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Research and Development for the ATLAS Forward Calorimetry at the Phase-II LHC

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Abstract. During the LHC Run-1 data taking period the ATLAS calorimeter system demonstrated an excellent performance of electron and photon reconstruction as well as hadronic jets and missing transverse energy measurements. These precision measurements played a major role in the discovery of the Higgs boson. Further studies of the Higgs properties and SUSY searches should be performed at the High Luminosity LHC (HL-LHC) which will run at 5-7 times the original design luminosity to provide 3000 fb^{-1} of data by 2037. Total irradiation doses will be more than doubled compared to the original design, taking into account a reduced safety factor of 2 representing our confidence in radiation background simulations. Moreover, the increased instantaneous luminosity will result in much higher detector occupancy. The ATLAS Forward Calorimeters (FCal) will be affected by these factors. A rich R&D program is ongoing to evaluate the consequences of the LHC modernization and to investigate different scenarios proposed for the Phase-II detector upgrade.

Introduction

The ATLAS Detector [1] is a general-purpose apparatus at the LHC designed for studying *pp*-collisions at the centre-of-mass energy of 14 TeV and an instantaneous luminosity of 10^{34} cm^{-2}s^{-1}.

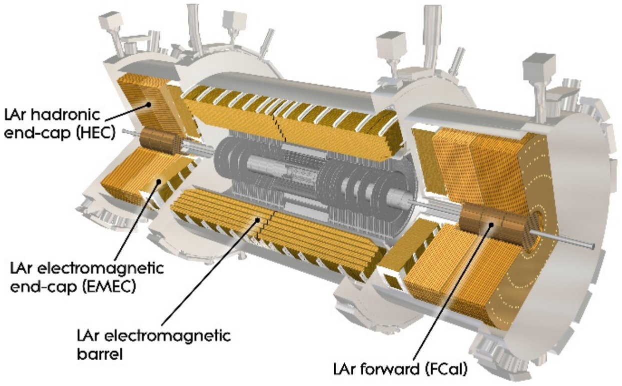

FIGURE 1. A general layout of the ATLAS liquid argon calorimeter system [1].

A general view of the ATLAS liquid argon calorimeter system is presented in Fig.1. The current very good performance of the calorimeter system which comprises the liquid-argon electromagnetic, hadronic (HEC) and forward (FCal) sub-systems, should be maintained also at HL-LHC instantaneous luminosities of $5{\cdot}10^{34}$ cm^{-2}s^{-1}. This corresponds to about 140 inelastic *pp*-collisions per beam-crossing. Although a number of studies have confirmed that the intrinsically radiation hard LAr technology will operate at the HL-LHC, the calorimeter upgrade program is proposed [2-3] to deal with the expected challenges and to maximize the physics performance and discovery potential of the experiment.

In contrast to the liquid argon electromagnetic and hadronic end-cap calorimeters, the performance of the forward (FCal) calorimeter will be degraded by high energy particle density at HL-LHC conditions. The upgrade program includes a new Liquid Argon Forward Calorimeter (sFCal), with higher granularity and smaller electrode gaps, with improved cooling to reduce the impact of the very high instantaneous luminosity at HL-LHC. It can lead to space-charge effects from ion-buildup in the LAr gap, as well as large reductions in the voltage on the electrodes, and finally to potential over-heating (possibly even local boiling) in the LAr. The scenario may also include a finely segmented Si - based preshower layer (HGTD) with precision time resolution covering approximately the pseudo-rapidity[1] range $2.4 < |\eta| < 4.0$, in order to assign charged particles to different collision vertices to mitigate pile-up effects in energy reconstruction . The readout electronics need to be upgraded because of radiation tolerance limits, lifetime, and because the on-detector front-end electronics cannot operate with the Level-0 and Level-1 trigger rates and latencies required for the HL-LHC luminosities.

Upgrade options for the ATLAS forward calorimeters

The effect of space charge on the pulse shape which affect the detector performance is under study in the HiLum experiment at Protvino. Heat flow measurements with a mock-up are also performed to study the possibility for argon over-heating and bubble formation in the cryostat. If it cannot be established that the liquid argon will not boil in the harsh HL-LHC environment, the upgrade of the forward region will be required. Upgrade options under investigation are:

- a new sFCal replacing existing FCal and employing smaller LAr gaps (100μm), with better cooling and higher transverse granularity;
- a miniFCal in front of the high-η part of the existing FCal, which would be based on either LAr/Cu technology (“cold” miniFCal option) or on Si/W or single-crystal diamond/Cu technology (the “warm” option).

