Development of a Solid-State Photomultiplier based Dual Readout Calorimeter module

Abstract

Unveiling the essence of the Universe is possibly the most exciting endeavour Science can pursue. Whether this is striven for by looking at the sky or exploring the heart of matter in the sub-atomic world, any experimental activity requires instruments and methods to be pushed beyond the state-of-the-art, Science and Technology to merge, Researchers and Engineers to join their efforts to turn bright ideas into reality on a never-ending journey of discoveries.

Elementary particle accelerating machines and giant detectors built around the interaction points of beams running at almost the speed of light represent an amazing example of this worldwide effort, where results achieved today trigger the long-term development of the next generation facilities. Whether the focus is currently on the Large Hadron Collider at CERN, the European Centre for Particle Physics in Geneva, Switzerland, future could be elsewhere. Among the projects being proposed, the Chinese Circular electron positron Collider (CepC) is one of the most appealing, reproducing at a fourfold scaled-up dimension the concept of the European based machines, starting with accelerated electron-positron beams. This is expected to probe at unprecedented precision the sub-atomic world, possibly detecting deviations from the robust Standard Model, disclosing the path to the next level of understanding conceivably including the nature of Dark Matter. Dark matter (DM) interactions with electrons, photons, and Z bosons could lead to direct production of DM particles with very clear signatures [1,2]. The reach by direct searches is obviously limited by the centre of mass energy but can be extended by high precision indirect searches via loop effects [3-5], up to masses at the TeV scale [3-8].

Extreme precision requires a leap also in detector technologies, designed to reconstruct with the highest accuracy and resolution the trajectories and the energy of the jets of particles springing off the colliding beams. Energy for electrically charged and neutral particles is reconstructed by calorimeters, where the incoming particle produces a shower of secondary particles by a cascade of interactions with the atomic system of the dense matter in the detector. Resolution in calorimetry is essentially a "fluctuation game", where the dominant term is related to the irreducible stochastic nature of the processes involved in the shower development. For showers initiated by hadrons (composite particles made from quarks, anti-quarks and gluons) the response is heavily affected by the event-by-event fluctuations in the electromagnetic (e.m.) component of the cascade, together with the undetected energy resulting by the break-up of nuclei.

It has been proven [9] that the e.m. fraction of the shower energy can be measured probing the Cherenkov light produced by particles in the shower exceeding the speed of light in the medium, together with scintillation light associated to every interacting particle. A series of prototypes experimentally validated the concept [9-18] and a breakthrough was achieved in 2016, when a small module based on fibres embedded in a copper converter and read-out by a matrix of Silicon Photomultipliers was commissioned and qualified on a beam test at CERN.

The main goal of the project is to capitalize on the existing know-how in detector, sensor, electronics and system development to develop a scalable design of a Dual Readout Calorimeter module for an experiment at the future CepC accelerating machine.

Scope

The main goal of the project is the development of a scalable Dual Readout Calorimeter (DRC) module for an experiment at the future CepC accelerating machine.

The DRC concept has been extensively proven and experimentally validated in a series of beam tests [9-18]. However, the use of standard Photo-Multiplier Tubes (PMT) to read out the Cherenkov and scintillation light has so far limited its development towards a full-scale system compliant with the integration in a particle detector at a colliding beam machine. Moreover, the need to bundle fibres routed to a single PMT has constrained the effective transverse granularity of the system, hampering the use of this technique in the Particle Flow approach to event reconstruction (see for instance [19] for its implementation in the CMS experiment).

These limitations can be overcome using Silicon Photo-Multipliers (SiPM), low-cost solid state sensors of light with single photon sensitivity, photon number resolving capability, magnetic field compliance and design flexibility due to the advances in Silicon technology. SiPM underwent a tremendous development since their invention, about 20 years ago; as of today, it is fair to say that off-the-shelf sensors achieved a full maturity and the focus of industry and research laboratories is on new materials and customized design in terms of spectral response, time resolution and notably dynamic range, a relevant issue for the application envisaged here. Concerning devices built on materials other than Silicon, a relevant advantage in the detection of the Cherenkov light may result using Silicon Carbide (SiC), essentially because of its solar light blindness and UV sensitivity. The evaluation of this new class of sensors will be pursued capitalizing on the activity performed within the INFN projects CALOCUBE [20] and CLASSIC [21], targeting the development of small area Avalanche Photo Diodes.

The full containment of a hadronic shower, essential to assess the ultimate calorimetric performance, requires an instrumented volume of high-density material. Presuming the converter to be copper (density ρ = 8.96 g/cm^3, interaction length λ_{int}= 151 mm) and the volume safely estimated to correspond to 10x3x3 $(\lambda_{int})^3$, its dimensions correspond to a cross section of $\approx$ 50x50 cm^2, a length of 150cm and a weight of about 2800 kg. However, the “essential volume” can be imagined to be assembled from “building blocks” of 10x10x150 cm^3 volume. Provided the time development and the financial envelope of the call, the activity will focus on the design, production, qualification and engineering of the “building block”, in terms of design features, sensor characteristics, front-end, mechanical issues, scalability and integration, as detailed in the following.

