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A muon source based on plasma accelerators

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ABSTRACT

The conceptual design of a compact source of GeV-class muons is presented, based on a plasma based electron–gamma collider. Evaluations of muon flux, spectra and brilliance are presented, carried out with ad-hoc Monte Carlo simulations of the electron–gamma collisions. These are analyzed in the context of a large spread of the invariant mass in the e–gamma interaction, due to the typical characteristics of plasma self-injected GeV electron beams, carrying large bunch charges with huge energy spread. The availability of a compact point-like muon source, triggerable at nsec level, may open a completely new scenario in the muon radiography application field.

1. Introduction

Muons presence on the Earth is due to the interaction between cosmic rays and the atmosphere: they are produced from pion $\pi^{\pm}$ and kaon $K^{\pm}$ decay in the high atmosphere (15 000 m), and they reach our planet surface with a medium kinetic energy of 4 GeV. Atmospheric muons flux is spread all over the solid angle Ω, and it is measured to be [1,2] $\frac{dN}{d\Omega dt} = 0.66\cos^2(\theta_z)$ sr^{-1}.cm^{-2}.min^{-1}, i.e. integrating over the upper hemisphere solid angle and considering only muons with momentum $p_{\mu} > 1$ GeV.c^{-1}, $\frac{dN}{dAdt} \simeq 1$ cm^{-2}.min^{-1}. Roughly, we could say that a human hand, anyway orientated, is crossed by a muon every minute.

GeV-class muons are keys to several strategic applications, in particular radiography of very thick objects (Volcanoes, Nuclear Power Plants, National Security) thanks to their high penetration/low stopping power (compared to photons/electrons…). A compact muon source based on the most advanced technologies could deliver a muon beam with 1–100 muons/s at GeV energy, collimated within hundreds/tens mrads. A Plasma Accelerator could guarantee the needed compactness of a GeV muon source (order of magnitude cheaper and shorter than GeV-class muon section of a typical muon collider). The combination of advancement in plasma accelerators (high charge GeV electron bunches) and in Compton Sources (high intensity tens MeV-class photon beams as in ELI-NP-GBS) allows to conceive such a source possible in the near future. The challenge consists in running a 10^{31} cm^{-2} s^{-1} luminosity (Lorentz Boosted) $e-\gamma$ collider at $E_{cm} = 400$ MeV to make a point-like, GeV-class, ns synchronized, muon source at 1 $\mu^{+,-}$/s with collimated emission (200 mrad) compact Muon Photo-Cathode producing μ-pairs with GeV-scale energy.

The basic ingredients of a plasma based muon source are: a laser driven self-injected plasma accelerator generating low-quality (large energy spread, large emittance) high charge (10 nC) electron bunch at $E > 1.5$ GeV (compare state of the art: 100 pC at 5 GeV, 1 nC at 500 MeV); a high-power interaction laser ELI-NP-GBS (Yb:Yag 1 J @ 1 kHz, state of the art 1 J @ 100 Hz). Control, reproduce, stabilize the $e-\gamma$ collisions at IP with μm-size beam spots within the gas jet of plasma accelerator. Embed the whole accelerator (3–5 m in size) into a thick radio-protection bunker absorbing all beams but the muons (escaping through bunker walls). Additional filtering of surviving e^-, γ' s w.r.t. positive muons through magnetic fan-out spectrometer. A proof-of-principle experiment can be proposed: $0.1-1$ μ-pair per second gated in 10 ns time frame covering a 4 m^2 detector located 3 m far from the point-like source (compare $400\times10^{-8}\times100 = 4\times10^{-4}$ atmospheric muons $\Rightarrow$ SNR > 250).

