Range extension for FASER electromagnetic calorimeter

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Abstract. The FASER calorimeter system has been upgraded to improve the dynamic range. The upgrade is based on the original calorimeter with only changes to the Photomultiplier Tube (PMT system). The basic concept is to introduce a light splitter between the calorimeter and the PMT: a few percent of the light is guided to one PMT (high range) while the majority of the light is guided to another PMT (low range). The splitting is selected such that the range of the PMTs has a significant overlap for cross calibration. The low range PMT is then calibrated with MIPs, while the high range PMT is cross calibrated to the low range PMT. This allows for significant dynamic range extension with a static system.

1 The FASER experiment and original calorimeter

ForwArd Search ExpeRiment, FASER [1], is a new CERN based experiment to look for new light, weakly interacting particles, such as dark photons. FASER is located in the forward region at LHC IP1 in an existing side tunnel. It is installed directly on the beam axes 480 m from the IP and has a transverse radius of only 10 cm covering the far-forward region (η>9.1) as shown in Fig. 1.

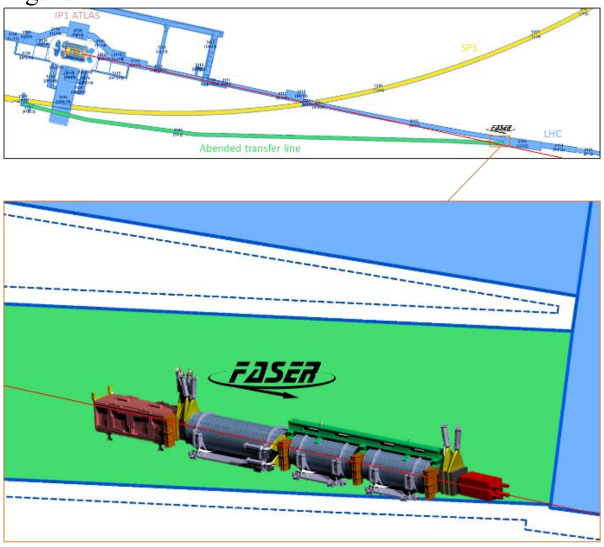

Fig. 1. Location for the FASER experiment in 480 m from LHC IP1.

The original FASER calorimeter was based on 4 LHCb outer ECAL modules. Those are 25 X_0 shashlik-type with 66 layers of interleaved plastic scintillator (4 mm) and lead (2 mm) with wavelength shifting fibers collecting the light. 1 classical photomultiplier tube, PMT, (Hamamatsu R7899-20, 10-stage) is used for readout per module. To move the energy range to the TeV scale needed for FASER, an absorption filter was placed in front of the PMT. With the filter installed, the MIP was only visible with the voltage maximized and to calibrate the operational setting, a cross calibration using a LED sources was used. This led to an uncertainty of the energy scale of 6 % at 500 GeV.
For TeV scale electrons, some leakage of the shower is expected, so an energy resolution calibration better than a few percent does not improve the measurement significantly.

2 Upgrade of the FASER calorimeter

The main purpose of the upgrade was to extend the range of the calorimeters to avoid the uncertainty from the filter installation. The method to extend the range was to split the light from the calorimeter module over two PMTs. This was done by introducing a light guide (light splitter) made of clear fibers. On the photomultiplier side the fiber bundle was split in 2 with a ratio of about 1:30 in the number of fibers for each position. A second photomultiplier was introduced for the additional fiber bundle. The concept is shown in Fig. 2.

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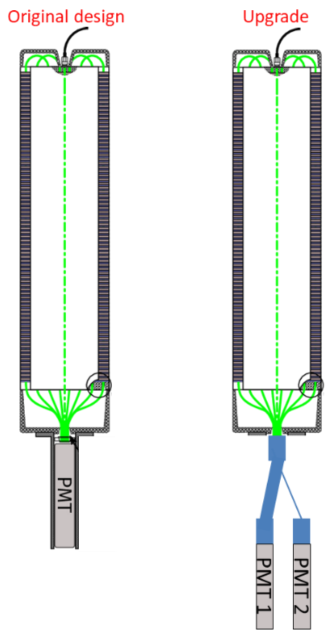

Fig. 2. Comparison of the original and upgraded PMT system.

The combined range is therefore almost a factor 30 larger, which should cover the full desired range.
The upgrade also has the added benefit that the cross calibration between the low and high range can be done continuously throughout the data taking, which eliminates for example drifts over time.
The fiber light guide is shown in Fig. 3.

