

A SHARED SUPERCONDUCTING LINAC FOR PROTONS AND MUONS*

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Abstract

It has been shown how a superconducting Linac that was designed to be a high-intensity proton driver for Fermilab [1] can be modified and augmented to also serve as the muon accelerating section for a neutrino factory [2]. In this report we consider the same approach, where the Linac does double duty, but with the idea that the Linac and other parameters are chosen to serve only as a neutrino factory. This "greenfield" approach allows the most economical choices for such a neutrino factory and could provide a baseline cost estimate to be compared to other approaches where other methods such as FFAG synchrotrons are used. Recent advances in muon cooling [3] have the promise of muon emittances that are compatible with high frequency superconducting accelerating structures that are by now sufficiently mature for reliable cost estimates. The muon cooling required for such an approach to a muon collider, although there have been impressive theoretical advances and simulation results, remains still to be proved. In this report we discuss the uncertainties in the design parameters that will depend on the muon cooling efforts that are now underway.

INTRODUCTION

The initial inspiration for the idea of a "double duty" Linac came from the proposed proton driver (PD) that has been considered as possible Fermilab 8 GeV Booster synchrotron replacement [1] and also could act as an ILC

string test. In an earlier work [2] it was shown that if sufficient muon beam cooling could be applied [3], the muons produced by the PD could be reinjected back into the PD and recirculated to energies appropriate for a neutrino factory based on a muon storage ring. In this case, the most expensive component of the neutrino factory, the PD, would be paid for as a Booster replacement and the neutrino factory cost could then be an incremental one, perhaps less than previous studies have indicated [4,5].

One of the attractive aspects of such a plan is the use of superconducting RF with a very high duty cycle to increase the repetition rate of the PD and thereby produce a copious supply of muons for the neutrino factory.

FERMILAB SCHEME

Figure 1 shows the scheme as it was envisioned for the Fermilab PD. Here, H^+ ions are accelerated to 8 GeV and charge-exchange injected into a special storage ring where they are formed into a few short, intense bunches. While these bunches are being formed, the phases of the PD RF sections are adjusted for muon acceleration. The proton bunches are then extracted onto a target where pions and muons are produced. The muons are collected, cooled, and preaccelerated to an energy such that their 6D emittance matches the acceptance of the $\beta=1$ section of the PD Linac. The muons then are injected into the PD Linac, where they recirculate three times to achieve an energy of 23 GeV.

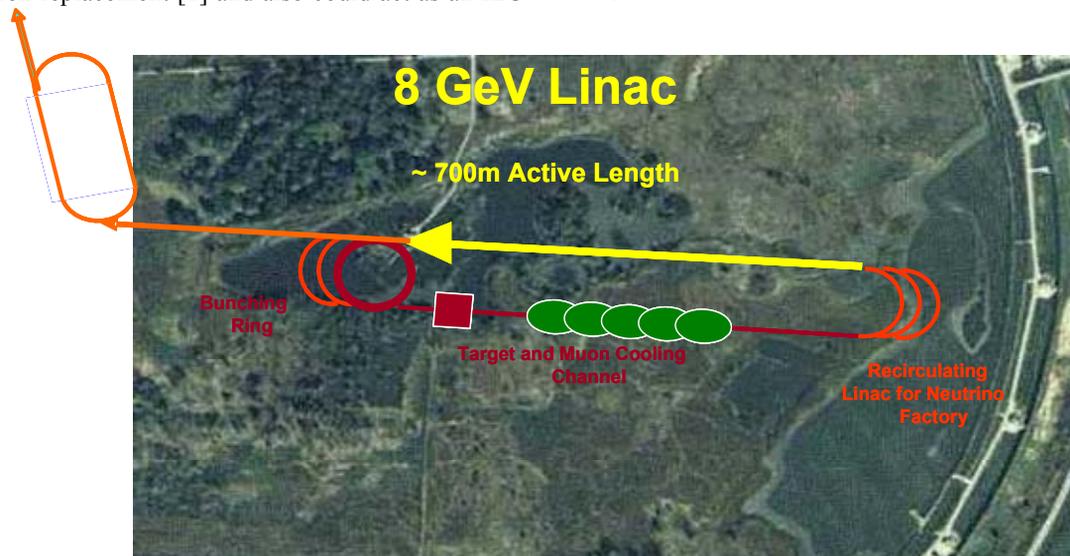


Figure 1: Schematic of Fermilab proposed 8 GeV Superconducting Proton Driver Linac used also as a muon recirculating Linac to provide muons for a 23 GeV neutrino factory storage ring.

