Irradiation Tests and Expected Performance of Readout Electronics of the ATLAS Hadronic Endcap Calorimeter for the HL-LHC

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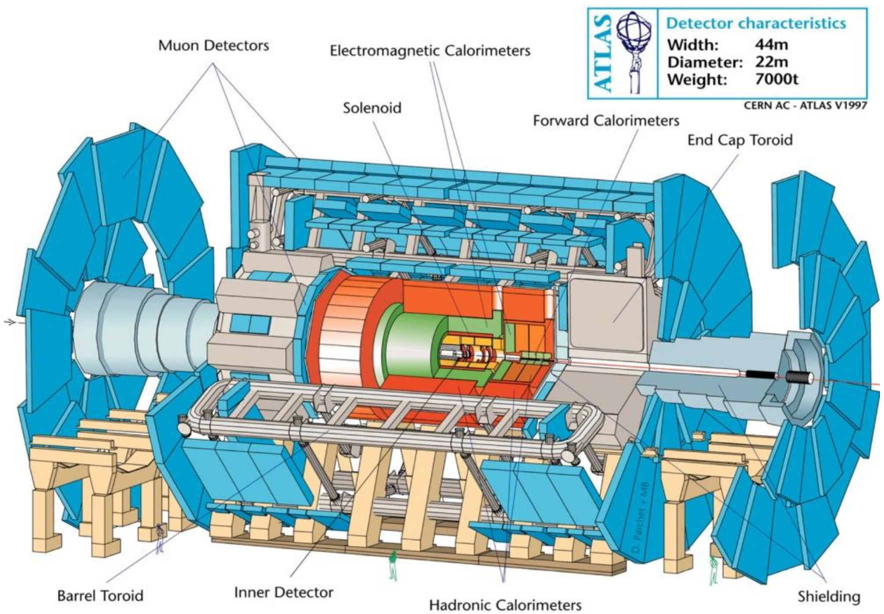
OUTLINE

- The ATLAS Detector & Calorimeter system at HL-LHC
- The HEC and cold electronics, expected radiation levels
- Proton & neutron tests and HEC electronics degradation
- Simulation algorithm & results
- Conclusions

The ATLAS Detector at the HL-LHC

- *One of two general purpose & Higgs discovery detectors at LHC*
- *The luminosity and the beam energy are important factors for discovery potential*



Upgrade plans for the LHC

- ***Phase 0 (2013-14)***

Upgrade to design energy and nominal luminosity
[$\sqrt{s}$=13-14 TeV & L=$1\cdot10^{34}cm^{-2}\,s^{-1}$]

- ***Phase 1 (~2018)***

Increase of luminosity to
[L= (2-3) $\cdot10^{34}cm^{-2}\,s^{-1}$]

- ***Phase 2 (~2022)***

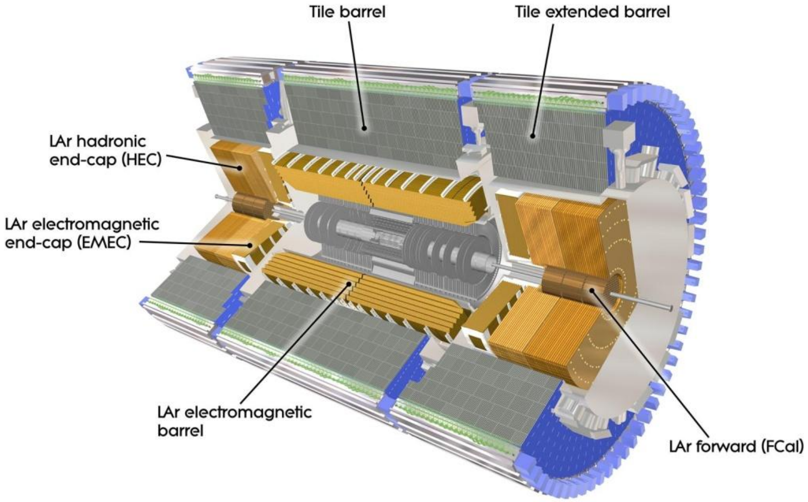
High-luminosity LHC (HL-LHC)
[L = (5-7) $\cdot10^{34}\,cm^{-2}\,s^{-1}$]

