A PORTABLE MUON SOURCE FOR ARTIFICIAL MUON MUOGRAPHY

L. Guo, M. Kuriki*, Z. Liptak, Hiroshima University, Hiroshima, Japan

Abstract

Muography is a useful technology for non-destructive inspection of a large-scale structure. Muography with cosmic ray muons has limitations such as low rates, particularly low muon rates in the horizontal direction, and energy spreading, which require long observation times and limit its resolution. Worldwide, large structures such as bridges built during the economic development period of the 1950s-1960s have reached the end of their useful life, and the principle of preventive maintenance is being applied to save the resources, by understanding their interiors and renewing them with priority given to structures that have deteriorated. At this time, a technology of non-destructive inspection applicable to such large structures is required, and Muography using a portable artificial muons source is a promising candidate for this purpose. In this presentation, the results of the investigation of the portable artificial muon source will be presented.

INTRODUCTION

Muons are elementary particles classified as leptons, similar to electrons but with approximately 200 times greater mass. They are generated when high-energy cosmic rays—mainly protons from outer space-collide with atomic nuclei in the Earth's atmosphere. These collisions produce showers of secondary particles, among which muons are the most penetrating. At sea level, roughly one muon per square centimeter per minute reaches the Earth's surface. Muons are naturally occurring and are continuously available as a source of radiation.

Muography [1] leverages the penetrating nature of muons to visualize and analyze the internal structure of large objects without causing any damage. As muons pass through matter, they lose energy and may scatter, depending on the density and atomic number (Z) of the material.

The biggest issue of Muography with the natural muons is the long observation time due to the limited flux of the natural muons. In particular, the rate of muons flying horizontally over the earth's surface is low, making it difficult to ensure sufficient statistical quantities and limited accuracy. Muons falling from the sky have relatively high rates, in which case the detector needs to be placed underground in the object being measured, which is generally difficult to install. We consider a portable muon source to solve these issues. The portable muon source generates a high-rate and mono-energy muon beam which improves the spatial resolution and the observation time. The mono-chromatic muon beam dramatically simplify the kinematics by the fixed initial state, the position and the momentum. The muon firing direction is controllable and muons can be fired at a high rate in the horizontal direction for easy detector installation, which is expected to reduce measurement time and improve resolution.

The high throughput non-destructive measurement by the portable muon source has a high social demand as we already discussed in Ref. [2]. From the 1950s to 1960s, social infrastructures such as roads and railroads were rapidly developed along with economic development in the world. These social infrastructures are now reaching the stage of renewal due to the end of their useful lives. The amount of resources required for the maintenance and renewal of social infrastructures is enormous, and it is desirable to reduce the amount of resources required without compromising safety. The Ministry of Land, Infrastructure, Transport and Tourism in Japan (MLIT) forecasts that maintenance and renewal costs for roads and other social infrastructure will be 5.2 trillion yen in 2018 and 5.9 trillion yen to 6.5 trillion yen by 2048. The cost of highway maintenance and management is 1.5 trillion. The same scale is assumed for railroad and electric power companies. Overall, infrastructure maintenance and management costs in the mid-21st century will be more than 10.4 trillion JPY/year. MILT advocate a policy of preventive maintenance. Those in good condition will have their operational life extended, and those in severely deteriorated condition will be replaced first. The evaluation requires a non-destructive inspection which is applicable to a large structure, such as large bridges and elevated road and rail structures. The needs for nondestructive testing using portable muon sources are high. MILT estimates that preventive maintenance will reduce maintenance costs by 30 % to 50 %. Assuming that 5 % of maintenance costs are inspection costs, the market size is 500 billion JPY/year.

