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MUON ACCUMULATOR RING REQUIREMENTS FOR A LOW EMITTANCE MUON COLLIDER FROM POSITRONS ON TARGET

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Abstract

Very low emittance muon beams can be produced by direct annihilation of about 45 GeV positrons on atomic electrons in a thin target. With such a muon beam source, a $\mu^+\mu^-$ collider can be designed in the multi-TeV range at very high luminosities. In this scheme two muon accumulator rings are foreseen to recollect the muon bunches that will be injected in the collider. We present in this paper the first consideration of the muon accumulator rings. Realistic muon beam emittance and energy spread coming from the muon target are described. Constraints on the accumulator ring requirements are derived.

INTRODUCTION

We propose to produce low emittance muon beams with a novel approach, using the electron-positron collisions at center-of-mass energy just above the $\mu^+\mu^-$ production threshold with minimal muon energy spread, corresponding to the direct annihilation of approximately 45 GeV positrons and atomic electrons in a thin target, O(0.01~ radiation lengths). Concept studies on this subject are reported in Refs. [1, 2]. A feasibility study of a muon collider based on muon electro-production has been studied in Ref. [3]. One important aspect of this scheme is that, unlike previous designs, muon cooling would not be needed.

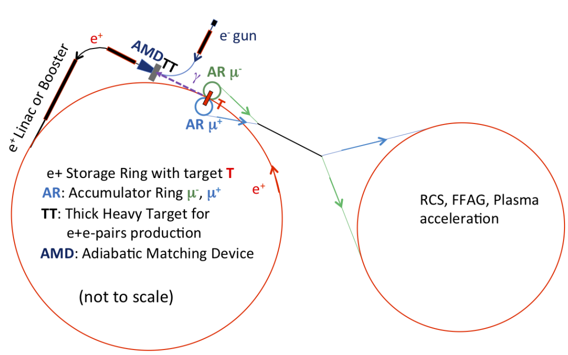

Figure 1: LEMMA Schematic layout.

The most important key properties of the muons produced by the positrons on target are: the final state muons are highly collimated and have very small emittance, with an average laboratory lifetime of about 500 μs. The very small emittance could allow high luminosity with smaller muon fluxes reducing both the machine backgrounds in the experiments and more importantly the activation risks due to neutrino interactions.

The very low muon production efficiency, due to the small production cross section, requires a scheme where positrons are recirculated after interaction on target. The ~22.5 GeV muons produced by the recirculating positron bunches are accumulated in isochronous rings (~63 m circumference with < 13 T dipoles), as shown in the schematic layout of Fig. 1.

This innovative scheme has many key topics to be investigated: a low emittance 45 GeV positron ring, O(100 kW) class target, high momentum acceptance muon accumulator rings (AR), high rate positron source.

The 45 GeV positron ring has been designed and beam dynamics studies of the ring–plus–target scheme performed [4]. In this paper we focus on the realistic muon beam produced by the realistic positron beam impinging on a 3 mm Beryllium target. We describe constraints in the accumulator ring design, mainly on emittance and energy spread.

The muons produced by 100 bunches stored in the e^+-ring during 25 turns will be accumulated in a single bunch in the μ-accumulator over 2500 accumulator turns, increasing the final muon bunch intensity. The whole accumulation process accounts for 500 μs, about one muon laboratory lifetime.

MUONS AT PRODUCTION

The 45 GeV positron ring described in [5], 6.3 km in circumference, has a low-β interaction region with $\beta^*(e+)$ of 0.5 m in both planes and zero dispersion. This translates in a positron beam spot size at the first turn through the target of $\sigma_{x,y}$= 50 μm, divergence of $\sigma_{x',y'}$= 0.1 mrad and energy spread of 0.1%.

After 30 machine turns (and through the target at each turn) the positron spot size becomes 70 μm, with divergence of $\sigma_{x',y'}$= 0.12 mrad and energy spread of 0.4%. Figure2 shows the energy spread and divergence for the μ^+ distribution after target resulting from the Geant4 simulation for a 3 mm beryllium target and for the Gaussian distribution of the positron beam impinging on the target. The Geant-

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4 simulation shows (not shown here) that the transverse distribution is proportional to the target length L and to the muon divergence $\sigma'(\mu^+)$. The μ production contribution to the beam spot is smaller than the positron beam ($\sigma_{e^+} \approx 50$ µm, $\sigma_{\mu^+} \approx 2$ µm), while the divergence is larger ($\sigma'(e^+) \approx 0.1\ mrad$, $\sigma'(\mu^+) \approx 1\ mrad$).