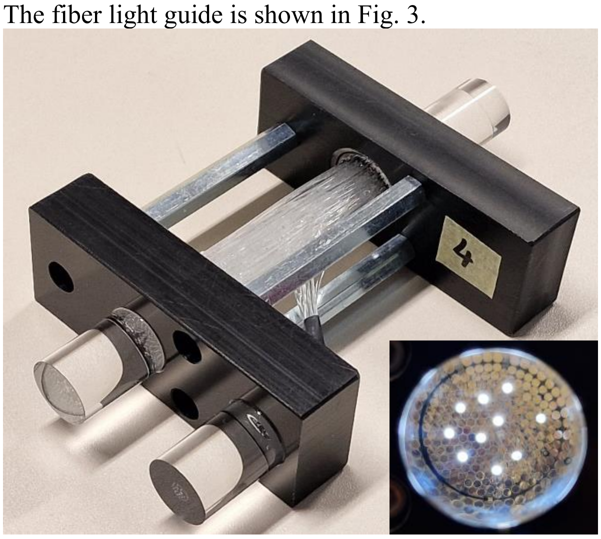

Fig. 3. Light guide to split the light to 2 PMTs. The fiber distribution for the high range (few fibers) are shown in the lower right comer.

It is composed of Kuraray clear-PS, Non-S type, round double cladded, Ø1.0 mm fibers and the light guide material is Plexiglas with a diameter of 16mm. The fibers for the high energy range (O(10) fibers) are distributed among the others to minimize bias in light selection.
New mechanics were made to house the upgraded PMT system. The main design criteria were that it had to fit in the envelop of the calorimeter, support the light splitter and 2 PMTs (including mu-metal for magnetic shielding) and be light tight. In addition, a RF shield of copper was added. The assembly is shown in Fig. 4.

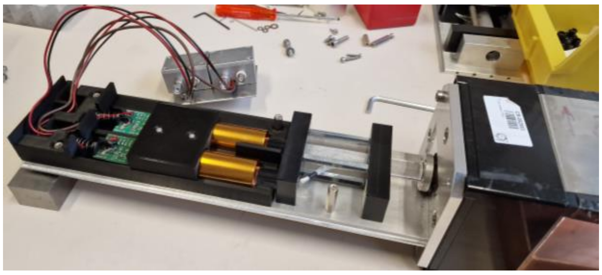

Fig. 4. Calorimeter module with light splitter and 2 PMTs with mu-metal.

3 Testing the upgrade

A laboratory test stand was made to test the light splitters. This was composed of a remotely controlled 2D table, on which a LED illuminated wavelength shifting fiber was mounted. The fiber position was scanned over the light surface of the first light mixer on the light splitter. The setup is shown in Fig. 5.

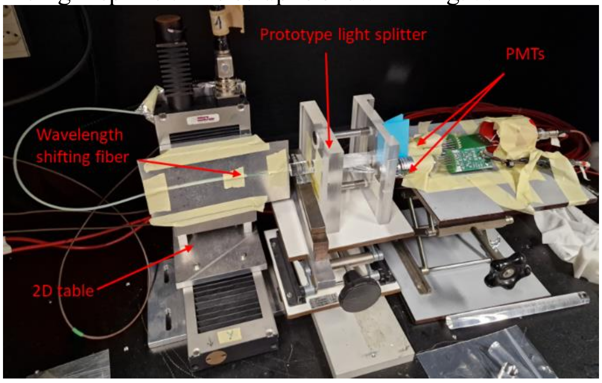

Fig. 5. Setup with 2D table for scanning the ratio of the light in the 2 PMT positions.

The results showed some dependence (in particular in early prototypes with few fibers) on the fiber position in the low light channels as seen in Fig. 6.

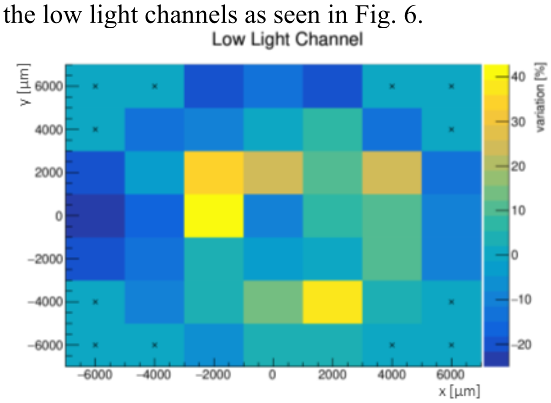

Fig. 6. Light variation in the low light channel when scanning over the input to the light splitter.

This is likely due to the test fiber aligning with a fiber for the low light channels. Since the use case is a shashlik-type calorimeter, the light is by nature rather equally distributed among the wavelength shifting fibers, so the position dependence is expected to cancel out.
To test in near real conditions, a full module with light splitter was installed at the CERN SPS H4 beam line. 200 GeV electron beam was used for the

characterization. The results on the ratio between the channels are shown in Fig. 7.

