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MUON CYCLOTRON FOR TRANSMISSION MUON MICROSCOPE

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Abstract

A transmission muon microscope is an unprecedented tool which enables its users to reconstruct 3D image of samples such as a living cell. Muons can gain penetrative power as their energy increase, though electrons above 1 MeV start to trigger electromagnetic showers and protons above 1 GeV cause nuclear reactions. Muons accelerated up to about 5 MeV are able to penetrate a living cell (~10 µm), which is impossible with ultra-high voltage (1 MeV) electron microscopes. In order to accelerate muons, efficient acceleration is necessary because the lifetime of muons is only 2.2 µm.

In addition, it is important to accelerate muons without increasing their energy dispersion. Cyclotron with a flat-top acceleration system is the best suited for the transmission muon microscope and is being developed at the J-PARC muon facility (MUSE). In this paper, the transmission muon microscope project and the development of the muon cyclotron will be presented.

INTRODUCTION

Muons at muon beam facilities are generated from pion decays, and these pions are produced via nuclear reactions of a proton beam in a muon production target. The conventional muon beams have been utilized for varieties of sciences such as magnetism study using the µSR (muon spin rotation) technique, non-destructive element analysis from muonic x-ray using a negative muon beam, and so on. However, the beam size of a conventional muon beam is relatively wide ($O(10)$ mm). Development of a high-intensity muon microbeam will open a unprecedented research area using muon microscope (a transmission muon microscope and scanning muon microscope), therefore it is a very important milestone in muon science and materials research.

A high intensity muon beam, so-called "surface muon" beam (4 MeV), is obtained from positive pion decays near the surface of a muon production target, but its energy spread is large (~10 %), which is determined by a momentum bite of bending magnets in the muon beamline. The large energy spread makes it impossible to obtain a muon microbeam due to chromatic aberration. Therefore, we re-accelerate ultra-slow muons to produce a high-intensity muon microbeam. At the J-PARC muon facility (MUSE) [1], ultra-slow muons are generated by laser ionization of a muonium (Mu, a bound state of μ^+ and e^-) [2]. Since muoniums are emitted from a hot tungsten target (2000 K), the initial energy of ultra-slow muons is cooled down to 0.2 eV. We plan to re-accelerate ultra-slow muons up to 5 MeV while keeping its energy spread less than 500 eV ($\Delta E/E = O(10^{-5})$), and then the beam is focused to a muon microbeam using a superconducting lens. The novel positive muon microbeam can be used for a transmission muon microscope. The penetrative power of muons enables us to obtain image of thick sample, such as a living cell (~10 µm).

An AVF cyclotron with a flat-top RF system is adopted to re-accelerate muons. Cyclotron's efficient acceleration is inevitable because the lifetime of a muon is only 2.2 µs. A flat-top RF system is also necessary not to increase energy spread. Ultra-slow muons are first accelerated electrostatically up to 30 keV and then injected into the muon cyclotron and accelerated up to 5 MeV. The muon intensity is about 10^4 /pulse with a repetition rate of 25 Hz. The beam parameters are summarized in Table 1.

Table 1: Beam Parameters

Particle	Positive muon μ^+
Mass	m_μ = 105.6 MeV/c^2
Lifetime	τ_μ = 2.2 µs
Injection	
Number of particles	10^4 /pulse
Repetition rate	25 Hz
Kinetic energy	30 keV
Pulse width	200 ps
Emittance (1σ)	1 π mm mrad
Extraction	
Kinetic energy	5 MeV
Energy width ($\Delta E/E$)	$O(10^{-5})$
Emittance (1σ)	0.1 π mm mrad

BASIC DESIGN OF MUON CYCLOTRON

Toward the installation of the muon cyclotron in FY2020, detailed design of the muon cyclotron has been almost finished and its fabrication is on-going simultaneously. Figure 1 is a schematic of our muon cyclotron. The external structure of the cyclotron is inherited from the HM-10 cyclotron of the Sumitomo Heavy Industries, Ltd., but the internal design is quite different. Major changes are as follows:

- Built-in ion source → external injection,
- installation of a flat-top RF cavity,
- increase of gaps between poles to extract the muon beam.

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Two acceleration cavities are used and one flat-top RF cavity to supply the 3rd harmonic wave is separately installed in the valley gaps. The remaining valley gap will be used for a muon beam probe. A 5 MeV muon beam is extracted obliquely upward and then bent to a downward direction where a superconducting objective lens, a sample to image, and a camera (muon detector) are placed.

