# LARGE ACCEPTANCE LINAC FOR MUON ACCELERATION

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## *Abstract*

Muon accelerators are extensively studied for Neutrino Factories and Muon Colliders (NF/MC) but there are recent needs for other applications in homeland security, and industry. We worked on simulations for a large-acceptance muon linac. The idea is to develop a linac that can accept pions/muons from a production target with large acceptance and to accelerate muons without any beam cooling. A muon linac that is operated at mixed buncher/acceleration mode is proposed in this paper. The current scheme has a high impact on NF/MC scenario since the injector section of 300-m can be replaced by a linac of about 10-m length.

## INTRODUCTION

Some applications of muons such as muon interrogation and radiography require intense muon beams of a few-100-MeV to 1-GeV energies. Muon accelerators studied for Neutrino Factory and Muon Collider (NF/MC) [1] consist of a proton driver of several-GeV for pion production, pion/muon capture solenoid of 20 T or above, a long (~100 m) decay section with a solenoidal field of a few Tesla, ionization cooling sections, and a RF bunching section. In total, it requires almost 300-m in length before the acceleration.

Our primary interest is to develop a compact muon source that provides $\mu^-$ beam at ~ 1 GeV which can be used for muon active interrogation by detecting the muonic x-rays. Our study also aims at developing a compact muon accelerator for industrial radiography use and/or medical research such as functional brain studies [2]. This paper describes results of simulations we worked to prove the principle of a compact muon accelerator system which can be used for the initial acceleration of muons. The concepts of a large-acceptance muon linac are described.

## SOLENOIDAL PION CAPTURE

There is a recent trend to capture pions/muons with large acceptance using superconducting solenoids. By producing pions in a high magnetic field, pions/muons are more parallel to the axis after they exit the solenoid. We are considering two options to capture pions: (1) a superconducting 5-T solenoid followed by two 2-T solenoids, and (2) a 20-T solenoid which is a hybrid of a superconducting and a pulsed solenoid. In the both cases, proton beam is injected at 6° angle to the solenoid axis.

The 5-T superconducting solenoid option is similar to the pion capture section of COMET [3] at JPARC or Mu2e [4] at FNAL. In our current scenario, the 5-T option is the standard configuration because it is less challenging. However, the muon yield of the 20-T option is 3-times higher than the 5-T case as mentioned in the later section. Radiation damage and heating to the 20-T pulsed solenoid is ignorable which will be the serious issues with the 5-T-superconducting-solenoid option.

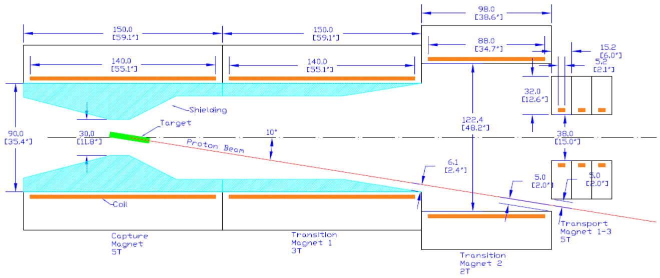

Figure 1: Drawing of the pion capture solenoid. It consists of three superconducting solenoids. The operation currents of the solenoids are 5 T (left), 2 T (center) and 2 T (right). Operating the center solenoid at 3 T would yield ~10% more muons but results in higher magnetic forces. A muon linac follows right after the capture section.

## MUON LINAC

To capture a muon beam with a large emittance, we propose to use a normal-conducting high-gradient muon linac with superconducting coils to maintain beam focus. The superconducting coils provide a continuous 5-T focusing field. For the cavity, we employed an independent-mode structure for our muon linac [5]. This so-called 0-mode allows larger aperture compared to the conventional π-mode cavities and provides larger acceptance for the pion/muon beam. The 0-mode cavity also reduces the maximal surface electric field especially in the low particle velocity region.