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GREENFIELD MODIFICATIONS

For synergy with the ILC, 1.3 GHz superconducting accelerating cavities as shown in figure 2 were chosen for the Fermilab PD. However, the required muon cooling and preacceleration could be eased by going with the 800 MHz of the SNS Linac.

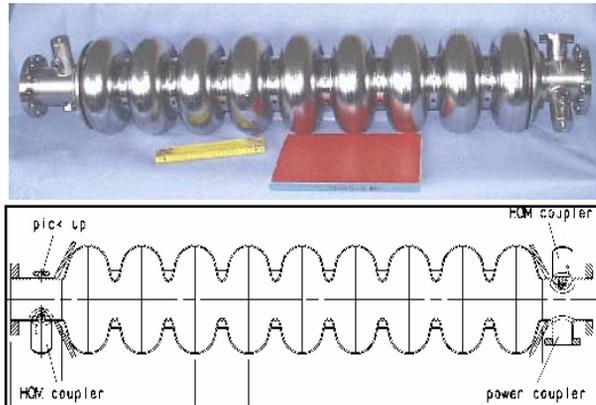


Figure 2: ILC superconducting cavities chosen for the proposed Fermilab PD.

The motivation to replace the present 8 GeV Booster synchrotron determined the energy of the Fermilab PD. However, as shown in figure 3 [6], the muon production rate for muons that are actually captured and cooled, scaled by power on the target, would argue that a lower energy Linac, perhaps as low as 5 GeV would be more cost effective.

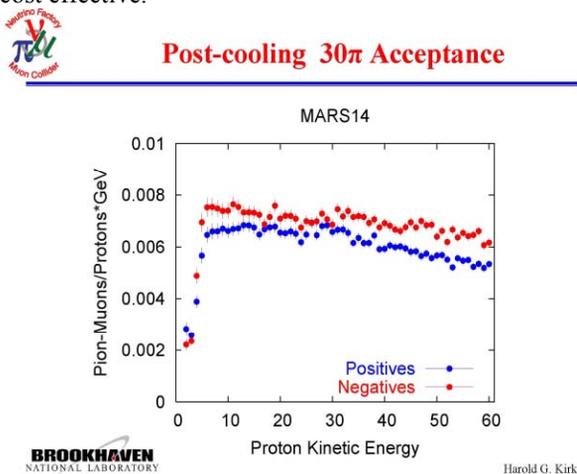


Figure 3: Muon capture rates (after cooling of 30 mm radian acceptance) normalized to proton beam power as a function of proton energy. To reduce the cost of a new site, the energy should be chosen to minimize the cost of the Linac and recirculating arcs given that the muon production rate is sufficiently high.

REPETITION RATE AND TARGETING

The PD repetition rate will be limited by the refrigeration and power capabilities of the superconducting cavities. The muon production rate will be limited by the target's ability to withstand shocks and

thermal stresses. The muon cooling rate will be limited by the heating of the ionization cooling energy absorber and by the RF cavities used to replenish the muon beam energy lost in the absorber. And ultimately, the rep rate of the muon storage ring will be limited by the lifetime of the muon, which at most neutrino factory energies of interest, is around 1 kHz.

One can imagine strategies for overcoming each of these limitations. For example, the target shock limitation for solid metal targets can be improved by hitting the production target at higher rep rates with fewer protons.

COOLING AND PREACCELERATION

There are several new schemes for cooling muon beams [7,8]. While most of these ideas are motivated by muon colliders, the fast and effective 6D muon cooling that is expected can be used to provide a beam that will fit into a PD aperture. In all cases, some combination of muon cooling and preacceleration will provide a beam with small enough emittance to be injected into the PD structures. This challenge becomes easier for the larger, lower frequency SNS cavities than for the ILC cavities. It is also easier in both cases if the PD lattice is made to be as strongly focusing as possible.

DEDICATED MUON SOURCE

Figure 4 is a conceptual picture of a muon source for a neutrino factory based on a double-duty Linac. H⁺ ions are accelerated in a 1.2 GeV Linac, as in the Fermilab design, injected into a $\beta=1$ Linac, accelerated to 3.2 GeV, transported in a low field arc to the second 2-GeV Linac, and accelerated to 5.2 GeV where they are charge-exchange injected into a Buncher Ring. The protons are bunched and targeted to produce the pions and muons to be collected and cooled.

