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

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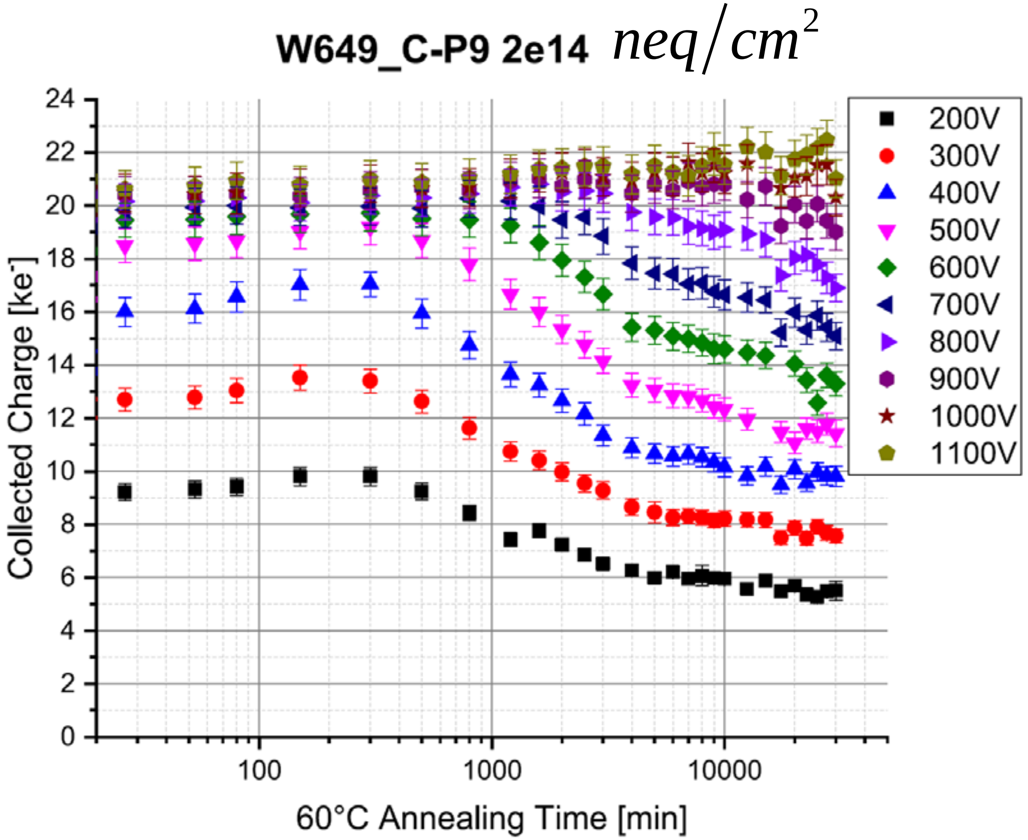
On behalf of the ATLAS ITk Collaboration

Motivation

- The ATLAS ITk – or for that matter any silicon detector - will suffer radiation damage and temperature dependent annealing
  - Increase of leakage current - operational consideration
  - Increase of Full Depletion Voltage – operational consideration
  - Reduction of Charge Collection Efficiency
    - At some level of degradation this will adversely affect the efficiency for track finding
  - Annealing is reduced at low temperature
  - Not possible to just keep detector at very low temperature permanently
    - For the ITK this period would be 14 years
    - Detector maintenance
    - Cooling system maintenance
    - Other possible warm ups
  - While the phenomenon of annealing after radiation damage is interesting in its own right, we have taken a more empirical approach

Parametrisation of Long Term Annealing

- Rather than trying to develop a deep theoretical understanding, I wanted to come up with some "physically motivated" parametrisation.
- The Hamburg Model seems to be the standard way of understanding annealing effects – so this is a starting point
- Initially looked at some ATLAS12 data
  - ATLAS*yy* are a series of strip sensor prototypes produced by Hamamatsu Photonics from designs by ATLAS ITk – ATLAS18 is the production series
  - The ATLAS12 data has been published in NIM A 924 (2019) 128-132 L. Wiik-Fuchs et al
  - That publication is a subset of data from Leena Diehl – Freiburg Ph.D. Thesis 2018
  - Leena Diehl kindly provided me with the numerical data, and also some additional measurements from her thesis



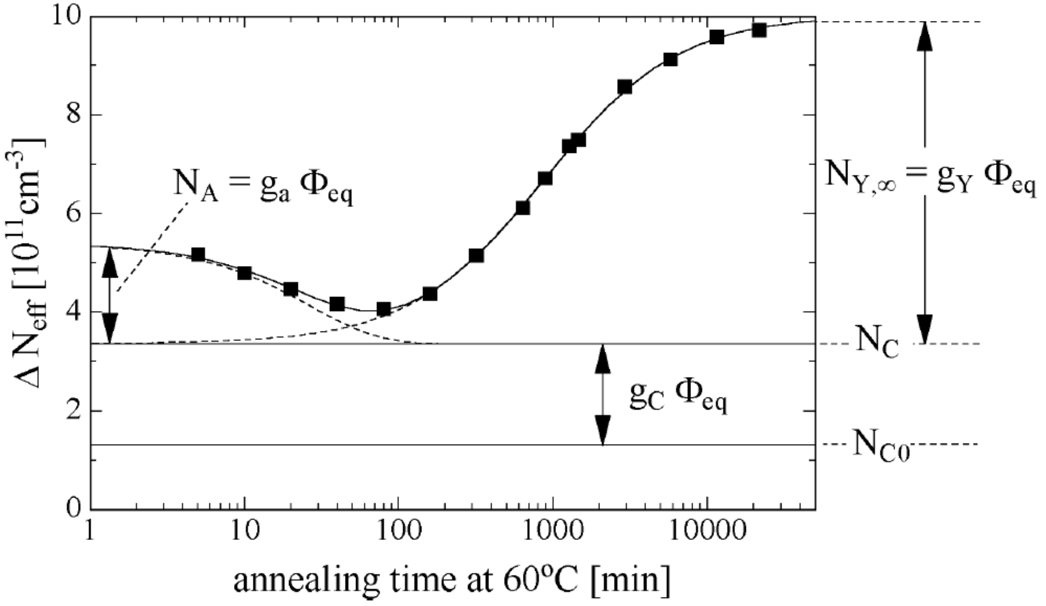


Figure 5.9: Annealing behavior of the radiation induced change in the effective doping concentration ΔN_{eff} at 60°C. The shown example is a sample of type WE-25kΩcm irradiated with a fluence of 1.4×10^{13} cm^{-2}.

NIM A 924 (2019) 128-132 L. Wiik-Fuchs et al

Michael Moll – DESY Thesis 99-040

Hamburg Model

- Effective doping concentration N_{eff} depends on Φ_{eq} - fluence of irradiation and time.
- The model hypothesises that there are three phases of annealing in time.
  - Short Term beneficial annealing

$$N_A\left(\Phi_{eq},t\right)=\Phi_{eq}g_a\exp\left(-t/\tau_a\right)$$

  - Constant

$$N_C\left(\Phi_{eq}\right)=N_{C,0}\Phi_{eq}g_a\left(1-\exp\left(C\Phi_{eq}\right)\right)+g_C\Phi_{eq}$$

  - Long term degradation

$$N_Y\left(\Phi_{eq},t\right)=\Phi_{eq}g_Y\left(1-\exp\left(-t/\tau_Y\right)\right)$$

  - Ansatz = Guess $CCE\propto\left(1/N_{eff}\right)$

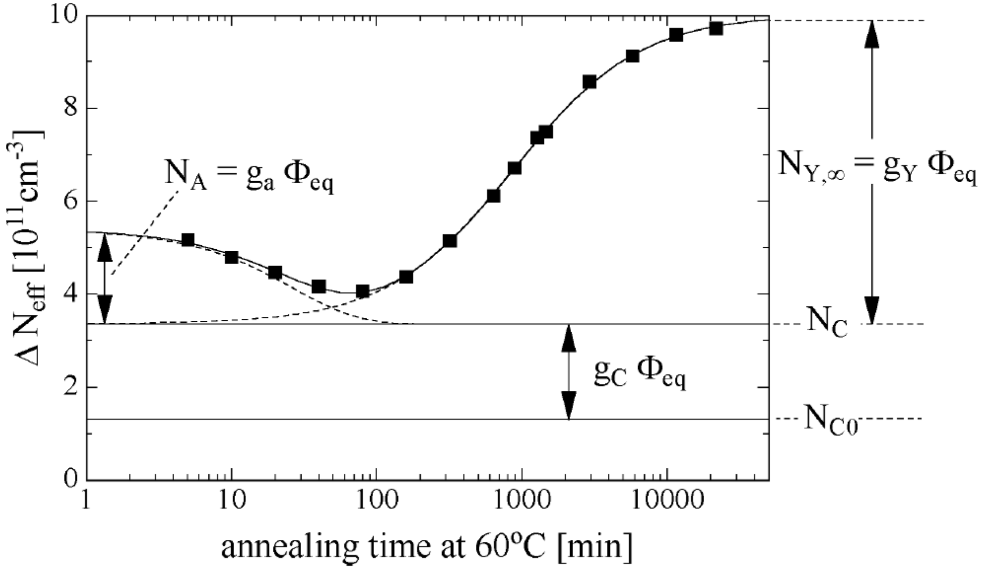


Figure 5.9: Annealing behavior of the radiation induced change in the effective doping concentration ΔN_{eff} at 60°C. The shown example is a sample of type WE-25kΩcm irradiated with a fluence of $1.4\times10^{13}\,\mathrm{cm}^{-2}$.