Muography, has emerged as a revolutionary tool for the non-destructive evaluation (NDE) of historical monuments and large-scale artworks. The primary significance of muography lies in its ability to scan massive structures without causing any physical damage or requiring radioactive sources. Currently, muography mostly relies on natural cosmic rays, which requires long exposure times (weeks to months) and specific detector placement (usually underneath or beside the target). The development of portable artificial muon sources would represent a paradigm shift in the field. While cosmic-ray muography is slow due to the low flux of natural muons, an artificial source can provide a high-intensity, controlled beam. This would reduce inspection times from months to hours, enabling rapid assessment of structural integrity after earthquakes or before restoration projects. Artificial sources allow for energy tuning. By controlling the momentum of the produced muons, researchers could distinguish between materials with similar densities (e.g., different types of stone or metal alloys), providing high-definition internal imaging of smaller artifacts like bronze

---

* mkuriki@hiroshima-u.ac.jp

statues or sealed sarcophagi. Portable sources eliminate the ”bottom-up” constraint. Researchers could move the source and detector around an object to perform Muon Computed Tomography (MuCT) from any angle. This is particularly vital for in-situ Analysis, i.e. scanning heavy artworks in museums that cannot be moved. It can be applicable to emergency surveys, i.e. checking the internal stability of historical buildings at risk of collapse. Beyond simple imaging, artificial muons can be used for Muonic X-ray Emission Analysis. When a negative muon is captured by an atom, it emits characteristic X-rays. Because muons are heavy, these X-rays are highly energetic and can escape from deep within an object, allowing for a non-destructive chemical ”fingerprint” of the interior of an artifact without sampling.

MUON PRODUCTION WITH ELECTRON BEAM

The muon production with electron beam is already discussed in Ref. [3]. The production rate is less than proton, but the electron beam system has a big advantage on its size. In addition, as described below, the low production efficiency can be compensated for by using Delta resonance at 1232 MeV [2,3].

As the technology for the electron accelerator, it is necessary to choose between normal-conduction acceleration and super-conduction acceleration. The normal-conducting accelerator has a limited input power due to the huge joule loss of the structure, and the resulting low acceleration gradient makes it difficult to build a portable 400-MeV accelerator because the accelerator itself, power supply, and cooling system are huge. Therefore, a system based on a superconducting accelerator will be considered. Considering a portable accelerator, it is important to downsize not only the accelerator itself, but also the power supply, refrigerator system, and other components as a system.

Based on our studies up to last year, we have shown that 4 K superconducting acceleration technology is advantageous for generating muons using a compact electron accelerator, as it enables the realization of high acceleration gradients while significantly reducing the size and load on the cryogenic system [2,3]. In this paper, as a new idea, we will examine muon generation via circular acceleration using an electron microtron, as described in the next chapter. The advantage of this idea is that it does not necessarily require a high gradient. This greatly enhances the feasibility of a portable microtron. However, the microtron we are considering is not a conventional microtron. Conventional microtrons require large magnetic poles and numerous orbits corresponding to different energy levels; while this allows for a significantly shorter length compared to linear accelerators, it actually increases the weight, making portability more difficult. Therefore, we will examine the Double-Sided Microtron here. In a Double-Sided Microtron, the mass of the magnetic poles can be significantly reduced. Furthermore, since the electron orbits on the long sides—where acceleration occurs—are independent of energy, the vacuum chamber can also be significantly reduced in size, making it possible to keep the weight down.

400 MeV Double-Sided Microtron

To realize a portable muon source, a compact and high-efficiency electron accelerator is required as a primary driver. We propose a Double-Sided Microtron (DSM) configuration with 4 K superconducting cavity capable of accelerating electrons up to 400 MeV. The DSM consists of four $\pi/4$ single-sided bending magnets that form a closed racetrack orbit. This configuration offers several advantages over conventional Microtron, including significant reductions in magnet mass and vacuum chamber volume, as well as easier beam injection from the inner region.

The double-sided Microtron is composed of the single-side bending as shown in Fig. 1. A particle entering at a certain angle to a magnetic pole will always emerge at the same angle. This property holds true for all energies. In other words, a particle entering at a certain angle to a magnetic pole will always emerge at the same angle, regardless of its energy. Particles with different energies have different distances between their points of entry and exit, $L = 2\rho \sin\theta$ where ρ is the orbit radius of the particle, and θ is the angle, as shown in the figure. This distance is proportional to the particle’s momentum.