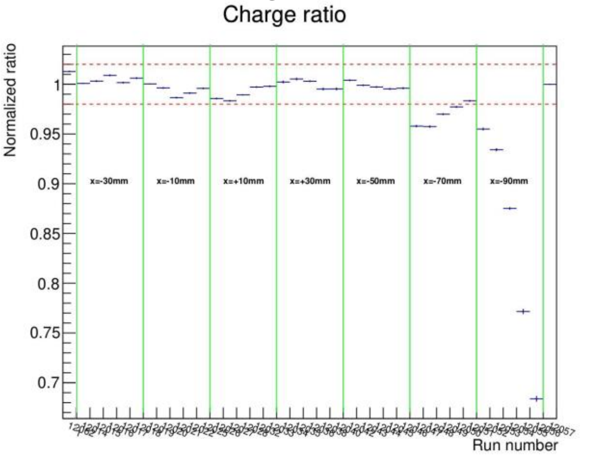

Fig. 7. Normalized ratio between the low and the high light channel as a function of different incident positions of the beam on the calorimeter.

Besides some edge effects, the ratio between the low and high signal channels is stable within ± 2 %. The splitting ratio on the prototype where much higher (1:1200) than desired (1:30) due to broken fibers, so the performance is expected to be improved on the final units.

4 Installation and readout

Five units (4 + spare) were produced. All units were tested for quality assurance on a cosmic test bench to verify performance. 4 units were then installed in FASER at the LHC in the Year End Technical Stop 2023/24. The calorimeter modules remained in position and the old single channel PMT and filters were removed. The new units were assembled on the existing calorimeter modules as shown in Fig. 8.

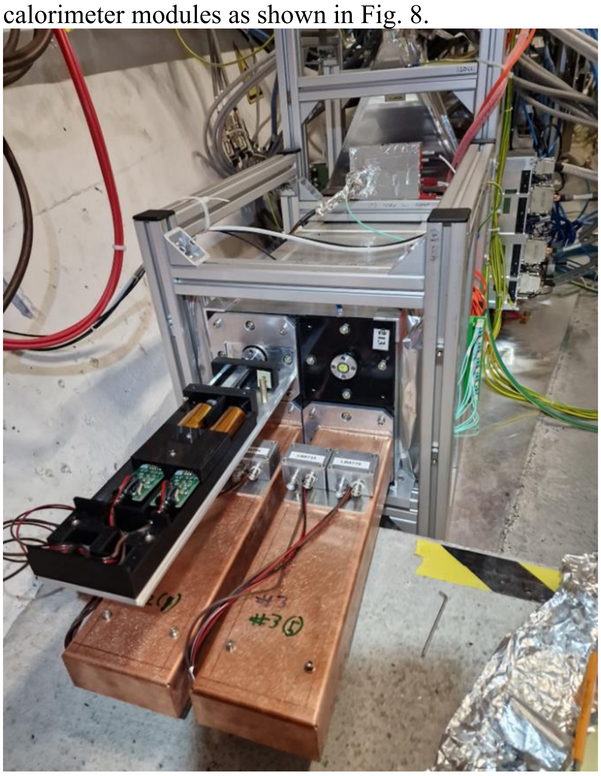

Fig. 8. Upgraded PMT system during installation.

An additional RF shield was installed around the full calorimeter PMT system. The full detector system is shown in Fig 9.

Fig. 9. Calorimeter module with light splitter and 2 PMTs with mu-metal.

The system is readout by a CAEN digitizer module VX1730S. This is a 500 MHz, 16 channel unit and the full signal shape (560 ns) is sampled and stored for offline analysis. The readout is housed in a rack inside the LHC side tunnel and is seen in the back of Fig. 9.

5 Early performance results from LHC

The voltage of the PMTs were fine adjusted to make the charge ratio between the high and low energy range 30 (to make it independent of the light ratio from the fibers).

Event selection and fitting:

- Events with high energy muons are selected (single well-reconstructed track and momentum above 20 GeV).
- Muon trajectory is extrapolated from the tracker to the calorimeter.
- The extrapolated position of the muons are segmented into 5 mm x 5 mm areas on the calorimeter.
- The charge distribution is fitted with Landau functions as shown in Fig. 10.
- Due to the angles of the modules compared to the beam direction, the edge locations are not considered as they will have signal distributed over more than one module.

