Simulation studies of low-emittance muon re-acceleration for muon microscopy application

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Abstract

While conventional muon beam can be used to investigate rather small samples, there is a strong requirement for still lower energy ultra-slow muons that can be stopped near sample surfaces, in thin films and near multi-layer interfaces. A number of muon cooling techniques have been suggested to produce ultra-slow muons, such as two-photon laser resonant ionization of muonium atoms and energy moderation of muons in a thin foil-degrader. In this work, in close collaboration with the Muon Science Establishment (MUSE) at Material and Life science experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC), we provide a brief overview of the primary muon production target, where two of the four associated secondary beam transport lines which are dedicated to experiments employing the ultra-slow muons. In particular, we present the simulation results of the ultra-slow muon production with tunable energies in the range of energies between 5.65 and 30 keV based on the simple energy moderation of transported muon beam in thin foil-degrader. In addition, we discuss accelerator optics design and beam acceleration simulation results provide a microbeam for muon microscopy.

INTRODUCTION

The spin polarized muon beam application in experimental methods that can probe deep inside a material is enhanced by its exquisite sensitivity to magnetism and its unique time window (μs order) for dynamical processes. Lower energy muons are available only from ordinary two-body pion decay. Most positive muon beams are generated from pions stopped at inner surface layer of the primary production target and decaying at rest, hence the common name, surface muons. The muon is emitted isotropically from the pion with momentum 29.8 MeV/c and kinetic energy of 4.119 MeV (in the rest frame of the pion). The intensity of surface muon beam can be estimated from the number of pions stopped near to the surface. While conventional muon beam can be used to investigate rather small samples, there is a strong requirement for still lower energy ultra slow muons that can be stopped near sample surfaces, in thin films and near multi-layer interfaces which are important for future technologies. The MUSE group at the Institute of Materials Structure Science, KEK, succeeded in extracting the worlds strongest pulsed muon beam, 2,500,000 muons per pulse (proton beam intensity of 212 kW and pulse repetition rate of 25 Hz) to the ultra-slow muon beam experimental area at MLF of J-PARC [1]. Fig. 1 shows sketch of muon science facility of J-PARC consisting of surface muon production target in the proton beam transport line tunnel which runs through the center of MLF building and associated four secondary beam lines. One of these secondary beam lines extracted at the angle of 60 degrees to the proton beam line backward, is designed for the ultra-slow muon microscopy experiments [2]. Another beam line extracted at the angle of 135 degrees to the proton beam line forward, will be followed by linear accelerator for new measurements of muon g-2 and electric dipole moment employing ultra-slow muon beam [3].

ULTRA-SLOW MUON BEAM GENERATION

Since surface muon beam is produced at 4.1 MeV kinetic energy and beam size of a few cm^2 to 10 cm^2, a number of cooling techniques are developed to create ultra low energy slow muons. Another attribute is, the surface muons are 100% spin polarized opposite to the direction of motion appears from the spin of pion which is zero and a definite helicity of the muon neutrino. The technique for generation of ultra-slow muons is based on producing muonium that is a pure leptonic system formed by electron capture of μ^+ near the surface of the hot tungsten foil. Transported muon beam will be focused on tungsten target to produce muonium. Thermal emission of muonium into a vacuum at target temperature of 2000 K proceeded with intense laser irradiation. The electrons are then stripped from the muonium atoms using two high-power new laser systems. One at wavelength of the muonium Lyman-α photo-excites the muonium from ground to $2P$ state, and then the other at wavelength of 355 nm ionizes the excited muonium. The ultra-cold muons produced this way will be fully polarized, with small transverse momentum. The thermalization process is the key point to cool down the muon beam. The basis of the technique has been described in detail previously [4, 5]. An alternative technique for generation of ultra-slow muons, originally has been developed using a continuous muon source at the Paul Scherrer Institute (PSI) in Switzerland. This method is based on energy moderation in a thin foil-degrader. Particularly suitable as moderators are van der Waals bound solids, such as solid argon, neon and nitrogen [6]. One drawback of the moderation method is that the intensity of the ultra-low energy muon beam emerging from the downstream side of the moderator is reduced several orders of magnitude below that of the incident surface muon beam. In addition, moderated muons still has larger

