EPJ Web of Conferences **320**, 00016 (2025) https://doi.org/10.1051/epjconf/202532000016
CALOR 2024

Performance of the new CMS-HF Online Radiation Damage Monitoring System

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Abstract. The CMS-HF Calorimeter is designed to detect forward going particles. Discovery type events are believed to produce high energy particles going at forward angles. Hence, it is important to determine the particle energies accurately by making sure that the detectors have the right calibration all the time. The CMS-HF calorimeters have quartz fibers as the active element. Particle showers caused by the high energy particles travelling through the calorimeter produce the Cherenkov light in the quartz fibers. Particle energies are determined from the signals produced in the PMTs by the Cherenkov light reaching them. Damage in the fibers caused by the radiation during the collisions increases the attenuation in the fibers resulting in less light reaching the PMTs for the same energy. The HF online radiation monitoring system is designed to measure the attenuation of the light in the fibers independently and to provide the correction factors for the energy calibration as a function of the luminosity during the run period. The system was upgraded and commissioned at the end of the Run II. The correction factors for the 2022 run period were obtained both in terms of time and luminosity. The results were normalized to those at the lowest eta values so that the measurements could be compared with the values obtained from the collision data. The recovery effect in the fibers is also observed in the measurements done by the online system. The same measurements were done for the 2023 run period.

1 Introduction

The Compact Muon Solenoid (CMS) experiment is one of the four large detectors in the LHC at CERN. The CMS detector is designed to discover new phenomena and test the Standard Model. The Hadronic Forward (HF) calorimeters are placed 11.2 m away from the collision point at each end of the CMS detector (Figure 1). The HF calorimeters cover a pseudorapidity range of $2.9 < |\eta| < 5.2$. They are especially important in studying the WW scattering, detecting forward jets that are important in the Vector Boson Fusion Higgs search and providing an alternate and accurate luminosity measurement.

The absorber is made of iron and the active elements are plastic cladded quartz fibers of 600 micron diameter. Fibers are inserted into the grooves separated by 5 mm in 5 mm thick steel plates. Each calorimeter is composed of 18 wedges with 20° in azimuthal angle. Each wedge is divided into 24 towers. Figure 2 shows the location of each tower and its η value. The higher η value means the tower is closer to the beamline and exposed to higher radiation.

High energy particles produce hadronic or electromagnetic showers in the absorber material. Some of the particles produced in the showers will pass through the quartz fibers and produce Cherenkov radiation. The light from the Cherenkov radiation is transferred through the same fibers and the air-core light guides onto the four-anode PMTs.

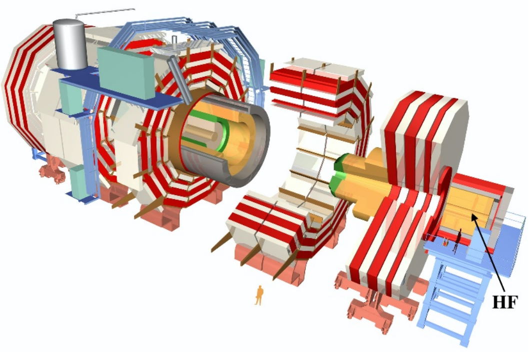

Figure 1. A view of the CMS detector. The HF Calorimeters are placed at each end of the detector (labeled as HF) [1].

It was shown in earlier test beam studies [2] that the quartz fibers undergo radiation damage as the accumulated luminosity increases, resulting in higher light attenuation in the fibers. Hence, the energy measurement in the HF calorimeter is degraded and corrections for the radiation damage should be applied. For this reason, radiation damage needs to be monitored as a function of the accumulated luminosity.

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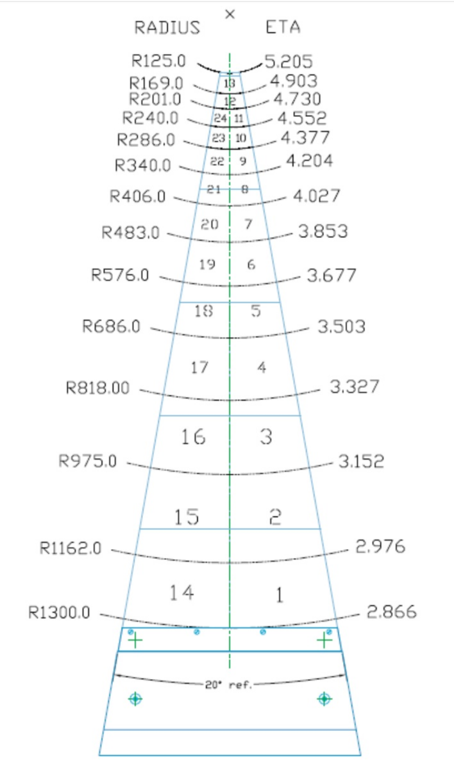

Figure 2. Schematics of an HF wedge showing the 24 towers and corresponding η values. Cross at the top shows the position of the beam [2].

