INTENSE MUON BEAMS FOR EXPERIMENTS AT PROJECT X*

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Abstract

A coherent approach for providing muon beams to several experiments for the intensity-frontier program at Project X is described. Concepts developed for the front end of a muon collider/neutrino factory facility, such as phase rotation and ionization cooling, are applied, but with significant differences. High-intensity experiments typically require high-duty-factor beams pulsed at a time interval commensurate with the muon lifetime. It is challenging to provide large RF voltages at high duty factor, especially in the presence of intense radiation and strong magnetic fields, which may preclude the use of superconducting RF cavities. As an alternative, cavities made of materials such as ultra-pure Al and Be, which become very good --but not super-- conductors at cryogenic temperatures, can be used.

INTRODUCTION

As part of its proposed Project X [1], Fermi National Accelerator Laboratory aspires to develop a world-class program of intensity-frontier experiments that perform very precise measurements and study extremely rare processes that may provide evidence for new physics beyond the Standard Model of particle physics. A 3-GeV superconducting linac that accelerates 1 mA of H⁻ beam in continuous-wave (CW) mode is proposed as the driver for that program. The plan is to split the beam so that three experimental areas, for kaon, muon, and nuclear experiments, can operate simultaneously.

Many experiments that study rare processes involve the detection of more than one particle in the final state. In these cases accidental coincidences between unrelated events, each of which supplies a particle that mimics one of the final-state particles of interest, are often the dominant background. To reduce the rate of such background events, high duty factors, i.e. beams that are "on" for a large fraction of the time, are essential. That in fact is the primary motivation for the decision to operate the 3-GeV Project-X linac in CW mode. Even when only one final-state particle is detectable, as in a muon-to-electron conversion experiment, a high duty factor may be useful to reduce singles rates in the detector, albeit at the expense of greater sensitivity to cosmic ray backgrounds.

For the muon experimental area, a number of experiments are under consideration [2], including searches for charged lepton flavor violation in processes such as muon to electron conversion in the field of a nucleus as well as in the decays $\mu \rightarrow e\, \gamma$ and $\mu \rightarrow 3e$. For several of the muon experiments that have been discussed, the signature of the rare process involves more than one detected particle in the final state. Thus those experiments require muon beams that have both high intensity and high duty factor.

Muon beams originate predominantly from the decay of pions produced when protons impinge on a target; as such, they are rather diffuse at first. Ionization cooling is necessary in order to concentrate high muon fluxes into usable phase-space volumes. Ionization cooling has undergone considerable conceptual development in connection with design efforts for muon colliders and neutrino factories [3]. Those facilities, however, will operate at low duty factor. In order to apply ionization cooling to the generation of low-energy beams having high duty factor, RF cavities are needed that can operate continuously in a harsh environment of intense radiation and strong magnetic fields.

Development of muon beam designs using this technology will allow the efficient and flexible operation of a diverse program of world-class experiments at the intensity frontier.

TECHNICAL APPROACH

The experiments that are being contemplated for the muon program in the Project-X era impose diverse requirements on the muon beam in terms of major parameters such as beam intensity, muon polarization, tolerable beam contamination, energy, emittances, time structure and duty factor. The Project-X CW linac is explicitly designed to provide high duty factor beams with flexible time structures to the intensity-frontier experiments. It is reasonable to take advantage of that capability by using the produced pions and their muon decay products directly, i.e. without intermediate processing that washes out the time structure delivered to the pion production target. A beam design that provides flexibility in the other major parameters would allow a diverse program of experiments to be implemented without major reconfigurations between experiments.

Besides preserving the time structures that can be delivered from the linac, the other major idea embodied in this proposal is to take advantage of the important conceptual advances in muon collection and ionization cooling that have occurred in conjunction with design efforts for the (common) front end of muon colliders and neutrino factories based on muon storage rings. However, there are differences that must be taken into account between muon collider front ends and ones meant to deliver low-energy muon beams. Table 1 compares the major parameters.

The need for high duty factor for the low-energy muon beam requires RF cavities that can operate continuously; that is the main complicating factor. The other differences make things easier and less expensive. So, for example, 1 MW on target is easier to handle than 4 MW and may allow the use of a solid target as opposed to the mercury jet target chosen for muon colliders. Also, the very short proton bunches delivered from the linac suggest that it may be possible to maintain the bunching throughout the pion/muon collection and ionization cooling system, thereby preserving the timing distribution delivered from the linac.

Table 1: Major parameters of beams for muon colliders and low-energy muon beams.