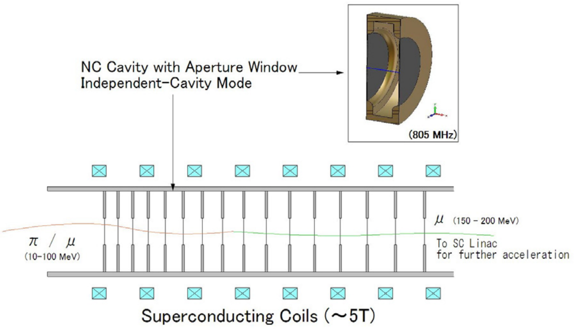

Figure 2: Drawing of the muon linac. Superconducting coils surrounding the linac are used to maintain focus the pion/muon beam transverse capture.

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Because of the large energy spread, the pion/muon that enters the linac is spread over 360° phase of the RF. Instead of using bunchers we designed a linac that is capable of accepting a beam with large energy and phase spreads. The linac operates with a unique accelerating mode namely “mixed buncher/acceleration mode”. As illusted in Fig.3, the mode is analogous to that of the RFQ where RF field is used for both bunching and acceleration. To increase the phase acceptances, the linac gradually shifts the phase of the RF from buncher mode (-53°) to acceleration mode (-26°). When operated in this mode, we found that a linac can accelerate a beam with a very-large energy spread. This is because when particles with the higher energies than the design energy is injected into the linac they move with effectively no energy gain or loss until they arrive at the cell that optimally matches their energies.

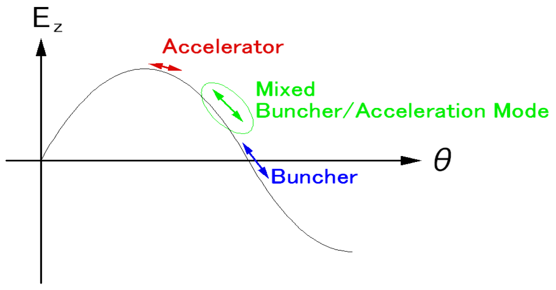

Figure 3: Mixed buncher/acceleration mode. The linac gradually shifts the phase of the RF.

## SIMULATION

We developed a Monte Carlo simulation code, LAMu (Linear Accelerator for Muons) to run the 3-D motion of the particles in the dynamic 2-D electromagnetic field of the muon linac. LAMu is written in Fortran 90 and parallelized by using OpenMP. In the simulation, pions are produced at the graphite production target (1-cm diameter, 30-cm length); captured by the solenoids; transferred and injected into the muon linac; accelerated to 200 MeV.

The largest uncertainty in the simulation comes from the lack of pion-production cross section toward 180° with intermediate proton energy. We are considering use of an 800-MeV proton energy so that we can test it at LANSCE. One useful reference of the cross section is Cochran's measurement that covers a 15° to 150° pion angle at proton energy of 730-MeV [6]. We tested major code such as Geant4 [7], MCNPX [8] and MARS15 [9] and found that they do not reproduce Cochran's result at Ep<100 MeV in the backward direction which is the region of our interest. So we decided to scale Cochran's cross section with the proton energy in our LaMu simulation.

A zero-mode cavity was proposed and designed for the muon linac. The RF field of the cavity was calculated by Micro Wave Studio [10]. Each cavity has aperture windows at the both ends where the pion/muon beams go through. In the simulation, the energy losses at the windows are calculated by the Bethe-Bloch equation.

Our standard designs of the linac are as follow: (1) 35-MV/m acceleration field; (2) 805-MHz RF frequency; (3) 6-cm radius beryllium aperture window of 0.2-mm thickness; (4) nominal injection and extraction energies are are 20 and 200 MeV.

A mixed buncher/acceleration mode is used to capture and accelerate the beam effectively. The muon linac has a length of 12.2 m (16.7 m including pion-capture section). The result of the simulation that includes pion-capture section and muon linac is shown in Fig.4 where the energy spectrum of pions and muons are shown.

