

DEVELOPMENT OF FFA AT CENTER FOR ACCELERATOR AND BEAM APPLIED SCIENCE OF KYUSHU UNIVERSITY

Y. Yonemura^{1,†}, H. Arima¹, N. Ikeda¹, K. Watanabe¹, N. Shigyo¹, T. Wakasa¹, T. Teranishi¹,
H. Nishibata², T. Iwamura¹, A. Takagi³, H. Nakayama³, Y. Mori⁴

¹Kyushu University, Fukuoka, Japan

²University of Teacher Education Fukuoka, Fukuoka, Japan

³KEK, Tsukuba, Japan

⁴Kyoto University, Kyoto, Japan

Abstract

Center for Accelerator and Beam Applied Science of Kyushu University has been established to promote activities in various fields such as, medical, educational and engineering fields at Kyushu University. An accelerator facility consists of a 10 MeV proton cyclotron, an 8 MeV tandem accelerator and a 150 MeV fixed-field alternating gradient accelerator (150 MeV FFA). In this paper, status of the hardware development and results of the beam commissioning of the FFA at Kyushu University are reported.

INTRODUCTION

Center for Accelerator and Beam Applied Science has been established to promote activities in all the related scientific, medical, engineering and educational fields at Kyushu University [1]. To realize the purpose of the center, Kyushu University has decided to construct a new facility merging three institutes that are Cockcroft-Walton Accelerator Laboratory of Faculty of Engineering, Institute for Irradiation and Analysis of Quantum Radiations and Kyushu University Tandem Accelerator Laboratory of Faculty of Science, on its new campus.

The facility consists mainly of a 10 MeV proton cyclotron, an 8 MV tandem accelerator [2] and a 150 MeV FFA. In this paper, status of hardware development and results of the beam commissioning of the FFA in Kyushu University is described.

OVERVIEW OF FACILITY

Figure 1 shows an overview of the accelerator facility of Kyushu University. The construction plan for the facility was divided into three phases. A building of the first phase was built in 2008, and the 150 MeV FFA and the cyclotron were constructed between 2009 and 2011. In the second phase, the construction of the buildings for the tandem accelerator and the experimental room was completed in 2014. The beam extraction line of the 150 MeV FFA and a beam injection line from the tandem accelerator to the 150 MeV FFA were constructed between 2015 and 2018. In the third phase, a new beam line from the 150 MeV FFA to the experimental room was constructed in 2024. The installation of an FFA-ERIT system [3, 4] at the end of the beamline is planned as part of a future project.

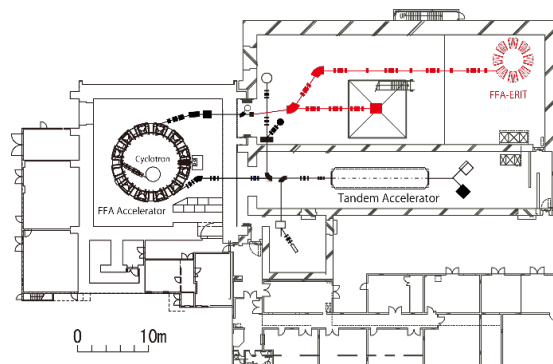


Figure 1: Overview of accelerator facility of Kyushu University. Devices highlighted in red are planned for future installation.

150 MeV FFA

The 150 MeV FFA has been developed at High Energy Accelerator Research Organization (KEK) as a prototype of proton FFA for various applications such as proton beam therapy [5]. The FFA was disassembled in June 2006, transported by land from KEK to Ito Campus of Kyushu University in March 2008.

Reconstruction of the FFA accelerator began at Center for Accelerator and Applied Beam Science of Kyushu University in 2008. Beam commissioning was started in 2011, and beam acceleration was successfully demonstrated in 2013.

The extraction kicker and the extraction magnetic septum were commissioned in 2017. The beam extraction was successfully demonstrated in 2019. The extraction beam line to the experimental room was constructed in 2024. The main parameters of the FFA are summarized in Table 1. Fig. 2 and Fig. 3 show a schematic overview of the FFA and the timing diagram of its beam operation, respectively.

Table 1: Design Parameters of 150 MeV FFA

| Beam | Proton / Helium |
|----------------------|-----------------------------|
| Energy | 10 – 125 MeV |
| Magnet type | radial sector (DFD triplet) |
| Average radius | 4.47 – 5.20 m |
| Revolution frequency | 1.5 – 4.6 MHz |
| Repetition rate | 100 Hz / 2 cavities |
| Beam current | 1.5 nA |

† ynmr@nucl.kyushu-u.ac.jp

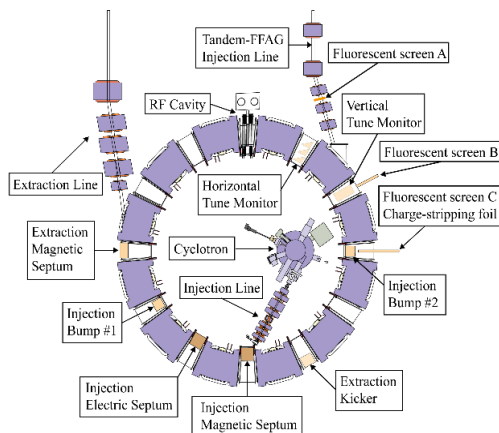


Figure 2: Schematic layout of 150 MeV FFA.