Radiation losses from H⁺ stripping determine the proton arc parameters and therefore the separation of the two 2-GeV Linacs to be about 240 m; with 10^{15} p/s, a bending radius of 96 m and field of 0.14 T, the stripping losses are 2 W/m. With the same bending radius, the highest energy muon arc requires 0.9 T. The path from the cooling system through the first arc at just over 2 GeV is responsible for almost all of the muon decays in the system and should correspond to a loss of about 30%, depending on the cooling system energy. The lower of the two 2 GeV Linacs in figure 4 could be of lower frequency and larger acceptance to reduce muon cooling demands.

Although several technological problems remain to be solved, a double-duty Linac for an intense muon source may be the most cost effective of all options, especially if new beam cooling techniques for muon colliders are successful.

MULTIPASS ISSUES

The maximum number of passes through a Linac section is limited by the effectiveness of the quadrupole

focusing as the energy increases for each pass. Assuming that the quadrupoles are at constant gradient, at some energy the focusing will become so weak that the beam envelope will be larger than the acceptance of the machine, even considering adiabatic damping.

In an OptiM study, we have shown that a lattice based on a triplet quadrupole structure is limited to only four passes in a scheme as shown in figure 4. A FODO lattice, on the other hand, seems capable of allowing the seven passes as shown in the figure. The smaller variation of the Twiss functions and the uniform decrease of the phase advance in both planes in the FODO lattice are advantages over the triplet lattice for a wide range of

acceptable energy and for easier matching to the recirculating arcs. The earlier passes through the Linac sections have 90 degree phase advance per cell which only slowly slips to lower, acceptable values as the energy increases.

An independent issue is the spreaders and recombiners at the ends of the Linac sections which would be difficult in a continuous beam situation such as for the CEBAF machine. However, since the muon bunch train occupies only a small part of the machine circumference, pulsed kicker magnets at the ends of the Linac sections can be used to distribute and collect the beams to and from the arcs.

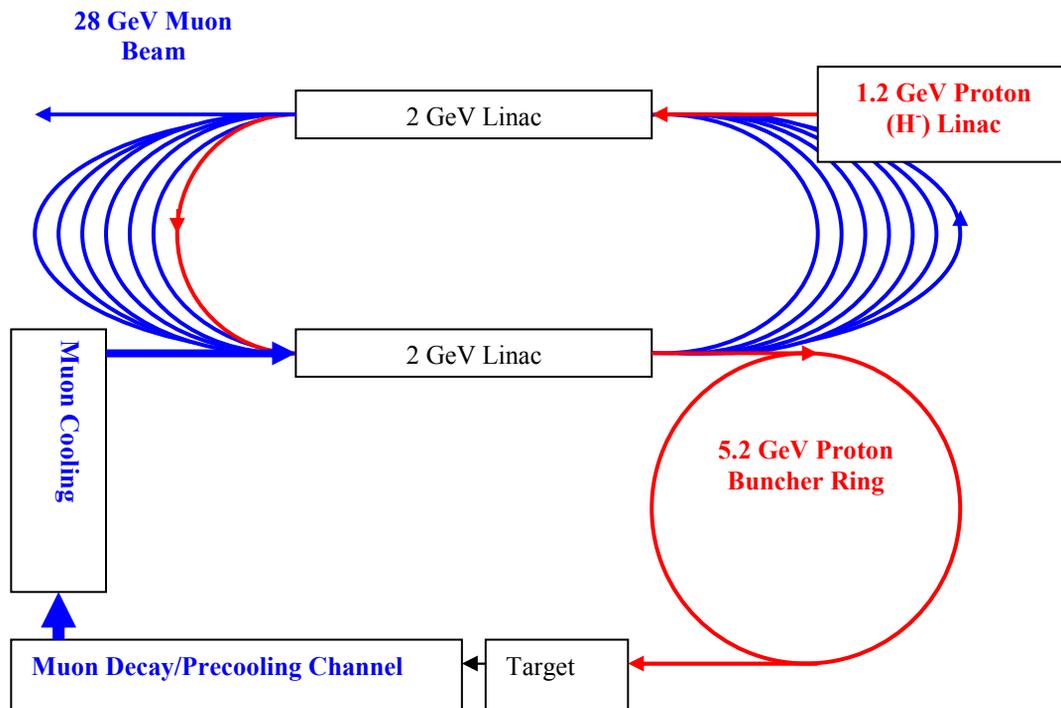


Figure 4: Schematic of a double-duty recirculating Linac for producing a high-energy, high-intensity muon beam for a neutrino factory. Protons (red) are charge exchange injected into the Buncher Ring and formed into short, intense bunches and then targeted to produce the muons (blue) to be cooled and recirculated through the same Linacs that produced the protons. A FODO quadrupole focusing structure is needed in the Linac sections in order to allow the seven passes as shown in the schematic.

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