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RECOVERING THE POSITRON BEAM AFTER MUON PRODUCTION IN THE LEMMA MUON SOURCE*

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Abstract

In the LEMMA muon source proposal [1–3] a positron beam at 45 GeV is used to produce muons at threshold by interaction with some targets. In order to release the required intensity on the main positron source, orders of magnitude higher than the state of the art, the possibility to recover the primary positron beam after the interaction with the targets was studied. The particles distribution, with a strongly degraded energy spread after the interaction, was injected back into a low emittance, large energy acceptance 45 GeV ring. Studies of injection efficiency were performed. The possibility of compressing the beam in a linac before injection was also studied. As a result, even without compression, about 80% of the disrupted e^+ beam can be injected back into the ring.

LEMMA MUON SOURCE

The Low Emittance Muon Accelerator (LEMMA) concept is based on muon production from a 45 GeV e^+ beam annihilating with the electrons of a target, close to threshold for $\mu^+\mu^-$ pair creation, thus generating muon beams with low enough transverse emittance for a high luminosity collider. In this scheme the e^+ bunches are extracted to impinge on multiple targets in long straight sections with multiple Interaction Points. A sketch of the scheme is shown in Fig. 1. The Positron Source (PS) and the first linac have to produce and inject 1000 bunches of 5×10^{11} e^+/bunch in the Damping Ring (DR), which stores 3.8 A e^+ at 5 GeV and has ~ 10 msec cooling time, thanks to damping wigglers. After the cooling, e^+ are extracted from the DR, accelerated in a SC linac to 45 GeV and injected in the Positron Ring (PR) in 10 msec. Once 1000 bunches are stored in the PR, they are extracted to collide with the targets in the Target Line (TL) for the muon production. This process can take 410 µsec. After muon production, the degraded e^+ bunches can be sent back to the PR to be damped, topped-up and extracted to the TL in a continuous cycle. One of the challenges of this design is the high demand on the number of e^+ to be produced by the source. With an e^+ source like the ILC [4] or CLIC one [5], which should produce 10^{14} e^+/sec, 5 sec are needed to fill the DR. However, the LEMMA scheme requires a much shorter period to produce, damp and accelerate the e^+ replacing the losses in the muon production process. For this reason, recovering the e^+ beam after the interaction with the targets for reinjection directly into the 45 GeV PS was studied. If ~ 80% of the "spent" e^+ beam can be recovered and injected in the PR, only 20% of the required e^+ would need to be produced in a time cycle of 50 msec, corresponding to the 20 Hz operation repetition frequency. The required e^+ production rate would then be 2×10^{15} e^+/sec

MUON PRODUCTION LINE

We studied [6] the effect of multiple scattering and bremsstrahlung with the target on the e^+ beam quality by tracking the 45 GeV e^+ beam through a sequence of thin targets connected by a transport line composed by quadrupoles only. In particular, a Gaussian bunch distribution of 3×10^4 particles with a transverse emittance of 6 nm, a bunch length of 3 mm and an energy spread of 0.1% has been focused into a thin Beryllium (*Be*) target of 0.86% of radiation length X_0 (equivalent to 3 mm of material). The simulated beam size and divergence at the target entry point are 150 µm and 40 µrad respectively, however multiple scattering over a single thin target increases the divergence by 23 µrad, therefore increasing the beam emittance.

Although the e^+ bunch population is not reduced significantly by the $\mu^+\mu^-$ production, the e^+ beam energy spread is mainly degraded by bremsstrahlung. On a single thin target 2.1% of particles go below the muon production energy threshold (at 43.7 GeV). Moreover, the energy loss distribution is highly non-linear and affects the subsequent particle transport. We studied the beam parameters considering a transport line connecting the beam exiting from the first target with the entry point of a second target located about 5 m downstream. The distance L^* between the target and the nearest quadrupole is 30 cm and the Twiss function at the target location β^* is 3.8 m, to match the beam size and divergence of the e^+ beam emittance. The quadrupole configuration of the transport line was conceived to have low chromatic amplitude at the e^+ beam energy, therefore mitigating the effect of energy loss.

In total we considered 10 thin Beryllium targets connected by 9 transport lines. Figure 2 shows the e^+ beam distribution (3×10^4 particles) after the interaction with the targets, which has been used for the simulation presented in this paper.

