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SIMULATION OF IMAGING USING ACCELERATED MUON BEAMS

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Abstract

Muons are elementary particles with strong penetrating power and cosmic-ray muons have been utilized to see through large structures such as the pyramids. Recently, we have succeeded in accelerating muons using a radio-frequency accelerator, opening the door to new imaging techniques using accelerated muon beams. Currently, imaging with cosmic-ray muons is limited in imaging time and resolution by their intensity and energy fluctuations. The muon beams can have high intensity and monochromatic energy, allowing for better resolution imaging in less time. In this paper, we review prospect of the muon acceleration and evaluate imaging of spent nuclear fuel in casks and a compressed concrete structure using cosmic-rays and beam muons.

INTRODUCTION

Muon is an elementary particle similar to the electron, with an electric charge of $-e$ and a spin of $\frac{1}{2}$, but with a mass 200 times heavier than electrons. Muons were discovered during the study of cosmic-rays in the middle of the second quarter of the 19th century [1], and have been widely used for transmission imaging of large to medium scale structures such as pyramids [2], nuclear reactors [3], and containers thanks to their strong penetrating power. Though imaging with cosmic-ray muons is a unique way to see through large or shielded structure, imaging with cosmic-ray muons is limited due to the muon flux and energy spread; in the scattering tomography [4] that measures the muon scattering angle, the scattering angle depends not only on the amount of material but also on the muon energy.

Half a century after its discovery, muons were successfully produced artificially using a proton accelerator [5], and are now widely used in various scientific fields. Recently, the acceleration of muons by a radio-frequency accelerator has been demonstrated for the first time [6]. It has opened a new era of accelerator science using accelerated muon beams, including the possibility of imaging using accelerated muon beams.

In this paper, we review the accelerated muon beam and discuss its application to transmission imaging.

ACCELERATED MUON BEAM

In recent years, the demand for muon acceleration has been increasing in many fields. Among the many future programs, the new experiment in the Japan Proton Accelerator Research Complex (J-PARC E34 [7]) is planning to measure the muon anomalous magnetic moment $(g - 2)$ and search for the electric dipole moment (EDM) as a pioneer in muon acceleration. In the J-PARC E34 experiment, muons are accelerated to 212 MeV after thermal muon generation (25 meV) by the muonium laser ionization cooling [8]. Since muons have a finite lifetime of about two microseconds, they need to be accelerated faster to avoid decay losses. From this point of view, a radio-frequency linear accelerator (linac) is adopted for muon acceleration. A schematic and basic parameters of the muon linac are shown in Fig. 1 and Table 1, respectively [9–12]. The muon acceleration has been realized [6] using a radio-frequency quadrupole linac, and the proof of principle for muon acceleration with radio-frequency electromagnetic field has been completed. Construction of the experiment is expected to begin soon, with data acquisition starting in FY2025.

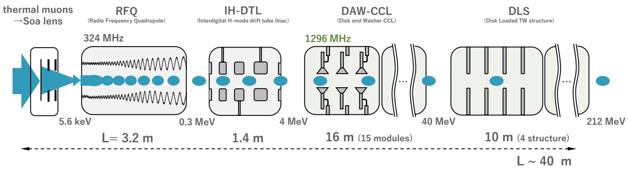

Figure 1: Configuration of the muon linac.

Table 1: Parameters of the Accelerated Muon Beam

Intensity	~ 10^6/s
Energy	212 MeV
Horizontal emittance	0.33 π mm mrad
Vertical emittance	0.21 π mm mrad
Spatial size	~ 1 mm
Directional spread	~ 1 mrad
Energy spread	0.04%

In order to realize a movable muon accelerator to inspect infrastructure such as roads, the accelerator needs to be more compact. One of the bottlenecks is a low velocity part of the muon accelerator; it needs approximately 10 m to accelerate few tens MeV in current design. In recent years, the automatic cyclotron resonance acceleration, which was realized in the electron acceleration [13, 14], has been discussed for the proton acceleration [15]. Since the muon's mass is about one-tenth that of the proton, the application of the acceleration scheme to muons moderates the strength of the required magnetic field. Figure 2 shows the simulation result for muon acceleration with the automatic cyclotron resonance scheme. A uniform magnetic field of 6.7 T is applied to the resonant cavity operating in TE_{111} mode with a frequency of 850 MHz. The injection energy and current of the muon beam are 10 keV and 2 μA, respectively, and the

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required peak power for the cavity is 5 MW. It can accelerate muons to 20 MeV with a length of 29 cm, which is much shorter than current designs. In order to achieve acceleration, more studies are needed, such as operating a high-power radio-frequency cavity in an axial magnetic field.