We parametrize the collected charge as a function of irradiation fluence as :

$$1 \Big/ \left(g_a \exp\left(-t/\tau_a\right) + g_C + g_Y \left(1 - \exp\left(-t/\tau_Y\right)\right)\right)$$

g_a - Coefficient for short term annealing

τ_a - Diffusion time for short term annealing

g_C - Constant term

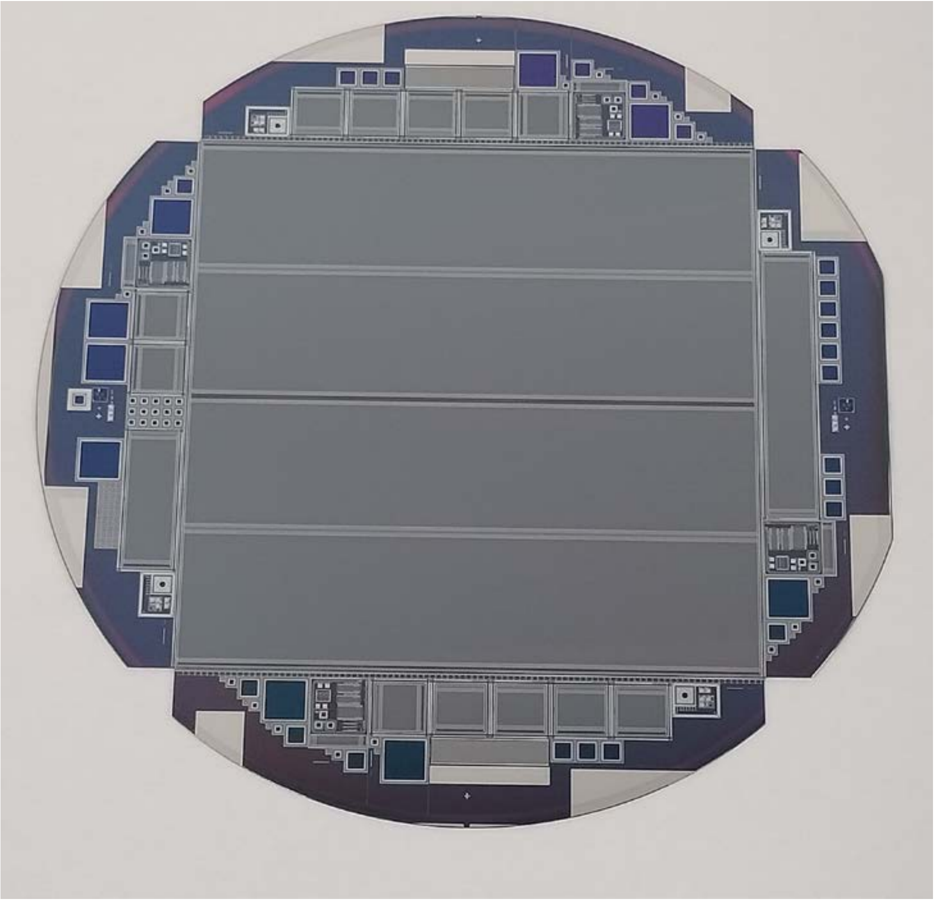
g_Y - Coefficient for long term annealing

τ_Y - Diffusion time for long term annealing

The dependence of the collected charge on fluence is incorporated in the g-coefficients

Miniature Sensors

- Each wafer produced by Hamamatsu contains full size sensors which are rectangular or trapezoidal in shape.
- This leaves space for other structures around the periphery of the wafer.
- ATLAS populates this area with test structures and miniature sensors.
- The miniature sensors are “identical” to full size sensors – same strip and bias/guard ring structures, and several sizes. The miniature sensors in this study are 1cm x 1cm with 104 strips of 8 mm length.
- In this study the miniature sensors were irradiated with 24 MeV protons (ATLAS12 at Karlsruhe) and reactor neutrons (ATLAS12 and ATLAS18 at Ljubljana)

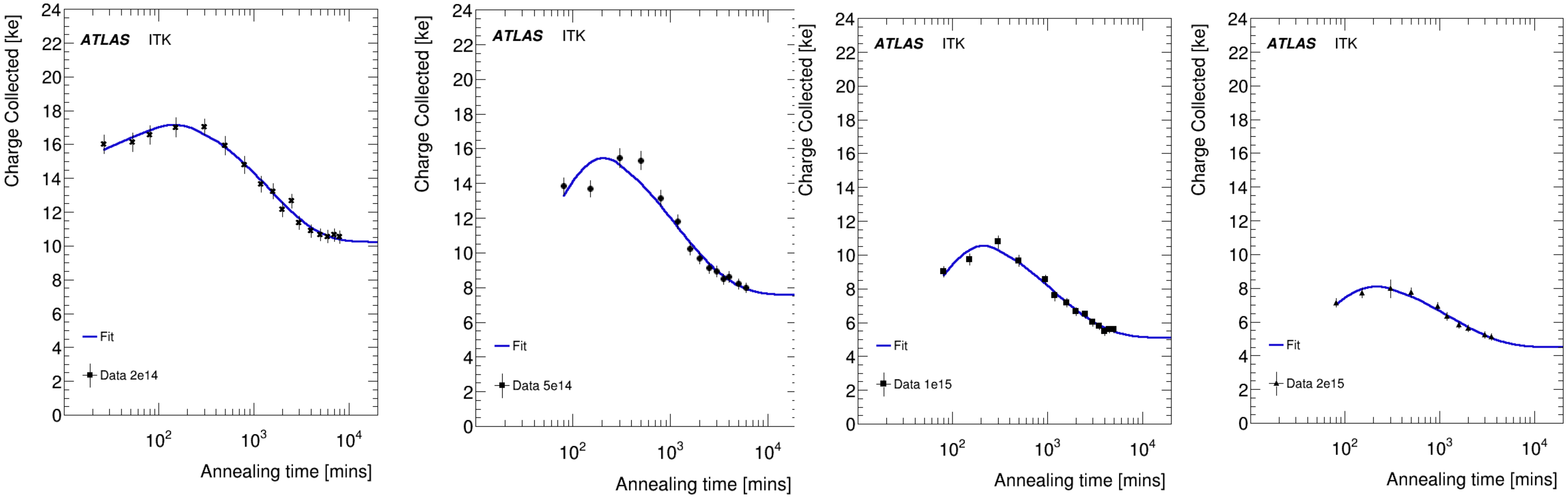


ATLAS18 Wafer

Fitting Procedure

- Initially fit distribution at each fluence with all parameters free
- To have some predictive power need to reduce number of parameters
- While the g-coefficients are functions of the irradiated fluence, it seems reasonable that the diffusion times are not.
- Refit the distributions at each fluence, with the diffusion times fixed.
    - We used the diffusion times from the fit at 2e14 neq/cm^2
- This extracts a set of g-parameters at each fluence
- We then fit an empirical function to the g-parameters as a function of fluence
- Then use fixed diffusion times and fitted function of g-parameters to give a “prediction” or closure test.
- We have data at many bias voltages
- Unirradiated full depletion voltage is 300V, and the ITk is limited to 500V – so we have only studied 400V and 500V in detail

