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POSITRON DRIVEN MUON SOURCE FOR A MUON COLLIDER: RECENT DEVELOPMENTS *

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Abstract

The design of a future multi-TeV μ collider needs new ideas to overcome the technological challenges related to μ production, cooling, accumulation and acceleration. In this paper an upgraded layout of a e^+ driven μ source, known as the Low EMittance Muon Accelerator (LEMMA) concept developed at INFN-LNF, is presented. In this new scheme the e^+ beam, stored in a ring with high energy acceptance and low emittance, is extracted and driven to a multi-target system, to produce μ pairs at threshold. Muons produced are accumulated in two rings before the fast acceleration and injection in a $\mu^+\mu^-$ collider.

INTRODUCTION

The Low Emittance Muon Accelerator (LEMMA) concept [1–3] is based on μ production from a 45 GeV e^+ beam annihilating with the electrons of a target close to threshold for $\mu^+\mu^-$ pair creation, thus generating, without any cooling, μ beams with low enough transverse emittance for a high energy collider. The initial design foresaw an e^+ storage ring with an internal target, in order to allow for multiple interactions of the e^+ with the electrons at rest in the target. However, this layout has encountered several limiting difficulties. An alternative design is presently under study, to identify the challenges within reach of the existing technology, and those requiring further innovation. In the new scheme e^+ bunches are extracted to impinge on multiple targets in a dedicated straight section. This scheme could release the impact of the average power on the targets and also reduce the number of e^+ from the source.

LAYOUT OF THE COMPLEX

In order to have a reliable μ production scheme, precise requirements on the muon source chain timing have been set. The complete μ production cycle should be ~410 μsec, of the order of the particle lifetime (467 μsec) at 22.5 GeV, thus reducing the intrinsic beam losses with respect to the accumulated μ intensity. After one production cycle, μ bunches must be immediately accelerated to increase their lifetime and reduce losses. Moreover, one complete cycle must accommodate enough time for the e^+ production and damping, in the main Positron Ring (PR) or in a dedicated Damping Ring (DR). Damping time must be compatible with a reasonable amount of synchrotron power emitted, ranging from 10 msec in a 5 GeV DR to 80 msec in a 45 GeV PR. This time is needed even in case it is possible to recuperate the e^+ bunches "spent" in the μ production which, after interacting with the targets, are strongly affected and have a degraded 6D emittance. It is evident that the impact of the μ production on the e^+ bunches should be minimized to allow for generating the maximum amount of μ for a single e^+ bunch passage, the study of different type of targets is in progress. Once an e^+ bunch has been "spent", it is mandatory to have a "fresh" e^+ bunch for the μ accumulation cycle. Furthermore, the different systems composing the μ source complex must not show unrealistic performances, taking into account the state-of-the-art of the existing technology and the possibility to have a future R&D program to fulfill the required parameters. Three different accelerator complex layouts are currently being studied, in order to choose the one fulfilling all the requirements. In the following we will detail the accelerator complex Scheme III, which at the moment seems the most promising.

Scheme III General Layout

Scheme III main components are (see sketch in Fig.1):

- e^+ Source (PS) at 300 MeV plus 5 GeV Linac,
- 5 GeV Damping Ring (DR),
- SC Linac or Energy Recovery Linac (ERL) to accelerate to 45 GeV, and decelerate to 5 GeV after μ production,
- 45 GeV PR to accumulate 1000 bunches needed for μ production,
- delay loops to synchronize e^+ and μ bunches,
- one or more Target Lines (TL) for the μ production,
- 2 Accumulation Rings (AR) where μ are stored until the μ bunch has a suitable number of particles,
- "embedded" e^+ source, for the production of the e^+ needed to restore the design e^+ beam current.

The PS and the first Linac have to produce and inject 1000 bunches of $5x10^{11}$ e^+/bunch in the DR, which stores 3.8 A e^+ and has a short (~10 msec) cooling time thanks

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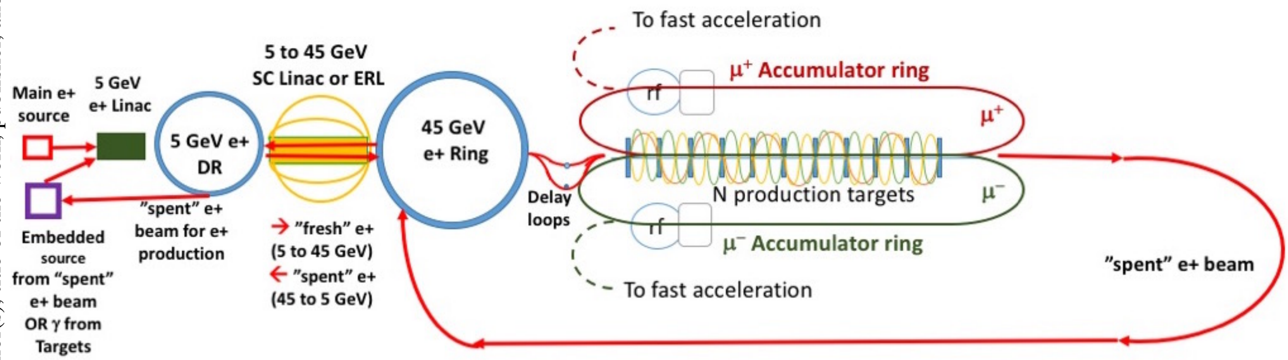