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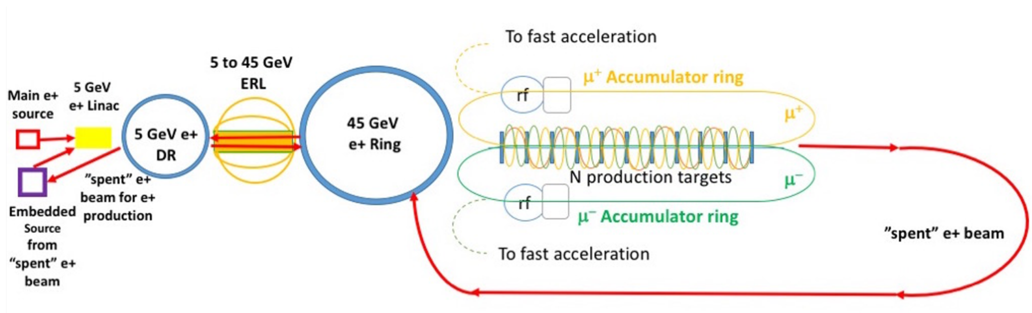

Figure 1: The LEMMA positron driven muon source.

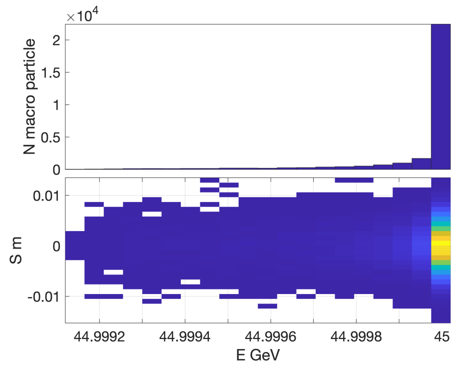

Figure 2: e^+ beam distribution after the interaction with the 10 targets.

POSITRON RING

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 5×10^{11} e^+/bunch with less important synchrotron losses, a 27 Km LHC-like ring was chosen. The lattice is inspired by the ESRF upgrade hybrid multi-bend achromat lattice [7]. The emittance of the e^+ beam hitting the targets has been chosen to be 6 nm, to avoid target damage due to excessive power deposition density. The emittance of the e^+ ring is 0.7 nm, quite smaller. In [2] three lattices for the PR, with different emittances, were studied. This one has been chosen since it has a larger energy acceptance ($\pm 8\%$) with respect to the one with 6 nm emittance ($\pm 6\%$). Moreover, a small emittance allows to recover the initial emittance of the beam on target in a shorter time. Ring parameters are listed in Table 1. In order to get small emittances, each of the 64 cells, 400 m long, includes as many dipoles as possible, reaching 77% dipole filling ratio. The dipoles have a maximum field of 0.61 T at 45 GeV, and a longitudinal tapering of this field is introduced to maximize dispersion at the chromaticity correction sections, thus reducing the sextupole strengths and providing the largest possible energy acceptance. Two chromaticity correction sections, using two families of sextupoles, are separated in the lattice by appropriate phase advance to cancel the second order nonlinearities introduced by the sextupoles themselves. No combined functions dipole-quadrupoles are used in the present version of the lattice, leaving margin for further reduction of the equilibrium emittance, if needed. The momentum acceptance is estimated at each element along the lattice cell, and ranges between a minimum of $\pm 4\%$ and maxima locally reaching $\pm 8\%$ (without errors). The transverse acceptance without errors is above 15 mm, thus suitable for off-axis injection to accumulate both the beam from the main e^+ source and the one from the recovered positron beam after target interaction.

Table 1: Positron Ring Parameters

Parameter	**Units**	
Circumference	km	27
Beam current	A	0.89
N. part/bunch		5 × 1011
N. bunches		1000
Hor. emittance	nm	0.7
Nat. bunch length	mm	1.9
Energy spread		7×10^{-4}
Damping time (x,y)	ms	68
Damping time (s)	ms	34
RF frequency	MHz	500
RF Voltage	MV	477
Max E acceptance	%	± 8

COMPRESSOR LINAC

A simulation of energy compression of the positron beam coming from the muon production target line of Fig. 3 has been performed with the Elegant code [8]. No other considerations have been taken into account except the effects of the chicane $R56$ parameter and the proper phasing of the accelerating field on the longitudinal phase space of the e^+ beam. For a preliminary design of the linac lattice an L-band structure has been considered for the accelerating module, based on the XFEL design [9], with an average accelerating field of $E_{acc} \sim 30$ MV/m, while for the longitudinal and transverse short range wakefields a pill-box approximation has been used following the treatment reported in [10, 11]. The linac consists in a 50 m long magnetic chicane upstream the booster to lengthen the beam and provide the energy-

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position correlation to the e+ beam, followed by a 500 m booster operated at a phase $\phi_{RF} = -90°$ for the first 400 m and at $\phi_{RF} = -60°$ for the rest of the linac to recover the average energy at $E_{av} \sim 45$ GeV. The longitudinal phase space evolution is shown in Fig. 3 where the longitudinal distribution of the e+ beam is shown at the entrance of the first matching section before the chicane a), at the exit of the magnetic chicane b) and at the exit of the linac c), where a final energy spread of $\sigma_\delta \sim 2\%$ rms is reached

