Laser muon sources : concepts and challenges

L. Drska

Czech Technical University, Prague, Czech Republic

Introduction. Muons are standard constituents of elementary particle model with the mass of 207 times electron mass. There exist two species of muon : negatively charged μ^- and positively charged μ^+ (antimuon). They are unstable particles with the lifetime in vacuum 2.2 μs. Muons are available nowadays in cosmic radiation or can be produced by accelerators [1]. The progress in laser technology - availability of high-intensity and highrep systems , inspires the study of their potential production as tertiary particles in laser-matter interaction.

Muons at ELI-BL. There exist several possibilities how to produce muons using high-intensity lasers :

<table>
<tr><td rowspan="4">Electromagnetic processes (Direct muon production)</td><td colspan="2">Electron / photon driven systems</td><td rowspan="2">High-energy mixed particle sources</td></tr>
<tr><td>1.1 Electron-electron collisions</td><td>1.2 Electron-nucleus collisions</td></tr>
<tr><td colspan="2">Photon-driven systems</td><td rowspan="2">Pure lepton sources</td></tr>
<tr><td>1.2 Gamma-gamma collisions</td><td>2.2 Photon-electron collisions</td></tr>
<tr><td rowspan="2">Hadron processes (Muon production via pion decay)</td><td colspan="2">Proton / ion driven systems</td><td rowspan="2">Medium energy sources</td></tr>
<tr><td>3.1 Flying pion decay</td><td>3.2 Stopped pion decay (surface muons)</td></tr>
</table>

The aim of this contribution is: (1) Formulate strategy for potential creation of applicable laser-driven muon source. (2) Recommend first-phase proof-of principle experiments in this area. The forward-looking study of this topic is strongly facilitated by the availability of extensive materials related to accelerator-driven muon sources. Some relevant simulations of laser-based systems are also available. Well-thought-out exploitation of this information allows to achieve the goal in view without extensive simulations. The feasibility study considers parameters of ELI Beamlines systems (HELL, ELIMAIA, P3) driven by L3 (1PW) and L4 (10 PW) lasers [2] .

The most prospective processes for future laser muonics using focused intensities < 10^{22} W/cm^2 are processes 1.2 Electron-nucleus collisions and 3.2 Surface muons. For intensities > 10^{22} W/cm^2 processes 2 should be bring to trial.

Muon detection. Detection and parameter measurement of muons in laser-driven process should be the first task. Potential recommended approaches are as follows:

Electromagnetic processes	*Peltiere diffusion chamber*	Nuclear emulsion
	Plastic scintillator sheet	Muon decay detection
Nuclear processes	Muon caused transmutation	*Muon driven fusion*

As the most interesting possibilities for the first experiment phase are considered diffusion chamber and muon fusion. *Diffusion chamber* : (1) Upgraded classical visualization detector with well elaborated evaluation methods. (2) Possibility to use in harsh laboratory environment. (3) Gated regime allows minimize the influence of cosmic radiation. (4) Tailored system with distant cameras and magnetic field commercialy available [3]. (5) Possibility to use in one-day experiment in the starting phase of ELI activity, parasitic regime could be applied. *Muon-driven fusion* : (1) Novel approach to muon radiation detection. (2) Selective detection of slow muons. (3) Multiplicative creation of fusion-produced particles. (4) Exploitation of the coincidence of fusion products. (5) Applicability for measurement of very weak sources.

Electron-nucleus collisions. The process 1.2 is an analogy to electromagnetic production of electron-positron pairs. It consists of two steps:

STEP 1 : BREMSSTRAHLUNG PROCESS	$e- + N \longrightarrow e-^{*} + N + \gamma$
STEP 2 : BETHE-HEITLER PROCESS	$\gamma + N \longrightarrow N + \mu^{-} + \mu^{+}$

The first calculation of the process 1.2 [4] neglecting more probable parallel processes evidently overestimates the muon yield in a real experiment. The novel detailed Monte Carlo simulation [5] indicates that for an applicable muon source the electron energy must be of several GeV, recommended value is 10 GeV. Detection and parameter measurement muons in this process should be the first task for the experiment. Schematic representation of its proposal is depicted in the fig. 1.

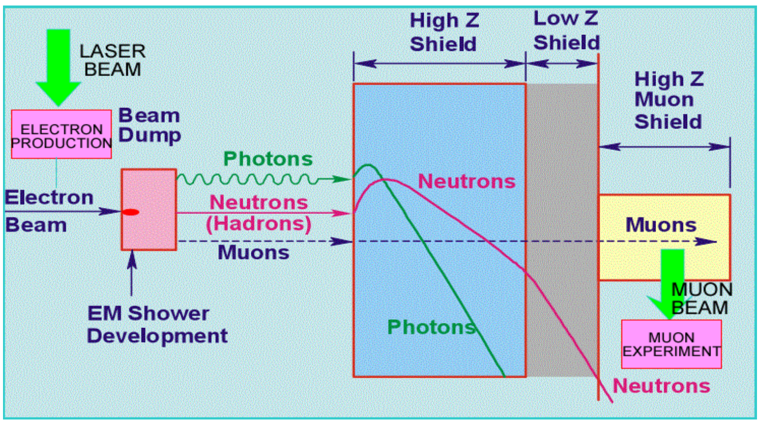

Fig. 1

Characterization of the source : Pulsed beamed source of high-energy muons (GeV region), broad energy spectrum, pulse duration of tens picoseconds.

