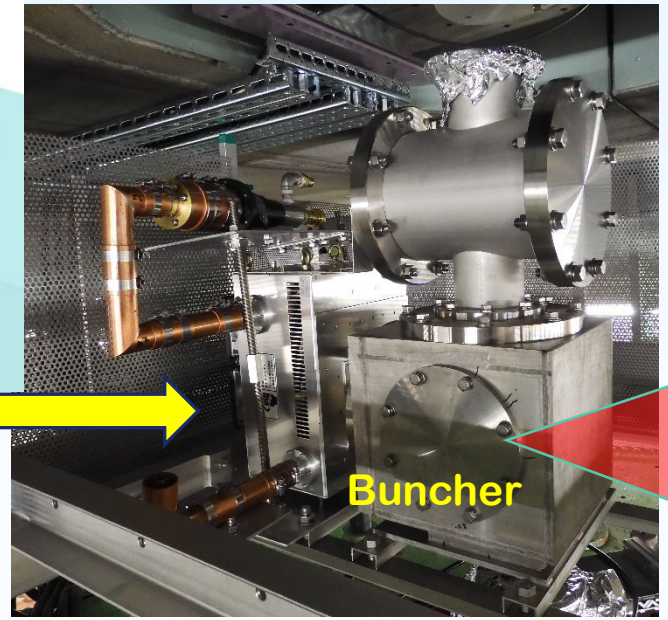
【Improvement】
- Increase of ion source acceleration voltage → ～50kV
- Increase of beam current → > several hundreds mA
- Redesign of LEBT optics → increase of injection efficiency
- Elevation of upper yoke → improvement of maintenance

