

A PORTABLE MUON SOURCE BY A COMPACT SUPERCONDUCTING ELECTRON ACCELERATOR

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Abstract

Muon is a useful for non-destructive inspection of a large-scale structure by Muography, Muon X-ray fluorescence spectroscopy, μ SR (Muon Spin Rotation) measurement, etc. Muon can be found in the cosmic ray, but Muography with the natural muon 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. The portable muon sources are also useful for on-site analysis of immovable cultural properties. In this presentation, a design study of the portable muon source is 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.

There are two primary techniques used in muon-based imaging. One is Muon Transmission Imaging (MTI). This method involves placing a muon detector behind the object of interest. By measuring the number of muons that successfully pass through the object and analyzing their energy loss, one can infer the density distribution within the object. Fewer muons passing through a region indicate higher density material. This technique has been used to study large structures such as pyramids and volcanoes.

Another is Muon Scattering Tomography (MST). Multiple position-sensitive detectors are placed before and after the object to measure the trajectory of incoming and outgoing muons. When muons interact with high- Z materials such as uranium or lead, they scatter at larger angles. By analyzing the scattering angles, this technique can identify the type and spatial distribution of materials inside an object. It is particularly useful for applications such as nuclear waste monitoring and detection of illicit materials.

Advantages of Muography with the natural muons are

- Non-invasive and Non-destructive: Allows internal inspection without altering or damaging the object.
- Radiation-free for the source: Uses naturally occurring cosmic-ray muons, eliminating the need for artificial radiation sources.
- Sensitive to High-Density Materials: Better suited than X-rays or neutrons for detecting high- Z materials.
- Scalable for Large Structures: Can be applied to inspect large-scale objects such as mountains, buildings, or reactors.

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 simplifies 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

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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 JPY in 2018 and 5.9 to 6.5 trillion JPY by 2048. The cost of highway maintenance and management is 1.5 trillion. The similar amount 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.

In addition to the social infrastructure, the portable muon source is useful even in non-destructive inspection of cultural properties. Non-destructive testing of cultural properties is important from two perspectives: academic research and understanding the state of preservation (preventive conservation of cultural properties). In the case of cultural properties, even if it is physically possible to move the object to a research institution for investigation, in many cases it is socially unacceptable to do so. The portable muon sources enable the preservation of cultural properties in their original locations while also facilitating academic research and ensuring optimal preservation conditions.

MUON PRODUCTION WITH ELECTRON BEAM

We consider the muon production with electron beam. For the production of muons, proton beams are usually used due to their high production efficiency. On the other hand, the mass of a proton is 1,800 times greater than that of an electron, and electrons are much easier to produce and accelerate than protons. Although electron beams are less efficient in muon production, it is easier to downsize the accelerator, which is advantageous for portability. In addition, as described below, the low production efficiency can be compensated for by using Delta resonance. Delta-resonance is 1232 MeV. It decays to multiple pions generating muons. By considering resonance between electron and proton through γ -p scattering in nucleus, the threshold energy of electron is 259 MeV. 400 MeV electron can induce the resonance with a large phase-space. As a design criteria, we consider 400 MeV and 100 μ A electron beam for Muon production.

Muon production is simulated with GEANT4 [3]. 8.0×10^8 400 MeV electron beam impinges on a carbon target, the length is 100 mm and 40 mm in diameter as shown in Fig. 1. The target is placed in a solenoid field with 3.5 Tesla. Muons captured by the solenoid field and transported to the

detector placed in 5 m downstream of the target are counted. 1.4×10^8 μ^+ and μ^- are generated with the beam [2].

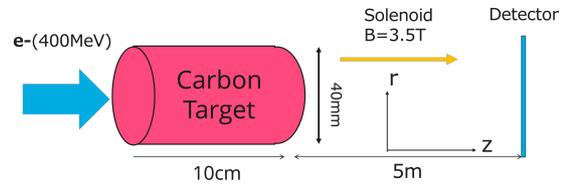


Figure 1: Layout of the muon production simulation.