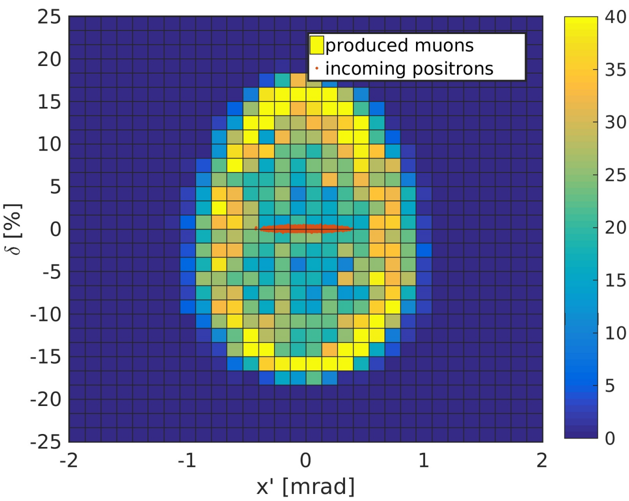

Figure 2: energy spread-divergence at target for the e^+ before target and μ after target ($\beta^*(e+) = 0.5$ m, 45 GeV).

OPTICS REQUIREMENTS AT TARGET

A target interaction region has been included in the positron ring lattice to preserve the positron beam emittance below 10 nm after multiple passes through the target, see Ref. [5]. This value has been used to explore the several possibilities for the optics functions at the target required in the positron and accumulator rings. Table 1 summarizes the results. The large angular divergence of the muon beam requires small beta functions at the target for both e^+ (to match the muon production angle θ_μ) and AR (to completely accept the generated μ beam). The small beta functions translate to smaller emittance for the muon beams and also to reduced e^+ spot size at the target, however, the spot size reduction is limited by target stress constraints, thus limiting the minimum beta functions that can be set at the target location.

Figure 3 shows the effect of reducing β^* by a factor ten at the target ($\beta^*(e+) = 5$ cm) compared to the previously optimized value of 50 cm. The distribution of the muons determines the β^* values in the AR, as described in Table 1. A reduction from 1 mrad to 0.5 mrad in the muon angular divergence could be achieved reducing the energy to 44 GeV.

The circulating muons undergo multiple Coulomb scattering in the target with each accumulator revolution. At each passage of the target the muons are scattered in angle by σ_θ, The beam particles will also be scattered in position with a Gaussian of width σ_x.

The beta-function at this location has to be proportional to the target thickness because the offset is proportional to the angle and the thickness. For perfectly matched beam

Table 1: Required e^+ and μ optics parameters at target, effect of muon accumulation not considered

θ_μ mrad	ϵ_{e^+} nm	$\beta^*_{e^+}$ m	σ_{e^+} µm	σ'_{e^+} mrad	σ'_μ mrad	ϵ_{μ^+} nm	β_μ m
1	10	0.01	10	1	1.41	14.1	0.01
1	10	0.49	70	0.14	1.01	70.7	0.07
1	10	1.00	100	0.10	1.0	100	0.10
0.5	10	0.01	10	1	1.12	11.2	0.01
0.5	10	1.00	100	0.1	0.51	51.4	0.20

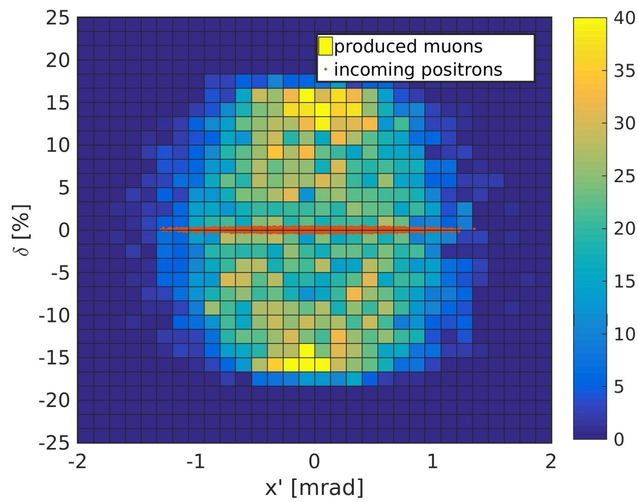

Figure 3: energy spread-divergence at target for the e^+ before target and μ after target ($\beta^*(e+) = 0.05\ m, 45\ GeV$).

phase space at the exit of the target holds:

$$\beta = \frac{4}{\sqrt{3}}L$$

and

$$\alpha = -\sqrt{3}$$

and an emittance growth

$$\Delta\epsilon = \sigma_\theta^2 \frac{L}{\sqrt{12}}$$

for the $L = 3$ mm Be target $\sigma_\theta \sim 59$ µrad. Averaging the over 2500 turns and taking into account the muon decay rate the final angular spread will be $\approx \sqrt{(1000)} \cdot \sigma_\theta \sim 1.85$ mrad, in agreement with simulations. The turn by turn effect on the muon beam divergence is shown in Fig. 4 where the contribution from the muon production angle is also included for three e^+ beam energies. The final angular spread is almost independent on the e^+ beam energy and the effect due to the muon production is visible only for positron energies above 50 GeV. This suggests to increase the $e+$ beam energy to benefit of the larger production cross section. The corresponding emittance increase for a perfectly matched phase space is $\epsilon_{total} = 3$ nm. The emittance growth due to

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multiple scattering effect could be drastically reduced using a crystal as a target, and designing an optics that allows channeling.