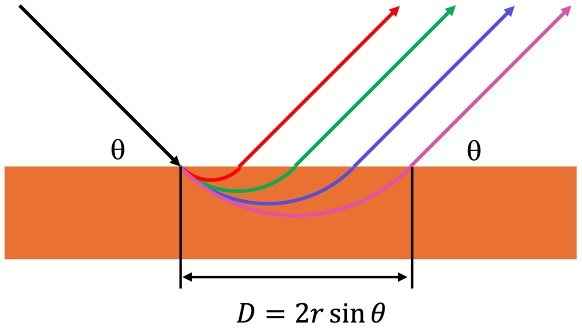

Figure 1: Particle orbits in Single-Sided Bending. The different color shows orbits of different momentum particles. A particle entering at a certain angle to a magnetic pole will always emerge at the same angle.

By utilizing this property, it is possible to construct closed orbits as shown in the Fig. 2 with four $\pi/4$ single-sided bending magnets. Since a magnetic pole with an incident angle of 45° rotates particles of any energy by 90°, arranging four such poles in a row allows for the formation of a circular orbit. As mentioned earlier, the distance of the parallel displacement of the orbit varies depending on the particle’s energy; therefore, as shown in the figure, on two sides, particles of all energies follow the same orbit, while on the other two sides, they follow different orbits depending on their energy. Therefore, we can place accelerating cavity not only in a straight section, but also in another section as shown in Fig. 3. That is why we call this system as Double-Sided Microtron.

The acceleration is performed by superconducting RF cavities located in the two straight sections. For electrons,

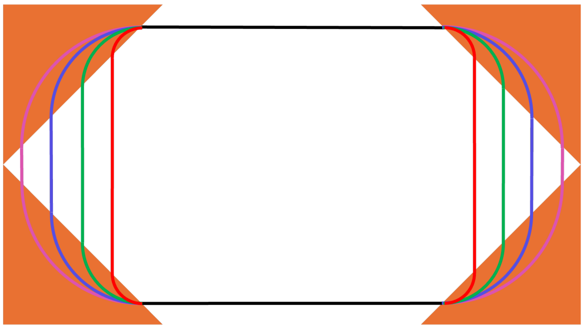

Figure 2: Race track type closed orbit composed of four $\pi/4$ single-side bending magnets is shown. Orbits by different momentum particles are drawn. In the two straight sections, the particle orbits by different momentum are merged.

which quickly reach the relativistic limit ($\beta \approx 1$), the synchronization condition for the orbit length C and the RF wavelength λ is given by:

$$C = 2L_s + 2\pi\rho + (4R - \rho) = \frac{p}{eB}(2\pi - 4) + 4R + 2L_s = n\lambda, \tag{1}$$

where L_s is the length of the straight section where the RF cavity is placed, R is the largest orbit radius of the bending, ρ is the orbit radius of a particle, B is the magnetic field of the bending, p is the momentum of the particle, e is electric charge, and n is an integer. The orbit length is increased for larger momentum particle. For synchronization between the RF and particle motion, increment of C per turn by acceleration has to satisfy as

$$dC = \frac{dp}{eB}(2\pi - 4) = n\lambda, \tag{2}$$

where dp is the momentum gain per turn. In our design, the magnetic field is 1.38 T, R is 1.0 m with 414 MeV as the highest energy. By assuming these parameters, the momentum gain must be $41n$ MeV/c. 20.5 MV/m field gradient with the total effective acceleration per tun 2 m meets this condition. An electron beam of 100 µA is accelerated to 414 MeV through 10 turns, with a total orbit width of only 2.0 m, making it suitable for mounting on a 2.5 m wide trailer for portability. Instead of 80 MV/m as the requirement for the muon production with a superconducting linac [3], 20.5 MV/m is enough in the case of DSMMG (Double-Sided Microtron Muon Generator).

Figure 3 shows the layout of muon generator based on the double-sided Microtron. Looking at the orbits between the four magnetic poles, the left and right sides feature multiple orbits arranged in a regular pattern depending on the particle's momentum. In contrast, on the top and bottom sides, the particle's orbit always follows the same path regardless of its momentum. Due to this property, superconducting accelerators are placed on the top and bottom orbits. Since microtron acceleration is possible if the acceleration voltage per revolution is an integer multiple of 41 MV, the acceleration voltage can be set to 20.5 MV per section. Unlike a conventional microtron, a major advantage is that the interior is not completely filled with orbits. As shown in the figure, it is possible to install an electron injector inside. We will use a superconducting RF electron gun as the injector. The expected energy at the electron gun exit is approximately 4 MeV. Since the electron beam has already reached the relativistic range, acceleration via $\beta = 1$ cavity is possible.

