

SIMULATION OF LARGE ACCEPTANCE LINAC FOR MUON

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

Abstract

Muon accelerators are proposed world wide for future neutrino factory, muon colliders and other applications. We carried out some simulation works on large acceptance muon linac that operates at novel “mixed buncher/acceleration mode”. Because of its large acceptance, the linac can accept pions/muons from a production target without any beam cooling and can accelerate them directly to high energy. The linac has following features: independent 805-MHz cavity structure with 8-cm-radius aperture window; inject ~100 MeV muon beam and accelerates to 200 MeV; 35 MV/m peak accelerating field. Further acceleration of the muon beam can be easily done by extending the muon linear accelerator. According to our simulation, the linac can accelerate more than 5 % of pions produced in 20 - 100 MeV energy range. The linac has a high impact on Neutrino Factory and Muon Collider (NF/MC) scenario since one can replace the 300-m injector section with a muon linac of only 10-m length.

INTRODUCTION

Beams of accelerated muons are of great interest for fundamental research as well as for industrial use. The 2.2- μ s life time of muons is long enough to accelerate them. Muon accelerators are extensively studied in Neutrino Factory and Muon Collider (NF/MC) scenarios [1]. Muon accelerators in the Neutrino Factories and Muon Collider (NF/MC) projects that typically include a proton driver of several-GeV energy to produce pions of relatively higher energies (>100 MeV). The pion/muon capture region has high magnetic field of 20 T or above, and then, it is followed by a long (~100 m) decay channel with a continuous solenoidal field of a few Tesla. The RF bunching and ionization-cooling sections which are required to prepare the beam for the subsequent acceleration of muons to higher energies add ~200-m more in length.

On the other hand, muon radiography of large-scale machinery using cosmic-ray muons is becoming popular [2], and a high-intensity pencil muon beam produced by the muon accelerator would be a valuable tool for dynamic investigation of machinery [3]. A compact and inexpensive muon source using a muon accelerator is also applicable for medical research such as brain-function studies [4]. However, the scales of the muon accelerators proposed in the NF/MC scenario are so large both in size and cost that it is impossible to apply them to industrial and/or medical use.

There is a significant need to have a compact and efficient accelerator that can capture a large fraction of a divergent muon beam from a production target. We carried out simulations to develop a compact muon linac based on a completely new concept.

Our approach is compared with MC/NF scenario in Table 1. Unlike NF/MC scenario, our linac aims to correct pions of relatively lower energy (<100 MeV) and use the linac itself as a decay section. By utilizing the low-energy pions, one can reduce the magnetic field of the capture section to ~6 T. Bunching and acceleration are carried out using a unique mode that resembles RFQ so that a buncher and long drift space is not needed. The linac has a large phase acceptance, too, so that it does not require a short pulsed high-energy proton synchrotron to produce pions: one can use cyclotron, FFAG [5] or linac of intermediate energy instead.

Table 1: Comparison of Injection Approach Between NF/MC Scenario and Current Approach

	MC/NF Approach	Current Approach
Injected Particle	Muon	Muon/Pion
Injection Energy	100 – 140 MeV	10 – 100 MeV
Acceptance	15 mm rad	~10 ⁴ mm rad
Phase Acceptance	11 %	30%
Length	~300 m	10 – 15 m

MIXED BUNCHER/ACCELERATION

The muon linac is operated with a unique accelerating mode namely “mixed buncher/acceleration mode”. The mode is analogous to RFQ where the RF field is used for both bunching and acceleration. As shown in Figure 1, intermediate phase of the RF between bunching and acceleration is used for this mode. In this unique mode, it was found that a linac can accelerate beam with huge energy spread, even 100 % or more, because particles with the higher energies moves with effectively no energy gain until it arrives at the cell that optimally matches its energy [6]. The acceleration and deceleration field before the certain cell almost cancel in total due to the mismatch of energy and phase [7].

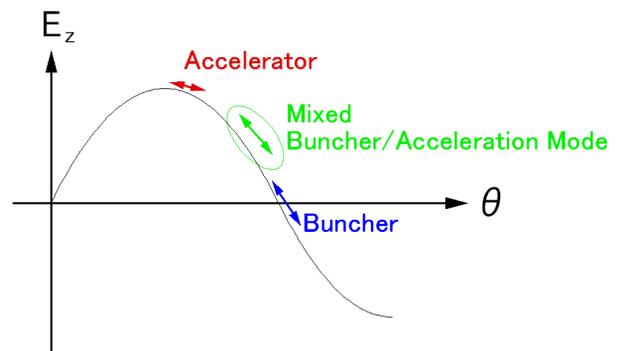


Figure 1: Illustration of mixed buncher/acceleration mode in the RF phase.

