DESIGN OF MUON ACCELERATORS FOR AN ADVANCED MUON FACILITY

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Abstract

We plan to develop a low-emittance muon beam for the next-generation muon facility at LANSCE. Use of a large-acceptance muon linear accelerator is a key technique for our scheme, and a preliminary accelerator design has been made. Description of high-collection low-emittance muon generation and some results of the simulations are described.

INTRODUCTION

Muon beams are produced at accelerator facilities worldwide. The muon beams are produced either by π decay at rest or in flight, and they typically have energies of a few MeV or higher. Those muon beams are commonly used for condensed matter physics studies with so called μSR (Muon Spin Rotation / Relaxation / Resonance) spectroscopy.

Muon-beam intensities of the muon have always been an issue for many experiments and there is a recent trend to produce intense muon beams by utilizing a high-intense proton drivers of a few MW such as J-PARC [1] and/or by collecting muons with larger acceptance channels [2]. Up to today, applications of the μSR studies are limited by the large beam sizes which are typically 10 cm^2. In this paper, we propose an efficient method to generate an "advanced muon beam" of < 1mm^2 size at several MeV. Such muon beams can be applicable not only to conventional condensed-matter physics research using μSR microscopy but also to novel μSR tomography which is a powerful tool to explore 3-dimensional dynamic behaviors of microscopic magnetism such as functional study of the human brain [3]. Further acceleration of the muon beam up to several-100 MeV is possible, which is applicable to muon radiography to study industrial large machinery.

ADVANCED MUON BEAM

As shown in Fig. 1, the advanced muon beam is generated in the following three steps: (1) large-acceptance collection of muons; (2) deceleration of muons down to ~100 keV using an energy absorber; (3) muon reacceleration up to 10 MeV with linear accelerators.

As for the initial muon source, we plan to use the so called "surface muon" which is produced by π^+ decay at rest on the surface skin of a production target resulting in a unique energy of 4 MeV or 30 MeV/c in momentum. We would use LANSCE (800 MeV, 0.7 mA) at LANL for the proton driver, parasitic to the Materials Test Station in LANSCE area A. It is worth noting that our method can basically be installed at any other facility that possesses an intermediate-energy particle accelerator.

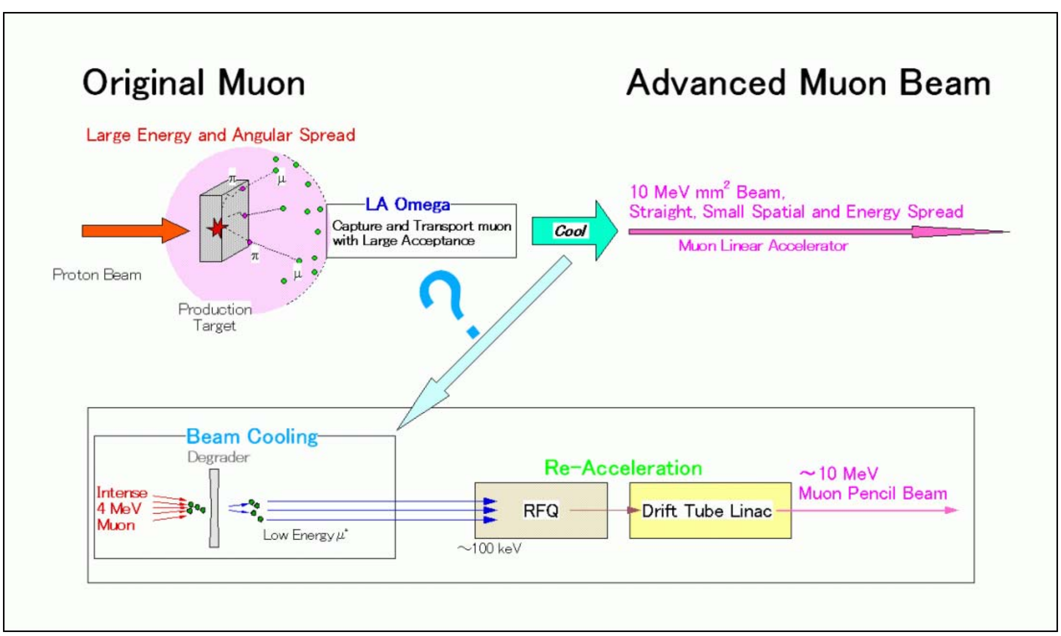

Figure 1: Schematic diagram of advanced-muon-beam generation.

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Large Acceptance Muon Channel

Utilization of large-acceptance solenoids with axial-focusing beam transport was demonstrated by the Dai Omega muon channel [2] at KEK, which realized a solid-angle acceptance of 1.4 srad. Dai Omega uses four super-conducting coils of 80-cm diameter to transport the 30-MeV/c surface-muon beam. We employed a similar design for our muon channel "LA Omega" shown in Fig.2. Three minor improvements are (1) use of a normal-conducting front coil resistant against intense radiation from a production target, (2) the low leakage magnetic field (~10^{-2} T) at the primary proton beam line, which is realized by magnetical shielding of the muon channel, and (3) the large-momentum-acceptance tune of the coils. Preliminary calculation shows that our LA Omega has a solid-angle acceptance of 1.1 srad at optimum momentum with 10 % momentum acceptance (Fig.3). The simulated muon beam size at the focus is 4 mm (FWHM). LA Omega is capable of producing the world's most intense muon beam of ~10^9 μ^+/s at LANSCE. However, the muon intensity may be limited by the production-target thickness to avoid proton-beam losses and scattering of the MTS beam.

