SIMULATION OF LARGE ACCEPTANCE MUON LINAC

H. Miyadera#, S.S. Kurennoy, A.J. Jason, LANL, Los Alamos, NM 87545, U.S.A.

Abstract

There has been a recent need for muon accelerators not only for future Neutrino Factories and Muon Colliders but also for other applications in industry and medical use. We carried out simulations on a large-acceptance muon linac with a new concept "mixed buncher/acceleration". The linac can accept pions/muons from a production target with large acceptance and accelerate muon without any beam cooling which makes the initial section of muon-linac system very compact. The linac has a high impact on Neutrino Factory and Muon Collider (NF/MC) scenario since the 300-m injector section can be replaced by the muon linac of only 10-m length. The current design of the linac consists of the following components: independent 805-MHz cavity structure with 6- or 8-cm-radius aperture window; injection of a broad range of pion/muon energies, 10 - 100 MeV, and acceleration to 150 - 200 MeV. Further acceleration of the muon beam are relatively easy since the beam is already bunched.

INTRODUCTION

High intense muon beams of a few 100 MeV to 1 GeV energies are of great interest not only for fundamental research but also for industrial use. Muon accelerators are studied for Neutrino Factory and Muon Collider (NF/MC) [1] and they consist of a proton driver of several-GeV energy for pion production, pion/muon capture region that has high magnetic field of 20 T or above. They also have a long (~100 m) decay section with a solenoidal field of a few Tesla. The ionization cooling and RF bunching add ~200-m more in length.

The goal of our study is to design and build a compact muon source using a muon accelerator so that it is applicable for muon radiography to study industrial machinery and/or medical research such as functional brain studies through muon-spin relaxation technique [2].

We carried out simulations to design such compact muon accelerator system. The main challenge is to accept significant fraction of pions from a production target and to accelerate pion/muon with high efficiency.

PION CAPTURE

It is known that one can capture pions effectively by placing a production target in the solenoidal field. As shown in Fig. 1, we are considering two options for the pion-capture solenoid: (1) 5-T superconducting solenoid followed byt two 2-T solenoids, and (2) 20-T pulsed solenoid followed by 5-T and 3-T solenoids. In the both cases, proton beam is injected with 6º tilted angle.

#harumo@lanl.gov

5-T Superconducting Solenoid

The 5-T superconducting configuration is similar to pion capture section of COMET at JPARC [3]. The technical challenges of this option are the radiation heating and radiation damage to the solenoid. Tungsten radiation shields will be inserted in the solenoid to reduce the neutrons from a graphite production target. According to MCNPX simulations [4], aluminium-stabilized NbTi wire is essential if one would like to operate the system above 1 µA proton current (800 MeV) since aluminium-stabilized conductor can stand 10-times more neutron damage than conventional copper-stabilized one. The 5-T superconducting pion-capture solenoid is our baseline.The simulations in the latter section are carried out with this configuration.

20-T Pulsed Solenoid

We are also considering to produce pions in much higher field of 20-T. One can inject more parallel beam into the muon linac by producing pions in the higher field and, according to our simulations, the muon yield in the case of 20-T capture will be 4-times higher compared to the 5-T solenoidal capture (muon yield after the acceleration). The 20-T field can be realized by pulsed solenoid which is turned on for ~10 µsec. Radiation effects to the pulsed solenoid are almost ignorable which are the advantages over the 5-T superconducting-solenoid option.

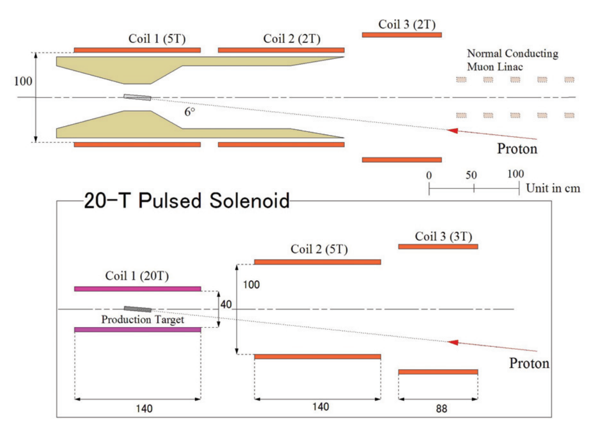

Figure 1: Two designs of pion capture solenoid, superconducting 5-T solenoid (up) and pulsed 20-T pulsed solenoid (down) .

MUON LINAC

As shown in Fig. 2, normal-conducting high-gradient muon linac is used for the initial acceleration. The cavities are placed inside the superconducting coils which provides continuous focusing field for pion and muon beams of large-emittances. A large angular acceptance is realized by the high field as well as the large aperture of the linac. Although half of the pions already decayed into the muons when they entered the linac section, the linac also works as a decay channel for the survived pions.

