MUON COOLING AND ACCELERATION EXPERIMENT AT TRIUMF

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Abstract

Here, we propose to develop an effective method for cooling and accelerating muons by channeling them in a crystal structure. Leading schemes for future high energy $\mu^+ \mu^-$ colliders [1, 2] rely on fast cooling and high gradient acceleration of short-lived muons. This experiment aims to prove that both processes can be integrated and achieved in the ultra-strong focusing environment of a solid state system. Practical demonstration of transverse cooling in a continuous focusing channel and verification of theoretically predicted cooling efficiencies are the first steps towards meeting the challenges of $\mu^+ \mu^-$ colliders [2]. Furthermore, experimental demonstration of high-acceleration gradients around GeV per meter promised by the high fields in a crystal channel would make $\mu^+ \mu^-$ colliders a real possibility.

I. THEORETICAL OVERVIEW

A. Cooling

Recent results on the radiation reaction of charged particles in a continuous focusing channel [3], indicate an efficient method to damp the transverse emittance of a muon beam. This could be done without diluting the longitudinal phase-space significantly. There is an excitation-free transverse ground state to which a channeling particle will always decay, by emission of an X-ray photon. In addition, the continuous focusing environment in a crystal channel eliminates any quantum excitations from random photon emission, by constraining the photon recoil selection rules. A relativistic muon entering the crystal with a pitch angle of θ_p that is within the critical channeling angle of a few mrad, will satisfy the "undulator" regime requirements given by the following inequality

$$\gamma\theta_p << 1. \tag{1}$$

In this case, the particle will lose a negligible amount of the total energy while damping to the transverse ground state. Muons of the same energy but different θ_p will all end up in the same transverse ground state, limited by the uncertainty principle. Theoretically predicted ground state emittance is given by the following expression

$$\gamma\varepsilon_{min} = \frac{\bar{\lambda}_\mu}{2}, \tag{2}$$

where $\bar{\lambda}_\mu$ is the Compton wavelength of a muon. Following the solution of Klein-Gordon equation [3], photons emitted in a "dipole regime", given by Eq.(1), obey the following selection rule

$$\Delta n = n_i - n_f = 1 \ , \tag{3}$$

linking energies of the initial, E_i, and the final , E_f, state of a radiating particle according to the following formula

$$E_f \approx E_i \left[1 - \frac{1}{2}(\gamma\theta_p)^2 \right] \ , \tag{4}$$

which yields a small longitudinal energy spread.

This combination of both the transverse and the longitudinal phase-space features makes a radiation damping mechanism a very interesting candidate for transverse muon cooling in an ultra strong focusing environment inside a crystal.

For μ^+s channeling in a Silicon crystal the characteristic transverse damping time, τ, is given by the following formula

$$\frac{1}{\tau} = 2r_\mu \ \frac{e\phi_1}{3m_\mu c} \ , \tag{5}$$

where r_μ is the classical radius of a muon and $e\phi_1 = 6 \times 10^{11}$ GeV/m^2 is the focusing strength for Silicon crystal [4].

Although the characteristic damping time, $\tau \approx 10^{-6}$ sec, for a spontaneous channeling radiation damping is rather long one can enhance the lattice reaction [9] by using the crystal lattice as a micro-undulator (external strain modulation of the inter atomic spacing in the crystal lattice, e.g. an acoustic wave of wavelength *l*). If the acoustic wavelength, *l*, matches the Doppler shifted betatron oscillations of the beam, $\gamma\lambda_\beta$, according to the following matching condition

$$\gamma\lambda_\beta = \sqrt{2}\, l \qquad , \quad \lambda_\beta = 2\pi \sqrt{\frac{m_\mu c^2}{e\phi_1}}, \tag{6}$$

a stimulated enhancement of the channeling radiation will occur – similar effect to the FEL amplification. In fact, if one could generate a standing acoustic wave of sizable amplitude in a crystal, then the relaxation time would shorten the damping time by more than three orders of magnitude.

B. Acceleration

According to previous calculations [4, 6], one can achieve acceleration gradients of GeV/m in the high fields found in a crystal channel. The first paper [4] explores the idea of inverse FEL coupling to a high-power optical driver. A strain modulated Silicon crystal acts as a microundulator for a channeled muon beam. This crystal is then placed in an optical cavity – between two axicone mirrors powered by a GWatt laser at visible frequencies.