COMPACT MUON SOURCE

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 difficulty of cooling for 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. For these reasons, a normal-conducting accelerator is not an option. 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.

The accelerator gradient determines the length of the accelerator. For the superconducting accelerator, the accelerator gradient is limited by the critical magnetic field which is the upper limit of the surface magnetic field maintaining the superconducting state. The accelerator gradient E_{acc} is determined as the product of the EB ratio R_{EB} determined by the cavity geometry and the critical field B_c as

$$E_{acc} = R_{EB} B_c \quad (1)$$

For Nb, B_c is considered in between the lower critical field $B_{c1} \sim 170$ mT and the superheating field $B_{SH} \sim 240$ mT. R_{EB} for TESLA cavity is 0.238 (MV/m)/mT resulting E_{acc} in between 40.5 MV/m and 57.1 MV/m. B_c , operating temperature T , and critical temperature T_c have the following relationship

$$B_c(T) = B_c(0) \left(1 - \frac{T}{T_c}\right) \quad (2)$$

Thus, a material with a higher critical temperature allows operation at a higher critical magnetic field and thus a higher acceleration gradient. Nb_3Sn has a critical temperature of 18 K, which is two times higher than that of Nb. Nb_3Sn is highly brittle and difficult to fabricate in the same way as Nb cavities; however, a method of plating or depositing Sn on Nb cavities and then quenching to promote the reaction to form a Nb_3Sn film on bulk Nb has been tested. 24 MV/m (Single cell, 4.4 K) and 10 MV/m (9 cell, 4.4 K) fields have already been demonstrated [4].

Recently, a method has been proposed in which a thin-film structure of insulators and superconductors can be used

to achieve an effectively higher critical field by using the effect of surface potentials to suppress the penetration of the magnetic field into the superconductors [5]. By assuming a superconductor, insulator, and superconductor multi-layer structure, namely S'-I-S structure, 95 MV/m is possible with Nb₃Sn surface with TESLA shape cavity [5].

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 $P_{\text{cool}} = LP$, where L is the effective total length of the accelerator cavity. L can be expressed with E as $L = 4.0 \times 10^8/E$ giving 400 MeV acceleration, resulting $P_{\text{cool}} = 4.0 \times 10^8 E/R$. The shunt impedance R is determined by the intrinsic quality factor Q and R/Q of the cavity, 1036 Ω for TESLA cavity.

There is a difficulty in estimating Q theoretically. It is determined by the surface resistance R_s of the cavity and the geometric factor G . The surface resistance is the sum of the BCS and residual resistance. The BCS resistance can be theoretically estimated as follows,

$$R_{\text{BCS}}(T) = A \frac{\omega^2}{T} e^{-\frac{\Delta}{kT}} \quad (3)$$

where ω is angular frequency, k is Boltzmann constant, T is temperature. R_{BCS} is estimated as $4.6 \times 10^{-13} \Omega$ and 6.1×10^{-10} for $T=2.0$ K and 4.4 K, respectively. Q values are 6.0×10^{14} and 4.5×10^{11} for $T=2.0$ K and 4.4 K, respectively. This Q -value is much higher than the experimentally confirmed value, $Q = 2.0 \times 10^{10}$, suggesting a large residual resistance [6]. We use this confirmed value $Q = 2.0 \times 10^{10}$ conservatively resulting $R = 2.1 \times 10^{14} \Omega$. It gives $P_{\text{cool}} = 2.0 \times 10^{-6} E$, i.e. the required cooling power P_{cool} is proportional to E .

