The ATLAS Radiation Dose Measurement System and its Extension to SLHC Experiments

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Abstract

In LHC experiments, a precise measurement of the radiation dose at various detector locations is crucial. In ATLAS, this task is performed by a set of radiation monitors (RADMON) which are able to record Non-Ionising Energy Loss (NIEL), the Total Ionizing Dose (TID) and measure fluences of thermal neutrons. These measurements are vital for understanding the changes in detector performance during ATLAS operation, verifying simulations and optimising the operation scenario. The RADMONs are multi-sensor boards, containing several RadFETs, diodes and DMILL transistors. It is clear that a similar system will be of even greater importance for SLHC environments due to the increased radiation dose.

I. Introduction

At the design luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the experiments at the Large Hadron Collider (LHC) will be exposed to a hostile radiation environment containing charged particles, photons and neutrons. It will be composed of particles from the proton-proton collisions in the interaction point and the products of these particles from their interactions with detector material. While the innermost parts will mainly be exposed to charged hadrons from the primary interactions, secondary neutrons play a more important role in the outer parts [1].

During 10 years of LHC operation, the electronics in the innermost part of the ATLAS detector will accumulate a Total Ionizing Dose (TID) of more than 100 kGy. The Non Ionizing Energy Loss (NIEL) of hadrons will cause bulk damage in silicon equivalent to the fluences of up to 10^{15} 1 MeV neutrons per cm^2. Monitoring of these quantities is therefore needed from the very beginning with low luminosity running until the end of operation. It will allow to understand and react on changes in the detector performance, predict the lifetime of components that are sensitive to irradiation and hence make an optimisation of the operation possible. Furthermore it will allow to cross-check simulations already at an early stage.

The planned upgrade of the LHC to Super-LHC (SLHC) will result in a luminosity that is ten times higher than the design luminosity of LHC, i.e. $10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [2]. TID and NIEL are thus expected to also increase by a factor of ten [3]. It is clear, that in this case monitoring the radiation levels will be even more important but also more demanding.

II. Radiation Measurement Techniques

In the ATLAS experiment the integrated radiation doses are measured using modules that contain different silicon devices. The readout can be done online and the information is made available in the control room. The Total Ionizing Dose in SiO_2 is measured with field-effect transistors. Effects due to bulk damage in silicon diodes are used to monitor the Non Ionising Energy Loss. DMILL npn bipolar transistors are sensitive to thermal neutrons and are used to measure their fluence. In order to be sensitive to low doses on the one hand and cover the full dose range during LHC running on the other hand transistors and diodes of different sensitivity are used.

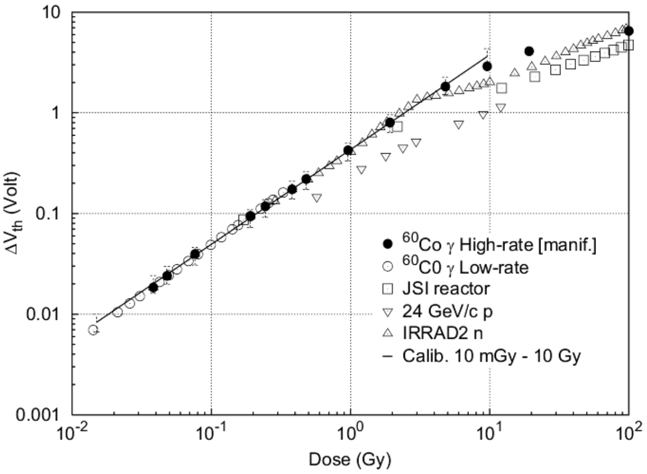
A. TID Measurement

Radiation sensitive p-MOS **F**ield **E**ffect **T**ransistors (RadFET) are used for the TID measurement. Electrons and holes that are created by ionising radiation in the oxide layer of the gate electrode have different mobilities. While the electrons can escape via the gate electrode, the holes are trapped in the SiO_2 layer and lead to a charge buildup. The resulting field must be compensated by a higher negative gate voltage V_G to open the channel. The increase of the gate voltage at fixed drain current is thus a measures of the TID. The relation is given by a power law

