Status of development of FFAs at Kyushu University

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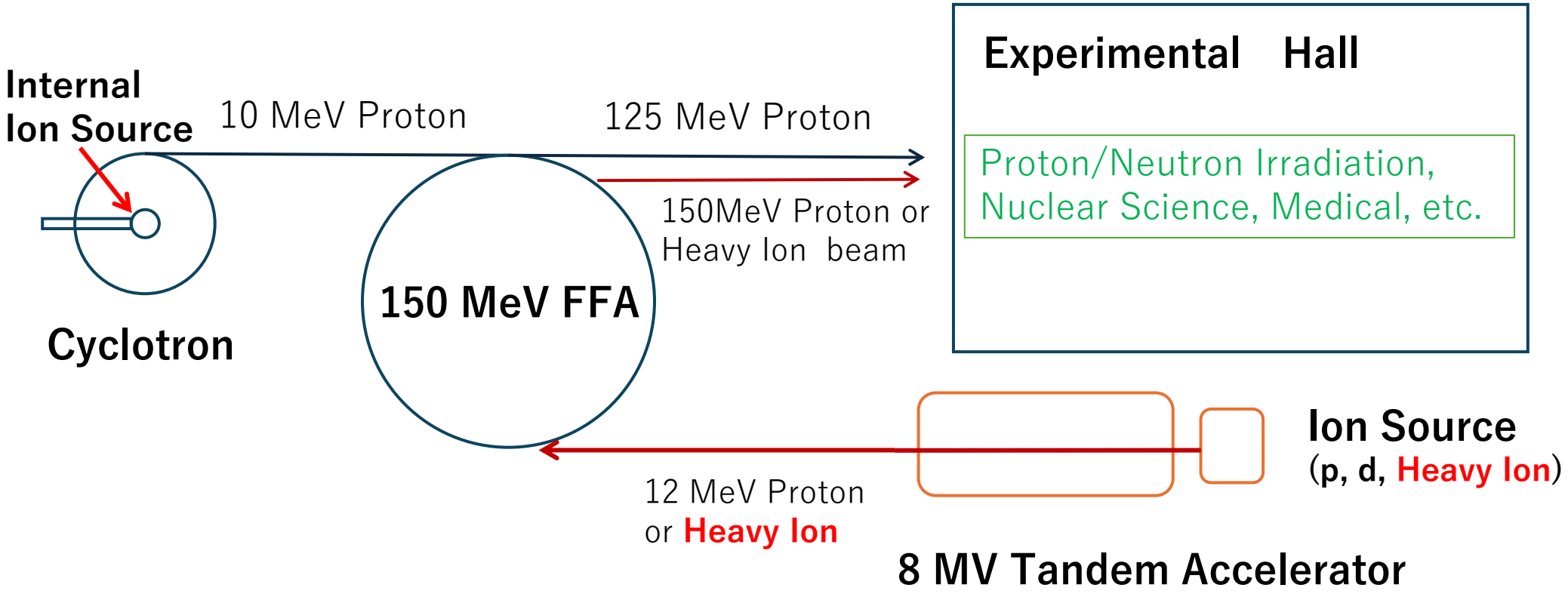
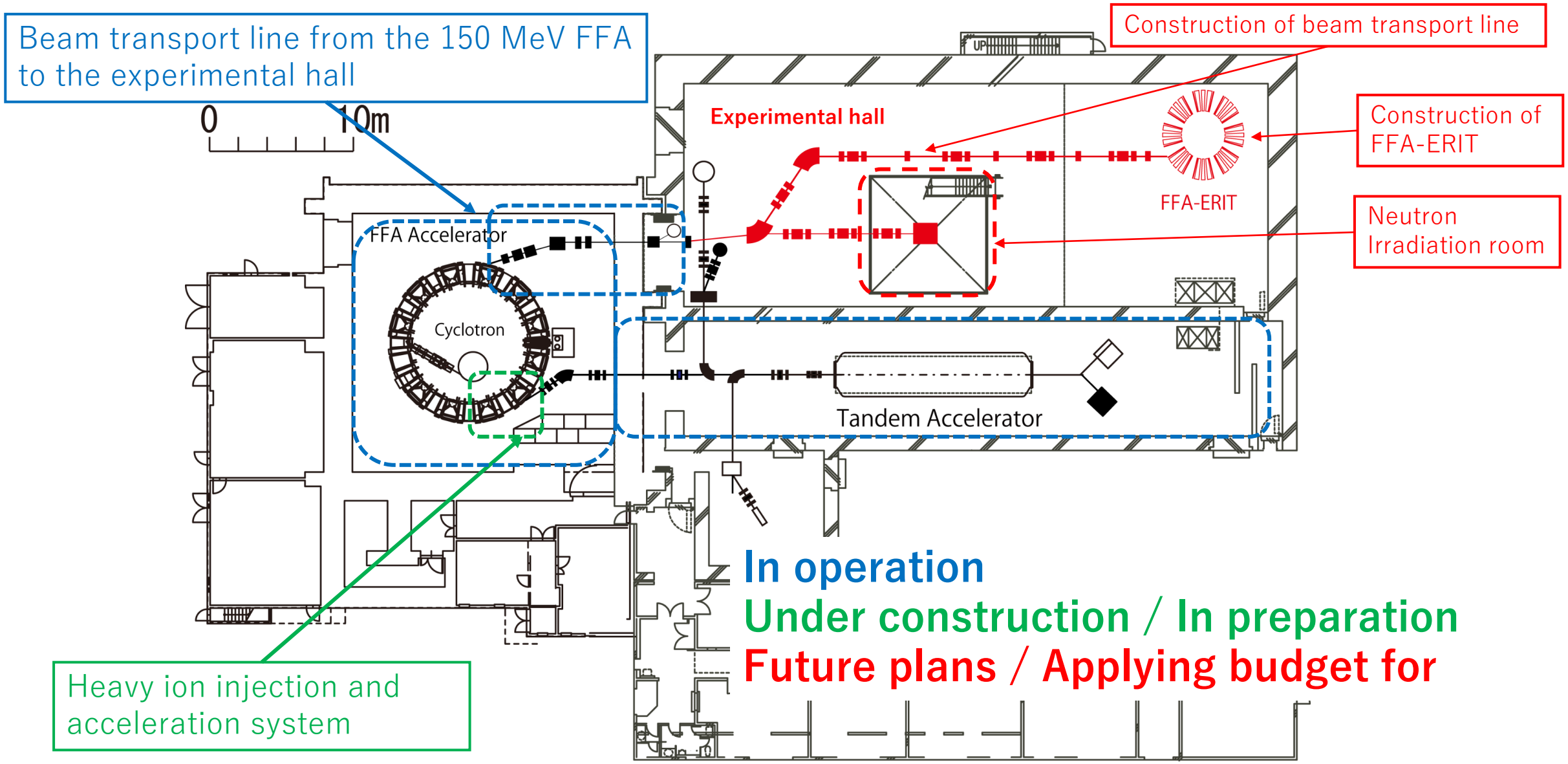
Contents

- Overview of the accelerator facility of Kyushu University
- Construction status of the accelerator facility
- Present status of development of FFAs at Kyushu University
- Summary

Overview of the accelerator facility of Kyushu University



Construction status of the accelerator facility in 2025



Ongoing and planned projects at FFA in Kyushu University

3 projects are on going, 1 project is planned.

Ongoing projects

1. Construction of the beam extraction line from the 150 MeV FFA to the experimental hall for beam applications

2. Injection and acceleration of heavy ion with the 150 MeV FFA

3. Development of a prototype machine of vertical FFA for Harmonytron

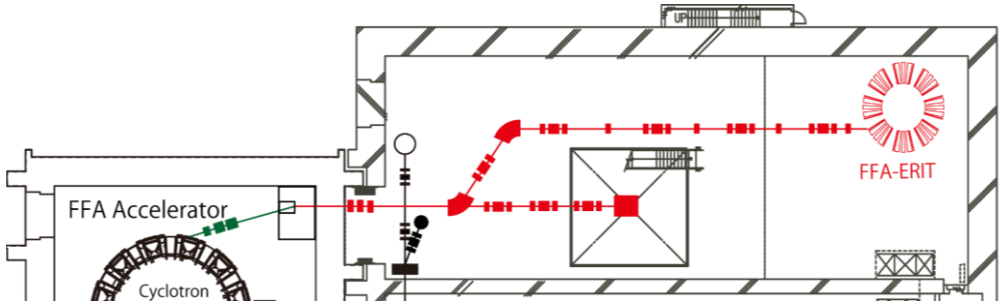
Planned project

4. Production of neutron and unstable nuclei with FFA-ERIT ring

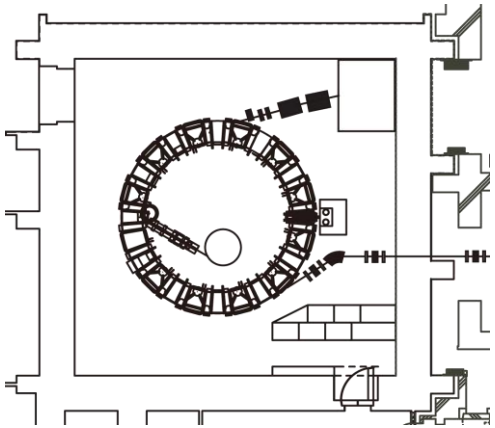
   ➔ Details has been reported in Mr. Tominaga's presentation.

1. Construction of the beam extraction line from the 150 MeV FFA to the experimental hall

To promote study of nuclear physics, material and neutron science, the construction of the experimental hall was initiated.

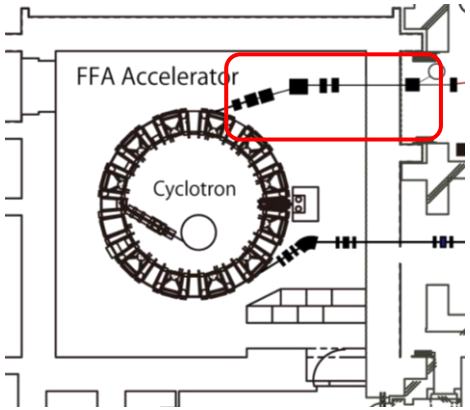


The 3rd stage of the construction facility was started on June 2024.
The radiation inspection has passed on August 2024. However, just two weeks later, the warehouse storing beam transport line components was destroyed by Typhoon.



August 2024

The project was delayed by 4 months



January 2025

The construction of a part of the beam transport line has been completed in January 2025.

