VERY LOW EMITTANCE MUON BEAM USING POSITRON BEAM ON TARGET

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Abstract

Muon beams are customarily obtained via K/π decays produced in proton interaction on target. In this paper we investigate the possibility to produce low emittance muon beams from electron-positron collisions at centre-of-mass energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry, corresponding to a positron beam of about 45 GeV interacting on electrons on target. Performances on both amorphous and crystal target are presented, and the general scheme for the muon production will be given. We present the main features of this scheme with a first preliminary evaluation of the performances that could be achieved by a multi-TeV muon collider.

INTRODUCTION

Muon beams are customarily obtained via K/π decays produced in proton interaction on target. Their use in high energy physics experiments has a continuous increasing interest for rare decays searches, precision measurement experiments, neutrino physics and for muon colliders feasibility studies. Several dedicated experiments are ongoing to produce high intensity muon beams with low emittance; see for example ref. [1]. In this paper we will investigate the possibility to produce low emittance muon beams from a novel approach, using the electron-positron collisions at centre-of-mass energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry, that corresponds to about 45 GeV positron beam interacting on an electron target. Previous studies on this subject are reported in ref. [2–4] and briefly discussed in ref. [5]. A feasibility study of a muon collider based on muon electroproduction has been studied in ref. [6]. Our proposal is simpler with respect to present conventional projects where muons are produced by a proton source. One important aspect is that in our proposal muon cooling would not be necessary. The most important key properties of the muons produced by the positrons on target are:

- the low and tuneable muon momentum in the centre of mass frame
- large boost, being about γ ~200.

These characteristic results in the following advantages:

- the final state muons are highly collimated and have very small emittance;
- the muons have an average laboratory lifetime of about 500 μs.

The very small emittance could allow high luminosity with modest muon fluxes reducing both the machine background in the experiments and more importantly the activation risks due to neutrino interactions.

MUON PRODUCTION

The cross section for continuum muon pair production $e^+e^- \rightarrow \mu^+\mu^-$ has maximum value of about 1μb at $\sqrt{s}$ ~0.230 GeV. In our proposal these values of $\sqrt{s}$ can be obtained from fixed target interactions with a positrons beam energy of $E_+ \approx s/(2m_e) \approx 45$ GeV where m_e is the electron mass, with a boost of $\gamma \approx E_+/\sqrt{s} \approx .\sqrt{s}/(2m_e) \approx 220$. The maximum scattering angle of the outcoming muons θ_μ^{max} depends on $\sqrt{s}$ In the approximation of $\beta_\mu = 1$, where β_μ:

$$\theta_\mu^{max} = \frac{4m_e}{s}\sqrt{\frac{s}{4} - m_\mu^2} \quad (1)$$

Muons produced with very small momentum in the rest frame are well contained in a cone of about $5 \cdot 10^{-4}$ rad for $\sqrt{s}$=0.212 GeV, the cone size increases to $\sim 1.2 \cdot 10^{-4}$ rad at $\sqrt{s}$=0.220 GeV. The difference between the maximum and the minimum energy of the muons produced at the positron target (ΔE_μ) also depends on $\sqrt{s}$, and with the $\beta_\mu = 1$ approximation we get:

$$\Delta E_\mu = \frac{\sqrt{s}}{2m_e}\sqrt{\frac{s}{4} - m_\mu^2} \quad (2)$$

The energy distribution of the muons has an RMS that increases with $\sqrt{s}$, from about 1 GeV at $\sqrt{s}$=0.212 GeV to 3 GeV at $\sqrt{s}$=0.220 GeV.

The number of $\mu^+\mu^-$ pairs produced per positron bunch on target is:

$$n(\mu^+\mu^-) = n^+\rho^- l\sigma(\mu^+\mu^-) \quad (3)$$

where n^+ is the number of positrons in the bunch, ρ^- is the electron density in the medium, l is the thickness of the target, and $\sigma(\mu^+\mu^-)$ is the muon pairs production cross section. In absence of intrinsic focusing effects the target thickness determine the muons beam emittance ϵ_μ. Assuming a uniform distribution in the transverse $x - x'$ plane:

$$\epsilon_\mu = \frac{xx'^{max}}{12} = \frac{l(\theta_\mu^{max})^2}{12} \quad (4)$$