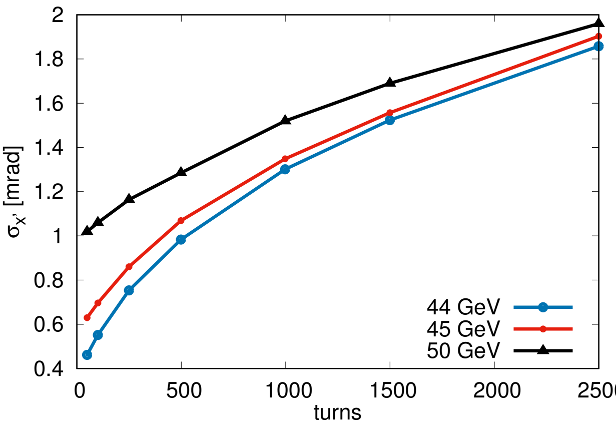

Figure 4: μ beam divergence in the AR due to multiple scattering with a 3 mm Be target as a function of turns for three different e^+ beam energies.

The muon energy distribution is uniform with end points at ±17% for $E_{e^+} = 45$ GeV. Figure 5 shows the reduction of energy spread obtained for $E_{e^+} = 44$ GeV. The muon production rate is reduced by a factor ~ 2, but the μ energy spread is reduced to $\sim 5\%$.

In order to keep the produced muon emittance, dispersion must be canceled at both the injection (target) and extraction regions of the accumulator rings.

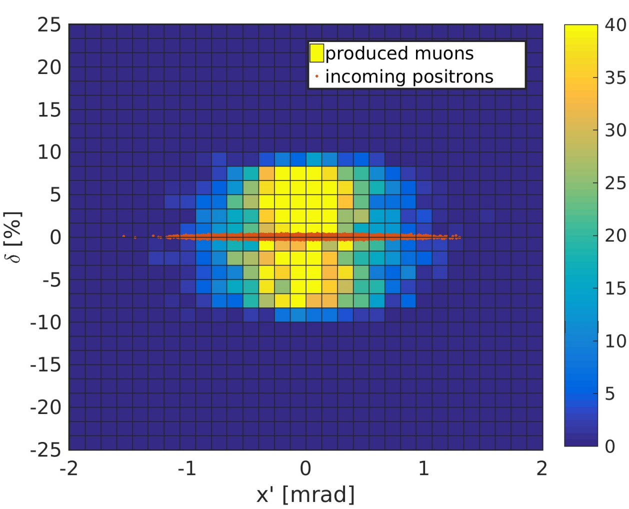

Figure 5: energy spread-divergence at target for the e^+ before target and μ after target ($\beta = 0.05$, $44\,GeV$)

Currently the accumulator is designed to be as long as the separation between two bunches in the e^+ ring, i.e. total length of 63 m. The design of an accumulator ring of 63 m with large energy acceptance seems very challenging. To simplify its design the option to use twice this length (126 m) could be exploited, leading nevertheless to a reduction of luminosity by a factor 2 ($\mathcal{L} \propto n_\mu I_\mu^2$ double number of bunches n_μ, half intensity per bunch I_μ).

The length of the μ-accumulators should match the spacing between two e^+ bunches to avoid longitudinal emittance increase of the produced μ beams.

In addition, the momentum compaction factor and chromaticities of the positron ring should be optimized to reduce the bunch lengthening of the positron beam due to energy loss when crossing the target. This cancellation should also be done in the muon accumulator rings to a higher order because of the large energy spread of the muons. To keep this energy spread at least constant the accumulators should be isochronous [11].

SEPARATION e^+ - μ^+

The positron ring interaction region has the challenging design condition to match three species of particles at two energies, i.e. e^+ at 45 GeV, and μ^+, μ^- at 22.5 GeV. In the current scheme this interaction region is common to both muon accumulators and the positron ring. The generation of the μ inside the target allows to introduce them in the same region of phase space of the μ generated at the previous accumulator turn.

A proper device has to be designed to separate the three beams entering and exiting the target. A first dipole compatible with the constraints of the synchrotron radiation from the positron beam provides a first separation of the three beams.

Further separation and injection of the muon beams can be obtained with an electrostatic separator/septum acting only on the muon beams followed by a septum.

CONCLUSION

We have discussed for the first time in this paper the characteristics of realistic muon beams exiting from a target. We give indication of emittance and energy spread from a Geant-4 simulation as a function of the positron beam size and divergence. The challenge of the accumulator ring design providing the optimal performances in terms of muon collider luminosity has been described. In summary, the accumulator rings have to be as small as possible (large dipole filling factor) and at the same time host an interaction region providing low β^* (values of the order of 1 cm) and zero dispersion and have to provide the largest possible energy acceptance (as large as 20%). As a future step the lattice of the muon accumulator rings will be designed, also considering the possibility of increasing the rings dimensions. Other types of targets will be considered as well with the aim of final muon parameters optimization.

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