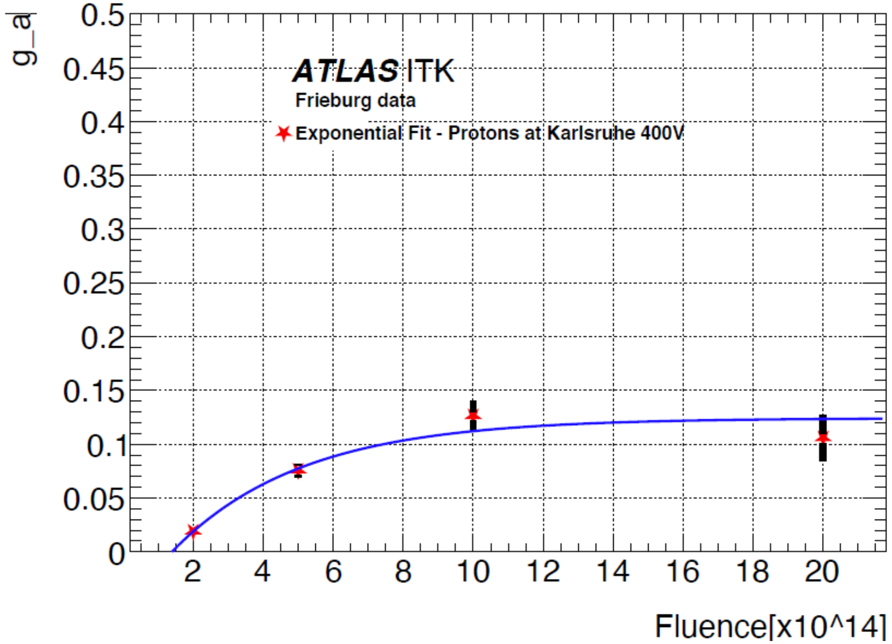
Fit model to 24 MeV Proton Data

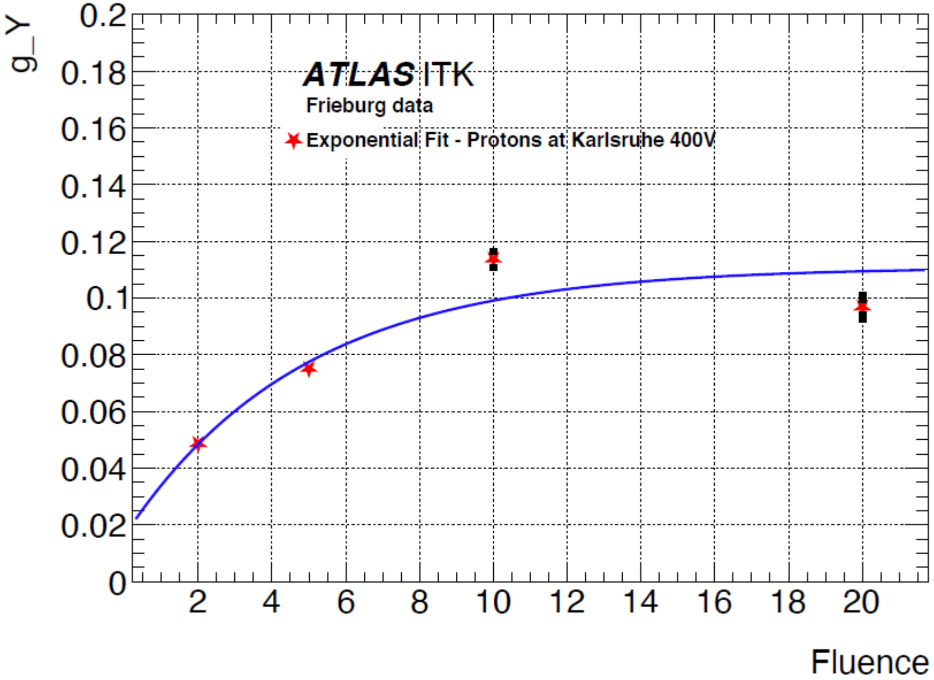


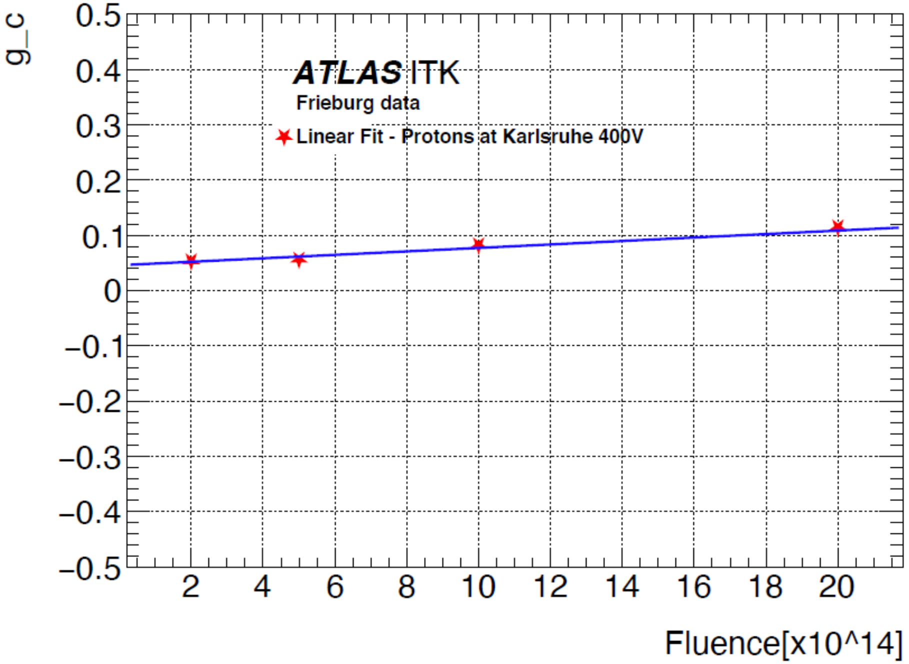
- Measured at Freiburg
- Annealing at 60 C
- ATLAS12
- 400 V Bias

- g- coefficients free at each fluence
- Diffusion times fixed to same value at each fluence $\tau_a = 53s, \tau_Y = 2296s$