Comparison	Mu collider	P-X Mu beam
Protons		
Beam energy	8 GeV	3 GeV
Beam power	4 MW	1 MW
Bunches/second	15	10^6
Duty factor	low	high
rms bunch length	3 nsec	20 psec
Muons		
muon/proton ratio	0.1	~0.001
required cooling	extreme	moderate

Note that RF capture into a single bunch precludes the necessity of the long drift that is needed in the muon collider case to allow a correlation to develop between the time of arrival at a downstream location and the momentum of the muons. (That correlation is used to facilitate capture of the muons into a train of about a dozen bunches separated by 5 nsec apiece for a muon collider.) Further preliminary concepts include the intention to capture forward-going pions from a thick target around the peak of their momentum distribution at ~300 MeV/c. The resulting decay muons cluster around 200 MeV/c, a momentum at which ionization cooling works well.

The μ/p ratio, i.e. the ratio of useful muons to protons incident on the production target, is an important figure of merit for low-energy beam designs. The value of 0.001 specified in Table 1 would enable a world-class program of experiments at the intensity frontier. Note that it is two orders of magnitude below the value resulting from simulations of the muon collider front end. As a result, much less elaborate measures are necessary to generate a useful low-energy beam.

Many muon experiments require the muons to stop in a thin stopping target. Thus the beam must be decelerated. Since the stopping target often must be as thin as possible, the momentum spread must first be reduced by ionization cooling. RF cavities would be used rather than an absorber for deceleration to avoid the longitudinal heating that happens in an absorber. (The spreading of a momentum distribution in an absorber follows from the fact that in the momentum range of interest, low-energy muons lose more energy than high-energy ones in traversing a given slab of material, amplifying any initial momentum spread.) Of course random variations in the amount of energy loss, known as straggling, add an additional heating term.

In transverse ionization cooling, passage of a beam through matter reduces the magnitude of the momentum vectors of the particles. The longitudinal momentum component is then restored by acceleration in RF cavities. Longitudinal cooling (which is really emittance exchange from longitudinal to transverse degrees of freedom) results when high-momentum particles are caused to traverse more material than the low-momentum ones. This process can also reduce the contamination of unwanted particles in a muon beam because the energy gain from the RF cavities is set to match the energy loss by ionization only for the muons. Of course transmission through a long beam path also purifies the beam because most contaminants, in particular pions, have a much shorter lifetime than the muons.

Some experiments require polarized muons. A polarized muon beam can be generated by a double momentum selection, first on the parent pions, then on the muons, because the forward-going and backward-going muons (in the pion rest frame) have opposite polarization. A channel that confines the pions and then the muons in RF buckets can deliver a muon beam of variable polarization merely by adjusting the phasing of the cavities to capture different ratios of pion to muon momenta. The acceptance of such a system is likely to be much larger than a system that does the two momentum selections by magnetic bending and momentum slits.

The expected advantages resulting from these very preliminary design concepts include a good muon/proton ratio, small momentum spread allowing use of very thin stopping targets, time distributions for the muons that reflect the flexible proton distributions at the pion production target, variable polarization, and very little beam contamination. Obviously, simulations are necessary to verify these expectations. Concomitant design work supported by simulations may result in significant changes from the initial design concepts described here.

SIMULATION RESULTS

We have performed a few preliminary simulations to illustrate our capabilities in this regard. G4Beamline, a program developed by Muons, Inc. that provides a user-friendly interface to Geant4 for designs of beams that pass through matter, was used for this purpose.

Fig. 1 illustrates the setup. A 3 GeV/c proton beam impinges from the left on a gold target about 1.6 interaction lengths thick. The target is located on the axis of a 10 T uniform solenoid, represented in yellow. The next element is another solenoid whose field tapers from 10 T to 4 T over 2 meters as its radius expands from 7.5 cm to 12 cm. The following element, represented in red, is a series of 325-MHz RF cavities embedded in a 4 T solenoid, operating at a gradient of 10 MV/meter.

Sources and Medium Energy Accelerators

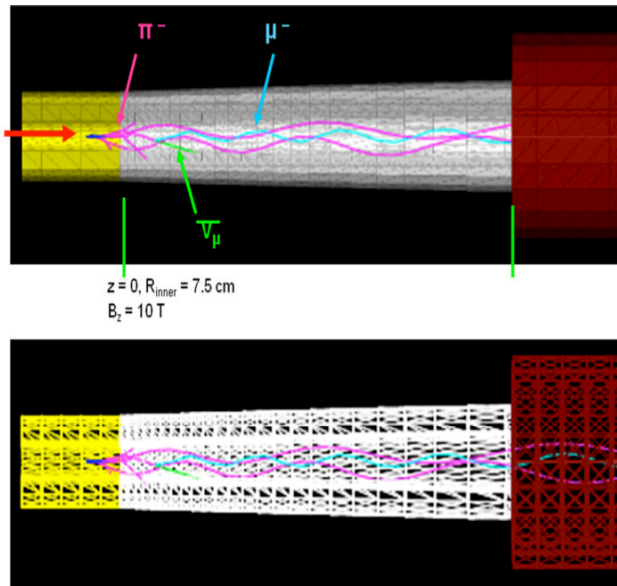**Accel/Storage Rings 19: Secondary Beams**

Figure 1: G4Beamline illustration of the upstream end of a channel starting at the target solenoid.

