Liquid Argon Calorimeter Performance at High Rates

Frank Seifert
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden.
E-mail: F.Seifert@physik.tu-dresden.de

Abstract. The expected increase of luminosity at HL-LHC by a factor of ten with respect to LHC luminosities has serious consequences for the signal reconstruction, radiation hardness requirements and operations of the ATLAS liquid-argon calorimeters in the endcap, respectively forward region. Small modules of each type of calorimeter have been built and exposed to a high intensity proton beam of 50 GeV at IHEP/Protvino. The beam is extracted via the bent crystal technique, offering the unique opportunity to cover intensities ranging from $10^6$ p/s up to $3\times10^{11}$ p/s. This exceeds the deposited energy per time expected at HL-LHC by more than a factor of 100. The correlation between beam intensity and the read-out signal has been studied. The data show clear indications of pulse shape distortion due to the high ionization build-up, in agreement with MC expectations. This is also confirmed from the dependence of the HV currents on beam intensity.

1. Introduction
The Large Hadron Collider (LHC) started operation in 2009 and delivered about 5 fb$^{-1}$ collision data to both multi-purpose experiments, ATLAS and CMS, at a center of mass energy of 7 TeV until the end of 2011. A data collection of around 20 fb$^{-1}$ at 8 TeV is expected until the end of 2012. The increase of the instantaneous luminosity of the LHC is planned in multiple steps of upgrades. Therefore several phases of shutdowns are foreseen, where machine upgrades as well as upgrades of the LHC detectors will take place.

The maximum instantaneous luminosity reached at the time of writing is about $6.5 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. A first shutdown is planned in 2013 and 2014 with the main goal to reach a center of mass energy of 13 TeV or 14 TeV. Also a luminosity of $1-2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ is expected to be reached after the so-called Phase 0 upgrade from 2014 on. After some years of data taking, the Phase I upgrade is planned to take place in 2018 with a luminosity of up to $3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ at the end of the period. Finally, a third shutdown period is foreseen in 2022 implementing the Phase II upgrade, after which the instantaneous luminosity is planned to be at $5-7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. This long term schedule is under discussion and might be modified in the future.

A main challenge after the Phase II upgrade is the operation of the liquid-argon (LAr) calorimeters of the ATLAS detector in the high luminosity environment, especially the endcap and forward calorimeters [1]. In the following, testbeam studies with small modules of the HEC, the EMEC and the FCal to prove their performance in high intensity environments are presented. The testbeam setup, the calorimeter test modules and the obtained results are described in more detail.
2. The ATLAS liquid-argon calorimeter system

The LAr calorimeter system of ATLAS uses copper, tungsten or lead as absorber material and liquid-argon as active medium. It is used for the EM barrel calorimeter, the EM endcap calorimeter (EMEC), the hadronic endcap calorimeter (HEC) and the forward calorimeter (FCal). Pictures or layouts of the EMEC, the HEC and the FCal calorimeters can be seen in Figure 1. The EM barrel and the EMEC modules use an accordion shape structure of the absorbers and LAr layers to reach a full coverage in \( \phi \) without any cracks. This is also shown in Figure 1 left.

![Figure 1. The LAr endcap calorimeter parts. From left to right: Photograph of one part of an EMEC module, graphics of a part of a HEC module and schematic structure of the FCal1 module. More details can be found in Reference [2].](image)

The FCal is included inside the endcap cryostat and consists of one EM module (FCal1) and two hadronic modules (FCal2, FCal3). The size of the LAr layers is typically 2.1 mm in the barrel, between 0.9 mm and 3.1 mm in the EMEC, 1.95 mm in the HEC, and 0.250 mm (0.375 mm, 0.50 mm) for the FCal1 (FCal2, FCal3). In the following, it is referred to the FCal1 module only as it is exposed to the highest particle intensities.

A Phase II upgrade scenario of the FCal for the highest luminosities includes the replacement of the FCal1 module with a new one. The layout would be similar to the current FCal1, but with 100 \( \mu \)m LAr gaps instead of the 250 \( \mu \)m ones. This so-called sFCal module is expected to show better performance during the high intensities after the Phase II upgrade.

3. Liquid-argon endcap calorimeter testbeam studies

In 2006 a testbeam project at the U-70 proton synchrotron in Protvino, Russia was set with the aim to test the current EMEC, HEC, FCal1 and the proposed upgraded sFCal module with the 100 \( \mu \)m LAr gaps in the high intensity environment of the high luminosity LHC (HL-LHC). A testbeam setup which simulates the particle flux distribution through the calorimeter test modules as it is in ATLAS over a wide intensity range was installed in beamline 23 at IHEP. Therefore, the RF bunch structure was kept and used to simulate well separated calorimeter input pulses. Every sixth RF bunch was filled with protons leading to one extracted bunch every 1 \( \mu \)s. One accelerator fill was extracted over roughly 1.2 s (spill) using a bent crystal extraction technique. The extracted beam intensity ranges from \( 10^6 \) p/spill to around \( 3 \times 10^{11} \) p/spill. The spill cycle time was about 9.5 s.

A schematic overview of the experimental setup in beamline 23 can be seen in Figure 2 [3]. The beam instrumentation consists of a secondary emission chamber for beam profile measurement, six scintillation counters for beam intensity monitoring in the low intensity region, a Cherenkov monitor for bunch-based beam intensity measurement, a scintillator hodoscope for beam...
position- and intensity monitoring and an ionisation chamber for beam intensity measurement over the whole intensity range.