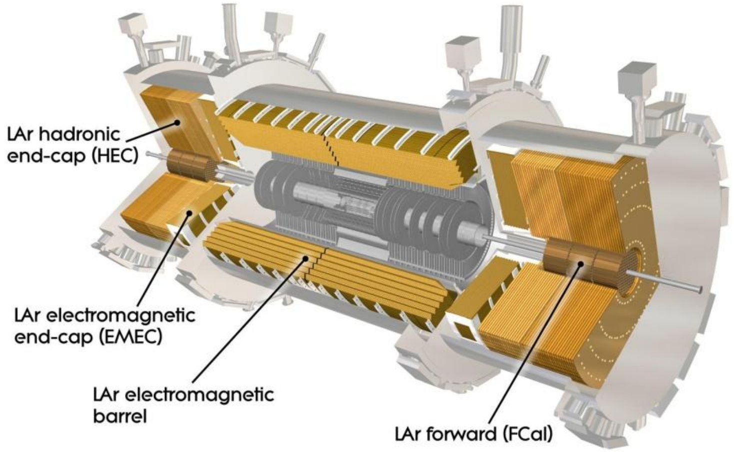
Calorimeter system of the ATLAS Detector

The ATLAS calorimeters:

- Electromagnetic (EM) & hadronic (H)
- Covering |η|<4.9 region
- 40 Mhz bunch crossing rate
- Design energy resolution:

$10\%/\sqrt{E} + 0.7\%$ for EM & $\sim 50\%/\sqrt{E}$ for H





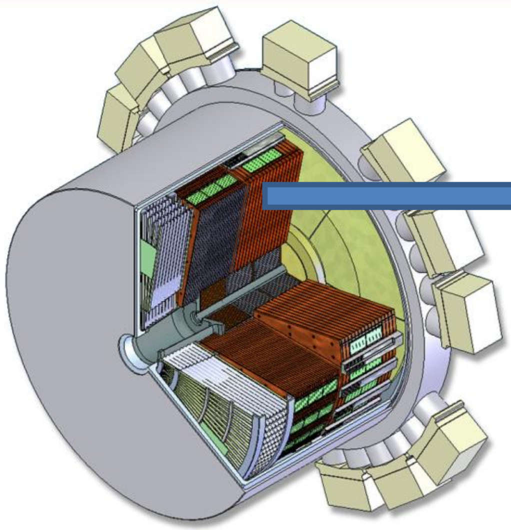
The Liquid Argon (LAr) calorimeter system consists of: material:

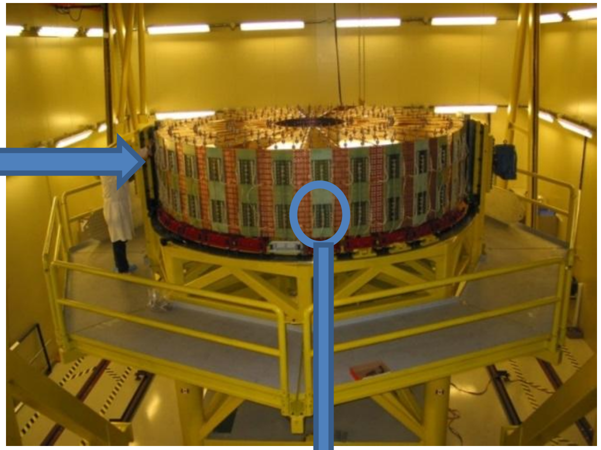
- Electromagnetic barrel (EMB) Pb&LAr
- Electromagnetic end-caps (EMEC) Pb&LAr
- Hadronic End-caps (HEC) Cu&LAr
- Forward calorimeter (Fcal) Cu,W&Lar

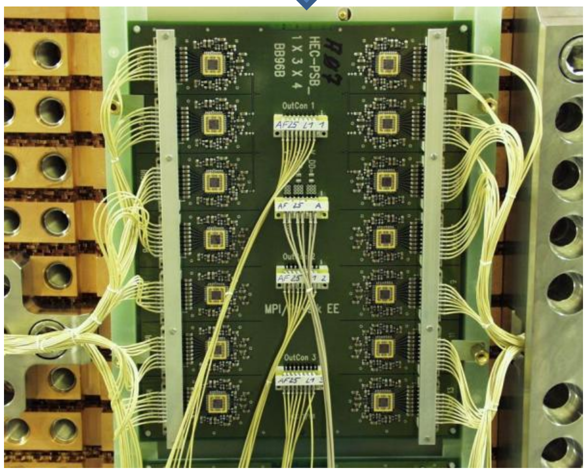
There are 182468 read-out channels in the whole LAr calorimeters