The refrigerator system depends on the operating temperature. 2 K operation requires the He in super-fluid state because the boiling point of the liquid helium at 1 atm is 4.2 K, a special refrigerator is required to operate a superconducting acceleration cavity at 2 K; Liquid helium is placed in a pressure vessel and depressurized to lower the boiling point to 2 K. The evacuation pump, Helium bag which stores the Helium gas, and the Helium liquefier are necessary. On the other hand, the system operating at 4.2 K requires only a helium liquefier, because the amount of helium gas is limited. Using a cryogenic system [7] at the Superconducting Test Facility (STF) as a reference, we estimate the size (area) of the required cryogenic system. The footprint (area) of the refrigerator can be expressed as a function of P_{cool} for each operation temperatures respectively, as

$$S_{4\text{K}} = 10.9 \frac{P_{\text{cool}}}{600} \quad (4)$$

$$S_{2\text{K}} = 20.7 \frac{P_{\text{cool}}}{600} + 1.1 + 3.4 \frac{P_{\text{cool}}}{30}. \quad (5)$$

Eq.(4) contains the helium liquefier and the liquid helium container. Eq. (5) contains the helium bag, the helium cold box, and the vacuum pump additionally. Figure 2 shows the area of the footprint as a function of the accelerator gradient.

The black dotted line shows the area of the linac, where the area of the linac is

$$S_{\text{Linac}}(E) = 2.0 + L \times 1.3 + 2.0, \quad (6)$$

2.0 is the length for the RF electron gun including the cathode preparation system, 1.3 is a packing factor which is the ratio of the cryomodule length to the effective accelerator length, and 2.0 is the length of the target system. 1.0 m width is assumed. The red and blue dotted lines in Fig. 2 show the area of the refrigerator system for 4K and 2K systems as a function of the acceleration field, respectively. The red and blue solid lines show the area of the total system as the sum of the accelerator and the refrigerator for 4 K and 2 K systems, respectively. The system area is minimized at

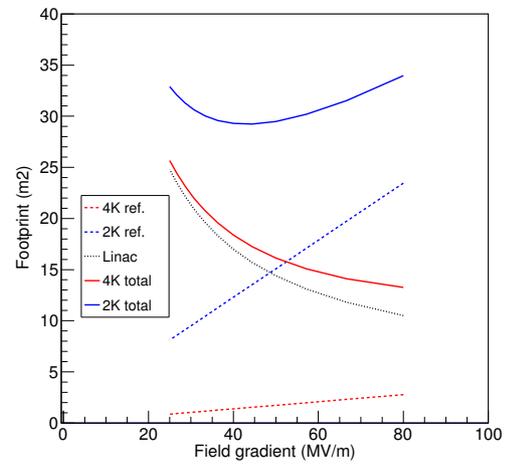


Figure 2: Area of the footprint of the system as a function of the acceleration gradient. The solid lines, dotted lines, and dashed lines show the total system area, the refrigerator area, and the linac area, respectively. The red and blue lines the date for 4 K and 2 K system, respectively.

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 3 shows an example of the portable muon source based on the the 4K system. Electron beam is generated SRF Gun [8]. As a RF amplifier, three units of R&K A1300 [9] are assumed. The accelerator including the cathode preparation system and the muon production target can be accommodated in a arem 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. 3. 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

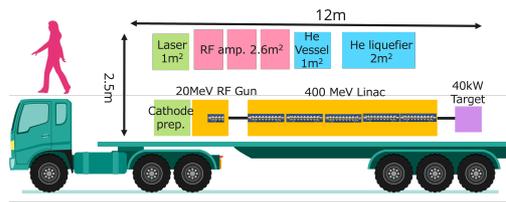


Figure 3: A layout of the portable muon source based on a linac operated at 4 K.

on a trailer and driven on Japanese roads without special legal permission.

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.

CONCLUSION

A portable muon source was investigated for non-destructive inspection of social infrastructure and on-site observation of cultural properties, etc. 4 K superconducting system at a gradient of 80 MV/m, which is achieved by the thin layer superconductors, is optimal in terms of miniaturisation. 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 authorised in Japan. Ad-

vancing social understanding of the benefits of the use of muons is a step towards realisation.

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