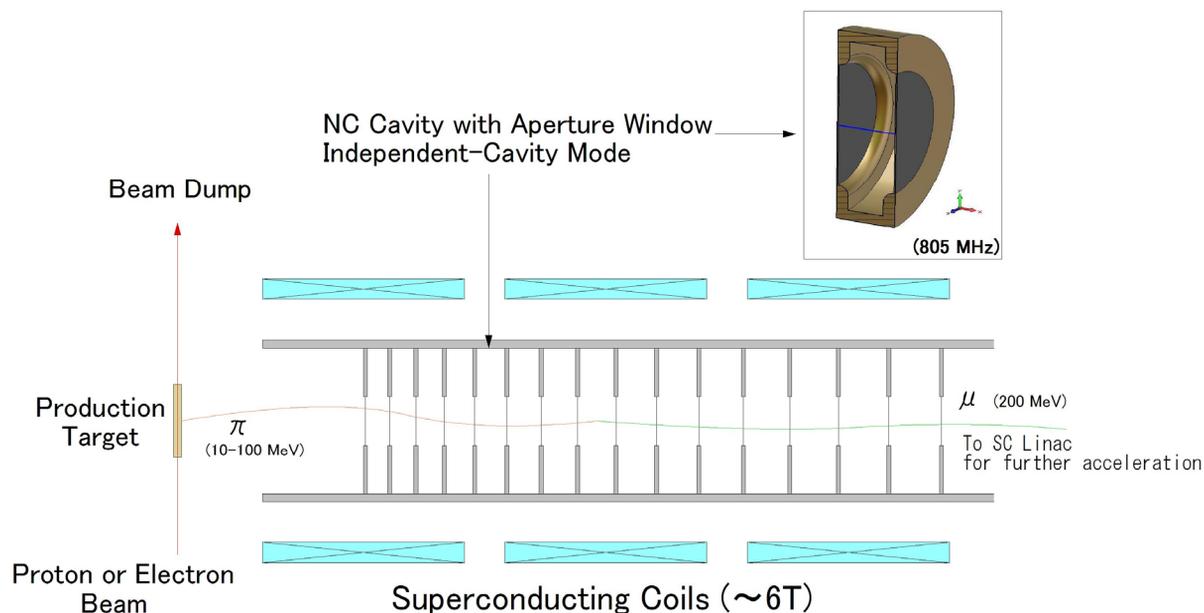


Figure 2: Schematic view of our linac setup with a drawing of independent-mode cavity.

Proposed muon-accelerator system is illustrated in Figure 2. Pions are produced by proton impact on a production target and are directly injected into a linac without any cooling of the beam. The linac is surrounded by super-conducting solenoids that produces ~ 6 T field to keep focusing pion and muon beams of large-emittances. The large angular acceptance is realized by this high field as well as a large aperture of the linac.

As for a cavity, a novel normal-conducting structure that takes advantage of the high penetrating ability of muons is employed: each cavity cell is sealed with thin beryllium window of large aperture (8-cm radius for 805 MHz). This so-called 0-mode allows relatively larger aperture compared to conventional π -mode cavity realizing larger acceptance of the pion beam, and reduces the maximal surface electric field at a fixed accelerating gradient by a factor of up to 15 especially in the low particle velocity region. Thus, it is possible to achieve higher gradient using this 0-mode. The 0-mode also reduces cavity-surface losses and the required peak RF power by an order of magnitude, depending on the cavity frequency and design beam velocity.

In the case of 0-mode linac, mixed buncher/acceleration mode can be realized by optimizing the RF-phase profile in the chain of independently fed cavities: this unique arrangement gives us the flexibility to shift the RF phase gradually along the linac from effective bunching to effective acceleration. It also provides an opportunity to optimize the phase-ramp profile for efficient capture and acceleration of pions/muons.

SIMULATION

We developed a Monte Carlo simulation code “LAMu” that is capable of handling dynamic 2-D electromagnetic field in a linac. Pion energy spectrum used in the code is obtained by MARS15 [8] simulation which impacted 800-

MeV proton beam on a graphite target of 1-cm thickness. 800-MeV is chosen because it is the energy of a proton beam at LANSCE. It is also an energy that can produce pion effectively. Pion decay into muon is included in the simulation code but particle interactions with aperture wall were not included in the initial simulations. The wall effect will be discussed in the following section.

The RF field distribution in the cavity was calculated by Micro Wave Studio [9]. We employed axisymmetric normal-conducting cavity with wide aperture of 8-cm radius, which operates at 805 MHz. We employed the RF frequency, 805 MHz, for our simulation because it is the standard RF frequency at LANSCE as well as SNS. We also worked on some calculations that suggested a 3-GHz cavity with 4-cm-radius aperture can be designed easily.

The length of the linac is longer than the conventional linac of the same gradient because of the mixed buncher/acceleration mode: the linac length is 12.1 m for a peak accelerating field of 35 MeV/m, and it scales with the accelerating field. The accelerating efficiencies of the linac are 0.6 for $E_\mu < 100$ MeV, 0.75 for $100 < E_\mu < 150$, and 0.9 for $150 < E_\mu$ where E_μ is the energy of the muon.

We worked on Monte Carlo simulation of the linac using our simulation code, LAMu. Pions of 0 – 100 MeV are injected into the linac: we assumed a DC pion beam for injection so that the initial RF phases of the pions are selected randomly in the simulation. Pion and muon spectrum after the acceleration is shown in Figure 3. The accelerated muon has energy spread of $\pm 20\%$ and they are all bunched within 25% phase of the RF so that the further acceleration will be less challenging.