Functional Model for Dependence of Coefficients on Fluence

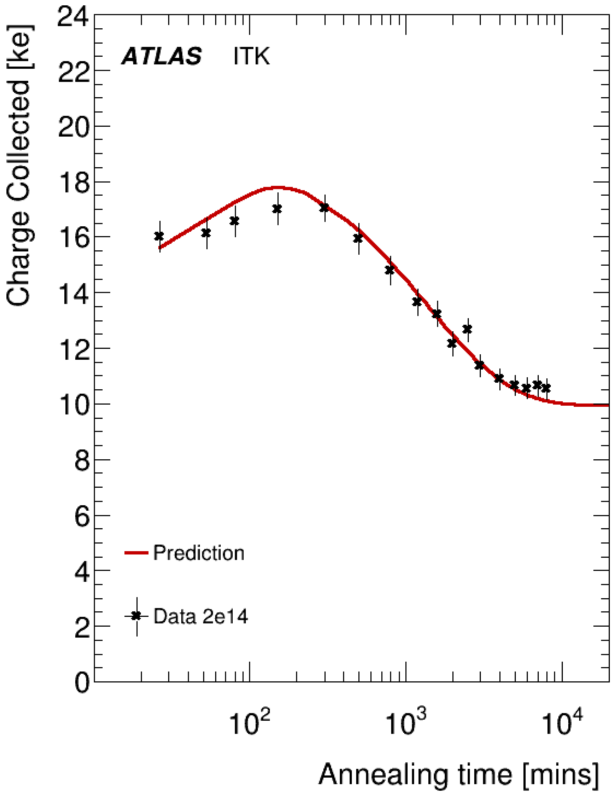


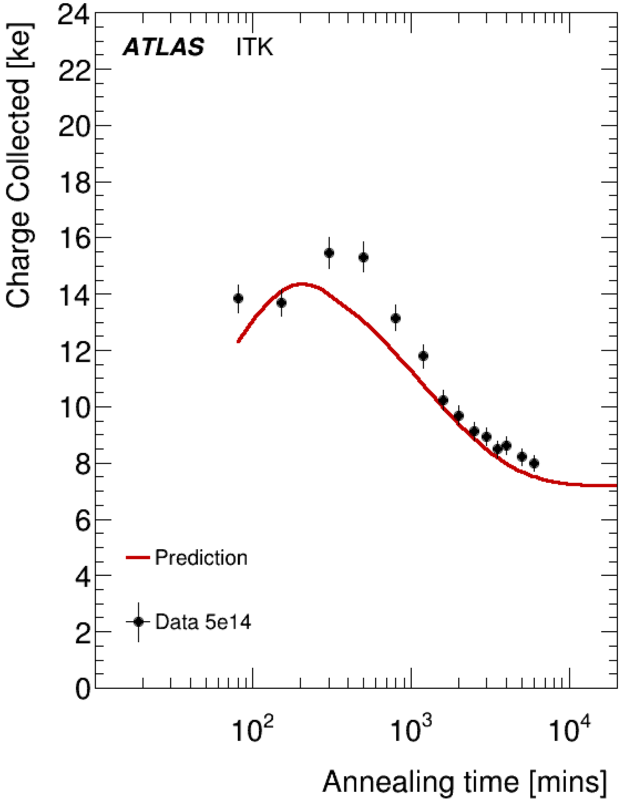


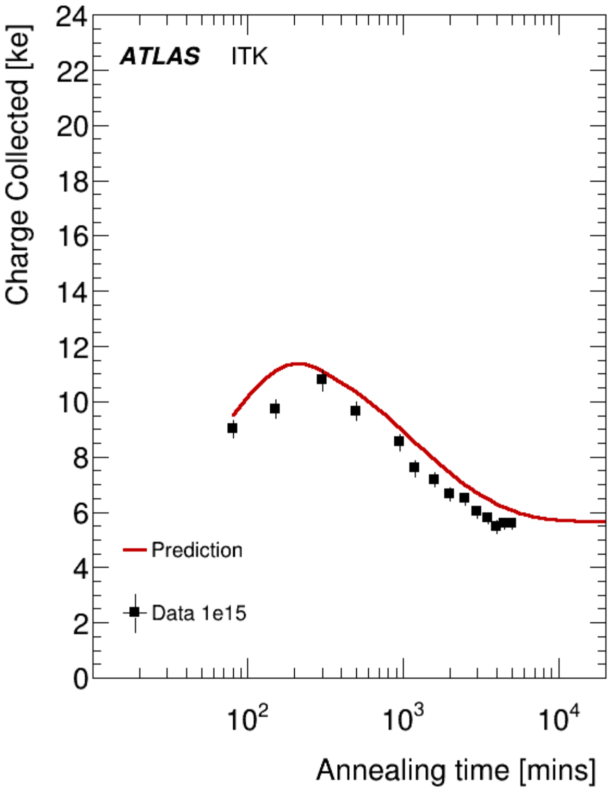


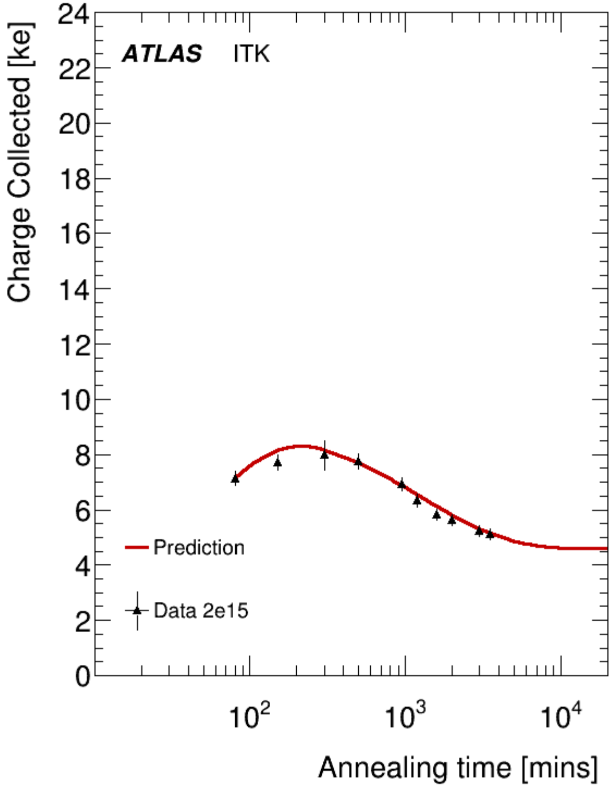
fitted g_a and g_Y to the form $a+b\left(1-\exp\left(-c\times fluence\right)\right)$ and g_C was taken as linear.

24 MeV protons at Karlsruhe – Closure Test



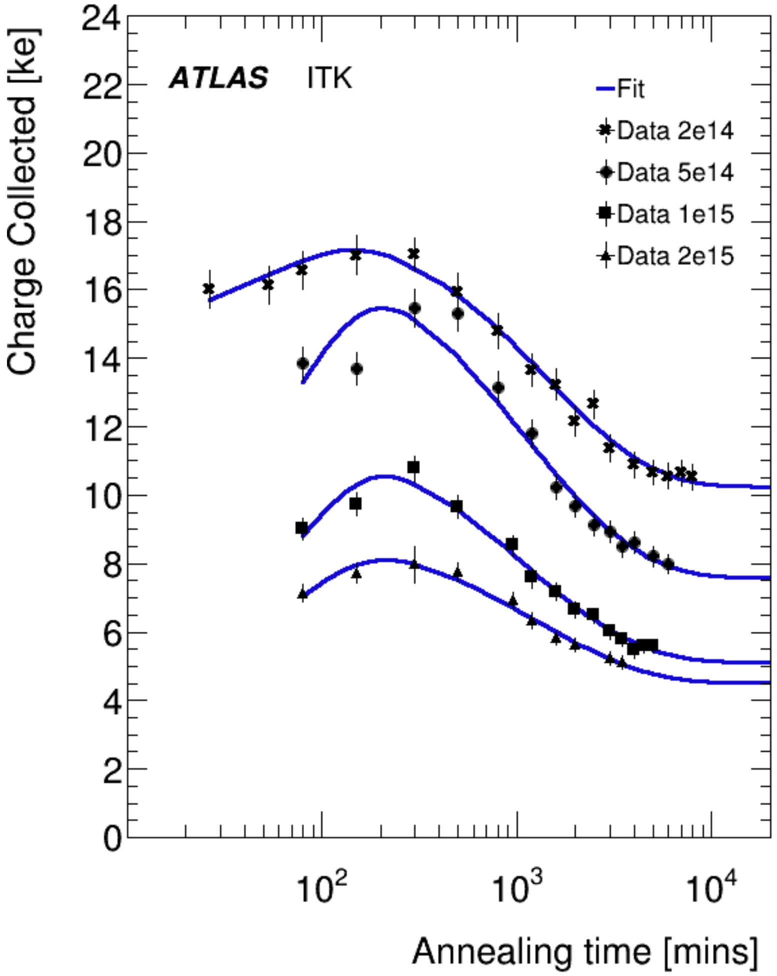


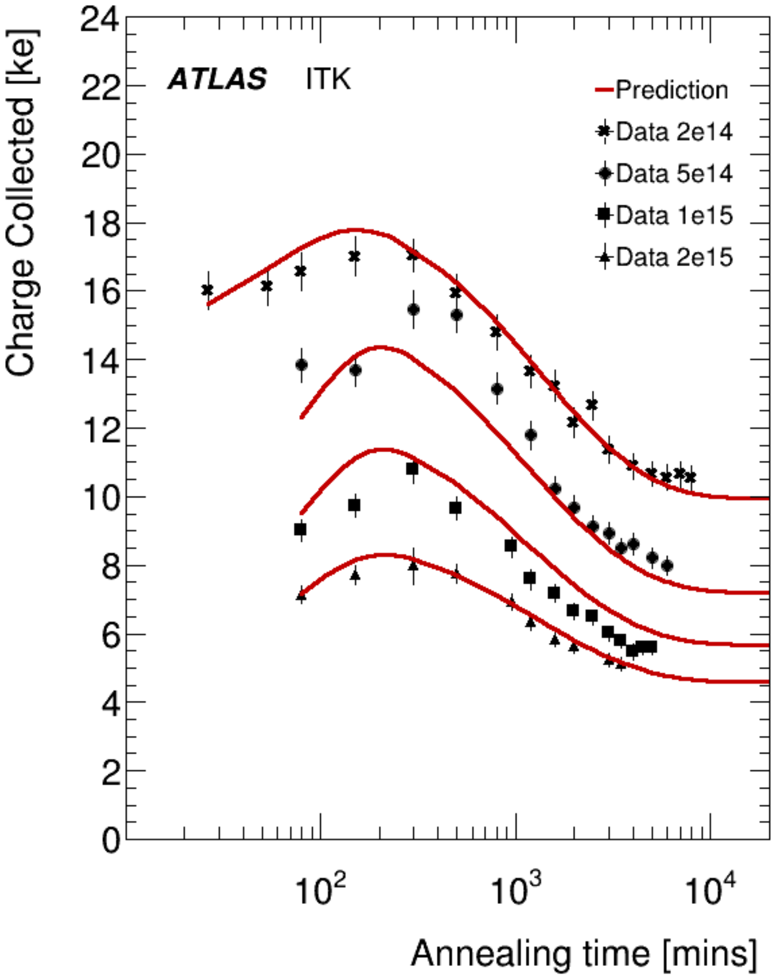




The fitted functional form of the g-parameters is used to predict the Collected Charge