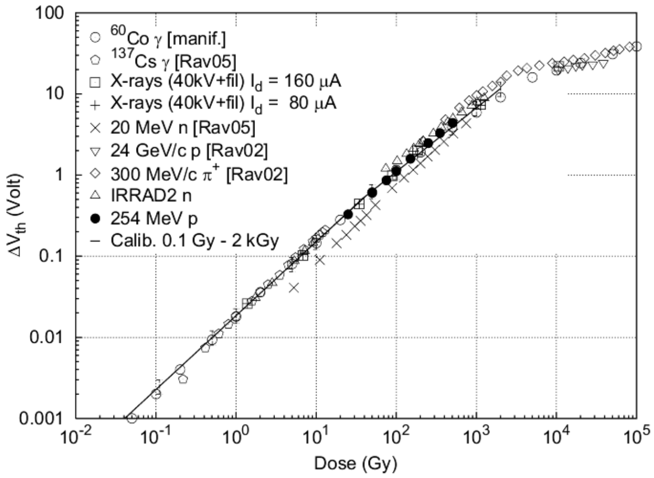
$$\Delta V_\mathrm{G}\,|_{I_\mathrm{drain=const.}} = a \times (TID)^b$$

where a and b are constants that are obtained from calibration measurements. The RadFETs are operated in unbiased mode, that means no gate voltage is applied during irradiation. Biased mode would mean a faster charge buildup and therefore a higher sensitivity on the one hand but reduced dynamic range on the other hand. It would require continuous operation. In detailed studies the CERN TS-LEA division has selected RadFETs that are best suited for the use in LHC experiments [4, 5]. Following these recommendations three RadFETs of different oxide thickness are chosen to be used in ATLAS [6]. They account for the need of high sensitivity in the beginning as well as capability of the whole dose range:

- high sensitivity, 1.6 μm oxide thickness, mGy sensitivity, up to a few Gy total dose, produced by CNRS LAAS, Toulouse, France
- intermediate, 0.25 μm oxide thickness, tens of kGy total dose, produced by REM Oxford, Ltd.
- low sensitivity, 0.13 μm oxide thickness, 10^5 Gy total dose, produced by REM Oxford Ltd.



(a) High sensitivity LAAS RadFET with $1.6\,\mu$m oxide thickness.



(b) Medium sensitivity REM RadFET with $0.25\,\mu$m oxide thickness.

Figure 1: Response curves of the high sensitivity (a) and medium sensitivity (b) RadFETs that are used in ATLAS. The threshold voltage shifts for drain currents of $100\,\mu$A (a) and $160\,\mu$A (b) are plotted versus TID. Measurements from irradiation with different particle types are taken into account. Taken from [5].

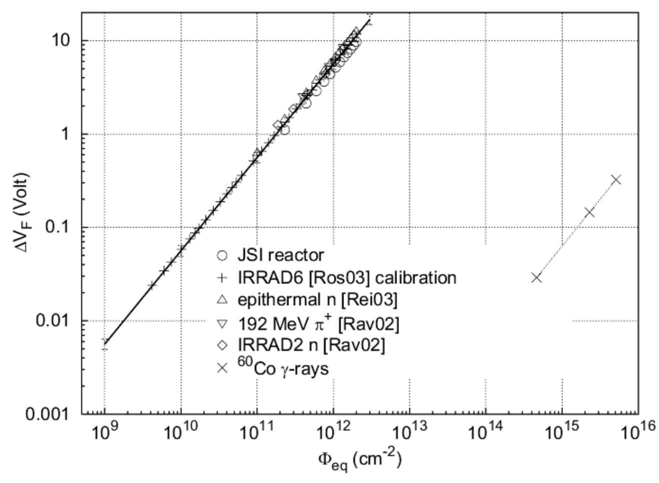
B. NIEL Measurements

Two methods, which are both based on effects due to bulk damage in silicon, are used to measure the NIEL in silicon: The change of the forward voltage on a p-i-n diode at given forward current and the leakage current increase in a reversed biased, fully depleted epitaxial pad diode.

