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Experimental Study and Empirical Modeling of Long Term Annealing of the ATLAS18 Strip Sensors

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In order to continue the program of the LHC, the accelerator will be upgraded to the High Luminosity LHC (HL-LHC), which will have a design luminosity of $5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, an order of magnitude greater than the present machine. In order to meet the occupancy and radiation hardness requirements resulting from this increase in luminosity, the present ATLAS tracking detector must be replaced. The ATLAS Collaboration is constructing a new central tracking system based completely on silicon sensors. In order to satisfy the radiation hardness requirements we have developed a new n-in-p sensor design. Extensive studies have shown that it results in detectors which comfortably reach the required end-of-life performance. The latest sensor layouts prepared for preproduction, known as ATLAS18, implement this design. However, as well as knowing the performance after a given irradiation fluence, operational considerations require an understanding of the time development of the annealing and resulting variation of the collected charge, of irradiated detectors at different temperatures. Here we describe the measurement of charge collection performance as a function of irradiated fluence and long term annealing time. We also describe a semi-empirical model based on these measurements which allows us to predict the end-of-life charge collection as a function of the temperature profile during operation of the detector. The use of the model to study the effect of annealing on the strip detector at a radius of 40 cm and an integrated irradiation fluence of 1.6×10^{15} 24 MeV neutron equiv. cm^{-2} is presented.

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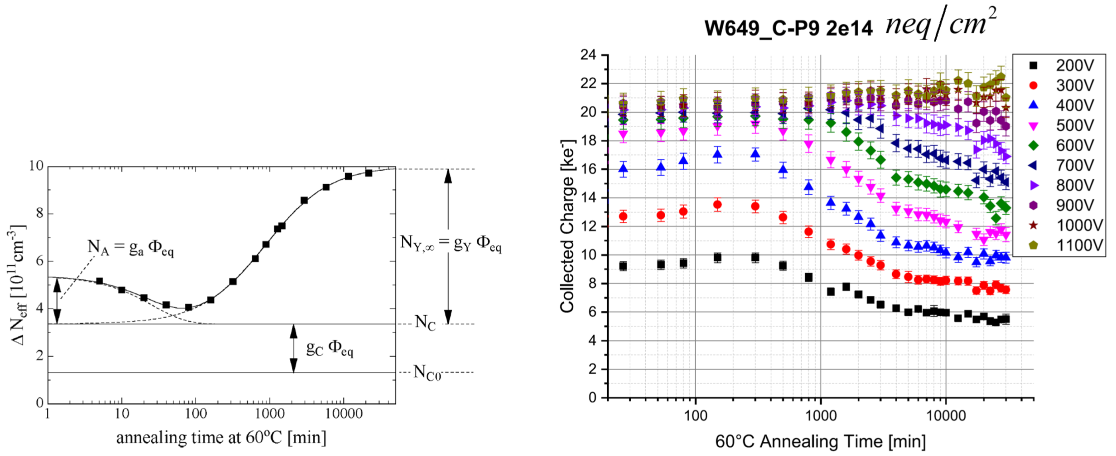
1. Introduction

In order to pursue the TeV scale physics program, the Large Hadron Collider luminosity will be upgraded to $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. With this luminosity ATLAS will be able to pursue a diverse physics program. Measurements associated with the Higgs will enable ATLAS to pursue the investigation of deviations from the standard model in areas such as the couplings to standard model particles and the Higgs self coupling. Searches for the production of particles outside the scope of the standard model, such as supersymmetric partners, will be extended to higher mass scales. While this increase in luminosity will dramatically extend the physics reach of ATLAS, it presents considerable challenges to the development of a detector that will perform adequately in the high particle multiplicity regime, and after the extended irradiation that the detector will experience. The present ATLAS tracking detector comprises a silicon pixel detector, a silicon strip detector, and a large straw tube combined tracker and transition radiation detector. This present tracking system will be able to cope with neither the track multiplicity nor the radiation damage level at the HL-LHC. Accordingly, the decision was taken to replace this existing system by a new integrated tracker, known as the Inner Tracker (ITk), based entirely on silicon detectors [1]. The ITk incorporates several innovative features, the most relevant for this discussion is that it was decided, in order to meet the requirements of radiation hardness and avoid type-inversion, to use bulk p-type silicon with n-type implants and p-stops between the implants [2] [3]. The silicon strip detector consists of a barrel and two endcaps. The sensors are 320 microns thick. In the barrel the sensors are rectangular with a strip pitch of 75.5 microns. In the endcap the sensors are fan shaped with six different geometries, and a strip pitch varying from 70 microns to 80 microns. The sensors are AC-coupled to the readout pre-amplifiers. The bias voltage is nominally −500V. The ITk is foreseen to be installed by 2029 and to be operated for 14 years. There are several proposed operating temperature profiles based on the expectation of the annealing behaviour of the sensors.