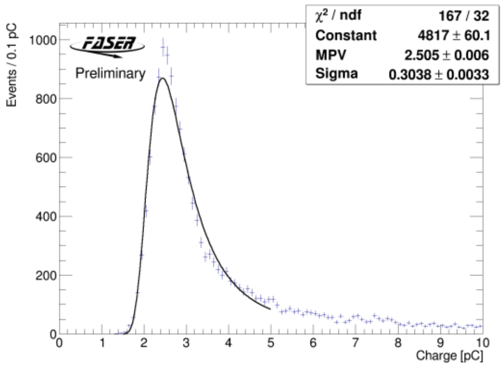

Fig. 10. Example of Landau fitted to the charge distribution.

From the raw results shown in Fig 11. there is an excess of charge in the same location on all 4 modules.

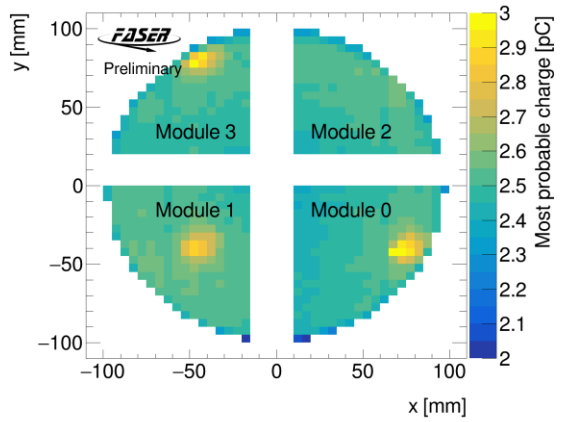

Fig. 11. 2D map of the modules with the edges removed. Excess of charge at the same location of each module is visible.

The explanation is likely that the muon is passing the light mixer, fibers and PMT window and introducing Cherenkov light. This is only an issue for calibration: The physics case is based on electrons, that will be stopped in the calorimeter. The regions which are probable to have additional Cherenkov light are excluded from the further results.

The cross calibration between the low and high energy is done with particles depositing energy in the range overlap. The charge of the two PMTs connected to the same module is shown in Fig 12.

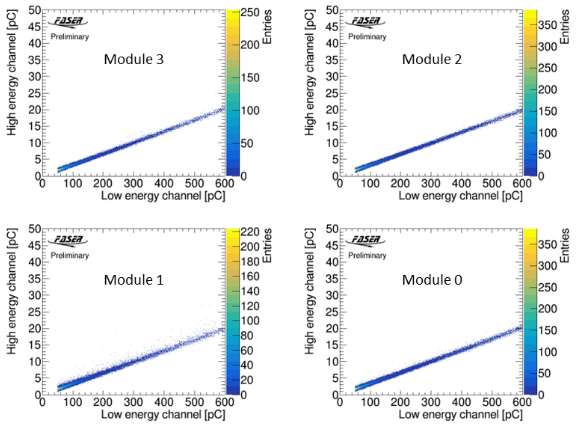

Fig. 12. Charge in high energy vs low energy channel of each calorimeter module for muons passing through the module in regions away from the PMTs and fiber bundle.

A clear correlation is measured, and the behavior is similar for the 4 modules.

The stability of the ratio of charge between the low and high range energy channel has been investigated and is shown in fig. 13.

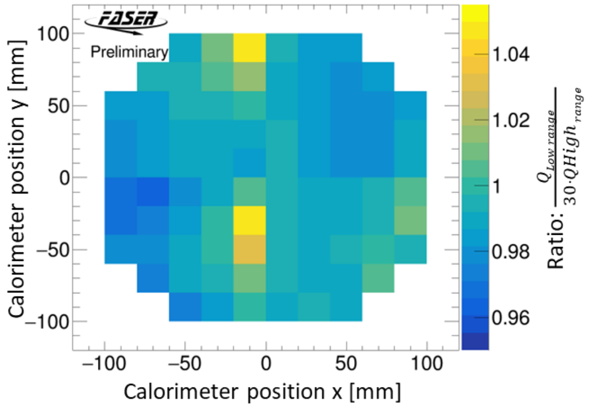

Fig. 13. Ratio of charge stability over the surface of the calorimeter.

Besides around the position were additional light from Cherenkov light (light mixer, fibers, PMT window) is expected, the ratio of charge between the low and high range energy is stable within a few percent.

6 Summary

The electromagnetic calorimeter of FASER has been upgraded to increase its dynamic range. The concept is based on light splitting with fibers.

The components have been characterized in laboratory test benches and test beam setups. No showstoppers were found and the components optimized.

The upgrade has been fully installed in FASER at LHC in the Year End Technical Stop 2023/24. The calorimeter modules remained in position and only the PMT part were replaced.

Early performance looks promising with good cross-calibration between the low and high energy range.

References

Journal articles

1. FASER Collaboration, The FASER Detector. JINST 19 (2024) P05066