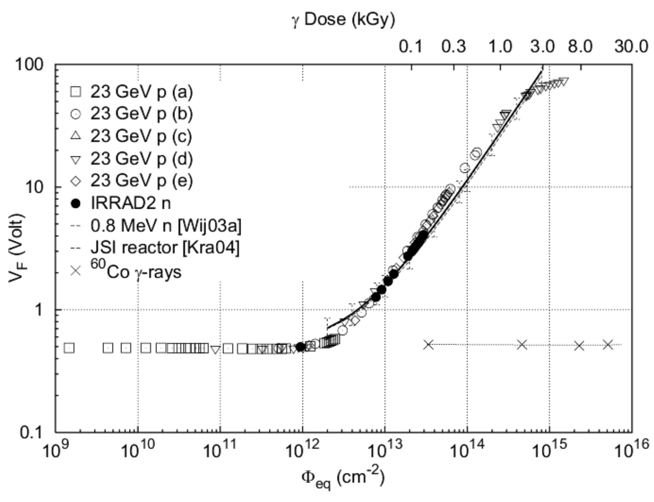
Bulk damage in a p-i-n diode leads to a reduced minority carrier lifetime and thus to an increase of the resistance. For the first method, the measured quantity is therefore the voltage change when driving a specific current through the diode. Two diodes are used in ATLAS:

- high sensitivity: p-i-n diode from CMRP, Wollongong, Australia, $10^8\,\mathrm{n/cm^2}$ to $2\times10^{12}\,\mathrm{n/cm^2}$
- low sensitivity: photo diode BPW34F from OSRAM, $10^{12}\,\mathrm{n/cm^2}$ up to $10^{15}\,\mathrm{n/cm^2}$

The relation between NIEL and voltage change at given forward current is linear over a large range, as shown in Fig. 2. The BPW34F diodes used in ATLAS have been pre-irradiated with $3\times10^{12}\,\mathrm{n/cm^2}$ in order to start in the linear regime. Like for the RadFETs the irradiation is done in unbiased mode. At higher fluences, as the forward voltage needed for 1 mA current increases, power dissipation which heats the diode during readout starts to influence the measurement. There are ongoing studies that aim to solve this problem and alow usage of these diodes at SLHC fluences. A possibility is the fluence dependent readout current i.e. reducing the readout current at high fluences. Another option is to apply the sequece of current pulses in order to estimate the change in temperature [7].



(a) High sensitivity CMRP p-i-n diode.



(b) Low sensitivity BPW34F diode.

Figure 2: Response curves of the high (a) and low (b) sensitivity p-i-n diodes that are used in the ATLAS experiment. The forward voltages at 1 mA forward current are plotted versus the equivalent fluence for irradiation in different radiation environments. Taken from [5].

For the second method to measure the NIEL, a diode is used in reversed biased mode. The leakage current increase is proportional to the NIEL [8]. The 1 MeV neutron equivalent fluence is given by

$$\Phi_{\mathrm{eq}} = \frac{\Delta I_{\mathrm{leakage}}}{\alpha(t,T) \times V}.$$

$\alpha(t,T)$ is the well measured damage constant which is independent of the silicon type but sensitive to temperature changes and annealing. V denotes the depleted volume. It has to be kept constant by fully depleting the diode also after irradiation. In ATLAS a $0.5 \times 0.5\,\mathrm{cm}^2$ silicon pad diode with guard ring structure from CiS, Erfurt, Germany is used. Its active thickness of $0.25\,\mu$m allows depletion with less than 30 V for the whole lifetime of the experiment. Annealing studies have shown, that it can also be used for fluences greater than $10^{15}\,\mathrm{n/cm}^2$.