The ATLAS ITk, or for that matter any silicon detector, will suffer radiation damage and temperature dependent annealing. For a given bias voltage, there will be an increase of leakage current. This is a potential problem for operating the detector in the long term, as the power supplies must be configured to cope with the leakage current which develops; additionally the cooling system must be capable of dealing with the developing heat load. The bias voltage required to fully deplete the sensors will also increase, and this is potentially a limiting feature. Effects such as these can be termed “operating considerations”, as they determine the conditions of voltage and temperature that the detector must be operated at. The ITk is a tracking detector and an ultimate limitation of its performance is the degradation of collected charge as the radiation dose accumulates

It is well known [4] that the degradation caused by irradiation improves for a short time after irradiation, and then undergoes further long term degradation. In terms of operating characteristics the leakage current will decrease with time. The collected charge will increase for a short time, and then undergo a long term decline. The effect of annealing on the leakage current is commonly parameterized by the Hamburg Model [5]. Figure 1(a) shows the form of the variation with annealing time of effective doping in the Hamburg Model.

Annealing is a strong function of temperature, and a naive solution would be to keep the ITk at low temperature for the 14 year lifetime of the detector. This is, in fact, not possible. During the operating lifetime of the detector there will be periods when the detector must be warmed up



(a) The effective doping as a function of annealing time at 60 ° C for n-type silicon, taken from [5].

(b) Charge collected as a function of annealing time at 60 ° C. Proton irradiated data measured at Freiburg [6].

Figure 1: Comparison of the annealing time development for collected charge and effective doping.

to room temperature for the maintenance of the detector, maintenance of associated services, such as the cooling system, and perhaps installation of new detector components in the central region. An important consideration is how these temperature cycles will effect the collected charge in the strip regions of the ITk. While annealing is an interesting phenomenon in its own right, we have taken the approach of developing a data driven semi-empirical model of annealing as a function of irradiation fluence and time.

2. A Semi-empirical Model of Collected Charge.

A first step was to look at data taken at Freiburg on ATLAS12 miniature sensors, this data includes the data presented in [6]. The ATLAS ITk strip sensors have gone through a series of prototypes, these are denoted ATLASyy, where for example ATLAS12 corresponds to 2012[1]. The ITk strip sensors are produced by Hamamatsu Photonics, and the production series is ATLAS18. The sensors are produced on six inch wafers. As well as sensors, the periphery of the wafer has a number of test structures which may be diced off and used in various studies. An ATLAS18 wafer is shown in Figure 2. The large rectangular structures are short strip main sensors, and the small square structures at the bottom of the wafer are miniature sensors. The miniature sensors (mini-sensors) are "identical" to the full size sensors. They have the same thickness, implant, strip, bias and guard ring structures as the main sensors, and several sizes are on the periphery of each wafer. The miniature sensors discussed here are 1cm × 1cm with 104 strips of 8mm length.

In Figure 1(b) the collected charge as a function of annealing time at 60 ° C is shown for various bias voltages. This particular mini-sensor is an ATLAS12 mini-sensor which was irradiated with 24 MeV protons at Karlsruhe Institute of Technology (KIT) and measured at Freiburg. It is evident that the variation of collected charge shows a similar temporal behaviour as the effective doping in Figure 1(a), but with the collected charge increasing in the short term, and decreasing in the long

[1]This was the year design work on the sensors started.

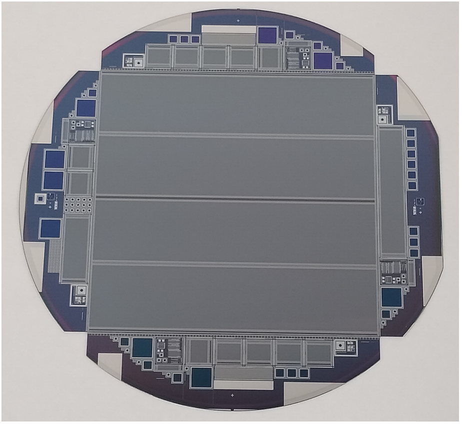


Figure 2: An ATLAS18 wafer. The large rectangular structures are short strip sensors. Around the periphery are various test structures, notably the small square miniature sensors.

term. It thus seems reasonable to parameterize the behaviour of the charge collection as an inverse of the Hamburg Model time dependence for the effective doping. The parameterization chosen is:

$$\frac{1}{(g_a \exp(-t/\tau_a) + g_c + g_Y (1 - \exp(-t/\tau_Y)))}$$

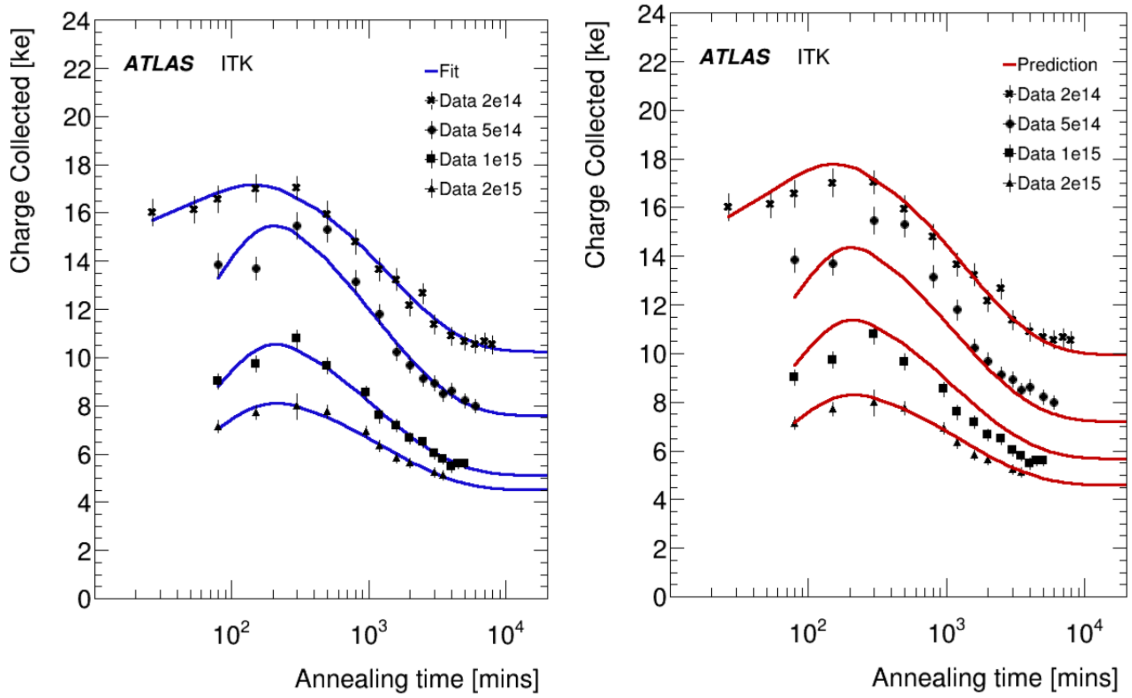
Where

- g_a is the coefficient for short term annealing
- τ_a is the diffusion time for short term annealing
- g_c is a constant term
- g_Y is the coefficient for long term annealing
- τ_Y is the diffusion time for long term annealing

The g_a and g_Y depend on the irradiation fluence, and this dependence is parameterized as (a+b$(1 - \exp(\mathrm{c} \times \mathrm{fluence})))$, while g_c is taken as a linear function of the fluence. The diffusion times are assumed to be a function of the bias voltage, the type of irradiating particle, but independent of the magnitude of the fluence. They are assumed to follow an Arrhenius function of temperature.

3. Modeling data taken for ATLAS12 mini-sensors.

In addition to the data from [6], Leena Diehl kindly provided us with data from her thesis [7]. This data comprises mini-sensors irradiated with 24 MeV protons at KIT and with neutrons at the TRIGA reactor in Ljubljana [8], at several fluences, and measured with 400V and 500V bias voltages. The 24 MeV data measured at 400V is shown in Figure 3. Figure 3(a) shows the fits of the model to the data. In the fits, the g coefficients at each fluence are fitted independently, however the diffusion times are fixed for all fluences to the results of a fit to the $2 \times 10^{14}\ \mathrm{n_{eq}} \cdot \mathrm{cm}^{-2}$ where both the coefficients and the diffusion times are left free. The values of the coefficients as a function



(a) The model fitted to the data to extract the coefficients of the model as a function of fluence.

(b) The “prediction” of the model using the the functional dependence of the coefficients as extracted from the fit in (a). We refer to this as the "closure test".

Figure 3: The model fitted to data from ATLAS12 sensors exposed to 24 MeV proton irradiation. The legends, e.g.2e14, refer to $2 \times 10^{14}\ \mathrm{n_{eq}} \cdot \mathrm{cm}^{-2}$. This data corresponds to the 400 volt bias voltage in Fig. 1.

