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MULTI-TARGET LATTICE FOR MUON PRODUCTION FROM e^+ BEAM ANNIHILATION ON TARGET

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Abstract

The Low Emittance Muon Accelerator (LEMMA) aims at producing small emittance muons from positron annihilation with electrons in a target. Given the low cross section of the production process, a large number of positrons on the target are required, exposing it to high power deposition and the beam to large degradation because of multiple scattering and bremstrahlung. A multi-target IP, and multi-IP line has been studied to reduce the power deposition per target and the degradation of the positron beam while preserving the number of muon pairs produced. The lattice copes with the focusing and transport of three beams at two different energies, the positron beam at 45 GeV, and μ^+ and μ^- beams at 22.5 GeV. Studies on the beam dynamics, number of targets, material and thickness of the targets are reported in this paper.

INTRODUCTION

The LEMMA collaboration [1] is studying the possibility of a muon collider where muons are produced from e^+e^- annihilation. In the current scheme a high intensity positron beam, above the production energy threshold at 43.7 GeV, collides with a fixed target. In this way, in fact, muons are produced with a small angular and energetic spread, resulting in a small emittance that avoids the need of beam cooling. Moreover, muons life time is extended to about 0.4 ms. On the other hand, the very small cross section of the $e^+e^- \to \mu^+\mu^-$ process (< 1 μbarn) requires a high positron rate on the target of approx. 10^{18} e^+/s to produce large muon population in less than one muon life time.

Target Power

One of the challenges is the energy deposition in the target. Under the scheme presented in [2–4], a train of 100 positron bunches separated 200 ns is recirculated 100 times over a 6 km ring intercepted by the fixed target. With a positron bunch population of 10^{12}, the temperature rise was estimated to reach 1000 K per bunch with a beam size of 50 μm [5], which could potentially destroy the target.

As a way to reduce the stress due to energy deposition in the target, a new production scheme with $5 \times 10^{11} e^+$/bunch, 1000 bunches at 10 Hz repetition rate is presented in [6], where it has been estimated that a Beryllium target of 10% Radiation Lengths (R.L.), equivalent to 35 mm, would be exposed to approximately 3 kW average power, and could withstand the operation.

In addition, also the possibility to split the target is being considered, in such a way to have multiple targets distributed in one Interaction Point (IP), and/or to use several IPs. In this context, the reference figure of merit is the muon emittance growth produced by the separation of the targets, which study is described in this paper.

Muon Beam

Previously, simulations in Geant [7] and [8] have been performed to study the beams phase space [9]. We recall in Fig. 1 the muon production kinematics, where muons have been produced from a positron beam at 45 GeV impinging in a Beryllium target.

The muon energy and angle of production depend one on the other due to kinematics. Given that the positron beam divergence (σ'_{e+}) and energy spread are small, the maximum values for the angle and energy distribution of the out-going muons depend on the positron beam nominal energy. We can calculate approximately the r.m.s. emittance of the muon beam as $\epsilon_\mu = \sigma_{e+} \cdot \sigma'_\mu$, where σ_{e+} is the positron beam size, and σ'_μ is the muon divergence which depends on the positron beam energy E_{oe+}. For a 45 GeV positron beam, we have $\epsilon_\mu \approx 0.5 \text{ mrad} \cdot \sigma_{e+}$.

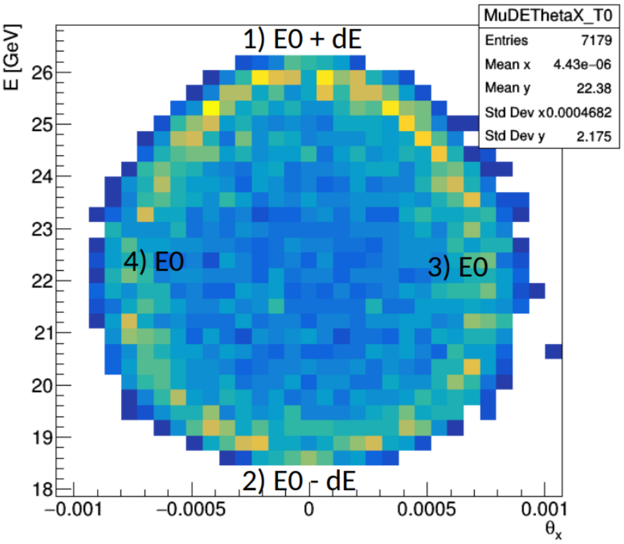

Figure 1: Energy vs Angle of muons produced from a positron beam with small energy spread and divergence.

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SINGLE IP, TEN TARGETS

The single IP consists in having one region where e$^+$ collide with several targets that have been distributed in slices aligned with the e+ beam and separated by small drifts in order to give space for power dissipation. Figure 2 shows schematically the region under discussion, where we chose Beryllium targets of 10.6 mm each separated by 20 mm, adding up to 0.3 R.L in total.