Beam buncher in the axial injection line

Beam buncher of charge and discharge type







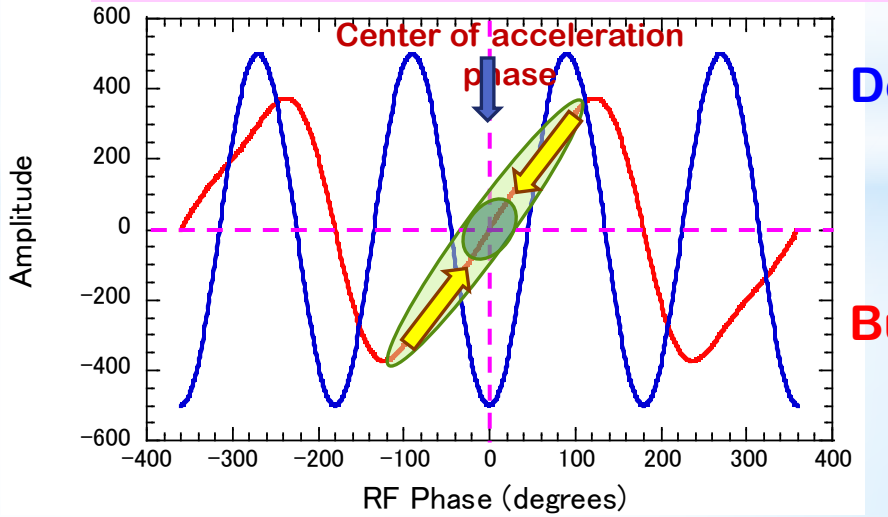
f_{RF} Double of particle frequency

$f_{Buncher}$ Same as particle frequency

↓

Same injection and acceleration conditions for ring cyclotron as before

Sub-harmonic bunching mode



Dee voltage

$$f_{Buncher} = \frac{1}{2} f_{RF}$$

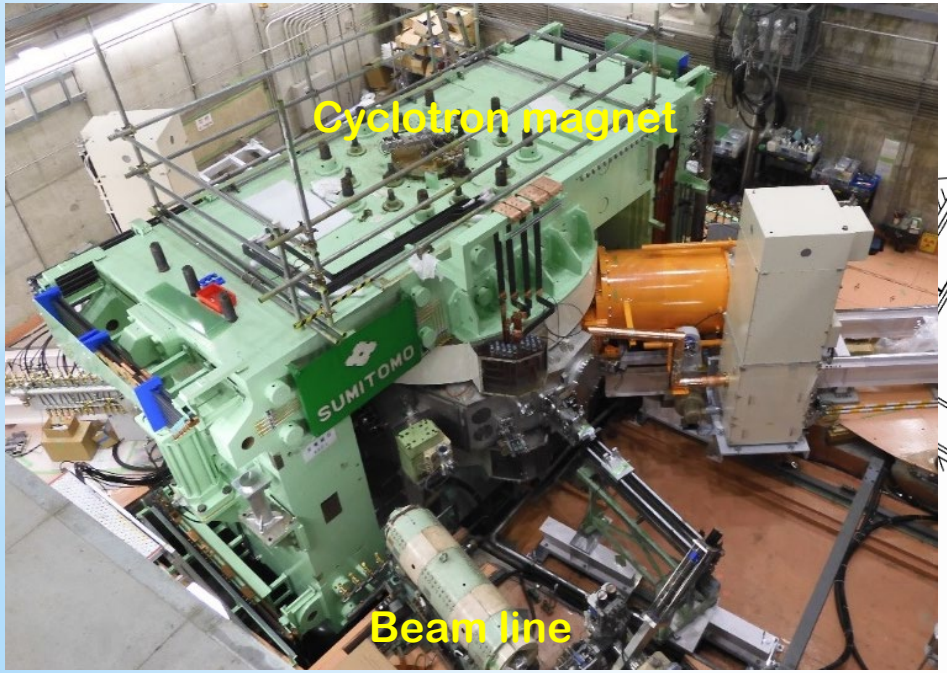
Buncher voltage

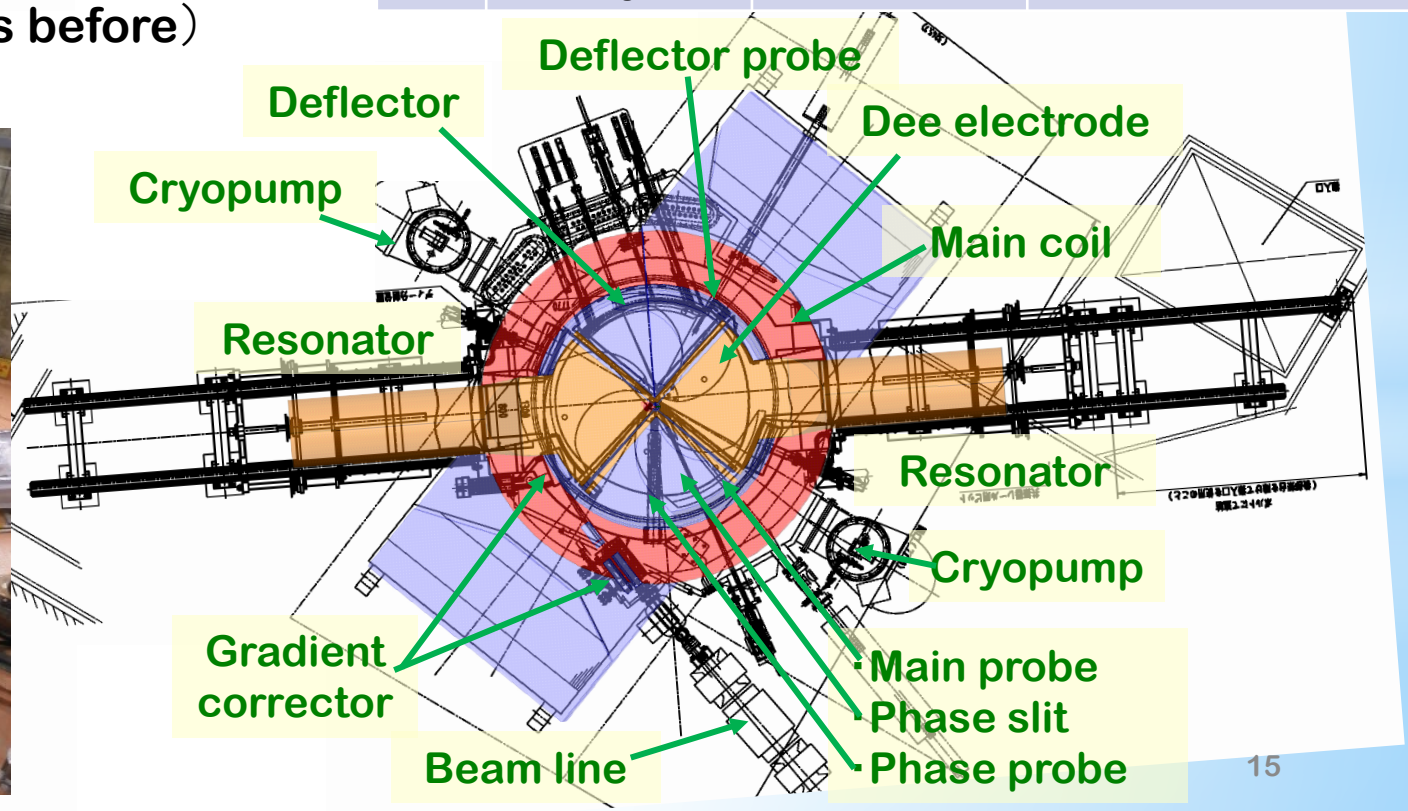
Upgrade of the RCNP AVF Cyclotron

●Main parameters of the upgraded AVF cyclotron

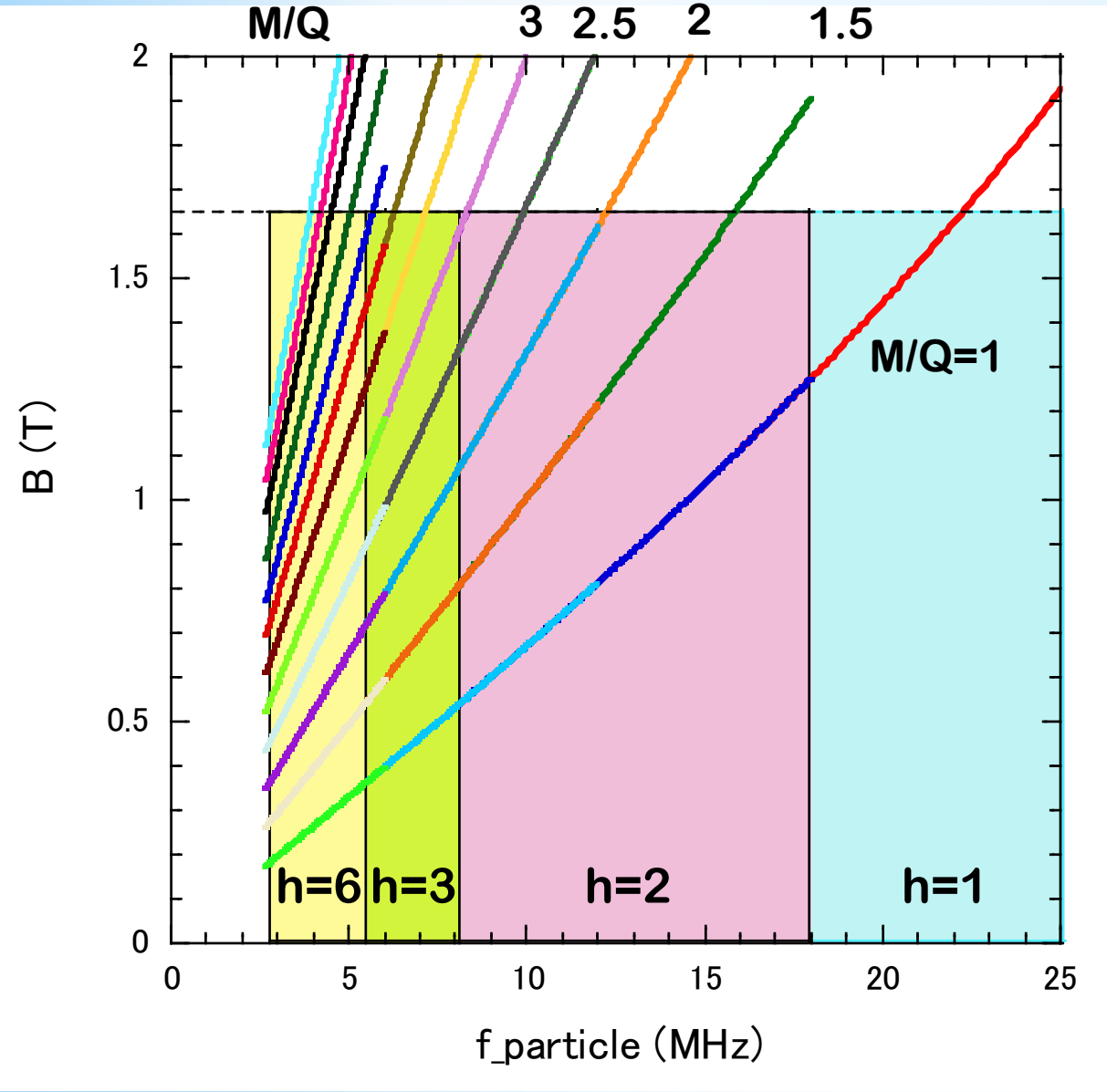
- K-value : 140 MeV （same as before）
- Extraction radius : 100 cm （same as before）
- Max. averaged field : 1.65 T （same as before）
- Resonator and Dee : Double （single before）
- Opening angle of Dee : 87 deg. （180 deg. before)
- RF frequency : 17～37 MHｚ （6～18MHz before）
- Acceleration harmonics : 1，2，3，6 （1，3 before）
- Max. Dee voltage : 60kV （same as before）

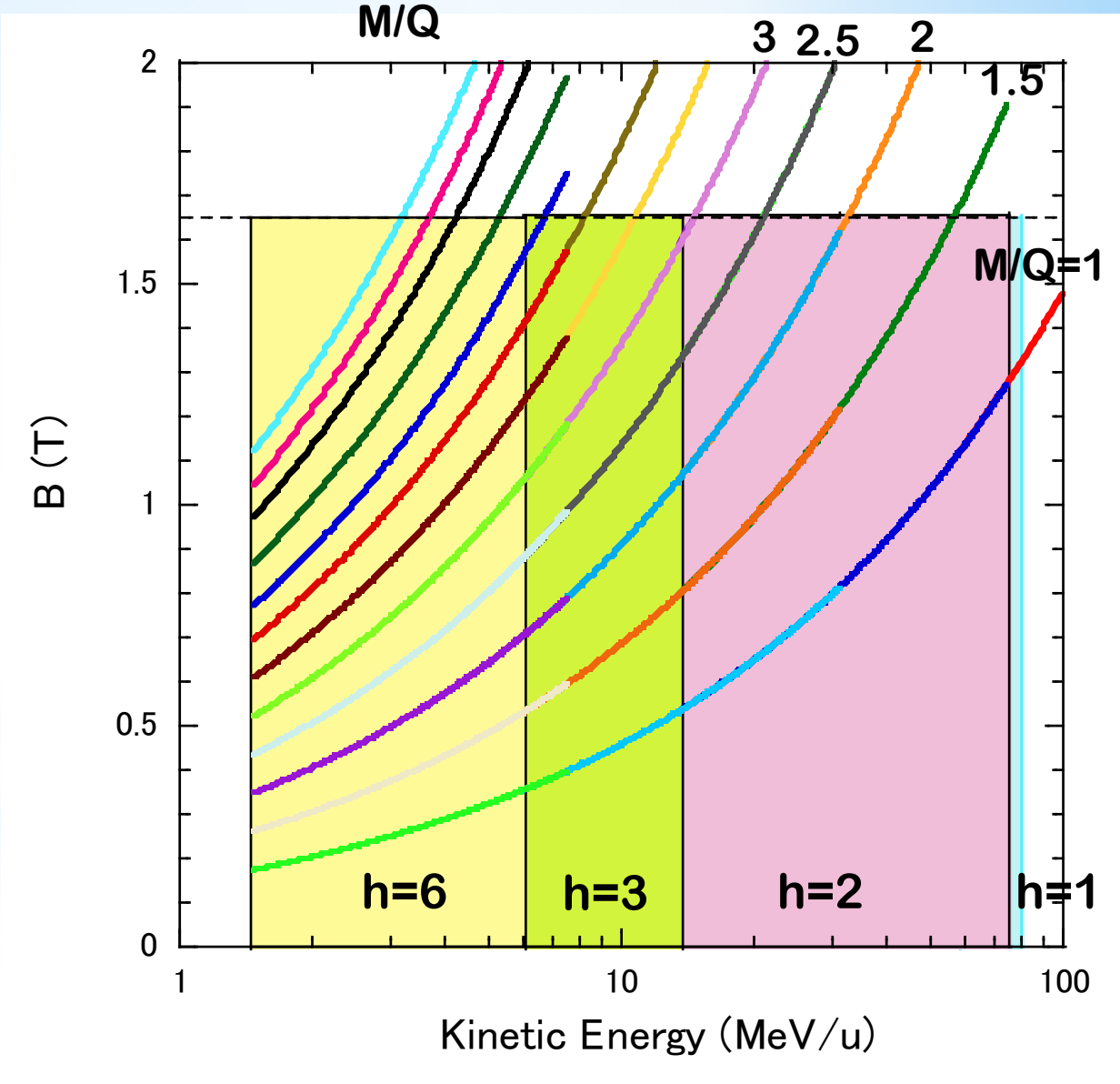
H	Particle	Energy (MeV/u)	Energy gain ratio to previous one
1	proton	66 to 80	1.4
2	proton	15 to 75	2.0
	Heavy Ion	15 to 32.5	2.0
3	Heavy Ion	7 to 31	1.4
6	Heavy Ion	2 to 7.5	2.0