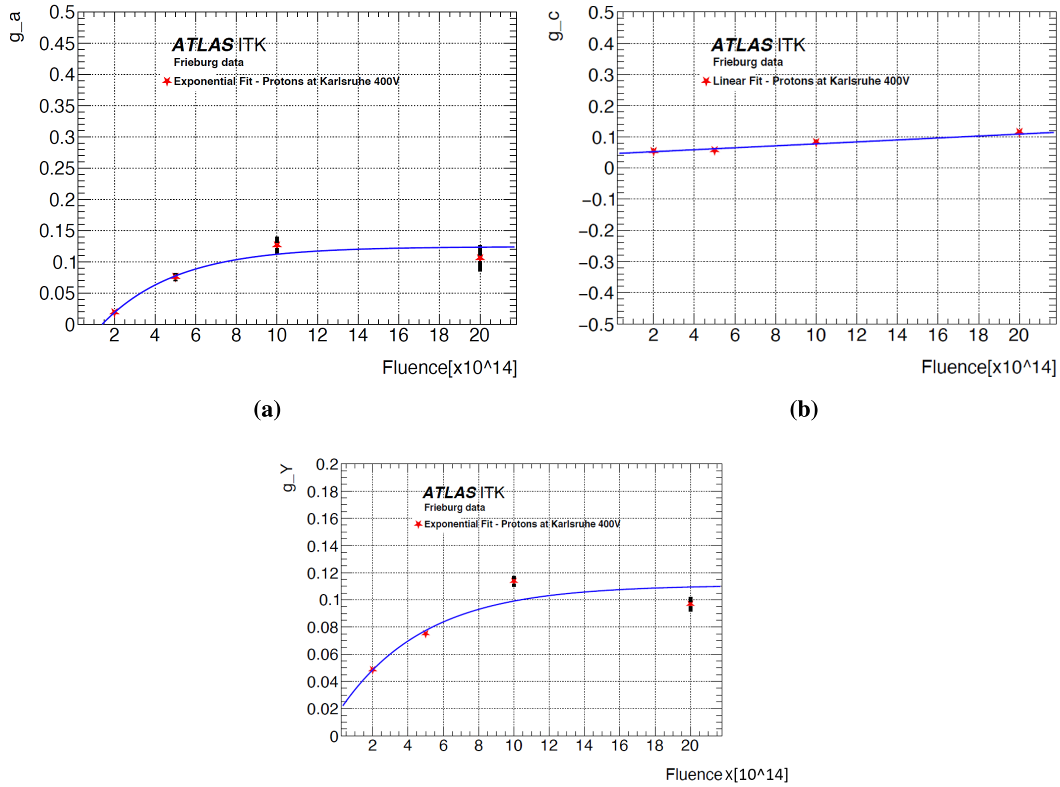
of fluence are shown in Figure 4, as are the fits of the parameterization described above. The fitted functions in Figure 4 are then used to "predict" the collected charge, as shown in Figure 3(b). We refer to this as a “closure test”. The same procedure is then applied to the 500V bias voltage data, shown in Figure 5, and ATLAS12 mini-sensors exposed to reactor neutrons in Figure 6.

4. Study of ATLAS18 mini-sensors.

The Quality Assurance (QA) process [9] for the ATLAS18 production sensors includes measuring the collected charge from mini-sensors produced on the same wafers as the main sensors, see Figure 2. As part of this process, the University of Toronto was supplied with a number of ATLAS18 mini-sensors irradiated at a variety of fluences of neutrons at the Ljubljana reactor. These mini-sensors were used to perform a study of collected charge as a function of annealing time, analogous to that described above for the ATLAS12 sensors.

4.1 Data Collection.

As part of the QA process Toronto constructed a dedicated charge collection measurement setup. It is based on the Alibava system [10], which allows for the measurement of the pulse height spectrum from mini-sensors exposed to electrons from an ^{90}Sr source. Figure 7(a) shows



