Upgrade plans for the ATLAS Forward Calorimeter at the HL-LHC

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Abstract. Although data-taking at CERN’s Large Hadron Collider (LHC) is expected to continue for a number of years, plans are already being developed for operation of the LHC and associated detectors at an increased instantaneous luminosity about 5 times the original design value of $10^{34} \text{ cm}^{-2} \text{s}^{-1}$. The increased particle flux at this high luminosity (HL) will have an impact on many sub-systems of the ATLAS detector. In particular, in the liquid argon forward calorimeter (FCal), which was designed for operation at LHC luminosities, the associated increase in the ionization load at HL-LHC luminosities creates a number of problems which can degrade its performance. These include space-charge effects in the liquid argon gaps, excessive drop in potential across the gaps due to large HV supply currents through the protection resistors, and an increase in temperature which may cause the liquid argon to boil. One solution, which would require opening both End-Cap cryostats, is the construction and installation of new FCals with narrower liquid argon gaps, lowering the values of the protection resistors, and the addition of cooling loops. A second proposed solution, which does not require opening the cryostat cold volume, is the addition of a small, warm calorimeter in front of each existing FCal, resulting in a reduction of the particle flux to levels at which the existing FCal can operate normally.

1. Introduction

Each of the two identical ATLAS Forward Calorimeters (FCal) is designed to work well in the harsh radiation environment near the LHC beams where the energy and density of the debris from the copious min-bias events are highest. The calorimeter design [1] is quite simple, employing only a few radiation tolerant materials. The active material of these sampling calorimeters is liquid argon. The ionization electrons drifting in the liquid argon gaps form the signal. These gaps are unusually small ($\sim 0.27$ mm in the first module) in order to avoid space-charge effects which would otherwise degrade the signal. Mechanical tolerances are held at the 1% level with a rod-tube electrode structure giving a good uniformity of response. Each FCal is made up of three modules, one behind the other, as seen from the interaction point (IP). The first, FCal1, is designed as an EM calorimeter with copper as the absorber material. Fig. 1 shows the structure of a unit cell of the FCal1 module. The second (FCal2) and the third (FCal3) are hadronic modules made of tungsten absorber in order to limit the longitudinal and transverse spread of the showers. Their unit cells look similar to the FCal1 unit cell.

The present ATLAS FCals perform very well at the luminosities reached to date ($\sim 6 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$) and are expected to continue to work well up to luminosities at the LHC design
value of $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ with a comfortable margin. But as the High Luminosity LHC (HL-LHC) phases in, several effects will lead to a degradation of the FCal response, first at the highest values of $|\eta|$ and then spreading to lower $|\eta|$ values as the luminosity approaches the new design value of $5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. The present CERN schedule projects this phase of the upgrade to come on-line after the long shutdown starting in 2022. Two R&D projects, in progress, are designed to project how the present FCal response will degrade at the HL-LHC luminosities. Each project is the subject of another talk at this conference [2][3].

Figure 1. FCal1 unit cell. Each FCal1 module is made up of 12,260 unit cells, each parallel to the LHC beam line. The nearest neighbor spacing is 7.5 mm. The copper rod diameter is 4.712 mm while the copper tube inner diameter is 5.250 mm, making the liquid argon gap 0.269 mm. The depth of the module and of each unit cell is 445 mm. The insulating PEEK fiber of diameter 0.25 mm is helically wound around the rod to keep it centered within the tube. The copper absorber surrounding the tube is not physically separated from the absorber of the neighbor cells.