The HEC and cold electronics

Endcap cryostat



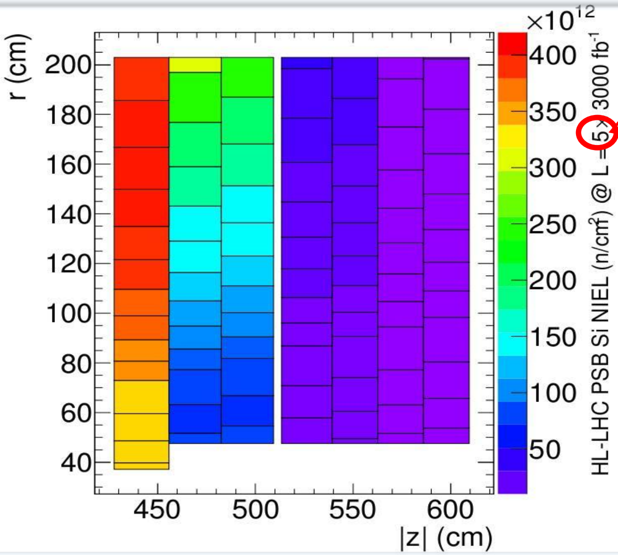




- Coverage: 1.5<|η|<3.2
- The Cu plates (thickness 25 mm & 50 mm)
- 4 wheels, 2 in each end-cap
- 4x32 modules, 5632 readout channels
- Signals are sent from read-out pads to the preamplifier and summing boards (PSBs)
- We use GaAs FET technology
- Electronics is located at the outer surface of the wheel inside the cryostat

Expected radiation in the HEC in HL-LHC

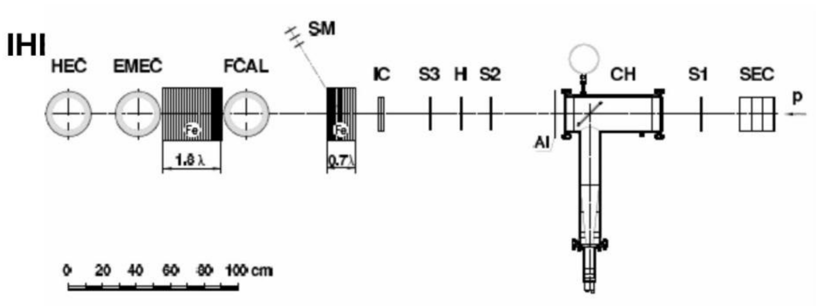
The plot shows simulated 1MeV equivalent neutron fluence in silicon (Si NIEL) in the HEC under HL-LHC conditions after 3000 fb^{-1} and with an applied safety factor (SF) of 5 (expected to be smaller) to account for simulation uncertainties & incomplete simulation (in term of geometry).



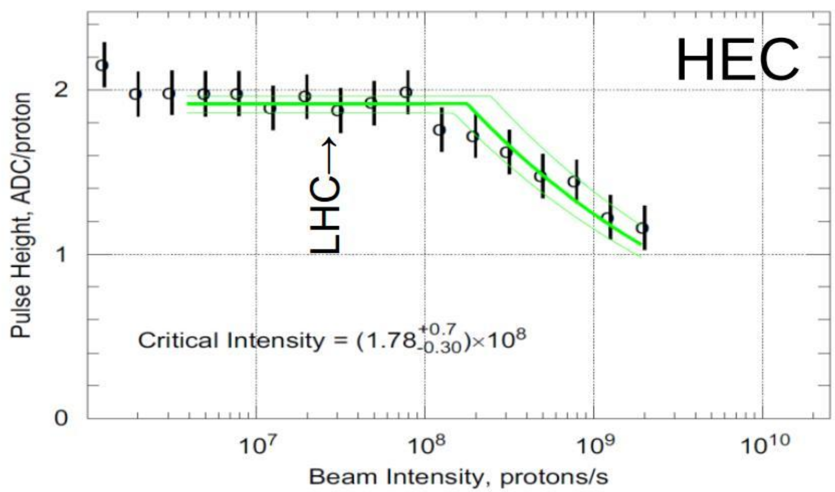
- At the LHC $L=10^{34}\ cm^{-2}s^{-1}$ & $L_{Int}=1000fb^{-1}$ expected radiation level:
  - ✓ $3.2x10^{12}h\ cm^{-2}$ for hadrons (>20MeV)
  - ✓ Si NIEL $1.7x10^{13}\ n_{eq}cm^{-2}$
- At the HL-LHC $L=5x10^{34}\ cm^{-2}s^{-1}$ & $L_{Int}=3000fb^{-1}$ expected radiation level:
  - ✓ $5.1x10^{13}h\ cm^{-2}$ for hadrons (>20MeV)
  - ✓ Si NIEL $4.1x10^{14}\ n_{eq}cm^{-2}$

Recent comparisons of 2012 data and simulated radiation levels show very good agreement.
SF should be revised soon thanks to the in situ radiation measurement and the future improved simulation.
The simulation SF for NIEL will be reduced to ~2.
New simulations for the HEC area are being prepared.