2. Muon photoproduction

For the muon source we consider the process:

$$e^- + \gamma \rightarrow \mu^+ + \mu^- + e^-$$

where the muon flux scales with the total cross section [3]:

$$\sigma_{MPP}(s) \simeq \frac{2\alpha^3}{m_{\mu}^2}\ln(2)\ln\left(\frac{s}{m_e^2}\right) \tag{1}$$

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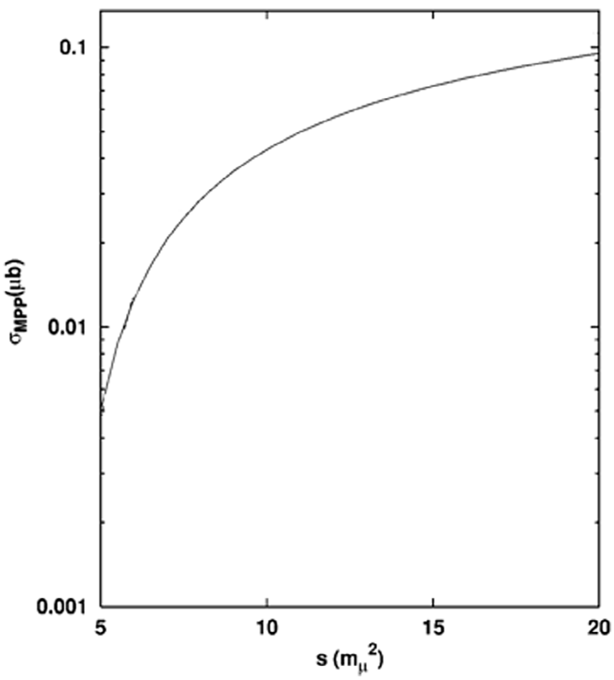

Fig. 1. σ_{MPP} as function of square of center-of-mass energy s (in unit of m_μ^2).

as function of the invariant mass $s = E_{cm}^2/m_\mu^2$, where $m_{\mu,e}$ is muons and electrons rest mass, $\alpha \approx 1/137$ is fine structure constant, $E_{cm} = 2\sqrt{\gamma m_e h\nu}$ is deduced from the kinematics of the system, where $h\nu$ is energy of laser photon. Since the cross section has a cut-off at $2m_\mu$, to exceed this energy cut-off we need to have an energy in the center of mass of the system bigger than about 200 MeV. The cross-section of $e^- + \gamma \rightarrow \mu^+ + \mu^- + e^-$ scattering is reported in Fig. 1.

A possible implementation of the muon source is shown in Fig. 2. Two high power, counter propagating laser pulses generate (counter propagating) high charge, low quality, electron bunches: one of those will collide with a third laser pulse in order to generate gamma photons by Compton back-scattering (CBS). Then, those photons collide with the other electron bunch to produce muon pairs. Notice that the third laser is not mandatory: its presence would allow to tune gamma rays energy so that both muon production cross section and system center of mass energy can also be tuned. Giving up this possible flexibility, allows to implement an easier set-up where gammas are produced by CBS with driving laser pulses.

Table 1
Electron beam parameters.

Electrons energy (GeV)	1.6
Energy spread (%)	10
$\sigma_{x,y}$ (μm)	1
$\sigma_{Px,Py}$ (MeV)	5
σ_z (μm)	5

Table 2
Laser parameters.

Pulse energy (J)	1
wavelength (nm)	1030
σ_l (μm)	5
σ_t (ps)	1.5

If we consider an electron beam whose energy is around 1.5 GeV, the photons should be the gamma rays with tens MeV of energy. Therefore the gamma rays are foreseen to be produced by a Compton source that can either use the same electron beam of the muon production, or another beam produced ad-hoc for the Compton interaction.

It is important to notice that in this proposed scheme of e^-, γ collision, the center of mass reference system moves relatively to the laboratory system with $\gamma_{cm} = \frac{E_{LAB}}{E_{CM}} \cong \frac{1}{2}\left(\sqrt{\frac{\gamma m_e}{h\nu}}\right)$, in the direction of the electron. Due to this fact, the muons created in center of mass system with energy close to rest mass energy will move with a γ_{CM} in the laboratory system. As a consequence, the proposed scheme provides a beam of muon that has a $\gamma_\mu \geq \gamma_{CM}$.

We constructed an ideal electron beam, with parameters similar to the state of the art of plasma accelerated beams [4,5], see Table 1.

The phase spaces are in Fig. 3.

The Compton source exploits the same electron beam and a Yb:Yag laser with parameters shown in Table 2.