24 MeV protons at Karlsruhe – Closure Test

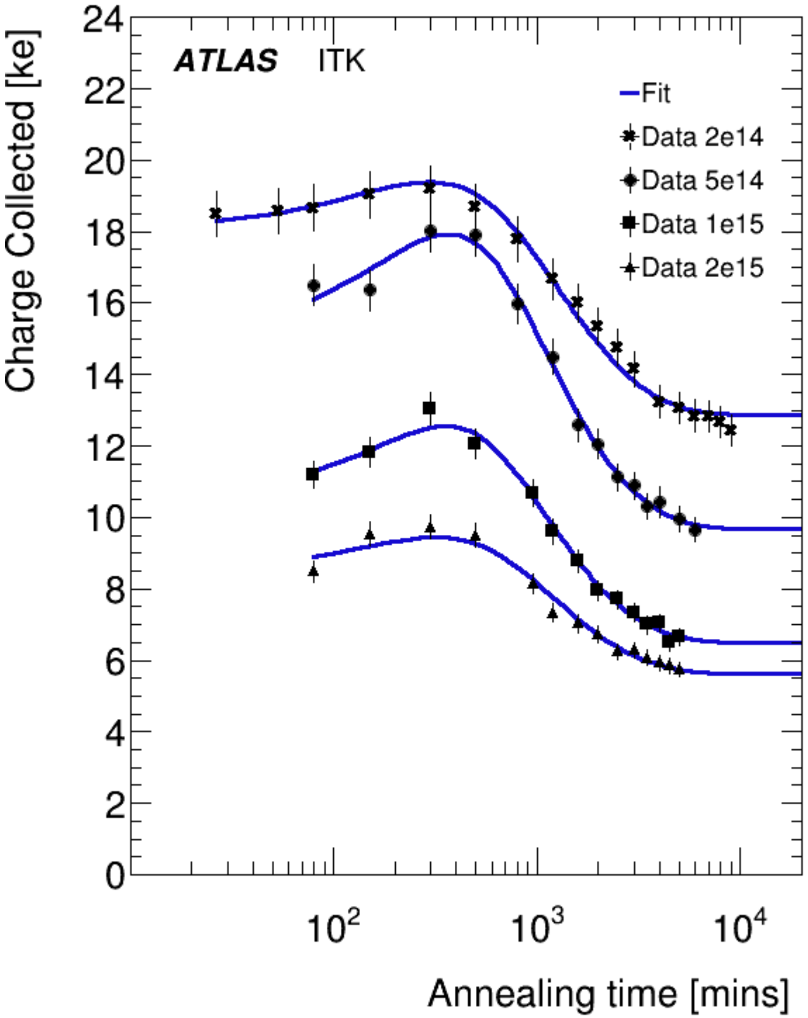


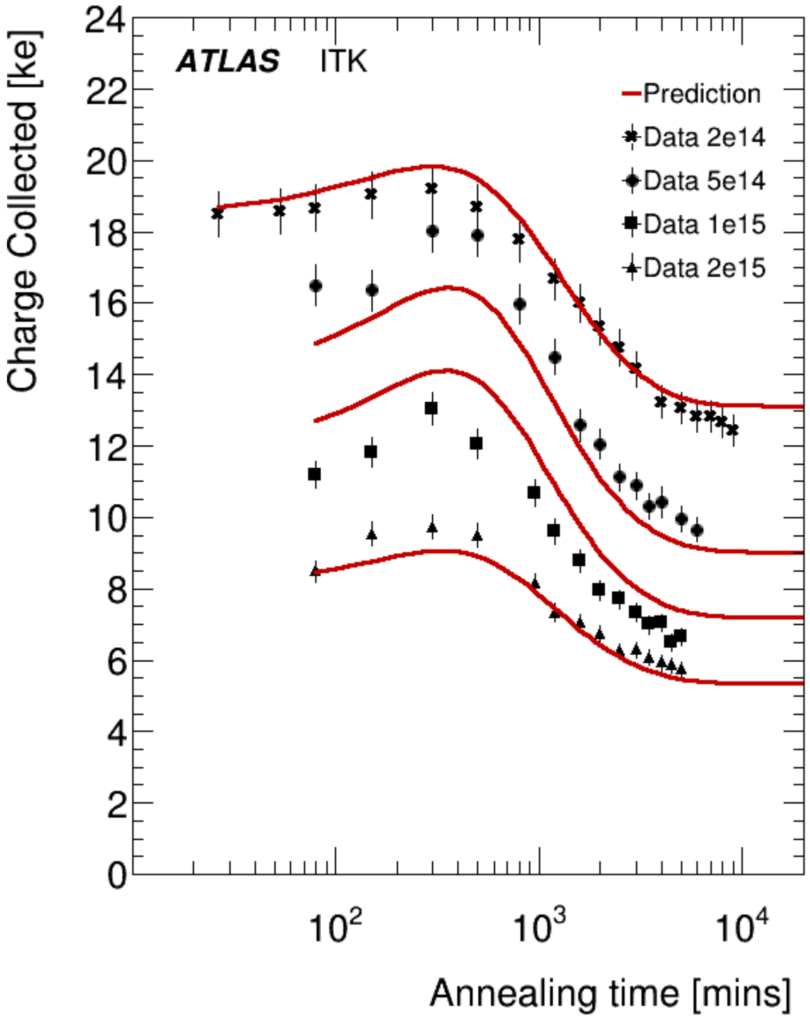


- ATLAS12
- 400 V Bias Voltage
- Measured at Freiburg
- Annealing at 60 C
- “Fit” is the independent fit to each fluence
- “Prediction” is the prediction of the model using the fitted coefficients as a function of fluence

This is a condensation of last three slides

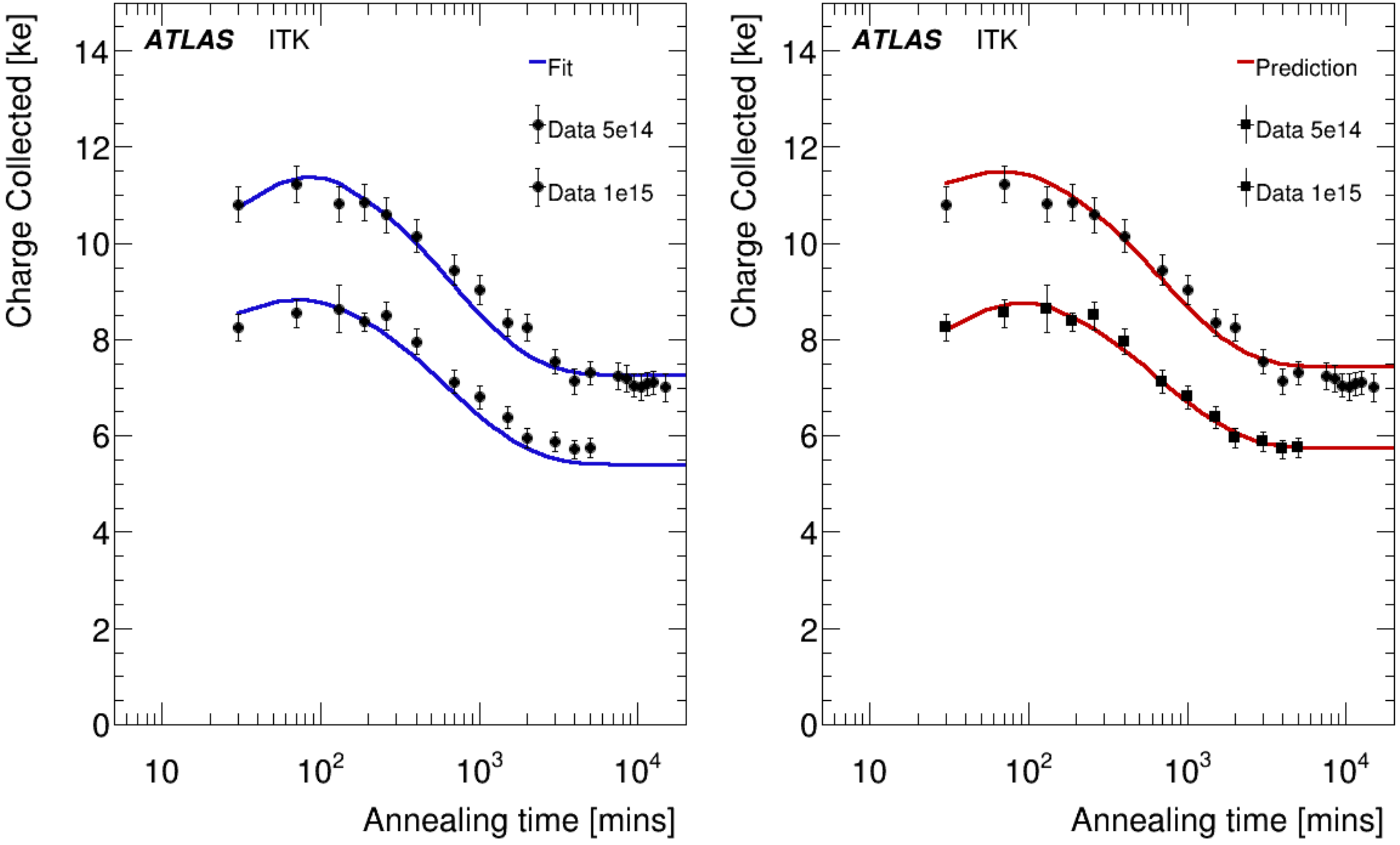
24 MeV protons at Karlsruhe – Closure Test





