Upgrade Plans for ATLAS Forward Calorimetry for the HL-LHC

J. Turner
on behalf of the ATLAS Liquid Argon Calorimeter Group

Carleton University, 1125 Colonel By Drive
Ottawa, ON, K1S 5B6, Canada

Abstract

Even though the LHC is still in an early phase of operation, plans are being developed to operate the machine and its detectors at up to 10 times the original design luminosity. This has a major impact on the Forward Calorimeter (FCal), which is exposed to some of the highest radiation rates in ATLAS. The FCal detector and its associated components were designed for operation at the maximum LHC luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. However at the higher luminosities projected for the HL-LHC, operation of the FCal may be compromised. Beam heating in the FCal could lead to the formation of argon bubbles in the detector, the ionization rate will result in space charge effects that will reduce the signal and the current draw will result in a voltage drop across the HV current limiting resistors. Two possible solutions are being considered to maintain FCal operation at HL-LHC. One is a complete replacement of the FCal system. A replacement FCal would have a similar design to the current calorimeter except for the addition of cooling loops, lower value HV protection resistors and the use of smaller ionization gaps, as small as 100 microns in the first compartment. The second solution is the installation of a small warm calorimeter, referred to as the Mini-FCal, to be placed in front of the FCal. This addition would reduce the ionization load in the first FCal compartment, which would keep a larger region of the FCal active and reduce the heat load to an acceptable level. The current concept for the Mini-FCal is a standard parallel plate calorimeter with copper absorbers and diamond sensors, which were chosen for their inherent radiation resistance. It is anticipated that neutrons will be the major cause of damage to the diamond sensors and the integrated flux of neutrons in the Mini-FCal after 3000 fb$^{-1}$ at the HL-LHC will be up to $2 \times 10^{17}$ neutrons/cm$^2$. Recent irradiation tests carried out by members of the ATLAS Liquid Argon group show that these sensors can still operate after irradiation up to these levels although with a large reduction in signal.

1. Introduction

The ATLAS detector [1] is one of two general purpose detectors operating at the LHC [2] in Geneva, Switzerland. It consists of an inner detector tracking system (ID) surrounded by a superconducting solenoid...
providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip detectors inside a transition radiation tracker. The electromagnetic calorimeter is a lead liquid-argon (LAr) detector in the barrel ($|\eta| < 1.475$) and the end-cap ($1.375 < |\eta| < 3.2$) regions, one of which is illustrated in Figure 1. In these regions, hadron calorimetry is based on two different detector technologies. The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are composed of scintillator/steel, while the hadronic end-cap calorimeters ($1.5 < |\eta| < 3.2$) are LAr/copper. The forward calorimeters ($3.1 < |\eta| < 4.9$) are instrumented with LAr/copper and LAr/tungsten, providing electromagnetic and hadronic energy measurements, respectively. The MS consists of three large superconducting toroids and a system of three stations of trigger chambers and precision tracking chambers.

Currently, the LHC is operating at a peak luminosity of around $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ and a centre of mass energy of $\sqrt{s} = 7 \text{ TeV}$. The ATLAS detector was designed to operate at a nominal instantaneous luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a centre of mass energy of 14 TeV, which should be achieved after the 2013-2014 shutdown. Plans for an upgrade to higher luminosities are already being explored. The High Luminosity LHC’s (HL-LHC) goal is to reach a peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, with luminosity leveling. The aim is to gather 250 fb$^{-1}$/year and a total of 3000 fb$^{-1}$, more than 10 times the amount of data expected to be collected prior to the start of HL-LHC operation.

2. Forward Calorimeter

The Forward Calorimeter (FCal) [3] is a liquid argon (LAr) sampling calorimeter which covers the pseudo-rapidity region $3.1 < |\eta| < 4.9$ and experiences the highest particle fluxes in the ATLAS calorimeter system. It consists of three disk shaped modules and is situated in the end-cap cryostat, as illustrated in Figure 1. It relies on tubular electrodes to form the narrow LAr gaps necessary for operation in the high flux regions at high $|\eta|$. Up to the nominal LHC luminosity, the small gaps prevent ion-build up in the LAr.

---

\[2\] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudo-rapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. 

---
which would otherwise distort the electric field within the gap and lead to signal degradation. The FCal1, the module closest to the interaction point, has gaps of only 269 μm, consists of 28 radiation lengths (X₀) of copper absorbers, and is optimized for EM calorimetry. The FCal2 and FCal3 modules have approximately 50% and 100% larger gaps, respectively. These modules use tungsten as the absorber, which provides 3.7 and 3.6 interaction lengths (λ) of material, respectively. The three FCal modules together correspond to a total of 10 λ of material, which is sufficient to contain hadronic showers at LHC energies.

