

Fast timing detectors for the muon system of a muon collider experiment

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Abstract—The muon collider offers a great discover potential for the future of high energy physics. Indeed, it combines the advantages of a lepton collider, with clean signatures and maximum available center of mass energy, with those of a hadron collider, such as low synchrotron radiation. However, it poses interesting challenges, mainly related to the fact that muons decay and their product interact with the material of the machine producing the so-called Beam-induced-Background. For this reason, a careful design of the experiments running at a muon collider must be performed, starting from simulation, and moving to the R&D on dedicated technologies. This contribution will focus on the muon system of a muon collider experiment: the current design limitations will be presented, together with the alternative solutions that are being considered. In particular, we are proposing to use the Picosec Micromegas technology for a dedicated timing layer in the muon system, which will improve the muon reconstruction performance in that region. The R&D on this technology will be discussed and preliminary results will be presented.

Keywords —Muon collider, time resolution, Picosec-Micromegas.

I. INTRODUCTION

THE future of high-energy physics lies in the ability to make collisions at a multi-TeV center-of-mass energy and to measure the products of the collisions with high precision. This will be crucial both for exploring new physics and for deepening the understanding of possible discoveries made by the LHC at high luminosity. Muon colliders thus offer great potential for discovery in the multi-TeV energy range: first, the large mass of muons, compared with that of electrons, implies enormous suppression of synchrotron radiation compared with electron beams of the same energy. In addition, the leptonic nature of muons poses a cleaner analysis environment, free of the accumulation problems characteristic of hadron colliders. The development of a muon collider obviously poses some major technological challenges, arising from the short muon lifetime, 2.2 μ s, and from the difficulty of producing large numbers of muons in groups with small emittance. In addition, the Beam-induced Background (BIB) due to muon decay affects the design of the machine and detector. Simulations performed with FLUKA show that the BIB is mainly composed

of neutrons, photons, and low-energy electrons/positrons. They deposit energy diffusely throughout the detector volume, with a significant dispersion of their arrival time with respect to crossing the bunch, due to their different velocities [1]. All these characteristics must be considered for proper detector design.

II. SIMULATION OF THE EXPERIMENT

The existing simulation framework is based on the iLCSoft framework, previously adopted by the CLIC Collaboration [2], and updated for Muon Collider developments. Currently, the simulation includes a tracking system based on multiple layers of silicon detectors, followed by electromagnetic and hadronic calorimeters. These three components are contained within a solenoidal magnet, which provides a field of 3.57 T. Outside the solenoid extends the muon system, based on multiple layers of gaseous detectors in both the barrel and endcap regions, as shown in Fig.1.

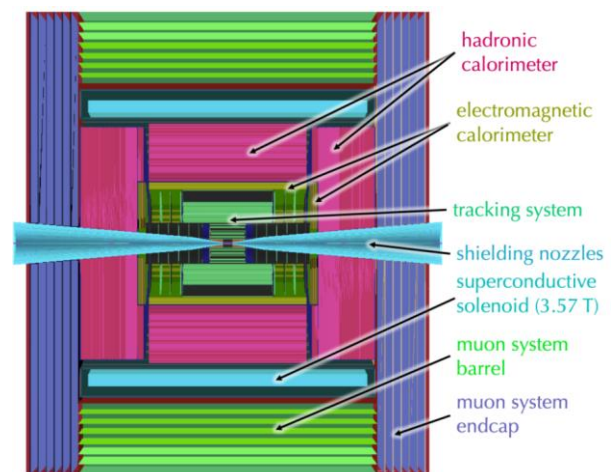


Fig. 1. Baseline detector design for a muon collider experiment [2].

The muon system is currently instrumented in the simulation with glass-RPC technology, however performed standalone simulations show that the hit rate expected in the endcap regions closest to the beamline are at the limit of the current performance reachable by such a detector (Fig. 2) [3].