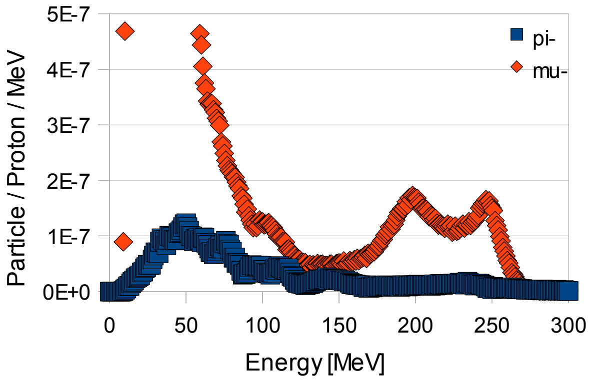

Figure 4: $\pi^-$ and $\mu^-$ spectrum after the muon linac. A graphite production target of 30-cm length and 1-cm diameter is used for the pion production.

In our standard configuration, the number of muons which are accelerated above 180 MeV is $2.1\times10^{-5}$ $\mu^-$/proton or $1.3\times10^{11}$ $\mu^-$ per 1-mA proton beam (800 MeV). The accelerated muon beam has the energy spread of ± 20%. The muons are bunched within 25% phase width of the RF so the further acceleration is less challenging.

As mentioned in the previous section, we are considering either to capture pions with a 5-T superconducting solenoid or 20-T pulsed solenoid. The linac-system efficiency with various magnetic fields of the initial capture solenoid are summarized in Table 1.

Table 1: Magnetic field of the capture solenoid and the accelerating efficiency of the linac. The capture solenoid is followed by two transfer solenoids that produces a 2-T solenoidal field.

| *Magnetic Field [T]* | $\pi^-$*/proton* | $\mu^-$*/proton* |
|---|---|---|
| 2 | $1.2 \times 10^{-6}$ | $7.5 \times 10^{-6}$ |
| 5 | $3.2 \times 10^{-6}$ | $2.1 \times 10^{-5}$ |
| 10 | $6.1 \times 10^{-6}$ | $4.0 \times 10^{-5}$ |
| 20 | $1.0 \times 10^{-5}$ | $6.2 \times 10^{-5}$ |

We chose the RF frequency of 805 MHz because of klystron availability. The higher frequency such as 1.3 GHz would reduce the peak RF power of the linac but also results in lower accelerating efficiency. The system efficiencies for some RF frequencies are shown in Table 2. The capture efficiency decrease significantly with the frequency because a bucket size in the phase-energy space becomes larger at low frequency. The increased particle losses at the aperture windows are partly responsible for the efficiency loss at the high frequency. However, we noticed that the aperture window of the muon linac can cool the transverse emittance of the beam through ionization cooling. On the other hand, adopting a lower frequency such as 402.5 MHz could quadruple the linac efficiency as compared to our standard 805-MHz cavity but it is not realistic to sustain the gradient of 35 MV/m at that frequency. It was found that the higher the gradient, the more efficient the linac can accelerate the beam. The breakdown may be suppressed by pressuring the cavities with hydrogen or helium gas or by coating the cavity surface.

Table 2: Frequency of the Cavity and the Linac Efficiency. Acceleration fields of 35 MV/m are used and aperture-window radii are 6-cm for all cases.

| *Frequency [MHz]* | *Cell* | $\pi^-/proton$ | $\mu^-/proton$ |
|---|---|---|---|
| 402.5 | 41 | $1.4 \times 10^{-5}$ | $8.1 \times 10^{-5}$ |
| 700 | 71 | $5.0 \times 10^{-6}$ | $3.3 \times 10^{-5}$ |
| 805 | 82 | $3.2 \times 10^{-6}$ | $2.1 \times 10^{-5}$ |
| 1000 | 101 | $1.7 \times 10^{-6}$ | $9.2 \times 10^{-6}$ |
| 1200 | 121 | $9.3 \times 10^{-7}$ | $3.5 \times 10^{-6}$ |
| 1300 | 132 | $7.8 \times 10^{-7}$ | $1.9 \times 10^{-6}$ |