Investigation of damage of typhoon to equipment of beam extraction system

Investigation of equipment failures has been conducted.

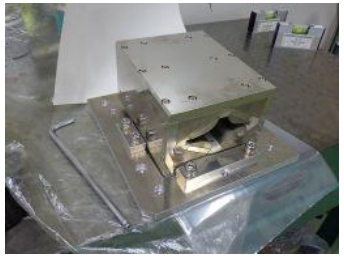
Equipment	State
Power sources of quadrupole / dipole / steering magnets	Failure
Power cable / HV cable	Total loss (internal water ingress)
Vacuum chambers	No damaged (Contaminated with mud)
Quadrupole / dipole / steering magnets	No damaged (Waterproof cover prevented damage)

The economic damage caused by the typhoon is estimated to be approximately 80 million JPY.
(about 544,000 USD or 464,000 EUR)

Construction of a Beam Transport Line

The beam transport line was assembled from the minimal surviving components.
Power supply units were repurposed from other existing systems.

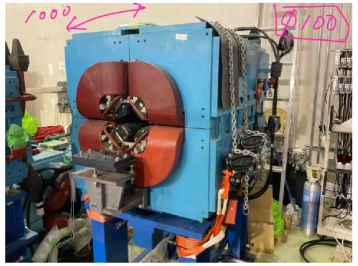
Currently, negotiations with the insurance company are ongoing.
Additional electromagnet power supplies are pending budget approval.



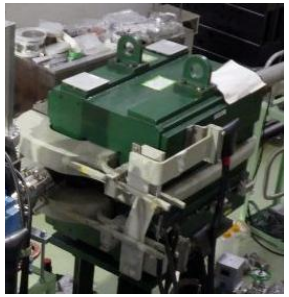
Qp
Permanent magnet
17 T/m L150 mm

Q1
quadrupole magnet
14.9 T/m, L150mm

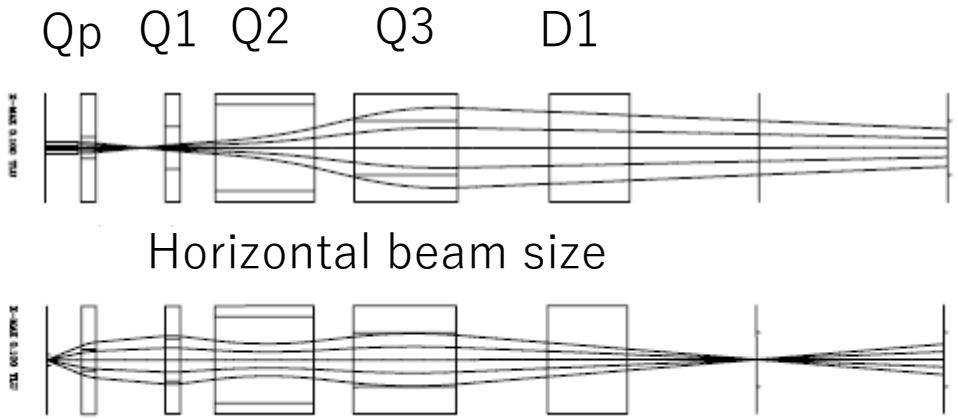
Q2
quadrupole magnet
6.6 T/m, L1000 mm



Q3
quadrupole magnet
8.5 T/m, L762 mm

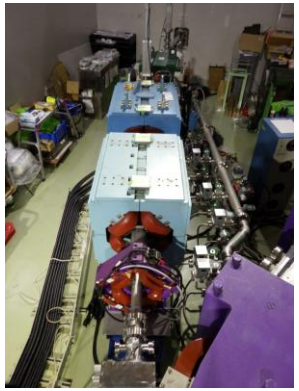


D1
Dipole magnet
0.85 T, L760 mm



Horizontal beam size

Vertical beam size



Construction of a part of the beam line has been completed in January 2025.

Commissioning for beam extraction

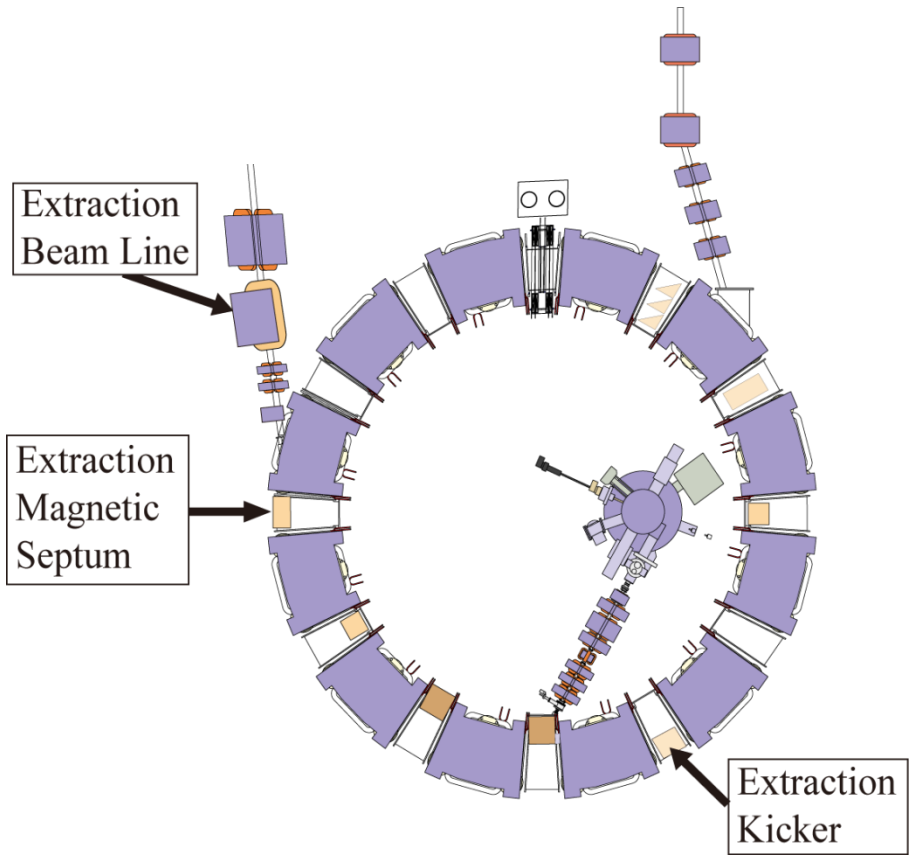
Beam commissioning started in January 2025.

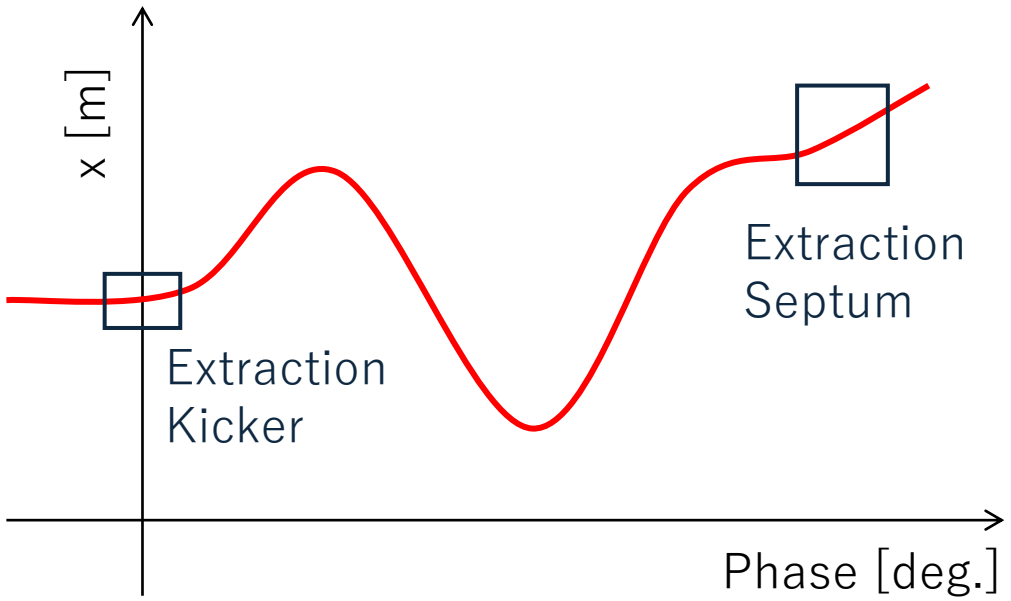
Experimental condition

- Particle: Proton from injector cyclotron
- Injection energy: 10 MeV
- Extraction energy: 78 MeV (1st Stage), 100 MeV (2nd Stage)
- Repetition rate: 20 Hz
- Operation time: 2 weeks (due to budget limitations)

As will be discussed later, beam commissioning was initiated at low energy to ensure equipment protection.