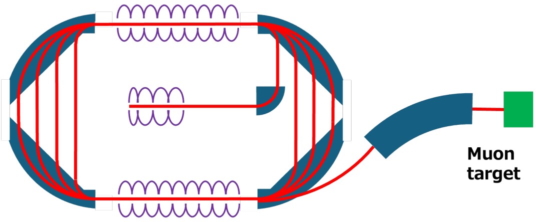

Figure 3: Schematic layout of the Double-Sided Microtron (DSM) showing the four bending magnets and two straight sections containing superconducting cavities.

Muon Production via Delta Resonance

The 400 MeV electron beam generated by the DSM is directed onto a graphite target to produce muons. The generation process primarily utilizes the Delta resonance ($\Delta(1232)$), which provides an effective cross-section for pion and subsequent muon production. Using a carbon target (40 mm in diameter and 100 mm in length), numerical simulations with GEANT4 indicate that a 100 µA electron beam can produce approximately 1.4×10^8 μ^+ and μ^- per second. To collect these muons, a high-field solenoid (e.g., $B = 3.5$ T) is employed downstream of the target.

Portable Muon Generator

Based on DSM, a portable muon generator can be composed. For the superconducting cavity, 4 K system has a big advantage to reduce the size of the system. In the superconducting accelerator system, cooling system (cryogenic system) and RF amplifier to provide the acceleration are dominant in its size, because RF power to induce the acceleration field is negligibly small, comparing the RF power to provide the beam energy. Nb_3Sn cavity is a good candidate in 4 K operation, because the critical temperature of this material is 18 K comparing to 9 K for pure Nb cavity. 2 K operation with Nb cavity which is currently widely used corresponds to 4 K operation with Nb_3Sn cavity. 24 MV/m (Single cell, 4.4 K) and 10 MV/m (9 cell, 4.4 K) fields have already been demonstrated [4].

Here, we estimate the required cooling power our system because the total system size strongly depend on the cryogenic system. The power dissipated per unit length of the cavity, denoted as P, scales with the square of the accelerating electric field E as $P = E^2/R$ where R is the shunt impedance of the cavity. The total required cooling power is $P_{\mathrm{cool}} = LP$, where L is the effective total length of the accelerator cavity. L is 2m in our case, because DSM has 2 m effective length for acceleration. We assume 2.6 GHz superconducting cavity instead of the conventional 1.3 GHz, because the system can be compact. The shunt impedance of the 2.6 GHz cavity was estimated as follows. The shunt impedance of a 3.5 cell RF gun cavity with a choke model cell is calculated as 4.3×10^{12} Ohm/m. The effective acceleration length is 0.2 m. If we input 20 W to this structure, 20.7 MV/m is induced resulting 4.1 MV acceleration at the end of the RF gun. The 3.5 cells RF Gun is designed by Superfish. The field map is shown in Fig. 4.

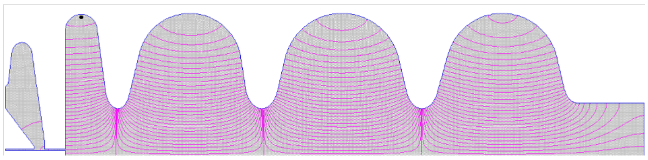

Figure 4: Field map of 3.5 cells superconducting RF Gun calculated by Superfish.

2.6 GHz 9 cell cavity, which is down scale of 1.3 GHz TESLA cavity, was designed with Superfish. The field map is shown in Fig 5. The shunt impedance 7.5×10^{12} Ohm/m. The effective acceleration length is 0.5 m. If we input 56 W/m to the cavity, 20.5 MV/m field is obtained. If we use four cavities, the effective acceleration length is 2.0 m resulting 41 MV total acceleration per turn. We need 112 W input to the four cavities.