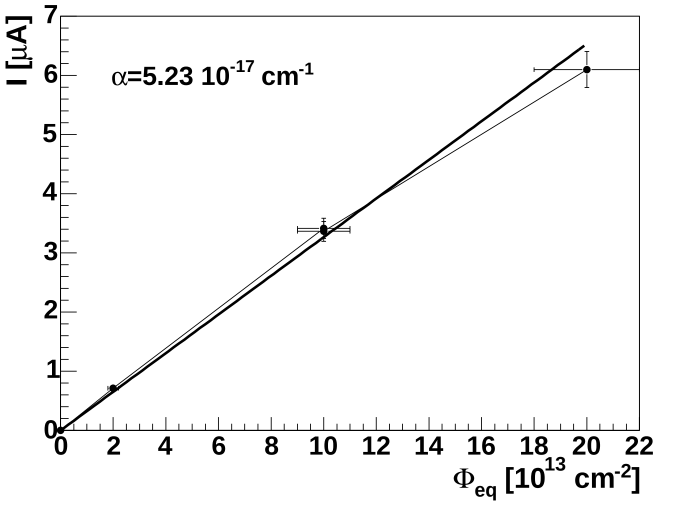


Figure 3: Leakage current of the fully depleted epitaxial diode versus the equivalent fluence. The measurement was done immediately after irradiation. The quoted damage constant α is for the unannealed case.

C. Thermal Neutron Fluence Measurement

DMILL npn bipolar transistors are used in the front-end electronics of the ATLAS Inner Detector. Their current emitter gain factor $\beta = I_{\mathrm{c}}/I_{\mathrm{b}}$ changes with irradiation. In order to understand the degradation in electronics performance it is therefore important to monitor this quantity.

Displacement damage in DMILL transistors is caused by fast hadrons as well as thermal neutrons. The energy of the thermal neutrons is not sufficient to directly cause the displacement damage. Rather it is due to the products of the process $^{10}\mathrm{B}(\mathrm{n},\,\alpha)^{7}\mathrm{Li}$ as pointed out in [9]. It was also shown in [9], that the degradation of β resulting from irradiation with fast hadrons and thermal neutrons can be written as

$$\frac{1}{\Delta\beta} = k_{\mathrm{T}} \times \Phi_{\mathrm{T}} + k_{\mathrm{eq}} \times \Phi_{\mathrm{eq}}$$

where Φ_{eq} is the 1 MeV equivalent fluence and Φ_{T} the fluence of thermal neutrons. k_{eq} and k_{T} refer to the corresponding damage factors that are determined from calibration measurements as shown in Fig. 4. Since Φ_{eq} is obtained from measurements with diodes as explained previously, DMILL transistors allow to determine the thermal neutron fluence.

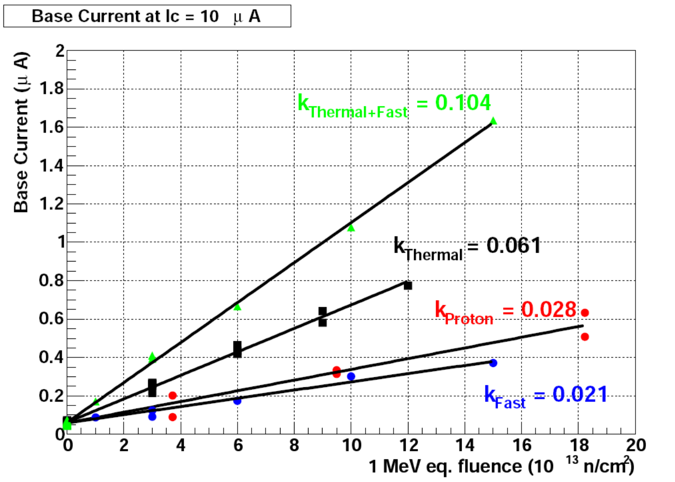


Figure 4: Response of the DMILL bipolar transistor. Plotted is the change in base current at $10\,\mu$A collector current as a function of the fluence. For protons, fast neutrons and for the admixture (fast+thermal, $\Phi_{\mathrm{fast}}/\Phi_{\mathrm{thermal}} \approx 0.7$) fluence is in 1 MeV neutron equivalent. For thermal neutrons the x-axis represents the fluence of thermal neutrons.

