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A COMPACT ELECTRON ACCELERATOR FOR MUON PRODUCTION

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Abstract

The muon is a unique particle. It is an elementary particle similar to the electron, but with a mass approximately 200 times greater. Because of their high penetrating power, muons can also be used for imaging such as non-destructive inspection and muon tomography for interior surveys of large structures. Muons derived exclusively from cosmic rays have heretofore been used for these applications, but the low rate and restricted angular range of cosmic rays restricts their usefulness. In this article, a compact and portable muon source based on super-conducting electron accelerator technology is considered. The addition of a muon accelerator provides a variable energy, portable muon source.

INTRODUCTION

The muon is an elementary particle similar to the electron, but with a mass approximately 200 times greater. Because of their high penetrating power, muons can is used for imaging techniques such as non-destructive inspection and muon tomography for interior surveys of large structures. Muons derived exclusively from cosmic rays have been used for these applications, but the low rate and restricted angular range of cosmic rays restrict their usefulness. To remove these limitations, a portable muon source with variable energy up to 10 GeV is desirable.

The existing muon sources are unsuitable for this purpose. At J-PARC, a high-power proton beam (up to 1 MW at 3 GeV) with a 250-m linear accelerator followed by a RCS (Rapid Cycle Synchrotron, circumference 348.333 m) generates muons from a carbon (graphite) target. Such large accelerating facilities are not feasible for the portable generation of muons. To address the possibility of creating such a source, we consider here a portable muon source based on a super-conducting electron linac.

MUON PRODUCTION

Muon production with electron beams is maximized at the Δ resonance (1232 MeV). The threshold energy of the Δ resonance of the electron-proton interaction is 259 MeV, and 400 MeV is a feasible compromise between muon yield and necessary electron energy. In this article, we assume a 400 MeV electron beam with 100 μA beam current.

Muon production with a 400 MeV electron beam incident on a carbon target was simulated in GEANT4 [1]. The carbon target is modeled as a cylinder 20 mm in radius and 100 mm in length. 8×10^8 electrons were injected on the center axis of the target and the number of muons was counted 5 m downstream of the target end. Figure 1 shows the kinetic energy distribution of generated μ^+, and 184 μ^+ and 178 μ^- were observed at the collection point. With the electron beam normalized to 100 μA, we expect to observe $1.4\times10^8\mu^+$ and μ^- per second, respectively.

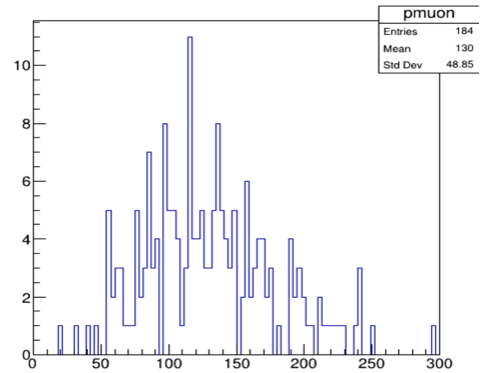

Figure 1: Generated μ^+ with 400 MeV electron beam in histogram of kinetic energy (MeV). 184 μ^+ were observed.

SUPERCONDUCTING ACCELERATOR

Superconducting accelerators provide a feasible way to generate a high power beam, because they can be operated in continuously with a high gradient. Similar operation with a normal conducting accelerator would be very difficult because of the huge Joule loss on the cavity surface. Therefore, in this study, we use a superconducting accelerator.

The surface resistance of a superconducting accelerator is much less than that in a normal conducting one, but it is not zero. It arises from two components: BCS resistance and residual resistance. BCS resistance is determined as $R_{BCS}(T) = A\omega^2/Te^{-\Delta/k_BT}$ where T is temperature, A is a constant, ω is the angular frequency of the RF, Δ is a constant determined by the material composition, and k_B is the Boltzmann constant. Δ can be approximated as $\Delta \sim 4.5k_BT_c$, where T_C is the critical temperature of material.

The resistance determines Q value of the cavity. The product of $(R/Q)\times Q$ determines the shunt impedance of the cavity, R, where (R/Q) is a constant determined only by the cavity geometry. A higher Q value gives a correspondingly higher accelerating field E, proportional to $E^2 = (R/Q)\times QP$, where P is the input power to the cavity.

Q values can be increased by operating the cavity at lower temperatures, but lower operating temperatures result in lower refrigeration efficiency. The efficiency of a refrigerator η_R is determined by the Carnot efficiency $\eta_C \sim T_O/T_{RT}$, where T_O is the operation temperature, T_{RT} is room temperature, and the mechanical efficiency η_M, as $\eta_R = \eta_M\eta_C = \eta_M T_O/T_{RT}$, i.e. T_O should be determined by optimizing the Q value and η_C.

R is saturated in the lower temperature region, because the residual resistance dominates R in this region. We assume $Q = 2\times10^{10}$ as the highest value, which is the highest value

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experimentally confirmed [2]. The shunt impedance at this Q value is $R = 2.1 \times 10^{14}\,\Omega$.