2. Luminosity limitations
Three possible limitations at HL-LHC luminosities have been identified so far. 1) Space-charge effects [4] will degrade the response. The slowly-drifting positive argon ions build up in the liquid argon and distort the electric field. At sufficiently high ionization rates the electric field falls almost to zero near the anode where electrons then also begin to accumulate. In this “dead region” of the gap electrons and positive argon ions recombine thereby degrading the signal. 2) The High Voltage protection resistors are too large for the d.c. currents expected at the HL-LHC luminosities. These resistors were designed to limit the current drawn from the supplies in case of arcing, thereby protecting the sensitive front-end electronics from large pulses. The potential drop across these resistors will cause the potential across the liquid argon gaps to sag to unacceptably low values at HL-LHC luminosities. 3) The heat generated in the calorimeter absorbers due to $dE/dx$ energy losses (and, to a lesser extent, due to the Ohmic heating from the electrical currents in the liquid argon gaps) will grow to levels which threaten to boil the liquid argon. We expect that temperature measurements in the ATLAS End-Cap calorimeters at the higher luminosities achieved this year, coupled with our detailed heat-flow simulations, should allow reasonably accurate projections of this boiling threshold. From simulations alone it appears to be close to $10^{35} \text{ cm}^{-2} \text{s}^{-1}$, a bit beyond the presently projected HL-LHC luminosity.

Fig. 2 shows one estimate of how the signal will degrade due to the first two limitations. This estimate has large uncertainties which will be reduced as the two R&D projects are completed.

3. Upgrade options
Three possible paths have been identified so far to address the degradation of the FCal performance at HL-LHC luminosities. Either 1) replace the present FCals with new ones designed for the higher luminosities, or 2) insert a new, small module, a miniFCal, in front of each of the present FCals, or 3) do nothing.

The first path will be forced upon us in the event the cold electronics for the Hadronic End-Cap Calorimeter (HEC) must be replaced. This electronics was not designed for the
HL-LHC integrated luminosities but the safety margin in effect at the design time may be sufficient to ensure their survivability. Another talk at this conference [5] will describe the present understanding of the future of the HEC cold electronics. In order to access the HEC cold electronics the FCal must first be removed from the cryostat. Because the FCal will be activated it cannot be re-installed due to excessive personnel exposure. Even if the present HEC cold electronics will survive, the replacement of the present FCal modules with new ones is still an option.

New FCal modules will have the same design as the present modules with the following exceptions. 1) The liquid argon gaps will be smaller (of order 0.10 mm for FCal1) to avoid degradation due to space-charge effects at the highest HL-LHC luminosities. Substantial R&D has shown that reliable gaps as small as 0.10 mm can be manufactured. 2) The protection resistors in the High Voltage distribution system (located inside the cryostat) will be reduced sufficiently so that the highest current draw will not significantly reduce the potential across the liquid argon gaps. The present protection resistor values are now understood to be overly conservative since not a single preamplifier has been lost due to arcing in the liquid argon gaps. 3) Liquid nitrogen cooling loops will be integrated into the outer periphery of the modules to better remove the heat due to the energy deposited in the modules.

Figure 2. Simulated electrical signals at the FCal1 electrodes (before shaping by the electronics) near \(|\eta|=4.7\) where the ionization rate is highest. These signals are on top of a constant (i.e. no simulated fluctuations) d.c. background of ionization due to various rates of min-bias events. Various luminosities are shown. In the spirit of a safety margin, luminosities in excess of the expected values are included in this study. Note that the signal not only degrades in amplitude but also the signal shape changes in a way which depends on the poorly known electron-argon ion recombination rate.

Figure 3. Inner portions of the ATLAS End-Cap Cryostat with parts of the Electromagnetic End-Cap Calorimeter, Hadronic End-Cap Calorimeter, and FCal calorimeter in view. Sections of the cryostat and of the calorimeter modules have been cut away to show more of the structure, represented schematically. Also shown is the proposed diamond wafer miniFCal at the far (from the IP) end of the cryostat alcove. The other miniFCal versions look similar on the scale of this drawing. The front-end electronics is seen mounted on the front face of the calorimeter at larger radius from the beams.
In terms of the ATLAS calorimeter performance, this first path is the best option. But there are concerns about replacing the FCals in the case that the present HEC cold electronics is deemed able to survive throughout the HL-LHC running. Although the End-Cap cryostats were designed to be re-opened, it was found that the seals would not hold during the original closing of the cold covers and so these covers were welded shut. This increases the difficulty of opening and then re-closing these cryostats. The associated risk, cost, and schedule will figure into the decision.