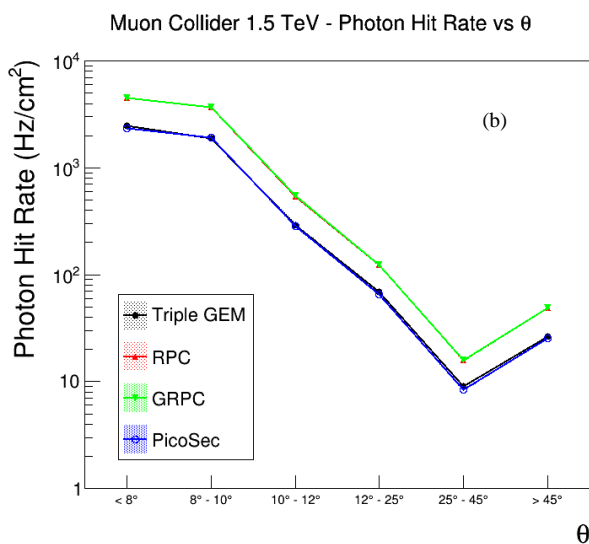
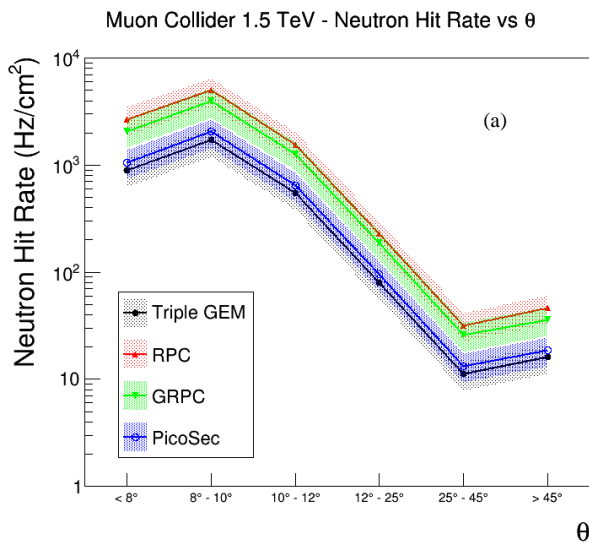


Fig. 2. Neutron (a) and photon (b) expected hit rate in the different regions of the muon system endcap [3].

For this reason, we are proposing an alternative design of the muon system fully based on Micropattern Gaseous Detectors (MPGD).

III. ALTERNATIVE MUON SYSTEM DESIGN

To reduce the combinatorial background due to BIB, a proposal is to implement an out-to-in muon reconstruction approach. Muons are initially identified as segment in the muon system and then matched with hits in the tracker system for the reconstruction of the full muon track. Fig. 3 outlines this process: it requires a muon system characterized by an excellent space and time resolution. The segment reconstruction could be performed with a multilayer tracking system based on MPGDs, such as Triple-GEM, which can assure a $\sim 100 \mu\text{m}$ space resolution. The timing instead must be comparable with the one in the inner tracking system, thus reaching $\sim 100 \text{ ps}$. A dedicated timing layer is thus needed.

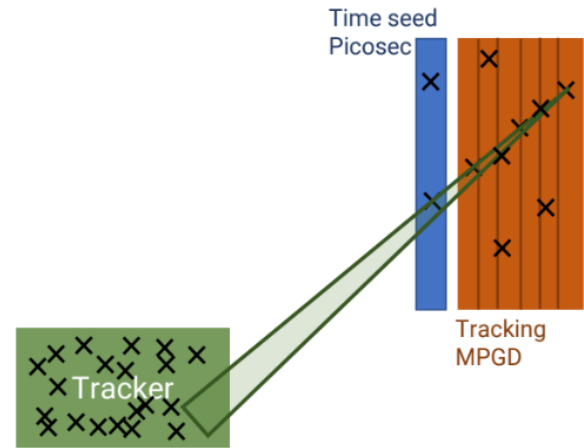


Fig. 3. Out-to-in muon reconstruction approach.

Classical MPGDs, such as Triple-GEM, cannot reach such a high time resolution due to fluctuations on the position of the first ionization cluster in the drift gap. The drift gap of a classical MPGD is indeed usually 3-5 mm-thick: the large uncertainty on the position of the first ionization cluster translate in a large fluctuation of the time of arrival of the electrons to the amplification layer and therefore in a large fluctuation of the time of arrival of the signal. Due to this effect, the time resolution of classical MPGDs is usually limited to 4-5 ns. To address this issue, the PicoSec Micromegas collaboration [4] developed the detector shown in Fig. 4. The PicoSec detector [5] is composed by a Cherenkov radiator (MgF_2), followed by a proper photocathode and a micromegas with reduced-thickness drift gap ($\sim 100 \mu\text{m}$ instead of few mm). When the particle passes through the radiator, Cherenkov photons are emitted and then converted into electrons by the photocathode.