The maximum accelerating field of the superconducting cavity is determined by the surface magnetic field. Superconducting Nb is a Type II superconductor which has two critical fields, B_{C1} and B_{C2}. Because operation with magnetic vortex penetration is unstable, superconducting accelerators are operated below B_{C1}, but the Meissner effect is maintained above B_{C1} due to the surface potential. Magnetic fields that makes the Meissner state absolutely unstable are known as super-heating fields, B_{SH}. The practical threshold field for superconducting cavity operation B_O is $B_{C1} < B_O < B_{SH}$. B_{C1} of Nb is 170 mT and a theoretical estimation of B_{SH} for Nb is 240 mT. Because the accelerating field E with a given surface magnetic field B is obtained as $E = (E/B)B$, where (E/B) is the E-B ratio of the cavity determined strictly by the goemetry. (E/B) for a TESLA cavity is $0.238\, MV/m/mT$, and the highest operating field of a Nb superconducting cavity is expected as $40.5 < E < 57.1[MV/m]$. The highest field obtained with a Nb superconducting cavity is 44 MV/m for European XFEL (9 cell cavity) [3] and 50 MV/m (single cell cavity) [4]. Those are consistent with the expectation.

Further higher fields are possible with higher T_C materials such as MgB_2 and Nb_3Sn. The T_{C1} of Nb_3Sn is 18 K double of that of Nb, which allows for a higher B field. 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 [5].

More improvement is proposed with a multi-layer superconductor. In this structure, layers of superconductor and insulator are formed one by one on a bulk superconductor. Magnetic flux attempting to penetrate the superconductor layer is pushed outward by the potential generated at the interface between the insulator and the superconductor, and penetration into the interior is suppressed. As a result, the superconducting state can be maintained in a large surface magnetic field. According to theoretical studies (numerical calculation), a Nb_3Sn multi-layer cavity can maintain a magnetic field up to 400 mT [6]. It follows that this a Tesla cavity can be operated with accelerating gradients up to 95 MV/m. In this study, we assume a Nb_3Sn cavity can be operated up to this gradient.

CRYOGENIC SYSTEM

The operation of a superconducting accelerator requires a refrigeration system. Due to the temperature dependence of the Carnot efficiency, lower operating temperatures require correspondingly higher capacity refrigerators. In addition, when operating at temperatures lower than 4.2 K (the boiling point of liquid He), the refrigeration vessel must be depressurized, requiring a depressurizing pump. Because the operation conditions are different for 4.4 K and 2.0 K T_O, we consider both cases.

Using the Superconducting Test Facility (STF), a superconducting accelerator based on a 1.3 GHz Tesla cavity) cryogenic system [7], as a reference, we estimate the size (area) of the required cryogenic system according to the refrigeration power P_R and operating temperature, T_O. The STF cryogenic system specifications are as follows, in mm:

- He liquefier (600 W) : 2400×3700.
- He gas bag : 2400×4100.
- Liquid He strage vessel (2000 l) : $\phi1600$.
- Depressurizing pump (30 W) : 2800×1200.
- 2 K cold box : $\phi1200$.

If the required system footprint is proportional to the capacity, the area of the cryogenic system for 4.4 K $S_{4.4}$ and 2 K S_2 in m^2 are estimated for P_C (cooling power in W) as:

$$S_{4.4} = 20.7\frac{P_C}{600} \quad (1)$$

$$S_2 = 20.7\frac{P_C}{600} + 1.1 + 3.4\frac{P_C}{30}\,. \quad (2)$$

Note that there are additional contributions from the 2 K cold box and pump system for the 2 K case.

ACCELERATOR DESIGN

We design the 400 MeV electron linac based on the 2 K or 4.4 K superconducting accelerators described above, with field gradients up to 95 MV/m constructed with Nb_3Sn multilayer superconductor. The average beam current is 100 µA.

The required cooling power is very important because it determines the capacity of the cryogenic system and has a significant impact on the system scale. The dissipated power of the linac P_C is $P_C = LE^2/R$, where L is the effective length of the linac, E is the acceleration field, R is the shunt impedance. With L set at $L = 400{\times}10^6/E$ [m], we get $P_C = 400 \times 10^6 E/R$. In practice, the number of TESLA-type acceleration tubes n with an effective acceleration length of 1 m each determines the required acceleration gradient. Finally, $P_C = 1.6 \times 10^{17} E/nR$.

The cryogenic system can be determined with P_C as a function of E. The actual accelerator length includes the length of the end-pipe of each accelerator, superconducting RF Gun, and a cathode preparation system. The linac length is $1.3n$ m, because each TESLA cavity has 0.3 m end-pipe section with 1 m accelerator section. We assume 4 m for the RF Gun and cathode preparation system. The cryomodule width is 1 m. The linear accelerator area S_L is therefore $S_L = 4.0 + 1.3n$.