Different detector technologies will be tested for HGTD, including:

- multi-channel plate-based detectors;
- single-crystal or poly-crystalline diamond sensors;
- various silicon-based detectors.

Detailed simulation studies and R&D’s are needed for optimization of the upgrade scenario.

Test-beam experiment at U-70 accelerator at Protvino

Optimization of detector parameters in the HiLum experiment at the Protvino U-70 beam-test forms a basis for the detector upgrades required for HL-LHC. Several prototype modules of the ATLAS forward calorimeters have been tested in high-intensity proton beams addressing, in particular, the effect of space charge on the pulse shape which affects the detector performance.

Beam-test results for two modules, one with a narrow LAr gap (119 μm) and another with nominal (269 μm) electrodes are compared in Fig. 2. Whereas the latter (shown in the inset) shows the fall of response at a critical beam intensity corresponding (within uncertainties [4]) to the nominal LHC luminosity, 10^{34} cm^{-2}s^{-1}, the narrow-gap electrodes demonstrate a stable response up to ten times higher intensities.

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[1] The ATLAS reference system is a Cartesian right-handed co-ordinate system, with the nominal collision point at the origin. The anti-clockwise beam direction defines the positive z-axis, while the positive x-axis is defined as pointing from the collision point to the centre of the LHC ring and the positive y-axis points upwards. The azimuthal angle φ is measured around the beam axis, and the polar angle θ is measured with respect to the z-axis. The pseudorapidity is defined as $\eta=-\ln\tan(\theta/2)$.

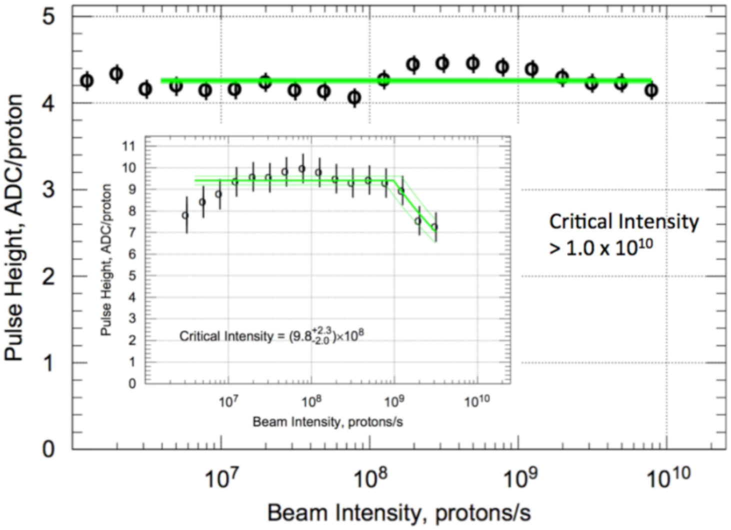


FIGURE 2. Response from the test cells of the forward calorimeter (signal pulse height) with two different gaps - small (119 μm) and nominal one (269 μm, shown in the inset) - to the increase of proton beam intensity [4].

Simulation results for the high-granularity sFCal

The expected improvements of the forward calorimeter performance will come from an increase of the readout granularity by a factor 4 in the range $3.2<|\eta|<4.3$ in the first FCal section. This will result in better η and ϕ resolutions for the calorimeter clusters, an increased sensitivity to the jet substructure and a reduced pile-up contribution per calorimeter cell.