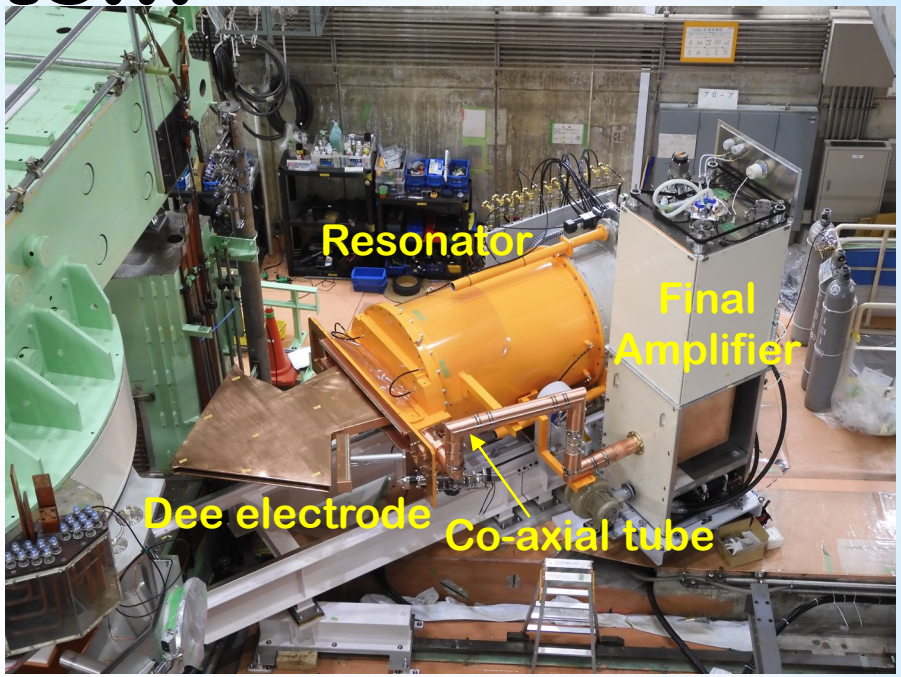
Operation Diagram of the AVF Cyclotron

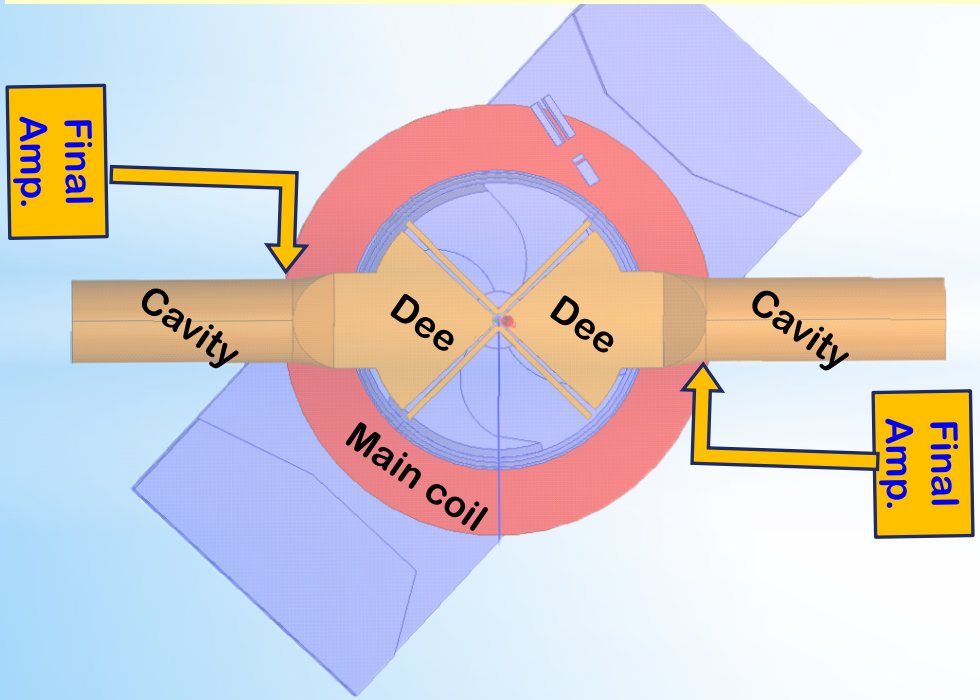


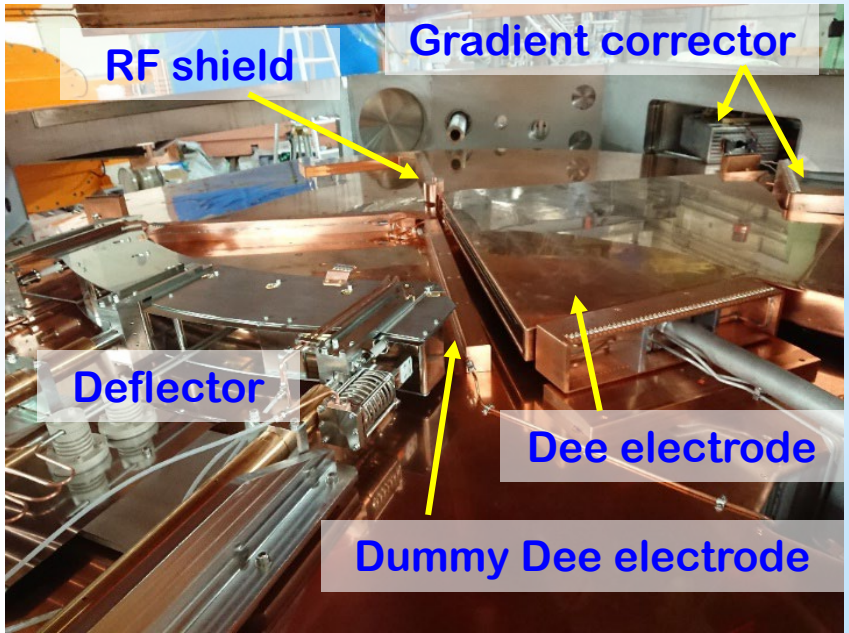


RF system

●Specification of RF system
- Resonator type: movable short, coaxial cavity
- Diameter of tubes: outer 1000 mm, inner 700 mm
- Stroke of short plate : 1200 mm
- Frequency range： 17～37 MHz
- Tuner : capacitive compensator with $\Delta f/f < 1.8\%$
- Max. Dee voltage： 60 kV
- Final amp. : EIMAC 4CW100,000E or 4CW50,000E
- Pre-amp. output power： 1 kW
  ・Power feeder： Capacitive coupler



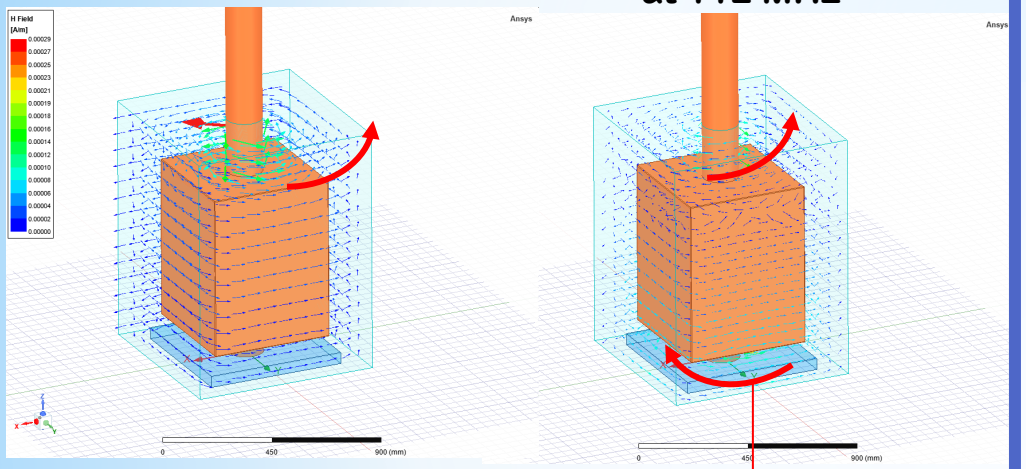




Troubles with Final Amplifier

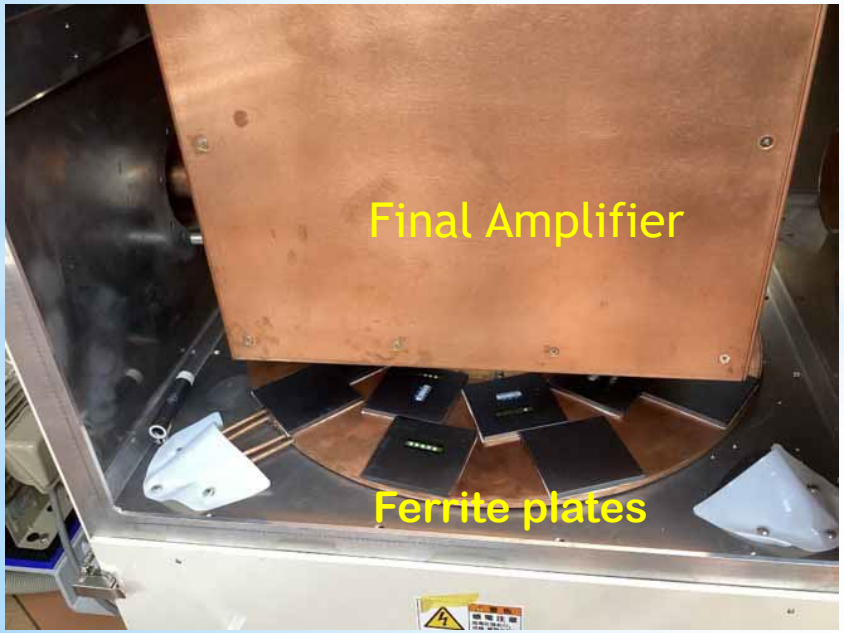
Fundamental mode at 33.6 MHz

Parasite RF component at 112 MHz

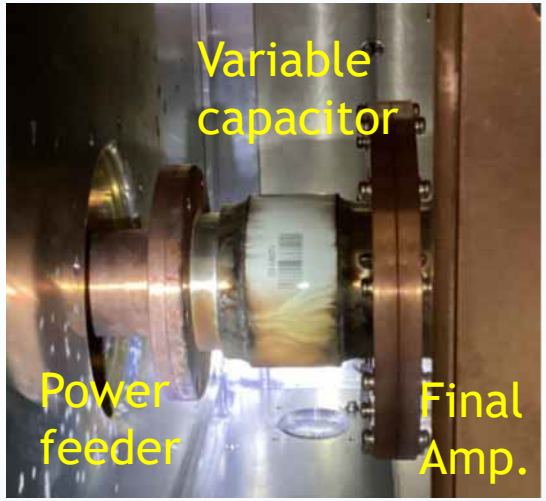


Calculation by ANSYS/HFSS

Magnetic field

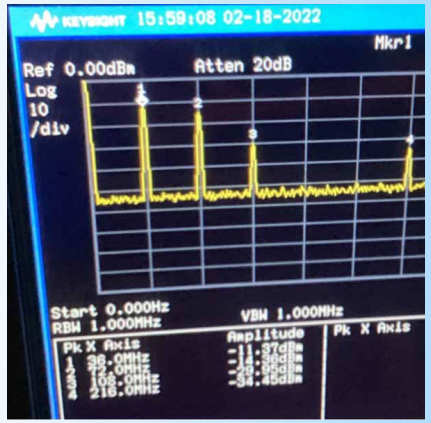


The variable vacuum capacitor connected to the power feeder at the amplifier output was damaged by sparking due to the harmonic component.