Configuration of Beam Extraction System

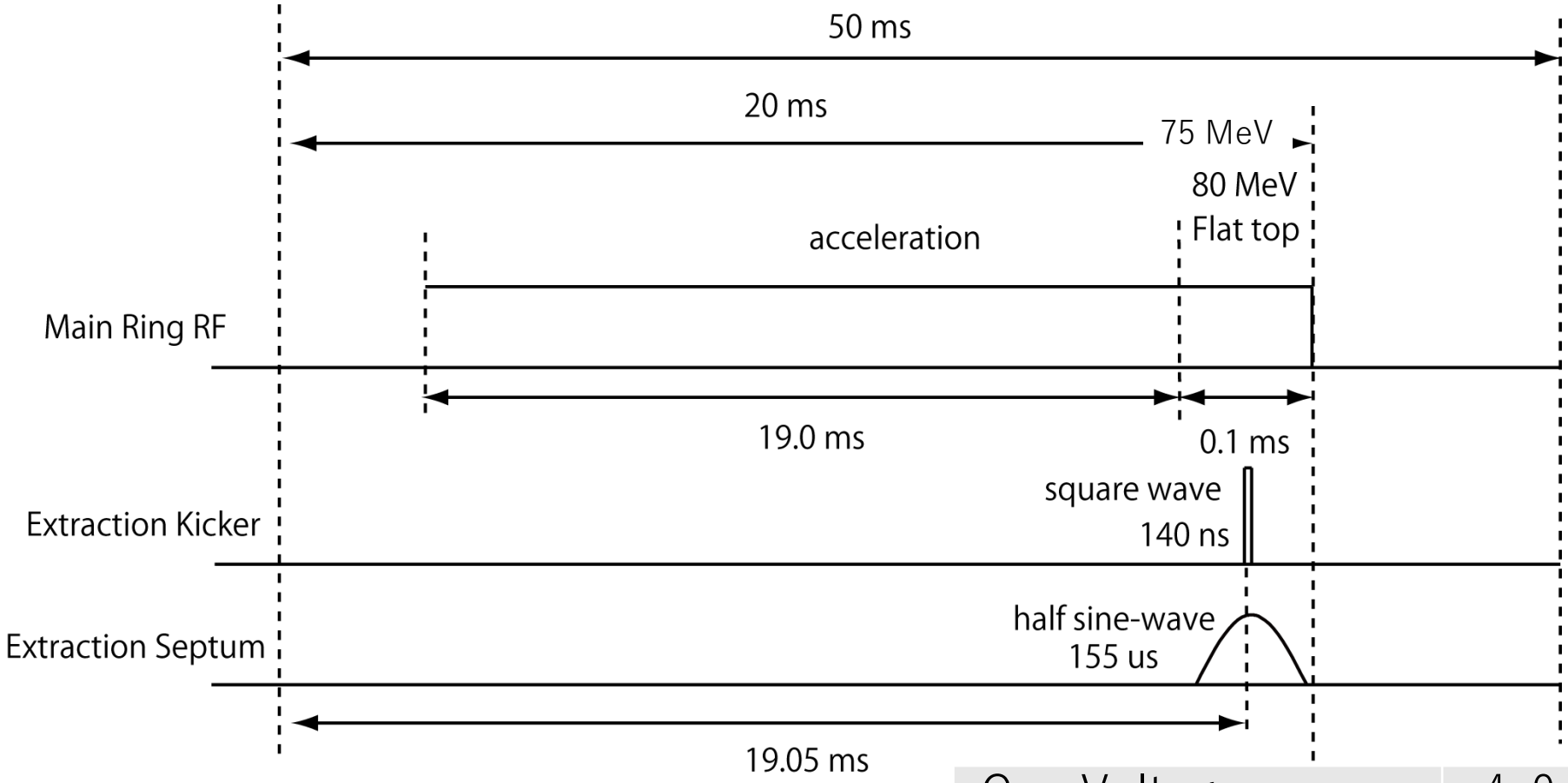




Extraction method : Fast extraction

Phase advance between kicker and septum: 440 deg.(4 cells) $\cong 3\pi$

Timing chart of beam acceleration and extraction

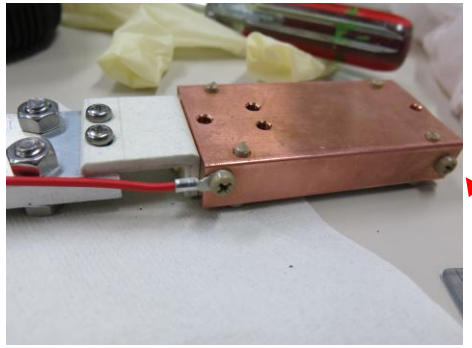


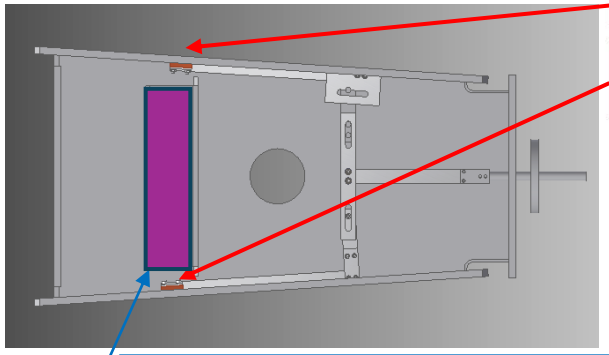
Repetition rate:
20 Hz

Acceleration cycle:
50 Hz (20 ms)

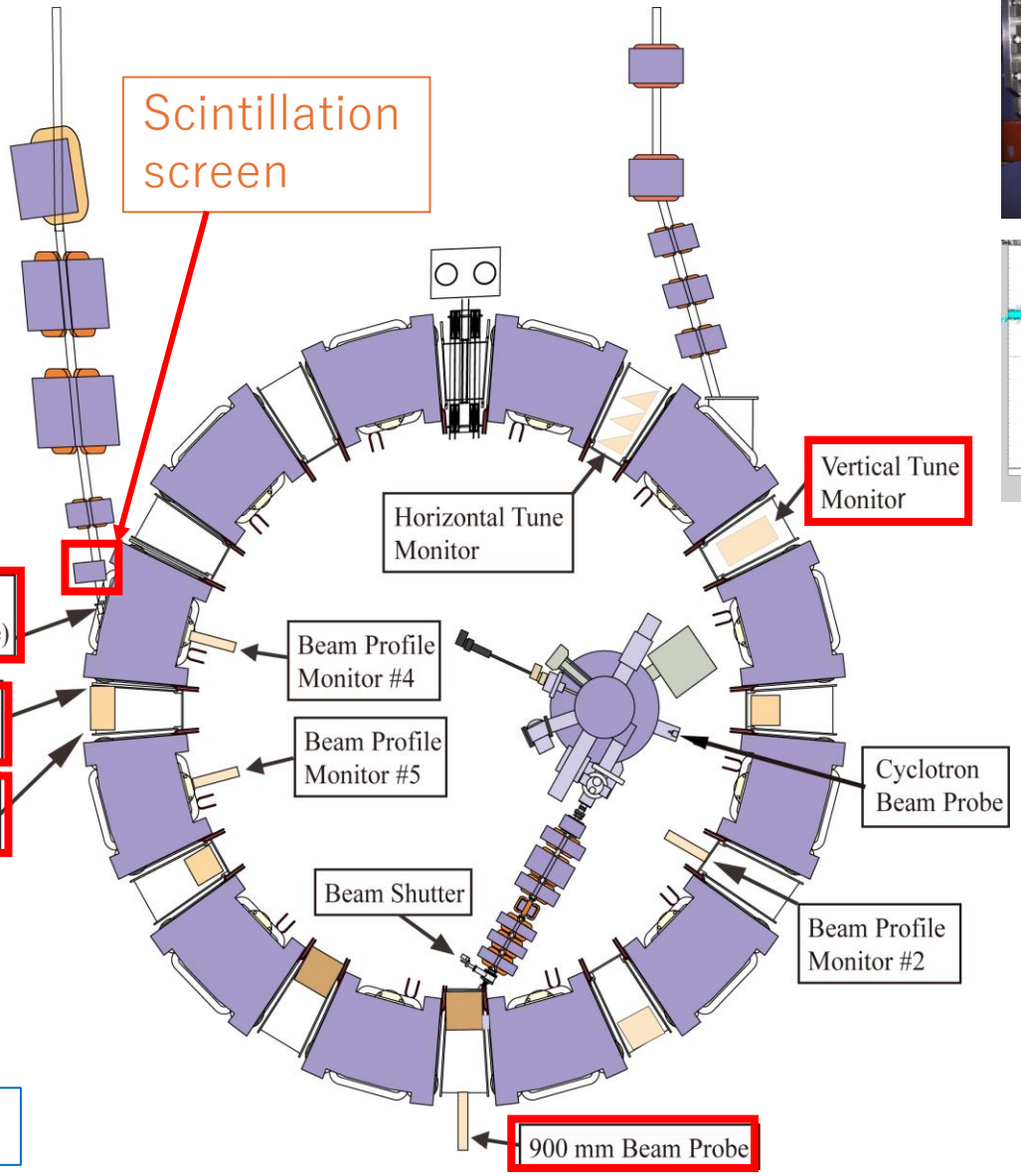
Gap Voltage	4 .0 kV/cavity
RF frequency	1.5 – 4.2 MHz
Synchronous Phase	20 deg.