Methodology

The “building block” is a stack of copper conversion layers, housing in grooves either a scintillating or a clear fibre. As of today, layers are 1.5 mm thick and the pitch between the fibres is 1.5 mm, for a 4.5% sampling fraction. Every fibre is routed to a single SiPM and individually read-out with a custom designed circuit based on discrete components. In addition, a sub-sample of the clear fibres will be sensed by SiC detectors to address the feasibility of deep UV Cherenkov detection.
Whether this is fair for a proof-of-concept, it clearly cannot be considered neither optimal nor scalable. Optimization, scalability and qualification are targeted in the following work plan, based on 4 work packages:

1. ***Simulation***. Numerical modelling is essential for steering the design, verifying the robustness against performance degradation and the compliance with the integration in the apparatus. Moreover, it is essential to assess the physics reach of the proposed experiment. Specific issues addressed here concern:
    a. In terms of design features (year 1):
        i. the performance variation as the sampling fraction (namely the fiber pitch) is changed
        ii. the effect of reducing the effective transverse granularity summing up electrically the response of a set of sensors, mapped to a single output electronics channel
    b. in terms of sensors (year 1):
        i. the required dynamic range, steering the development of dedicated SiPM in case what is required exceeds the available cell density (≈10000 cells/mm^2)
        ii. a study of the trade-off between sensitivity, linearity and dynamic range, connected to the operational voltage of the SiPM
        iii. optimization of the SiC device design in terms of active layer thickness, front electrode geometry and optical couplings
        iv. a study of the trade-off between sensitivity, linearity and dynamic range, connected to the operational voltage of the SiC
    c. in terms of system integration, the implementation of a Dual Readout Calorimeter in the full simulation of an experimental apparatus at the CepC collider (year 1-3)
    d. the effect on performance of a pre-shower radiator and sampler in front of the calorimeter
    e. in terms of performance (year 1-3):
        i. the qualification of the proposed system through a set of benchmark reactions
        ii. the comparison against an imaging calorimeter
    f. Physics reach on Dark Matter Searches:
        i. Direct Searches: analysis of the Higgs invisible decay via recoil mass method (ZH->qq(Z)+Missing Energy(Higgs))
        ii. Indirect Searches: high precision measurements of the ElectroWeak sector

2. *Sensors, electrical and electronics design, data acquisition (DAQ) (year 1-2)*. The key issues to be addressed can be specified as follows:
    a. On sensors, the major point is certainly the cell density, impacting on linearity of the response and dynamic range. Single detector adjustment of the bias voltage shall be envisaged, together with a temperature dependent feedback for gain stabilization.
    b. As far as circuit design, the major question is the optimal circuit for summing signals from a plurality of sensors into a single output channel
    c. Concerning the front-end, the development shall certainly evaluate the use of Application Specific Integrated Circuits (ASIC). As of today, a variety of ASIC have been designed by industry and researchers. This task shall analyze, compare and qualify available ASIC with the goal of
        i. select the optimal one
        ii. OR define the specifications for a dedicated design to be pursued at later stage, progressing on the "building block" development adopting the best possible ASIC on the market
    d. The essence of the DAQ will be the transmission of the zero-suppressed digitized signals to the equipment computer. Signals correspond to either the peak or the integral of a single electronics channel response, digitized on or off chip. Timing and trigger logic will be implemented on FPGA.

3. *Mechanics (year 1-3)*. A variety of techniques (extrusion, rolling, scraping and milling) for machining the converter layers have been tested, essentially by John Hauptman and collaborators at Iowa State University and by Fabrizio Scuri at INFN-Pisa. None has been qualified for a large-scale production and identifying an industrial and cost-effective process, including moulding, is a relevant issue.

4. *System integration & qualification (year 1-3)*. The work package is based on two major steps:
    a. Construction and qualification of a single ASIC based module (64 channels) by the mid-term (1.5 years)
    b. Construction and qualification of a 10x10x150 cm^3 module based on a plurality of ASIC, in a number depending on the channels/ASIC and the number of SiPM(SiC)/electronics channel (year 3).

    Quality control and single channel equalization will be performed in the laboratories of the collaborating institutions. The final assessment will be based on beam tests at CERN or in other major laboratories.

