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MCORD — MPD COSMIC RAY DETECTOR FOR NICA

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Детектор космических лучей MCORD для NICA

Многоцелевой детектор (MPD) входит в состав комплекса NICA, расположенного в Дубне (Россия). Для полной функциональности детектору нужна дополнительная система пуска для калибровки MPD-подсистем в отсутствие пучка и отклонения частиц космических лучей (главным образом мюонов). Эта система может быть также полезна для астрофизических наблюдений космических ливней, инициируемых первичными частицами высоких энергий. Консорциум NICA-PL, состоящий из нескольких польских научных учреждений, был сформирован для определения целей и основных предположений для детектора космических лучей MPD (MCORD). В статье описана ранняя стадия проектирования детектора MCORD на основе пластиковых сцинтилляторов с кремниевыми фотоумножителями для сцинтилляционного считывания и электронной системы на основе MicroTCA-ящика. Также представлены планы по моделированию работы детектора MCORD.

MCORD — MPD Cosmic Ray Detector for NICA

The Multi-Purpose Detector (MPD) is a part of the Nuclotron-based Ion Collider fAcility (NICA) located in Dubna, Russia. For full functionality, the MPD needs an additional trigger system for off-beam calibration of MPD subdetectors and for rejection of cosmic ray particles (mainly muons). The system could also be useful for astrophysics observations of cosmic showers initiated by high energy primary particles. The consortium NICA-PL composed of several Polish scientific institutions has been formed to define goals and basic assumptions for MPD Cosmic Ray Detector (MCORD). This article describes the early stage design of the MCORD detector based on plastic scintillators with silicon photomultiplier photodetectors for scintillation readout and of the electronic system based on MicroTCA crate. Plans for simulations of MCORD detector performance are also presented.

1. INTRODUCTION

A new accelerator complex was designed at the Joint Institute for Nuclear Research in Dubna to study properties of dense baryonic matter (see Fig. 1). One of the main parts of the Nuclotron-based Ion Collider fAcility (NICA) [1] is the Multi-Purpose Detector (MPD) [2]. The MPD was designed to track products emitted during ion–ion collisions that will take place in one of the two crossing points of beams accelerated in opposite directions. The MPD is placed in a dedicated experimental hall and its operation is maintained by a Slow Control System [3–5] installed in racks located on a platform placed by the MPD (see Fig. 2).

The role of the MPD is to provide information necessary for reconstructing each event. However, cosmic muons are one of the sources of background in high energy physics instrumentation as they generate similar or even identical signals to charged particles produced during collisions or during decays of neutral products. Therefore, the MPD needs an additional triggering system that could be used to discriminate signals induced by cosmic showers (mainly muons). Such a system
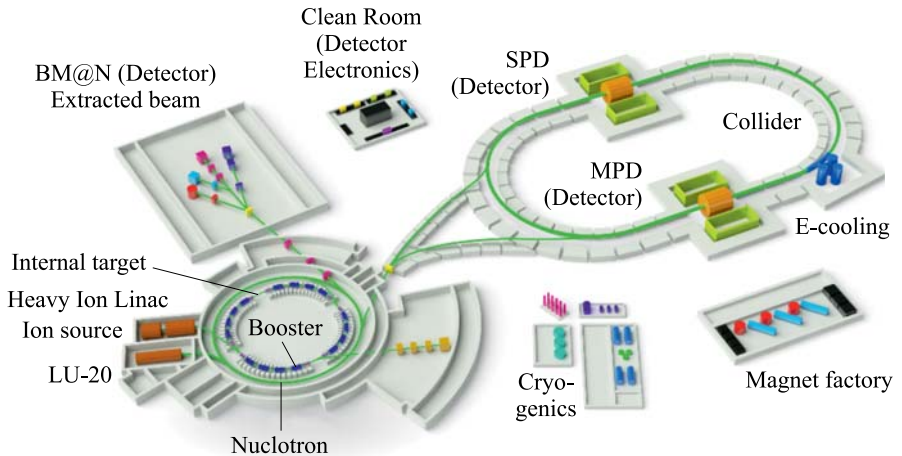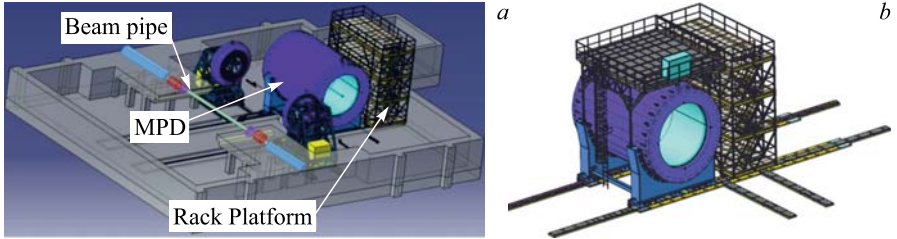