In the case of high-duty-factor operation, cooling of the aperture window is not trivial. The estimated heating of an aperture window is about 60 kW for 100 % duty-factor operation. The aperture-window size of 6-cm radius was chosen since the accelerating efficiency saturate at that radius as shown in Table 3. The acceptance usually scales with $B_z \cdot a^2$ where $B_z$ is the magnetic field of the solenoid and $a$ is the radius of the aperture window but the saturation is due to the fact that $E_z$, accelerating field, is maximum on the axis and decreases with the larger radius.

Table 3: Aperture Radius of the Cavity and the Accelerating Efficiency Linac

| *Aperture [cm]* | $\pi^-/proton$ | $\mu^-/proton$ |
|---|---|---|
| 1 | $3.5 \times 10^{-7}$ | $6.7 \times 10^{-7}$ |
| 2 | $9.6 \times 10^{-7}$ | $3.2 \times 10^{-6}$ |
| 3 | $1.8 \times 10^{-6}$ | $8.3 \times 10^{-6}$ |
| 4 | $2.6 \times 10^{-6}$ | $1.5 \times 10^{-5}$ |
| 5 | $3.0 \times 10^{-6}$ | $1.9 \times 10^{-5}$ |
| 6 | $3.2 \times 10^{-6}$ | $2.1 \times 10^{-5}$ |

The accelerating efficiency of the muon linac with various solenoidal field of the surrounding coils are tabulated in Table 4. It is known that when a solenoidal field is applied parallel to a cavity, it could cause a breakdown because of electrons trapping. We are going to work on some development to prevent the breakdown. One of the ideas is to coat the cavity surface to prevent the breakdown. The other option to prevent breakdown is to use gas-pressurized cavities. The technique was demonstrated at FNAL where 20-atm hydrogen gas was used to achieve a high gradient of 80 MV/m [11]. The pressurized cavity also provides emittance cooling of the muon beam, too.

Table 4: Magnetic Field of the Linac Coil and the Accelerating Efficiency of the Linac

| *Magnetic Field [T]* | $\pi^-/proton$ | $\mu^-/proton$ |
|---|---|---|
| 1 | $2.4 \times 10^{-7}$ | $4.0 \times 10^{-7}$ |
| 2 | $1.2 \times 10^{-6}$ | $4.1 \times 10^{-6}$ |
| 4 | $2.8 \times 10^{-6}$ | $1.6. \times 10^{-5}$ |
| 5 | $3.2 \times 10^{-6}$ | $2.1 \times 10^{-5}$ |
| 7 | $4.1 \times 10^{-6}$ | $2.7 \times 10^{-5}$ |
| 10 | $4.6 \times 10^{-6}$ | $2.8 \times 10^{-5}$ |

## FUTURE CONSIDERATION

The muon accelerator in the current paper will provide a compact and inexpensive solution for muon interrogation and radiography. In the extreme case where we combine a 20-T capture solenoid and a 402.5 MHz cavity, we get $2\times10^{-4}$ $\mu^-$/proton and $8\times10^{-4}$ $\mu^+$/proton which makes $2\times10^{12}$ $\mu^-$ and $8\times10^{12}$ $\mu^+$ for a proton beam of 1-MW power. This can be a promising option for neutrino factory. Here, we propose our muon linac to be the first stage of the Neutrino Factories and Muon Colliders. In our scenario, a proton accelerator of an intermediate energy can be used instead of a several-GeV machine. We could cool the muon beam after the initial acceleration through the recently proposed 6-D muon cooling [12] before the further acceleration by a recirculating linac [13] as in the present NF/MC scenario.

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