HiLumi experiment at Protvino



Setup of high intensity proton beams at IHEP (Protvino)



Dependence of the HEC signal (at 1.2 kV) on beam intensity.

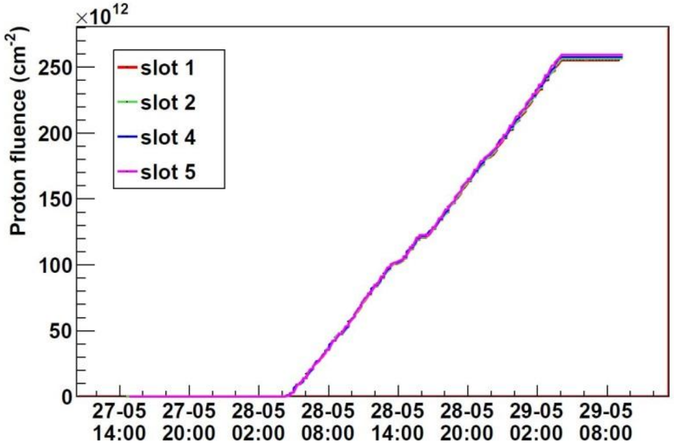
HiLumi results:

- Beam & critical intensity at HV of 1.2 kV & L = 10^{34} cm^{-2}s^{-1} is 4.8×10^7 p/s & $(1.8\pm0.7) \times 10^8$ p/s respectively
- HEC is operated at HV of 1.8 kV critical intensity ~4.0×10^8 p/s, which is well above the HL-LHC requirements

The present design of HEC will allow a safe operation in a harsh Hl-LHC environment
[NIM. A669 (2012) 47–65]

Proton irradiation at PSI

We used the Proton Irradiation Facility at Paul Scherrer Institute (PIF at PSI) (Villigen, Switzerland) with a 198.9 MeV proton beam of 2.71 nA



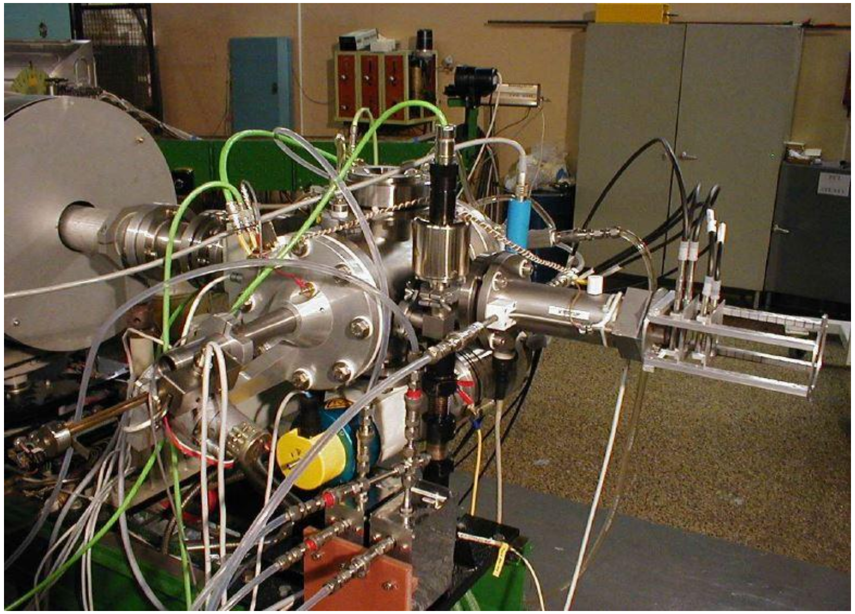
A narrow beam has been used to evaluate the radiation hardness against hadrons up to a fluence of 2.6×10^{14} p/cm^{-2} after 22.05 h of beam time.

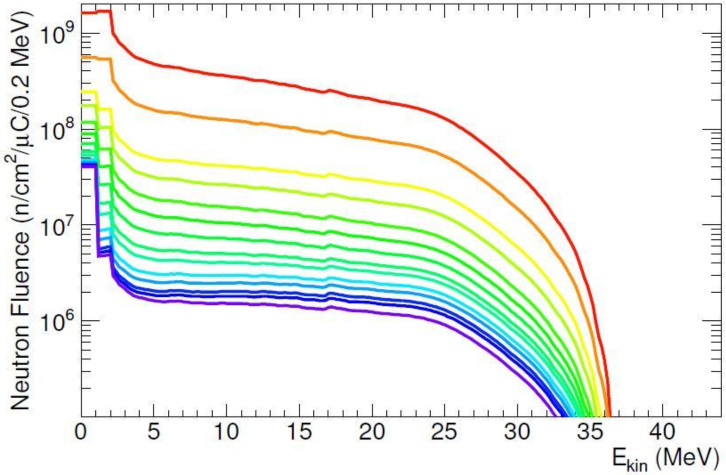
Flux is almost independent of slot position

