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Low emittance muon beam in the 2 to 40 GeV energy range for muon and neutrino experiments

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I present a scheme to obtain a 2 to 40 GeV low emittance muon beam, not requiring cooling and within today's technological resources, to be used for early commissioning of muon accelerator projects, or alternatively dedicated muon and neutrino parameter measurements.
In particular, a muon rate of 5×10^4 μ/s in a normalized transverse emittance of 5 π μm at 22 GeV, and energy spread of 1 GeV obtained from $O(10^{11})$ e^+/s on target at 44 GeV. This emittance is below the expected results of advanced emittance cooling techniques for muons produced from protons-on-target, and represents an alternative for the duration of complete muon cooling studies.
The scheme has beam designed to adjust the muon beam energy in the GeV energy range to the needs for precise parameter measurements of muons and neutrinos.
Furthermore, the muon rate could be in principle increased proportionally to the availability of higher positron rates, already foreseen for future collider projects.

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There is an increasing interest in the accelerator community to study a high luminosity and high energy muon–muon collider that could continue the exploration of the particle physics energy frontier using leptons [1], while studies of a muon source based on protons-on-target (PoT) collisions [2] show that it could achieve, in principle, an instantaneous luminosity above 10^{34} cm^{-2} s^{-1} in the TeV energy range from $O(10^{12})$ muons per bunch inside an emittance foreseen to be reduced with advanced muon emittance cooling concepts. The results of the initial test limited to conclude on the muon beam transverse emittance have been recently released [3] giving positive indications of emittance cooling, while, the total combination of transverse and longitudinal emittance cooling remains yet untested. Alternatively, a low emittance muon beam can be generated from positrons on target. These studies are carried out by the LEMMA (Low EMittance Muon Accelerator) [4–7] team at INFN/Italy, who is interested in creating a muon bunch population in the order of 10^9 particles in an extremely small normalized transverse emittance ϵ_n of 0.04 π μm at 22.5 GeV and longitudinal emittance of about 3×1 π mm GeV, to produce luminosities in the order of 10^{34} cm^{-2} s^{-1}.

Recent results on the LEMMA muon source [8] have been able to show a ten fold increase in the muon production efficiency, reaching 0.5×10^{-6} μ pairs per impinging positron (μ/e^+), in a reduced transverse normalized emittance of 5 π μm at 22 GeV and longitudinal emittance of 3 π mm GeV, while at the same time reducing the power deposition per target by more than a factor ten. Although the transverse emittance attained is still larger than the LEMMA goal, it already offers the possibility of a muon source with an emittance below the one foreseen from protons after cooling. Therefore, the studies of the LEMMA muon source provide an alternative to cooling available with today's technology.

Muon sources have been used or suggested for studies on muon and neutrino parameters [9] along varying energy and intensity. For example, accelerator facilities like nuSTORM (Neutrinos from STORED Muons) [10–12], nuMAX (Neutrinos from a Muon Accelerator Complex) [13], the Muon $g-2$ experiment [14] and MUonE [15] have been designed in the GeV energy range considering larger muon emittances or projecting in the future the usage of a small emittance given that results from cooling are favorable.

Instead, muon facilities could benefit from having today a low emittance muon beam to increase the precision of their measurements, reduce the experiment complexity or even consider and earlier commissioning at low intensity. For example, we could expect to have an instantaneous luminosity of 10^{33} cm^{-2} s^{-1} from the collision of a muon beam with the electrons in a high density fixed target (similar to the MUonE experiment). Let's assume a muon flux Φ of 5×10^4 μ/s, impinging on a target l 40 m long, density ρ_m of 20 g cm^{-3}, from which we get the luminosity [16] $L = \Phi\rho l = 1.2 \times 10^{33}$ cm^{-2}s^{-1}, where we have use the Avogadro Number N_a (approximately 6×10^{23} nuclei/mol) and assumed a factor 1/2 coming from the ratio Z/A of the material atomic number Z to the mass number A, in order to calculate $\rho = \rho_m \frac{Z}{A} N_a$. Note that for a muon beam with energy varying from 2 to 40 GeV on a fixed target collision, the center of mass energy is in the range of 115 to 228 MeV.