In the same study, recovery of the fibers from the radiation damage was also seen once the radiation was removed. For the plastic cladded quartz fibers, fibers may recover by about 15% while most of the recovery happening in the first hour (Figure 3).

The energy of the original high energy particle is determined by combining all the charge collected from the light coming from the fibers. During the collisions the fibers will be irradiated continuously and their transparency decreases as a result of this irradiation. Increased attenuation causes an underestimation of the measured energy of the particles. The calibration of the detector should be corrected for this decrease due to the radiation damage. The radiation damage in the fibers should be measured by an independent system.

2 The HF Online Radiation Damage Monitoring System

The HF online radiation damage monitoring (RADDAM) system uses a fast light pulse, split at the entrance of the special fibers placed in the detectors for this purpose. One part of the light goes to the PMT directly and the other part goes into the fiber, traverses the whole length of the fiber and is reflected from the end back to the entrance and then to the PMT. Reflected pulse arrives at the PMT about 25 ns later than the direct pulse. To determine the radiation damage in that fiber, the ratio of the reflected pulse height to the direct pulse height is monitored as a function of the accumulated luminosity. The system is shown in Figure 4 [3]. With this system, the relative radiation damage in a specific period can be measured: in other words, the incremental radiation damage can be determined directly.

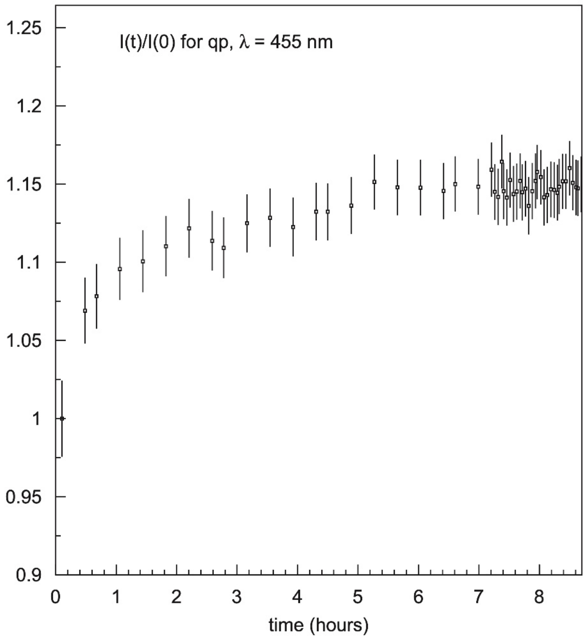

Figure 3. Radiation damage recovery of a plastic cladded quartz fiber at 455-460 nm after an irradiation of 400 Mrad [2].

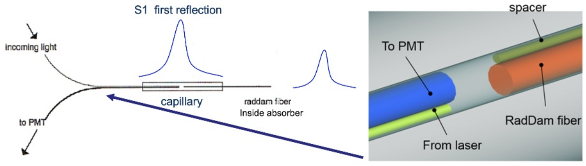

Figure 4. The working principle of the HF Online RADDAM System.

The HF online radiation monitoring system was upgraded and commissioned at the end of the Run II period [4, 5]. During the commissioning, data were taken whenever there were no collisions. The test beam measurements [2] show that the fibers start recovering as soon as the irradiation on them stops. When the irradiation resumes, the fibers go back to the last damage level.

As seen in the results of the commissioning in [5], recovery in the fibers is seen when the beam is off. Because of the recovery, correction factors obtained from the HF online radiation monitoring system for the calibration of the detectors may not be reliable. Even selecting the data taken very close to the collision runs, will not result in an accurate correction factor. However, runs taken within one hour after the collisions stop can be used with a systematic error of 4-7% since the test beam study shows that the average recovery in one hour is about that much (Figure 3).

