STUDIES OF A SCHEME FOR LOW EMITTANCE MUON BEAM PRODUCTION FROM POSITRONS ON TARGET

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Abstract

We are studying a new scheme to produce very low emittance muon beams using a positron beam of about 45 GeV interacting on electrons on target. This is a challenging and innovative scheme that needs a full design study. One of the innovative topics to be investigated is the behaviour of the positron beam stored in a low emittance ring with a thin target, that is directly inserted in the ring chamber to produce muons. Muons can be immediately collected at the exit of the target and transported to two μ^+ and μ^- accumulator rings and then injected in muon collider rings. We focus in this paper on the simulation of the e$^+$ beam interacting with the target, its degradation in the 6-D phase space and the optimization of the e$^+$ ring design to maximize the energy acceptance. We will investigate the performances of this scheme, ring optics plus target system, comparing different multi-turn simulations.

INTRODUCTION

Muon beams are customarily obtained via K/π decays produced in proton interaction on target. A complete design study using this scheme, including the muon cooling system has been performed by the Muon Accelerator Program [1,2]. 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 minimal muon energy spread, corresponding to the direct annihilation of approximately 45 GeV positrons and atomic electrons in a thin target, O(0.01$\sim$ radiation lengths). Concept studies on this subject are reported in Refs. [3,4]. A feasibility study of a muon collider based on muon electro-production has been studied in Ref. [5]. One important aspect of this scheme is that, unlike previous designs, muon cooling would not be needed.

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, the muons have 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 low value of the production cross section, makes convenient a scheme where positrons are recirculated after the interaction on target.

A preliminary layout (not to scale) is shown in Fig. 1. Muons with $\sim$20 GeV are produced by the interaction of positrons on target circulating in a storage ring, then accumulated in isochronous rings ($\sim$60 m circumference with 13 T dipoles). In addition to muons, in the target high intensity and high energy photons are produced. A positron source using these photons based on adiabatic matching device [6] is under study to replace the positrons losses in the ring. 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, high rate positron source.

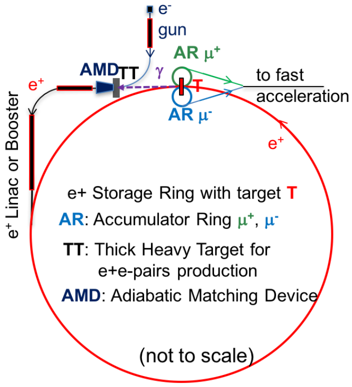

Figure 1: Scheme for low emittance muon beam production.

A first design of a 45 GeV positron ring with low emittance and high momentum acceptance will be described in the following. The effects on beam parameters due to target insertion will be analysed from the point of view of the beam lifetime and the beam degradation.

POSITRON STORAGE RING

A 45 GeV low emittance positron storage ring has been conceived to recirculate a beam strongly affected by bremsstrahlung and multiple Coulomb scattering when the target is inserted in the ring.

The ring is composed by 32 cells of 197 m each for a total length of 6.3 km. The cell is shown in Figure 2 and main ring parameters are in Table 1. Bremsstrahlung causes beam energy loss, thus the importance to maximise the ring momentum acceptance. Figure 3 shows that the cell reaches 8%

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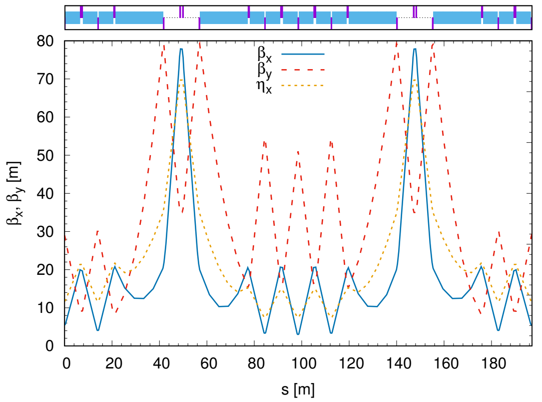

Figure 2: One cell of the e$^+$ ring Twiss functions.