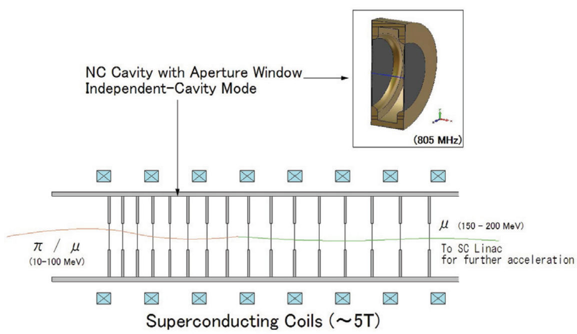

Figure 2: Schematic drawing of the muon linac.

The muon linac is operated with a unique accelerating mode namely "mixed buncher/acceleration mode" where the RF field is used for both bunching and acceleration. As shown in Figure 3, an intermediate phase of the between bunching and acceleration is chosen for this mode: the muon linac starts from the mostly bunching mode and then gradually shifts to the acceleration mode. The principle of the mode is similar to an RFQ.

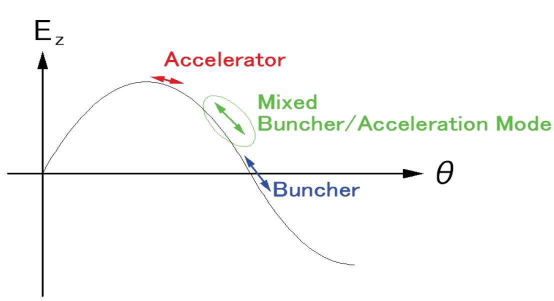

Figure 3: Illustration of mixed buncher/acceleration mode in the RF phase.

A novel normal-conducting structure, independent-mode cavity, is proposed for the muon linac: each cavity cell is sealed with thin beryllium windows (<0.2-mm thickness) of large aperture (6- or 8-cm radius for 805 MHz, the 6-cm radius is the current baseline) [8]. This so-called 0-mode allows larger aperture compared to the conventional π-mode cavities which results in larger acceptance for the pion/muon beam. The 0-mode cavity also reduces the maximal surface electric field at a fixed accelerating gradient especially in the low particle velocity region. The mixed buncher/acceleration mode can be realized by optimizing the RF-phase profile in the chain of independently fed cavities.

SIMULATION

We developed a Monte Carlo simulation code, LAMu (Linear Accelerator for Muon) to design a muon linac. The code is capable of handling a dynamic 2-D electromagnetic field in a linac. We performed some simulation to demonstrate our muon-linac concept.

Code Overview

LAMu is written in Fortran 90 and parallelized by using Open MP. A computer with 8 CPUs (HP Z800) is used for the simulations in the current paper.

For the pion production, LAMu uses cross-section measured by Cochran et al. at 730 MeV proton energy [5]. We compared some codes that can produce pions such as MCNPX, Geant 4 [6] and MARS 15 [7], however, the agreement with the measurements are poor below 100-MeV pion energy especially in the backward direction. This is actually the region of our interest so we used Cochran's cross-section and included energy losses of the pions in the production target. Then, we used MARS 15 to optimize the geometry of the production target and the optimized graphite target has following dimensions: 30-cm in length and 0.5-cm in radius. We scaled the absolute pion yield from the target to 800-MeV proton energy by comparing Cochran's spectrum to MARS15 simulation. The 800-MeV is chosen because it is the energy of a proton beam at LANSCE and it is also an optimum energy that can produce pion effectively. In the LAMu simulation, pions of 10 – 140 MeV are produced in the production target; energy losses of pions in the production target are calculated; particles are transported through the pion-capture solenoid shown in Fig. 1 (5-T superconducting solenoid); injected into the muon linac and accelerated to 200 MeV. The pion beam has continuous time structure and the initial RF phases of the pions are selected randomly. We do not have any buncher before the muon linac and the bunching of the muon beam is carried out in the linac as described in the previous section.

LAMu can handle axisymmetric magnetic field which keeps pion and muon beams focused inside the cavity. The RF field distributions in the cavity were calculated by Micro Wave Studio [9]. We employed an axisymmetric normal-conducting cavity with a wide aperture of 6-cm radius that operates at 805 MHz. We also tested 8-cm radius aperture window which resulted in 10 % more muons than 6-cm window. The 805 MHz was chosen because it is the standard RF frequency at LANSCE and the Klystrons are available. The higher frequency such as 1.3 GHz would reduce the peak RF power of the linac but results in lower accelerating efficiency because of the smaller aperture windows. Field map of the solenoids are provided by the external files and superinposed. The particle motions in the field are calculated by fourth order Adam's method.

In the case of zero-mode cavity, muons go through aperture windows and the energy losses at the windows are calculated by the Bethe-Bloch equation. We noticed that the aperture wall of the muon linac can cool the transverse emittance of the beam through ionization cooling. Other physics processes such as pion decay and energy loss in the gas (for pressurized cavity) are included in the simulation code, too.

Simulation Results

We ran some LAMu simulations to optimize parameters of the muon linac. We used 35 MV/m for the peak gradient of the cavity; the injection and the extraction energies of the linac are 20 and 200 MeV. The optimized muon linac has a length of 12.2 m (16.7 m including pion-capture section) and it starts bunching the muon beam at -53º RF phase and then gradually shifts to the accelerating phase of -26º.

