Q-Wall, a Novel Quartz-Cherenkov Calorimeter Concept

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Abstract. Future collider experiments and the upgrade of the existing large-scale experiments impose unprecedented radiation conditions for the calorimeter systems, particularly in the forward region. The calorimeters envisaged for these operating conditions must be sufficiently radiation-hard and robust in order to perform as expected for the entire lifetime of the experiments. In this context, a novel calorimeter design utilizing quartz-Cherenkov calorimetry, termed Q-Wall has been developed. The Q-Wall concept is a sampling calorimeter that alternates between plates of absorber (Fe, Pb, W, etc.) and active planes. The active planes comprise compact arrays of PMTs with either very thick quartz windows or fused silica pads optically coupled to traditional PMT windows. In these active elements, charged particles with $\beta > 0.685$ produce Cherenkov radiation which impinges directly onto the photocathode of the PMT. The Q-Wall concept holds the promise of a very fast and highly granular tracking calorimeter suitable for high radiation environments.
A prototype module of Q-Wall was constructed and tested at CERN test beam. The prototype consisted of three photodetector setups: multianode PMTs directly coupled to ultraviolet-transmitting (UVT) plexiglass in a 2 x 2 and 3 x 3 configuration, an 8 x 8 array of SiPMs coupled to a 5 x 5 array of borosilicate glass cubes, and a 3 x 3 array of SiPMs connected to a 3 x 3 array of borosilicate glass cubes. Here we report on the results of these tests and compare them with electromagnetic shower development simulations with Geant4.

1 Introduction

Calorimetry in high energy physics is crucial for new discoveries via measurements, examples including the Higgs Boson. In future experiments, calorimeters must: a) work in very high radiation environments for many years; b) operate at high frequency and with sub-nanosecond time resolution; and c) be configurable in compact and dense units for high energy calorimetry (energy measurement).

In the very forward region of pp scattering at e.g. the LHC there is a high multiplicity of particles with a broad energy spectrum [**?**]. These particles are emitted at small angles relative to the circulating beams, leading to intense radiation exposure that might accumulate to several Grads over a decade [**?**]. For a detector to function optimally in these conditions, it requires radiation-hardness and precise positional (and temporal) measurement capabilities, while having high energy resolution.

Exemplifying this is the forward region ($|\eta| > 3$) in the CMS detector at the LHC [**?**]. Being near the LHC beam pipes, this area encounters space limitations and high radiation, complicating instrumentation. Historically, CMS has adopted Cherenkov calorimetry for its forward detectors, with three such calorimeters having utilized quartz Cherenkov radiators coupled to PMTs in the CMS forward region:

- The Hadronic Forward (HF) calorimeter, covering the $|\eta|$ range from 3 to 5,
- The CASTOR calorimeter, spanning $|\eta|$ 5.1 to 6.55,
- The Zero Degree Calorimeter (ZDC) extending the η-coverage beyond 8.1.

All these calorimeter systems are designed and built to survive several decades at the expense of energy resolu-

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tion and lateral and longitudinal segmentation. For these and future forward calorimeter systems, a high segmentation and radiation-resistant electromagnetic calorimeter section would offer several advantages such as:

- More effective pileup mitigation and better jet identification,
- Improved timing information,
- Enhanced measurement of the incident electromagnetic component of jets,
- Enhanced vertex reconstruction for the events in the forward region,
- Mitigation of the radiation damage on the downstream calorimeter system and
- Advanced muon tagging capabilities.

Detectors that utilize quartz Cherenkov radiators coupled to fast and radiation-hard photodetectors are exceptionally well-suited to meet the requirements from such an electromagnetic calorimeter system. Quartz, as a detector material, is extremely radiation-hard. Microchannel Plates (MCPs) and photomultiplier tubes (PMTs) are attractive options as photodetectors with their relatively high efficiencies, high gains and low transit time spreads. The simplest design would be quartz blocks coupled to multi-anode PMTs, the so-called Q-Wall. Here we describe the details and variants of the Q-Wall designs and report on the results of beam tests and compare them with electromagnetic shower development simulations with Geant4.

2 The Q-Wall Concept and the Prototypes

The design integrates radiation-resistant quartz tiles/blocks with equally resilient PMTs. As charged particles traverse the quartz array, they produce Cherenkov light, which is then captured and measured by the PMTs. Figure 1 shows a simulation image of a muon traversing five consecutive Q-Wall cells interspersed with 1 X_0 Fe absorbers. The inclined muon trajectory and the localization of the Cherenkov light demonstrates the tracking power of Q-Wall.