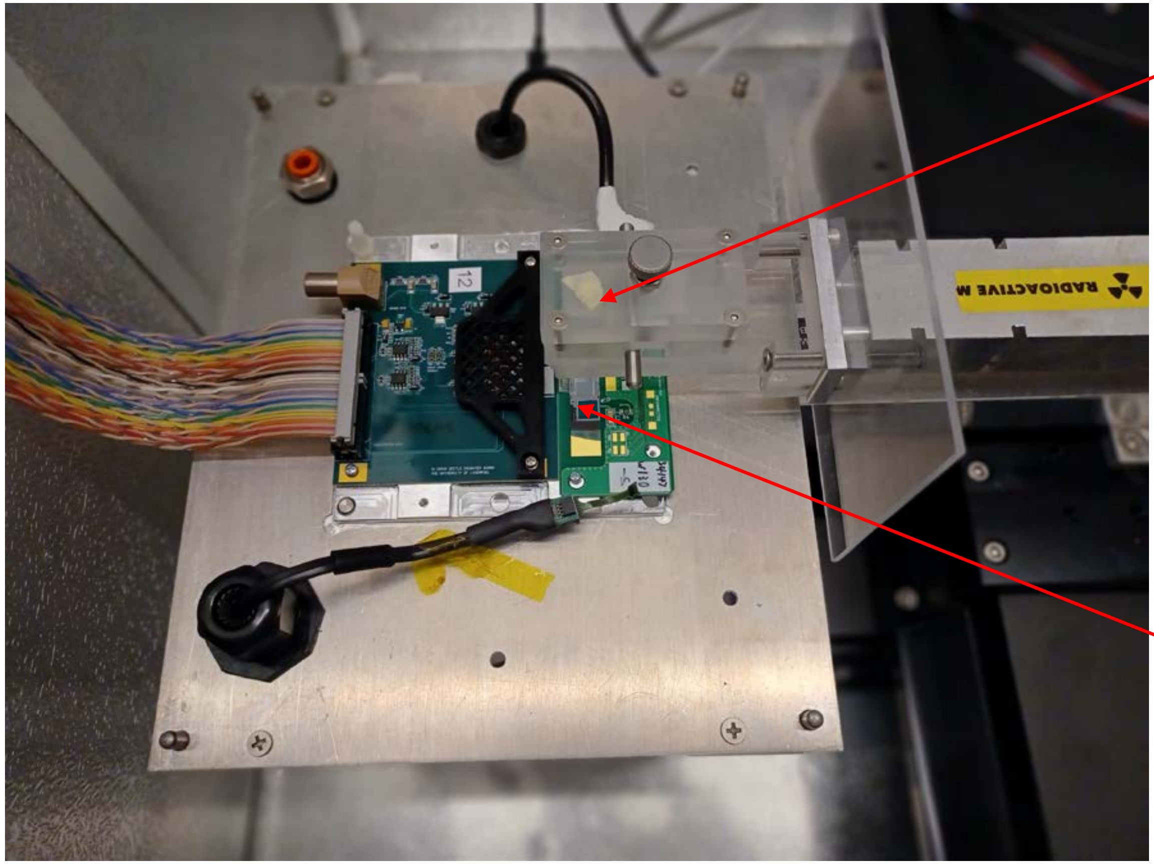
- ATLAS12
- 500 V Bias Voltage
- Measured at Freiburg
- Annealing at 60 C
- Fits to the coefficients are done independently at 400V and 500V

Reactor Neutrons – Closure Test

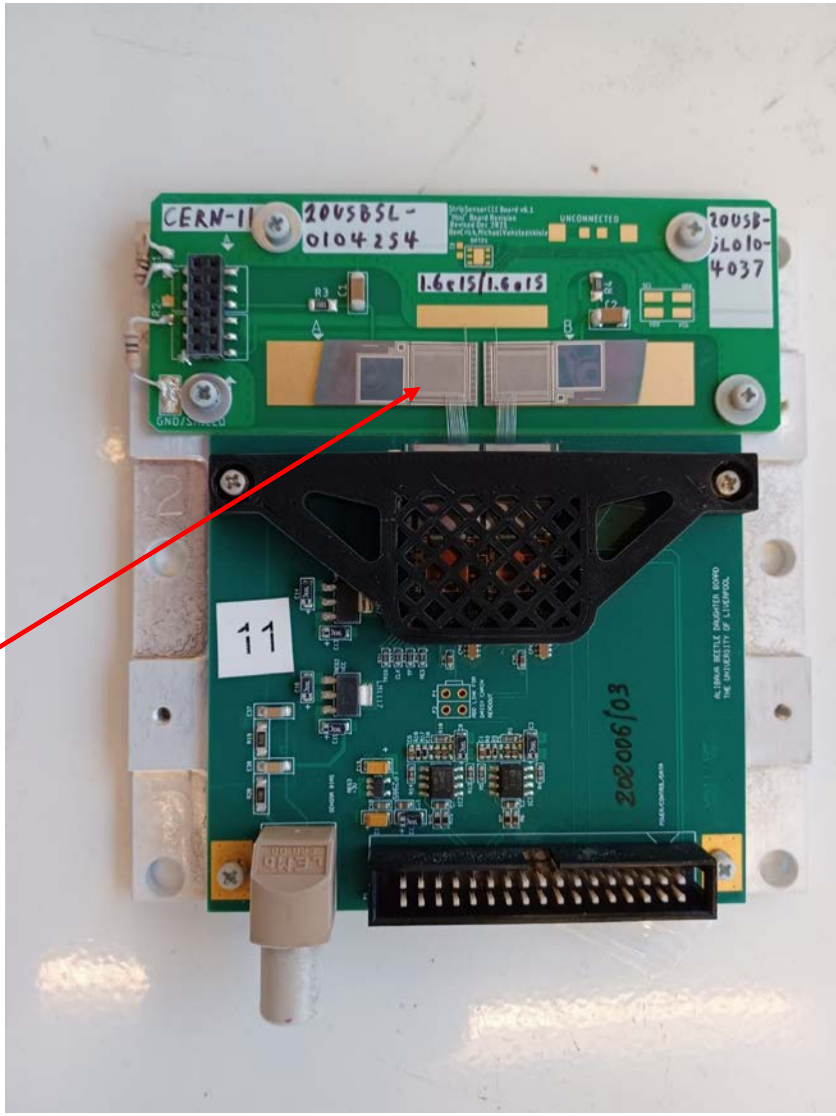


- ATLAS12
- 500 V Bias Voltage
- Annealing at 60 C
- Measured at Freiburg
- All neutron data irradiated at Ljubljana

Toronto Measurement of CCE of Miniature Sensors



^{90}Sr



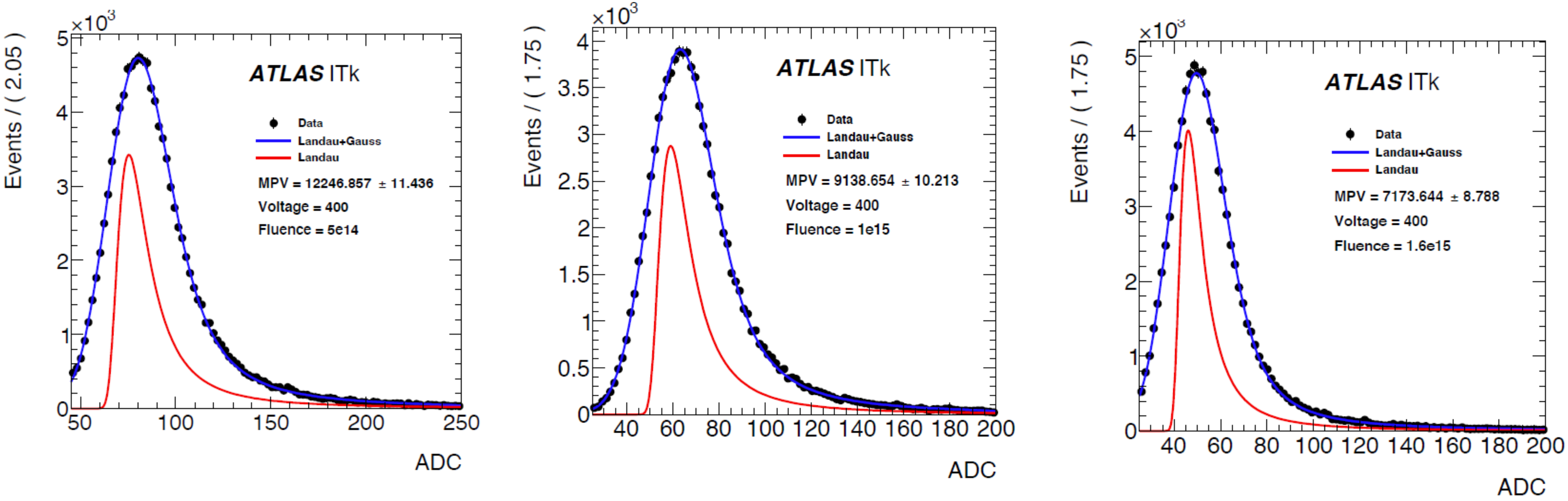
Mini-sensor

Uses Alibava readout system to measure pulse height spectrum
Measurements done in freezer at -27 C

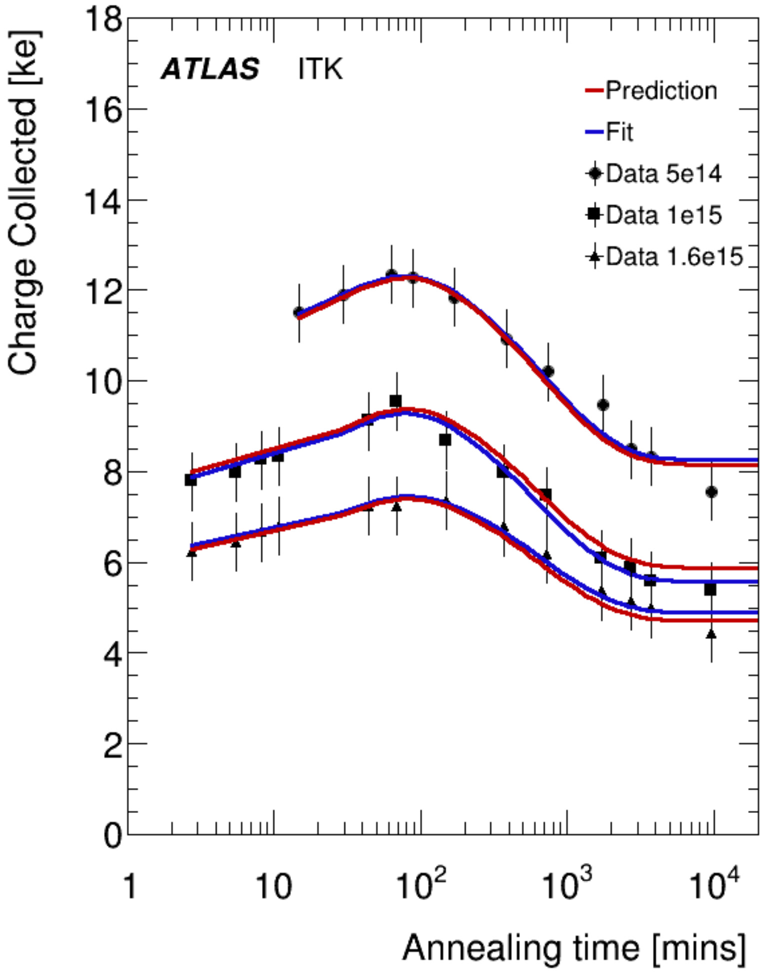
Measurement Procedure at Toronto

- Gain of all Alibava daughter boards calibrated as a function of temperature
- Used sensor mounting board with improved HV filtering
- Took data for Bias Voltage 50V to 1100V
- Pulse height spectra fitted to Landau + Gaussian
- Most probable value of Laudau plotted