Each FCal electrode consists of a rod at high voltage, a tube at ground, and a helically-wound PEEK fibre that maintains the gap between the rod and tube, as illustrated in Figure 2. The rest of the gap contains liquid argon. The rods form part of the absorber and are thus made of copper in the FCal1 and tungsten in the FCal2 and FCal3.

3. High-Luminosity Upgrade Plans for the Forward Calorimeter

The high luminosities planned for the HL-LHC pose several potential problems for the ATLAS detector as a whole. Studies are underway to investigate the replacement or modification of various ATLAS subsystems. For the FCal, there are three main issues for operation at an instantaneous luminosity of 5 x 10³⁴ cm⁻²s⁻¹. The current FCal gap size, designed for operation at peak luminosities of 10³⁴ cm⁻²s⁻¹, is not sufficient to prevent ion build-up in some regions of the FCal at HL-LHC luminosities. The HV distribution to the FCal electrodes is via one or two MΩ protection resistors located on summing boards mounted on the rear of the HEC, inside the cryostat. With increased current draw due to higher luminosities, the voltage drop across these resistors increases, reducing the voltage applied to the electrodes and therefore the electric field within the gap. These problems compound one another; as the electric field in the gap decreases due to the voltage drop across the HV distribution resistors, charge build-up increases. There is also the possibility that beam-heating from the very high ionization load could lead to localized boiling of the LAr.

Preliminary estimates of the signal degradation due to these problems have been produced. At nominal LHC luminosities, some signal degradation is expected in the central region of the FCal1 module, which is exposed to the highest particle fluxes. At 3 x 10³⁴ cm⁻²s⁻¹, the FCal1 module is expected to see a signal drop of 20% or more in the pseudorapidity range of 4.3 < |η| < 4.9. Extracting useful information from this region will likely be impeded. The region extending to |η| of 3.8 will see a HV drop of -30 V or more, but still provide useful signal. The rest of the FCal1 module should operate nominally at the HL-LHC levels. ATLAS is currently in the process of confirming these predictions. Finite Element Analysis studies predict that HL-LHC luminosities are not quite sufficient to induce argon boiling, though with little safety margin. The effect of signal loss in the FCal on physics searches is under active investigation.

If the signal loss in the FCal proves detrimental to the search for new physics, or if beam heating compromises much of the detector, then the above problems will have to be ameliorated to the point where
the effect on physics is sufficiently small. Due to high levels of activation, modifications of the current FCal will likely prove too expensive and complicated. This leaves two viable solutions; the first is the replacement of the entire FCal with a new Forward Calorimeter, called the super FCal (sFCal), designed to operate in the high flux environment expected of the HL-LHC. It would require smaller LAr gaps to prevent ion build-up, as little as 100 μm in the FCal1 module. The HiLum experiment [4] has proven that it is possible to operate a LAr calorimeter with 100 μm gaps at the particle fluxes expected at the HL-LHC. A new HV distribution circuit with lower HV protection resistors will also be necessary, as well as the addition of cooling loops to prevent beam heating problems. The installation of the sFCal will require the removal of the current FCal and opening part of the end-cap cryostat. The exact nature of the process required is still being investigated; the existing FCal summing boards may have to be abandoned and a new set installed elsewhere. A preliminary mock-up of the sFCal is illustrated in Figure 3, with the new set of summing boards positioned in front of the FCal cold bulkhead. It has also been proposed that a portion of the space occupied by Plug 3 be used to house the new summing boards.

A simpler solution to the FCal’s problems, which avoids opening the end-cap cryostat, has also been developed. It involves the installation of a small, warm calorimeter, known as the Mini-FCal, between the FCal and the ATLAS interaction point, which would absorb a large portion of the particle flux that would otherwise enter the FCal1 and FCal2 modules, reducing it to a level at which the modules can operate normally. It is believed that this solution addresses all three major problems facing the FCal at higher luminosities. The Mini-FCal does introduce a transition region at its outer edge that degrades the overall performance of this region of |η|.

4. Mini-FCal

The Mini-FCal design consists of a cylindrical sampling calorimeter consisting of 10.5 radiation lengths of copper-absorber plates and 11 layers of diamond sensor planes bonded to a ceramic substrate, for a total depth of 30 cm. It has a radius of approximately 175 mm and over 8000 sensors per Mini-FCal. The substrate is made of Rogers 4003, a composite ceramic. To keep the Mini-FCal at room temperature, cooling pipes filled with water run along the lower edge. Signal cables will be run along its upper edge to preamplifier boards mounted on the front face of the end-cap cryostat. The Mini-FCal design and its location...
are illustrated in Figure 4. It is located directly in front of the FCal and is supported by the warm wall of the end-cap cryostat. This space is currently occupied by a neutron-absorbing material, borated polyethylene, which can easily be removed and replaced with a new design that results in acceptable neutron levels in the inner detector. Borated polyethylene has been tested to HL-LHC luminosities with satisfactory results. The position of the Mini-FCal exposes it to high level of particle flux and, therefore, a very radiation hard active material such as diamond is required.