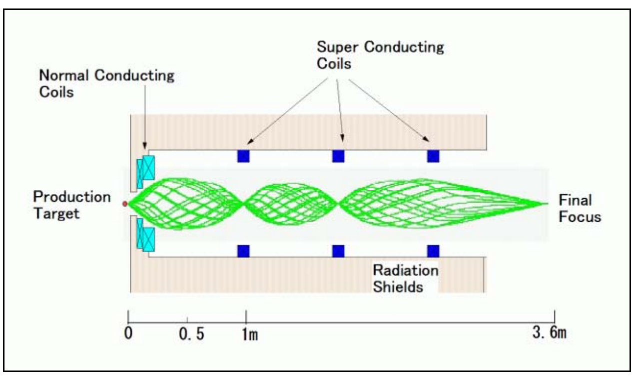

Figure 2: Schematic view of LA Omega muon channel.

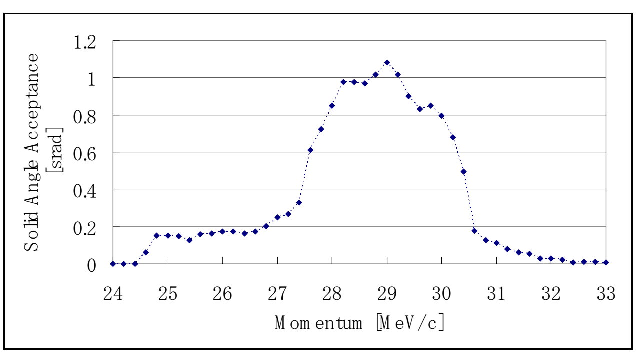

Figure 3: Momentum acceptance of LA Omega.

Energy Degrader

We plan to decelerate the 4-MeV muon beam to ~100 keV by a simple wedge-shaped energy absorber. Alternative methods are the use of low energy muon beams known as slow muon beams (E_μ: ~10 eV) developed at PSI [4] that uses a noble-gas moderator or an ultra-slow muon beam (E_μ: 0.2eV) developed at KEK [5] and RIKEN-RAL that uses resonant ionization of thermal-energy muonium from hot tungsten. The efficiencies of these methods remain at 10^{-5} levels while a simple wedge energy absorber is capable to decelerate the surface-muon beam of 4 MeV down to ~100 keV with almost 10^{-2} efficiency.

The wedge absorber works effectively when used with an axial-focusing channel such as LA Omega since angles of the muons that reach the absorber placed at the beam focus are correlated with the muon momentum.

Initial Acceleration

The initial acceleration of the degraded muon is the key part of the project. A Radio Frequency Quadrupole (RFQ) linac seems to be the best choice since the degraded muon has an almost DC time structure; an RFQ accepts 360 degrees of phase and bunches the particles together losing only a few percent. The RFQ can be operated with the same time structure as LANSCE (120 Hz, 0.6-ms pulse width) so that all the muons produced are effectively used.

Selection of RF frequency is important in accelerator design: an RF frequency of 400 MHz or higher seem to be efficient for the following linac, while a lower frequency such as 200 MHz can realize larger acceptance. We designed three RFQs using the PARMTEQ code developed at LANL. The specifications of those RFQs are given in Table 1.

Table 1:Specifications of designed RFQ.

	RFQ-A	RFQ-B	RFQ-C
Frequency [MHz]	400	400	200
Length [m]	2.3	6.5	10.7
Peak Power [kW]	500	3450	5281
Injection Energy [keV]	20	80	100
Ejection Energy [keV]	500	1000	1000
Acceptance [cm rad]	0.03	0.64	1.34
Energy Acceptance [keV]	5	17	45

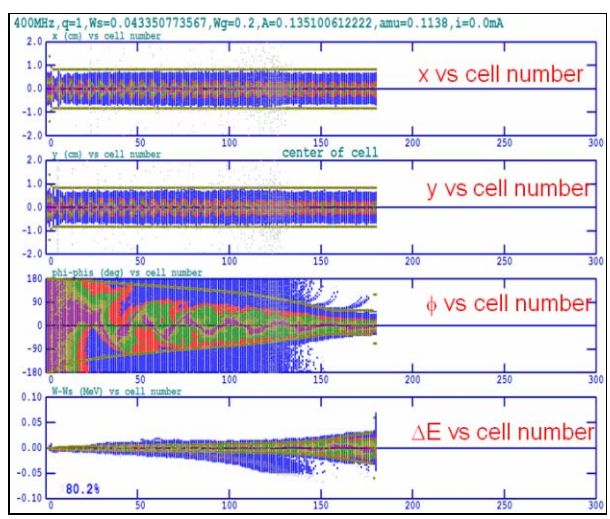

Figure 4: PARMTEQ beam transport simulation in RFQ-A. Parameters of the RFQ is on Table 1.