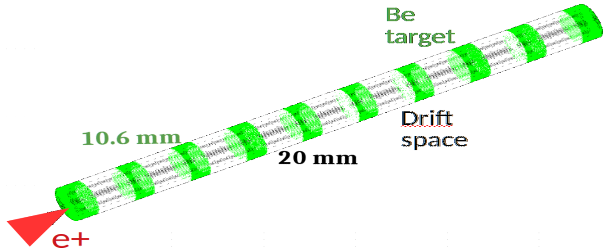

Figure 2: Single IP with multiple targets.

A custom Fast Monte-Carlo for positron and muon transport, called MUFASA [10], was written in Root [11] and validated with Geant4, to speed up the calculations.

We estimated the muon emittance from two different positron beams: the first one from a positron beam size at the first target of $\sigma_{e+} = 20$ µm and emittance of $\epsilon_{e+} = 70$ pm (Fig. 3 TOP). The 10 nm muon emittance in the first target is given by the beam size of impinging positrons as explained before, while, the emittance grows to 26 nm in the nine consecutive targets because of the muon beam multiple scattering with the targets. A second, more conservative case, from a positron beam size $\sigma_{e+} = 150$ µm and emittance of $\epsilon_{e+} = 6$ nm gives a muon beam emittance of 70 nm and grows up to 110 nm as shown in Fig. 3 (BOTTOM green line).

MULTIPLE IP

In addition to splitting the target in several slices on one IP, the multiple IP concept consists in the separation of the targets by a transport line where magnets are common to the three beams (e$^+$, μ^+ and μ^-). This transport line should focus the beams at each IP to achieve the production of new muons with minimal growth to the final beam emittance. A 3-D view, obtained with MDISim [12] and Root, is shown in Fig. 4.

Several constraints in the design had to be balanced. First, the length should be as small as possible in order to minimize muon decay issue. Secondly, focalizing three beams at different energies imposes constraints on the minimum number of elements in the line. Then, chromaticity can not be corrected with dipoles+sextupoles because this would split the three beams, therefore, other methods should be used to mitigate the chromatic effect. Moreover, we will need a minimum amount of space between IPs and closest quadrupoles to accommodate the targets. Lastly, the optics β-functions have to be small to mitigate the effect of multiple scattering to mitigate the emittance growth.

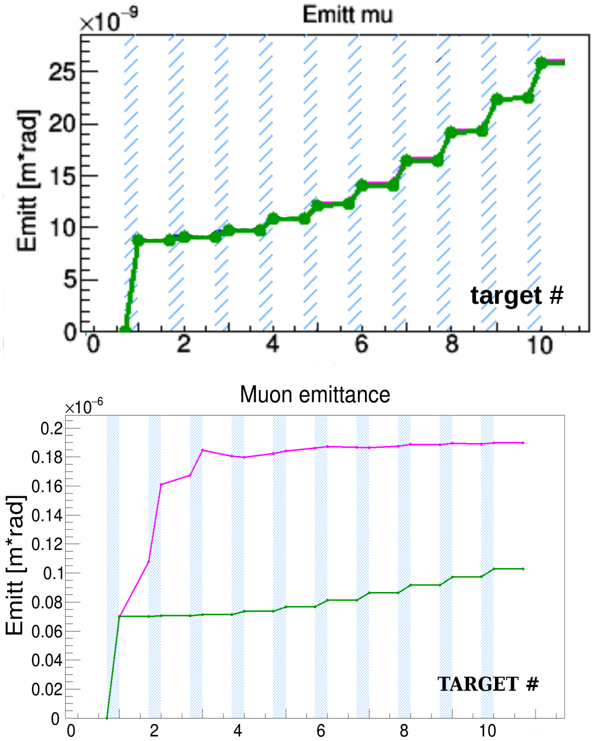

Figure 3: (TOP) Muon beam emittance when crossing 0.3 R.L. of Beryllium divided in 10 pieces separated by 2 cm produced from a positron beam size of 20 µm and emittance of 0.07 nm. (BOTTOM) Comparison of μ emittance growth in the Multiple (magenta) and Single (green) IP schemes as a function of the target number. The e^+ beam size is 150 µm in both cases.

Fixing the distance from IP to quads to 30 cm, we present the best lattice design. It is less than 5 m long, with quadrupole magnet gradients at 200 T/m, 1 cm of aperture radius, separated by drift spaces of about 20 cm. Two triplets are used to focus the beams at 45 GeV and 18 GeV on both transverse planes. These triplets are put in asymmetry in order to partially cancel chromaticity at 45 GeV as in the apochromatic design [13]. Optics functions calculated in MAD-X [14] at both energies are shown in Fig. 5.

Figure 3 (BOTTOM) shows the effect of splitting 0.3 R.L. of Beryllium in ten pieces located in one IP (green line) or in 10 IPs (magenta line). When having multiple IPs, the initial emittance grows because of the chromaticity and large energy spread of the muon beam, as they are produced between 18.5 GeV and 26 GeV (±18% energy spread).

The final achieved emittance is just below 200 nm, giving an important contribution larger than a factor two to the initial emittance. Several additional lattice optics configurations where tried to minimize the effect of chromaticity at the expense of lower energy acceptance.