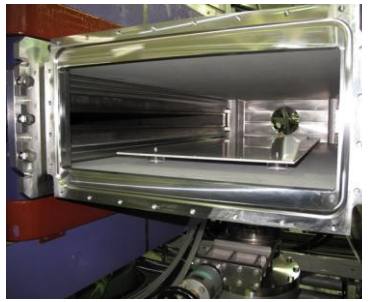
Layout of beam monitors

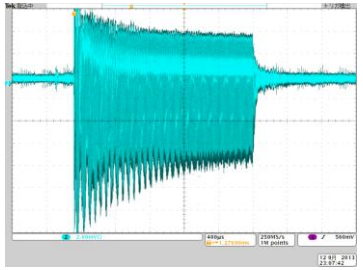


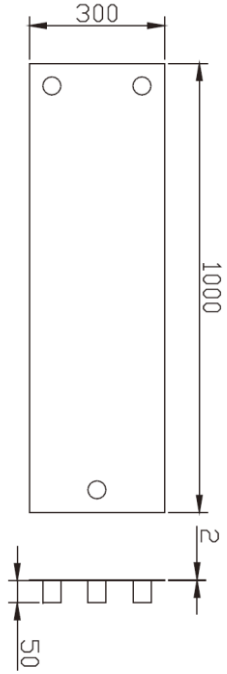


Extraction magnetic septum



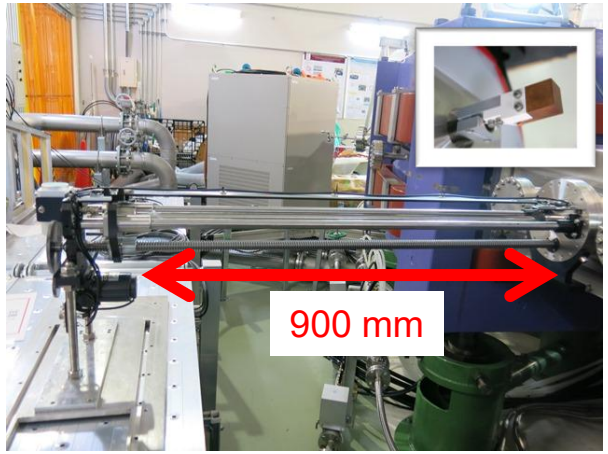






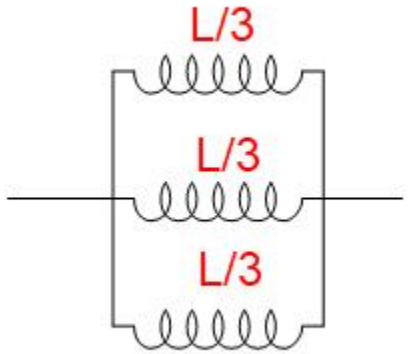
Bunch monitor

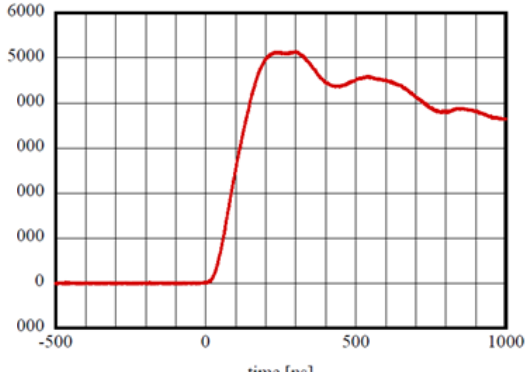
Copper electrode



Destructive beam monitor

Extraction kicker





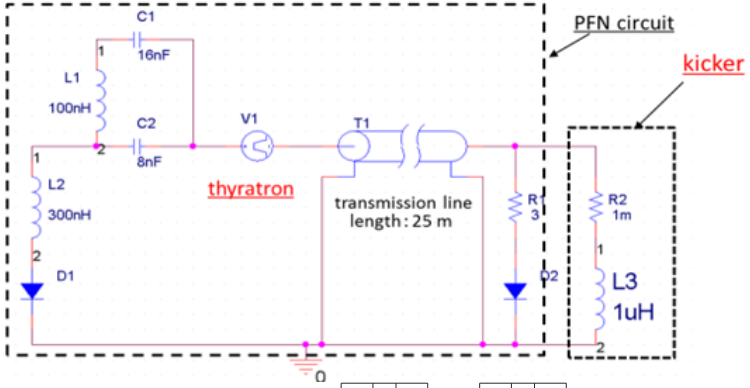
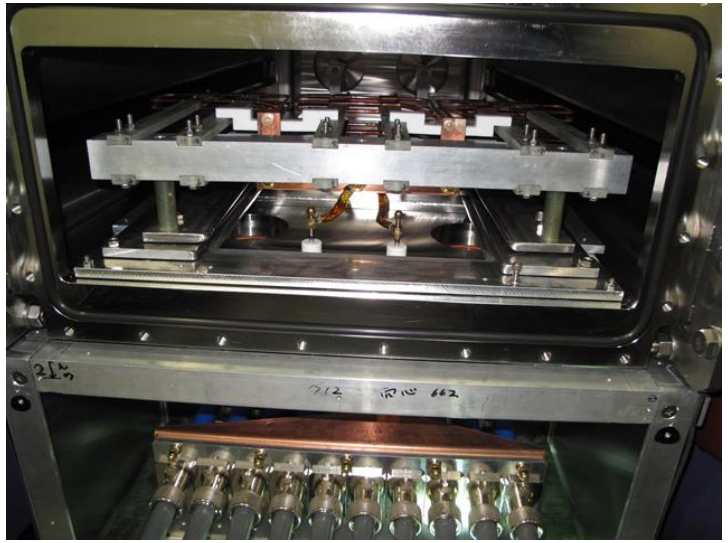
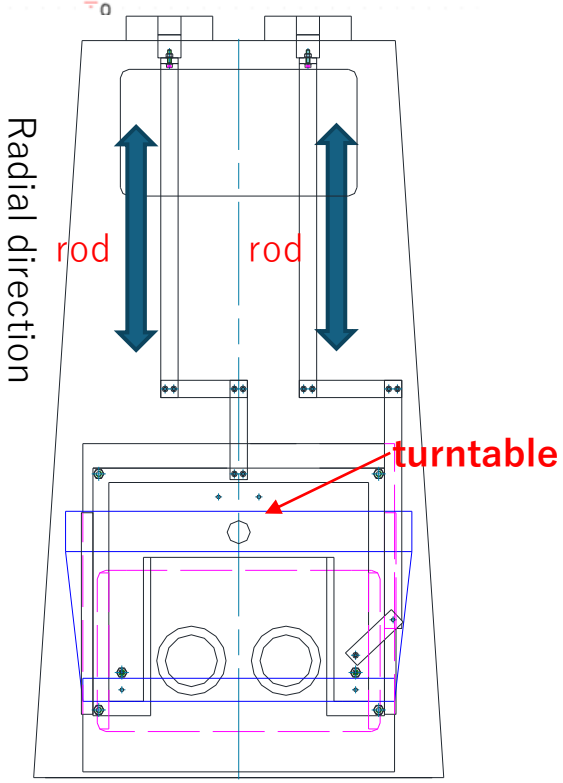


Table 4: Design parameters extraction kicker

Magnet type	3 air core coils
Magnet length	600 mm
Gap width, height	60 mm, 26.4 mm
Switching device	Thyratron (E2VCX1175)
Output wave form	Square wave
Rise time, Flat top	160 ns (5 – 96 %), 140 ns
Peak current	5100 A
Charging voltage	40 kV





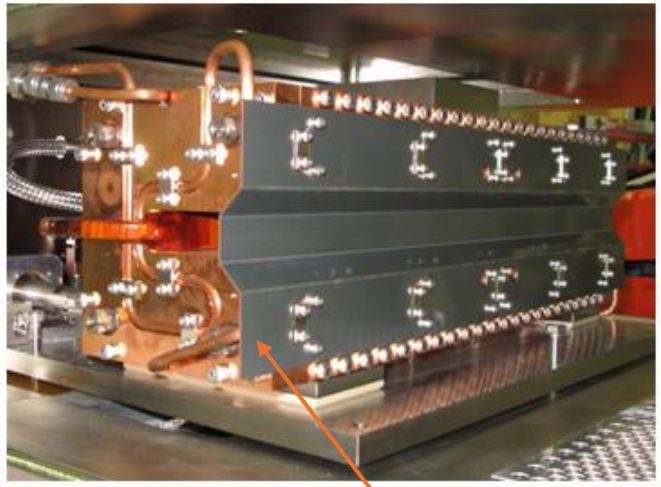
The position and angle were adjusted to maximize the extracted beam intensity.

Extraction septum

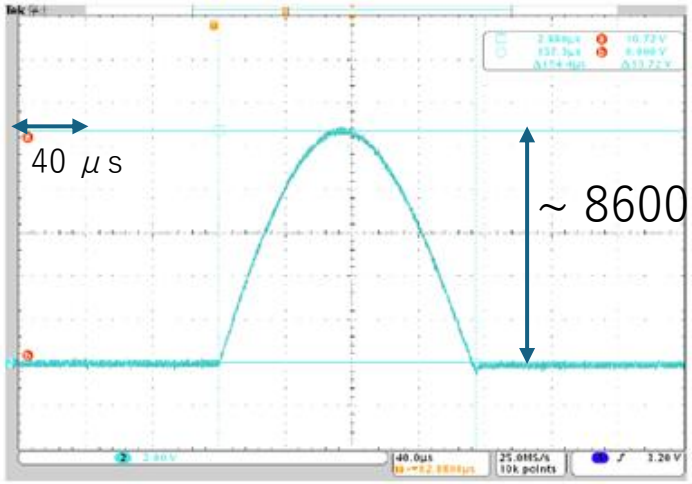
The extraction septum magnet is a pulsed C-type bending magnet with a field suppression plate.

Table 3: Design parameters of extraction septum

Magnet length	460 mm
Gap width, height	70 mm, 23 mm
Output waveform	Half sinusoidal wave
Switching device	Thyristor (FT1500EY-24)
Time length	155 μs
Peak current	8600 A
Charging voltage	3.7 kV

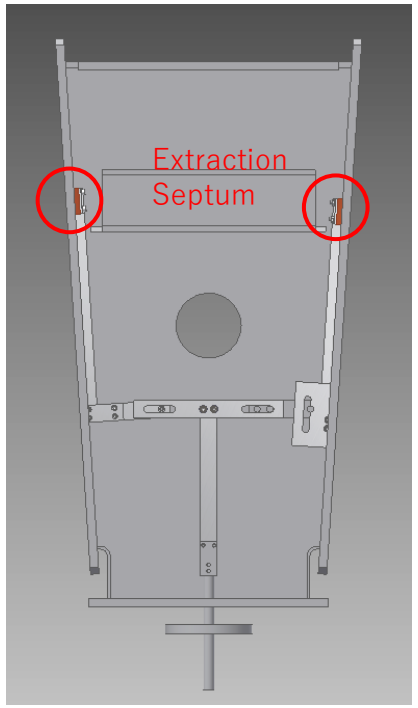


Field suppression plate



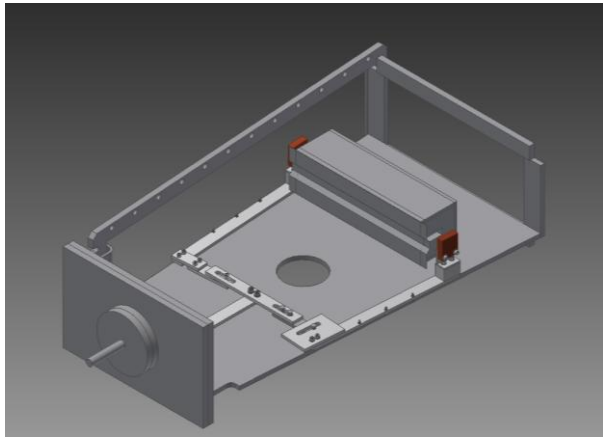
Waveform of output current

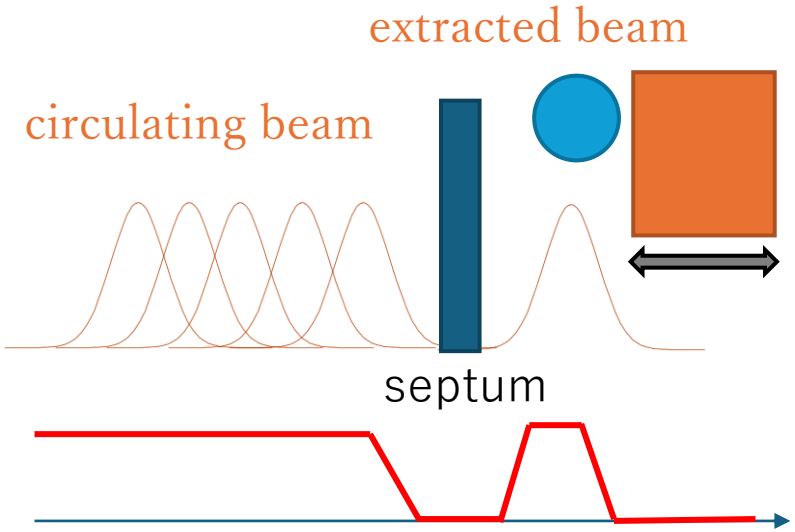
Beam shutters at extraction septum

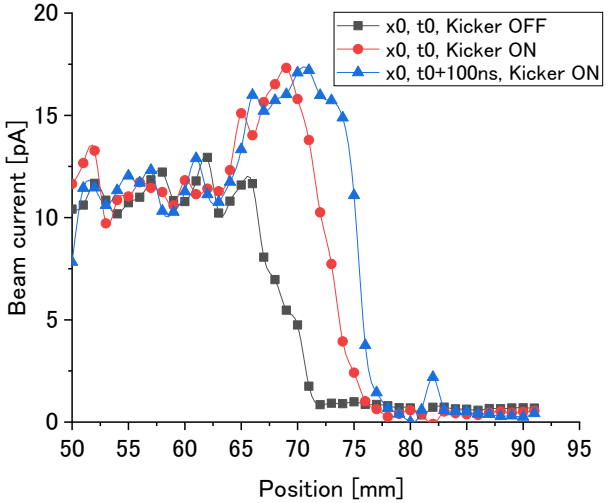


Movable beam shutter #1 (Inlet)