The simulations of Compton γ−rays have been done with the Monte Carlo code CAIN [6]. Fig. 4 shows the gamma spectrum, with a total number of photon of about $1.7 \cdot 10^{11}$ and energy $E_{ph} = 4\gamma^2 E$ laser ranging from 0 up to 70 MeV. However only photons with energy bigger than 25 MeV participate in the muon production. The propagation of the beams has been done with the code ROSE [7]. The code ROSE (Rate Of Scattering Events) has been implemented for studying the

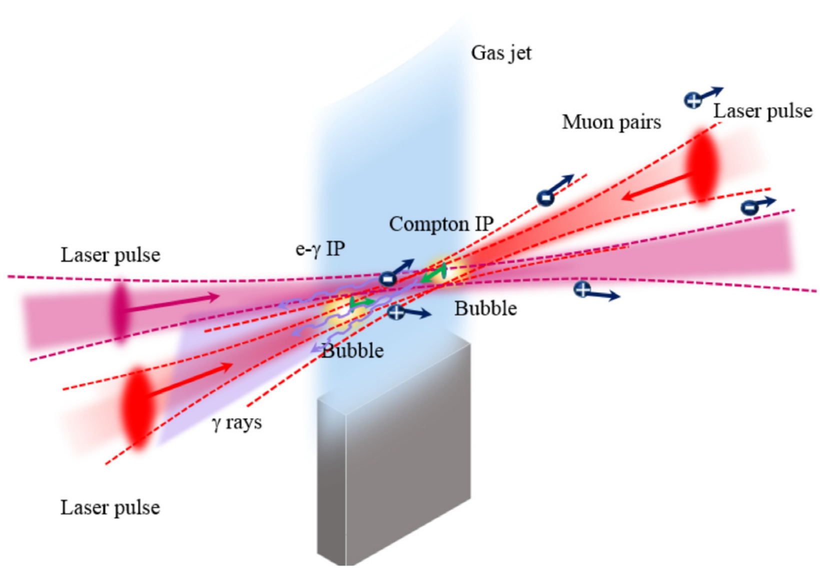

Fig. 2. Scheme of source.

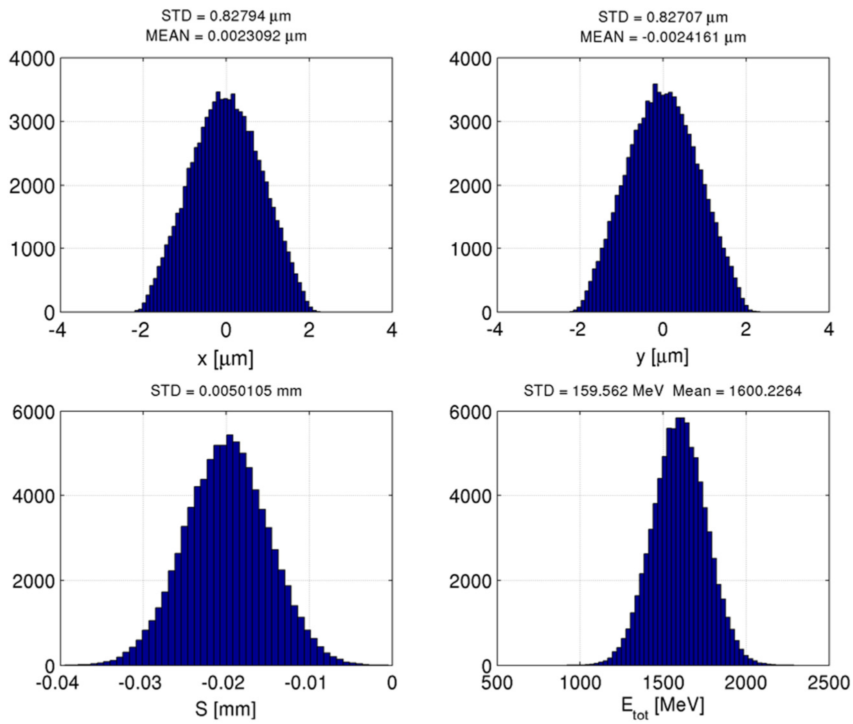

Fig. 3. Electron beam phase-space.