The second path is very attractive from a risk and schedule point-of-view. The present End-Cap cryostats include a cylindrical “alcove”, coaxial with the beam line, and extending from the front face of the cryostat to the cryostat walls just in front of the FCal1 module as can be seen in Fig. 3. This alcove is open to the air and has space for a cylindrical calorimeter of outer radius of about 175 mm. A warm sampling calorimeter of sufficient depth in this location ahead of the present FCal would reduce the energy deposited in the present FCal modules so that the three problems described above would be avoided. The challenge is to find a sensitive medium which will survive the radiation and yet make a calorimeter with adequate performance.

The miniFCal proponents have considered diamond wafers (of order 1 by 1 cm$^2$) as the sensitive material. See Fig. 4. The charge collected from the wafers would form the signal. While diamond is known for its radiation hardness, the environment near shower maximum in the forward region is particularly severe. Neutron fluxes of order $3 \times 10^{16}$ n/cm$^2$/yr are predicted [6] at HL-LHC luminosities. Measurements [7] at TRIUMF show the response of diamond wafers near hadronic shower max dropping by about a factor 20 during an exposure of about $2 \times 10^{17}$ protons/cm$^2$.

More R&D would be necessary to develop the diamond wafer technology to the point of producing a reliable calorimeter for a working experiment. Questions to address are: 1) How linear is the diamond signal response to energy deposit? 2) Over what dynamic range is this response linear? 3) What is the in situ calibration method? 4) What energy resolution can be achieved? 4) Is the signal sufficiently stable with environmental conditions? 5) Is the sampling fraction large enough to minimize spurious signals? 6) Is the response sufficiently uniform over
the face of the calorimeter? One of the strong features of the ATLAS liquid argon calorimeter system is that it has minimal transitions in $\eta$ and $\phi$. The miniFCal would introduce an awkward transition in an $\eta$ region which presently has very uniform response. Finally there is worry that the cost of the diamond wafers is rather high.

Because of concerns about the degradation of the diamond wafer response with exposure to neutrons, two other technologies for a miniFCal have been considered. Ionization of xenon gas is likely to have stable response over the years of HL-LHC running. High pressures, of order 10 atmospheres, will help in reaching an acceptable sampling fraction. But the miniFCal must have sufficient density to limit the spread of showers in the longitudinal and transverse directions and this pushes the sampling fraction down to uncomfortable levels. Furthermore locating a pressure vessel in a semi-enclosed volume surrounded by the rather thin End-Cap cryostat warm wall and open to the ATLAS inner tracker raises safety concerns.

The other alternative is the well-understood liquid argon technology. In this case the miniFCal unit cell might be of similar or the same design as that proposed for the upgraded FCal1. This miniFCal might sit in its own cold vessel but share the warm vessel of the End-Cap cryostat. But the cold cryostat walls, the signal and HV cold feedthroughs, and the cryostat services will require additional space which will reduce the fiducial coverage of the miniFCal and add dead material which will degrade the overall calorimeter performance.

The miniFCal concept, regardless of technology, involves trade-offs which will lead to compromises in the calorimetric performance in the forward region. The “do nothing” path also leads to degraded calorimetric performance in this region as described above. Which is worse? The answer is not yet clear, mostly because the miniFCal technologies have not been developed far enough to allow reasonable projections. But the two liquid argon R&D studies at high ionization rates [2][3] must also be completed before the degradation of the present FCal will be well-understood. And even then we anticipate there will be aspects of the degradation which will remain uncertain.

4. Summary
In summary, the present ATLAS liquid argon FCal works well and is expected to continue to work well up to luminosities a little above the LHC design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. At higher luminosities the performance of the present FCal will start to degrade due to space-charge effects, sagging of the potential across the liquid argon gaps, and possible boiling of the liquid argon. Three paths for dealing with the degradation have been identified. Either 1) replace the present FCals with ones designed for higher ionization rates, or 2) place a new miniFCal in front of each of the present FCals, or 3) do nothing and suffer the degraded performance of the present FCals. Paths 2) and 3) both lead to degraded performance. The magnitude of this degradation and its effects on ATLAS physics may be determined with further R&D.

References