Movable beam shutter #2 (Outlet)



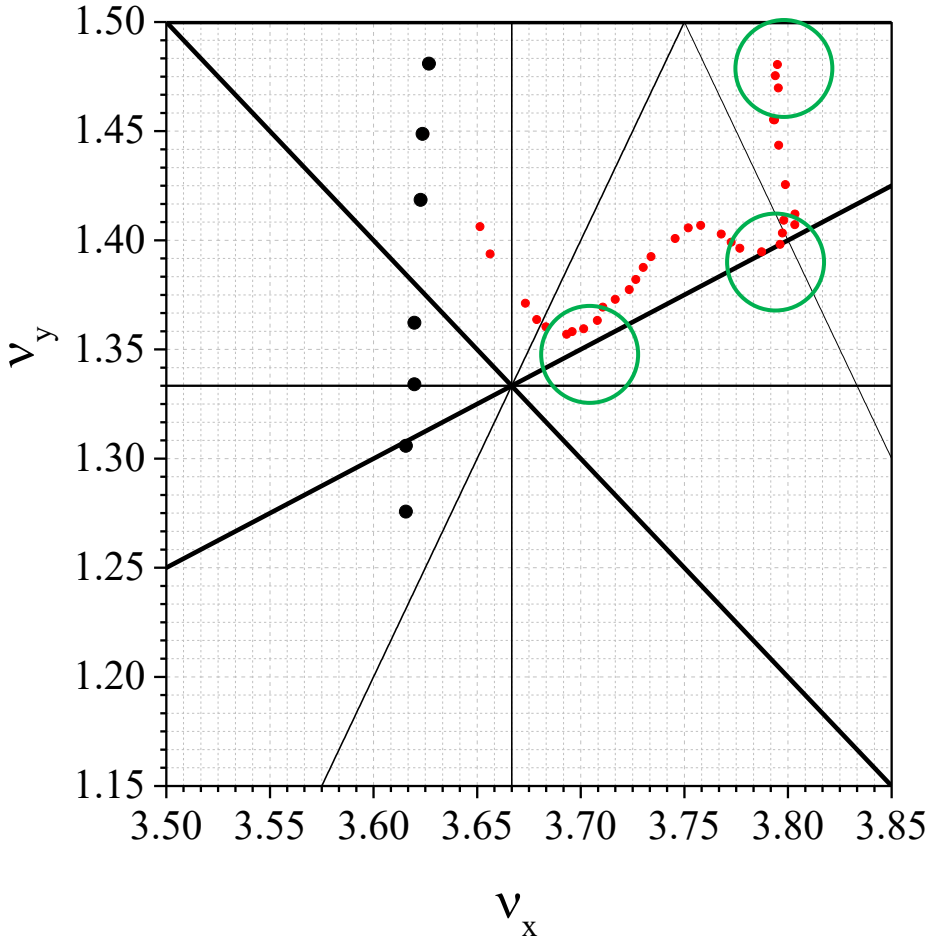




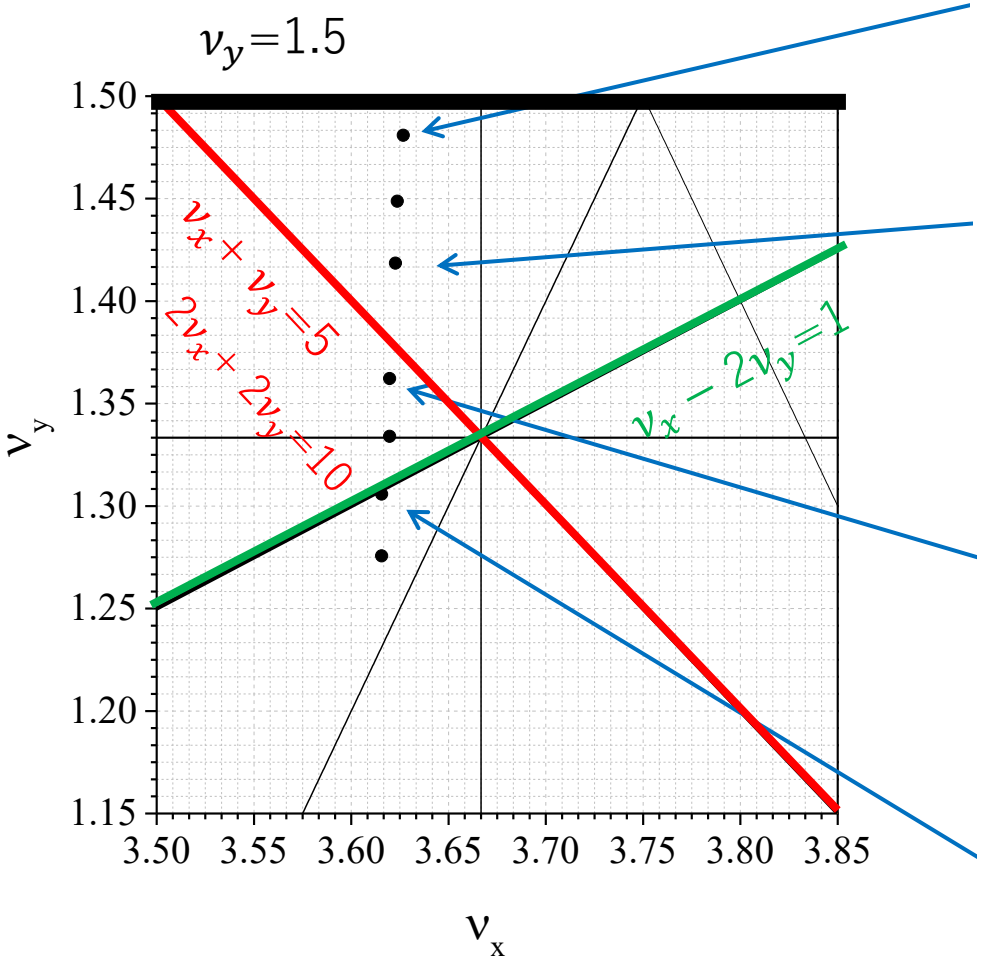
The position and angle of kicker magnet were adjusted, and
the excitation timing of the kicker and septum magnet was optimized
to maximize the intensity of the extracted beam at the beam shutter #2.

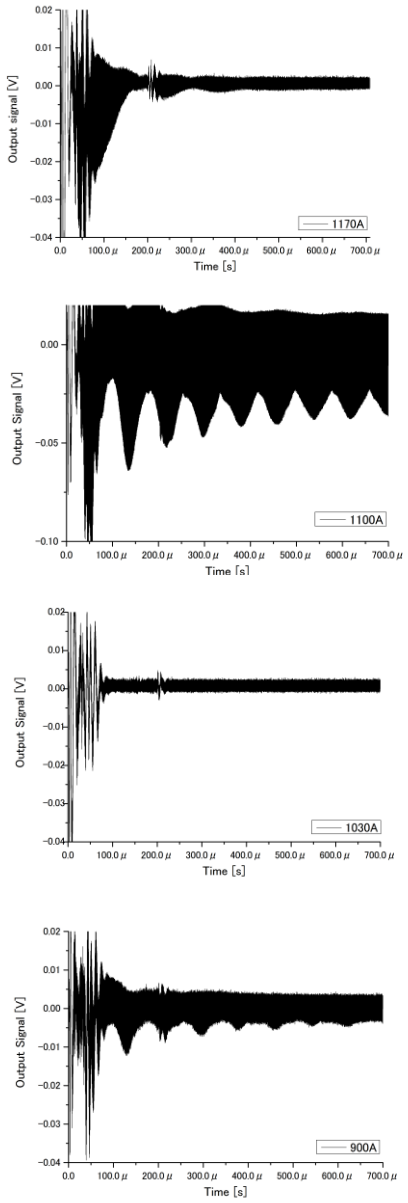
Beam losses caused by betatron resonance

$\nu_x + \nu_y = 5$, $\nu_y = 1.5$ and $\nu_x - 2\nu_y = 1$ are strong resonance lines.



Vertical tune should be corrected.