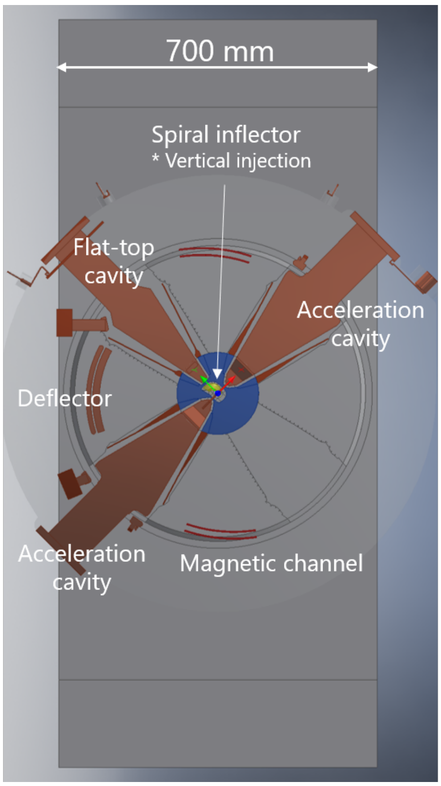

Figure 1: Muon cyclotron.

Parameters of the muon cyclotron are summarized in Table 2. Hill gaps are increased from the HM-10 cyclotron in order to install an electrostatic deflector and a passive-type magnetic channel to extract the muon beam. The RF frequency of the acceleration cavities is 108 MHz. In order to inject a 30 keV muon beam into the cyclotron, a spiral inflector is used.

MAGNET DESIGN

Isochronous condition is severe to suppress energy spread of the muon beam. The phase acceptance of a flat-top RF acceleration using the 3rd harmonic wave is 8.23° to achieve $\Delta E/E = 10^{-5}$. We designed the shape of the magnet using Opera-3D [3]. The 1/4 model implemented in the simulation is shown in Fig. 2. A passive-type magnetic channel is also implemented in the simulation to be used in the calculation of beam extraction.

Figure 3 shows deviation from the isochronous magnetic field and acceleration phase as a function of the radius of a beam orbit. The fluctuation of the acceleration phase is less than 5 % even without passive shimming of the magnet. For fine tuning of the isochronous condition, the magnet has shimming plates in the $R > 90$ mm region with a step of $\Delta R = 10$ mm. The thickness of shimming plates can be changed by ±3 mm with a precision of 0.1 mm.

Table 2: Cyclotron Parameters

Magnet	
Average field	0.4 T
Number of magnet sectors	4
Hill gap	54 mm
Valley gap	200 mm
Extraction radius	262 mm
Trim coils	None
RF	
Number of dees	2(main) / 1(flat-top)
Harmonic mode	2
RF frequency	108 MHz
Dee voltage	50 kV
Flat-top RF frequency	324 MHz
Flat-top dee voltage	10 kV
Injection	
Spiral inflector	±4.5 kV
Extraction	
Deflector	±7.5 kV/mm
Magnetic channel	Passive

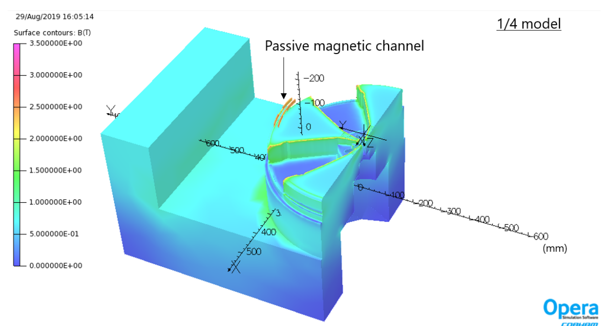

Figure 2: Opera 3D model of the magnet and the magnetic channel.

DESIGN OF RF CAVITIES

RF cavities are designed using CST Microwave Studio [4]. The main acceleration cavities are 1/4-wave resonators and connected via a copper bar. Its resonant frequency is 108 MHz and the Q-value is 5400. The dee voltage with 12 kW RF power is shown in Fig. 4. Beam couplers (feeder and pickup) are also designed, and the reflection of the RF power is enough small as shown in Fig. 5.