Figure 1: Layout of Scheme III for μ production via 45 GeV e^+ beam.

to damping wigglers. After the cooling, the e^+ beam is extracted from the DR, accelerated in a SC Linac or ERL to 45 GeV and injected in the PR in 10 msec, with a pulsed current of the injector Linac of 8 mA. In the meantime the PS can continue to top-up the DR. Once 1000 bunches are stored in the PR, they are extracted to collide with the targets in the TL for μ production. This process can take 410 μsec. After μ production, degraded e^+ bunches are sent back to the PR with a reduced injection efficiency, estimated to 70% due to the high energy spread generated in the targets interactions. With a slow extraction (~20 msec) the "spent" e^+ bunches are slowly extracted from the PR, decelerated to 5 GeV in the SC Linac, and sent back to the DR. At the same time the produced μ bunches are extracted and accelerated to the final collider energy in a separate accelerators chain. In the following 30 msec the DR provides for cooling of both the e^+ produced by the PS and those coming back from the PR. The cycle is then repeated at 20 Hz. Since the PR is not circulating any beam during the DR cooling phase, the synchrotron radiation emission duty cycle is reduced, decreasing also the total synchrotron power budget.

POSITRON SOURCE

The e^+ source has to provide trains of 1000 bunches with $5x10^{11}$ e+/bunch to inject in the DR. With an e^+ source like the ILC [5] or CLIC one [6], which produce 10^{14} e+/sec, 5 sec are needed to fill the DR. However, the source which needs to replace the e^+ lost in the μ production process is challenging, since the time available to produce, damp and accelerate the e^+ is very short. We assume that ~70% of the "spent" e^+ can be recovered, injected in the PR, slowly extracted and decelerated and injected back in the DR. Therefore only 30% of the required e^+ need to be produced in a time cycle t_{cycle} = 50 msec, corresponding to the 20 Hz repetition frequency. We assume to inject the bunches in the DR during 20 msec and to store them for 30 msec to damp the emittance. The required e^+ production rate is then $3x10^{15}$ e+/sec. In order to achieve such a high rate of e^+ production we need to explore all the techniques developed for the future linear colliders like hybrid targets (crystal target + tungsten target) [6] and rotating targets [5] and we will develop an R&D program on new targets. The required energy acceptance for the DR is demanding: it has to be of the order of ±10%. An optimization of the e^+ capture system in order to take advantage of the large energy acceptance could improve the e^+ yield. Another possibility to reduce the requested e^+ rate is to increase the energy acceptance of the PR, so reducing the fraction of lost e^+ to be replaced by the source. The option to use a Linac to compress the "spent" e^+ beam, so to be able to re-inject at least 90% of the spent beam into the PR, is being also studied. Moreover, since the 45 GeV e+ passing through the μ targets produce a large number of high energy photons, the feasibility of an "embedded" source [7] that uses these γ to produce new e^+ impinging on a 5 radiation length ($5X_0$) tungsten target is under study.

POSITRON RINGS

The 45 GeV PR should have small beam emittance, mostly round beams, and a large energy acceptance in order to be able to accommodate also the "spent" beam coming back after the μ production. In order to store the 1000 bunches with $5x10^{11}$ e^+/bunch with less important synchrotron losses, a 27 Km LHC-like ring was chosen.

Table 1: 45 GeV PR Parameters for 3 Different Emittances

Parameter	0.7 nm	6 nm	10 nm
Circumference [Km]	27	27	27
N. cells	64	32	32
I_b [A]	0.89	0.89	0.89
N_{part} /bunch	$5x10^{11}$	$5x10^{11}$	$5x10^{11}$
N. bunches	1000	1000	1000
Nat. σ_z [mm]	1.9	3.6	3.8
Energy spread	$7x10^{-4}$	$7x10^{-4}$	$9x10^{-4}$
$\tau_{x,y}$ [ms]	68	66	42
Energy acceptance [%]	± 8	± 6	± 2
SR power [MW]	106	109	170

At present several lattices have been studied, with horizontal emittances ranging from 0.7 to 20 nm (see Table 1). Their energy acceptance ranges from ±2 to ±8 %, and work

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is in progress to improve it. The lattices are all inspired to the ESRF upgrade hybrid multi-bend achromat lattice [4], with different number of cells and different dipole lengths in order to tune emittance and damping time.