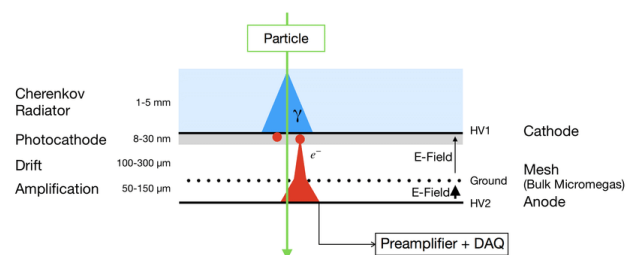


Fig. 4. PicoSec micromegas detector [5].

The electrons then enter the micromegas and are amplified, generating the visible signal. The advantage is that all the electrons are produced in the same position, at the level of the photocathode, thus zeroing the fluctuations. The time resolution reachable with this configuration is of the order of $\sim 20 \text{ ps}$ [5].

IV. DEDICATED R&D ON PICOSEC DETECTOR

In order to use such a technology in the context of a muon collider experiment, few dedicated R&Ds are needed, which are summarized in Fig. 5. The current baseline for the Cherenkov

radiator is MgF_2 , which has a high UV transparency, but is fragile, costly and can be produced with a maximum size of the order of $\sim 100 \text{ cm}^2$. The main alternatives considered are quartz and sapphire, which up to now could not return the desired performance. Indeed, for example quartz used in combination with CsI as photocathode has a measured number of photoelectrons/MIP ~ 2 , seven times lower than MgF_2 with CsI, which turns out in a measured time resolution of a least a factor four lower.

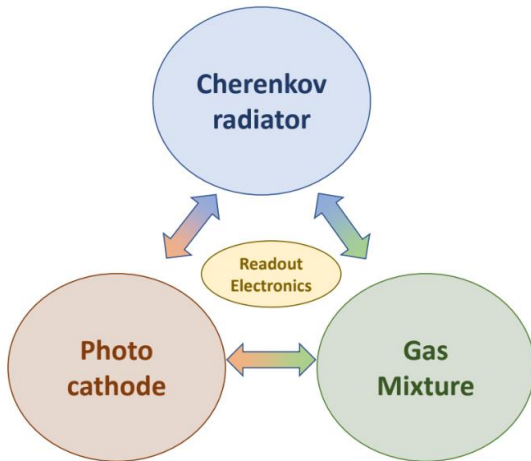


Fig. 5. Outline of the R&D activities on Picosec micromegas detector.

Moving to the photocathode, the current baseline is CsI, which has a high quantum efficiency to UV ($\sim 10 \text{ p.e./MIP}$) and is easy to coat by Chemical Vapour Deposition. However, it's hygroscopic, which forces a sealed operation with dry gas, and can be easily damaged by ion bombardment. Alternatives considered includes metallic (Al, Cr, Au) and carbon-based photocathodes (DLC, B4C). This last category is being currently investigated, but it seems to be still limited by the number of p.e./MIP produced, which is at least a factor 3 lower than for the baseline configuration.

The most interesting results so far have been obtained by the search of alternative gas mixtures. The baseline, $\text{Ne}/\text{C}_2\text{H}_6/\text{CF}_4$ (80/10/10), is costly, flammable, and most importantly has a very high Global Warming Potential (see Table I).