Human and financial resources

The Italian team is composed as follows:

- Massimo Caccia, professor at Università degli Studi dell'Insubria, Como – I.N.F.N. Milano. Principal Investigator
- Roberto Ferrari, Research Director, I.N.F.N. Pavia
- Franco Bedeschi, Research Director, I.N.F.N. Pisa
- Chiara Roda, professor at Università degli Studi di Pisa - I.N.F.N. Pisa

- Sebastiano Albergo, professor at Università degli Studi di Catania - I.N.F.N. Catania
- Alessia Tricomi, professor at Università degli Studi di Catania - I.N.F.N. Catania
- Alessandro Cardini, First Class Research Officer at I.N.F.N. Cagliari
- Romualdo Santoro, Research Officer, at Università degli Studi dell'Insubria, Como – I.N.F.N. Milano
- Gabriella Gaudio, Research Officer, I.N.F.N. Pavia
- Piergiulio Lenzi, Research Officer, Università di Firenze - I.N.F.N. Firenze
- Antonella Sciuto, Research Officer, CNR-IMM HQ Catania - I.N.F.N. Catania
- Evelin Meoni, Research Officer at Università della Calabria, I.N.F.N. Cosenza
- Massimiliano Antonello, Ph.D. Student at Università degli Studi dell'Insubria, Como – I.N.F.N. Milano.

The core of the Chinese team is composed by the following scientists, where the main interest is also outlined:

- **Manqi RUAN**, Associate researcher of IHEP, convener of CEPC simulation group, **Principal Investigator** (reconstruction and Physics analysis)
- Honghao Zhang, Professor of ZhongShan University, theorist (Dark Matter search at CepC by precision Electro Weak measurements)
- Haijun Yang, Professor of Shanghai Jiaotong University, experimentalist & convener of CEPC Calorimeter Group (optimization of the calorimeter)
- Chengdong FU, Associate researcher of IHEP, Geant4 expert (detector simulation)

The required **financial contribution** amounts to 80 kEUR/year by each of the two parties. This is considered adequate to complete the envisaged scientific program and it complies with the co-funding scheme, accounting both available resources and costs of the staff personnel.

Expected results

The main project result is the development and qualification of a scalable cost-effective technology for the construction of a Dual Readout Calorimeter (DRC) compliant with the integration in an experimental apparatus at a colliding beam machine. Intermediate milestones are:

- The qualification of the existing front-end Application Specific Integrated Circuit ⇒ definition of the specifications for the optimal ASIC
- The qualification of the existing Silicon Photomultipliers, especially in terms of dynamic range ⇒ definition of the specifications for the optimal SiPM
- The development and qualification of SiC sensors
- The identification of an industrial procedure to produce the converter layers.

The beam test results are expected to provide an input for the final assessment of the performance, required to correspond to an energy resolution at the $15\%/\sqrt{E}$ level for e.m. showers and $50\%/\sqrt{E}$ for hadronic showers, with a rejection factor between e.m. and hadronic showers at the level of 500.

Finally, simulation is expected to:

- Assess the compliance of a high transverse granularity DRC with a particle flow event reconstruction procedure

- Evaluate advantages related to a pre-shower detector
- Compare a DRC to a high granularity imaging calorimeter
- Measure the sensitivity to direct and indirect Dark Matter searches.

External collaborations

Dual Readout calorimetry has been so far developed within the framework of the CERN RD52 collaboration, driven by prof. Richard Wigmans at the Texas Institute of Technology. By the time of writing, the following set of institutions confirmed the will to join the activity outlined here:

- Texas Tech University, U.S.A. – prof. Richard Wigmans
- Iowa State University, U.S.A. – prof. John Hauptman
- Kyungpook National University, South Korea – prof. Sehwook Lee
- University College at London, U.K. – dr. Michele Cascella, Senior Research Associate
- University of Sussex, U.K. – dr. Iacopo Vivarelli, reader

Industrial collaboration is essential to this project. The readout of the SiPM based demonstrator has been developed in partnership with Nuclear Instruments (http://www.nuclearinstruments.eu), an Italian start-up company with a focus on custom electronics for scientific instruments; Nuclear Instruments has been proven to be a reliable partner and it is willing to continue.

Whether instrumental for the project accomplishment and in compliance with the market rules, the consortium intends to establish collaborations with high-tech companies in the domain of mechanics and sensors.

As far as the latter, detectors have been so far provided by HAMAMATSU Photonics, a leading company in low-light detection. Considered the small business related to this project, customization would not be very likely and appealing for HAMAMATSU but it could be of interest to L-Foundry, a Silicon plant located in Italy and majority owned by SMIC (Semiconductor Manufacturing International Corporation), a Chinese major player on the semiconductor market. L-Foundry and Fondazione Bruno Kessler, located in Trento, have a joint project on the development of SiPM for industrial applications and research. Whether contacts with L-Foundry fail, other producers will be addressed, notably Sensl (based in Ireland) and KETEK (located in Germany), former partners and collaborators of the P.I.

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