The flat-top RF cavity to provide the 3rd harmonic wave is a 1/2 wave resonator (Fig. 6) based on an open patent [5]. The Q-value is 5700 and the radial distribution of its voltage is shown in Fig. 4.

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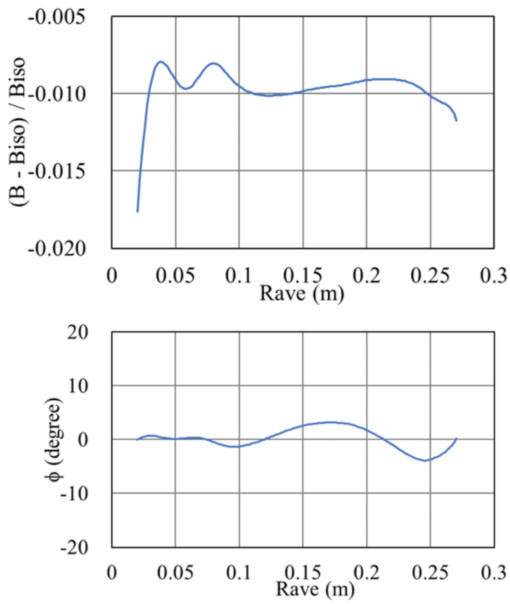

Figure 3: (Top) Deviation from the isochronous magnetic field and (bottom) acceleration phase (bottom) as a function of the radius of a beam orbit.

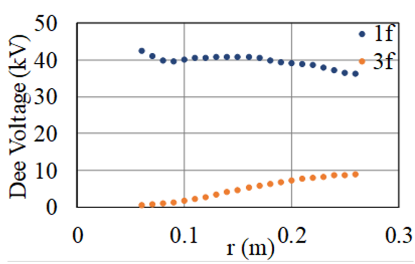

Figure 4: Acceleration voltages of the main (1f) and the flat-top RF (3f) cavities.

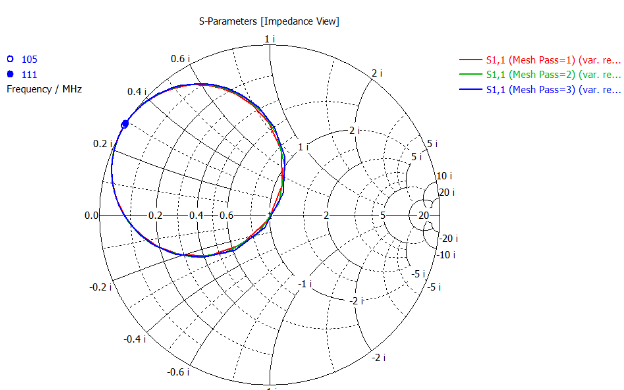

Figure 5: S-parameter (S11) of the feeder of the main acceleration cavity.

SPIRAL INFLECTOR

A spiral inflector is used to inject 30 keV muons vertically into the muon cyclotron. The electric radius of the inflector is 40 mm, and the tilt parameter (k') is −0.42. The magnetic field in the injection region is not constant is the muon cyclotron, therefore the inflector is designed considering the change of the magnetic radius. The gap of the electrodes is 6 mm and voltages of about ±4.5 kV are supplied. The electric field distribution is calculated using Opera-3D (Fig. 7).

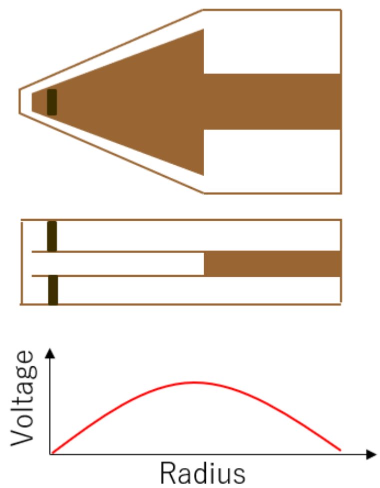

Figure 6: Schematic design of a flat-top RF cavity.