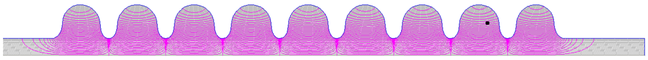

Figure 5: Field map of 9 cells superconducting accelerator calculated by Superfish.

The total input RF power to induce the acceleration field is 132 W including the RF gun and DSM.

If we operate 10 mA average current in a macro pulse, the duty of the system is only 1% to obtain 100 µA average current. The required cooling power is scaled with this duty factor, the required RF power and the cooing power is only 1.32 W.

In previous study, we estimated refrigerator system based on liquid He circulation type. Using the Superconducting Test Facility (STF), a superconducting accelerator based on a 1.3 GHz Tesla cavity) cryogenic system [5], as a reference, we estimate the size (area) of the required cryogenic system. The footprint (area) of the refrigerator S can be estimated as a function of P_{cool} for 4 K system [3]:

$$S = 10.9\frac{P_{\mathrm{cool}}}{600}. \tag{3}$$

Equation (3) contains the helium liquefier and the liquid helium container. Applying the required cooling power of DSMMG, 1.32 W, the expected area is 0.024 m^2 which suggests the estimation is not feasible. If a system utilizing liquid helium is adopted, it is suggested that it can be operated with the minimum necessary system configuration.

The cooling power 1.32 W can be operated by conduction cooling system. For example, a compact cryocooler employing Joule-Thomson effect (SHI RDK-415D2 4 K Cryocooler Series) can generate 4.2 K with 1.5 W cooling power. One cryocooler for 5 cavities is not realistic, because the conduction cooling channels between the cooling head and the cavity are hard to design. Instead, a cryocooler is attached to each cavity. Maybe, low power model RDK-305D2 4 K Cryocooler Series by SHI is enough our purpose. The cooling power is 0.4 W at 4.2 K. The Cryocooler is directly attached to the cryomodule and does't contribute to the system footprint. To drive the cryocooler, we need a compressor, F-40 Indoor Water-Cooled Compressor Series by SHI. The dimension of the compressor is 532 x 442 x 493 mm (H x W x D), which is compact.

Regarding system footprint, liquid helium circulation systems and Joule Thomson-effect mechanical cryocoolers are comparable. Nevertheless, when considering operational overhead, mechanical cryocoolers are preferable due to the high maintenance requirements associated with liquid helium.

The system area is minimized at 40 MV/m for 2 K system, lowering the acceleration gradient is advantageous in terms of overall system downsizing, as the refrigerator which occupies a larger fraction, can be made smaller if the heat load is lowered. On the other hand, in the 4 K system, the refrigerator only accounts for a small proportion, so it is advantageous to increase the acceleration gradient and reduce the length of the accelerator. Figure 6 shows an example of the portable muon source based on the the 4 K system.

For RF amplifier, we need solid state amplifier with 40 kW output 2.6 GHz with 1% duty. Currently, there are no off-the-shelf products that meet our requirements, but it appears that a custom-made product could be manufactured. For example, R&K A1300 [6] largely meet our specifications, but their operating frequency of 1.3 GHz differs from our requirements.

The portable muon source based on the double-sided microtron including the muon production target can be accommodated in a area with 12 m in length and 2.5 m width. This system can be accommodated in a typical trailer in Japan (12 m long and 2.5 m wide), as shown in Fig.7. This size is defined by the Japanese Road Traffic Law and allows the vehicle to be driven on ordinary roads without special legal permission. This means that the muon source can be loaded on a trailer and driven on Japanese roads without special legal permission.

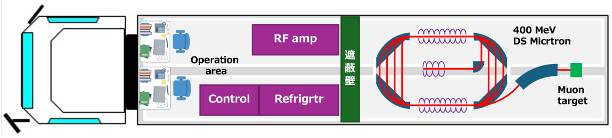

Figure 6: A schematic view of portable muon source (DSMMG) which is mounted on a conventional trailer.

The system can be compared with the system based on the 4 K superconducting linac as shown in Fig. 7.

The radiation shielding and the legal treatment of the portable radiation generator requires separate careful considerations. Currently, portable radiation generators above 4 MeV are not legally permitted under Japanese law. Increased understanding of the social benefits of the portable muon sources should lead to the operation of the portable muon source.