Table 1: Positron Ring Parameters

Parameter	Units	
Energy	GeV	45
Circumference	m	6300
Coupling(full current)	%	1
Emittance x	m	5.73×10^{-9}
Emittance y	m	5.73×10^{-11}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron tune		0.068
Transverse damping time	turns	175
Longitudinal damping time	turns	87.5
Energy loss/turn	GeV	0.511
Momentum compaction		1.1×10^{-4}
RF acceptance	%	± 7.2
Energy spread	dE/E	1×10^{-3}
SR power	MW	120

of momentum acceptance (without errors), obtained from particle tracking along the ring with three different tracking codes: Accelerator Toolbox (AT) [7], MAD-X and MAD-X PTC [8]. A good agreement is found between MAD-X PTC and AT and they are used in the following. Coulomb scattering in the target changes the beam size and divergence. To minimize the beam degradation by this process, we need to have the angular contribution from the multiple scattering similar or smaller than the beam divergence at the target. While the contribution to the divergence from multiple scattering is completely determined by the target, the contribution to the beam size is expected to be proportional to the β-function at the target location.

In addition, to suppress the e$^+$ beam size increase due to Bremsstrahlung energy loss, we add the requirement that the dispersion function at the target location has to be minimized.

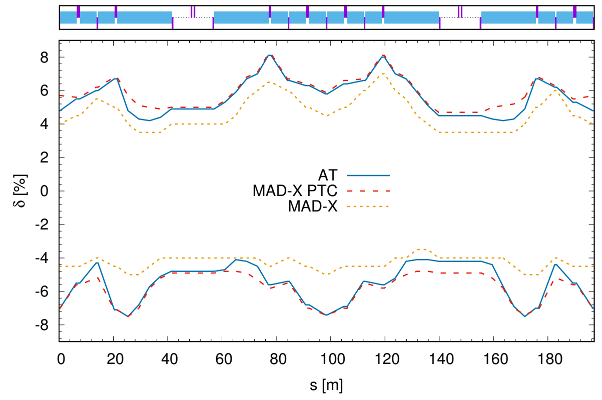

Figure 3: Momentum acceptance of the positron ring cell obtained from tracking with MAD-X, MAD-X PTC and AT.

A preliminary low-β interaction region (IR) with low dispersion at the target location has been designed. Figure 4 shows the Twiss functions and layout. At the target location, in the center of the IR, the optical functions are $\beta_x = 1.56$ m, $\beta_y = 1.70$ m, $D_x = 5.4$ mm. IR optics optimization is necessary. In particular the positron ring emittance with target has to be matched to the minimum transverse e$^+$ beam size compatible with the limit of target thermo-mechanical stress. In addition effects of muon emittance degradation in accumulator ring as well as the intrinsic muon scattering angle have to be taken into account.

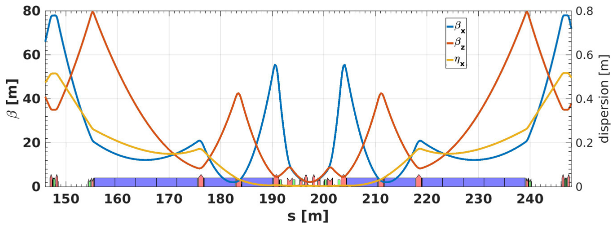

Figure 4: Preliminary design for the interaction region.

MULTI-TURN SIMULATIONS

There is no standard simulation package that integrates the detailed study of the target phenomenology and the accelerator performance simultaneously, therefore, the multi-turn simulation has been divided in two parts: particle tracking and positron interaction with target.

Particle tracking in the ring is performed with AT and MAD-X PTC, while positron interaction with the target is done either with GEANT4 [9] or FLUKA [10].

The effect of the target on the positron beam has been studied for different locations through the cell and at the IR, with different materials and thicknesses. Results from AT/GEANT and MAD-X PTC/GEANT or MAD-X PTC/FLUKA are compared and described in the following. Further studies are needed to optimize the scheme. Figure 5 shows the number of particles as a function of machine turns. On the left is the result obtained with AT and MAD-X PTC with Be 3 mm thickness, showing good agreement. The