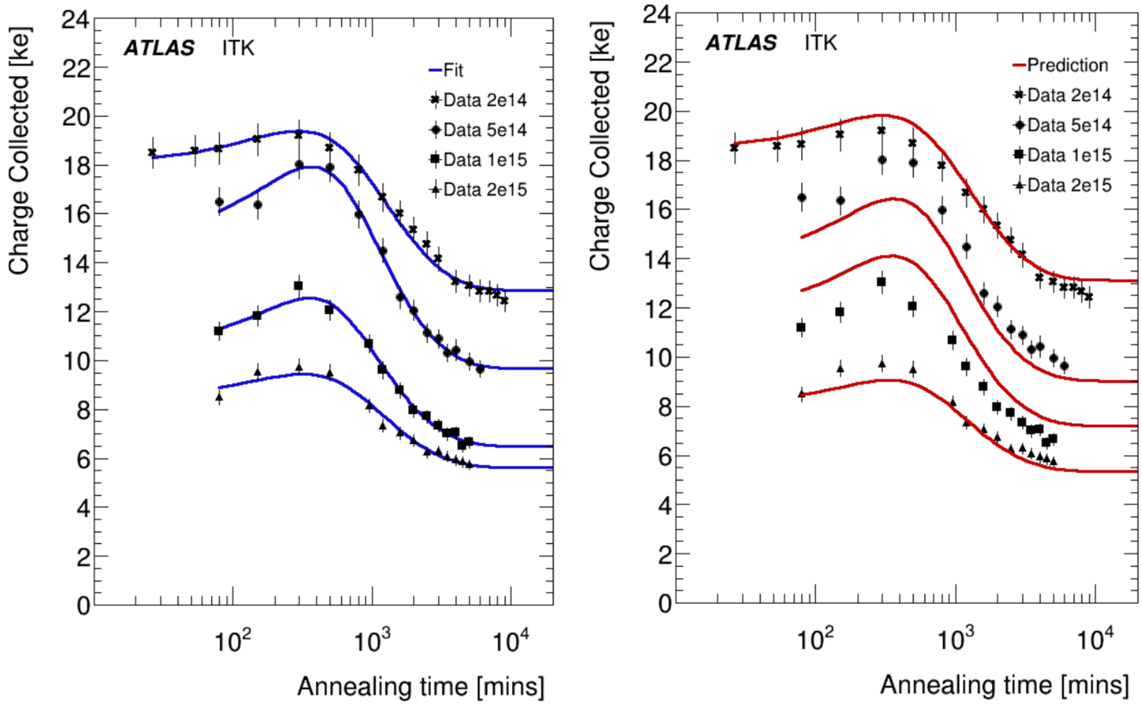
(a) **(b)** **(c)**

Figure 4: The model coefficients determined from the fits in Fig. 3a.

two mini-sensors mounted on, and wire bonded to, the Alibava daughter board. The daughter board allows the acquisition of the pulse height from the mini-sensors. The mini-sensors are the two square structures towards the top of the board. Since the mini-sensors have been heavily irradiated the leakage current from the bias voltage would be prohibitive, so the measurements are performed in a freezer at $-25\ ^\circ$ C and a relative humidity of 10%. Figure 7(b) shows the daughter board assembly mounted inside the freezer. The source carrier marked "radioactive" is externally computer controlled, which allows the source position to be scanned across the miniature sensors in the cold. The Ailbava daughter boards have a temperature dependent gain, and this was calibrated using unirradiated mini-sensors. Data was taken at a range of bias voltages from 50V to 1100V. Examples of the measured pulse height distributions are shown in Figure 8. These pulse height distributions were fitted by a Landau convoluted with a Gaussian; the latter to take account of noise. The most probable value of the Landau is plotted as the collected charge.

4.2 Analysis of ATLAS18 Data.

The data on collected charge for the ATLAS18 mini-sensors was analysed in the same manner described above for ATLAS12. The data at each fluence was fitted to determine the coefficients of the model, with the diffusion times fixed across all fluences. In Figure 9(a) we show the data collected at a bias voltage of 400V and in Figure 9(b) that collected with a bias voltage of 500V.



(a) Fit of model to data, to extract fluence dependent coefficients.

(b) Closure test.

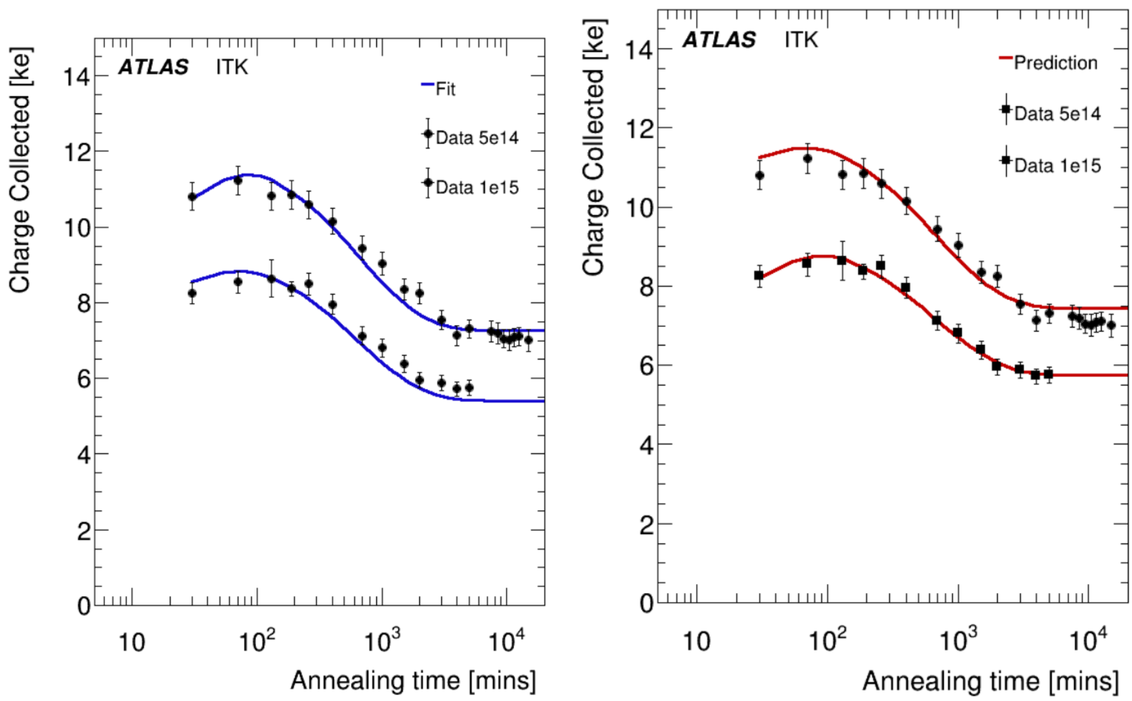
Figure 5: The model fitted to data from ATLAS12 sensors exposed to 24 MeV proton irradiation. The legends, e.g.2e14, refer to $2 \times 10^{14}\ n_{eq} \cdot cm^{-2}$. This data corresponds to the 500 volt bias voltage in Fig. 1.