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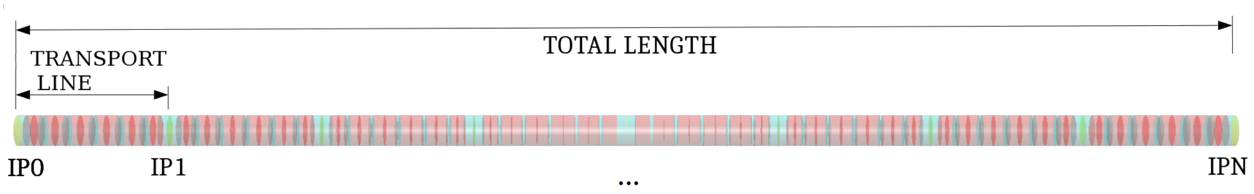

Figure 4: Muon and positron beam transport through a common line with targets in multiple IPs.

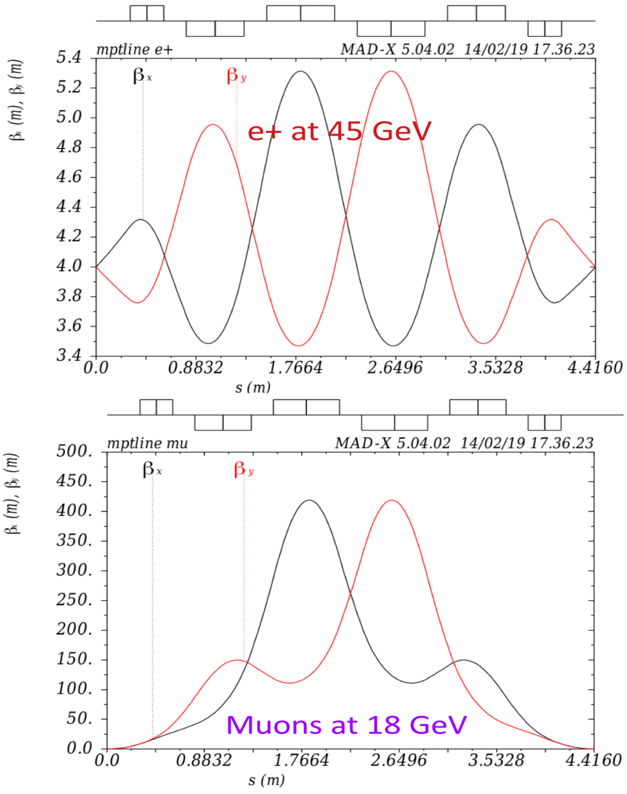

Figure 5: Transport line optics at 45 GeV (TOP), and at 18 GeV (BOTTOM).

MUON PRODUCTION EFFICIENCY

From Different Materials

We call the target *production efficiency*, **eff**, the ratio of muon pairs produced by e^+ impinging on a target, μ/e^+.

The Beryllium efficiency was compared with two possible Carbon materials because of the higher resistance to thermal stress of Carbon. Table 1 shows the results. Carbon composites would reduce the muon production efficiency by about 25%. In addition, liquid H_2, with a density of 0.07 g/cm^3, would double the efficiency which could be advantage because of minimum emittance growth from multiple scattering.

Table 1: Muon production efficiency for Beryllium, two Carbon composites and liquid Hydrogen. Density and length in m and X_0 are included.

Material	Density	Length		eff
	[g/cm^3]	[m]	[X_0]	[$10^{-6}\mu/e^+$]
Be	1.85	0.106	0.3	1.3
C	2.27	0.057	0.3	1.0
C A412	1.7	0.075	0.3	1.0
H_2	0.07	2.664	0.3	2.9

CONCLUSIONS

LEMMA is studying the production of low emittance muon beams from e^+e^- annihilation, where a high rate of e^+ is required to create a high intensity muon bunch. This implies an extreme stress on the fixed target because of energy deposition. As a way to mitigate such stress, several schemes are being considered. First, splitting the target in several slices over one IP to promote the energy dissipation. Second, because of possible limitations when putting all targets in one IP, we consider longer targets split into several IPs. Third, the reduction of the positron rate. We show results on the emittance obtained in the first two cases.

The best emittance is achieved with one IP and the smallest positron beam size possible, e.g. 26 nm muon emittance from a 10 µm positron beam with low divergence.

A more conservative case is also presented of 100 nm muon emittance from a 150 µm positron beam with 6 nm of emittance.

The multiple IP case effectively transports the three beams from IP to IP but produces larger emittance because of lattice chromaticity. Several efforts have been made to reduce the chromatic effect, but they succeed to the expense of smaller energy acceptance, which means lower number of muon transported, and therefore does not seem a viable solution.

In addition, we have done a parametric study of the muon efficiency for three different materials, Beryllium and two Carbon composites, showing a lower efficiency of Carbon by 20 to 25% with respect to Beryllium. However, it has been estimated that Carbon composites could withstand higher energy deposition rates.

Apart from these two materials, liquid H_2 yields twice the number of muons with respect to the same number of R.L. of Beryllium but the feasibility of use is not clear.

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