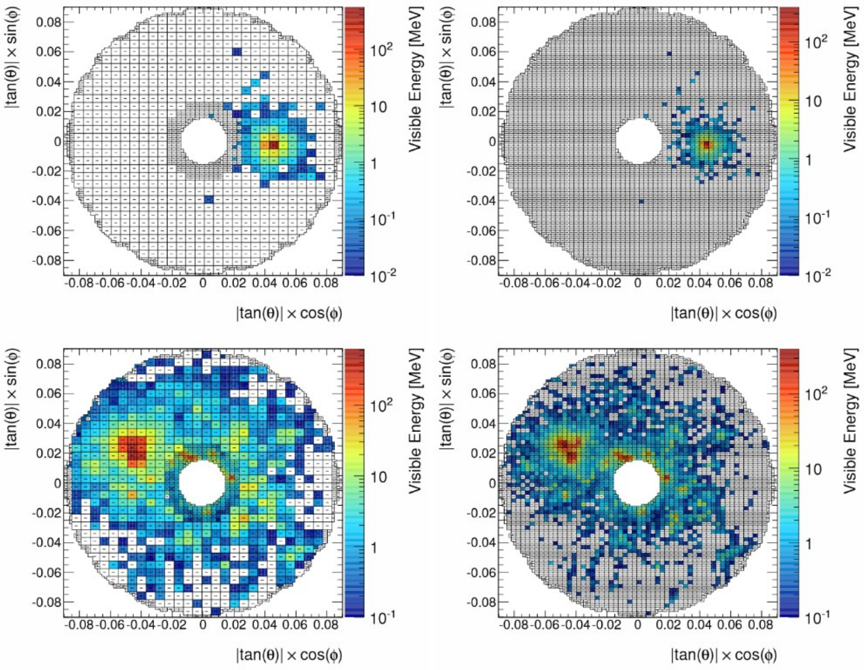


FIGURE 3. Event for the same electron (upper plot) and the same single jet (lower plot) in the FCal (left) and the high-granularity sFCal (right).

The effect of improvements in the readout granularity is evident from the simulation results presented in Fig.3. The plots show the energy deposited in the calorimeter cells for one electron and for one hadronic jet simulated for both the present FCal detector and for the geometry of the high-granularity sFCal implemented in the full chain of the ATLAS simulation infrastructure.

LAr calorimeter readout electronics

The current LAr calorimeter readout electronics is incompatible with the future L0 and L1 trigger rates of 1 MHz and 400 kHz. It will be improved in two steps. In the Phase-I upgrade the trigger readout will be equipped with additional electronics to provide better granularity signals to the L1 trigger system. The Phase-II L0 trigger will be based on calorimeter and muon spectrometer signals. Full replacement of the front-end and back-end readout system is foreseen for the Phase-II upgrade. Only the HEC pre-amplifier system, which is designed to withstand HL-LHC radiation doses and is located inside the cryostat, and LAr trigger digitizer board (LTDB) installed during the Phase-I upgrade [5] will not be replaced.