Neutron tests at NPI in Řež

Fast Neutron Facility at Nuclear Physics Institute (NPI) in Řež near Prague

- A 36 MeV proton beam (in the cyclotron U-120 at NPI) was used for the neutron beam production
- A D_2O target was installed to produce neutrons with $E_{kin} \approx 14$MeV mean energy





- Neutron flux up to 10^{11} n/cm^2/s
- Maximum neutron energy of ~36MeV

Neutron & proton tests results

Irradiation tests program:

- Up to 16 boards were placed in aluminum frame aligned along beam axis
- S-parameter measurement with Vector Network Analyzer in frequency range from 300kHz to 100MHz and DC values monitoring were done on-line, as well as linearity scan with 500 ns triangular pulses of varying amplitude
- Both individual preamplifiers and integrated HEC BB96 ASICs (system = several preamplifiers + summing amplifier) were measured

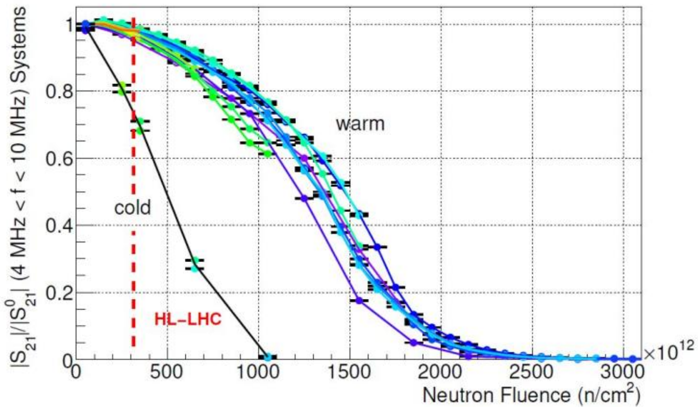
In-situ measurement at room temperature

- Continuous measurements were performed during irradiation
- Influence of long cables was taken into account by calibration measurement (setup was installed in low radiation area)

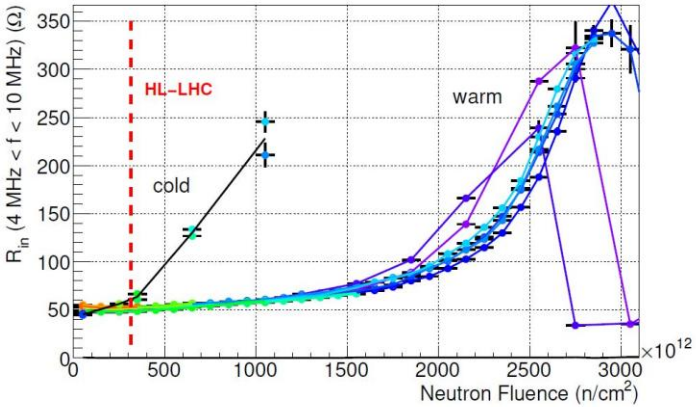
Post-irradiation measurement at cryogenic temperatures

- Measurement at MPI after deactivation
- Boards immersed in liquid N_2 in a small cryostat