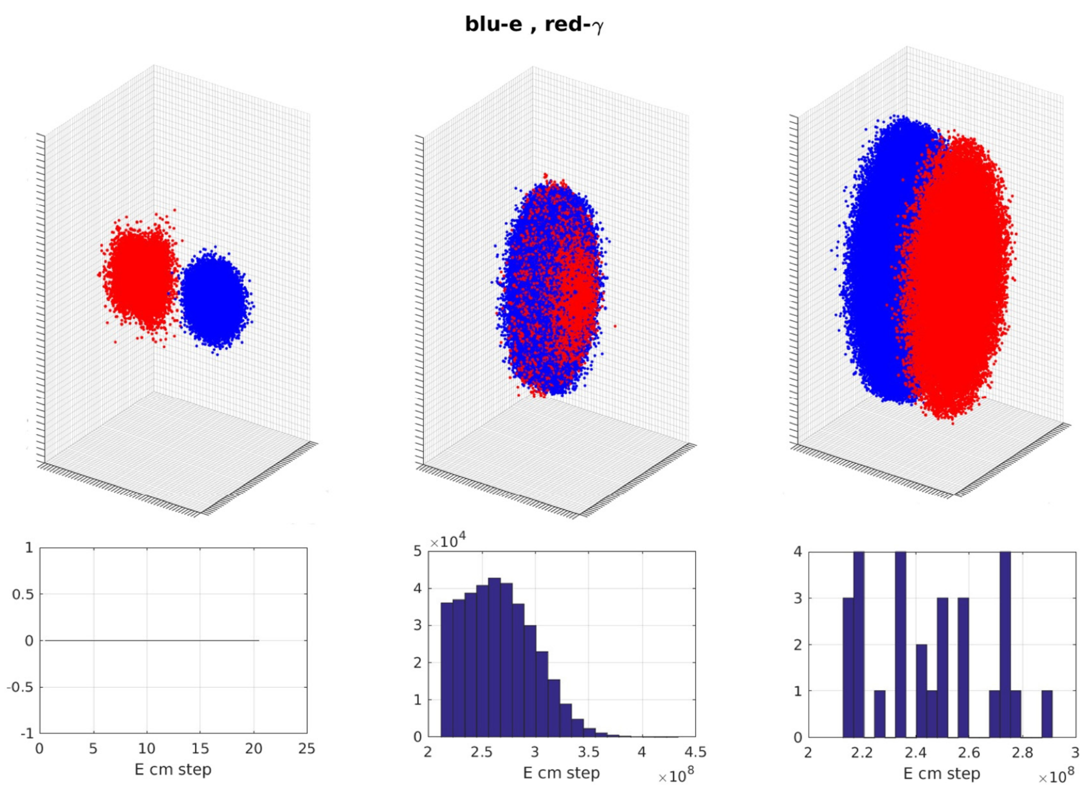

Fig. 4. Propagation of particle in ROSE code at various instance.

photon–photon scattering and then applied to other particle collisions and decays, as Breit–Wheeler, TPP, Compton scattering [8–11]. Starting from two colliding beams of massive particles or photons (say beam 1 and beam 2) defined through the phase spaces of an appropriate number $N_{1;2}$ of macroparticles of weight respectively $q_{1;2}$, the procedure requires the definition of a common space grid where the kinematics takes place. The tracking of both beams during their overlapping up to the end of the scattering process permits to dimension the total space window. The initial time t_0 is the instant when the first collisions occur, the time evolution being discretized over a total of NT steps. Fig. 4 shows few

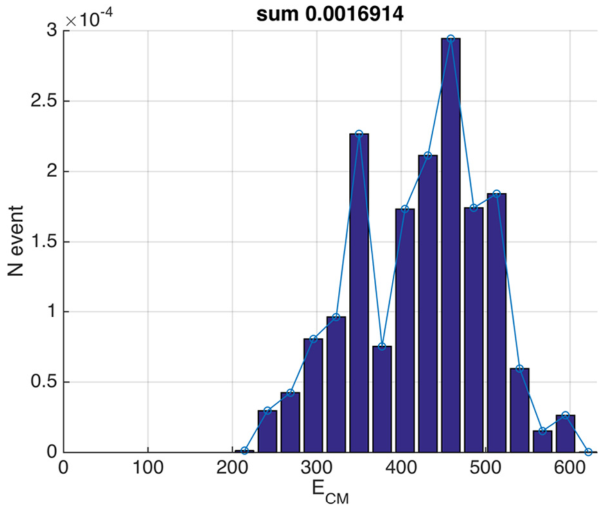

Fig. 5. Energy distributions of muons.