Fig. 1. The NICA complex [1]

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Fig. 2. *a*) Room for the MPD; *b*) MPD detectors and Platform for MPD electronic racks [2, 1]

could also be used for off-beam calibration of the MPD response to muons and to provide data for astrophysics measurements of high energy muon showers. In order to enrich the MPD with these features, we propose to surround it with a cosmic-ray detector called MCORD.

A similar system was constructed at CERN for the ALICE detector (ACORDE [6]). The main difference is that ALICE is located deep underground, whereas the MPD is located at ground level. The specific location of ALICE and ACORDE forms a natural barrier that filters low energy muons and most of the other charged particles and gamma rays. Moreover, detected muons come only from the zenith direction. The MPD with MCORD will be located at ground level; therefore, it will detect muons coming from all directions between zenith and horizon, filtered to some extent only by concrete walls of the experimental hall.

MCORD should be able to provide information on the time, position, direction and amplitude of signal induced by particles passing through. Based on these data, calibration of TPC detectors and TOF detectors should be possible. MCORD signals should also serve as a veto trigger for a cosmic shower to avoid misinterpretation of events from ion–ion collisions. Since MCORD will cover a substantial fraction of the MPD volume, it could also be very useful for observation of cosmic showers initiated by extremely high energy primary particles coming from horizon direction.

The MCORD detector will be designed and constructed by a Polish consortium NICA-PL established by a few scientific institutions. Within the course of the project, there will be several workpackages devoted to the MCORD detector design and construction. Besides experimental work, the choice of optimal detectors will be supported by simulations performed using MCNPX, GEANT4, CORSIKA, and Showersim.

Preliminary discussions between partners involved in the project point to plastic scintillators with light readout as most suitable candidates for a detector module. In the initial stage of the project, experiments and simulations will be done to choose the optimum shape of scintillators, the configuration of pho-

todetectors and readout electronics. Based on the output of this study, MCORD shape and size will be proposed taking into account requirements from the MPD users, the performance of the MCORD system and production cost of the device. In the second phase of the project, several detector modules will be provided for calibration and testing the TOF and TPC detectors. The final stage of the project involves the construction of the full-size MCORD detector around the MPD surface.

2. SYSTEM DESCRIPTION

The MPD is a large-size device 8 m in length and 6 m in diameter. Therefore, the MCORD detector needs to be designed using relatively cheap and efficient materials. The most common material for muon detection is plastic scintillator. Since the MPD detector comprises a large magnet around which the MCORD detector should be installed, we propose to use photodetectors insensitive to the magnetic field. Such a feature is offered by semiconductor detectors like silicon photomultipliers (SiPMs), also known as multi-pixel photon counters (MPPCs).

The main features of the MCORD detector should be 2D positional sensitivity, precise timing information and cost-effectiveness (low price per unit module). However, fulfilling these requirements pose contradictory constraints on the detector design. Therefore, not only the optimization but also some trade-off on the detector's performance is necessary.

Concerning the detector cost, plastic scintillators are one of the best candidates for MCORD detection medium as they are one of the cheapest charged particles sensitive materials [7, 8]. They are relatively bright, provide fast scintillation pulses and can be produced in large sizes. To ensure 2D positional sensitivity, we propose to use long, narrow slabs of plastic scintillators with double-sided light readout using SiPM photodetectors. The time difference in light propagation through the plastic scintillator will be used to define the particle interaction point along the detector module, whereas the width and thickness of the slab will give limits on the muon track point in the plane perpendicular to the long detector axis.

During development of the large-scale systems like MCORD, simulations of the muon interactions with scintillators, building walls, and detector elements play an important role in the estimation of the system performance and cost reduction. For that purpose, several parameters need to be calculated utilizing simulations:

• energy distribution of cosmic muons as a function of emission angle,

• the composition of the cosmic particles as a function of emission angle,

• simulation of the muons deposition energy through walls and MPD detector yoke,

• particle tracking, muon time-of-flight (TOF) distribution for various geometries of the detectors.