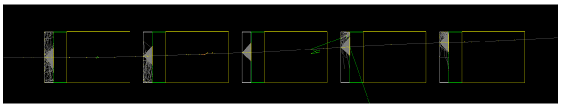

Figure 1. Simulation image of a muon traversing five consecutive Q-Wall cells interspersed with 1 X_0 Fe absorbers.

In order to validate the suitability of the Q-Wall concept for electromagnetic calorimetry, we constructed a Q-Wall module with ultraviolet transmitting plexiglass tiles and multi-anode PMTs. In addition, we constructed another Q-Wall module with matrices of Silicon Photomultipliers (SiPMs) coupled with small borosilicate glass cubes in order to explore the effect of high lateral segmentation although the SiPM readout version cannot be the baseline design for forward electromagnetic calorimetry. Figure 2 shows the pictures and sketches of the Q-Wall modules with PMT readout (top) and SiPM readout (bottom).

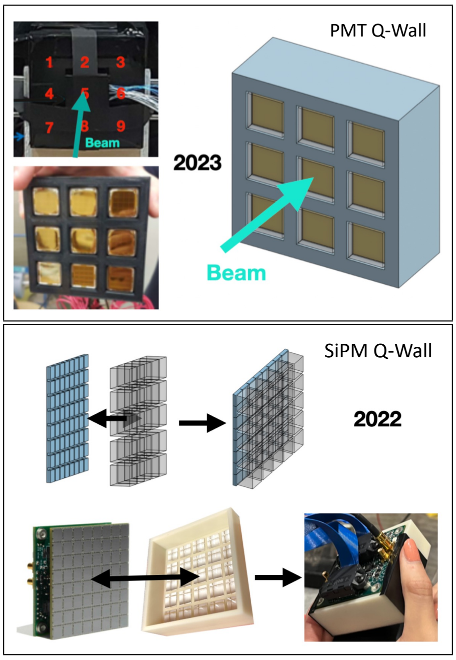

Figure 2. The pictures and sketches of the Q-Wall modules with PMT (top) and SiPM (bottom) readout.

3 Beam Tests

Both Q-Wall prototype modules were tested at CERN SPS beam line. The electromagnetic shower development was mimicked by the variable upstream absorber amount. Different PMTs were used in different test campaigns: Hamamatsu R7600 and R5900. The SiPMs in the SiPM Q-Wall module were Onsemi C Series 6 x 6 mm in an 8 x 8 array. Figure 3 shows a sketch and a picture of the beam test setup.

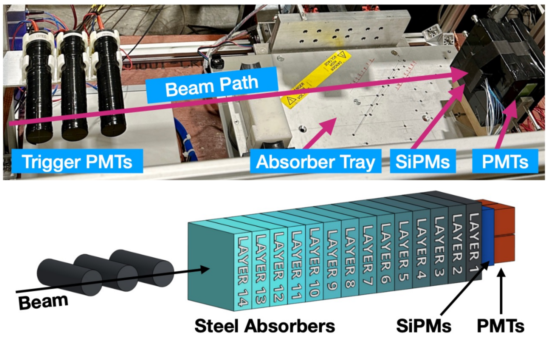

Figure 3. A sketch and a picture of the beam test setup.

Two test campaigns were conducted in 2022 and 2023. Below is a list of components of the test setup:

- Beam-Defining Telescope: Trigger creation and coincidence verification.
- XYϕ Motion Table: A remote controlled motion table allowed precise XY positioning and scanning across the detector surfaces and for placement of steel absorber plates.

- SiPMs Paired with Borosilicate Glass Cubes: 64 SiPMs (2022) or 9 SiPMs (2023) with 1 cm borosilicate glass cubes.
- PMTs Paired with Plexiglass Tiles: A collection of 4 PMTs (2022) or 9 PMTs (2023) with plexiglass tiles.
- A DAQ System: A VME ADC DAQ recorded signals from the PMTs, and a Vertilon IQSP582 was used with the SiPMs. A NIM crate was used to create and provide triggers to the VME and Vertilon DAQs. High voltage was provided by a LeCroy HV4032A to the PMTs. A Vertilon SIB464 SiPM interface board provided low voltage to the SiPMs.

For MIP (Minimum Ionizing Particle) calibration, 50 GeV/c electron beam was used with no upstream absorbers. Beam was centered on each PMT individually to measure the MIP signal. Figure 4 shows the MIP response of the four PMT channels where Ch1 and Ch2 are connected to R5900 PMTs and Ch3 and Ch4 are connected to R7600 PMTs. The MIP peaks are well defined and the interacting electron signal can be easily identified. The MIP peaks can be isolated and fit with gaussians to obtain the mean MIP response.