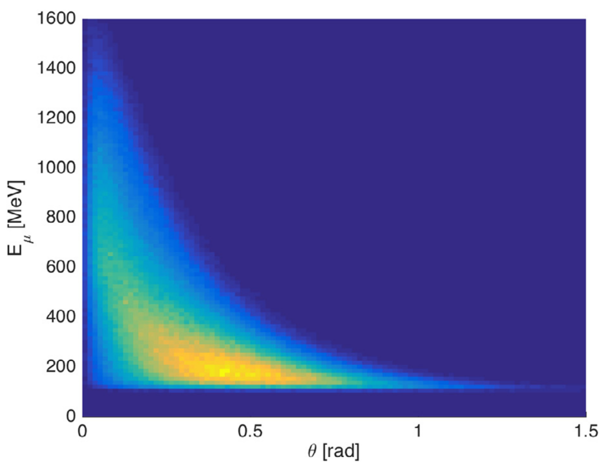

Fig. 6. Energy-Angular distribution of muons.

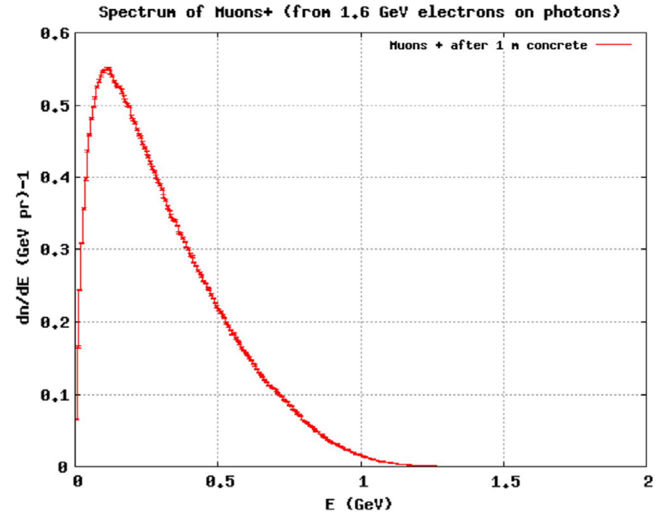

Fig. 8. The spectrum of emerging muon per primary incident muon for the case of 1 m concrete wall.

temporal snapshot of the interaction (upper line) and the number of interactions as function of the energy of the center of mass at the relative shot given by the convolution of the energy distribution of the possible events with the cross section. The final output of muons is presented in Fig. 5.

To get the distributions of muons, simulations by event generator WHIZARD [12] were done. The energy of the produced muons ranges between 105.65 MeV (the muon is produced at rest, i.e. backward in CM) and about 2 GeV (all of the electron energy is transferred to the muon). The energy distribution of the produced muons is peaked around 150 MeV. The almost totality of the muons is emitted in a cone of aperture θ of 1 radiant, the most part of them within a angle $1/\gamma_{cm} \simeq 350$ milliradiants with the peak of emission around 100 millirads. Notice that, for the sake of simplicity, in this work we do not take into consideration effects of plasma fields on produced muons. The Energy-Angular distribution of generated muons is presented in Fig. 6.