The installation of the Mini-FCal is simple compared to the installation of the sFCal; inserting it into its position will likely not require opening of the cryostat. The end-cap cryostat can be moved by two metres, providing enough room between the inner ATLAS detectors and the end-cap for a crew to install the Mini-FCal. The current neutron absorbing material will need to be removed. The Mini-FCal can then be inserted into position next to the FCal along with a new neutron moderator that is also shown in Figure 4. This is estimated to take between six and eight months. However, it is unclear whether the existing warm tube can sustain the additional load. Replacement of the warm tube would require the removal of the warm wall of the end-cap cryostat, lengthening the installation period.

4.1. Diamond Sensors

A voltage applied across a diamond sensor creates an electric field, which is used to gather charge on the electrodes. All tests carried out for the Mini-FCal use sensors based on polycrystalline chemical vapour deposition (pCVD) diamond\(^3\), which has a non-uniform crystal structure. The diamond is grown on a substrate material. The crystal structure nearest the substrate has a high concentration of grain boundaries, as the diamond begins growing in multiple places. Boundary concentration decreases as the diamond grows. These boundaries act as trapping centers and reduce signal amplitude. Uneven growth leads to an uneven surface at the growth side of the diamond, creating variations in the thickness of the detector that lead to variations in signal. To improve signal quality, both sides can be ground down, reducing the number of grain boundaries in the sensor and providing a more uniform thickness throughout the detector. To reduce costs, the Mini-FCal design calls for using diamonds as grown.

DDL produces three grades of polycrystalline diamond. In order of decreasing purity they are: electrical, optical and polycrystalline. All grades of sensor are currently being investigated for use in the Mini-FCal.

\(^3\)Manufactured by Diamond Detectors Ltd (DDL), 16 FleetBridge Business Centre, Upton Road, Poole, Dorset, UK, BH17 7AF
Sensors from 200 - 800 $\mu$m thick have been tested, with results favouring thinner detectors: 300 $\mu$m detectors are currently proposed for the Mini-FCal. A bias of 1 V/$\mu$m is applied, though much higher voltages can be applied to diamond before the onset of breakdown.

Tests to investigate the use of diamond as a sensitive material for a forward calorimeter have been undertaken. The single most important test was to determine whether or not diamond is sufficiently radiation hard to survive the HL-LHC. Ten years of HL-LHC running is assumed to correspond to approximately $2 \times 10^{17}$ neutrons/cm$^2$ in the proposed location of the Mini-FCal. Though radiation damage varies both from particle type and energy, it is thought to be similar enough that irradiation studies with protons, which are much easier to accomplish, can be undertaken with results that can be compared, at some level, to neutron radiation damage. The RD42 collaboration at CERN has investigated diamond sensor response up to fluences of approximately $2 \times 10^{16}$ protons/cm$^2$ [5]. Those tests saw the sensor response drop to approximately 20% of the initial response, consistent with an exponential decay. Tests at TRIUMF [6] exposed four diamond detectors to 500 MeV/c protons over the course of 12 days. At the end of the run the diamonds had been exposed to an average fluence of $2.25 \times 10^{17}$ protons/cm$^2$ with a peak of $5 \times 10^{17}$ protons/cm$^2$, verified by aluminum activation foils in the beamline. The response of the detectors as a function of integrated particle fluence is plotted in Figure 5a. This is similar to the fluence currently expected in the Mini-FCal after 10 years of HL-LHC operation. The detectors remained operational, but at 5% of their original signal amplitude. Corrections will have to be applied to the degraded signals from the diamond detectors to make them useful for calorimetry at HL-LHC luminosities. See Section 4.2.

4.2. Simulation Studies

The design of the Mini-FCal has been motivated at every step by a number of simulations of the energy deposited within and the particle flux through various configurations of the Mini-FCal. Early simulations of the Mini-FCal predicted a neutron flux in excess of $10^{17}$ n/cm$^2$ in a copper Mini-FCal, or triple that value in a tungsten one. This eliminated the possible use of tungsten as an absorber material in the Mini-FCal. The expected effect of the Mini-FCal on the energy deposited in the FCal1 module has also been simulated and
Fig. 7: On the left is a simulation of the variation of fluence in the Mini-FCal after a year of HL-LHC operation. The y-axis is the radius from the beampipe, the x-axis shows the depth in the Mini-FCal. The colour code gives the fluence in $10^{15}$ n/cm$^2$. On the right is the effect of radiation damage on the signal from diamond sensors and the effect of a possible correction. Note that the simulation used to produce this plot does not take into account electronic noise.

can be seen in Figure 5b. The Mini-FCal accomplishes its purpose well, reducing the energy deposited in the FCal1 module by up to a factor of 3.