In the plots the fit and closure test are plotted together. The mini-sensors were annealed at 60 ° C. The fitted model coefficients for a bias voltage of 500V are shown in Figure 10.

5. Comparison of Model with Data.

We have used the model to study various long term running temperature scenarios for the ITk strips. We have also used it to study the effect of operating the strips at −25 ° C, but with a warm up period of 100 days in HL-LHC long shutdown 4. A third study was on the effect of maintenance warm up periods for the maintenance of the CO_2 cooling system of 10 days each year, and 40 days in long shutdown periods 4 and 5. In the study of different temperature profiles we also experimentally studied the behaviour of the sensors by repeatedly irradiating them with neutrons and annealing them at 60 ° C between irradiations. The experimental study was done at the Jožef Stefan Institute and samples were irradiated at the TRIGA reactor in Ljubljana [8]. The final irradiation corresponded to an integrated luminosity of 4000 inverse femtobarns. The three temperature profiles studied are referred to as "Warm Start", "Cold Start with short Warm up", and "Cold Start with long warm up". "Cold" in this context means −25 ° C and warm means +20 ° C. In detail the scenarios studied were:

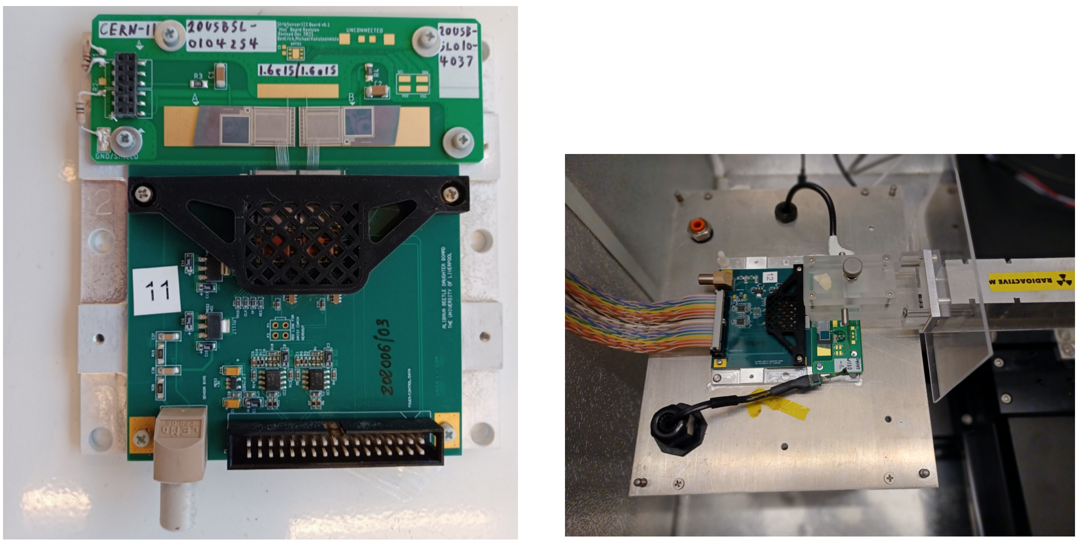
- Warm Start



(a) Model fitted to data to extract fluence dependent coefficients.

(b) Closure test.

Figure 6: The model fitted to data from ATLAS12 sensors exposed to reactor neutron irradiation. This data corresponds to the 500 volt bias voltage.



(a) Detail of Alibava daughter board. The two miniature sensors are visible with the wire bonds connecting them to the daughter board.

(b) View inside freezer showing mounting of Alibava DAQ daughter board and ^{90}Sr source on computer controlled arm.

Figure 7: Setup at Toronto used to accumulate ATLAS18 neutron irradiated data.