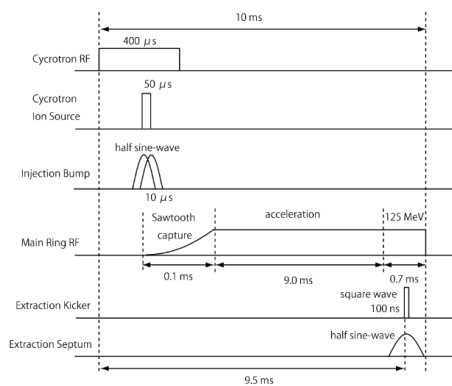


Figure 3: Timing diagram of beam injection, acceleration and extraction system.

Injection System of Heavy Ion Beam

Conventionally, the multiturn injection method is employed for positive ions in synchrotrons, including FFA accelerators. A novel charge exchange injection method for positive heavy ions using the large momentum acceptance of the FFA accelerator was employed [6]. In this injection method, the charge state of the injected positive ions is increased using a charge-stripping foil.

A schematic diagram of the injection system for a heavy positive ion beam is shown in Fig. 4. In the accelerator facility at Kyushu University, a tandem accelerator is employed as an injector for a FFA accelerator. He⁻ ions are extracted from the ion source and accelerated to 7 MeV. The electrons are stripped by an argon charge-stripping gas at the center of the tandem accelerator, and then, He⁻ ions are converted to He⁺ ions. The He⁺ beam is accelerated to 14 MeV with tandem accelerator and injected into the 150 MeV FFA. The He⁺ beam is converted to a He²⁺ beam by the charge-stripping foil.

As the first step to verify the injection method, an orbit shift from one charge state to the other was demonstrated. A charge injection system, which converts a He⁺ beam to a He²⁺ beam, is developed for a 150 MeV FFA. 14 MeV He²⁺ beam was successfully circulated.

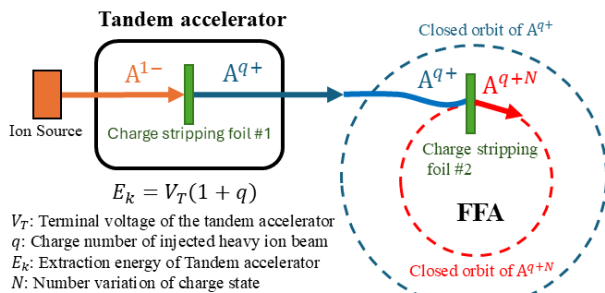


Figure 4: A schematic diagram of the injection system for a heavy positive ion beam.

Injection System of Proton Beam

A cyclotron which accelerates protons to 10 MeV is employed as the injector for the 150 MeV FFA. The injection system consists of an injection magnetic septum, an injection electric septum, and a pair of injection bump magnets. An injected beam is deflected by the injection magnetic septum, and its position and angle are adjusted by the injection electric septum. The bump magnets make bump orbit in those septa.

The bump magnet consists of an air-core coil to avoid coupling with the fringing field. The coil consists of 49 wires with a diameter of 0.6 mm to reduce the skin effect and the heat generation. The measured inductance of the magnet is 5.6 μH. The switching power source supplies a half-sinusoidal pulse current to the bump magnet. The output peak current and pulse width are 2000 A and 10 μs, respectively.

Acceleration System

The rapid cycling acceleration of the 150 MeV FFA was successfully achieved using the magnetic alloy (MA) cavity. However, the cooling system for the MA cores had a technical difficulty related to the thermomechanical reliability [7]. To address this difficulty, a new type of the RF cavity with a high-efficiency cooling system has been developed. The main parameters of the cavity are summarized in Table 2.

Table 2: Design Parameters of RF System

| | |
|-----------------|--------------------|
| Gap Voltage | 4.0 kV/cavity |
| Power tube | 4CW150,000E×2 |
| Class | B class, Push-pull |
| Core material | FINEMET (FT3M) |
| RF frequency | 1.5-4.6 |
| Shunt impedance | 200 Ω |

Figure 5 shows a schematic overview of the RF cavity. The cavity consists of two MA cores, and the water-cooled plates attached to one side of each core. Most part of the internal area of the cooling plate is covered by the coolant passages to increase the contact area between the plate and the cooling water.