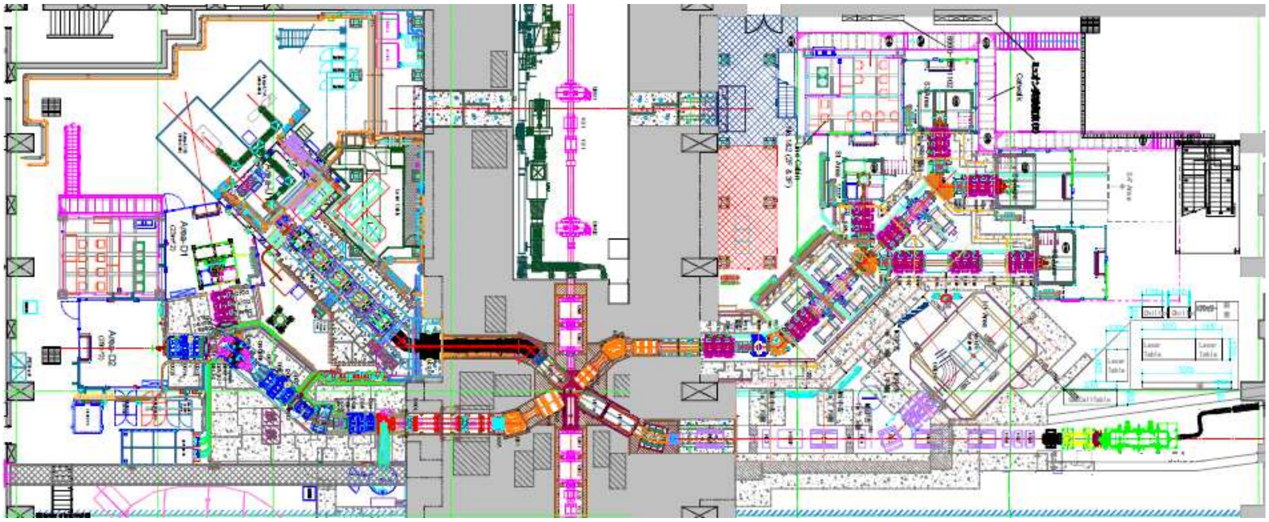

Figure 1: Top view of the muon production target and associated four beam transport lines (J-PARC MLF). Two of these beam lines are extracted at the angle of 60 degrees to the proton beam line (backward), and the others are at 135 degrees (forward).

beam size and large divergence. Research for studying implantation-depth-dependent properties of thin samples, nanomaterials, multilayered thin films or superconductors prefers ultra-slow muons with optimized beam parameters such as suitable energy range and small beam spot size. It is experimentally shown that, moderated positive muon beams with tunable energies in the range of 0 to 30 keV are possible. This energy range corresponds to implantation depths in solids of less than a nanometer to several hundred nanometers. The implantation depth can be easily controlled on a scale ranging from several nanometers to hundreds of nanometers by re-accelerating muons from eV energies to tens of keV or MeV.

MUON RE-ACCELERATION

The ultra-slow muon microscope will be the first experimental instrumentation in the world with the following two excellent capabilities, which are essential for materials and life science experimental research: (1) ultra-slow muon for depth profiling with nanometer depth resolution, and (2) high-density micro-beam for three-dimensional imaging inside materials with micrometer spatial resolution [7]. To produce micrometer size beam at the designed energy of 300 keV, muons are to be re-accelerated by the electric fields associated with changing magnetic flux. RF acceleration is not applicable due to experimental requirements such as variable implantation-depth (variable energy), scalable energy up to 1 MeV and considering into account large initial beam size. An induction accelerator as shown in fig. 2, will generally contain a number of individual accelerator modules that each add a given increment of energy to the charged particles that pass through it. Each module as shown in fig. 3 is comprised of a pulse transformer -insulated gate bipolar transistor (IGBT) that powers an induction cell containing an induction core made from Finmet3 material [8]. A key point about this multistage induction accelerator module, the beam senses a large net accelerating field. The charged particles, in effect, do the integration of the axial electric field in the vacuum beam pipe to achieve a final energy equal to the sum of all the individual module voltage. Working principle of induction accelerator can be explained schematically from fig. 4 in which four individual modules are placed in series. A pulsed transformer provides power to energize the induction module.

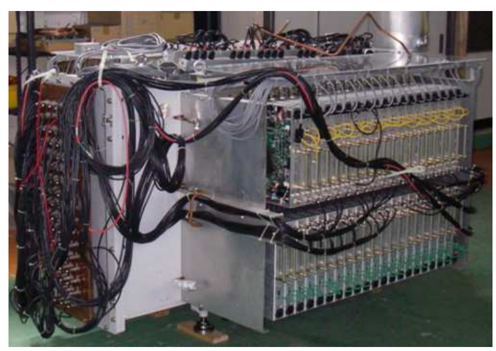

Figure 2: Induction accelerator modules.