The degraded muon beam has a large-energy spread so that it is essential for our RFQ to have a large-energy acceptance. It was found that an RFQ can be designed to have a large-energy acceptance [6], up to 50 %.

Fig.5 shows the muon-beam profile after acceleration by RFQ-A in Table 1. Two types of muon beams were injected: (a) a monochromatic 20-keV muon beam, and (b) a 20-keV muon beam with 5-keV energy spread. It is interesting that even when the muon beam with large-energy spread is injected into an RFQ, the beam profile of the ejected beam remains almost the same as with the monochromatic injection. This occurs because the higher energy muon moves with effectively no energy gain until it arrives at the cell that optimally matches its energy. The acceleration and deceleration field before the certain cell almost cancel in total due to the mismatch of energy and phase while the alternating quadrupole fields of the RFQ provide focusing.

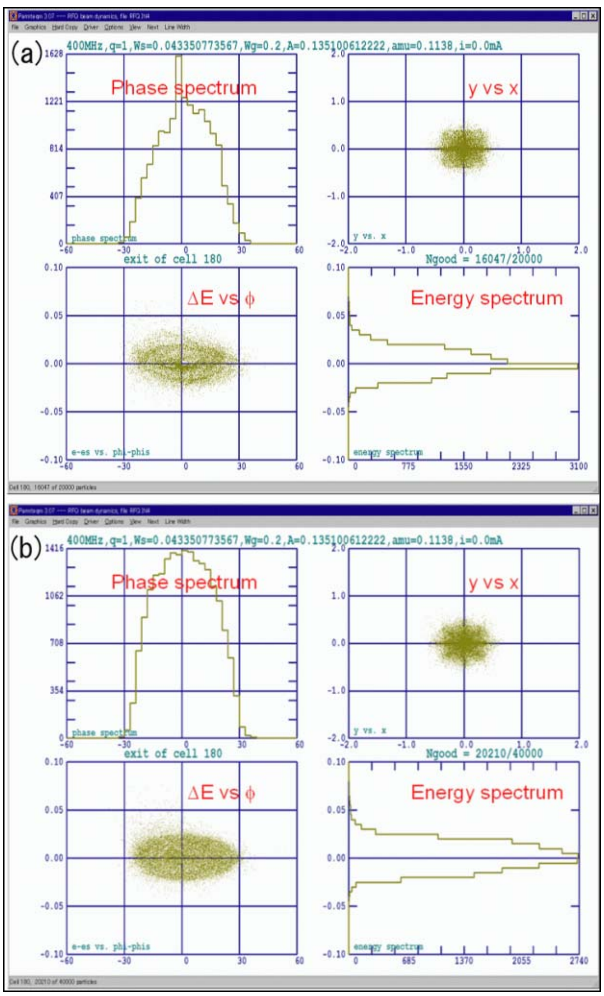

Figure 5: Phase, spatial and energy distributions of muon beam after acceleration with initial beams of (a) monochromatic 20 keV and (b) 20 keV, ΔE = 5 keV.

Further Acceleration

Because of cost and power considerations, a Drift Tube Linac (DTL) will be used for further acceleration of the muon. In this case we employed RFQ-A for the initial acceleration of the muon. It is estimated that the beam after the DTL can be focused to a spatial size of < 1 mm^2 at 10 MeV since the lab emittance has been drastically decreased by the acceleration. The estimated beam luminosity at 10 MeV is several 10^9 μ^+/cm^2s which is 4 orders or more higher than any existing muon facilities in the world.

CONCLUSION

As described in this paper, the Advanced Muon Facility scheme has two significant features: (1) LA Omega produces the world's most intense surface-muon beam of 10^9 μ^+/s; (2) a low emittance muon beam will be generated by using deceleration and reacceleration of the beam. The advanced muon beam can broaden the applications of μSR to nano- and bio-science studies. At the same time, the muon accelerator of our project may be useful for the future Neutrino Factory and Muon Collider for particle-physics experiments.

Table 2: Comparison with other Muon Facilities..

Facility	Proton Beam	Muon	Beam
LA Omega	800 MeV, 700 μA	10^9 μ^+/s	Quasi-DC
Dai Omega	500 MeV, 5 μA	10^6 μ^+/s	Pulsed
J-PARC	3000 MeV, 333 μA	$3x10^7$ μ^+/s	Pulsed
RAL	800 MeV, 200 μA	10^6 μ^+/s	Pulsed
JINR	660 MeV, 2 μA	$5x10^4$ μ^+/s	DC
TRIUMF	500 MeV, 200 μA	10^6 μ^+/s	DC
PSI	590 MeV, 2000 μA	$3x10^8$ μ^+/s	DC

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