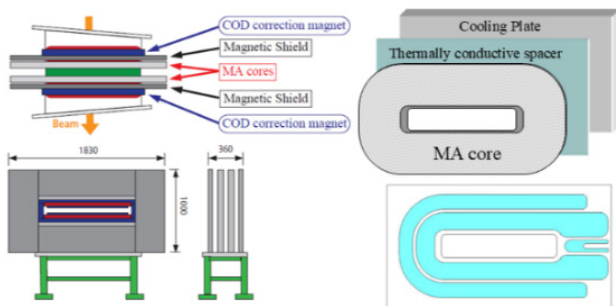


Figure 5: Overview of RF cavity.

Extraction System

The extraction system consists of an extraction kicker magnet and an extraction septum magnet. The extraction septum magnet is a pulsed C-type bending magnet equipped with a field suppression plate. The design parameters of the septum magnet are summarized in Table 3 [8].

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 μ s |
| Peak current | 8600 A |
| Charging voltage | 3.7 kV |

The kicker magnet consists of three air-core coils, which are electrically connected in parallel to reduce the total inductance of the magnet. The switching power supply consists of a thyatron and a pulse forming network (PFN). The design parameters of the extraction kicker magnet are summarized in Table 4. Figure 6 shows a circuit diagram of the extraction kicker system and its output current waveform. Figure 7 shows an overview of the kicker magnet.

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 | Thyatron (E2VCX1175) |
| Output wave form | Square wave |
| Rise time, Flat top | 160 ns (5 – 96 %), 140 ns |
| Peak current | 5100 A |
| Charging voltage | 40 kV |

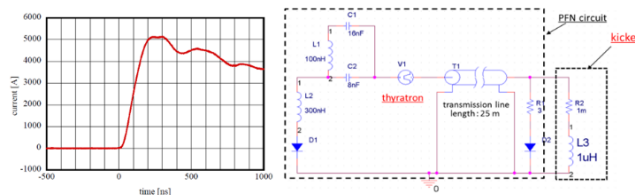


Figure 6: Output current waveform and circuit diagram of extraction kicker.

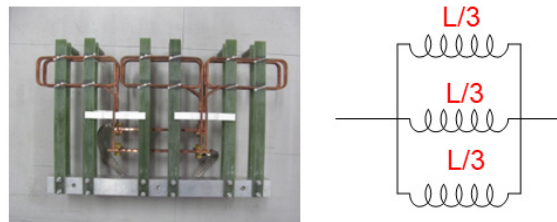


Figure 7: Kicker magnet consists of three air-core coils.

SUMMARY

The beam extraction line from the FFA to the experimental room has been constructed and the beam commissioning is currently in progress. A preliminary experiment on the injection of helium beam injection to the FFA using the new scheme have been successfully conducted. The installation of an FFA-ERIT system is planned as a future project.

REFERENCES

- [1] Y. Yonemura *et al.*, “Status of center for accelerator and beam applied science of Kyushu University”, in *Proc. EPAC’08*, Genoa, Italy, Jun. 2008, pp.3521-3523.
- [2] T. Teranishi *et al.*, “Construction of an 8MV tandem accelerator at Kyushu University - Present status report”, in *Proc. PASJ2013*, Nagoya, Japan, Aug. 2013, pp.310-312.
- [3] Y. Mori, “Development of FFAG accelerators and their applications for intense secondary particle,” *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 562, no. 2, pp. 591-595, Jun. 2006. doi:10.1016/j.nima.2006.02.044
- [4] K. Okabe, *et al.*, “Development of FFAG-ERIT system for BNCT”, in *Proc. Cyclotrons’07*, Giardini-Naxos, Italy, Oct. 2007, pp. 210-214.
- [5] Y. Yonemura *et al.*, “Development of FFAG accelerator at KEK”, in *Proc. PAC’05*, Knoxville, TN, USA, May 2005, paper FPAE026, pp. 1943-1945.
- [6] Y. Yonemura *et al.*, “Heavy Ion Injection of Fixed-Field Alternating Gradient Accelerator”, *Prog. Theor. Exp. Phys.*, vol. 2024, no. 2, p. 023G01, Feb. 2024. doi:10.1093/ptep/ptae017
- [7] Y. Yonemura *et al.*, “Development of RF acceleration system for 150 MeV FFAG accelerator”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 576, no. 2-3, pp. 294-300, 2007. doi:10.1016/j.nima.2006.11.072
- [8] M. Aiba, *et al.*, “Beam extraction of 150 MeV FFAG”, in *Proc. EPAC’06*, Edinburgh, UK, Jun. 2006, paper TUPLS076, pp. 1672-1674.