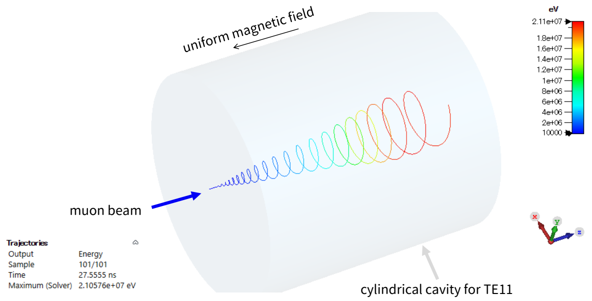

Figure 2: Example of beam tracking simulation in CST PS [16]. Muon beam trajectory is shown with its energy.

IMAGING SIMULATION

To investigate the opportunities of the imaging using the accelerated muon beams, the simulation for the scattering tomography has been developed using geant4 [17]. The energy of the accelerated muon beam in the simulation is 3 GeV, and the energy and directional divergence spread follow Table 1. For comparison, cosmic-ray muons are generated according to the model in [18] and imaging with cosmic-ray muons are also simulated. The imaging analysis is done based on Point-of Closest-Approach (PoCA) [19].

In this paper, two potential applications, spent nuclear fuel in a cask and a compressed concrete structure, are studied.

Spent Nuclear Fuel in a Cask Figure 3 shows the cask model and Table 2 shows the material composition. The muon direction before and after incidence on the cask is measured by two virtual detectors located across the cask.

Figure 4 shows scattering image based on the displacement method [20]. It is clear that imaging with accelerated muon beams (right) can achieve better resolution in less time than imaging with cosmic-ray muons (left). Further simulation studies are required to estimate the imaging resolution, required performance for the detector etc.

Table 2: Material Composition of the Simulation Model

Name	Material	Density [g/cm^3]
Tank	Steel	8.00
Buffer	SiO_2:Al_2O_3 = 0.8:0.2	2.54
Container	Steel	8.00
Box	Air	1.2e-3
Fuel	UO_2:Zry = 0.84:0.16	4.24

Compressed Concrete Structure Figure 5 shows the compressed concrete model for the simulation. The muon direction before and after incidence on the concrete is measured by two virtual detectors located across the concrete.

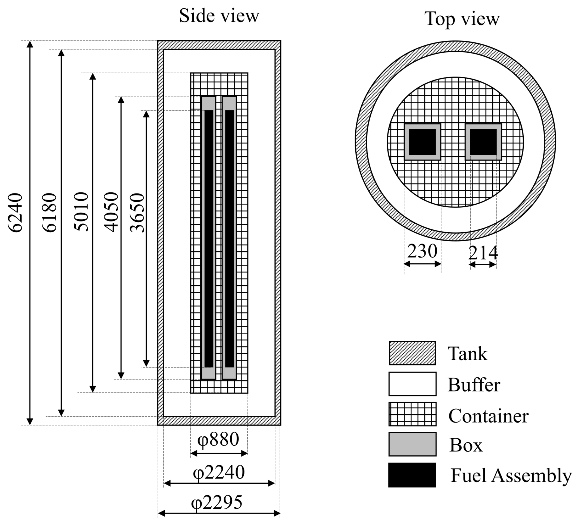

Figure 3: Model of the simulation for imaging of spent nuclear fuel in a cask.

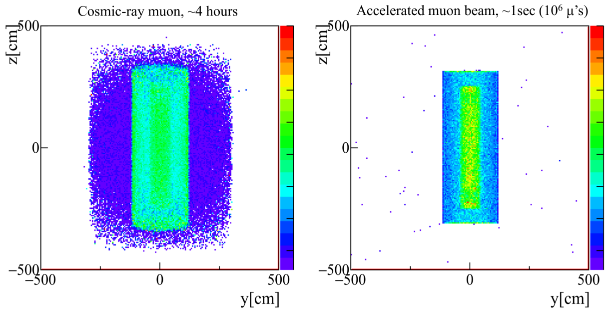

Figure 4: Simulated images (left) cosmic-ray, (rigth) accelerated muons.