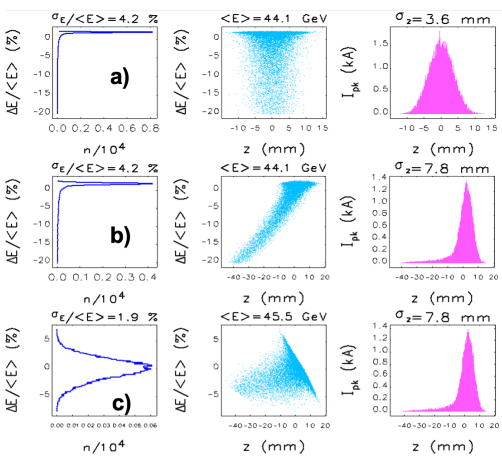

Figure 3: Longitudinal phase space distribution of the e+ beam in the compressor linac: a) at the entrance of the matching section upstream the magnetic chicane, b) at the exit of the chicane, c) at the exit of the linac.

INJECTION INTO PR

The positron beam distributions shown in Figs. 2 and 3 were tracked into the PR for 4096 turns. The 6D tracking of about 3×10^4 particles was performed using AT [12] and includes thick multipoles, radiation damping in all elements, and quantum diffusion modelled, in first approximation, as a single additional element in the lattice [13]. The PR model does not include a dedicated injection cell nor a dedicated straight. The beam is then injected on-axis in the position of largest momentum acceptance (*QD9C* in the centre of the cell). The injected beam transverse distribution is modified to match the correct beta functions at injection, assuming a perfect and lossless transfer line between the target line, the linac and the positron ring. Due to the large number of elements in the lattice and large number of particles and turns to be studied, the use of a computing cluster is mandatory. For each injection efficiency and beam size evolution estimate, about 200 cores were used for about 2h. Figure 4 shows the evolution of the injected beam emittance after injection, with the initial beam distribution after the targets (blue, orange), and after the linac compressor (green). In about 200 ms the injected recovered positron beam reaches the PR equilibrium emittance, while the 6 nm emittance needed on target is reached after about 60 ms, slightly longer than the 50 ms corresponding to 20 Hz repetition rate [2]. A beam injected with a larger energy offset (3.5%) takes about 50 ms more to reach the equilibrium values. The emittance increase with energy offset is mainly due to the fact that the injection point has non zero dispersion. The same simulation is performed for several energy offsets in order to profit at most of the available local momentum acceptance of the PR. The injection efficiency in each case is displayed in Fig. 5.

For a beam injected directly after the targets the efficiency has a maximum (83%) for an energy offset of about 3.5%. The beam distribution after the compressor linac has a maximum injection efficiency of 86% obtained when the beam is injected on energy. The injection efficiency in this case is also referred to the beam just after the targets to include the losses generated by the compression.

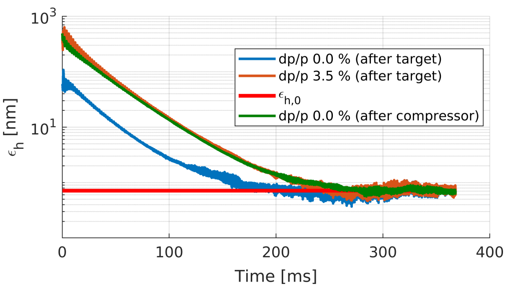

Figure 4: Horizontal injected beam emittance after injection in the PR with the initial beam distribution after the targets (blue, orange) for two different injected beam energy offsets, and after the linac compressor (green).

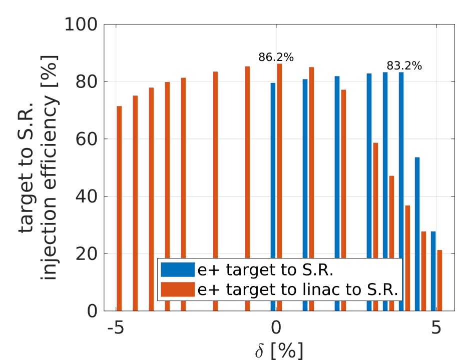

Figure 5: Injection efficiency vs beam energy offset, for the beam distribution after the targets (blue) and after compressor linac (red).

CONCLUSION

This work aimed at studying if the disrupted LEMMA e+ beam, after the interaction with muon production targets, could be injected back into the ring, to release the stress on the main e+ source. From the first studies an injection efficiency of 86% has been achieved for the beam compressed in the linac and 83% for that coming directly for the targets. Optimization of the positron ring acceptance and design of a zero dispersion injection section could improve these efficiencies. Further improvement could be achieved with the optimization of final distribution of the compressor linac beam.

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