Surface muons. The most effective process of muon production could be the mechanism 3.2.About the single pion production threshold of the 280 MeV in the center-of-mass frame the following two-step process is current (Fig. 2):

STEP 1 : PION GENERATION USING PROTON BEAMS

$$p + p \rightarrow p + n + \pi^+ \qquad p + n \rightarrow p + n + \pi^0$$
$$p + p \rightarrow p + p + \pi^0 \qquad p + n \rightarrow p + p + \pi^-$$
$$p + p \rightarrow d + \pi^+ \qquad p + n \rightarrow n + n + \pi^+.$$

STEP 2 : PION DECAY: MUON GENERATION

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

Fig. 2

This is the standard method for muon production using large accelerator facilities. We can benefit from detailed simulations of these processes [6] [7].

Fig. 3 shows potential development steps for an applicable laser-driven muon source based on the mechanism 3.2. Without question, the key task presents the step 2 – production of ions with energy of several hundred MeV. The energy of this order is necessary also for oncological application , the progress in this intensively studied area will pave to the route for laser muonics. Inspirations for remaining steps (muon collection, focusing, deceleration) can be found in the solutions for accelerator facilities [7] [8] .

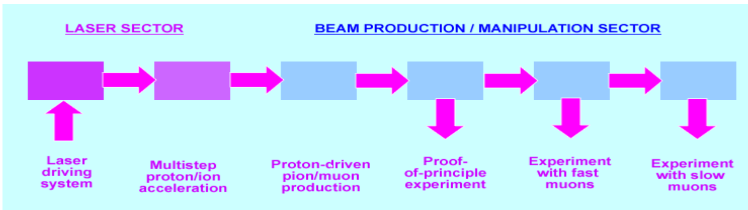

Fig.3

Characterization of the source : Pulsed isotropic monoenergetic source (4.12 MeV, 29.8 MeV/c^2), exponential-shape pulse with the decay constant of 2.6 x 10^{-8} s.

Muon applications. There exist extensive area of muon applications [9] [10] [11] . Most interesting ones could be specific applications possible only for laser facilities. Some examples are listed below.

Muon diagnostics of laser-produced plasmas	Signature of very energetic electrons in laser plasma Muon scattering diagnostics of high-parameter plasmas Muon radiography / tomography of dense plasma systems
Muon processes in laser-driven systems	Muon acceleration / deceleration in laser-produced plasmas Muonium production in laser-created plasmas Muonic atoms in strongly ionized high – Z systems

Conclusion. Realistic near-future research of laser-driven muon sources can be started with electron-photon process 1.2. Potential steps of this programme could be as follows: (1) Development and testing of detection / diagnostic methods for muons in complex radiation environment using an accelerator facility. (2) Development of a laser- driven source of fast electrons with energy of several GeV with enhanced high energy component. (3) Detailed simulations and proof-of-principle experiments demonstrating fast muon creation using laser-driven beam of relativistic electrons. (4) Measurement of the yield, energy and angular distribution of muons produced by electron beam for varesious parameters of the experiment. (5) Production of a separated laser-driven muon beam and searching of its use with regard to its competitivity with cosmic and accelerator sources.
Potential exploitation of the process 3.2 (hadron driven system) depends on the progress in the development of proton/ion beams with sufficient high energy. Experiments with systems based on processes 2.1 / 2.2 (hard photon excitation) [12] need focused intensities of the order 10^{23} W/cm^2 and in this respect should be considered as a long-term challenge.

References

[1] Nagamine K: Introductory Muon Science, Cambridge University 2003.

[2] Weber S. et al.: P3 : An installation for high-energy density physics and ultra-high intensity laser- matter inte reaction at ELI-Beamlines, Matter and Radiation at Extremes 2 (2017),149.

[3] Nuledo https://www.nuledo.com/en/our-products/nuledo-custom-cloud-chamber/.

[4] Titov A. et al. : Dimuon production by laser-wakefield accelerated electrons, Phys. Rev. Spec. Top. **12**, (2009) ,111301 .

[5] Rao B.S. et al. : Bright muon source driven by GeV electron beams from a compact laser wakefield accelerator. arXiv:1804.03886[physics.plasm-ph]

[6] Bungau A. et al.:Simulation of muon production targets. Technical Report RAL-TR-2016-003.

[7] Berg F. et al.: Target studies for surface muon production. Phys. Rev. Spec. Top. AB 19 (2016), 024701.

[8] Dreesen W. et al. : Detection of petawatt laser-induced muon source for rapid high-Z material detection. Technical Report DOE/NV/25946-2262 .

[9] Nagamine K.: Radiography with cosmic-ray and compact accelerator muons; Exploring inner-structure of large-scale objects and landforms. Proc. Jpn. Acad. Ser. B Phys. Biol. Sci. 92 (2009),265 .

[10] Morenzoni E.: Physics with Muons : From Atomic Physics to Condensed Matter Physics. Lecture course 402-0770-00L (ETH-Zürich). Lecture course PHY 432 (Univ. Zürich).

[11] Drska L. : Tertiary particle physics with ELI : concepts and challenges. SPIE Optics + Optoelectronics, Research using extreme light, Prague , April 24 – 27, 2017.

[12] Serafini L. et al. : A muon source based on plasma accelerators. arXiv:1711.06022[physics.acc-ph]