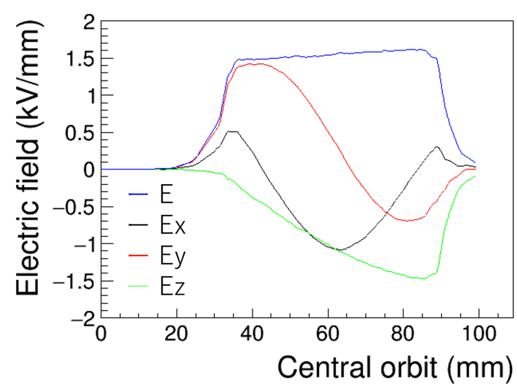

Figure 7: Electric field distribution in the spiral inflector.

BEAM ORBIT CALCULATION

Beam dynamics of muons is calculated using electromagnetic fields obtained by 1.1 μs, half of the lifetime of muons), therefore 60 % of injected muons can survive the acceleration period. Multiparticle tracking is performed assuming Gaussian distributions of 1 π.mm.mrad (1σ). Figure 8 shows the beam orbit inside the cyclotron, and the extraction loss in the deflector is only 2 %, which is negligible compared to the loss due to the muon's short lifetime. The rms emittances of R- and z-direction of the extracted muon beam are about 0.3 π.mm.mrad.

Figure 9 shows the energy spread as a function of the turn number. The energy spread of the extracted muon beam is less than 1 keV ($\Delta E/E < 2 \times 10^{-4}$). The current values of the emittance and the energy spread is quite small, but we are now trying to improve more by re-designing the central region of the cyclotron.

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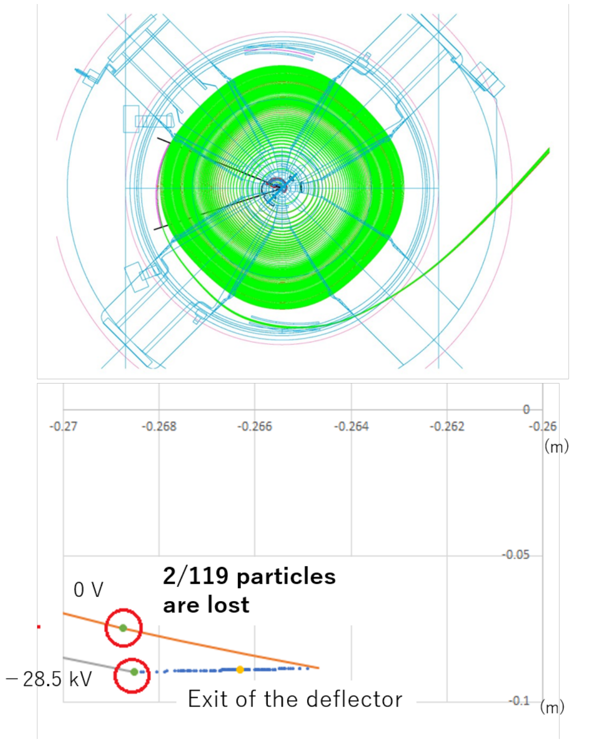

Figure 8: Beam orbit in the muon cyclotron. When 119 muons are injected, only 2 muons are lost near the exit of the electrostatic deflector.

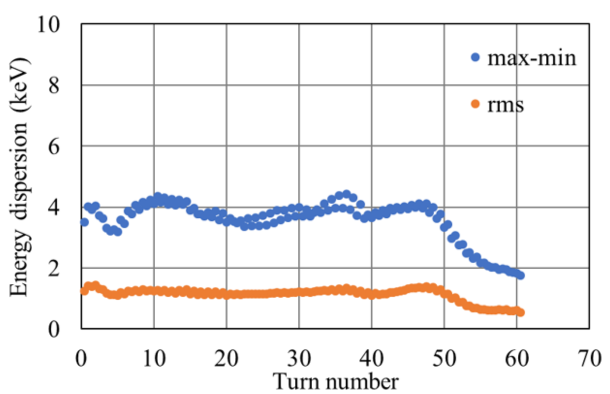

Figure 9: Change of the energy dispersion as a function of the turn number.

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CONCLUSION

We are developing the muon cyclotron for the transmission muon microscope, which will be installed in the J-PARC muon facility (MUSE) in FY2020. An AVF cyclotron with a flat-top RF system is adopted to re-accelerate ultra slow muons without increasing energy spread. The detailed design is performed using 3D electromagnetic field simulations and multiparticle beam orbit calculation. Energy spread less than 2×10^{-4} has been achieved already, but we are trying to reduce it down to $O(10^{-5})$ by tuning the design of the central region of the cyclotron.

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