The length of the power feeder can be changed to avoid reflection of the harmonic components and abnormal oscillation

Plate pickup



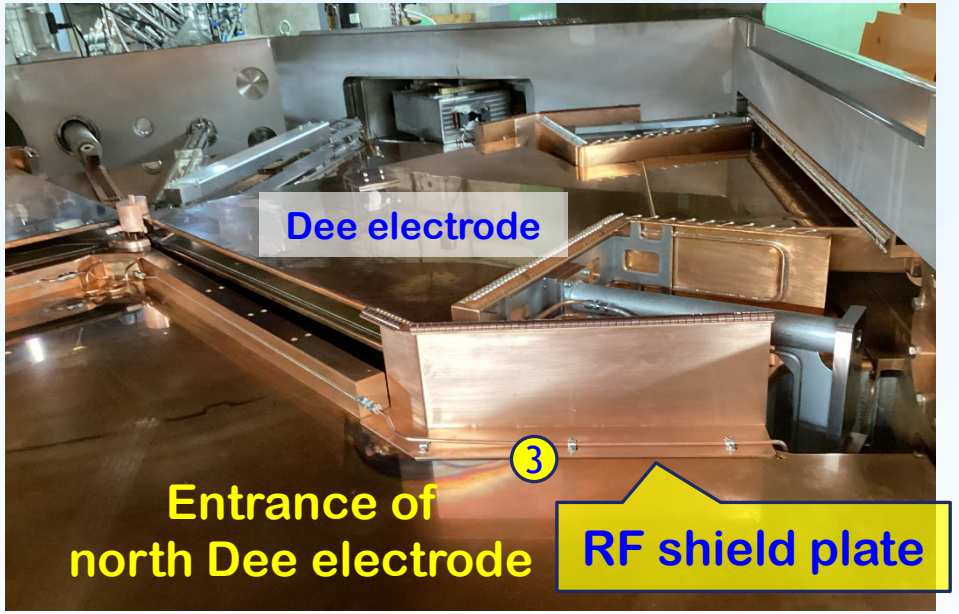
Add 716 mm

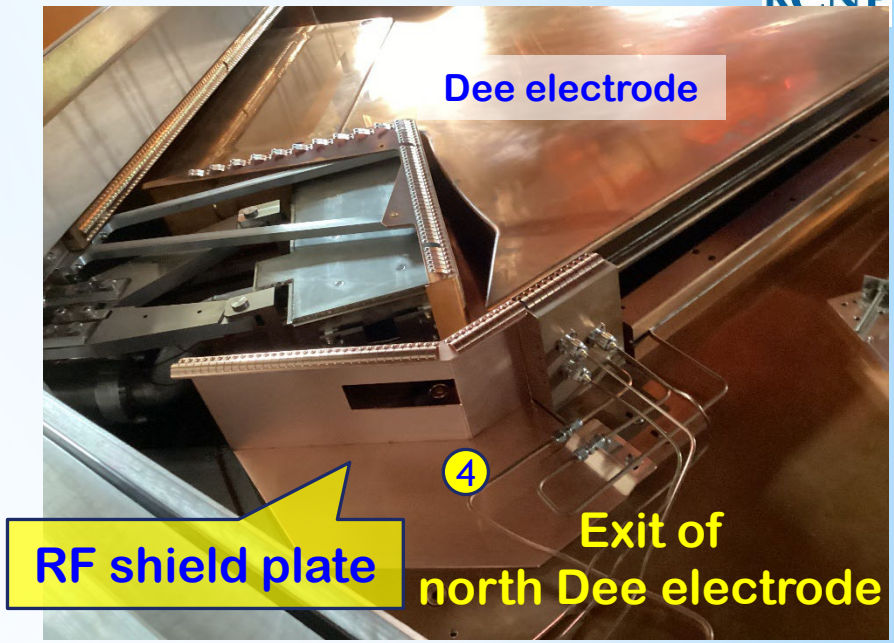
Add two 716 mm

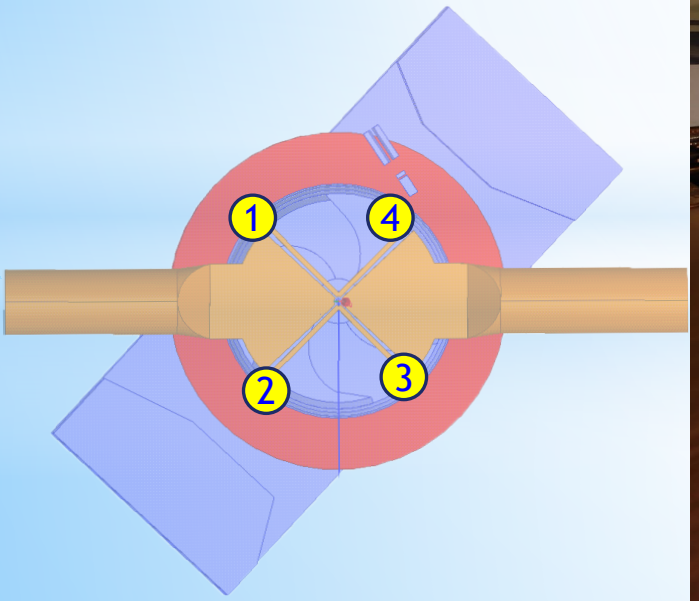
Reinforcement of RF shield

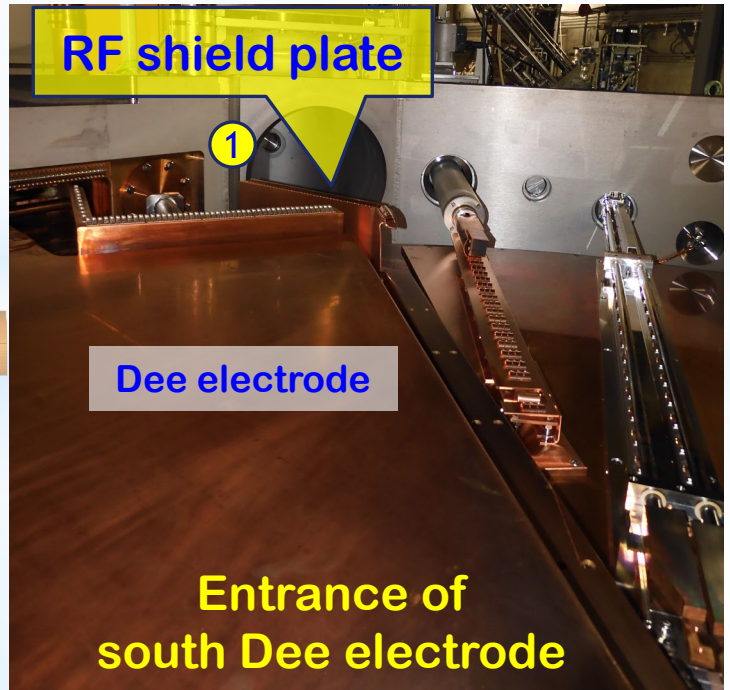
Troubles with beam probes and phase slit caused by RF noises

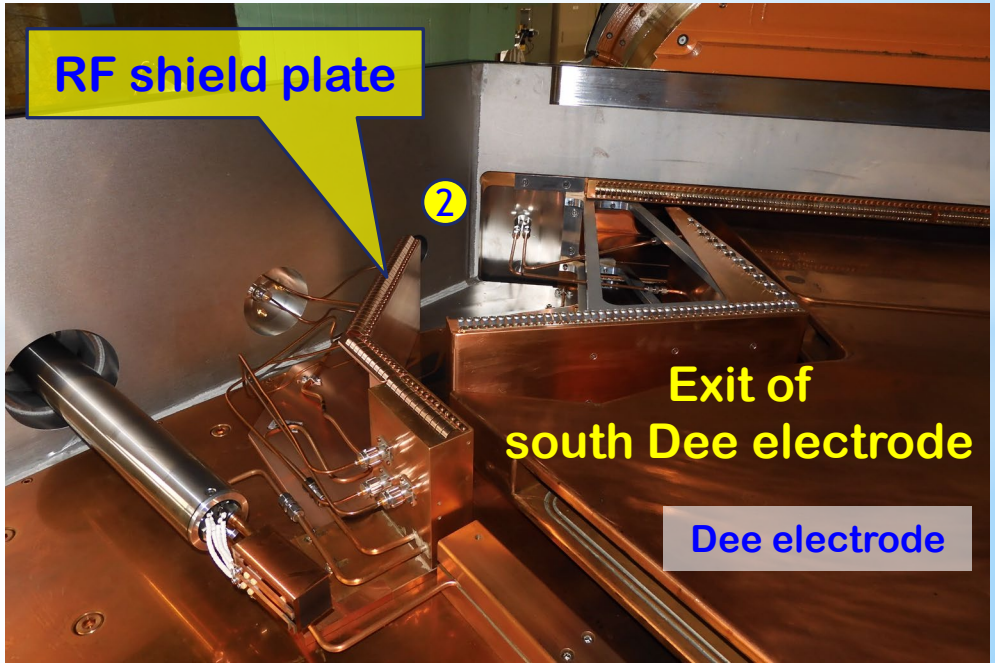
Additional RF shield plates were placed at the outside of dummy dee electrodes.