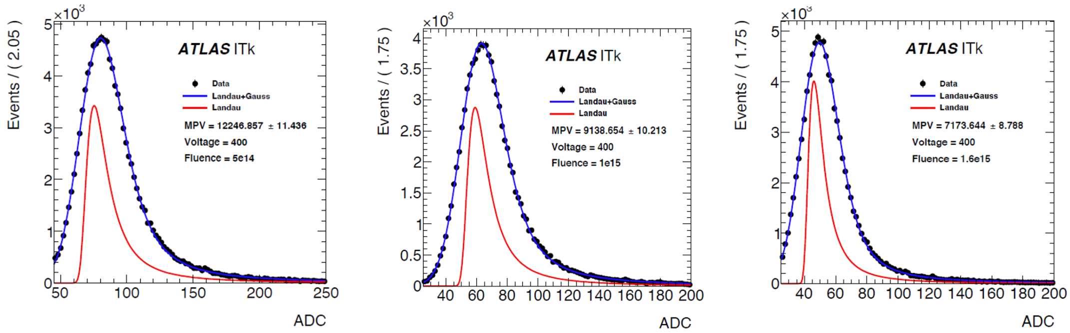
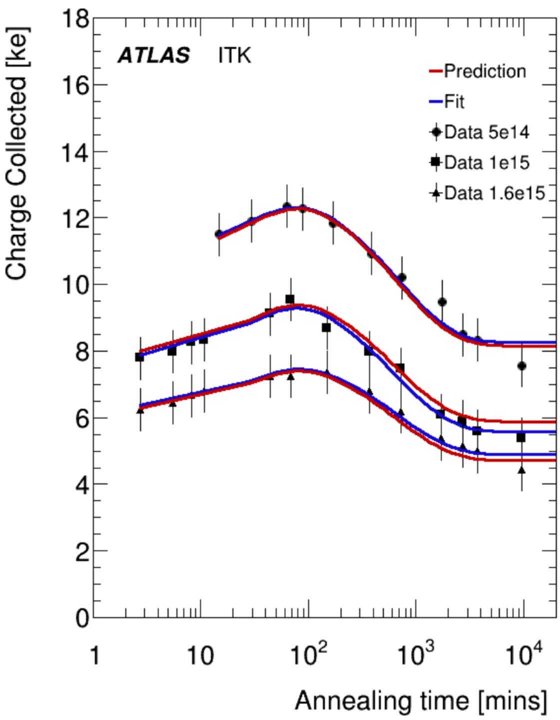
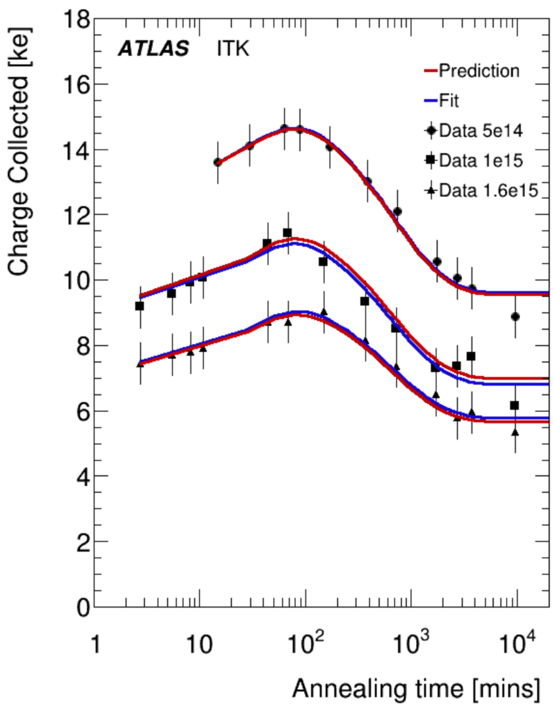


Figure 8: The pulse height distributions from the ^{90}Sr setup for three different fluences. A convolution of a Gaussian (for noise) and a Landau distribution is fitted to the data. The most probable value of the Landau represents the collected charge.

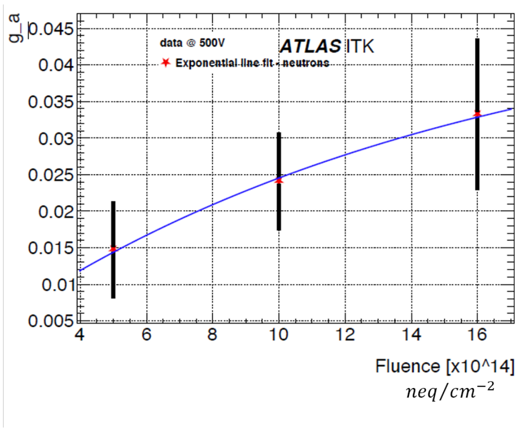


(a) 400V bias voltage.

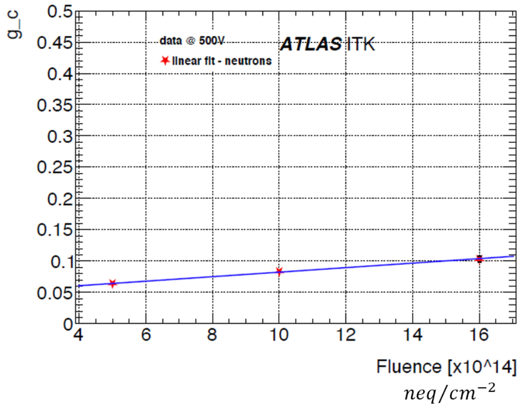


(b) 500V bias voltage.

Figure 9: The model fitted to the neutron irradiation data measured at Toronto. The fits and closure are plotted together.