A beam of relativistic particles while channeling through the crystal follows a well defined trajectory. For planar channeling of charged particles in [110] crystallographic direction the center of the channeling axis is modulated by the acoustic wave periodicity to produce an undulator effect: i.e., the particles are periodically accelerated perpendicular to their flight path as they traverse the channel. The micro-undulator wavelength, l, (for a typical acoustic modulation) falls in the range 1000–5000Å, far shorter than those of any macroscopic undulator. Furthermore, the electrostatic crystal-fields involve the line averaged nuclear field and can be two or more orders of magnitude larger than the equivalent fields of macroscopic magnetic undulators. Both of these factors hold the promise of greatly enhanced coupling between the beam and the accelerating electromagnetic wave.

The key to collective acceleration via inverse FEL mechanism is a spontaneous bunching of initially uniform beam channeling through a periodic crystal structure and interacting with the electromagnetic wave. Appropriate phase matching results in energy flow from the wave to the particle beam. This particular kind of particle density fluctuation has the form of a propagating density wave of the same frequency, ω, as the emitted electromagnetic wave. The phase velocity of the moving bunch matches the velocity of particles in the beam. This energy–momentum conservation condition translates into the following acoustic – optical wavelength constraint

$$\lambda = \left(1 + \frac{1}{\beta}\right) l \,, \qquad \beta = 1 \,, \tag{7}$$

which in our numerical example fixes the accelerating optical wavelength at $\lambda = 1000$ nm.

The nominal acceleration efficiency in units of MeV/m will, obviously, depend on the energy density of the actual optical cavity. The recent advances in high power laser technology based upon diode laser pumped solid state lasers [5] promise a power of a few MWatts, optically focused to provide energy densities of $E^{max} = 10^{10}$ V/m, where E^{max} is the electric field amplitude of the standing cavity mode. The final accelerating efficiency [4] is equivalent to an accelerating gradient of 2 GeV/m.

One can also test the inverse Cerenkov acceleration mechanism [6], since the index of refraction for Silicon is very large, n = 1.5. Matching the phase velocity of the optical mode to the muon velocity requires relatively large crossing angle (between the beam and the laser pulse). This enhances the longitudinal projection of the radial component of the electric field, which in turn yields high accelerating gradient.

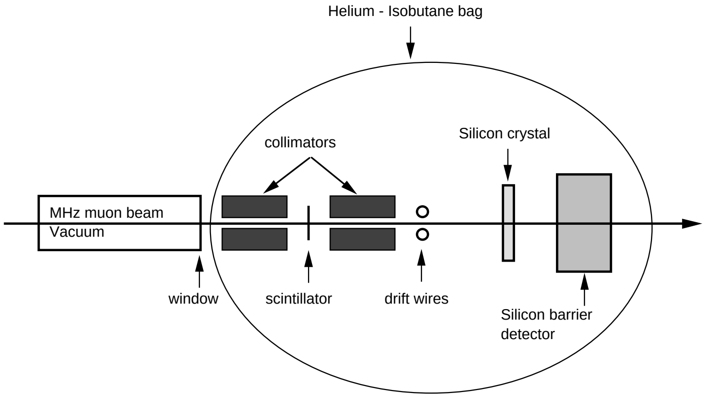
II. EXPERIMENTAL OVERVIEW

The experiment will be done in three stages. The first step, called the transmission experiment, will show channeling of muons in a 4-mm thick Silicon crystal wafer. The second step will measure the cooling of channeled muons. Finally, the third step will incorporate acceleration.

A. Phase I - Transmission

TRIUMF's M13 beamline is the best choice for effective channeling through a 4-mm sample of Silicon crystal. It provides surface muons at high intensity – about 1.2×10^6 per second [7]. They carry momentum of 35 MeV/c with a longitudinal spread of about 4% FWHM. As a TRANSPORT simulation shows, for optimum tuning of the final focus quadrupole doublet in M13 one could achieve a spot size of 2 cm x 2 cm with horizontal and vertical divergences of 10 mrad and 65 mrad respectively. The critical planar channeling angle in a Silicon crystal is about 12 mrad for 35 MeV/c positive muons, if one extrapolates critical angle measurements from proton channeling [8]. In this case, a sizable fraction of the incident muons will channel into the crystal.

We intend to carry out a measurements of the critical angle for channeling muons and the ionization energy loss for channeled versus unchanneled muons. We will use the 35 MeV/c momentum surface muons provided by the M13 beamline at TRIUMF, which was selected based on our assessment of the quality of the muon beam. At this energy, the stopping power of amorphous Silicon is high, about 3 mm. In this case, only channeled muons will survive the crystal. Unchanneled particles are subject to typical energy loss mechanisms of ionization and bremstrahlung. Whereas, the energy loss of channeled particles is severely reduced [8]. A schematic of the proposed setup for the transmission experiment is illustrated schematically below.