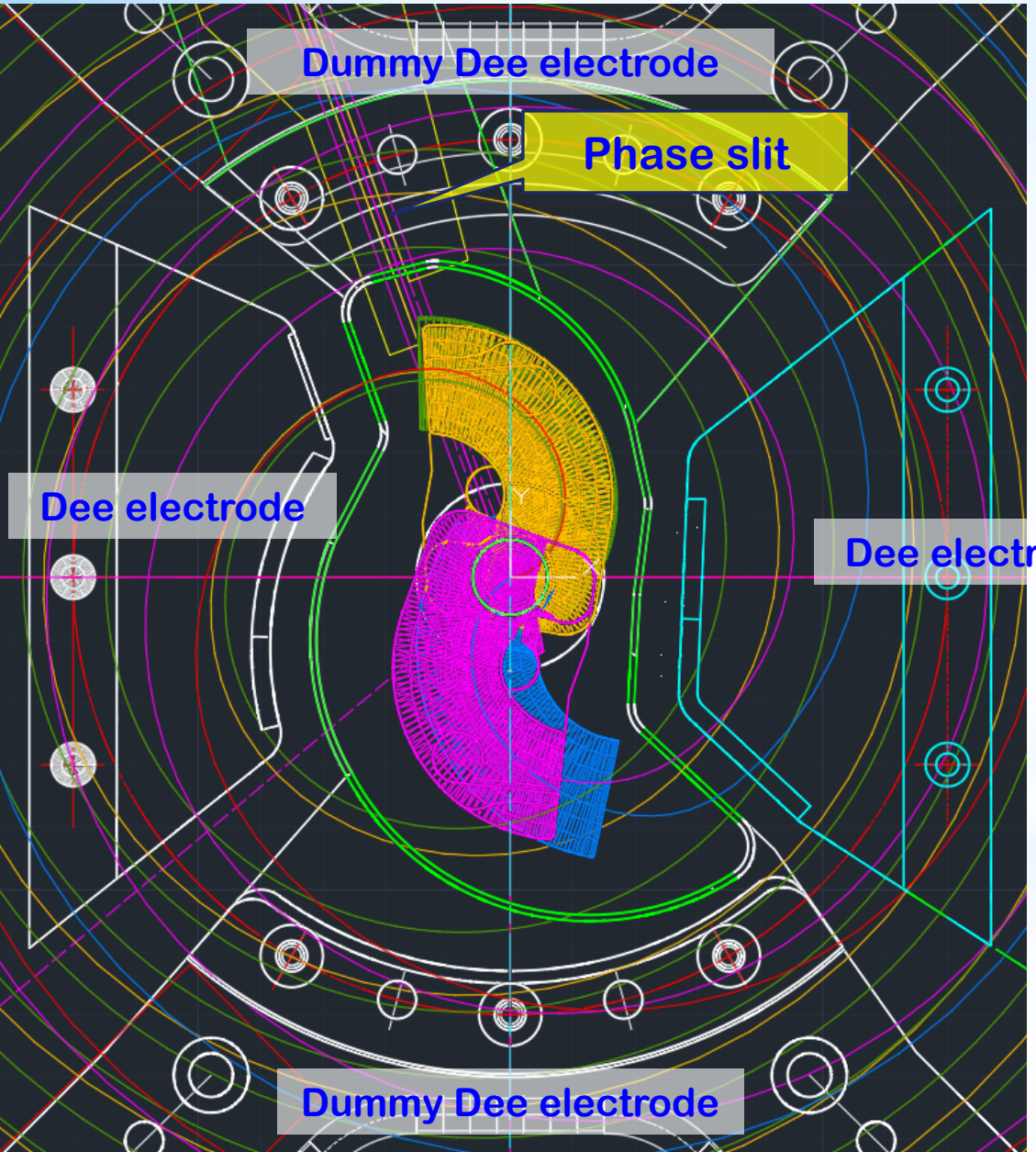


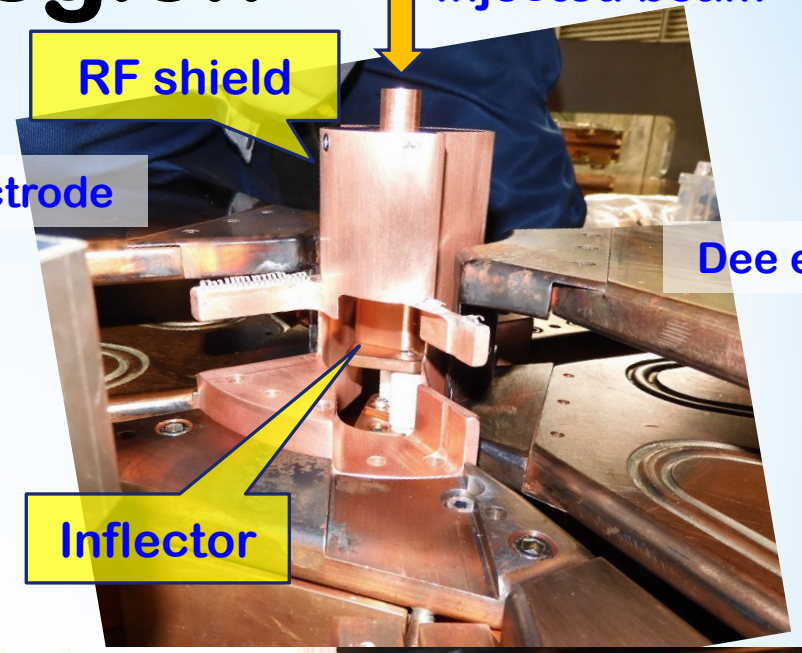


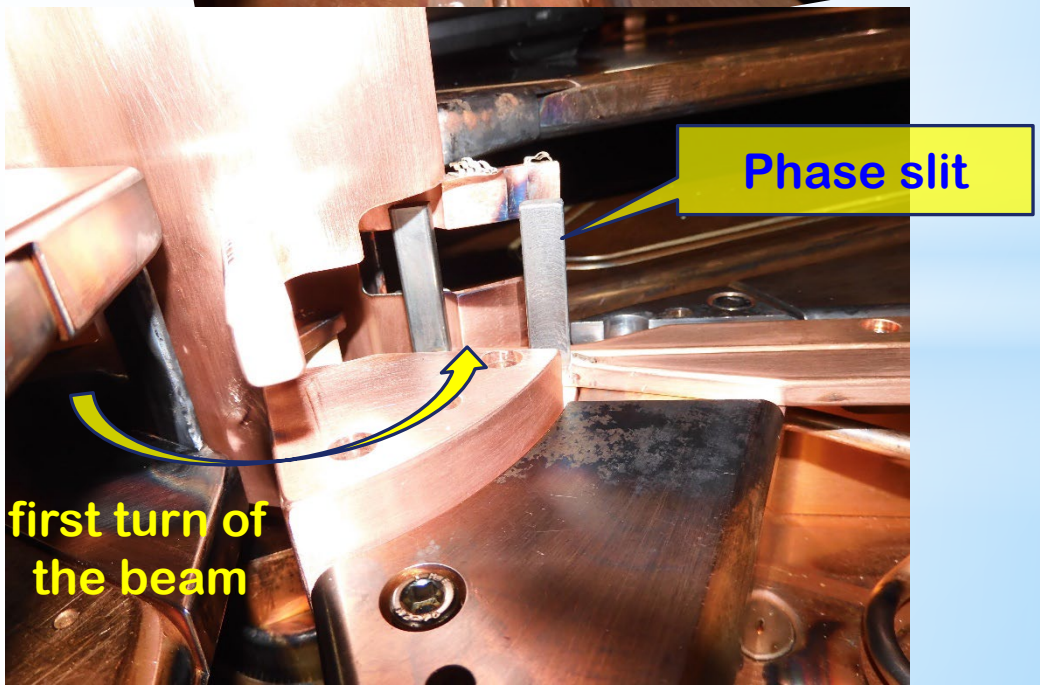




Central Region

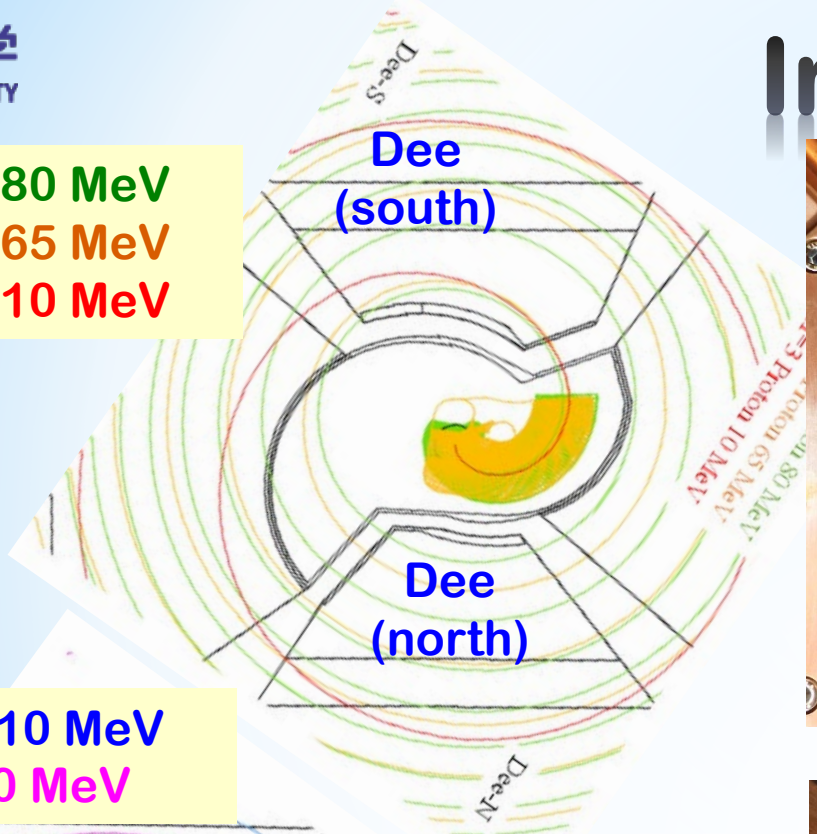


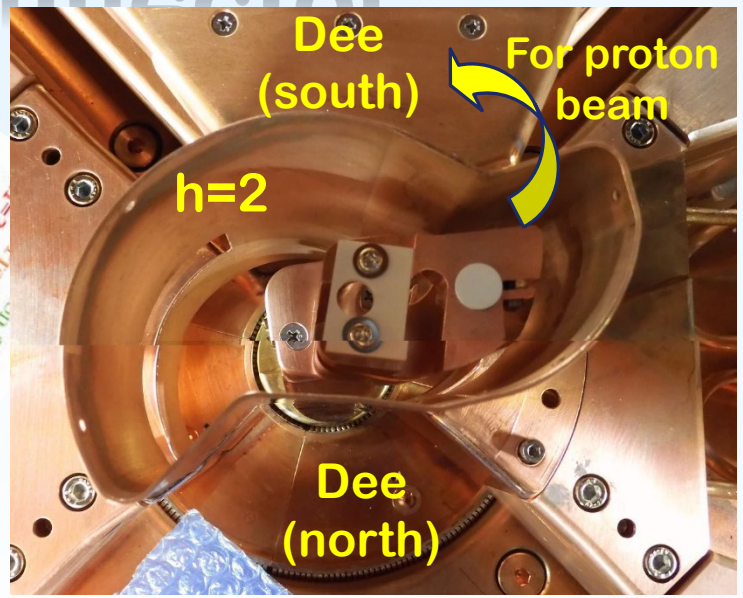


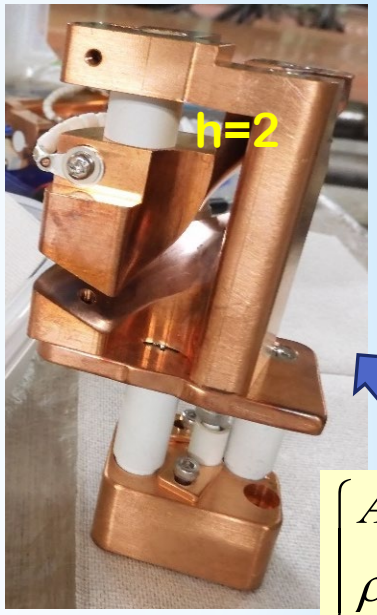


Inflector

H=1 Proton 80 MeV
H=2 Proton 65 MeV