Radiation damage could be estimated by using the collision data by looking at the energy collected at each tower as a function of the luminosity [6]. These are normalized to the values at the lowest η tower to cancel out the systematic effects, such as the fluctuations in the luminosity, geometrical variations, etc. The measurement is similar to the HF online RADDAM system; with the collision data, incremental radiation damage can be determined within a specific period. However, the radiation damage measurements done by the HF online RADDAM system are direct measurements and do not include any underlying assumption. Radiation damage estimates done by using the collision data is further normalized to the lowest η value ($\eta = 3.1$). Hence, the radiation damage estimates using the collision data are doubly normalized values and show lower radiation damage values. The assumption is that at $\eta = 3.1$ value, there is no radiation damage, which is not exactly true.

2.1 2022 results

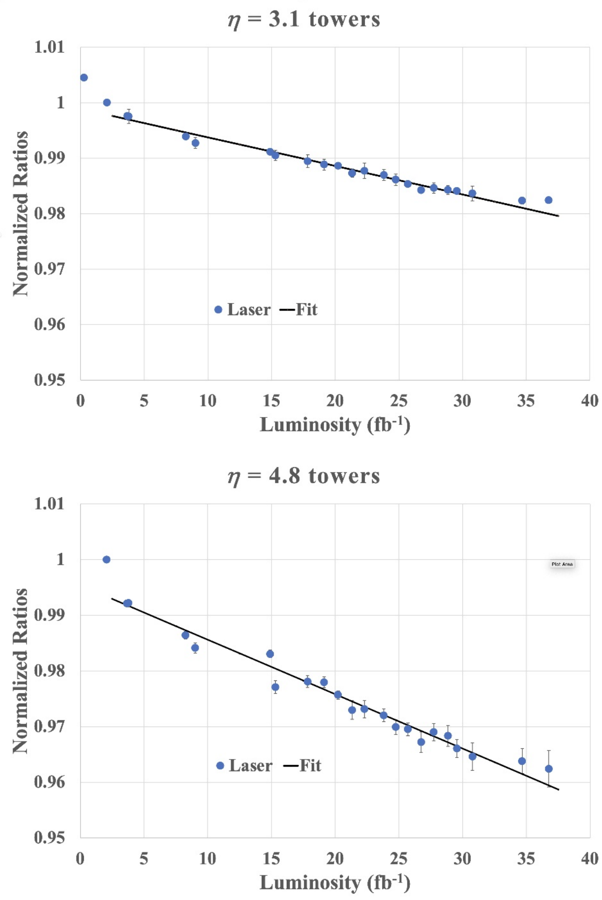

Figure 5. The relative radiation damage results obtained by the HF online radiation damage monitoring system. Incremental damage estimates as function of the accumulated luminosity values are shown for $\eta = 3.1$ and $\eta = 4.8$ channels. Normalized ratio is obtained by dividing each ratio to the ratio for the first run.

During the first year of the Run III, after the commissioning of the HF online radiation damage monitoring system, 86 special runs were taken with the system. These runs included seven sets of pulse height and timing information for direct and reflected signals in 56 channels. A set is selected with both signals placed in two adjacent time slices completely separated from each other. Then the ratios of the pedestal-subtracted signals are calculated event by event. Events with bad timing are eliminated by applying cuts to the TDC signals [5]. Out of 86 runs, only 23 of them were within one hour after the collisions stop. The results of these 23 runs were used and 23 ratios for a specific channel was normalized to the first ratio to find the change in the attenuation as a function of the luminosity for the period.

Figure 5 shows the results for two η channels. Straight lines in the plots are obtained by making a linear fit to the data. These relative results show a total of 2 to 4% incremental damage for 2022 run period, from $\eta = 3.1$ to $\eta = 5.1$. The results shown on these plots are obtained by averaging over the azimuthal angle (ϕ) channels for a specific η value and then are further averaged between the plus and minus sides (between the two sides). Commissioning studies show that the radiation damage values do not vary for different ϕ values and between both sides.