As a multiple scattering estimate shows a muon beam going through 75 microns of mylar gains 20 mrad divergence, which is comparable with the incident beam divergence coming from M13 beamline (12 mrad critical angle for planar channeling in Silicon). The beam will incident from the left. After it passes through a window the beam is collimated with a lead brick with 1 mm hole, followed by a thin scintillator and another lead brick with a hole. A pair of drift wires are placed just outside the second collimator exit. A 3 mm Silicon crystal wafer is mounted on a goniometer table (appropriate orientation in two planes). The muons then enter the crystal at some incident angle, θ with respect to the axis of the crystal. The crystal's orientation is controlled remotely by a goniometer (just downstream of the crystal). It is important to align the crystal with the beam. A rough alignment will be performed with X-rays. Then we will use the tracking information and a goniometer to maximize the number of channeled muons exiting the crystal.

Entire set up will be enclosed in a Helium bag. The multiple scattering angle of 0.3 mrad per cm of Helium characterizes the level of beam divergence increase due to the background medium. Silicon barrier detector will be placed immediately after the Silicon wafer to measure energy spectrum of the channeled muons. The exiting muon energy and flux will be measured with a surface-barrier detector. Such detectors are capable of about 20 keV energy resolution at 35 MeV/c. The data will indicate the yield as a function of θ, allowing extraction of the critical angle within which muons are effectively channeled. Furthermore, we can measure the energy spread of the exiting beam. This will indicate the degree of energy struggling we should expect when compared to the incident energy distribution provided by the beamline.

B. Phase II - Cooling

This phase of the experiment will test the cooling mechanisms summarized in the theory section above. The beam momentum will be about 250 MeV/c as provided by forward decay muons [7] in M11. In this case, both channeled and unchanneled muons will penetrate the 4-cm crystal and the cooling process can be compared for the two. In addition, a higher energy beam, tests cooling at the energies considered for realistic collider schemes. The first step of Phase II is to measure initial and final emittances of an unmodified crystal. A schematic of our proposed experimental setup is similar to the one described previously. We will track each muon individually using five sets of drift chambers. This way we can identify channeled and unchanneled particles on an event-by-event basis. We can also obtain the exact initial and final emittances for channeled and unchanneled muons separately. It is also possible to separate channeled and unchanneled muons by plotting their energy loss. The trigger will be provided by scintillation counters upstream, combined with a veto counter that rejects muons which do not intersect the crystal. A time-of-flight counter will be placed in a downstream position, to be used in concert with the 1 picosecond timing pulse provided by the M11 beamline. This will aid in particle identification since some positrons and pions will likely contaminate the beam. To enhance the cooling, we will generate a strain modulation of the planar channels. An acoustic wave of 1 GHz is excited via a piezoelectric transducer. We will also detect predicted channeling radiation by surrounding the crystal with CsI scintillation detectors, which are sensitive to X-rays. The M11 beamline is presently a source of high energy pions [7]. Straightforward modification of the beamline will provide a collimated beam of forward-decay muons at high intensity – about 10^6 per second at 250 MeV/c. The longitudinal momentum spread is about 2% FWHM. Assuming optimum tuning of the final focus quadrupole doublet in M11, we can achieve a spot size of 3 cm x 2 cm with horizontal and vertical divergences of 10 mrad and 16 mrad respectively. The critical angle for planar channeling of μ^+ at 250 MeV/c in Silicon is about 7 mrad, extrapolating from proton channeling data. A sizable fraction of the muons should channel through a few centimeters of the crystal.

C. Phase III - Acceleration

Two schemes high gradient acceleration will be tested. Initially, an unmodified crystal will be used to demonstrate inverse Cerenkov [7] and inverse FEL [4] acceleration of muons. The optical setup is analogous to the Inverse Cerenkov Accelerator Experiment at Brookhaven. It provides a pulse of radially polarized light, which couples energy to the muon beam channeling through a crystal via the inverse FEL mechanism. Here a strain modulation in the crystal imposed by an acoustic wave plays the role of an ultra-short wave undulator. Optical energy will be transferred to the muon beam with an efficiency of GeV per meter. A 4-cm Silicon crystal would provide a 40 MeV energy burst. Using a bending magnet in between drift chambers, we will measure the final energy of muons channeling through the crystal. The initial energy of each muons is provided by a spectrometer in the beamline.

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