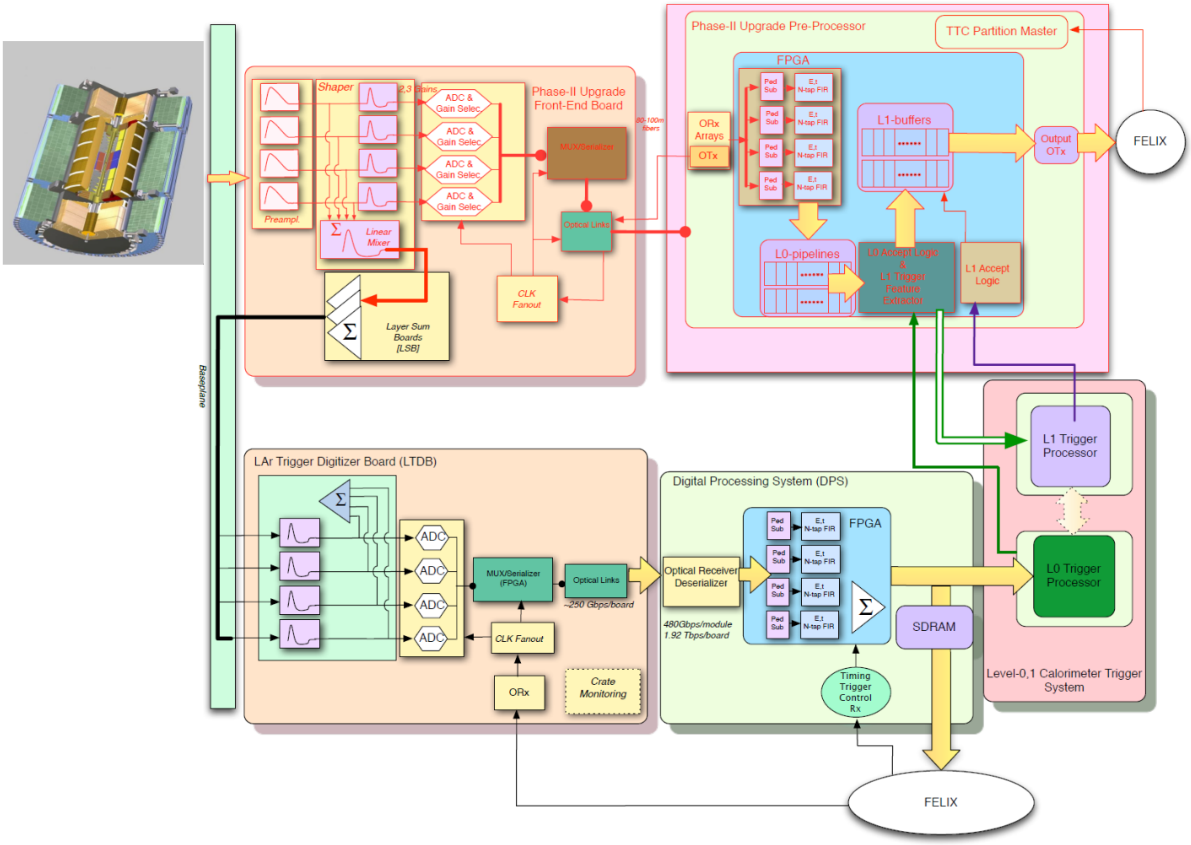


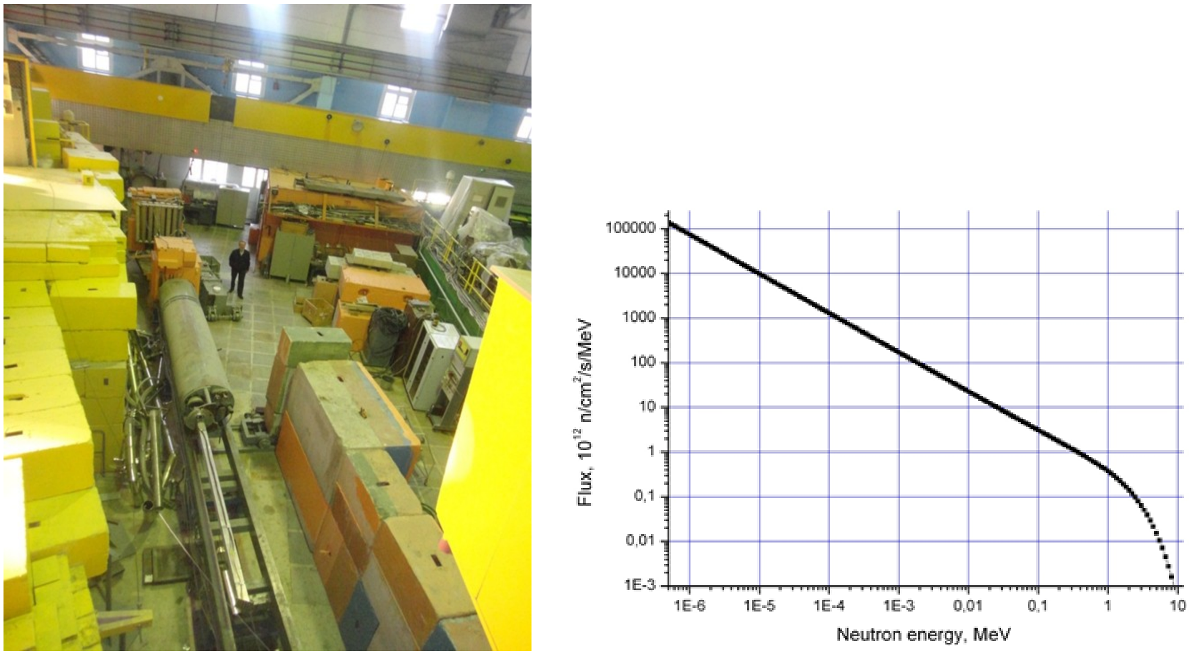
FIGURE 4. Architecture of the Phase-II readout system of the ATLAS LAr calorimeters.

The layout of the Phase-II LAr readout is presented in Fig. 4. Pre-amplification, shaping and digitization of signals from all 183000 LAr detector channels will be performed on the new Front-end Boards (FEB2) at the rate of 40 or 80 MHz. The data will be received by the back-end pre-processor system for energy calibration and pile-up suppression. The FEB2 will also produce input signals to the LTDBs which will feed L0 trigger system with inputs for the so-called Super-Cell readout.