For simulation of the energy deposition, optimization of the systems geometry tracking and TOF characteristics, MCNPX (Monte Carlo N-Particle Transport Code System for Multiparticle and High Energy Applications) [9] and GEANT4 (toolet for the simulation of the passage of particles through matter) [10] codes are good solutions. The former has been developed since the 1960s, and the latter was initially released in 1998; thus, both codes are mature and well tested in a wide range of applications for radiation detection. Energy distribution and composition of the cosmic radiation will be calculated using specialized simulation codes such as CORSICA.

An exemplary particle tracking using MCNPX code for a single plastic scintillator is shown in Fig. 3. The muons of energy 1 GeV are passing through 1 meter of concrete, then depose energy in the plastic scintillator and traveling through another layer of concrete. Such a geometry will be further extended with more complex geometry, including the MPD detector.
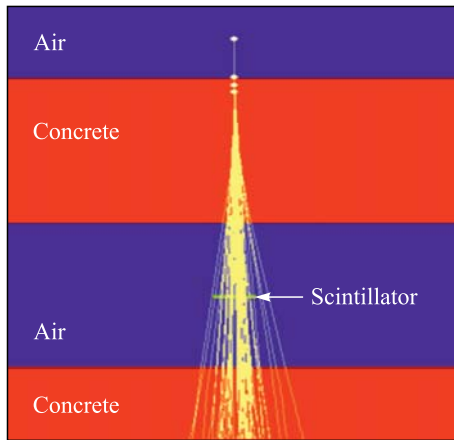

Fig. 3. Exemplary muon tracking (blue volume — air, red — concrete, green — scintillator)
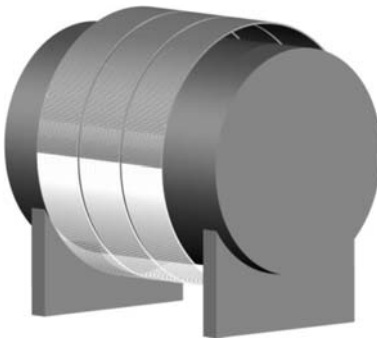

Fig. 4. Conceptual design of the MCORD detector surrounding the MPD detector at the NICA complex
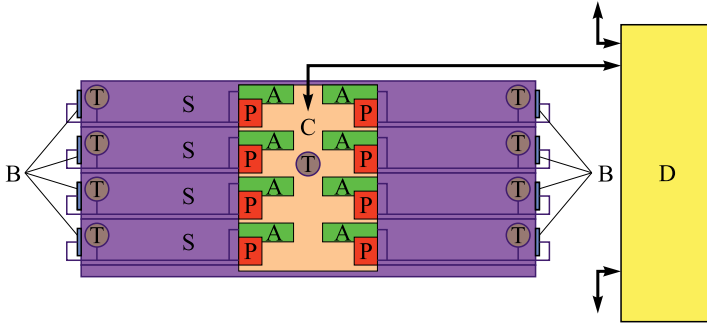
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Fig. 5. Conceptual design of the MCORD detector readout chain: S (violet) — plastic scintillator, B (blue) — SiPM, P (red) — power supply with temperature compensation circuit, T (brown) — temperature sensor, A (green) — amplifier, D (yellow) — MicroTCA system with ADC boards, C (orange) — Analog Front End Module

Detector modules will be arranged in a barrel shape around the central part of the MPD detector. Depending on the granularity of the MCORD detector, it will comprise a few hundred up to a few thousand double-side readout detectors, as presented in Fig. 4. The schematic of the signal readout path is presented in Fig. 5.

When a muon hits a scintillator it starts to emit light. A SiPM illuminated by that light generates an electrical output proportional to the number of detected photons. SiPMs are characterized by a high gain (10^5–10^6), single photon detection capability, fast counting and low-bias voltage ($\sim$ 30–70 V) [11]. Insensitivity to the magnetic field is one of the greatest advantages of SiPMs over classical PMTs. However, there are also disadvantages, like SiPM gain sensitivity to temperature changes, and this requires the application of temperature compensation circuits coupled with power supplies. The analog output signal from a SiPM is amplified and shaped by an amplifier in an Analog Front End Module and subsequently is sent to a MicroTCA System (MicroTCA® is a modular, open standard for building high performance switched fabric computer systems in a small form factor) [12]. One MicroTCA System receives signals from many Analog Front End Modules. A relevant controller will be designed to maintain operation of the detector power supplies, temperature compensation circuits, amplifiers, and digitizers.