Gas Mixture	100-year Global Warming Potential (normalized to CO ₂)
$\text{Ne}/\text{C}_2\text{H}_6/\text{CF}_4$ (80/10/10)	740
$\text{Ne}/\text{iC}_4\text{H}_{10}$ (94/6)	0.2
Ar/CO_2 (93/7)	0.07
$\text{Ar}/\text{CO}_2/\text{iC}_4\text{H}_{10}$ (93/5/2)	0.11

As alternative, Ar-based and Ne-based gas mixtures are being tested, as listed in Table I. Ar-based gas mixtures turned out to have a too small operation range: it is therefore extremely difficult to find and operational configuration in which the detector is stable and the signal is visible. On the other hand,

interesting results were obtained with $\text{Ne}/\text{iC}_4\text{H}_{10}$: Fig. 6 compares the time resolution measured with the baseline mixture (a) and with $\text{Ne}/\text{iC}_4\text{H}_{10}$ (b). The RMS of the two plots show that the time resolution is of the same order of magnitude between the two and it's around the value expected in a configuration with 6 nm B4C photocathode (which has only 3 p.e./MIP and therefore gives a lower time resolution than CsI).

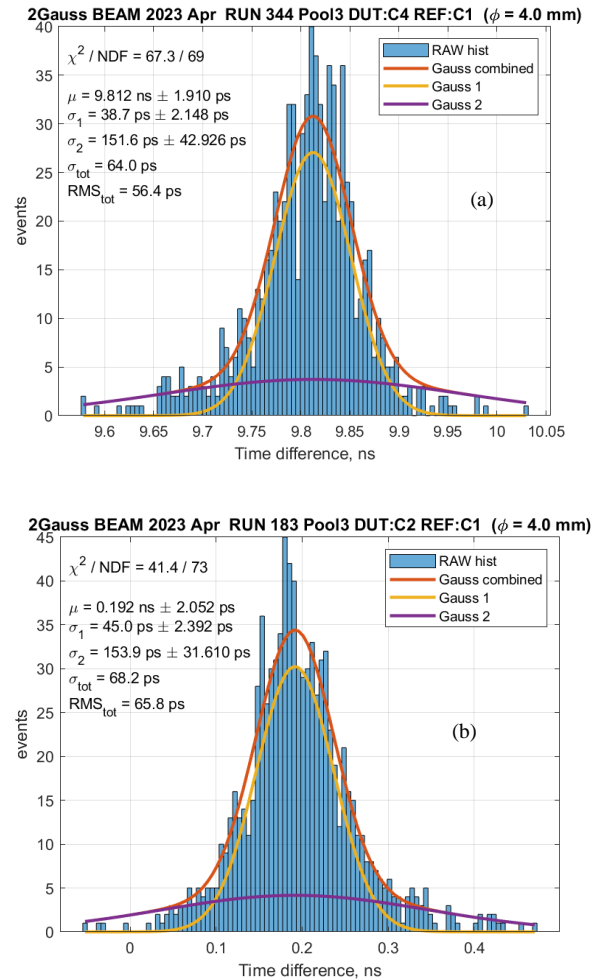


Fig. 6. Time resolution with (a) $\text{Ne}/\text{C}_2\text{H}_6/\text{CF}_4$, (b) $\text{Ne}/\text{iC}_4\text{H}_{10}$

This preliminary result is only the first of a systematic study that is being performed on this item and that will continue in the next few years.

Finally, it is worth to mention that other two elements must but developed to prepare Picosec for the installation on a large-scale experiment at the muon collider. On one side, dedicated integrated electronics able to sustain such a high time resolution must be developed. On the other side, a careful design of the mechanics of the detector must be carried out: indeed, so far, the largest prototypes reach a surface of $10 \times 10 \text{ cm}^2$. Increase the dimension of a single Picosec detector could turn out in a reduced time resolution, due to the difficulty in maintaining a flat geometry in the micromegas and in the production of a proper radiator. A possibility could be to couple several $10 \times 10 \text{ cm}^2$ detectors to cover large areas: a dedicated R&D is needed and will start in the next few months.

V. CONCLUSIONS

The muon collider is an interesting opportunity for the future of high energy physics. It poses however challenging operational conditions, mainly related to the presence of BIB. The design of a proper experiment is ongoing: MPGDs are being considered as candidate detectors for the muon system. Picosec is a candidate technology for a timing layer in the muon system: a dedicated R&D is ongoing, mainly focused on optimization of the Cherenkov radiator, photocathode and gas mixture. Future R&D activities will have to focus on the readout electronics, as well as on the mechanics needed for the instrumentation of large surfaces.

ACKNOWLEDGMENT

We warmly thank the RD51 Picosec-Micromegas Collaboration for the precious support and help.

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