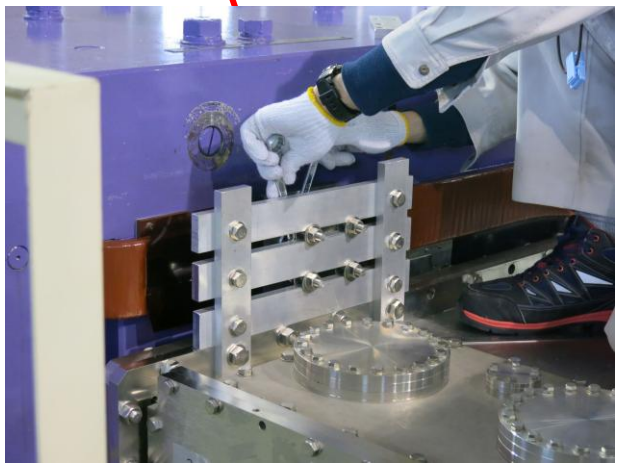




Additional magnetic plate to adjust vertical tune

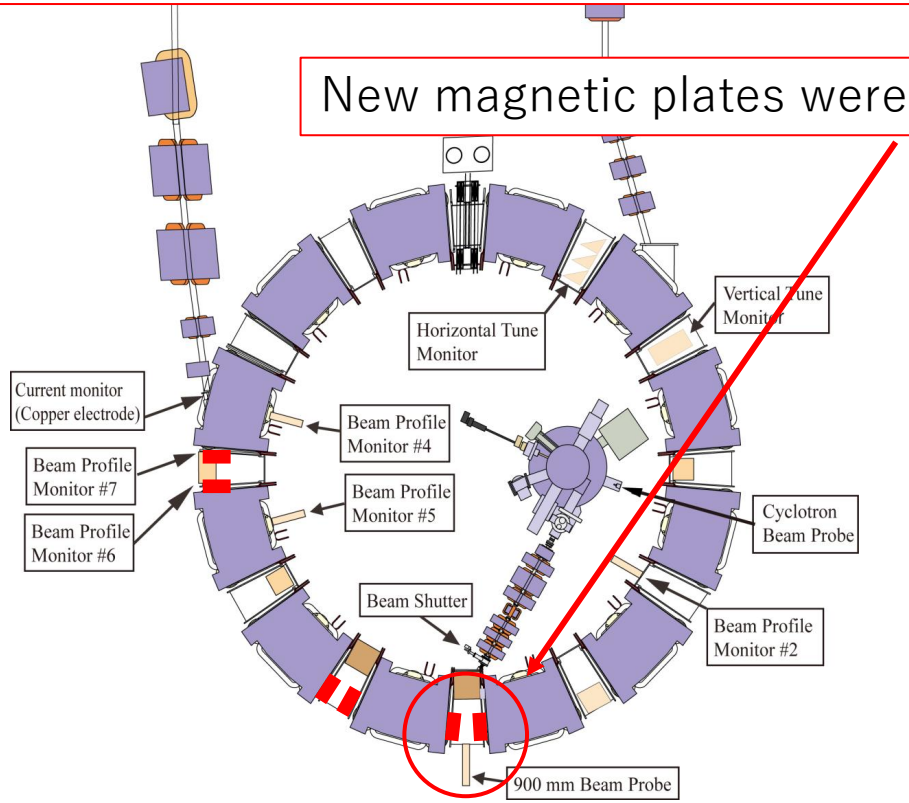
In order to reduce beam loss during acceleration, additional magnetic plates for vertical tune adjustment are installed on both sides of the magnet.

Dimension
300 x 140 x 15

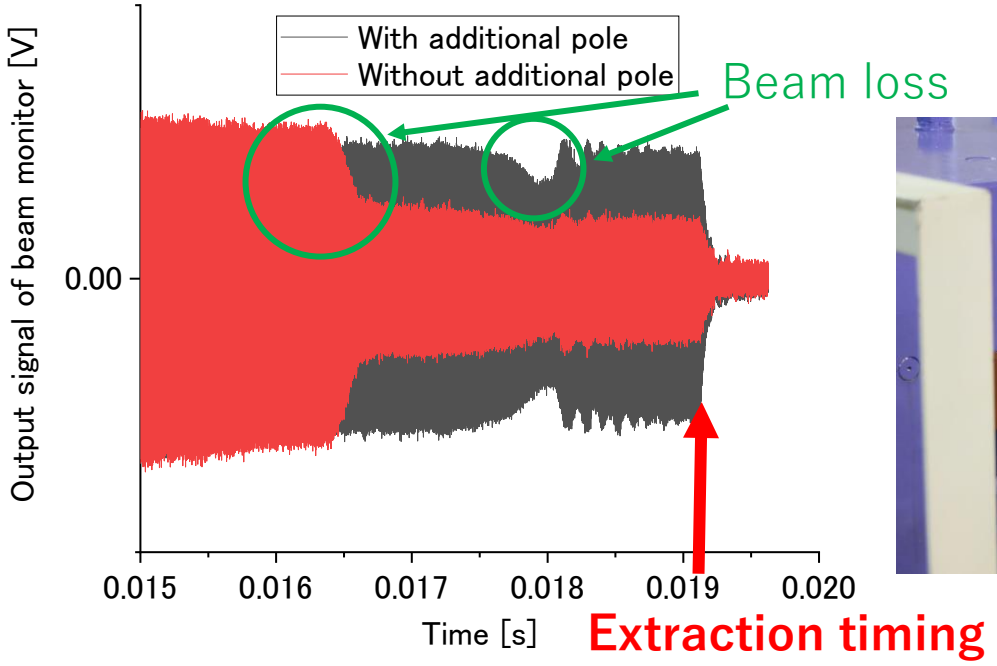


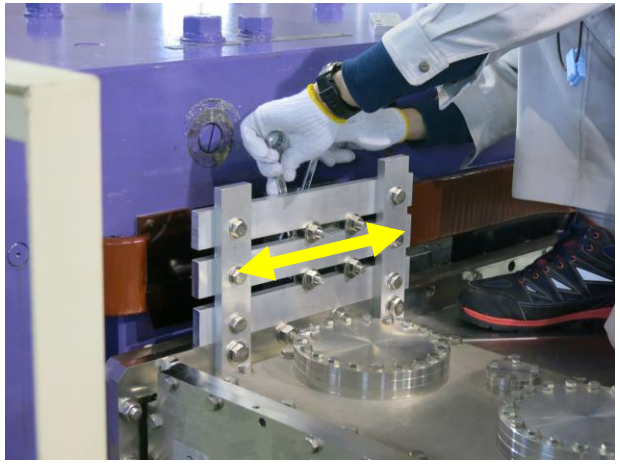
- The magnetic poles are installed at the locations indicated by red rectangles.

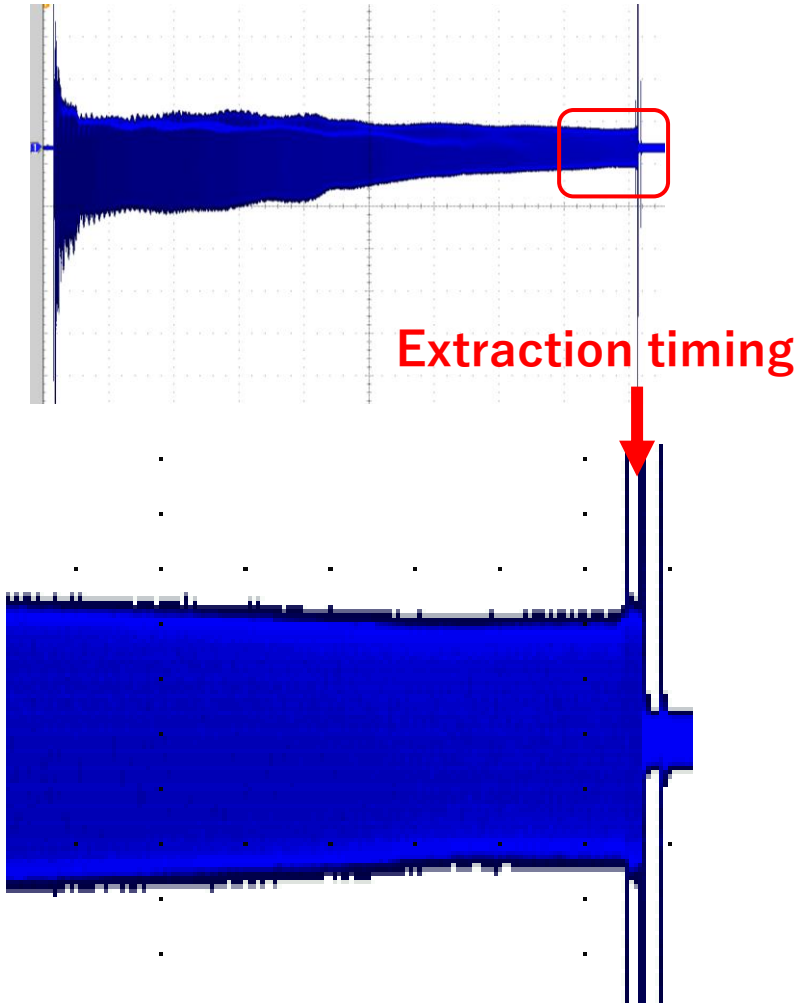
New magnetic plates were installed



Reduction of beam loss near the extraction orbit





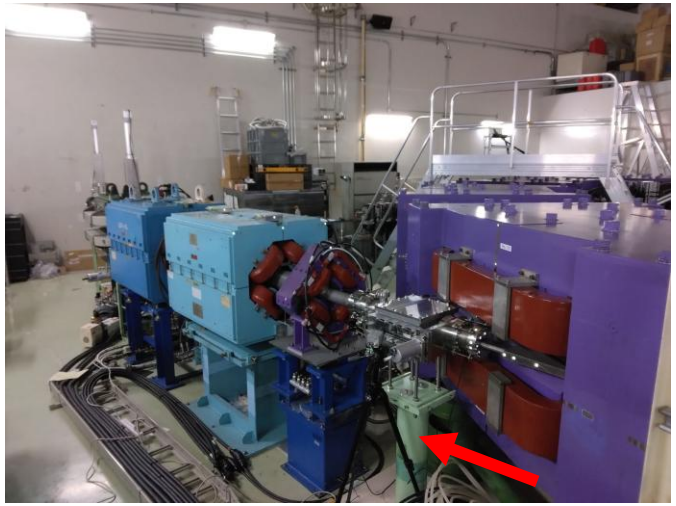


The optimization of the positions of the additional magnetic poles effectively reduces beam loss in near the extraction orbit.

