Irradiation tests and expected performance of readout electronics of the ATLAS Hadronic Endcap calorimeter for the HL-LHC

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ABSTRACT: The readout electronics of the ATLAS Hadronic Endcap Calorimeter will have to withstand an about 3–5 times higher radiation doses at the future high-luminosity LHC compared to the LHC design values. The radiation damages of the front-end electronics made in GaAs technology could significantly affect the hadronic endcap calorimeter performance. Recent measurements of characteristics of neutron and proton irradiated ASICs at room and liquid argon temperatures are reported, which allow an improved assessment of the expected degradation in high-luminosity LHC conditions. The results of these measurements are furthermore applied to simulations of the calorimeter performance. Results from replacement technologies, like Si CMOS, are also presented.

KEYWORDS: Radiation damage to electronic components; Calorimeters; Radiation-hard electronics; Front-end electronics for detector readout

1On behalf of the ATLAS Liquid Argon Calorimeter Group.
1 Introduction

The Large Hadron Collider (LHC) is the largest scientific instrument ever built. Proton-proton collision data were collected at centre-of-mass energies of 7 and 8 TeV during Run 1. The discovery of a SM-like Higgs boson is not the only goal of the LHC. There are many other goals such as searches for SUSY, Dark Matter, Dark Energy, origin of matter-antimatter asymmetry and so on. To extend further its discovery potential, the LHC will need a major upgrade to increase the luminosity.

After the first long shutdown, the approved program will continue in 2015 at close to the design energy and luminosity of 14 TeV and $10^{34}\text{cm}^{-2}\text{s}^{-1}$ respectively. In 2018 there will be a second long shutdown, after which the LHC will resume operation at an increased luminosity of $(2 - 3) \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. It is proposed to make a further Phase-II upgrade in the third long shutdown LS3 (2022-2023) to achieve luminosities well in excess of design with the high-luminosity LHC (HL-LHC) yielding a total integrated luminosity of 3000 fb$^{-1}$ after ten additional years of running. The nominal luminosity for HL-LHC is $5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, corresponding to an average number of proton-proton interactions in the same bunch crossing (pile-up) of $\langle \mu \rangle = 140$. An upper limit on the possible instantaneous luminosity of $7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, corresponding to $\langle \mu \rangle = 200$ is also considered here [1].

The HL-LHC conditions also require major changes of many ATLAS systems, especially those located at large pseudorapidity. The forward calorimeter (FCal) will face severe problems, whereas the electromagnetic barrel (EMB) and endcap (EMEC), and hadronic endcap calorimeter (HEC) will be capable of handling the harsh conditions. However, the whole front end electronics, all on-detector front-end boards especially, will have to be replaced for several reasons: radiation hardness but also capability to run at high luminosity.
2 HEC, cold electronics and expected radiation doses

2.1 HEC and its cold electronics

The hadronic endcap calorimeter of the ATLAS experiment [2] is a copper-liquid argon sampling calorimeter [3]. The HEC covers the pseudorapidity range of $1.5 < |\eta| < 3.2$. The HEC is housed within the two liquid argon end-cap cryostats with the EMEC and FCal. It consists of two wheels (front wheel HEC1 and rear wheel HEC2) per endcap (figure 1 left). The wheel is made of 32 identical modules. Each module in HEC1/HEC2 has 24/16 copper plates ($25/50\text{mm}$ thick) and $8.5\text{mm}$ liquid argon gaps, which are instrumented with active read-out pads. Signals from the read-out pads are sent to preamplifier (PA) and summing boards (PSB) mounted on the perimeter of the wheels inside the cryostat. The PSB boards carry highly-integrated PA’s and summing amplifier chips (figure 1 right) based on the Gallium-Arsenide (GaAs) FET technology. These ASICs (BB96) [4] are currently used in ATLAS for the HEC readout. The signals from a set of PA’s (4, 8, or 16) are summed in one output signal, which is transmitted to the cryostat feed-through [5]. There are 5632 read-out channels in the HEC.