Several alternatives are under study in various groups of the LAr community for the analog, ADC and optical link parts of the front-end. The R&D program includes development of a new radiation-tolerant calibration board, the radiation and performance tests of commercial analog and digital components for the low-voltage power system of the HEC. Efforts continue on development of the back-end system relying on commercial components.

Irradiation facility at the IBR-2m reactor at JINR Dubna

The detector materials and electronic components must satisfy the future trigger and radiation tolerance requirements. An intensive program of irradiation tests has been carried out at the pulsed neutron IBR-2 reactor at JINR Dubna during the period of the ATLAS detector construction. To provide adequate conditions for radiation hardness tests aimed at the HL-LHC conditions the irradiation facility has been modernized [6]. The general view is shown in Fig. 5a. The plot in Fig. 5b represents the measured neutron flux as a function of the neutron energy.

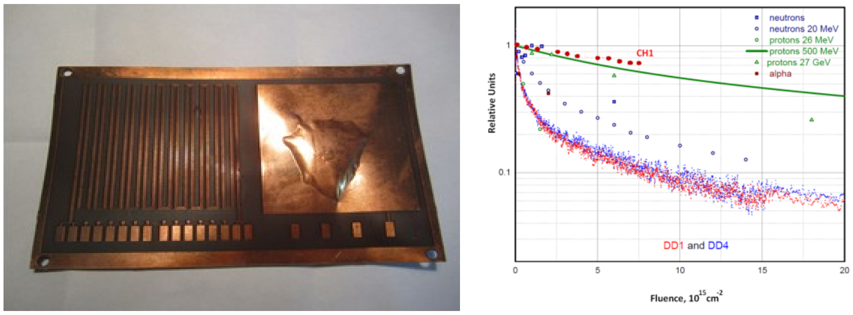


a) b)

FIGURE 5. General view of the Dubna irradiation facility (a) and the fast neutron flux (b).

Samples for the irradiation tests are located in a container with lateral dimensions of 16cm×16cm at the edge of an extension arm which is mounted at the head of a movable platform. To control the neutron fluence, activation foils are placed near irradiated materials and the induced activity is subsequently measured. The maximum fluence of neutrons with energies above 1 MeV for the sample placed at a distance of 30 mm from the reactor moderator is 10^{18} n cm^{-2}. High flux of fast neutrons and a large beam aperture makes the facility very suitable for testing detectors and electronics which are supposed to be used in the Phase-II upgrade program.

Some examples of the tests performed recently at the Dubna facility are presented in Fig. 6. The plot on the left (6a) shows a “standard” PCB sample made of FR4 and irradiated to the neutron fluence about 3×10^{17} n cm^{-2}. The radiation damages resulted in outgassing from the plastic material which caused destruction of the PCB. Similar results were observed for another popular material – G10. In the same tests (doses) the PCB samples made of Rogers 4450B and Arlon 85N survived [7], but more tests are required for the final conclusion.



a) b)

FIGURE 6. Irradiation tests examples: (a) PCB sample made of FR4 and irradiated to fluence about 3×10^{17}n cm^{-2}; (b) signal degradation of the diamond sensors in various beams (see legend), DD1 and DD4 are two poly-crystalline sensors irradiated in Dubna in 2012 and CH1 denotes recent irradiation results for a single-crystal diamond sensor from Nanjing University (China).

The plot on the right (6b) shows compilation of the irradiation tests performed on diamond sensors in various beams (see legend) [8]. The bottom curve made of small red and blue dots represents data for two poly-crystalline sensors (DD1 and DD4) irradiated in Dubna in 2012: only 2% of the initial response remained after the fluence of 10^{17} n cm^{-2}. The very recent tests performed at the IBR-2m on a single-crystal sensors from the Nanjing University (China) and labelled as CH1 [9] show much better resistance to neutron irradiation. These sensors are therefore promising candidates for a future application in high energy physics experiments.

Conclusions

A rich R&D program is proposed for ATLAS calorimetry, including modernization of the design and development of new detectors. The final selection of the upgrade options and technologies will be driven by performance considerations and results of risk analyses. Intensive simulation studies and comprehensive tests, including mock-up, test-beam and irradiation tests are ongoing in order to prepare the ATLAS LAr calorimeters for the HL-LHC running.

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