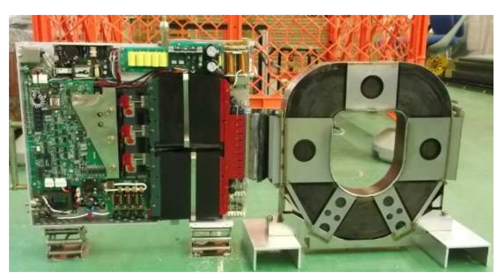

Figure 3: IGBT and an induction core.

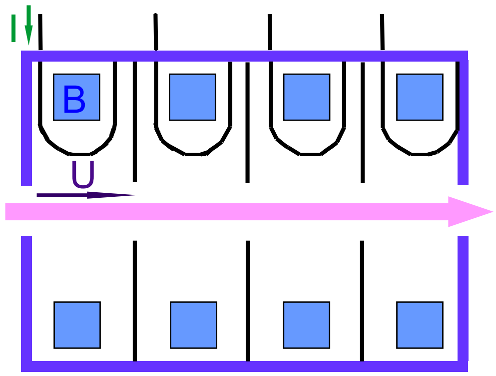

Figure 4: Induction accelerator composed of four individual modules placed in series.

The electric acceleration field is confined primarily to the axis of the system by the conducting walls surrounding the induction core. Each core has one turn as the primary and transformer has four turns for secondary. The accelerating voltage is associated with a changing magnetic field by $U = -d\Phi/dt$, where Φ is the magnetic flux in the core. To produce a high accelerating voltage the magnetic flux has to be changed very fast. Transistors are used for the rapid change of the current. Accelerating voltage of 15 kV per module is possible, to produce 300 KeV muon beam 20 induction modules are combined.

SIMULATION RESULTS

The secondary beam lines extracted from primary target in the proton beam line and transport surface muons to the experimental area. Transport beam line in which muon acceleration linac for g-2 measurements will be installed, is the sequence of radiation shield from graphite target zone, superconducting solenoid, bending magnet, a couple of kicker magnets, separator, a couple of beam transport solenoids and quadrupole triplet for final beam focusing on to the tungsten or degrader foil. Ultra-slow muon beam line is composed of radiation shield from graphite target zone, large angle paramagnetic solenoid, curved superconducting solenoid and superconducting axial focusing magnet. Final focusing part of the beam transport line is a section to produce ultra-slow muons by means of tungten target or degrader-foil. Fig. 5 shows the simulation of muon beam energy moderation (from 4.5 MeV to 0) passing through lithium fluoride (LiF, 2.635 g/cm^3) foil. From this estimation we define the foil thickness as 788 μm corresponding to 30 keV. Fig. 6 shows the simulation of muon beam energy moderation in terms of reference particle momentum passing through lithium fluoride foil. Momentum decreases (starting from 30 MeV/c to 0) as a function of foil thickness, the corresponding values are consistent with previous result.

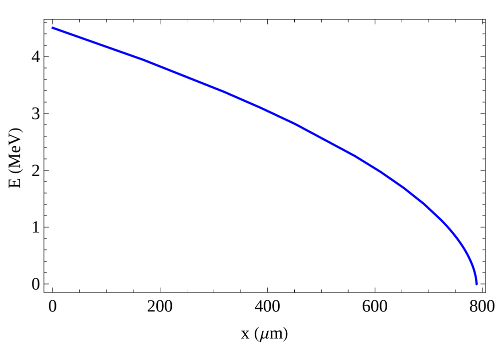

Figure 5: Energy moderation of muons as a function of degrader thickness.

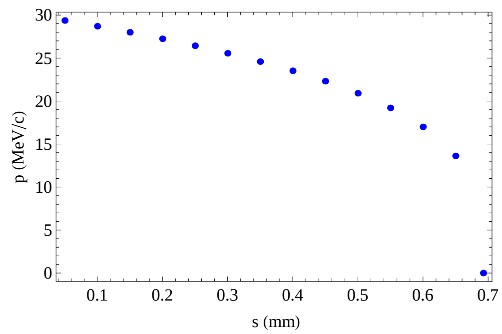

Figure 6: Energy moderation of muons in terms of momentum as a function of degrader thickness.

CONCLUSION AND OUTLOOK

In this paper we present a brief overview of experimental muon science facility employing ultra-slow muons and preliminary results of the ultra-slow muon production simulations with tunable energies in the range of between 5.65 and 30 keV. In addition, we discuss muon beam re-acceleration method to provide a microbeam for muon microscopy applications.

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