2.2 Expected radiation doses and their effects

As mentioned above, an expected integral luminosity after ten years of HL-LHC running is $3000\text{fb}^{-1}$. The corresponding simulated $1\text{MeV}$ equivalent neutron fluence in silicon (SiNIEL) in the HEC cold electronics and with an applied safety factor of 5 to account for simulation uncertainties and incomplete simulation (in terms of geometry) is shown in figure 2. The expected radiation level in the HEC is $5.1 \times 10^{13} \text{h/cm}^2$ for hadrons ($>20\text{MeV}$) and $4.1 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ for neutrons. Recent comparisons of 2012 data and simulated radiation levels show very good agreement. The safety factor conservatively set at 5 is currently being revised and is expected to be reduced.

The most affected is the forward region of the detector where HEC, EMEC and FCal are located. The limitations in operation, signal reconstruction and radiation hardness of the end-cap and forward calorimeters at very high intensities have been studied in the Hilum [6] R&D project. Small modules of the EMEC, HEC and FCal calorimeters were built, placed in separate cryostats and exposed to high intensity proton beams of $50\text{GeV}$ at IHEP (Protvino, Russia). The maximum
beam intensity of up to $3 \times 10^{11} \text{p/s}$ was well beyond the maximum expected at HL-LHC. An instantaneous luminosity of $7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ at the HL-LHC corresponds to a beam intensity at IHEP of typically $3.4 \times 10^8 \text{p/s}$. These numbers are presently still subject to large systematic uncertainties due to shower simulation (12%), beam position (9%) and beam spread (18%).

The observed change in the pulse shape (saturation) was found in qualitative agreement with predictions and with the simulations carried out for space-charge limited regime caused by the ionization rate increase.

3 Irradiation tests

To measure radiation hardness of materials which are used in the HEC and their electronics radiation tests with protons and neutrons were conducted.

3.1 Proton irradiation tests

The proton irradiation test has been done at the Paul Scherrer Institute Villigen, Switzerland. A narrow beam of protons with 200MeV energy has been used to evaluate the radiation hardness against hadrons up to a fluence of $2.6 \times 10^{14} \text{p/cm}^2$ after 22h of beam time. The transistors were mounted on boards, which were then placed in 14 equidistant positions inside an aluminium frame with 17mm distance between slots and placed in the beam line (figure 3 left). The 6 boards closest to the beam window housed transistors in SiGe bipolar and Si CMOS FET technology (studied for the future replacement), and the GaAs FET based BB96 ASICs (currently used for the HEC readout). The proton flux was almost independent of slot position.
3.2 Neutron irradiation tests

The neutron irradiation tests were performed at the Fast Neutron Facility at the Nuclear Physics Institute of the ASCR in Rež near Prague, Czech Republic, with a 12 – 14 µA and 36 MeV proton beam at the variable-energy cyclotron U-120 hitting a 16 mm thick D₂O target to produce a neutron spectrum with a maximum neutron energy of 34 MeV and mean energy of 14 MeV [7]. The integrated fluence was about $2.2 \times 10^{16} \text{ncm}^{-2}$ (in terms of the 1 MeV equivalent NIEL in Si) in the first slot and falling inversely with distance squared for the following slots [8]. Similar to the setup in the proton test, 16 equidistant slots with distances of 17 mm between adjacent boards have been equipped and placed in front of the 3 mm steel plate enclosing the target (figure 3 right): 8 slots were equipped with the BB96 GaAs ASICs, 2 slots - with radiation diodes and activation foils, and the remaining slots - with test structures for the HEC power supplies.