Only a few optimization has been carried out and further optimizations can be done by changing the accelerating efficiency and/or by tuning the phase of each cavity.

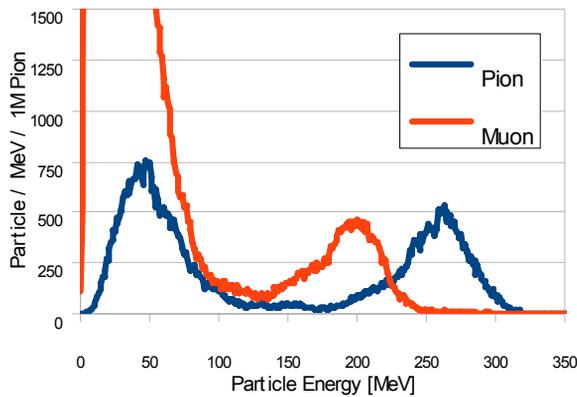


Figure 3: Pion and muon spectrum after the linac with acceleration field of 35 MeV/m.

Fraction of particles, muon and pion, accelerated to 200 MeV as a function of peak accelerating gradient is shown in Figure 4. In the mixed buncher/acceleration mode, a high accelerating gradient is a key parameter to capture particles with high efficiency. This is because particles that drop out of an accelerating bucket can be captured in the following bucket if the accelerating gradient is high enough.

As for the high gradient cavity, a high pressurized cavity was demonstrated at FNAL where 20-atm hydrogen gas was used to realize 80 MeV/m [10].

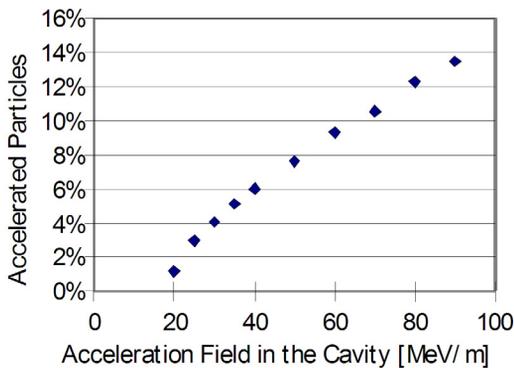


Figure 4: Fraction of accelerated particle plotted with various acceleration field of the cavity.

Particle Loss at the Wall

The main advantage of using the 0-mode linac is that it provides very high accelerating gradients while reducing both the surface peak electric fields and the cavity-wall power losses. The disadvantage of the 0-mode is particle

losses at the wall. The previous simulations did not include any particle scattering effects of pions and muons at the wall. Those effects were added to the simulation to estimate the particle losses. With the beryllium aperture seal of 1-mm thickness, the total particle losses were 59 % and 13 % for the accelerating field of 35 and 80 MeV/m. We can either reduce the thickness of the seal, or design 0-mode cavity without aperture seal to improve the efficiency of the linac. The aperture seal is not necessary if the two cavities are well separated in distance.

FUTURE CONSIDERATION

To apply for industrial and/or medical use, the muon accelerator in the current paper could be coupled with a compact proton accelerator such as cyclotron, linac, or FFAG to make whole system compact and inexpensive. This is due to the large phase acceptance of the linac: the average phase acceptance of the linac is 30 % and, for specific energy, it has nearly 80 % phase acceptance.

Another possible application of this technology could be in Neutrino Factories and/or Muon Colliders. Acceleration of low energy muons is commensurate with the recently proposed “Low Emittance Muon Collider” approach [11]. In our scenario, (1) pions are produced by a proton accelerator of intermediate energy; (2) a large-acceptance muon linac in the current paper captures 10 – 100 MeV pions and accelerate them to 200 MeV; (3) muon cooling channel such as MANX [12] can be used to cool the muon beam; (4) further acceleration can be done by linac and recirculating linac as in the present MC scenario.

REFERENCES

- [1] J.S. Berg et al., Phys. Rev. ST-AB, 9 (2006) 011001..
- [2] W.B. Gilboy et al., Nucl. Instr. Meth. B263 (2007) 317.
- [3] K. Nagamine et al., Physica B404 (2009) 1020.
- [4] K. Nagamine et al., Proc. Jpn. Acad., A83 (2007) 120.
- [5] R. Cywinski et al., Physica B404 (2009) 1024.
- [6] Private communication with M. Okamura (BNL).
- [7] H. Miyadera et al., Proc. of PAC07 (2007) 3032.
- [8] N.V. Mokhov, MARS15, www-ap.fnal.gov/MARS/
- [9] Micro Wave Studio, v.2009, CST, www.cst.com
- [10] K. Yonehara et al., Nucl. Phys. B149 (2005) 286.
- [11] R.P. Johnson, Proc. PAC07 (2007)706.
- [12] K. Yonehara et al., Proc. of PAC07 (2007) 2969.