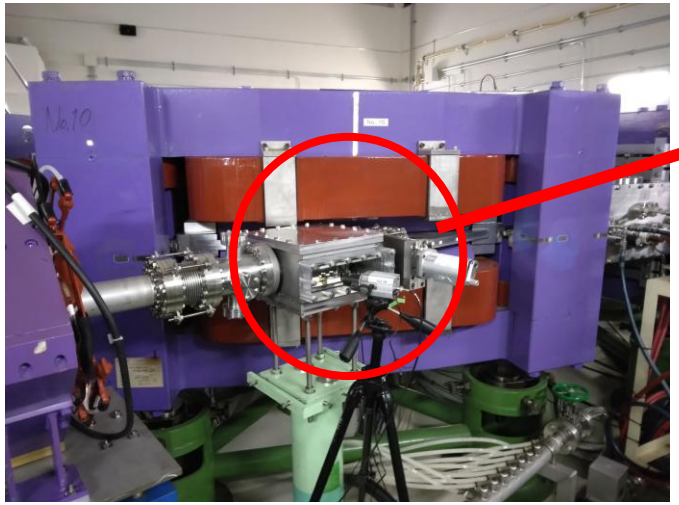
Beam at extraction

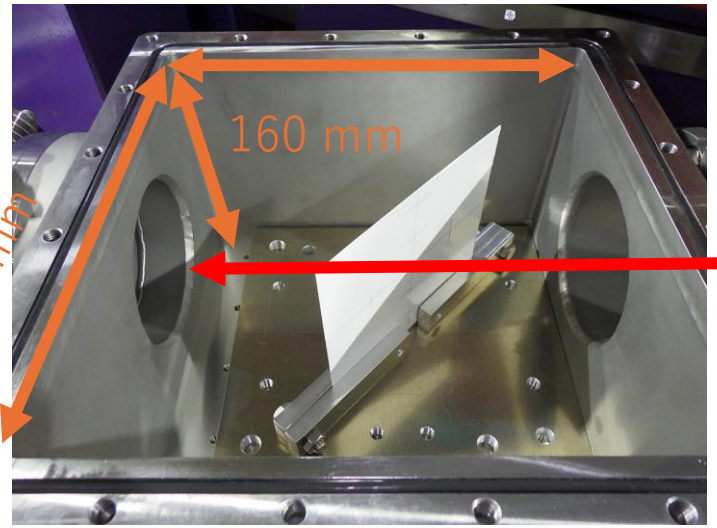
Beam profile was measured with a scintillation screen.

- Measured horizontal beam size: ~ 100 mm
  Vertical beam size: ~10 mm
- Energy: 78 MeV (100MeV in the future)
- Extracted beam at the extraction port is approximately 15 pA.



Extracted proton beam

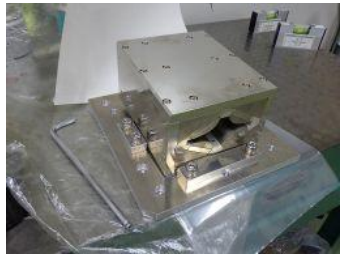




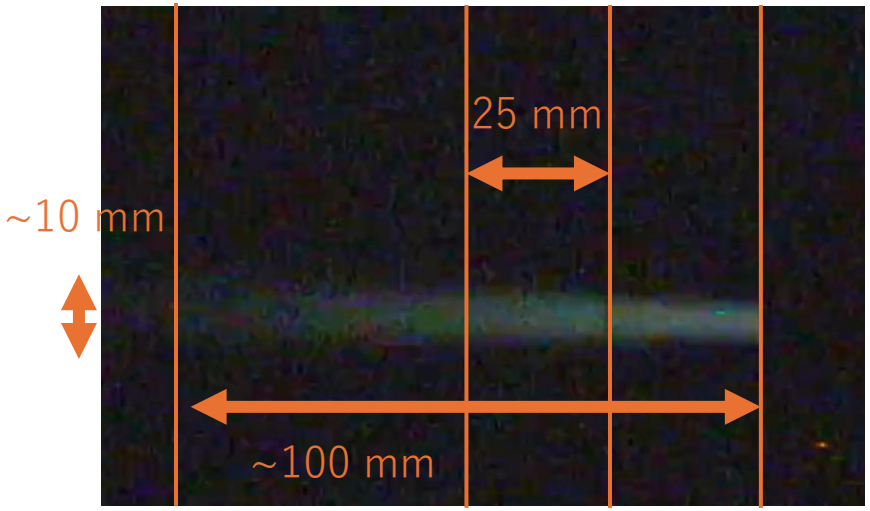
Proton Beam

Scintillation screen installed in vacuum chamber

Beam commissioning of beam transport line will resume in October after maintenance and installation of a quadrupole permanent magnet.



quadrupole permanent magnet



Beam profile measured with scintillation screen

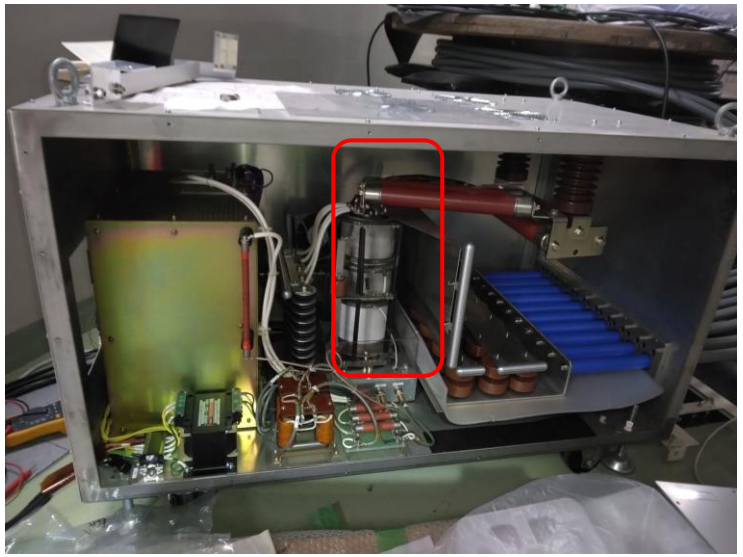
Equipment failures during beam commissioning

1. **<u>Water leakage occurred from the ion source cathode of cyclotron</u>**

➔ Corrosion caused by cooling water
➔ The cathode was replaced.

2. **<u>A hydrogen gas leak occurred from the supply system connected to the ion source due to aging degradation.</u>**

➔ Replacement of the gas supply system is currently in progress.



Discharge area of Thyratrons

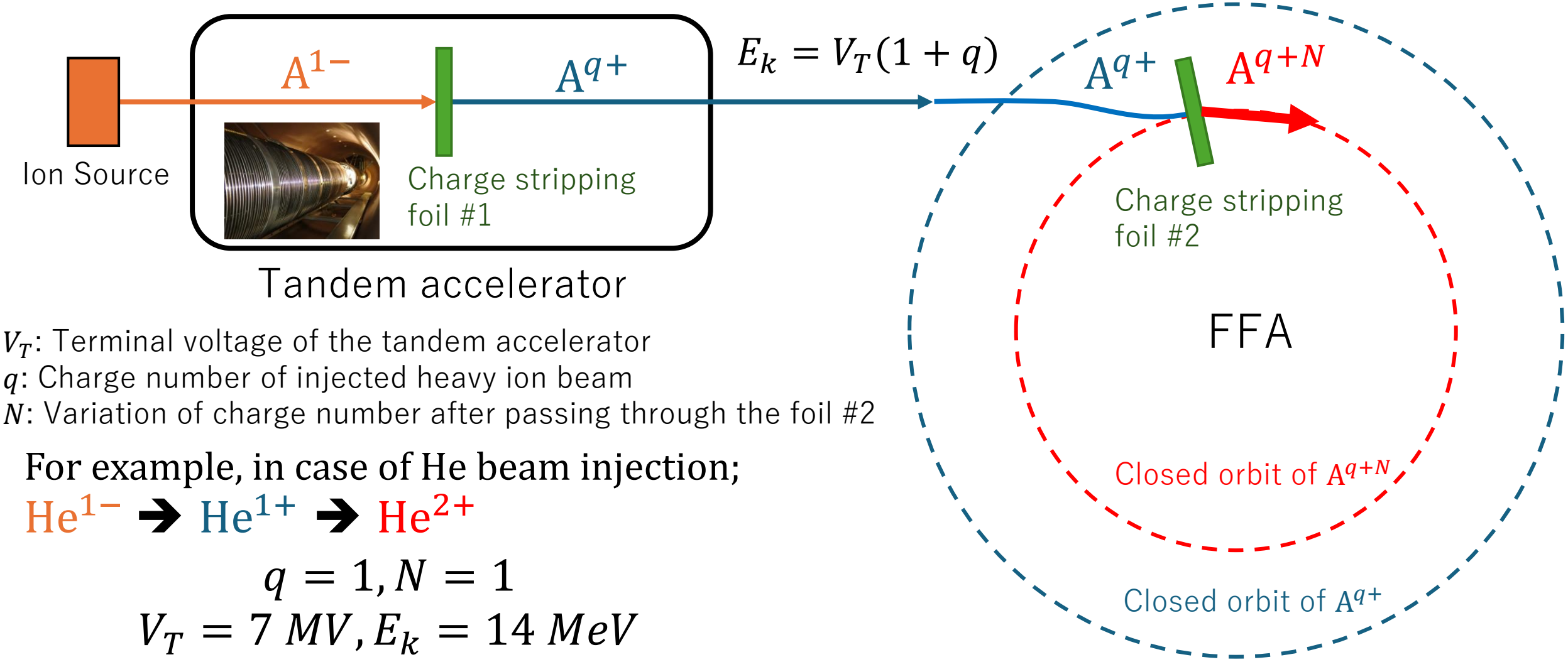
3. **<u>Discharge occurred along the side of the thyratron</u>**

To prevent discharge, the charging voltage was lowered from 42 kV to 38 kV,
resulting in a drop in output current from 5100 A to 4700 A and reduced beam extraction efficiency.

A redesigned power enclosure is being implemented to increase the clearance between the thyratron and the chassis. Improvements to the surrounding circuitry of the thyratron are also underway.

2. Injection and acceleration of heavy ion with the 150 MeV FFA

Experiments are underway to demonstrate heavy-ion injection and acceleration using an FFA



V_T: Terminal voltage of the tandem accelerator
q: Charge number of injected heavy ion beam
N: Variation of charge number after passing through the foil #2

For example, in case of He beam injection;

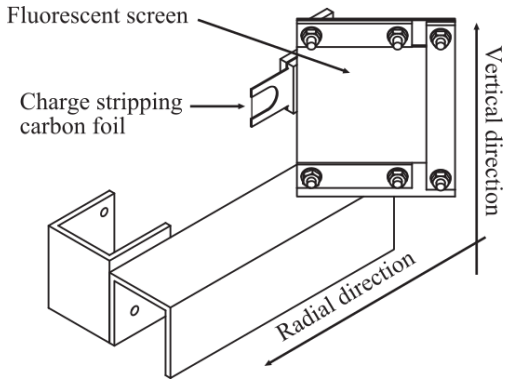
He^{1-} ➔ He^{1+} ➔ He^{2+}

$$q = 1, N = 1$$
$$V_T = 7\ MV, E_k = 14\ MeV$$

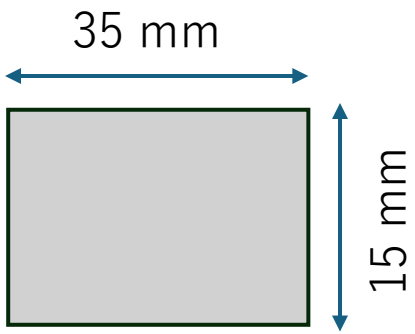
As the first step to verify the injection method, an orbit shift from one charge state to the other is demonstrated.