The results of the simulation is shown in Fig. 4 where the pion and muon spectrum after the acceleration are shown. The accelerated muons have the energy spread of ± 20% and they are all bunched within a 25% phase width of the RF so the further acceleration will be less challenging. One can use superconducting π-mode linac to accelerate muons to further energy.

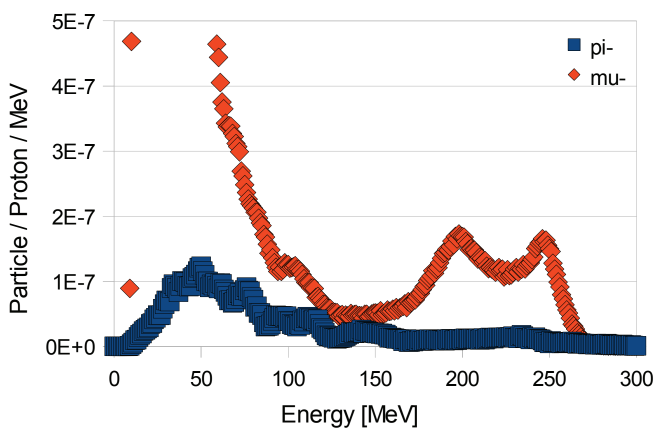

Figure 4: π^- and μ^- spectrum after the muon linac. Graphite production target of 30-cm length and 0.5-cm radius are used for the pion production and the superconducting solenoids shown in Fig. 1 are used to capture pions before the linac section. Each cavity has the beryllium aperture window of 6-cm radius and 0.2-mm thickness. The accelerating gradient of 35 MV/m is used.

In Fig.5, the number of muons accelerated above 180 MeV per proton is shown as a function of peak accelerating gradient. Beam losses at the aperture windows are included in the simulation. The accelerating efficiency becomes higher with the gradient because an accelerating buckets becomes larger in the phase space. The number of cavity decrease linearly with the gradient so the particle losses at the aperture foils become less significant at high gradient. According to the result, the minimum gradient needed to capture muons into the accelerating buckets was 20 MV/m. The high accelerating gradient is obviously a key feature to realize the high efficiency muon acceleration.

One promising option to realize the high gradient is to use gas-pressurized cavities. It was demonstrated at FNAL where 20-atm hydrogen gas was used to realize 80 MV/m [10]. The pressurized cavity provides emittance cooling of the muon beam, too. However, the high-gradient cavity requires high-power RF source. A 800-MHz Magnicon with 120-MW peak power [11] is proposed for the muon collider which could also reduce the total cost of the muon linac in the current paper. The magnicon is designed for 160 kW average power so the muon linac needs to be pulsed.

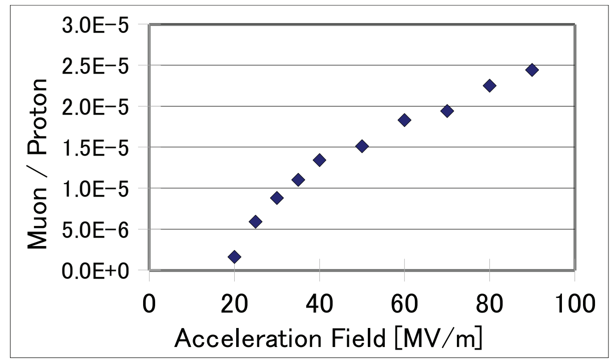

Figure 5: Number of accelerated μ^- per proton plotted versus acceleration field.

FUTURE CONSIDERATION

For industrial and medical applications, the muon accelerator in the current paper will provide a compact and inexpensive solution. We propose to apply our muon linac for Neutrino Factories and Muon Colliders, too. In our scenario, (1) pions are produced by a compact proton accelerator of intermediate energy; (2) a large-acceptance muon linac in the current paper captures 10 – 100 MeV pions and accelerates them to 200 MeV; (3) 6-D muon cooling section [12] is followed after the muon linac; (4) further acceleration can be done by a recirculating linac as in the present NF/MC scenario.

REFERENCES

[1] J.S. Berg et al., Phys. Rev. ST-AB, 9 (2006) 011001.
[2] K. Nagamine et al., Proc. Jpn. Acad., B83 (2007) 120.
[3] Y. Kuno, Nucl Phys B (Proc. Suppl.) 353 (2007) 353.
[4] D.B. Pelowitz et al., mcnpx.lanl.gov
[5] D.R.F. Cochran et al., Phys. Rev. D6 (1972) 3085.
[6] J. Allison et al., IEEE Trans. Nucl. Sci. 53 (2006) 270.
[7] N.V. Mokhov, MARS15, www-ap.fnal.gov/MARS/
[8] S.S. Kurennoy et al., "Large-Acceptance Linac for Accelerating Low-Energy Muons", IPAC 10.
[9] Micro Wave Studio, v.2009, CST, www.cst.com
[10] K. Yonehara et al., Nucl. Phys. B149 (2005) 286.
[11] O.A. Nezhevnko et al., Proc.of EPAC 04 (2004) 1099.
[12] K. Yonehara et al., Proc. of PAC07 (2007) 2969.