HEC Cold Electronics degradation



Forward transmission coefficient normalized to the value before irradiation

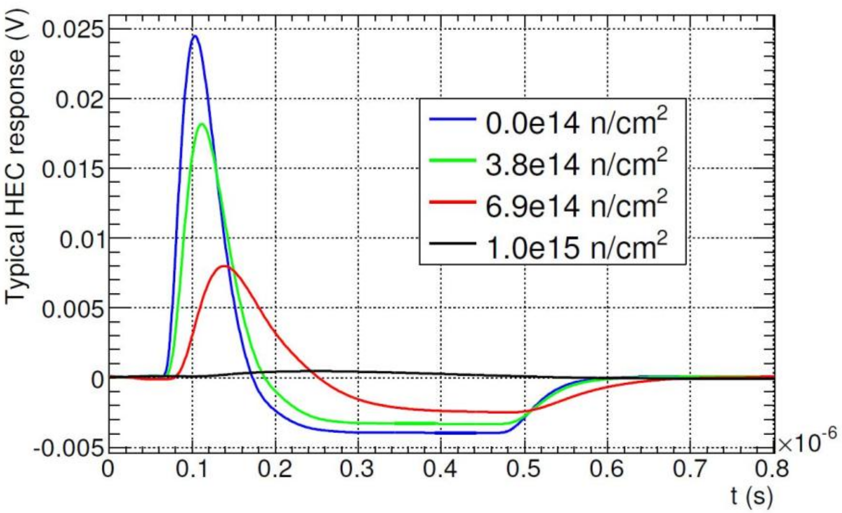


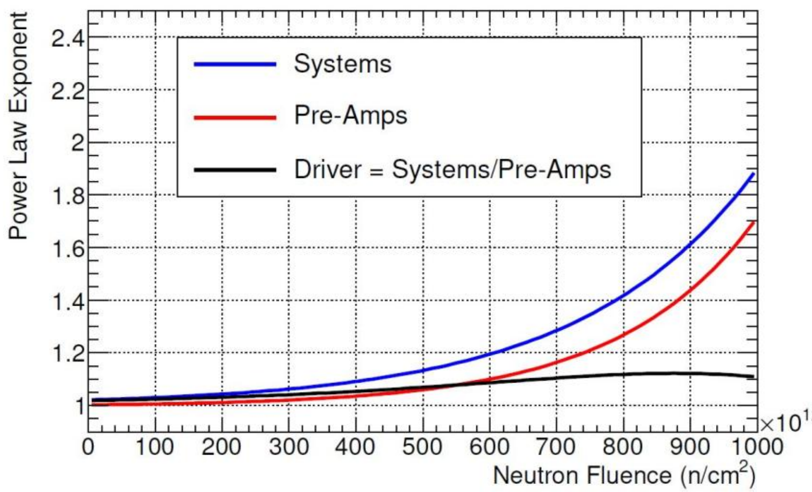
Input impedance for the systems

evaluated in the frequency range of the shaper electronics (4MHz < f < 10 MHz) as function of neutron fluence for both warm and cold conditions.

- Neutron irradiations in warm and three months after the irradiation in cold vs. the fluence
- The neutron fluence is given Si NIEL
- The red vertical lines indicate the HL-LHC limit including a safety factor of 5 new, reduced simulation safety factors will be applied in future work.
- The effect of protons is about 4−5 times larger than neutrons at the same fluence values.

Inputs for simulation of HEC performance





Simulated typical response to a 400 ns triangular ionization current in the HEC

Gain degradation with neutron fluence is evident

Relative non-linearity as function of neutron fluence:

- Superimposed fits to the data of non-linearity of the preamplifiers only
- Same for the system consisting of preamplifier and driver
- Their ratio, which can be interpreted as the non-linearity of the driver stage alone.

Simulation algorithm

Readout channels are different in terms of the number of preamplifiers they have summed. There could be 4, 8 or 16 PAs summed together.
We have to select the degradation factor g_i to the gain of the i-th preamp, depends on its location in the HEC cryostat (i.e. one value for each HEC Layer). Depending on the number of PA's in the readout chain and the number of calibration lines involved, we calculate correction factor which is the same one for every PA in the chain.

A new value of the energy deposited in each HEC sub-gap: $E_{deg} = E_{init} \cdot g_i$,

g_i - gain degradation factor (randomly selected using a Gaussian),

Degraded energy , $E_{degr} = E_{deg} \cdot C_g$, corrected for calibration by the factor

$C_g = 4/(g_1+g_2+g_3+g_4)$, depends on the number of summed channels

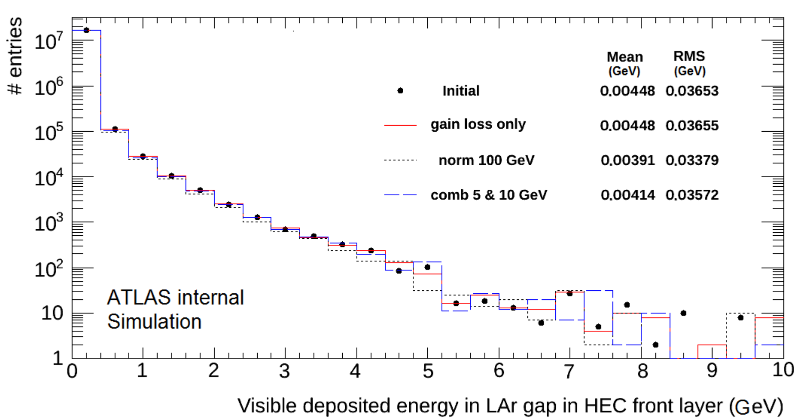
The final value to **replace the initial one** in the jet energy reconstruction