Upgrade of Charge exchange injection system

Improvement of the charge conversion system is required prior to the heavy-ion acceleration demonstration.
To improve injection efficiency, it is necessary to enlarge the size of the carbon film and reduce its thickness

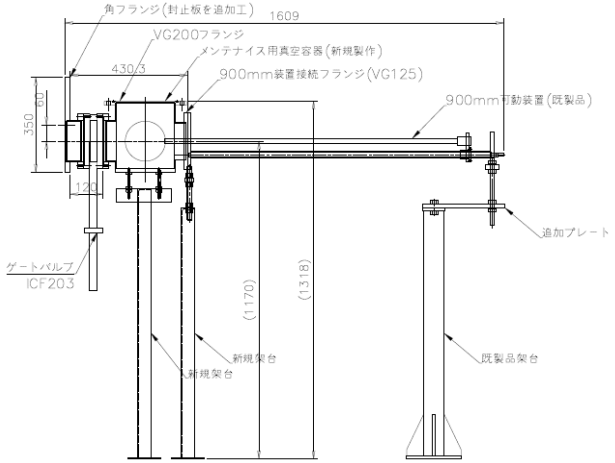


Carbon foil for injection test
10 mm × 10 mm
50 μg/cm^2



35 mm × 15 mm
10 μg/cm^2

Since foil replacement takes long time,
a simple replacement mechanism is required



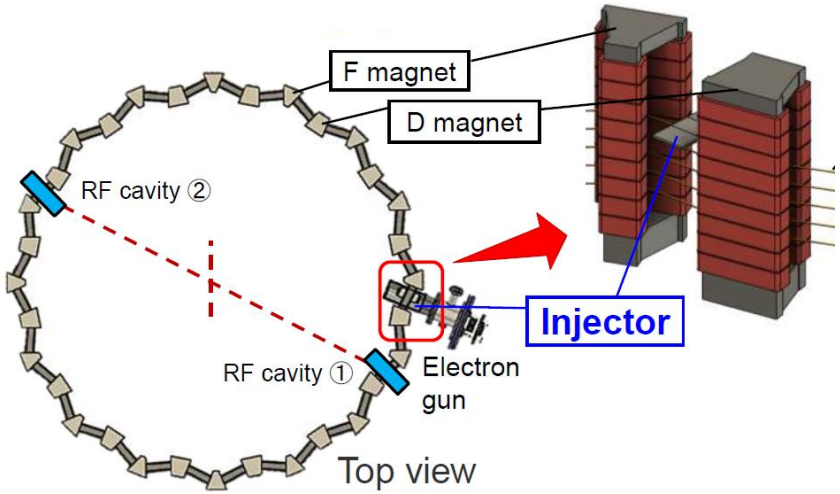
Design and development of an independent vacuum chamber for foil replacement

A budget for system renewal was secured, and the new equipment is currently under fabrication

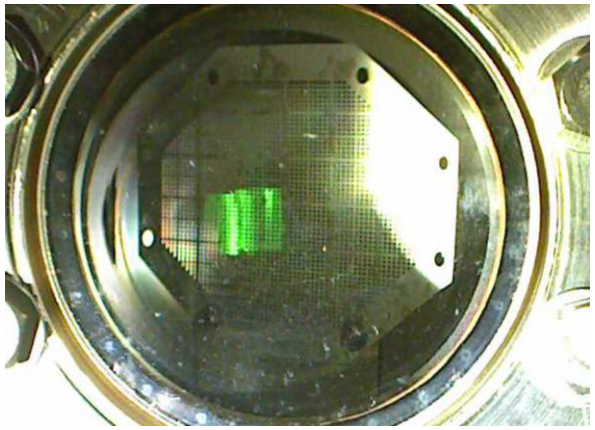
Status of development of vertical FFA

Beam transport tests are currently being conducted to verify the principle of vertical FFA.

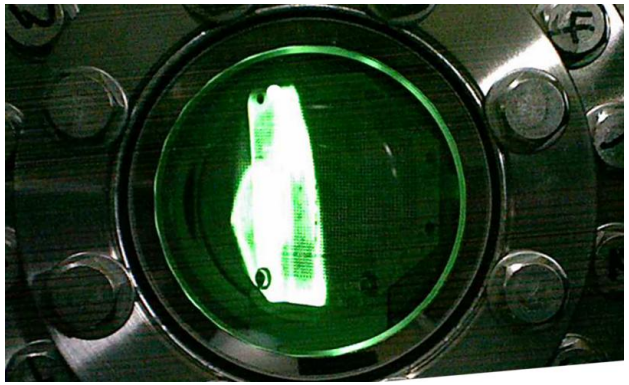
The position and profile of the beam injected from the electron gun are currently being adjusted. The initiation of a beam transport test will be started.



1/4 cell of vertical FFA



A fluorescent screen coated with ZnS on its surface.



As Arima-san has secured research funding for vertical FFA studies, Installation of the additional cells is planned.

Construction plan of facility for production of neutron and unstable nuclei with FFA-ERIT

A construction budget has been requested for this fiscal year.

In the 1st stage (2026~?)

1. **Neutron production using 11 MeV of proton beam from the tandem accelerator.**

   11 MeV proton beam + Be target

2. **Preliminary research for a new method with ERIT scheme for production of unstable nuclei**

➔ Prof. Sakaguchi's and Mr. Kitagawa's presentation

- To measure production efficiency
- To examine the separation method of produced nuclei

Stable nuclei Beam:

5~6 MeV/A of $^{7}_{3}\mathrm{Li}$ (charge state: +1)

$3 \leq Z(Atomic\ number) \leq 20$

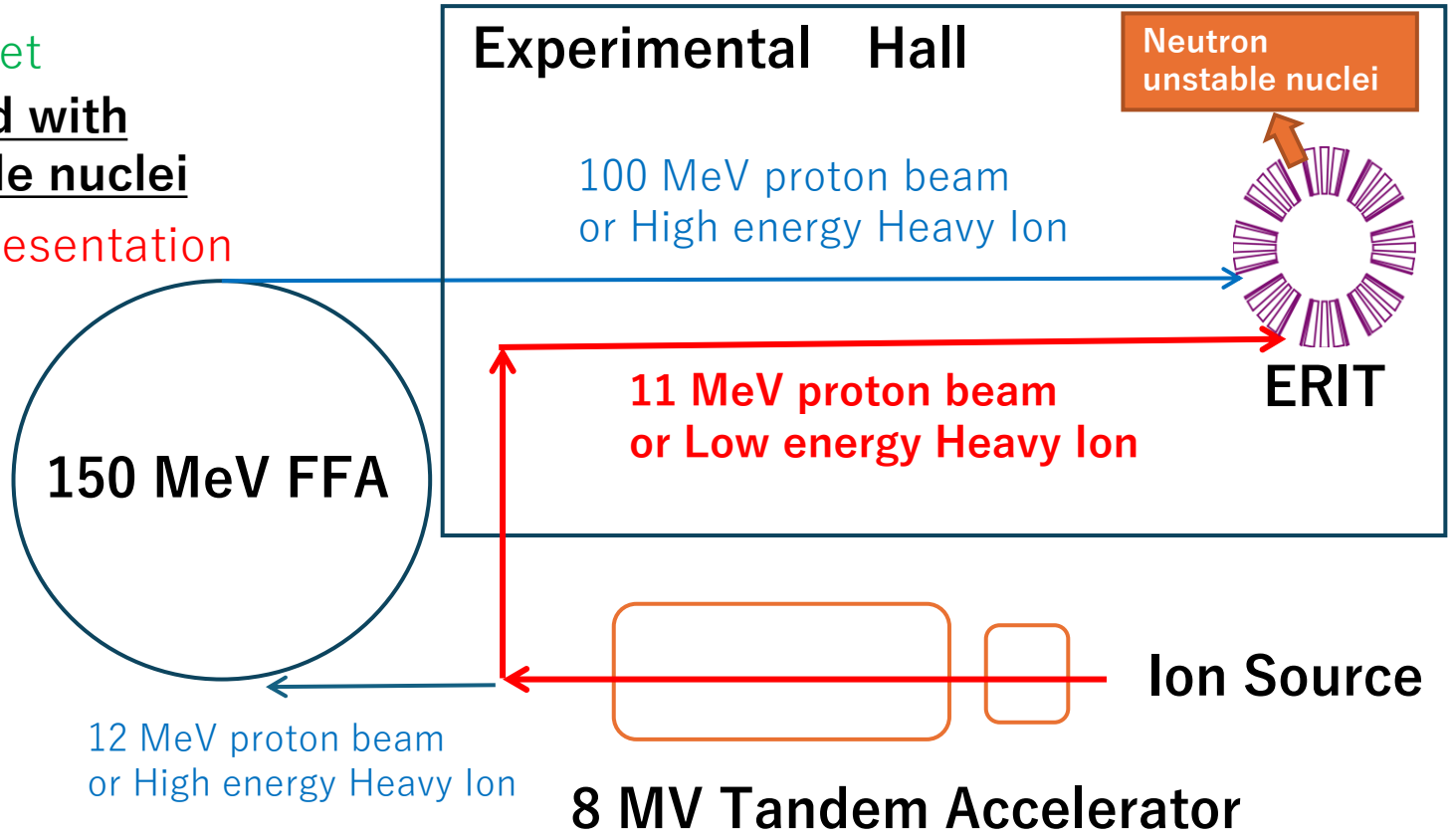
Stable nuclei Target:

Heavy nuclei target (Bi ?)

In the 2nd stage (undecided)

Remodeled ERIT for medium-energy beam

➔ Mr. Tominaga's presentation



Summary

- The present status of the accelerator facility in Kyushu University is reported.
- The development of a prototype machine of the vertical FFA is in progress.
- Upgrading of charge exchange injection and acceleration system for heavy ion beam is in progress.
- The construction of the beam transport line from the FFA to the experimental hall has been completed. Beam commissioning started in January 2025.