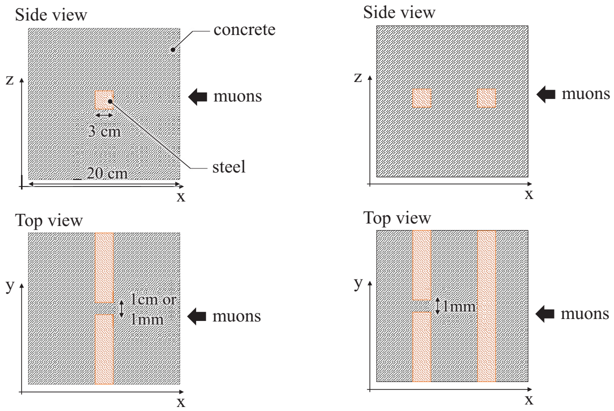

Figure 5: Model of the simulation for imaging of compressed concrete structure.

Figure 6 left (right) shows imaging result of left figure on Fig. 5 with 1 cm (1 mm) defect with cosmic-rays. The number of cosmic-ray muons is equivalent to several dozen days of data acquisition. The 1 cm defect can be clearly observed, whereas the 1 mm defect can not be seen.

Figure 7 left shows imaging for the 1-mm defect model using beam muons. The number of beam muons is equiv-

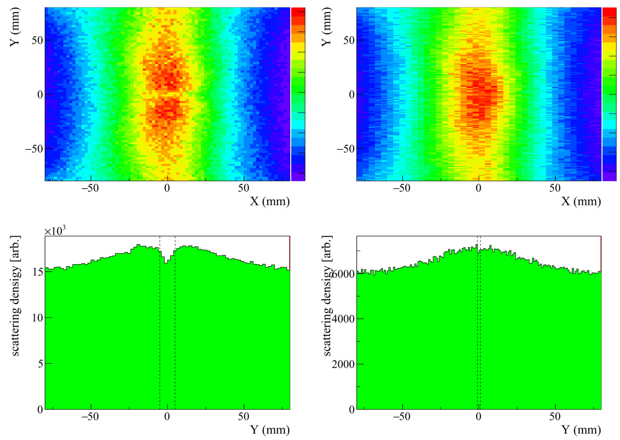

Figure 6: Imaging of a compressed concrete structure with cosmic-ray muons.

alent to several minutes of data acquisition. Thanks to the well defined direction and energy, the 1-mm defect can be clearly observed. Figure 7 right shows imaging for model of Fig. 5 right. Thanks to the strong penetrating power, the 1-mm defect in the steel on the far side can be observed, which should be not possible using conventional method with X-rays. There is no clear separation of the two steel bars due to the PoCA method, assuming scattering at a single point, and further analytical studies are needed to separate the structures.

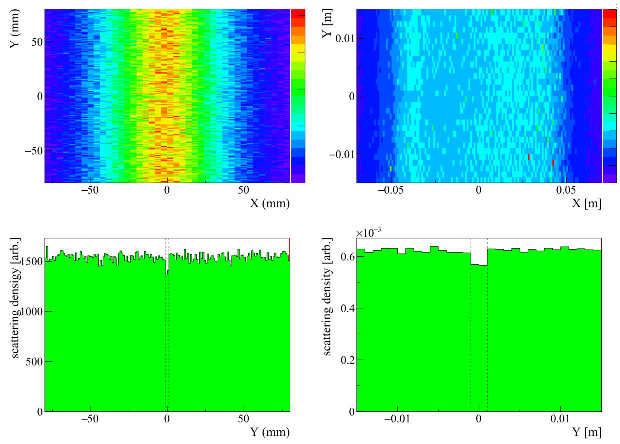

Figure 7: Imaging of a compressed concrete structure with beam muons.

SUMMARY

Muon acceleration has recently been demonstrated and the first muon linac will be started soon. The simulation for scattering tomography using beam muons are studied and compared to that using cosmic-ray muons. The first results show the great potential of imaging with accelerated muon beams. Further research will be conducted to realize a compact muon accelerator and new imaging methods in the future.

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