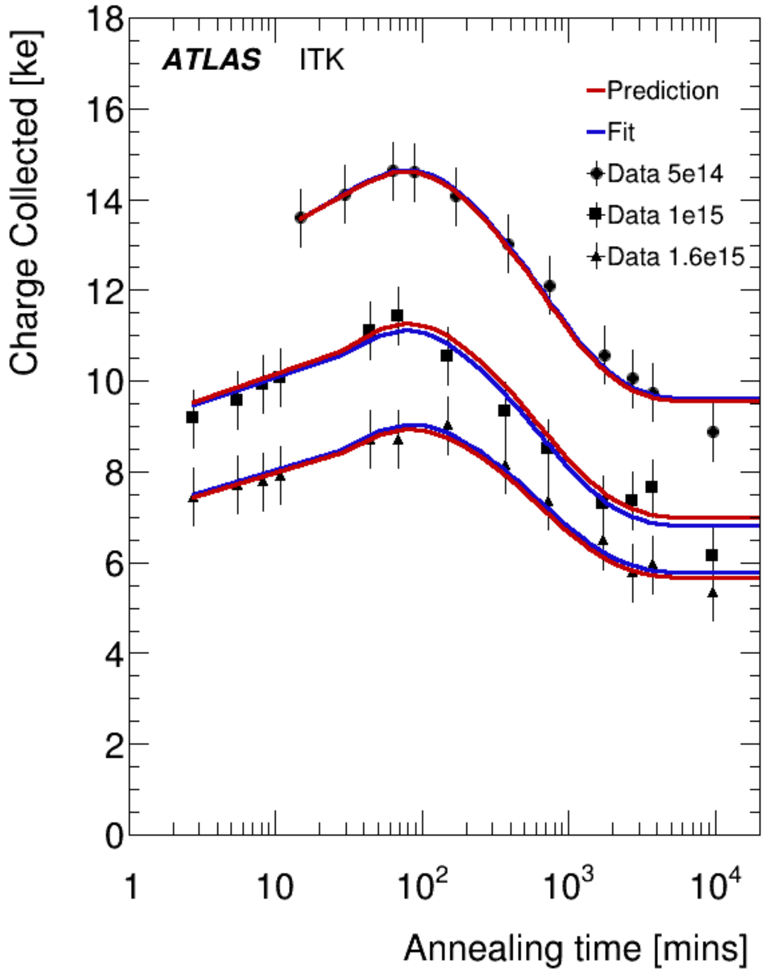
150 Mins Annealing at 60 deg



Fits and Closure of ATLAS18 - Neutrons

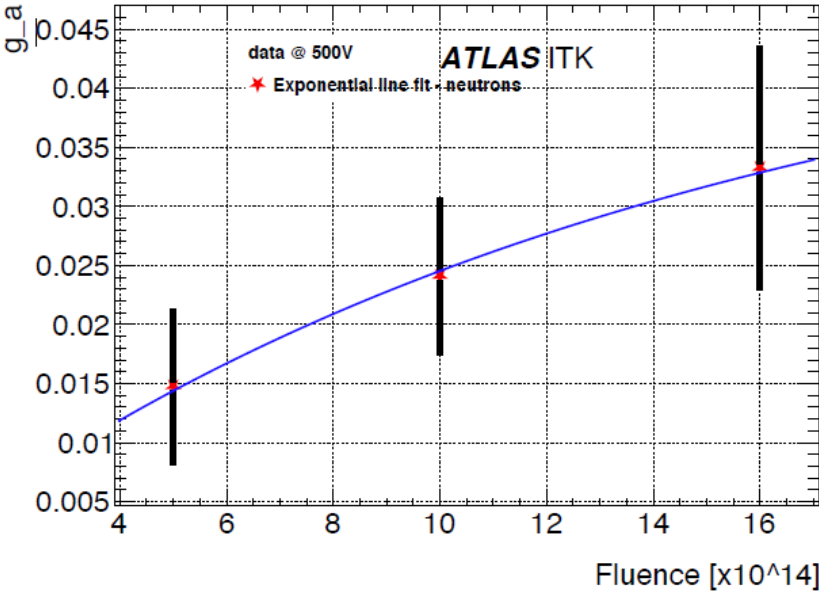


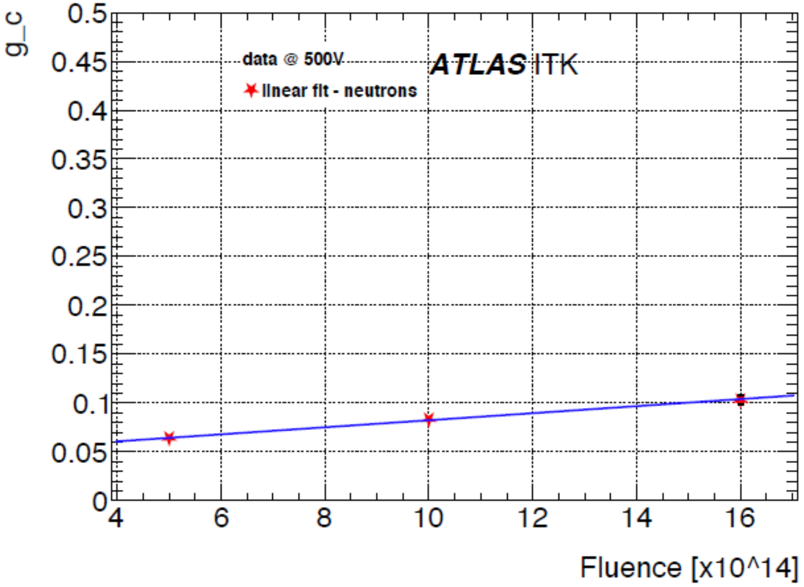
- Measured in Toronto
- 400V Bias Voltage
- Annealing at 60 C