procedure is $E_{new} = (E_{degr})^p \cdot C_{norm}$, p - non-linearity factor,

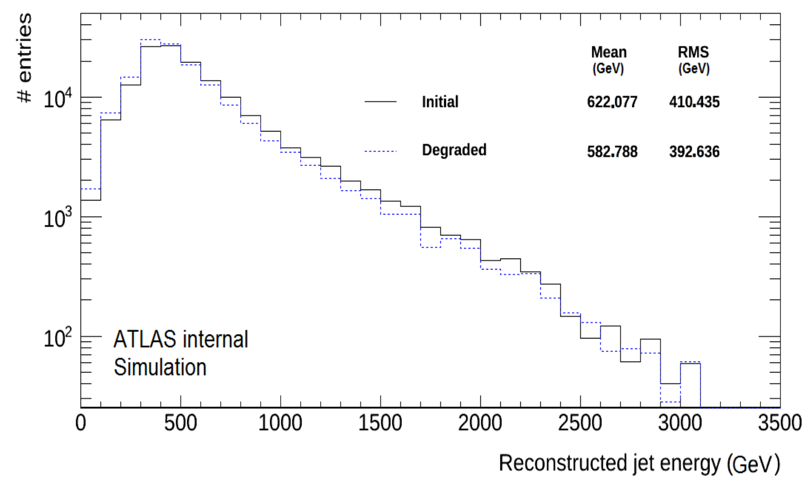
$C_{norm} = 10^{4\cdot(1-p)}$ - normalization factor (for 4 PA's).

Simulation plots

- The di-jet dataset was chosen to study the HEC performance degradation due to the radiation damages.
- 74400 generated (PYTHIA) and fully simulated (GEANT4) di-jet events have been used for analysis



The Monte-Carlo simulation for spectra of visible energy deposited in LAr gap and recorded in the front longitudinal HEC segment (on the left).

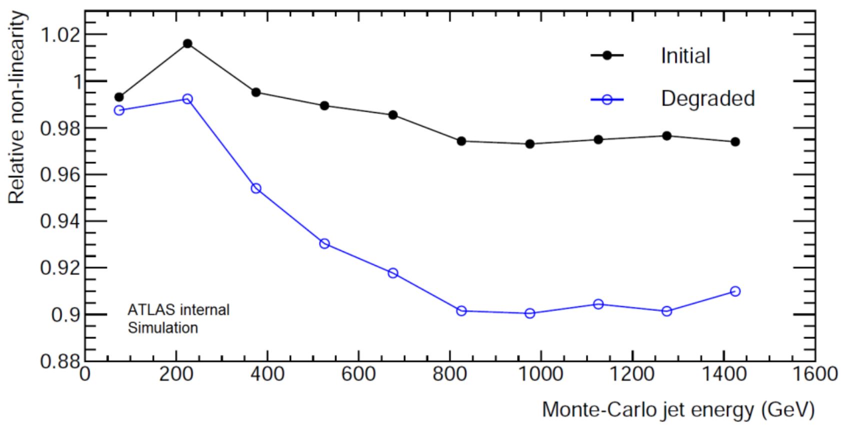


Total jet energy distributions for two leading jets reconstructed from the ***initial*** *and the* ***degraded*** *values of the deposited energy.*

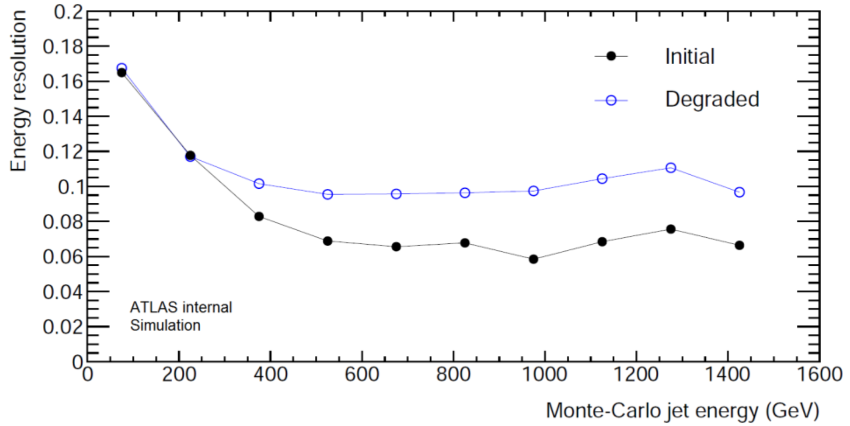
The “initial” and “degraded” spectra are similar