H=3 Proton 10 MeV

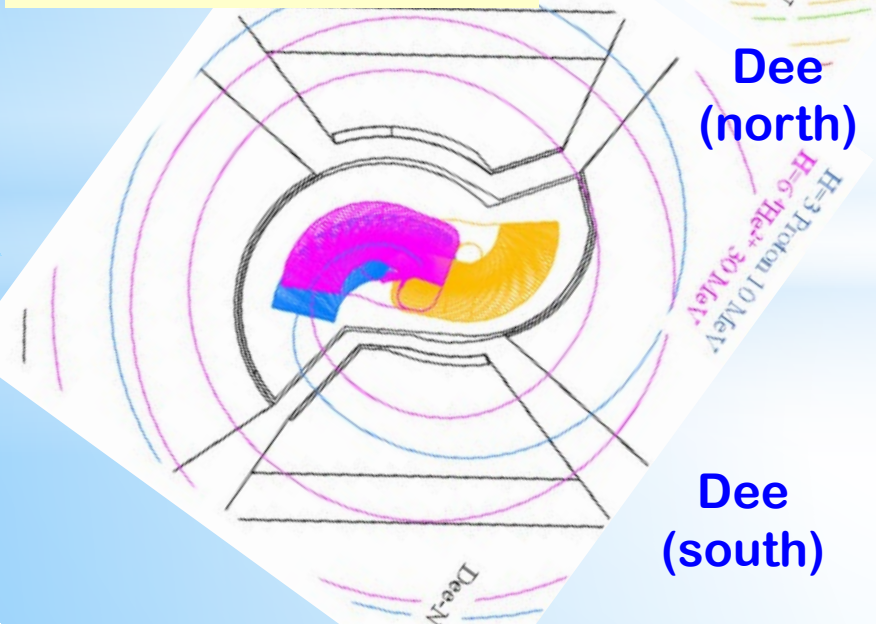


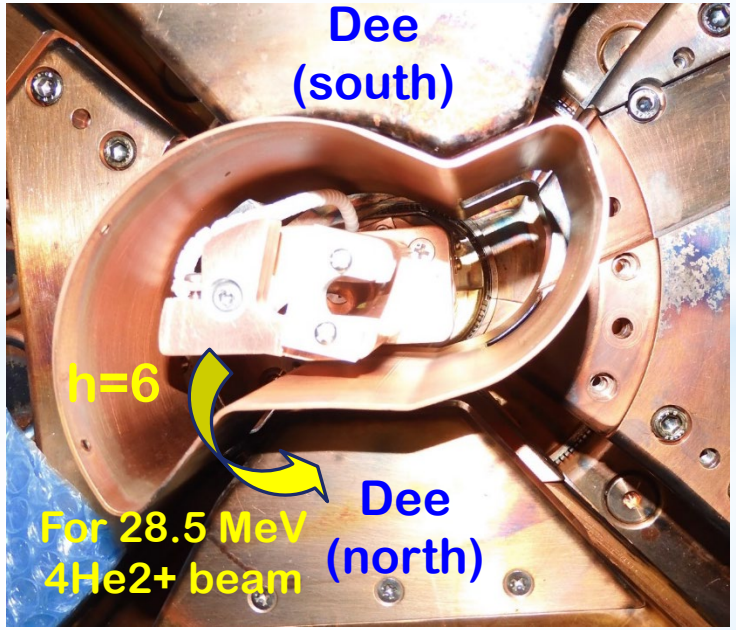




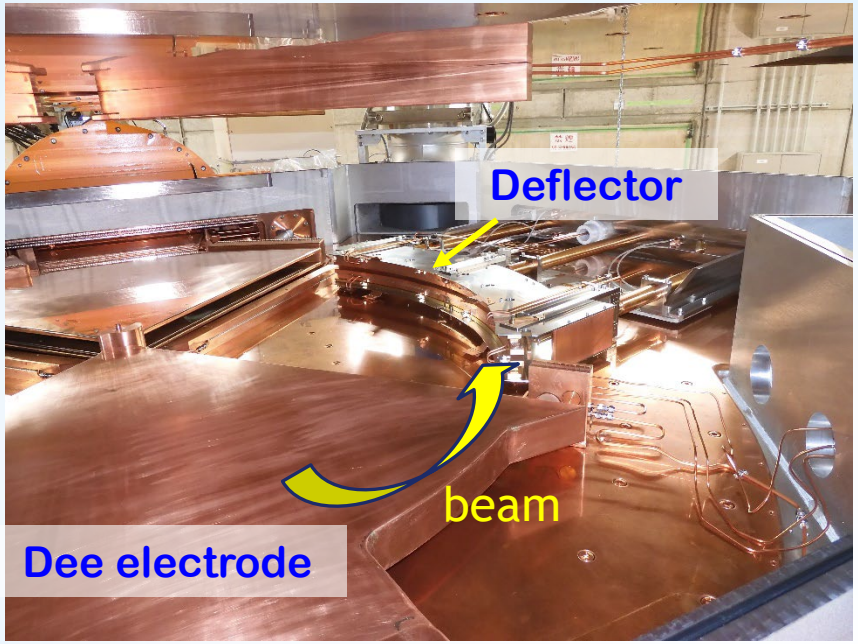
$$\begin{cases} A = 49.8(mm) \\ \rho = 28.4(mm) \\ k' = 0.4 \\ K = 1.077 \end{cases}$$

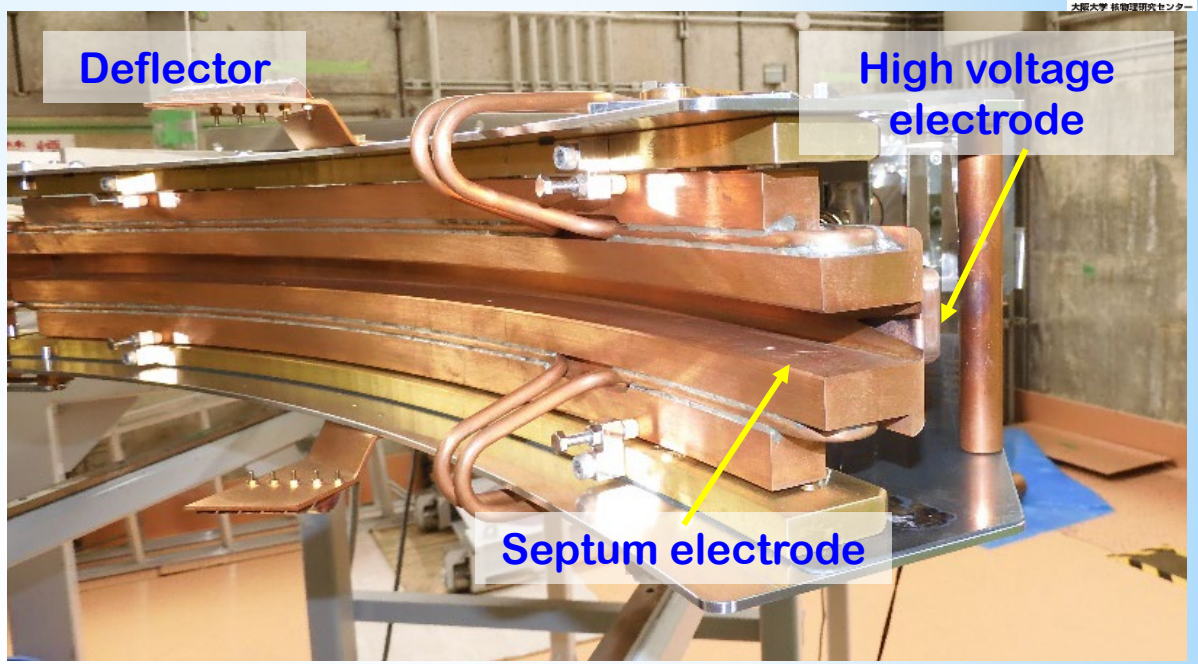
H=3 Proton 10 MeV
H=6 $^4He^{2+}$ 30 MeV