3. READOUT ELECTRONICS

Each SiPM detector is directly connected to the Analog Front-End Module (AFEM). This module consists of a very simple amplifier and a shaper. The shaper is dedicated to pulse forming. Pulses after this module have reduced bandwidth and thus increased duration. The bandwidth limitation reduces hardware requirements for readout equipment and minimizes RF interferences. AFEM
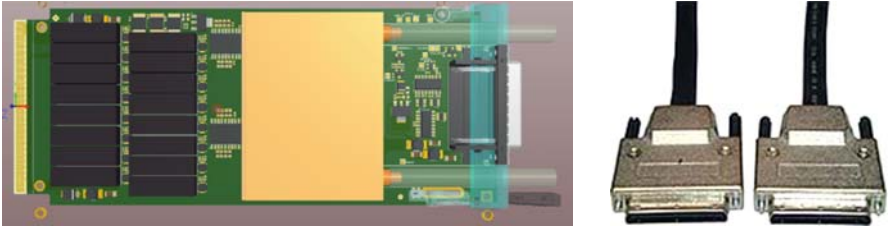
Fig. 6. Example of Analog Front-End Module and VHDCI connector for LVDS signals

is located close to the detector. Because of this, all AFEM hardware must be radiation hard. Moreover, AFEM consists of a power supply for SiMP detectors and a sensor temperature compensation circuit. Analog signals are transmitted to the ADC located on the FMC boards located in the MTCA processing system. Signals are transmitted via standard VHDCI connectors and 24- or 32-channel cable. Each channel consists of a pair of wires, and signals are transmitted using differential signaling. An example of AFE module and VHDCI connectors are shown in Fig. 6.

The signal processing system is based on Micro TCA.4 standard. This is a modular system for acquisition, control, management and data processing. Version 4 of this standard was developed and standardized by DESY. The main advantage of this standard is the high-speed backplane — up to 40 Gbit/s based on gigabit links. The chassis integrates embedded computer, management controller, PCIe Gen 3 and Ethernet hub. The standard implements control of parameters like supply and temperatures using IPMI standard. These features make it feasible for data acquisition and processing application in HEP experiments. An architecture of MicroTCA.4 standard is shown in Fig. 7.

The TCA standard allows one to install up to 12 cards in AMC (Advanced Mezzanine Card) standard. For MCORD, industry standard AMC-FMC carriers will be used. FMC (FPGA Mezzanine Card) is an ANSI standard that provides a standard mezzanine card form factor, connectors, and modular interface to an FPGA located on a baseboard.

The architecture shown in Fig. 7 has many advantages. The basic elements of the system are highlighted in blue. In addition to the FMC and AMC-FMC modules, there is MCH (MTCA Carrier Hub) and optional Computing Module. The MCH has gigabit ports that enable connection of multiple cassettes into one system. RTM and AFE modules can be optionally used for precise analog signal processing and will not be used in this experiment. Computing module is not foreseen for MCORD either.