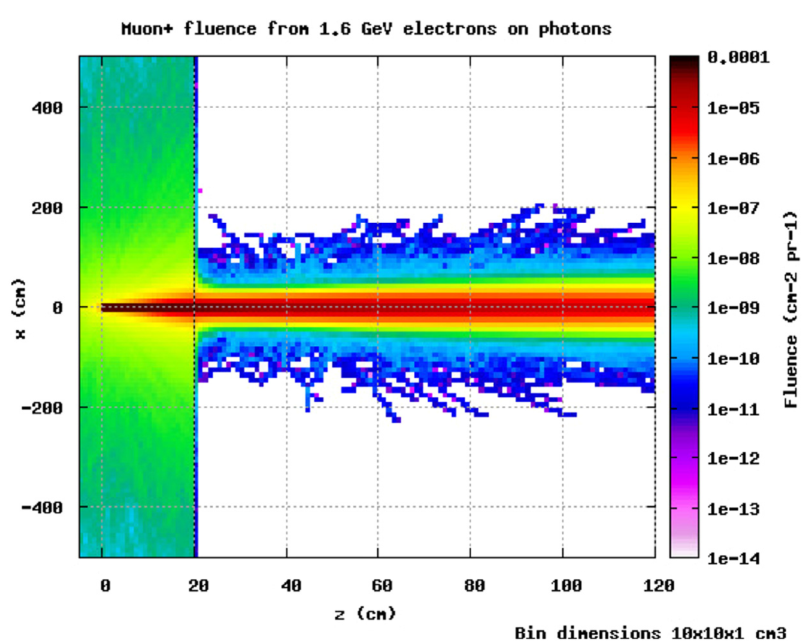

Fig. 7. The number of emerging muon per primary incident muon for the case of 1 m concrete wall.

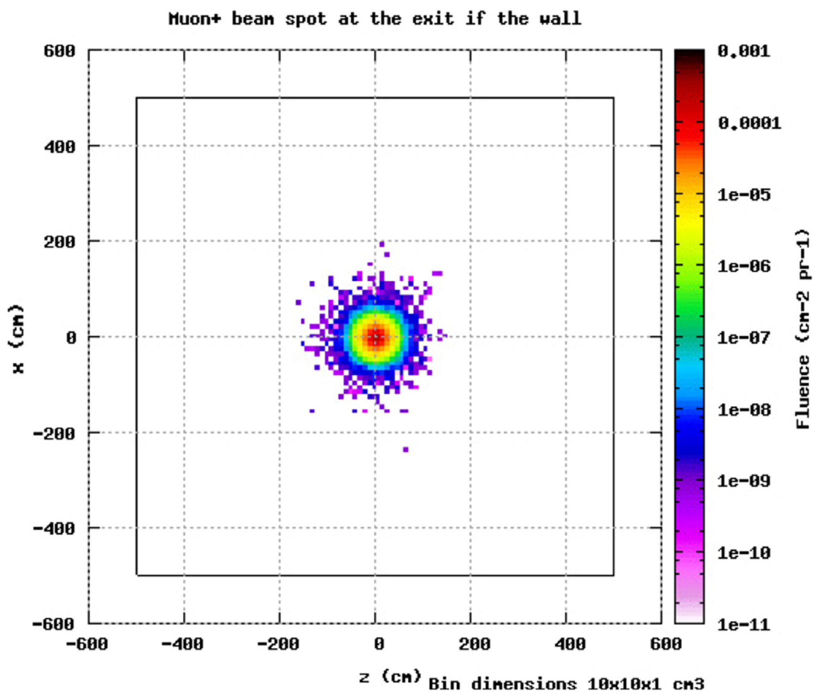

Fig. 9. The beam spot of the muon beam at the exit of the concrete.

The produced muons are then driven to a concrete wall. The dynamics (or the interactions) of the muons inside the concrete wall has been evaluated by the FLUKA [13,14] code Two thicknesses have been considered 1 m concrete. The results of the FLUKA evaluation, obtained with 20 different runs of the roughly 10^6 primary muons are shown in the following plots. The cut off used in the simulations was 100 keV. The number of emerging muons per primary incident muon is $\approx 0.244 \pm 0.007\%$ and $\approx 0.005 \pm 0.15\%$ for the case of 1 m and 3 m concrete wall respectively presented on Fig. 7.

The spectrum of the emitted muons (integrated over angle) is shown in Fig. 8 in case of 1 m.

The beam spot of the muon beam at the exit of the concrete is shown on Fig. 9.

3. Conclusion

Advancement in fiber-lasers, expected to meet laser–plasma based TeV collider requirements at 10–100 kHz rep rate, offers the opportunity to develop a Compact Muon Source delivering the muon beam with 1–100 muons/s at GeV energy, collimated within hundreds/tens mrads, synchronized at nsec level, based on a compact O(10 m) and cheap O(10 M€) system.

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