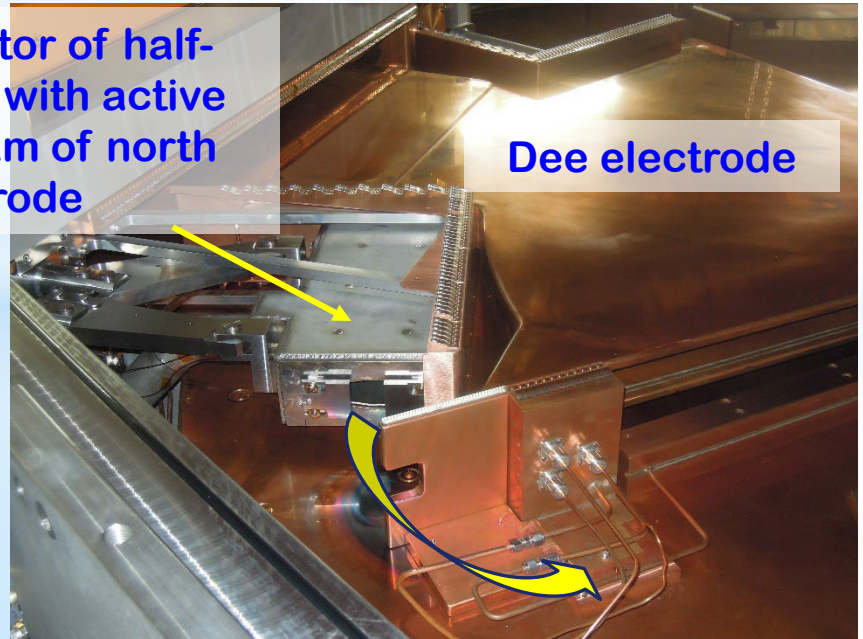


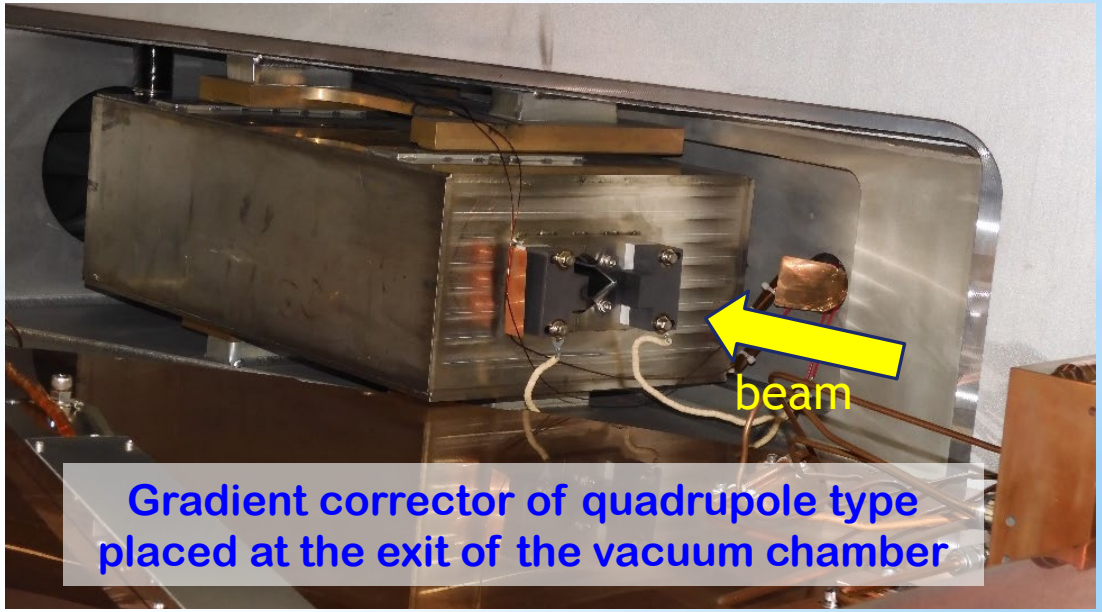
Beam Extraction System





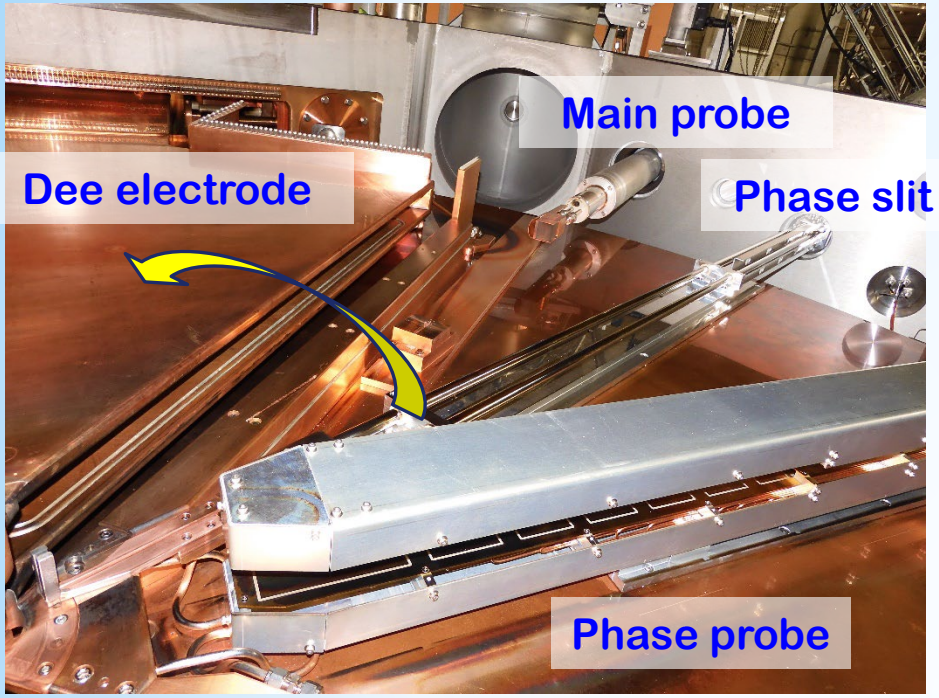
Gradient corrector of half-quadrupole type with active coils down stream of north dee electrode

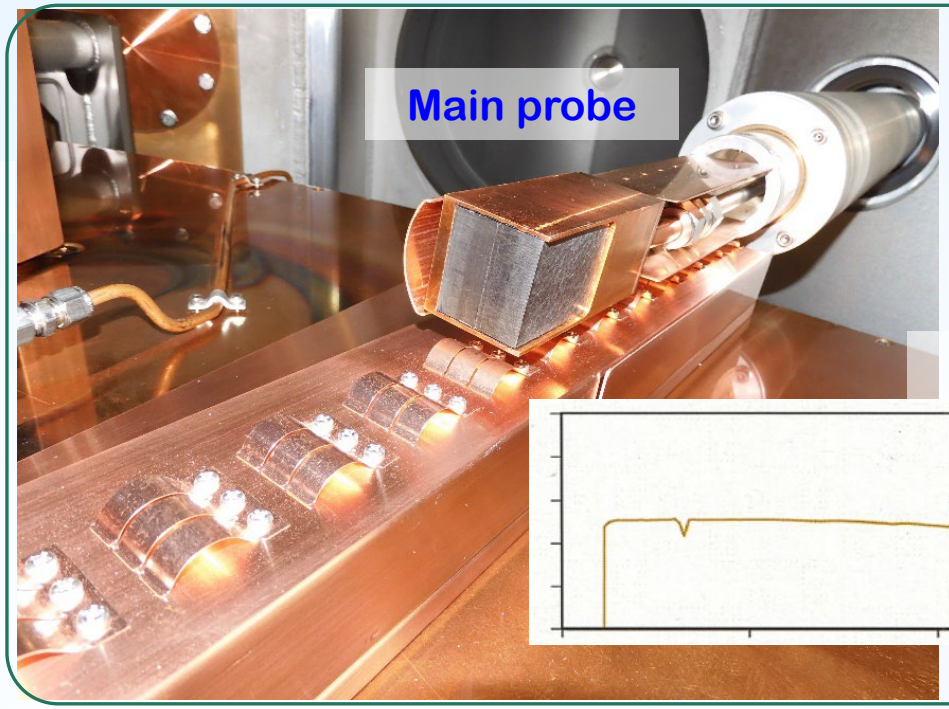




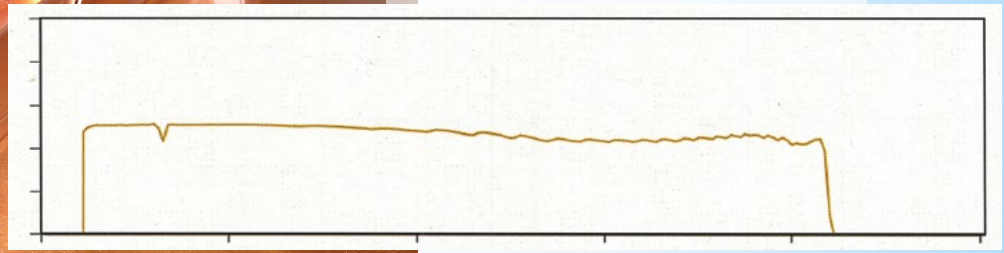
Gradient corrector of quadrupole type placed at the exit of the vacuum chamber