Fig. 2 shows preliminary results of this simple example simulation. The top pictures show the tracks continuing downstream through the RF cavities. A few more pion decays are visible. The picture on the lower right is a scatter plot of the momenta, in MeV/c, of pions and muons versus their time of arrival, in nsec, at a location 17 meters downstream from the target. The RF cavities were phased to capture the bunch of pions and muons shown in the red oval. The tables on the lower left show the results. For example, 785 particles (muons and pions) are contained in the oval bunch 17 m downstream from the target per 100,000 protons incident on the production target. The muon to proton ratio at 32 meters is 622/100000, or 0.0062. Many of the 84 pions that have not yet decayed will also produce useful muons. These ratios are to be compared to the desired ratio of at least 0.001 at the end of the beam after cooling and deceleration.

The lower table in Fig. 2 compares the transverse and longitudinal emittances of the simulated distribution of muons in the oval bunch to the acceptances of an HCC that might be used for longitudinal cooling. The transverse emittances can be contained in the HCC, but the longitudinal emittances are about a factor of two too large. That motivates a change in the capture frequency from 325 to 650 MHz in a future simulation. A smaller bucket may still produce an acceptable ratio of muons to protons.

This kind of channel needs CW RF cavities to manipulate the beam. The initial design strategy is to use superconducting RF cavities wherever that is feasible. However, the channel components, particularly at the upstream end, will be immersed in an intense radiation field. Furthermore, focusing by strong magnetic fields is necessary to confine the large transverse emittances of the beam. Superconducting RF cavities will not operate in

strong magnetic fields, and intense radiation may cause them to quench. Wherever possible, shielding (against radiation and magnetic fields) will be implemented. However, it seems inevitable that it will be necessary to use normally-conducting cavities in parts of the channel. Operating such cavities at room temperature with high gradients would cause excessive heat loss and consume too much RF power. The solution proposed here is to use materials that become very good conductors at low temperature for the walls of the cavities. Two materials are prime candidates for this application: beryllium and aluminum. Studies of limitations due to magnetostrictive effects and anomalous skin depth, especially at higher frequencies, are essential first steps.
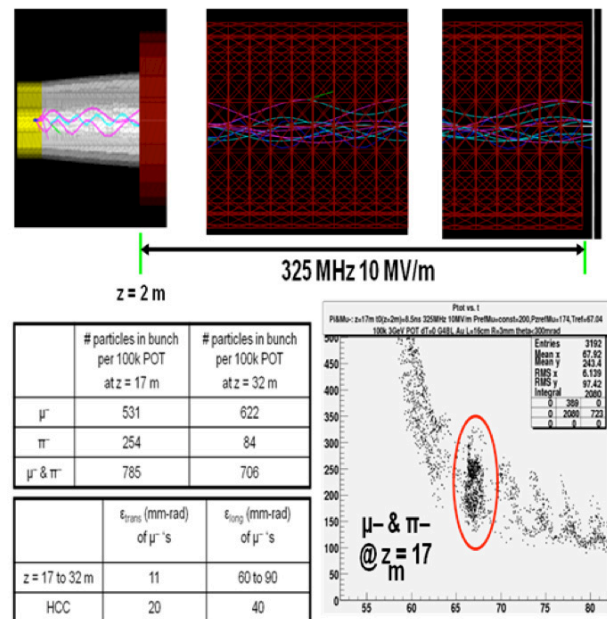

Figure 2: Results of the G4Beamline simulation of the upstream end of a channel.

CONCLUSIONS AND FUTURE PLANS

There are promising new preliminary concepts for using the beam from the Project-X CW linac directly to provide high-duty-factor muon beams with a variety of useful characteristics. Further development is needed for design, simulation, and optimization of the whole channel, as well as RD&D on hyperconductive RF cavities—the enabling technology.

REFERENCES

[1] Information about Project X can be found at the following web site: http://projectx.fnal.gov.

[2] Several workshops on Project-X muon physics have been held. The agenda and presentations for the most recent one can be found at the following site: http://indico.fnal.gov/conferenceDisplay.py?confId=3719

[3] c.f. http://map.fnal.gov/