The low emittance muon beam allows to have a high muon flux density reducing the requirements on the target transverse dimensions. The lifetime of the muon beam at 22 GeV is as long as 0.4 ms which gives the possibility to consider a ring to recirculate the muon beam through a shorter target, as in [17, 18], possibly rising the luminosity by a factor 10 to 100. Furthermore, the muon rate of 5×10^4 μ/s could be obtained from a positron rate of 10^{11} e^+/s that is within the reach of several laboratories around the world, and higher muon rates could be achieved with dedicated efforts to design a custom positron source. With respect to neutrino experiments, previous measurements of interesting neutrino cross sections [19] report values well above 10^{-39} cm^2 at 1 GeV. Estimating 1 year as 2×10^7 s, in 5 years of run we should be able to detect a large number of the 100 muon to neutrino decay events in the GeV energy range. The scheme provides two main advantages: the high muon flux density and the energy tunability beyond atmospheric neutrinos in the GeV scale that would have a neutrino flux of 1 to 0.001 s^{-1} cm^{-2}, see Fig. 4.1 of [20].

I would like to present, as input for further discussion, the production scheme of a low emittance muon beam in the energy range of 2 to 40 GeV as a source of muons and neutrinos. Muons are produced from positron–electron annihilation of a 44 GeV e^+ beam in multiple fixed targets, producing a small normalized muon beam emittance of 5 π μm at 22 GeV without the need of cooling, therefore, the required technology is available today.

Details of the scheme are shown in Fig. 1, where the main parameters are display on each stage. It starts with low energy electrons that are accelerated to a fixed target where e^+e^- pairs are produced. Positrons are captured and accelerated to be injected in a small damping ring which reduces the beam emittance. The positron bunch is extracted, accelerated to 44 GeV and passed through a series of targets connected by a transport line that preserves the emittance of the newly created muon beam and mitigates the degradation of the positron beam. One of the two muon species is selected to be transported for experiments. A list of possible target materials is given in Table 1.

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Material	Symbol	Density (g/cm^3)
Molybdenum	Mo	10.28
Silver	Ag	10.49
Lead	Pb	11.34
Thorium	Th	11.7
Rhodium	Rh	12.41
Mercury	Hg	13.53
Tantalum	Ta	16.69
Uranium	U	19.1
Tungsten	W	19.25
Gold	Au	19.30
Plutonium	Pu	19.85
Rhenium	Re	21.02
Platinum	Pt	21.45
Iridium	Ir	22.56
Osmium	Os	22.59

Table 1: List of materials with density near 20 g/cm^3.

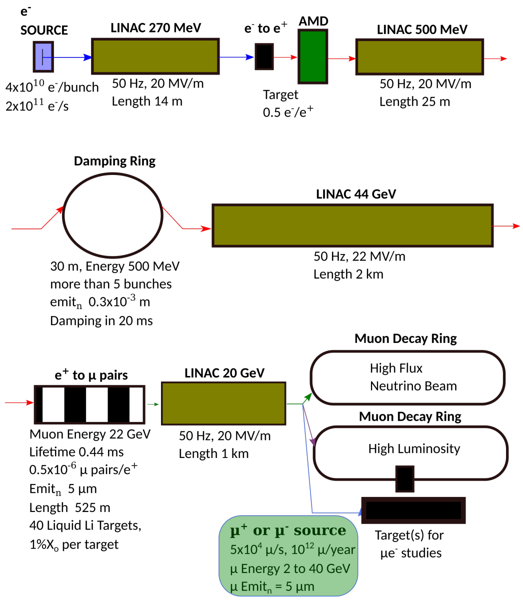

Figure 1: Low emittance muon beam production scheme for muon and neutrino studies.

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