III. The Radiation Monitor Hybrid

The highest radiation levels will occur in the ATLAS Inner Detector around the pp-collision point. Due to the large range of doses all sensors listed in the previous sections are used in this part of the detector to cover the entire range of expected doses and provide a high level of redundancy. Three different RadFETs, two different p-i-n diodes, one epitaxial diode and two equivalent DMILL bipolar transistors are combined to one module that also includes an NTC sensor.

Mainly due to the very uncertain temperature conditions at some locations in the Inner Detector, where the expected temperatures are between -20° and $+20^\circ$ C, the modules were made of ceramics. They provide mechanical support and electrical connection for the sensors and the bottom side of the ceramics is covered with a thin layer of material with electrical resistance $R = 320\,\Omega$ which serves as heater. The heater will be used to keep the board at a constant temperature a few degrees above 20° C.

Outside the Inner Detector the ranges of expected dose levels are smaller. Therefore TID and NIEL damage will be measured with modules that contain only two sensors: the most sensitive RadFET and the most sensitive p-i-n diode. It also contains a NTC sensor but no resistive heating.

There are 14 modules placed in the Inner Detector. Simplified modules are located in the calorimeters (6 in Tile and 18 in LAr), in the muon forward detectors (16) and in the so called Patch-Panel-2 area (10) which is in the muon barrel region.

IV. Readout

Readout of all modules is done online. Standard ATLAS components are used for this purpose to ensure full compatibility with the overall ATLAS Detector Control System (DCS) and to simplify the integration. For the readout Embedded Local Monitor Boards (ELMB) are used. They host 64 12-bit ADC channels ($0-4.5$ V) with the conversion frequency ranging from $2-100$ Hz [10]. 16 channel 12-bit ELMB-DACs [11] are used as current source. The maximum output current is 20 mA per channel and the maximum output voltage of a DAC channel can be up to 30 V. Up to four DAC boards can be connected to and controlled by an ELMB. Every 15 to 60 minutes a read out cycle will be carried out. It comprises: 1. applying the chosen bias to each sensor, 2. waiting for 50 ms to 1000 ms depending on the sensor type and 3. reading out the voltage or current. The sensors will be biased only during the readout cycles which are much shorter than the total exposure time. Irradiation can therefore be assumed to be taken out in unbiased mode.

Communication between the computer that runs the DCS software and the ELMBs is done via CAN bus. The DCS software is PVSS [12], a commercial SCADA software that is used by all LHC experiments. System status and online values for doses can be monitored from the ATLAS control room. All values are archived in an online database that can easily be queried from the control room. When doses have reached a significant value, the archived data will be used for a detailed offline analysis. This will allow a precise validation of existing simulations. Correlations between doses and luminosity will be determined and used to predict the expected dose levels at SLHC.

V. Tests in a Mixed Particle Environment

At the CERN-PS 23 GeV protons of the primary beam can be directed to an irradiation facility called IRRAD1. During the operation the protons produce a radiation field of secondary particles consisting of charged hadrons, neutrons and photons. This low dose rate mixed particle environment can be used for irradiation tests and is called IRRAD6.

Two Inner Detector style RADMON modules where placed in the IRRAD6 environment for more than three month.[1] As in ATLAS, the readout of the sensors on the two modules is done with one ELMB and two ELMB-DACs. The aim is to perform a long term study under realistic conditions concerning both the mixed particle environment and the readout chain.

The number of protons that are delivered to the irradiation facility is determined by a Secondary Emission Counter (SEC). In a previous study that has been carried out at the IRRAD6 conversion factors have been obtained that allow to specify the TID and NIEL rates from the SEC measurement [13]. A 50 % uncertainty is quoted for this conversion factors which also takes into account that the beamline has changed in the meantime [14]. For the dose measurements of the ATLAS RADMON modules the uncertainty is assumed to be 20 % [4, 14].