The other modules are optional and can be used for future upgrades of the system. The T2 Clock Distribution module enables the use of the White Rabbit standard [13] to synchronize multiple AMCs and MTCAs with sub-ns
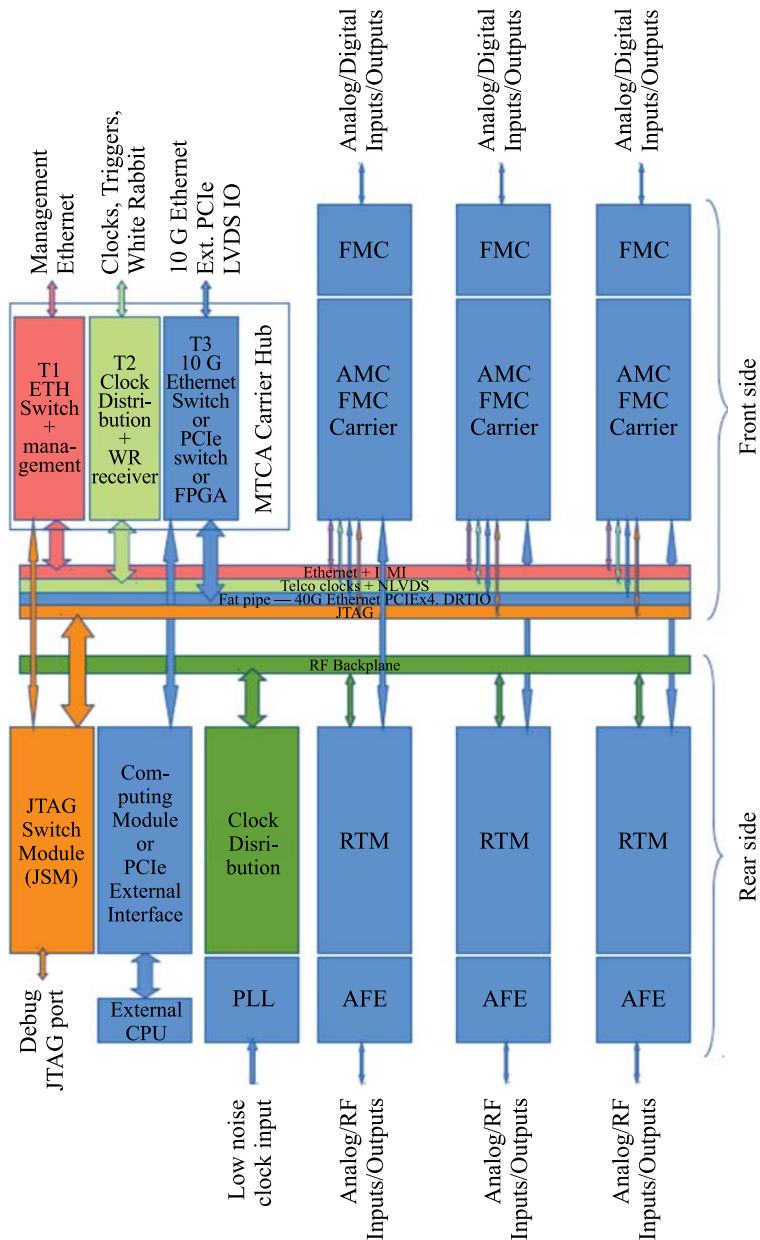
Fig. 7. Architecture of MicroTCA crate, ver. 4
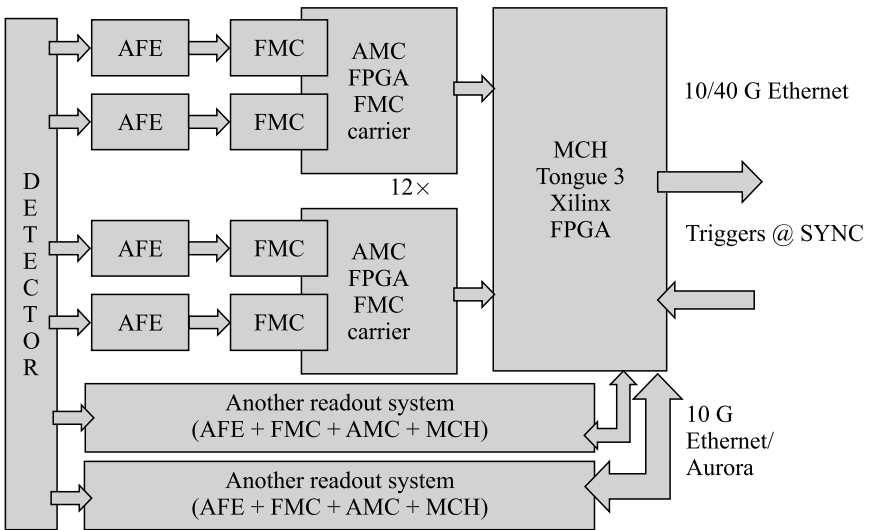
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Fig. 8. FMC ADC board

Fig. 9. System architecture based on the MicroTCA standard

accuracy. JTAG Switch Module allows remote debugging of FPGA devices. This is useful during development of the software, it enables remote access to the system installed in the tunnel or experimental area under radiation conditions. A complete system architecture is shown in Fig. 9.