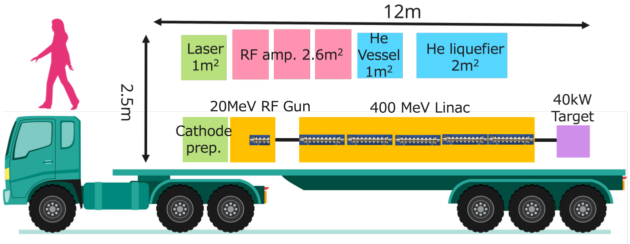

Figure 7: A layout of the portable muon source based on superconducting linac operated at 4 K.

Challenges and Solutions in Muon Acceleration

While the DSM is an excellent driver for electrons, direct acceleration of muons in a microtron presents a significant challenge due to their mass (m_μ = 105.6 MeV). Unlike electrons, Lorentz β varies from much less than unity, muons generated from pion decay have a velocity $\beta \sim 0.3$ to $\beta \approx 0.95$ at $E_k = 400$ MeV. This variation breaks the constant-period synchronization condition of microtron

$$\Delta L = 2\pi\Delta\rho = \frac{mc}{eB}\left(\frac{1}{\beta} + \frac{1}{\beta\gamma^2}\right)\Delta\gamma, \qquad (4)$$

which is difficult to maintain as a constant value. To overcome this, we propose a "Constant Period Microtron" with adjustable geometry. By dividing one magnetic pole into two parts and adjusting the distance L_B between them for each energy level, the circulation period T can be maintained as a constant.

$$T = \frac{1}{c\beta}(2\pi\rho + 2L_B + 2L_s), \qquad (5)$$

where ρ is the bending radius and L_s is the length of the straight section. The required distance L_B to satisfy the harmonic condition $T = nT_{RF}$ is:

$$L_B = \frac{c\beta}{2}\tau_0 - \pi\rho - L_s. \qquad (6)$$

By utilizing this degree of freedom, it is theoretically possible to accelerate muons efficiently while maintaining the phase-synchronous condition across a wide energy range.

CONCLUSION

A portable muon source based on double-sided microtron was investigated for non-destructive inspection of social infrastructure and humanities researches. The required field gradient is 20.5 MV/m for double-sided micrtron which can be compared with the 4 K superconducting linac which requires 80 MV/m. To realize the system, there is no break through needed. The entire system can be loaded onto a standard trailer. Careful consideration of radiation shielding is required. The use of outdoor radiation generators with energies exceeding 4 MeV is not authorized in Japan. Advancing social understanding of the benefits of the use of muons is a step towards realization. We have begun studying a compact system capable of re-accelerating generated muons.

ACKNOWLEDGEMENTS

This study was inspired by discussions with Dr. M. Otani. This work is partly supported by Program for co-creating startup ecosystem PSI2025_S2D73 and Grants-in-Aid for Scientific Research 26H01503.

REFERENCES

[1] K. Nagamine, "Radiography with cosmic-ray and compact accelerator muons; Exploring inner-structure of large-scale objects and landforms", *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci.*, vol. 92, no. 8, pp. 265–289, 2016. `doi:10.2183/pjab.92.265`.

[2] M. Kuriki and Z. Liptak, "A compact electron accelerator for muon production", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 452–455. `doi:10.18429/JACoW-IPAC2024-MOPR02`

[3] M. Kuriki, H. Hayano, T. Takahashi, and S. Yamashita, "A portable muon source for artificial muon muography", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 1345–1348. `doi:10.18429/JACoW-IPAC2025-TUPM080`

[4] S. Posen *et al.*, "Advances in Nb3Sn superconducting radiofrequency cavities towards first practical accelerator applications", *Supercond. Sci. Technol*, vol. 34, pp. 025007, 2021. `doi:10.1088/1361-6668/abc7f7`

[5] J. Yoshida *et al.*, "Development of STF cryogenic system in KEK", in *Proc. PAC'07*, Albuquerque, NM, USA, 2007, pp. 2701–2703, `doi:10.1109/PAC.2007.4440357`

[6] R&K Company ltd. `https://rk-microwave.com/`