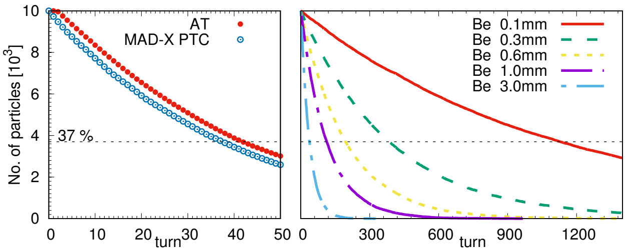

Figure 5: Number of e$^+$ vs turns number. Left : tracking with AT/GEANT and MAD-X PTC/GEANT with a 3 mm Be target. Right: tracking with MAD-X PTC for various Be target thicknesses.

beam lifetime ranges between 37 and 40 turns. On the right, we show the result with several thicknesses while tracking with MAD-X PTC. A positron beam emittance growth has been observed by simulations after the interaction with the target. In general, the emittance growth has two main components: multiple scattering and energy loss due to interaction with target. The longitudinal phase space distribution is modified by the radiative energy loss in the target. Values of 2% of beam energy spread have been observed in simulation.

To analyse independently the multiple scattering and energy loss effects we considered alternatively the changes due to the target in the transverse phase space (dominated by multiple scattering) and in the longitudinal phase space (dominated by energy loss). Figure 6 show the transverse beam size and divergence evolution with the number of turns. The beam size has an additional contribution due to multiple Coulomb scattering normally distributed. At the equilibrium the r.m.s. is: $\sigma_{MS} = 1/2\sqrt{n_D}\sigma'_{MS}\beta$ where n_D is the transverse damping time in turns units and σ'_{MS} is the MS contribution for single pass in target(σ'_{MS}=25μrad for 3 mm Be target). The low β value used for the IR optics allows a strong reduction for the σ growth.

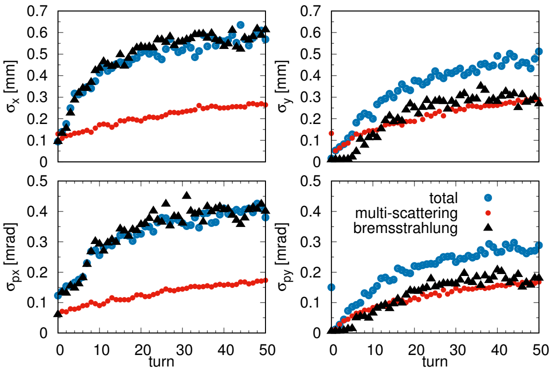

Figure 6: Evolution of beam size and divergence.

Different materials have also been tested. For equivalent electron density in the target, lighter material will provide smaller beam perturbation at the cost of larger intrinsic muon beam emittances. Figure 7 shows the number of survived positrons as a function of machine turns for different material targets. A 10 mm Lithium target might provide sizeably larger lifetime at the cost of a factor 3 increase for the intrinsic muon beam emittance. In addition, Liquid Lithium jet targets have capabilities to sustain high fluxes [11]. Further studies are needed in order to optimize the target materials. In particular, target thermo-mechanical stress for various options have to be compared and the use of crystal targets in channeling regime has to be fully explored as they could strongly reduce the beam perturbation [4].

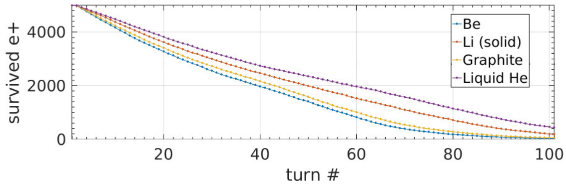

Figure 7: Number of e$^+$ vs turns number for different target materials. Target thickness has been chosen to obtain a constant muon yield.

CONCLUSION AND PERSPECTIVES

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

We presented the preliminary study of 45 GeV a positron ring with a thin Beryllium target insertion. The ring has an high momentum acceptance allowing for a lifetime of about 40 turns for a 3 mm Be target. A beam emittance growth due to interaction with target has been observed. A dedicated cell has been designed to show that the emittance growth can be contained with proper optics parameters at target location.

Progresses need to account for all other topics like target material, muon accumulation issues, positron source and injection. In addition, experimental tests are foreseen. An experiment with 45 GeV positron beam will be performed at the CERN north area to measure both the muon production and the positron beam degradation.

Fast acceleration [12] and muon collider lattices [13, 14] have been deeply studied for "conventional" muon acceleration. We foresee to start our muon collider design from these previous studies.

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