3.3 Results of irradiation tests

During the irradiation the scattering parameters (S-parameters) of the BB96 ASICs have been continuously measured for the frequency range from 300 kHz to 100 MHz with a vector network analyzer to study the ASICs performance as a function of the fluence up to the maximum value at the end of the irradiation. The gain parameter for the FET transistor is the real part of the transconductance, for the Bipolar transistors it is the differential current gain and in case of the HEC BB96 PA’s - the transresistance $r_m = \frac{N_{\text{out}}}{M_{\text{in}}} = |S_{21} \cdot Z_{\text{in}}|$, which relates the output voltage to the input current. The most important parameters are the forward transmission coefficient $S_{21}$ and the input port reflection coefficient $S_{11}$, which can be translated into the input impedance $Z_{\text{in}} = 50 \Omega \left(1 + S_{11}\right)/(1 - S_{11})$, for our case of vanishing feedback coefficient $S_{12}$ and low load reflection. The product of the two gives the transimpedance gain in the frequency domain. This can be interpreted as the input current to output voltage signal amplification. The forward transmission coefficient was normalized to the value before irradiation and evaluated in the frequency range of the shaper electronics in ATLAS (4 MHz $< f < 10$ MHz). It was measured in-situ for the full systems consisting of one PA and a summing amplifier (Systems in the following text) during the proton and neutron irradiations, and
presented in figure 4. It shows that the device-to-device fluctuations increase with irradiation and that the effect of protons is about 4–5 times larger on the voltage gain compared to that of neutrons at the same fluence values.

About three months after the neutron irradiation tests at NPI in Řež the irradiated boards have been shipped to the MPP lab in Munich and re-tested with the same set of measurements as in-situ in both warm and cold (liquid nitrogen) conditions. The performance in cold is roughly equivalent to that in warm at 3 times larger fluences. The performance degrades quickly beyond \((3 - 4) \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2\) in cold conditions. Since up to 16 PA’s are summed by one summing amplifier in ATLAS the non-linearities for the PA’s cannot be corrected. Beyond neutron fluences of \((3 - 4) \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2\) the non-linearity quickly rises above the limit. Most of the non-linear behavior stems from the pre-amplification, not the driver.

4 Simulation of the HEC electronics degradation

A di-jet dataset was chosen to study the HEC performance degradation due to the radiation damages. A total of 74400 di-jet events have been generated by PYTHIA and fully simulated by GEANT4 for the ATLAS detector geometry. For each of four locations (layers) of HEC PSB an average value of the expected neutron fluence has been used as presented in figure 2. The readout channels are different in terms of the number of PA’s they have summed. There could be 4, 8 or 16 PA’s summed together. We selected a degradation factor \(g_i\) to the gain of the \(i\)-th PA, depending on its location in the HEC cryostat (i.e. one value for each HEC layer) using a Gaussian function with parameters as presented in table 1. The degraded value of the energy deposited in each HEC sub-gap was calculated as \(E’ = E_{\text{init}} \cdot g_i\). The PA output signals are summed actively by the summing stage of the ASIC and an overall calibration factor was applied to the summed output. For a group of typically 4 summed PA’s one correction coefficient \(C_g = 4/(g_1 + g_2 + g_3 + g_4)\) is determined and applied to each of the four PA’s individually, such that \(E'' = E’ \cdot C_g\).

The signal non-linearity cannot be corrected by means of the HEC calibration system. The non-linearity effect was introduced in the simulation by taking into account the measured increase of the power law exponent with the increase of radiation dose. The average values of the selected

![Figure 4. Forward transmission coefficient as measured during the proton (left) and neutron (right) irradiations vs. the fluence. The neutron fluence is given in 1MeV equivalent for silicon. The red vertical lines indicate HL-LHC limits including a safety factor of 5 [8].](image-url)
Table 1. Average values of the HEC electronics degradation parameters.

| PSB layer | n-fluence gain decrease | non-linearity factor, $\overline{\gamma}$ | exponent, $\gamma$ |
|-----------|-------------------------|-----------------------------|------------------|
| 0         | 4.0·$10^{14}$           | 0.830±0.025                 | 1.021±0.004      |
| 1         | 3.0·$10^{14}$           | 0.870±0.019                 | 1.013±0.003      |
| 2         | 1.0·$10^{14}$           | 0.960±0.007                 | 1.005±0.001      |
| 3         | 1.0·$10^{14}$           | 0.960±0.007                 | 1.005±0.001      |

Figure 5. The expected effects of electronics degradation on the HEC performance: energy dependence of the jet energy resolution (left) and relative non-linearity (right).

degradation parameters are shown in table 1. Again, a randomly selected (using a Gaussian function) non-linearity factor, $\gamma$, was assigned to each PA and a new value of the deposited energy was calculated as $E_{\text{degr}} = (E')^\gamma E_{\text{ref}}^{(1-\gamma)}$, where $E_{\text{ref}}$ denotes a renormalization energy scale in order to equalize the visible energy before and after the degradation at the selected energy point. In the analysis, the reference energy was set to 5GeV and 10GeV, to account for different sampling fractions in front and rear longitudinal sections of the HEC, respectively.