The whole system will consist of up to three MicroTCA crates. Signals from the detector are processed locally by AFE modules and transmitted to the

FMC cards which provide AD conversion. There are two FMC cards on each AMC carrier board. Up to 12 AMC cards on each MicroTCA crate can be installed. The data after processing in the AMC FPGA are transferred using the MTCA backplane to the MCH module. MCH contains large Kintex FPGA which performs further processing. There are two trigger levels:

- First trigger level is implemented in the AMC FPGA.
- Second level trigger is implemented in the FPGA on the MCH module.

One of three MCH FPGAs serves also as a hub that receives data from other MTCA crates using the 10 Gbit serial link.

The number of input channels of the whole system depends on the bandwidth of ADCs. The idea is to reduce the ADC sampling speed to reduce the amount of data that needs processing. Several parameters of detector pulses are calculated using the algorithm implemented in the FPGA:

- time of flight,
- the time difference between channel pairs,
- energy.

Since the shape of the pulse is known in advance, on-line deconvolution algorithms can be utilized to calculate the parameters with accuracy much higher than sampling period.

There are a few options that depend on selection of FMC-ADC cards:

- 8 channels/14 bit @ 250 MS/s (highest performance),
- 16 channels/14 bit @ 125 MS/s (shown in Fig. 8),
- 24 channels/14 bit @ 80 MS/s,
- 32 channels/14 bit @ 50 MS/s (lowest cost).

The lowest cost option is 50 MS/s which provides 32 channels. This option reduces the number of MicroTCA crates required for MCORD. The highest performance option is 250 MS/s and offers the best quality of input signals processing. Depending on the required signal processing capability, the number of channels per one MicroTCA system is:

- at 250 MS/s: 192 channels/crate,
- at 125 MS/s: 384 channels/crate,
- at 80 MS/s: 576 channels/crate,
- at 50 MS/s: 768 channels/crate.

Series of tests with detector prototype are required to decide which option is suitable for the final MCORD readout system.

4. FPGA-BASED MUON TRIGGER

The muon trigger, implemented in the FPGA, will utilize signals produced by the photon detectors connected at both ends of the scintillator strips. The signals will be shaped and converted to the digital form using the ADC converters.

Depending on the required analog signal bandwidth, 14-bit resolution ADCs with 50–250 Ms/s will be used. The ADC converters type will be selected by using the appropriate FMC module.

The digitized signal will be processed in the FPGA to calculate the time and amplitude of signals at both ends. The position of the hit along the scintillator will be calculated from the time difference between those signals. Possibility to use the amplitude difference and constant fraction discriminator will also be investigated. If extremely high position measurement is needed, it should be possible to provide the additional high-speed digital channel with FPGA-based TDC.

The track and direction of the muon will be calculated in the FPGA based on coincident hits from different detector layers. The fast and low latency process of a muons trajectory identification will be based on the muon trajectory processor original concept for the Overlap Muon Track Finder [14, 15] in the CMS muon trigger system [16].

5. SUMMARY

This work is a part of the activities of the consortium NICA-PL. The paper has presented the concept of building a universal, reconfigurable, fast and modular electronic muon trigger system for the MPD detector. Detection part is based on low-cost plastic scintillators with silicon photomultiplier photodetectors for scintillation readout.

The MTCA standard, with the backplane version 4.0 designed specifically for the use in HEP experiments, will be employed for the construction of the device. The applied solution is based on commonly used apparatus used at CERN and GSI. It has been proposed to use exchangeable analog and digital modules, including primarily FMC blocks containing appropriately matched A/D converter circuits. The proposed hardware solution allows for easy modification of the system in terms of the required number of channels and, as a consequence, the required number of FMC/AMC modules and MTCA cassettes (including MCH).

The key issue is to use the FPGAs for fast, low-latency, numerically advanced signal processing from detectors in order to accurately determine the time and place of passage of the ionizing particle by a scintillator. The proposed approach will allow one to obtain high precision and quality measurement data, despite the assumed limit of analogue transmission bandwidth in order to minimize the level of interference, as well as the construction costs of a complete device. The use of layers of FPGAs placed on the AMC and MCH modules, respectively, enables the functional structuring of the muon trigger by separating the main stages of the process. The use of a fast, universal communication 10 Gbit network ensures low latency and high throughput, and also allows for the simple expansion of

the system by attaching subsequent cassettes to a common local communication network.

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