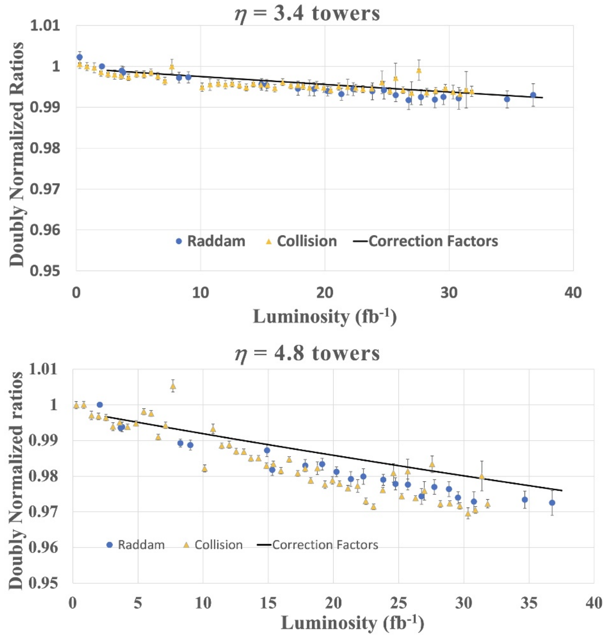

Figure 6. Comparing the doubly normalized results of the HF online radiation damage monitoring system results to the collision estimates for $\eta = 3.4$ and $\eta = 4.8$ channels. The doubly normalized ratios from the collision data are obtained by dividing the normalized ratios for each η to the normalized ratio for the $\eta = 3.1$. Straight lines are the correction factors calculated using the fit to these ratio estimates, determined from the collision data.

As explained above, the radiation damage estimates are doubly normalized to the $\eta = 3.1$ channel. Doubly normalized 2022 results of the HF online radiation damage monitoring system are calculated by normalizing all the channels to the $\eta = 3.1$ channel. Then these doubly normalized values can be compared with the values obtained from the collision data [7]. Figure 6 shows the

HF online radiation damage monitoring system results for two η channels (η = 3.4 and η = 4.8), since they are normalized to η = 3.1 channel. Straight lines on the graphs are the correction factors obtained by fitting the estimates from the collision data to an exponential function. The exponential function is determined from the test beam measurements mentioned above [2].

When doubly normalized HF online radiation damage monitoring system results are compared to the doubly normalized collision data, they seem to show higher radiation damage in almost all the channels, even though the HF online radiation monitoring system results include a few percent of recovery. The doubly normalized results of the HF online radiation damage monitoring system show a total of 1 to 3% relative incremental damage for 2022 run period, from η = 3.4 to η = 5.1.

2.2 2023 results

The HF online radiation damage monitoring system started taking data when the collisions started in 2023. However, after a few runs, there were some changes in the hardware that caused the HF online radiation damage monitoring system to be unstable and the system could not take useful data. Figure 7 compares a good laser delay timing scan for a good run in 2022 to a run taken in 2023. The 2023 run shows just noise. There is no signal. In addition to these problems, the collider stopped running due to some problems cutting the data taking period short. There were no good data to make a reasonable radiation damage estimate for 2023.

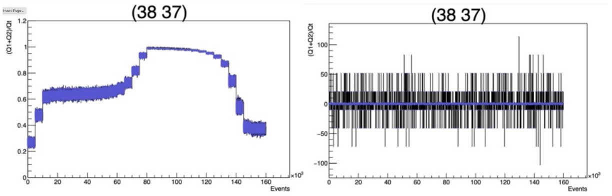

Figure 7. RADDAM laser delay timing scans for a good run in 2022 (left) and a bad run in 2023 (right). 2023 run shows only noise.

3 Conclusion

It is shown that the new HF online radiation damage monitoring system clearly separates the direct and the reflected signals, enabling a clean monitoring of the radiation damage. Furthermore, the HF online radiation damage monitoring system performs well as demonstrated in 2022 run. During the 2022 run period, a total of 2 to 4% radiation damage is observed in the HF Fibers at η = 3.1 through 5.1.

Fiber recovery continues to play an important role and complicates the online radiation damage monitoring. One possible way of reducing the recovery effect is to take the online radiation damage monitoring data during the ”abort gap,” in-between the collisions.

All the problems that were experienced in 2023 seemed to be solved and the 2024 run period has started with optimal running conditions. The HF online radiation damage monitoring system will continue to take data during the 2024 run period both in the regular mode after the collisions stop and also during the abort gap. Once the 2024 data taking period ends, results obtained from both ways of taking data will be compared.

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