Performance of jet reconstruction

This is for a NIEL corresponding to 3000 fb^{-1} with safety factor 5 applied



The non-linearity for initial and "degraded" jets energies

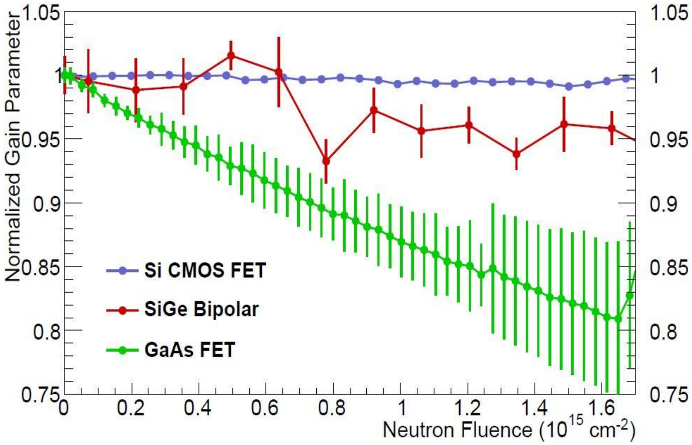


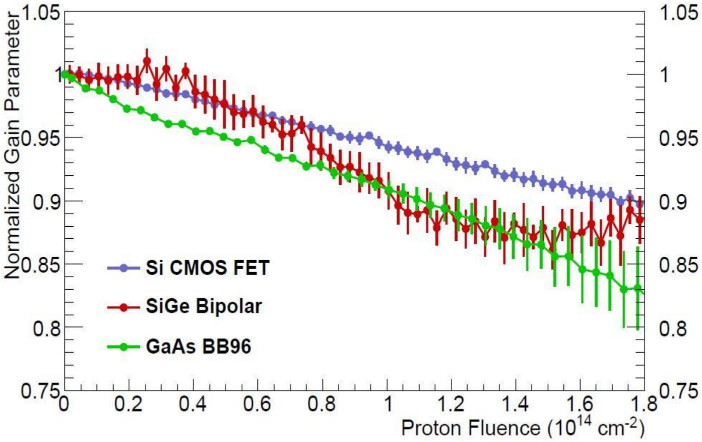
The jet energy resolution for initial and "degraded" jets

Degradation of performance is evident. Non-linearity effects cannot be corrected by the HEC on-line calibration system.

Alternative technologies: Si CMOS FET & SiGe Bipolar

Plots demonstrate sample averages, error bars are sample RMS





Average gain degradation after irradiation with expected HL-LHC radiation levels including a safety factor of 5 (expected to be smaller):

Technology	Particle fluence	
	$5.1 \cdot 10^{13}$ p/cm^2	$4.1 \cdot 10^{14}$ n/cm^2
Si CMOS FET	-3%	0%
SiGe Bipolar	-3%	-1%
GaAs FET	-	-5%
GaAs BB96	-5%	-8%

- Alternative technologies more radiation hard than current GaAs technology
- Current HEC chips (GaAs) degrade significantly, but don't break down
- SiGe Bipolar transistors require stabilization of operation point
- We found a preference for Si CMOS as alternative technology

Upgrade Options of the HEC

The data collected in Phase-0 as well as physics simulation with degraded HEC cold electronics and with degraded FCal detectors will show whether the existing detectors may be used for HL-LHC (option 0) or whether ATLAS will have to apply one of the following three options (1-3):

• **Option 0:** No change neither of the HEC cold electronics nor of the FCal detectors.

The other options are about opening cryostat (or not).

• **Option 1:** If the HEC cold electronics have to be replaced, the large cold cryostat cover would have to be opened and the irradiated FCal would have to be removed.
A newly build cold Fcal would then be inserted before closing the cryostat.

• **Option 2:** If the HEC cold electronics do not have to be replaced, the cold FCal would be replaced by a new one of the sFCal type. It is anticipated that only the small cover of the cold vessel, the FCal bulkhead, would have to be removed.

• **Option 3:** If the HEC cold electronics do not have to be replaced, the cold FCal would stay in place and a new small calorimeter would be placed in front of it. In this case only the cryostat warm vessel would have to be opened.

Conclusions (1)

- The GaAs ASIC has been exposed to neutron and proton radiation with fluences corresponding to ten years of the HL-LHC running.
- NIEL measurements from neutrons set the most stringent limits on the present HEC readout electronics.
- The radiation levels expected for HL-LHC including a simulation safety factors of 5 are at the working limit for the currently used BB96 ASICs. Although, recent estimation of NIEL simulation safety factors suggests reduced.
- The measured gain parameters and non-linearity of the ASIC response were applied to Monte-Carlo simulations of the HEC detector in order to extract the expected energy.

Conclusions (2)

- The impact on physics analyses at HL-LHC with degraded electronics is under investigation, some first results have been presented for di-jet events and more detailed study is ongoing.
- Decision whether HEC cold electronics need to be exchanged has not yet been taken, several options for the phase 2 upgrade are still being considered.
- Ageing properties of GaAs technology at LAr temperatures are being investigated
- Si CMOS technology seems to be a viable alternative.

Thank you for you attention