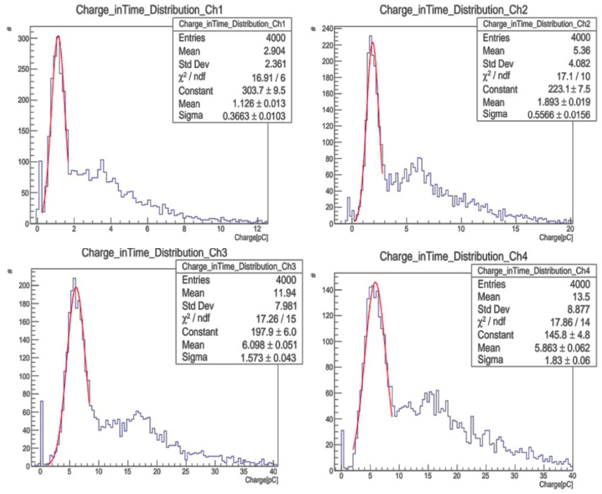

Figure 4. The MIP response of the four PMT channels (Ch1, Ch2 : R5900 ; Ch3,Ch4 : R7600).

Figure 5 shows the total charge distributions of the Q-Wall modules for various upstream absorber thicknesses with 50 GeV electron beam. The distributions show scaling with the shower depth and can be represented by gaussians relatively well.

Figure 6 shows the longitudinal shower development of 100 GeV electrons measured with the SiPM Q-Wall module with fine sampling. The profiles are normalized to the same value, therefore, the color represents the SiPM signal intensity. The electromagnetic shower maximum is observed at around 6 X_0. The SiPM Q-Wall setup enables detailed measurements of electromagnetic shower shapes.

Figure 7 shows the longitudinal shower shapes for the PMT Q-Wall (top) and SiPM Q-Wall (bottom) modules. The profiles scale with the energy and the shower maxima are at the expected depth. At this moment, an accurate matching of the simulations and the data is not possible, but it can be observed that the simulation results are along the line of the measurements. Full digitization of the simulated response is underway. The SiPM Q-Wall module results were obtained at different beam test campaigns: with 8 x 8 array in 2022 (Fig. 7 bottom left) and with 3 x 3 array in 2023 (Fig. 7 bottom right). Finer longitudinal granularity is better for longitudinal shower development sampling. Simulation work for these setups is underway.

Figure 8 shows the simulated radial shower shapes for 50 GeV (top) and 100 GeV (bottom) electrons. Radial shower shapes were simulated at various shower depths (number of charged particles as a function of the radial distance from the incident particle direction): 1 cm (0.57 X_0), 6 cm (3.41 X_0), 12 cm (6.82 X_0) and 18 cm (10.23 X_0). Transverse shower development simulation is within expectations (Moliere radius of iron is 17.2 mm). Data-simulation matching is underway (needs accurate signal digitization).

4 Conclusions

The first modules of a Q-Wall electromagnetic calorimeter was constructed with quartz tiles and PMTs/SiPMs and tested with electron beams. The performance of the first modules is within expectations and is qualitatively reproduced with simulations. Further simulation studies including the full digitization of the response and the response of a full-scale calorimeter are underway.

The photodetector is an integral part of the calorimeter. Alternatives to PMTs such as microchannel plates could provide further features such as higher timing resolution. Developing specialized photodetectors could enhance the functionality of Q-Wall calorimeters e.g. higher sensitivity to neutrons and using tungsten absorbers.

The Q-Wall concept provides a viable choice for electromagnetic calorimetry in high radiation environments.

References

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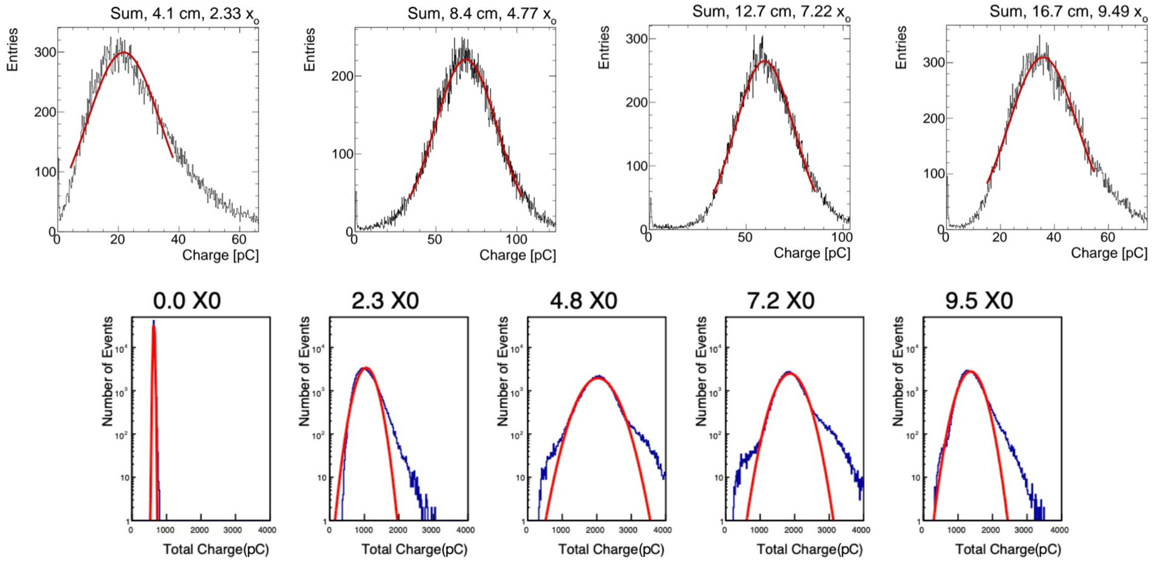