The number of $\mu^+\mu^-$ pairs produced per crossing has the form given by the relation 3, with $\rho = N_A/A\rho Z$ being Z the atomic number, A the mass number, N_A the Avogadro

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constant and ρ the material density. In addition, the multiple scattering contributes to the emittance increase according to: $x'_{RMS} \sim \frac{0.0136}{P(\text{GeV})}\sqrt{0.5l}$ with l expressed in radiations length unit and $x_{RMS} \sim x'_{RMS} 0.5l\sqrt{3}$ The bremsstrahlung process governs the positrons beam degradation in this case and it scales with the radiation length. On one side to minimise the emittance there is the need of a small length l, on the other side compact materials have typically small radiation length causing an increase of the emittance due multiple scattering and fast positron beam degradation due to bremsstrahlung. The production efficiency is instead proportional to the electrons density. Positrons survival probability is also an issue to be considered not only for long targets (as long as one radiation length: $l \sim X_0$) but also if the positron beam is recirculated to increase the positron rate impinging the target. Positrons interactions on different targets have been studied with GEANT4 [7]. The results shows that the optimal target has to be thin and not to heavy. Diamond, and Be have the best performances.

It is known that channeling phenomena are present in crystals with particles incident angles with respect to the crystal structure smaller than a critical angle $\sim \sqrt{2U/E}$ where E is the particle energy and U is the typical crystal energy level ($O(100$ eV) for Diamond). For complete channeling there is no contribution to emittance increase due to the target thickness and very low emittances can be obtained independently on the target thickness. In addition the losses due to interactions with nuclei are strongly reduced as shown in Fig. 1. Channeling has been implemented by including the

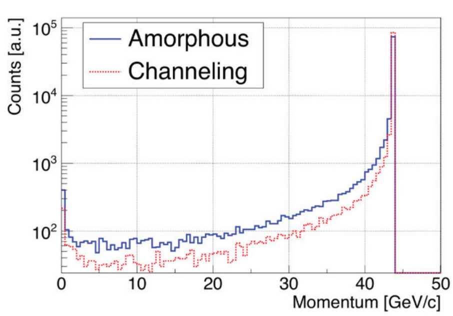

Figure 1: positrons energy distributions at the exit of a 4.1 mm Si target both for crystal and amorphous state for a beam energy of 43.8 GeV

GEANT4-channeling package into GEANT4 [8]. The package includes the modification of the average density of matter experienced by a channeled particle and the modification of the particle trajectory due to the interaction with the crystalline planes. The package currently does not account for the coherent radiation generated by a channeled particle.

For a 22 GeV muon the critical angle is about 0.1 mrad. The value of θ_μ^{max} is around 0.1 mrad for E_+=43.72 GeV. At this energy the dimuon production cross section is slightly above 0.1 μb and the muon energy spread at 22 GeV is below 1.5%. We think this could be a good option in the case of an Higgs factory at center of mass energy of 125 GeV where a beam energy spread of about $5 \cdot 10^{-5}$ is required.

A superior positron source is required to compensate the extremely low muon production efficiency $eff(\mu^+\mu^-) < 10^{-5}$. The present record positrons production rate has been reached at the SLAC linac SLC. ILC positron source has been designed to provide $3.9 \cdot 10^{14} e^+$/s. Two order of magnitudes more intense sources are foreseen for LHeC.

The low value of the muon conversion efficiency requires a muon accumulator ring to reach $O(10^8)$ muons per bunch. The muons could be recombined in two rings intercepting the positron beamline in the interaction point of positrons on target in order to preserve the emittance. The muon laboratory lifetime τ_μ^{lab} is about 460 μs so that the recombination of the muon bunches need to be fast, around 1 $\gamma\tau_\mu$

We considered as a first set of parameters the number of positrons per bunch equal to: $N_b(e^+) = 4 \cdot 10^{11}$, a bunch train of 2500 bunches with a bunch spacing of 200 ns. This would give a number of positrons per bunch train of $N_{tot}(e^+) = 10^{15}$. According to the LHeC positron rate design, up to four bunch trains per second are feasible. We propose that positrons at the exit of the target are collected and conveniently reused.