Figure 5 shows TID and NIEL values versus time as they were obtained from RadFET and p-i-n diode measurements respectively. The response shapes of the RadFETs and p-i-n diodes compare well to the SEC result. One has to consider that the SEC does neither account for the dose rates due to activation of the environment nor does annealing play any role for it. Both effects can be observed in the plateau regions, i.e. when there was no beam. From the inserts in Figure 5 it can be seen that the sensitivity of the system is about 10^{-3} Gy for TID measurement and 10^9 n/cm^2 for measuremetns of NIEL.

The response of the high sensitivity RadFET (LAAS) is reduced for protons as can be seen from the calibration curves in Fig. 1(a). The IRRAD6 environment is proton rich and therefore the calibration constants have to be rescaled for this very special case as it was done for the data shown in Fig. 5(b).

VI. Conclusions

In ATLAS, especially in the Inner Detector, the radiation environment will be very hostile during LHC running. It is therefore essential to monitor the accumulated doses in order to understand and react on changes in the detector performance. Furthermore will the monitoring allow to check simulations and to determine the correlation between dose rate and luminosity. This will be of great importance to predict the expected doses at SLHC. The same method might be used to monitor the dose levels beyond the dynamic range of available sensors.

A set of RadFETs and diodes has been selected as monitoring devices for integrated Total Ionizing Dose and Non Ionizing Energy Loss in the ATLAS detector respectively. Sensors of different sensitivity ensure that measurements will be possible from very low doses up to the maximal doses expected in the experiments lifetime. Furthermore, DMILL bipolar transistors are used to monitor their degradation with irradiation. Together with NIEL measurements from the diodes, they allow to determine the thermal neutron fluence. Extending the maximum doses that can be measured with RadFETs and diodes to SLHC like values is possible but detailed studies and measurements have to be done. The ideas include thinner active volumes, extension of calibrations to non linear regions, usage of higher depletion voltages etc.

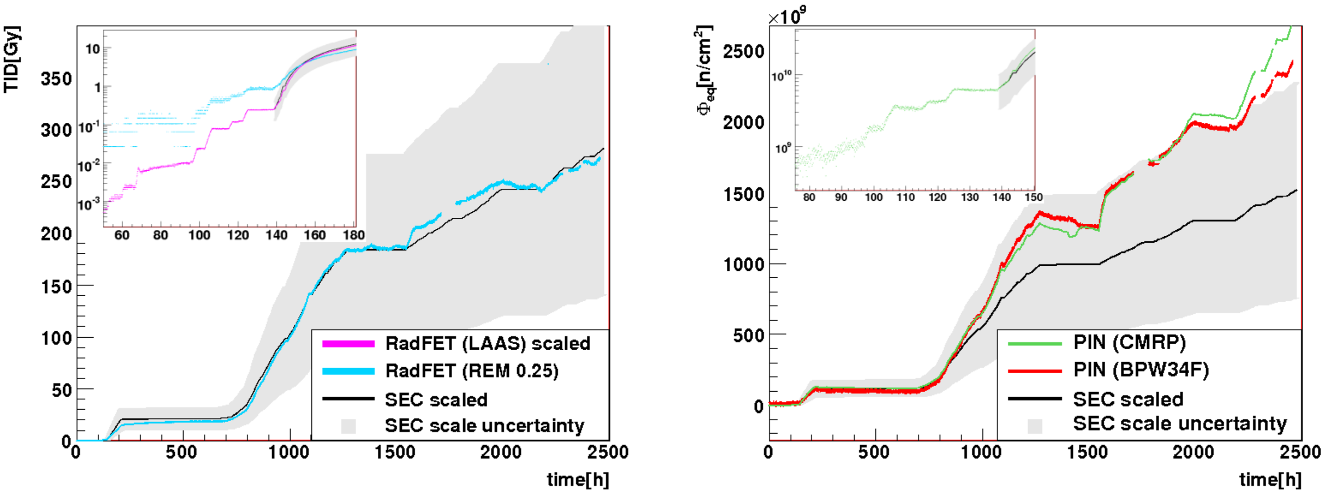
Two kinds of hybrid modules have been developed and installed in the ATLAS detector: One for the Inner Detector containing sensors for different dose ranges and a simplified type with only one RadFET and one diode for the other detector parts. The system is fully operational and all modules are read out online in the context of the ATLAS Detector Control System.