Beam Diagnostics



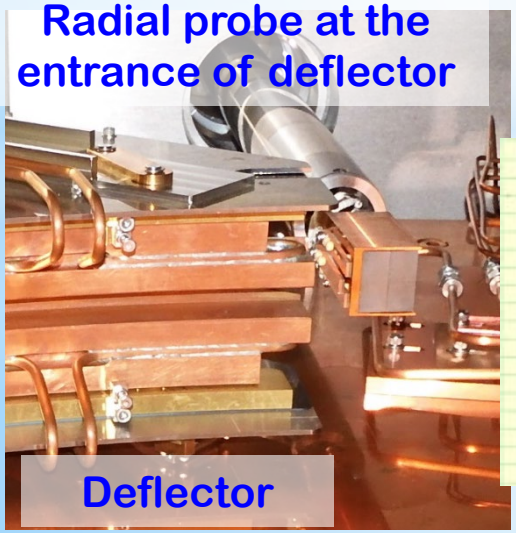


Beam distribution

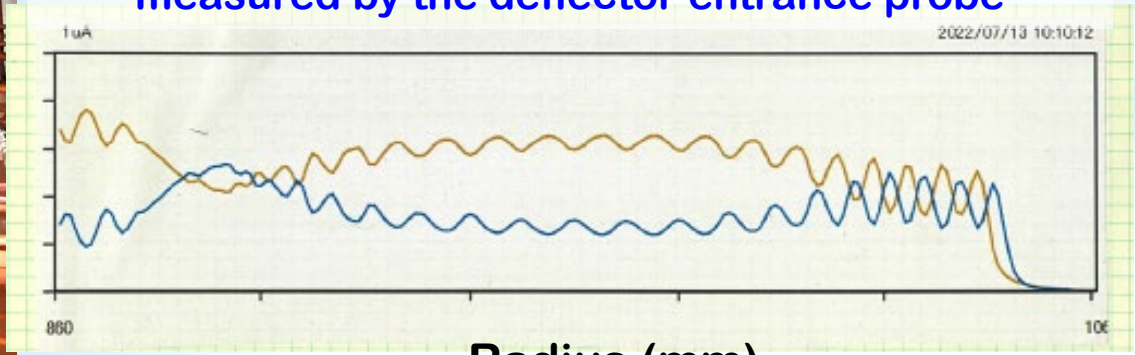


Radius (mm)

Radial probe at the entrance of deflector

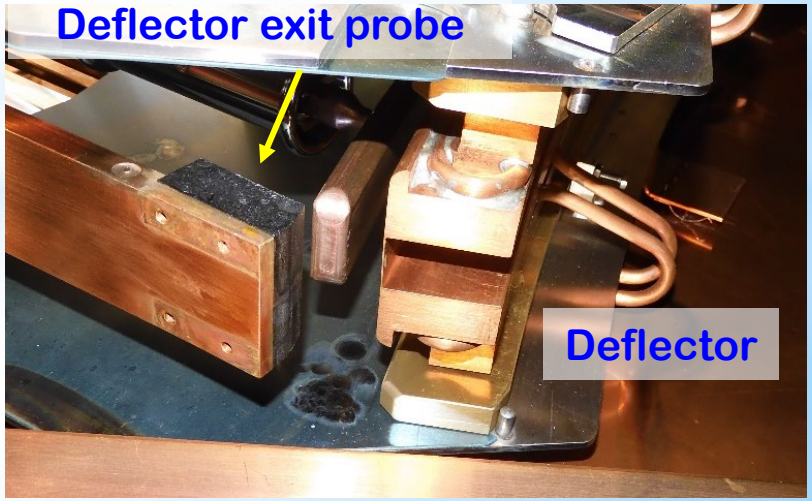


Example of turn pattern of 65 MeV proton measured by the deflector entrance probe



Radius (mm)

Deflector exit probe

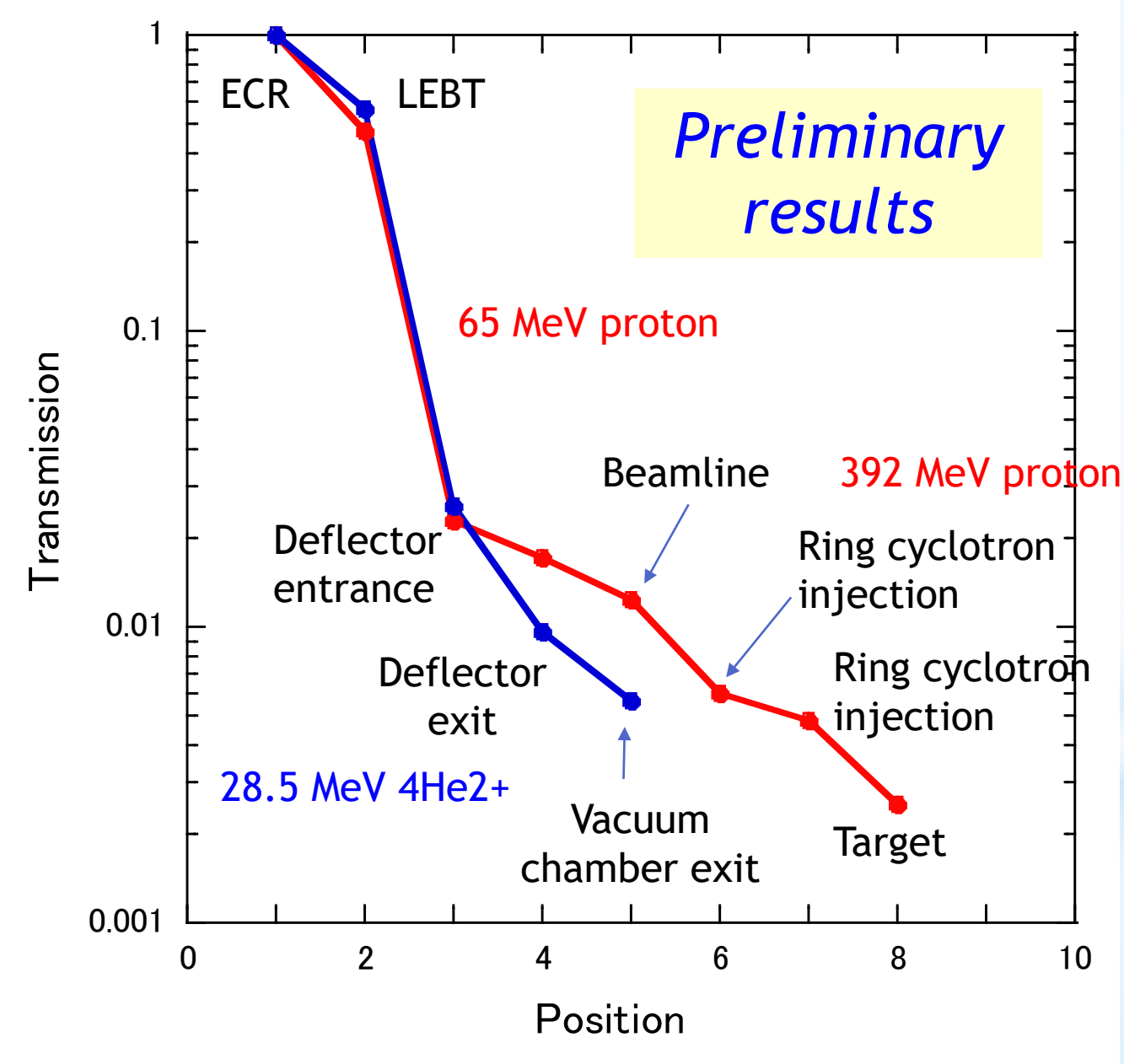


4. Beam commissioning

*Beam commissioning in 2022

- 3/16 obtained permission for acceleration from Government
- 3/27 started beam injection into the AVF cyclotron for acceleration of 65 MeV protons
- 3/31 observed injected beam at a radius of 20 cm
- 4/5 observed proton beam at the entrance of the deflector
- 4/18 resumed operation
- 4/21 observed the first extracted proton beam at a Faraday cup of the beam line
- 5/10 passed at the radiation facility inspection using a 65 MeV proton beam
- 5/middle, 6/end provided a 65 MeV proton beam for joint research experiment
- 5/end transported to WS-course for Grand-RAIDEN commissioning
- 7/end, 9/middle, 10/end provided 28.5 MeV 4He beam for At-211 production
- 10/beginning accelerated protons up to 392 MeV by the ring cyclotron
- 11/end to 12/beginning 392 MeV proton beam was provided for semi-conductor soft-error experiment
- 12/beginning Commissioning for high resolution experiment with Grand-RAIDEN and for muon source MuSIC
- from April 2023 Regular experiments will be started.

*Beam Transmission



5. Summary

1) Upgrade of the RCNP AVF cyclotron to increase the beam intensity and to improve the beam quality was completed in 2021
   - Ion sources : acceleration voltage was increased to 50 kV.
   - LEBT : subharmonic bunching system was available.
   - Inflector : the design was optimized for higher injection beam energy.
   - Cyclotron magnet : the main magnet was reused besides trim and valley coils.
   - RF system : the resonator and amplifier system were fully modified.
     Frequency = 17 - 37MHz, h = 1, 2, 3, 6
   - Extraction system : consists of a deflector and two gradient corrector.

2) Beam commissioning
   - March 2022 Beam was injected into the central region.
   - April 2022 Beam was extracted from the cyclotron.
   - May 2022 We passed the facility inspection and beam commissioning was started.
   - Now Commissioning is ongoing for increase of the beam intensity and improvement of the beam quality.
     28.5 MeV 4He2+ beam for At-211 production
     65 and 392 MeV proton beam for neutron production and precise nuclear physics experiment

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Thank you for your attention.