Figure 5. The total charge distributions of the Q-Wall modules for various upstream absorber thicknesses with 50 GeV electron beam.

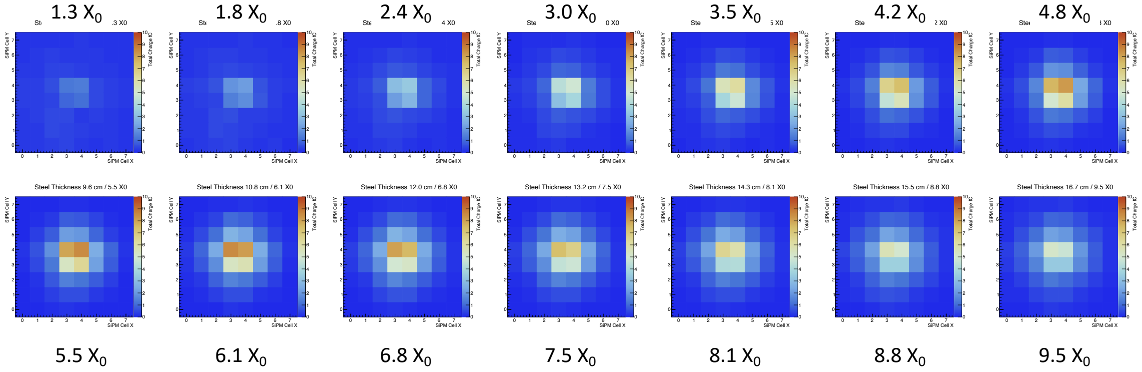

Figure 6. The longitudinal shower development of 100 GeV electrons.

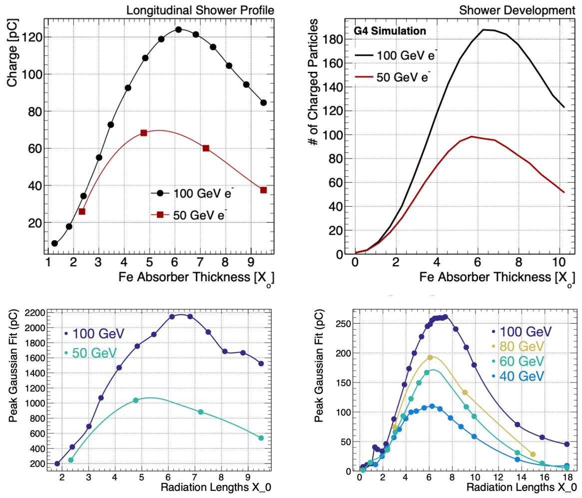

Figure 7. The longitudinal shower shapes for the PMT Q-Wall (top) (data on the left and the simulation results on the right) and SiPM Q-Wall modules (bottom) (with 8 x 8 array in 2022 on the left and with 3 x 3 array in 2023 on the right).

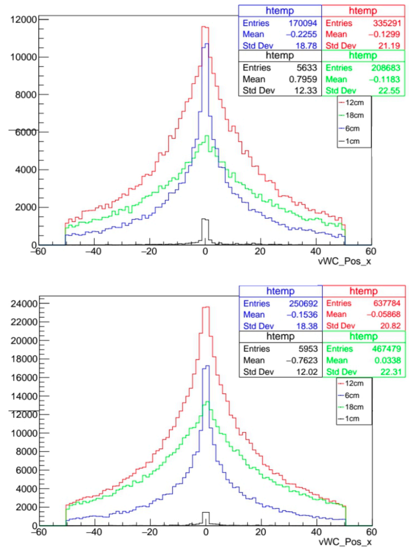

Figure 8. The simulated radial shower shapes for 50 GeV (top) and 100 GeV (bottom) electrons.