After the beam instrumentation a first iron absorber of 0.7 \( \lambda \) and the cryostat housing the FCal test module is installed. Then a second iron absorber of 1.8 \( \lambda \) follows to adjust the particle flux through the following test modules of the EMEC and the HEC. This setup was optimized with Monte-Carlo simulations using the 2D gaussian beam shape of about 10 mm size.

The FCal test module consists of two parts with four tube groups each (four readout channels and four HV channels), one with the 250 \( \mu m \) LAr gaps and one with the proposed 100 \( \mu m \) ones for the sFCal. Either of these parts can be centered to the beam. The EMEC module consists of four absorber plates and three copper electrodes with 2 mm LAr gaps in between. The HV is divided in three separate channels and the readout is split perpendicular to the beam axis into four readout channels. The HEC module includes four HV and four readout channels and the size of the test modules upright to the beam is \( \approx 36 \, cm^2 \) with a sensitive area of nearly 25 cm\(^2\). A schematic view of the modules is shown in Figure 3 and more details can be found in [3].

Charged particles passing the LAr gaps induce the typical triangular pulse. This is shaped by the front end electronics, similar to ATLAS, and the readout is done by 25 ns sampling ADCs. Two of them are used in normal- and delayed mode so that an effective sampling period of 12.5 ns is reached. Two gains, low and medium, are available and the understanding of the whole readout chain is very good [3]. Figure 4 shows the average signal pulse shape of the EMEC module for four different beam intensity ranges. One main goal was to study the signal degradation of the calorimeter pulses with increased beam intensities. This is already visible in Figure 4 where the beam intensity increases from the upper left plot to the lower right plot.

The reason for the signal degradation is the positive ion buildup in the gaps, which becomes critical when it equals the charge at the electrodes. This leads to high currents drawn over the protection resistors and reduced electric fields over the gaps, which are partly even zero above the critical intensity. In this case the drift of the produced electrons is reduced or even completely stopped, leading to a reduction of the induced signal. The absolute ionization rate, \( D \), divided by the critical ionization rate, \( D_C \), is defined as the relative ionization rate, \( r \):  
\[ r = \frac{D}{D_C} \]  

The amount of the signal degradation is then dependent on \( r \) and also on the recombination

![Figure 2. Schematic view of the experimental setup [3] in beamline 23 at IHEP, Protvino. The beam direction is from right to left. More details are described in the text.](image-url)
Figure 3. The calorimeter test modules. From right to left: the FCal module, the EMEC module and the HEC module. More details are given in the text and in Reference [3].

Figure 4. Average signal pulse of the EMEC calorimeter test module for four different intensity ranges, increasing from the upper left to the lower right [3].

rate w. The theoretical prediction for the dependence of the signal amplitude (normalized to the bunch intensity), $s$, on $r$ is flat below the critical intensity and drops proportional to:

$$s \propto \frac{1}{r^{1/4}}$$  \hspace{1cm} (2)
above the critical intensity \cite{4}. More details can be found in Reference \cite{4}. Therefore, the breakpoint in the behaviour can be used to determine the critical intensity in the operation for each calorimeter module.

The dependence of the calorimeter signal response per proton on the beam intensity was studied in detail for all calorimeter test modules during the testbeam runs between 2008 and 2010. A summary of the results can be seen in Figure 5 together with the fitted model function. The expected dependence with the flat plateau until the critical intensity and the decreasing behaviour is clearly visible. The beam intensity corresponding to the nominal LHC luminosity of \(10^{34} \text{cm}^{-2}\text{s}^{-1}\) was calculated and compared to the obtained critical beam intensity for each calorimeter module (nominal voltage equivalent). The measured results are such that the critical intensity for the EMEC is at about 5 times the nominal LHC intensity, for the HEC at around 8 times and the FCal with the 250 \(\mu\text{m}\) LAr gaps becomes critical already at 1.5 times the nominal LHC intensity. This confirms the expectations and underlines the need to adapt the EM FCal part after the Phase II upgrade. The proposed sFCal design with the 100 \(\mu\text{m}\) LAr gaps shows no signal degradation below intensities of about 10 times the nominal LHC intensity, which

![Figure 5](image_url)

**Figure 5.** Response of the calorimeter signal amplitude (ADC counts per proton) in dependence of the beam intensity. Top left: EMEC module, bottom left: HEC module, top right: FCal module, bottom right: sFCal module. \cite{3}.

shows that it is suitable to run during the high luminosity phase. Due to substantial systematic effects at the highest beam intensities, the significance of the breakpoint at the critical intensity has to be taken with care \cite{3}.

In addition the HV return currents of the FCal and the EMEC calorimeter test modules have been measured with high accuracy during the testbeam runs and their dependence on the
beam intensity was studied. For the FCal, it was possible to show that the currents with high precision depend linearly on the beam intensity (below the critical region, see Figure 6 left) and that, therefore, a relative luminosity measurement of the LHC with the EMEC and FCal return currents is possible [5]. This method has become one of the main methods for measuring relative luminosity changes in ATLAS.

Figure 6. HV return currents in dependence on the beam intensity for the FCal test module (left) from data taken in 2008 and the EMEC (right) test modules from data taken in the 2010 run [3].

Further, the HV currents of the EMEC module were analysed to compare them with the predictions at and above the critical intensity. After a linear behaviour below the critical intensity a dependence on the beam intensity to the power $p = 0.75$ is predicted [4]. Figure 6 (right) shows the measured data together with the corresponding model fit with the critical intensity, $I_C$, the critical current, $i_C$, and the power, $p$, as free fit parameters. The result of the fit is a dependence above the critical intensity with a power $p = 0.76 \pm 0.03$ in agreement to the predictions [3].

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