A mixed particle environment at the CERN-PS is used for a long term irradiation study under realistic conditions. It proves the applicability of the sensors to such an environment as well as the functionality and stability of the read out chain.

VII. Acknowledements

The authors would very much like to thank Maurice Glaser for making the test in the IRRAD6 environment possible. Many thanks to him and Federico Ravotti for sharing their great expertise in the field of radiation sensors and for their help understanding the collected data.

[1] At the time of writing the irradiation is still ongoing.



(a) TID measured with LAAS 1.6 μm and REM 0.25 μm RadFETs.

(b) NIEL measured with CMRP and BPW34F p-i-n diodes.

Figure 5: Long term irradiation measurements of the TID (a) and NIEL (b) in the IRRAD6 mixed particle environment. In (a) measurements with the LAAS 1.6 μm and the REM 0.25 μm RadFET are plotted. High sensitivity LAAS RadFET can be used only up to about 10 Gy. NIEL measurements with both p-i-n diodes in use (CMRP and BPW34F) are shown in (b) where calibration for the CMRP is only valid for values below 2×10^{12} n/cm^2. The insert shows the high sensitivity of the CMRP. Also shown are the values obtained by converting the SEC proton counting. The plotted SEC measurement only starts after about five days because before that the beam conditions where very uncertain and the conversion factors can not be applied for this part.

References

[1] I. Dawson and C. Buttar, "The radiation environment in the ATLAS inner detector," Nucl. Instrum. Meth. A **453** (2000) 461.

[2] CERN Council Strategy Group, "Briefing Book for the Zeuthen Workshop of the CERN Council Strategy Group," http://council-strategygroup.web.cern.ch/council-strategygroup/BB1/BB1.pdf.

[3] I. Dawson, "Radiation background issues for an upgraded ATLAS inner-tracker," Talk given at the ATLAS Tracker Upgrade Workshop in Genova, July 2005.

[4] F. Ravotti *et al.*, "Sensor Catalogue", CERN-TS-NOTE-2005-002.

[5] F. Ravotti, "Development and characterisation of radiation monitoring sensors for the high energy physics experiments of the CERN LHC accelerator," CERN-THESIS-2007-013

[6] I. Mandic, V. Cindro, A. Gorisek, G. Kramberger and M. Mikuz, "Online integrating radiation monitoring system for the ATLAS detector at the Large Hadron Collider," IEEE Trans. Nucl. Sci. **54** (2007) 1143.

[7] M. Glaser, private communication.

[8] M. Moll, E. Fretwurst and G. Lindstrom [CERN-ROSE/RD48 Collaboration], "Leakage current of hadron irradiated silicon detectors - material dependence," Nucl. Instrum. Meth. A **426** (1999) 87.

[9] I. Mandic *et al.*, "Bulk damage in DMILL npn bipolar transistors caused by thermal neutrons versus protons and fast neutrons," IEEE Trans. Nucl. Sci. **51** (2004) 1752.

[10] http://atlas.web.cern.ch/Atlas/GROUPS/DAQTRIG/. . .
. . .DCS/ELMB/elmb.html

[11] http://www.nikhef.nl/pub/departments/ct/po/html/. . .
. . .ELMB/DAC10.pdf

[12] http://www.pvss.com/

[13] F. Ravotti, M. Glaser, A. B. Rosenfeld, M. F. L. Lerch, A. G. Holmes-Siedle and G. Sarrabayrouse, "Radiation monitoring in mixed environments at CERN: From the IRRAD6 facility to the LHC experiments," IEEE Trans. Nucl. Sci. **54** (2007) 1170.

[14] M. Glaser, private communication.