(a)



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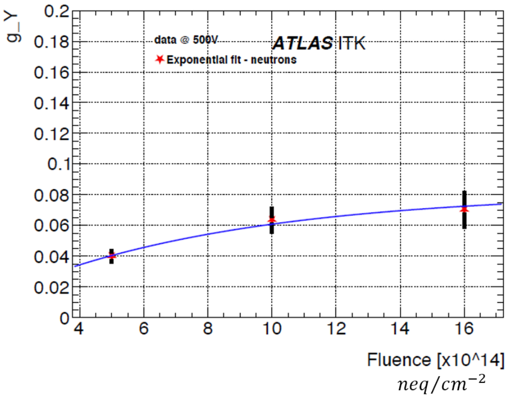


(c)

Figure 10: The model coefficients determined from the fits in Fig. 9b.

- Equivalent of 2 years running at nominal HL-LHC fluence, followed by 1 year annealing at +7 ° C and then 1 year annealing at −3 ° C
- an additional 3 years nominal fluence. followed by 4 years annealing at −13 ° C
- an additional 4 years nominal fluence. followed by 3 years annealing at −20 ° C
- an additional 5 years nominal fluence. followed by 5 years annealing at −25 ° C

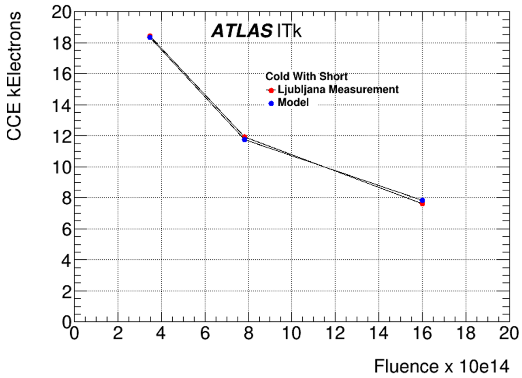
• Cold start with short warm ups

- Operation at −25 ° C, 10 days warm during long shut downs 4 and 5

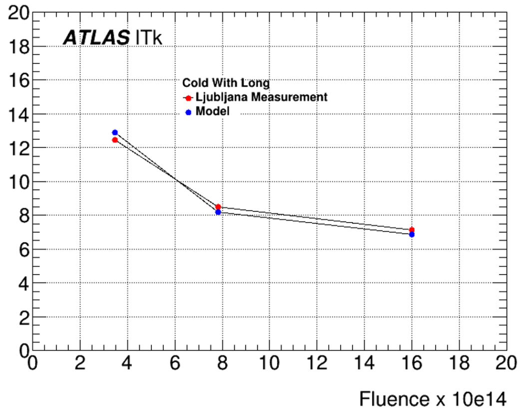
• Cold start with long warm ups

- Operation at −25 ° C, 100 days warm during long shut downs 4 and 5

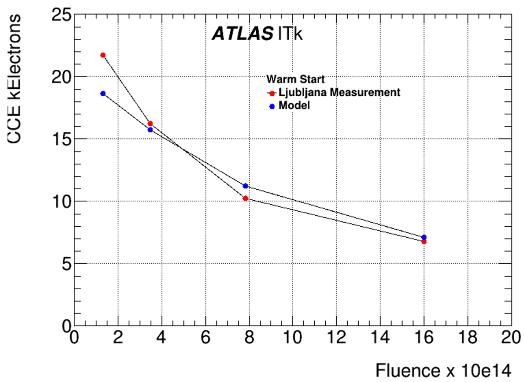
The comparison of the measurements of the collected charge in the neutron irradiated mini-sensors and the prediction of the model is shown in Figure 11. In the reactor experiment the procedure was to accumulate the fluence for a given running period over a short irradiation, and then to allow the sensor to anneal at the chosen temperature. In the model the irradiation was assumed



(a) Cold running with short warmup periods.



(b) Cold running with long warmup periods.



(c) Warm start running, with successively reducing temperature.

Figure 11: Comparison of the predicted collected charge from the model with measurements at Ljubjana. The three plots correspond to three different temperature profiles for running.

to be a delta function, and then the annealing was modeled. This is an excellent approximation for long cold periods of irradiation followed by warm periods of annealing, since there is essentially no annealing at the low temperature. Long shutdown 4 will be approximately four years after ITk installation and long shutdown 5 approximately eight years. In all three scenarios the collected charge remained greater than 6350 electron equivalent. This corresponds to Signal/Noise = 10, and corresponds to the worst case *viz.* detector end-of-life.

6. Conclusion

We have developed a semi-empirical model of the the effect of annealing on the collected charge in the ATLAS18 sensors. The model is inspired by the well-known Hamburg Model, and it has been optimized to reproduce our measurement of the charge collected after long term annealing at elevated temperature. The model has been cross compared with experimental measurements in a different situation as described in section 5. The agreement is rather good. We have also used the model to study various possible maintenance situations during the life time of the ITk.

7. Acknowledgements

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