This scheme foresees a bunch structure that can be obtained for example in positron storage. A current of $I_{tot}(e^+) = 240$ mA, corresponding to $N_b(e^+) = 3 \cdot 10^{11}$ positrons per bunch, and 200 ns bunch spacing, provide a rate of $1.5 \cdot 10^{18}$ positrons on target per second. Muons could be recombined in two rings with a circumference of 60 m intercepting the positron ring in the interaction point on target.

The positron loss rate has to match the positron source capability. Using LHeC positron source rate the positron loss on target has to be below 1%. A Beryllium target 3 mm thick provides a positron survival probability of 2% and 0.5% for an energy acceptance of 5% and 25%(about a factor of four larger than what currently achieved), respectively. This requirement could be relaxed considering that the large momentum acceptance is required only for the low energy side. The power on the target due to ionization energy is about 300 kW requiring carefully studies of power dissipation. Diamond offers better performances from this point of view. The muons transverse phase space at the target exit is shown in Fig. 2.

Multi-TeV collider

We consider that μ^+ and μ^- beams are produced, as described in previous section, from a 45 GeV positron beam impinging on a 3 mm Beryllium target. We consider $3 \cdot 10^{11}$ positrons per bunch with 100 bunches that circulate in a 6 km positron ring with an energy acceptance as large as ±5%. The muon bunches that are produced by the positron beam are accumulated in two separate combiner rings, one for μ^+ and one for μ^-, with a circumference of 60 m and circulating for 2500 turns.

The muon collider ring would have bunches of μ^+ and μ^- with energy of 22 GeV with $4.5 \cdot 10^7$ muon particles,

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Table 1: Comparison of muon beam properties for high energy applications obtained with our proposal from a positron source and with the conventional proton source.

	positron source	proton source
μ rate[Hz]	$9 \cdot 10^{10}$	$2 \cdot 10^{13}$
μ/bunch	$4.5 \cdot 10^{7}$	$2 \cdot 10^{12}$
normalised ϵ [μm-mrad]	40	25000

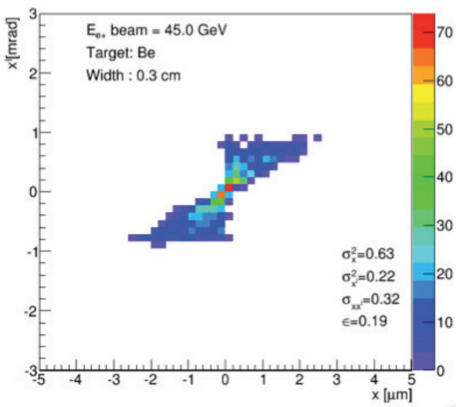

Figure 2: Transverse phase space distribution of muons at the target exit

emittance 0.19 μm-mrad, and beam energy spread of 9%, produced with a spacing of 500 μs (2 KHz rate). Bunches can be accelerated to the nominal energy as studied by the Muon Acceleration Program (MAP) working group [9].

The relevant parameters needed to determine the luminosity in our proposal of muon collider are reported in Table 1. These performances can be compared with those reported in Ref. [9], also shown in Table 1. From this table it is clear that the quality of the muons produced from a positron source as we propose in this paper is much better than the one obtainable with a proton source; however, the muons rate is a key parameter. We think that further studies are needed to set a maximum limit in our scheme.

Promising values of luminosities can be obtained with these parameters, being in the range of $L \approx 10^{34}$ cm^{-2}s^{-1}.

CONCLUSION

We have presented a novel scheme for the production of muons starting from a positron beam on target, discussing the critical aspects and key parameters of this idea and giving a consistent set of possible parameters that show its feasibility. This scheme has several advantages, the most important one is that it solves the problem of muon cooling. In fact, muon beams are generated already with very low emittances i.e. comparable to that obtained with electron beams. In addition, it might be able to provide luminosity with low muon fluxes avoiding the problems of irradiation typical with the conventional proposal. A critical point is the production of the necessary muon rate: it requires detailed studies to assess the maximum possible value. First results presented in this paper shows that first class positron sources proposed for ILC and LHeC need are marginally sufficient to this purpose. An improvement in the positron rate is required for a muon collider purpose. Target survival needs also deep studies. A first set of parameters for a muon collider at high energy has been shown to assess the potentiality of this proposal.

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