The 5 GeV DR should provide fast cooling of the e^+ produced by the source. A 6.3 Km long DR could provide the requested damping time (~10 msec) with about 100 damping wigglers, similar to those in the ILC TDR [5]. A preliminary design was studied, based on the same lattice as the PR, with 32 cells and an emittance of 70 pm. The lattice shows a good dynamic aperture and a ±10% momentum acceptance.

MUON PRODUCTION LINES

The previous LEMMA scheme [2] showed both a large instantaneous and average energy deposition on the target (PEDD). The new scheme could solve these issues. In the following a description of the studies performed for this option is summarized. Two different configurations, described in detail in [8], this conference, were studied.

Multiple IPs, Ten Targets TL

In the first layout the e^+ beam impinges on 10 targets for a total $0.3X_0$ of Be, split in 10 IPs separated by a transport line (TL) common to 3 beams (e^+, μ^+ and μ^-), needed to focus the beams at each IP to achieve the μ production with minimal emittance growth. The TL length should be as small as possible in order to minimize μ decay issue. To focus 3 beams at different energies imposes constraints on the minimum number of elements in the line. The chromaticity cannot be corrected with sextupoles because this would split the 3 beams, therefore other methods should be used. The best lattice design achieved so far has a total length of < 5 m, with quadrupole gradients of 200 T/m, 1 cm of aperture radius, separated by drift spaces of ~20 cm. Two triplets are used to focus the 45 GeV e^+ and 18 GeV μ^+ μ^- on both transverse planes. These triplets are asymmetric in order to partially cancel chromaticity at 45 GeV as in the "apochromatic" design [9]. While the chromaticity is well corrected for the e^+ beam, for the μ beam it is not. As a consequence, the μ beam shows a rapid emittance growth as shown in Fig. 2 (magenta line). The e^+ beam spot on the target here is $\sigma_{e+} = 150$ μm. Between the first and second IP, the emittance grows because of the combination of non corrected chromaticity and large energy spread of the μ beam, since they are produced between 18.5 GeV and 26 GeV, a ±18% energy spread. The final achieved emittance after 10 targets is just below 200 nm, a value larger than a factor of two of the initial one. Therefore, a new layout with a single IP, with several targets very close to each other, has been studied.

Single IP, Ten Targets TL

The single IP line consists in one region where e^+ collide with one target sliced in 10, each slice separated by a very small drift in order to still allow for power dissipation. For a $\sigma_{e+} = 150$ μm beam spot at the first target, the total μ emittance growth is 100 nm because of the μ beam multiple scattering within targets, see Fig. 2 (green line). Of course the smaller the σ_{e+} at the targets, the smaller will be the final μ emittance. At present, different e^+ beam spots are being studied, since this parameter is crucial both for the μ emittance and for the amount of PEDD and temperature rise of the target.

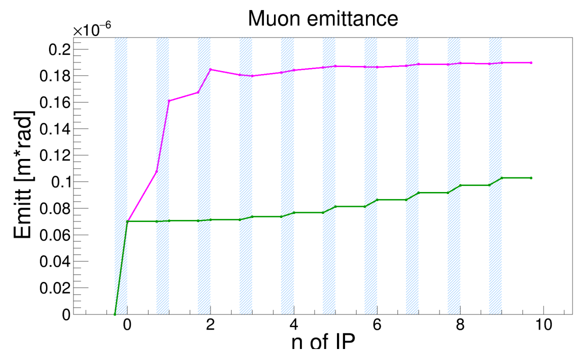

Figure 2: Comparison of μ emittance growth in the Multiple (magenta) and Single (green) IP schemes, as a function of the target number (0 to 9). σ_{e+}=150 μm in both cases.

The design of two μ^+ and μ^- AR to store the μ produced over several passages of the e^+ beam, was also performed [8]. These rings must be short (~120 m) in order to complete 1000 turns before μ decay. In the current scheme, μ are not injected but generated directly inside the ring. Therefore, the interaction region is common to a transport line for e^+ and two accumulator rings, one for μ^+ and one for μ^-, this poses some design issues currently under study.

FUTURE R&D

A solid R&D program to increase the μ beams quality, and consequently the final luminosity, is foreseen. The use of H_2 targets, with respect to Be and C, could improve the integrated thickness, reducing the number of passages and increasing the rate of "fresh" bunches/passage. With a linear dependence on the μ/bunch number, a quadratic increase of the final luminosity can be expected, a simple scaling with Z gives a factor 15 increase of the luminosity. An increase in the efficiency of the PS, such as the rotating target conceived for ILC and the possibility to develop immersed e^+ capture systems with very high peak B field in the AMD (20 T as in MAP [10]) and in the capture solenoid, could increase the repetition rate of a factor 5-10, with a linear dependence on the luminosity. To further reduce the production emittance, since the LEMMA higher production energy results in a longer μ lifetime, also a moderate cooling mechanism, such as stochastic, optical stochastic, crystal, and electron cooling can be envisaged. A full evaluation of these mechanisms could reduce the μ emittance by 1-2 order of magnitude, with a linear impact on the final luminosity.

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