Finally, the initial values of the deposited energy in every HEC sub-gap, $E_{\text{init}}$, were replaced in each event by the degraded values, $E_{\text{degr}}$, and the regular digitization and reconstruction algorithms were applied. The degraded pulse shape and autocorrelation functions corresponding to the assumed fluence values for each individual HEC channel were used in the digitization step instead of the default ATLAS values.

The effect of electronics degradation on the HEC performance is clearly seen from the results shown in figure 5. The energy dependence of the ratio of the RMS of the reconstructed jet energy over the mean reconstructed jet energy (jet energy resolution) is shown in figure 5 left, whereas figure 5 right demonstrates the ratio between the mean reconstructed jet energy and the true value (linearity) as a function of truth jet energy. The results are presented for initial and degraded jets. A significant deterioration of the jet energy resolution and the linearity is evident.

5 Alternative technologies

Due to the increase of the integrated luminosity by up to a factor of 5 in the HL-LHC, it was decided to re-examine the radiation hardness of the current HEC cold electronics and of potentially
Table 2. Loss of gain of various transistor technologies under proton and neutron irradiation. The neutron fluences are quoted for Si-NIEL in ATLAS under warm conditions.

| Technology      | Proton fluence | Neutron fluence |
|-----------------|----------------|-----------------|
|                 | $5.1 \times 10^{13}$ p/cm$^2$ | $4.1 \times 10^{14}$ n$_{eq}$/cm$^2$ |
| Si CMOS FET     | -3%            | 0%              |
| SiGe Bipolar    | -3%            | -1%             |
| GaAs FET        | -              | -5%             |
| GaAs BB96       | -5%            | -8%             |

more radiation hard, alternative technologies. The three different transistor technologies tested were: Si CMOS FET in SGB25V 250nm technology from IHP, SiGe Bipolar HBT (IHP SGB25V 250nm and IBM 8WLBiCMOS 130nm), and the GaAs FET currently used in ATLAS, either the Triquint CFH800 250nm transistors themselves (referred to as GaAs FET) or integrated into the HEC BB96 PA's and Systems (referred to as GaAs BB96) [9]. The results of the test of alternatives and technologies which are currently used, are shown in table 2. The absolute errors are about 0.05% for the Si CMOS, 1% for the GaAs and 2% for the SiGe Bipolar. Also the fluence error translates to an additional relative error on the gain of 15% for all measurements. As the single GaAs FETs were missing in the proton beam, the cold measurements were done only for the BB96 and only for the neutron irradiation.

The Si CMOS FETS and the SiGe Bipolar transistors are more radiation hard than the currently used GaAs FETs. From the irradiation tests the protons seem to cause more damage to the electronics than the neutron irradiation for the Si CMOS and SiGe Bipolar transistors. But one should note that an order of magnitude more neutrons than protons are expected to impact the HEC cold electronics. In the case of the GaAs FETs, the gain degradation is roughly the same for both types of irradiation, although quantitative assessment suffers from the fact that two different gain parameters (transconductance vs. transresistance) were compared.

6 Conclusion

The GaAs technology currently used in the HEC cold electronics degrades measurably at the expected radiation levels, in particular under the more realistic cold conditions. The gain losses can be calibrated out on average, but the non-linearities of the PA’s cannot be corrected. The two effects taken together lead to a significant degradation of the HEC performance, which needs further investigation in terms of its impact on physics measurements. Both, the Si CMOS FETs and the SiGe Bipolar transistors, considered as alternative technologies are more radiation hard than the currently used GaAs FETs. Preference is given to the Si CMOS FETs, since the SiGe Bipolar transistors, due to their operation at cold temperatures, require a stabilization of their operation point [4], which would lead to a more complex circuitry.
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