Various diamond sensor tiling schemes have been simulated using the GEANT4 program [7] to optimize the response of the Mini-FCal. These simulations included the Mini-FCal and the existing ATLAS detector. Originally, simple square sensors of 1 cm$^2$ were chosen to reduce manufacturing costs. Layouts based on this sensor shape provided sub-optimal coverage and gave a poor energy resolution. The simple square sensors were then replaced with trapezoidal sensors that varied in dimension based on their position in the sensor layer. Each was still approximately 1 cm$^2$ in area. After several simulation iterations, it was decided that sensors would be placed on both sides of the substrate. This has allowed for near-perfect coverage for each detector plane. The current layout is illustrated in Figure 6. The corners of each sensor are notched to prevent voltage breakdown between them. The gap between the inner four sensor rings and the outer six is due to the change in the aspect ratio of the sensors necessary to provide full surface coverage.

Practical limitations on the number of readout channels require that there be less than 1000 used per Mini-FCal. This necessitates the ganging of eight or more sensors per channel. Due to the variation in particle fluence throughout the Mini-FCal, illustrated in Figure 7a, and the reduction of signal amplitude in diamond sensors with particle fluence, as described in Section 4.1, the ganging of Mini-FCal sensors is not a simple procedure. Care must be taken to gang sensors that have the same levels of radiation damage, otherwise the variations in signal amplitude will reduce energy resolution. The sum of the signal response from the entire gang will be corrected for based on the estimated average of the fluence at the positions of the corresponding sensors within the Mini-FCal. An example of how this might work is shown in Figure 7b, where a 25 GeV electron is reconstructed. The summed energy from the Mini-FCal is seen on the far right of the plot. On the left is the same plot after one year of HL-LHC irradiation, or 250 fb$^{-1}$. In the middle is that energy after correction factors have been applied to each gang, which is simply the factor by which the gangs signal amplitude has decreased from its initial value prior to irradiation. The variation is due to the varying levels of irradiation in each sensor and the variation in damage curves between detectors. Various ganging schemes have been simulated and these studies are on-going.

Studies of the possible energy resolution of the Mini-FCal have also been undertaken. Due to the nature of the diamond sensors, the signal amplitude from the sensors will degrade with time, as discussed in Section 4.1. This leads to a deterioration in the energy resolution in the Mini-FCal with time, as illustrated in Figure 8. The energy resolution is worse for low-energy particles, but rapidly improves to less than 5% and 6% for
5. Conclusion and Outlook

In summary, there are three potential problems facing the FCal at the luminosities projected for the HL-LHC: beam heating, ion build-up in the LAr gaps, and voltage drops across the HV resistors. Two solutions have been explored to solve these problems: a complete replacement of the current FCal, known as the sFCal, and the insertion of a small, warm calorimeter in front of the FCal, known as the Mini-FCal.

The technology of the sFCal is proven, thanks to the successful test of a 100 \( \mu \)m LAr gap at the HiLum experiment. Engineering difficulties involved in extracting the current FCal, relocating the highly irradiated detector, and installing the new detector in a limited time window still remain.

The installation of the Mini-FCal is expected to be much simpler, although complications may arise if the warm tube requires replacement. The sensor technology has been proven to operate successfully at the expected HL-LHC luminosities, though at 5% of their original signal amplitude, making them more difficult to use for calorimetry. However, with the proper corrections applied, initial studies indicate that the signal might be adequate for the Mini-FCals purpose.

6. Acknowledgements

I would like to thank the ATLAS liquid argon group for their help and advice, as well as the opportunity to present this information.

References

[1] G. Aad, et al., The ATLAS experiment at the CERN large hadron collider, Journal of Instrumentation 3 (2008) S08003.
[2] L. Evans, P. Bryant, LHC machine, Journal of Instrumentation 3 (2008) S08001.
[3] A. Artamonov, et al., The ATLAS forward calorimeter, Journal of Instrumentation 3 (2008) P02010.
[4] A. Glatte, et al., Liquid argon calorimeter performance at high rates, submitted to Nucl. Instr. and Meth. A, September 2011.
[5] M. Barbero, et al. (RD42 Collaboration), Development of diamond tracking detectors for high luminosity experiments at the LHC, CERN/LHCC.
[6] D. Axen, et al., Diamond detector irradiation tests at TRIUMF, Journal of Instrumentation 6 (2011) P05011.
[7] S. Agostinelli, et al., GEANT4 - a simulation toolkit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506 (2003) 205–303.