Figure 2 shows the footprint area as a function of the acceleration field. The dotted line shows the area of the linear accelerator, excluding the target area. The red and blue dashed lines show the area of the cryogenic system for 4.4 K and 2 K, respectively. Because 2 K requires a 2 K cold box and depressure pump system and also exhibits lower Carnot efficiency, it requires a larger cryogenic system. The red and blue solid lines show the total area including the linear accelerator and the cryogenic system for 4.4 K and 2 K,

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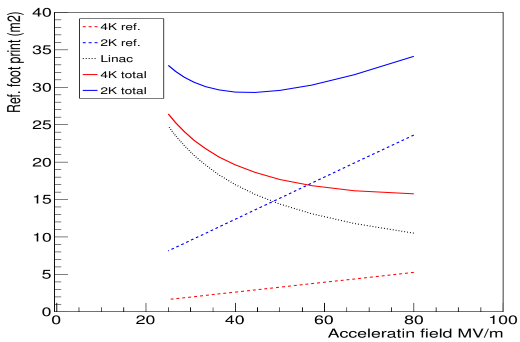

Figure 2: Area of the system as a function of the field.

Table 1: Electric Power For the 4.4 K and 2 K System

Item	2 K	4.4 K
RF	156	156
Refrigerator	36	32
Other	10	10
Total	202	198

respectively. For the 2 K case, there is an optimum around 40 MV/m. In the 4 K case, 80 MV/m is optimal.

An ELBE type 1.3 GHz superconducting RF gun [8] is employed as the electron gun. We use a CsK_2Sb cathode driven by a green laser (530 nm). By assuming 1% quantum efficiency, a 24 mW laser is required. For 325 MHz mode-lock frequency, the micro pulse charge required is 3.2 pC with 75 pJ laser pulse energy.

We need RF power not only to drive the cavity but also for the beam acceleration. The required input power is given as 400 MeV $\times$ 100 µA = 40 kW. This value is much larger than the RF power needed to drive the cavity, ~160 W at 80 MV/m, and thus RF power for the beam acceleration is dominant. Among various RF power sources, we select a solid-state amplifier, A1300BW10-6372R produced by the R&K Company limited [9]. The module output power is 16 kW at 1.3 GHz with 0.8 m $\times$ 1.1 m footprint. Three modules (48 kW) are enough to drive our system. The total electric power is then 156 kW.

Each system's total electric power is estimated as shown in Table 1. Other power needs include the laser system, magnets, cooling water, control system, etc. The acceleration gradient for the 4.4 K system is 80 MV/m, and 40 MV/m for the 2 K system. The Joule loss per unit length is proportional to the square of the acceleration gradient. Since the 4.4 K system has half the number of acceleration cavities of the 2 K system, the cooling power required for the 4.4 K system is double that of the 2 K system. Since the Carnot efficiency is approximately double that of a 2 K system for 4.4 K, the required cooling power is about the same for both systems. The total electricity is therefore similar in each case.

Since 2 K operation increases the area required for the cryogenic system, the acceleration gradient must be lowered to optimize the overall system area. On the other hand, 4.4 K

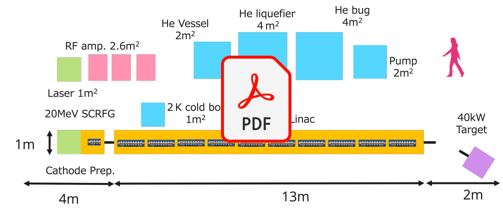

Figure 3: Layout of muon source based on 2 K Superconducting electron accelerator.

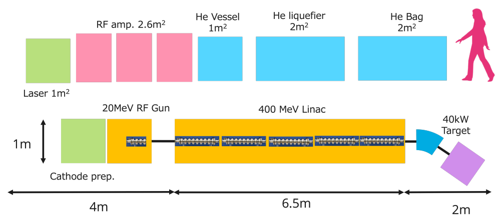

Figure 4: Layout of muon source based on 4 K Superconducting electron accelerator.

operation does not require a 2 K cold box and a pump for depressurization, so the necessary cryogenic area is smaller. Therefore, an acceleration gradient of about 80 MV/m is optimal. Figures 3 and 4 shows examples of the system layout for 2 K and 4 K cases, respectively. The total length of the 2 K system is 20 m. The typical trailer length in Japan is 18 m including the cab, so it is difficult to install a 2 K system. With special permits vehicles can be up to 25 meters, so extra administrative costs and effort would be needed to install the 2 K system. In practice, making a 2 K system portable may be difficult because it would also need to include radiation shielding, etc., and the actual system would be much larger.

The total length of 4.4 K system is 13.4 m. Since a typical trailer system (18 m) allows for a cargo bed length of about 15 m, this system would be feasible on this vehicle; there is also a margin of about 2 m, making it highly feasible as a portable accelerator, even including radiation shielding.

CONCLUSION

We have studied a compact and high-power electron linear accelerator based on the superconducting linear accelerator generating 400 MeV energy with 100 µA beam current. Employing the multi-layer Nb_3Sn superconductor makes up to 95 MV/m acceleration field possible. A linac with an 80 MV/m acceleratingfield operated on 4.4 K is optimum to minimize the system footprint. The total system length, including the RF Gun and the muon production target, is 12.5 m. Since a typical trailer system (18 m) allows for a cargo bed length of about 15 m, this system would be feasible on such a vehicle; there is also a margin of about 3 m, making it highly feasible as a portable accelerator, even including radiation shielding.

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