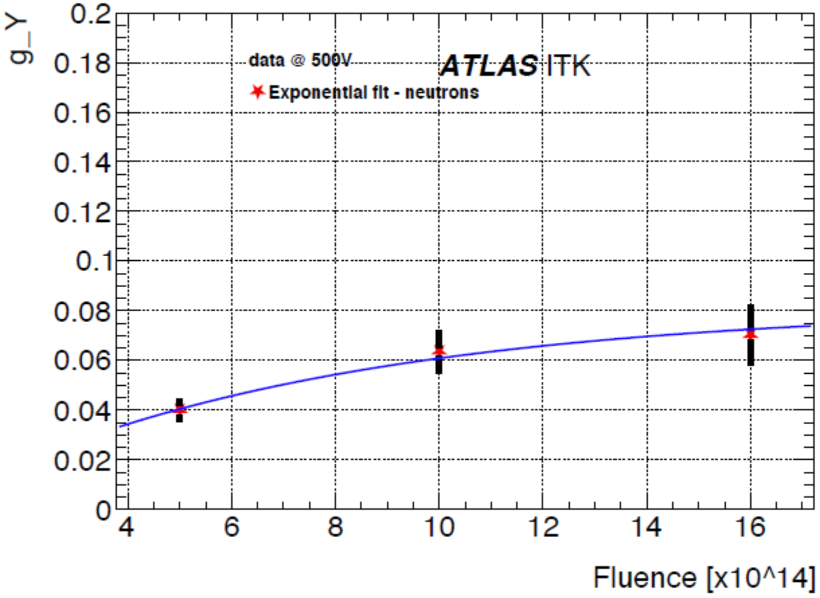


- Measured in Toronto
- 500V Bias Voltage
- Annealing at 60 C

g-coefficients for ATLAS18 Neutrons







- Measured in Toronto
- 500V Bias Voltage

Use of Model in Assessing Long Term Running Scenarios

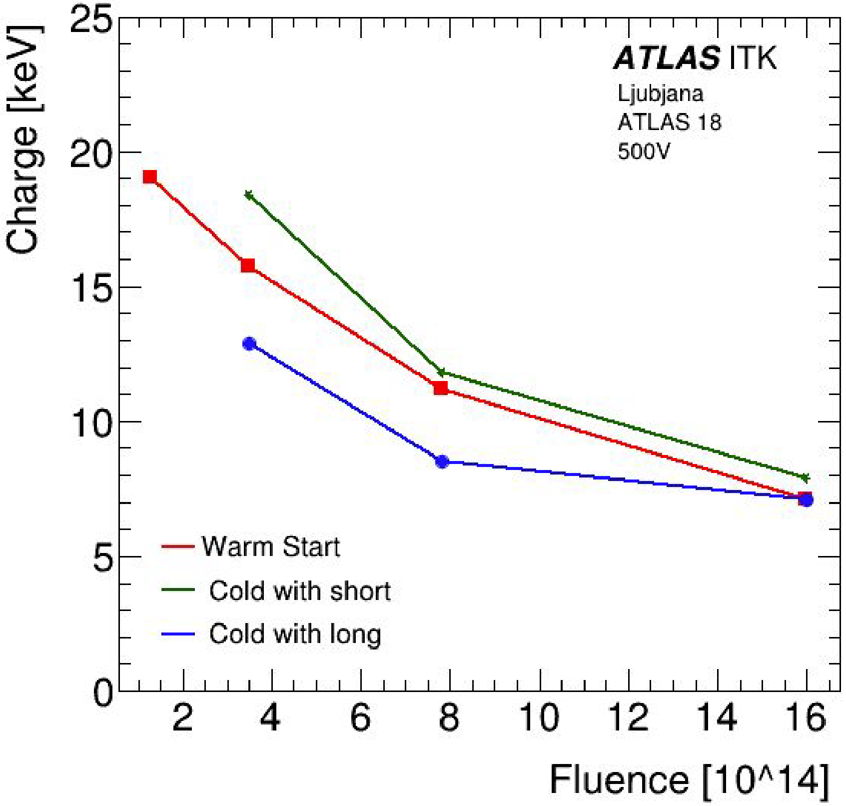
We have used model to investigate the end of life CCE in several possible situations

1) Alternative temperature Profiles during running
    - Starting cold -25C, and running cold except for
        - Long warmups
        - Short warms ups
    - Starting at room temp and progressively reducing temperature
- Allows data/model comparison

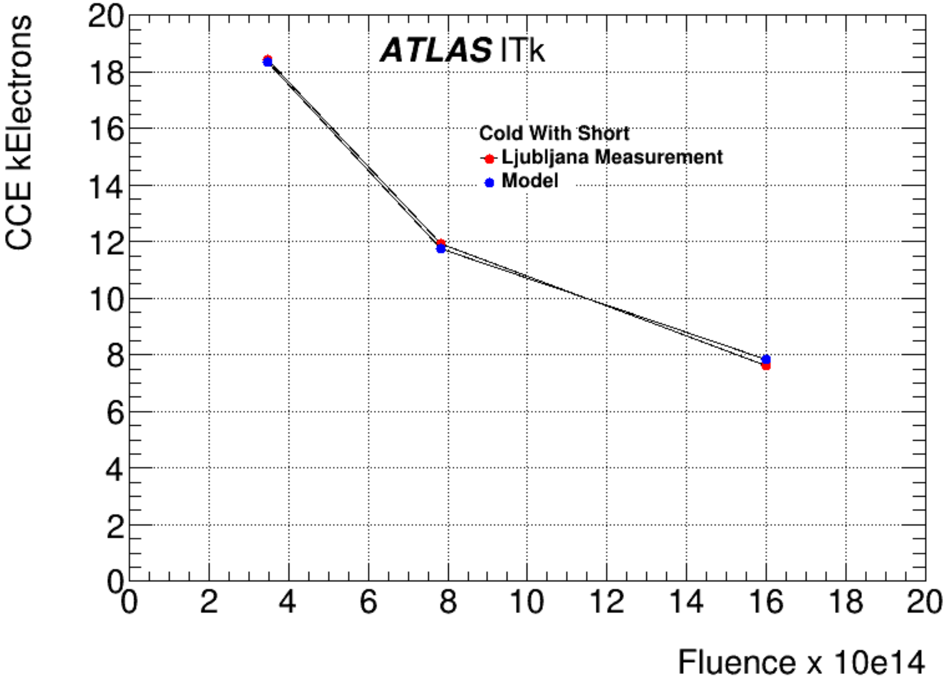
2) A staging scenario where the pixel installation was delayed until Long Shutdown#5 (LS5), but the Strips were installed in LS4, run cold, and then warmed up for 100 days in LS5

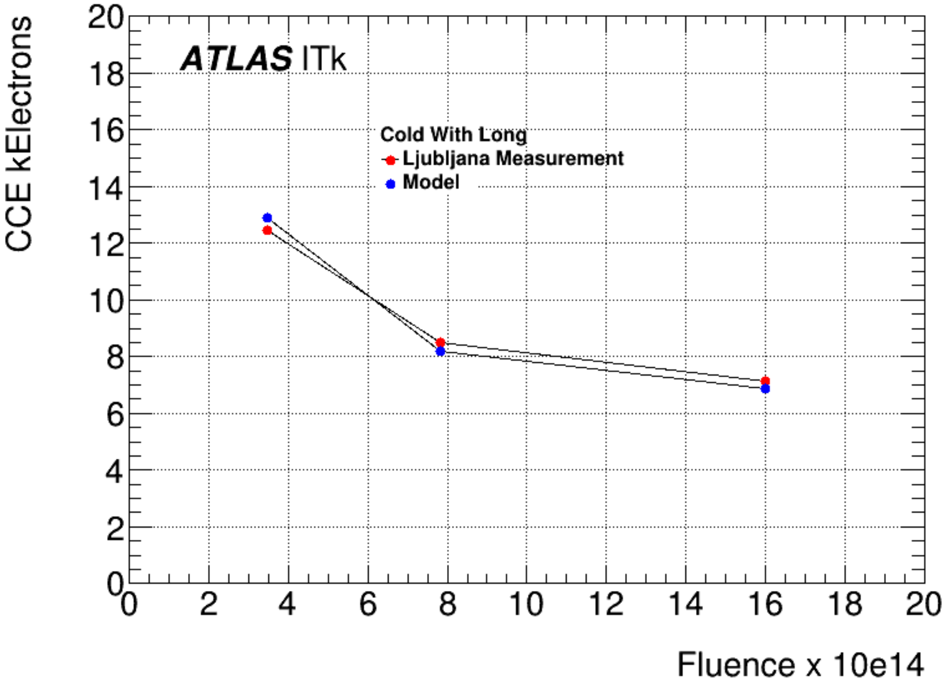
3) A scheduled maintenance of the CO_2 cooling system, during which the ITk is warmed up for 10 days each year and 40 days in LS4 and LS5

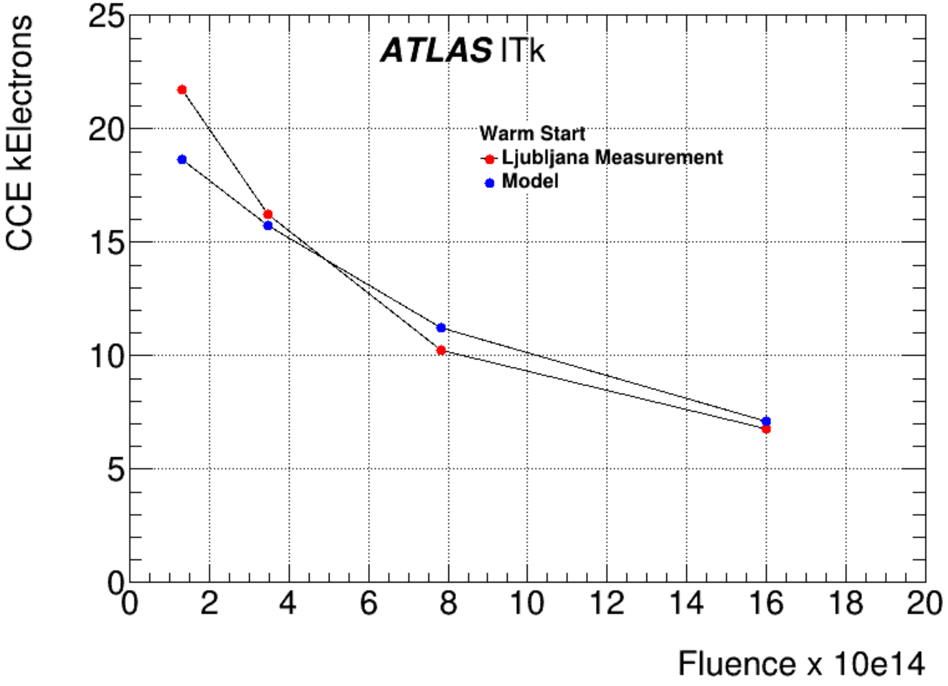
CCE measured using Ljubjana Alibava setup



- In all three scenarios the collected charge remained greater than 6350 electron equiv
- This corresponds to Signal/Noise = 10 , and corresponds to the worst case *viz* detector end-of-life







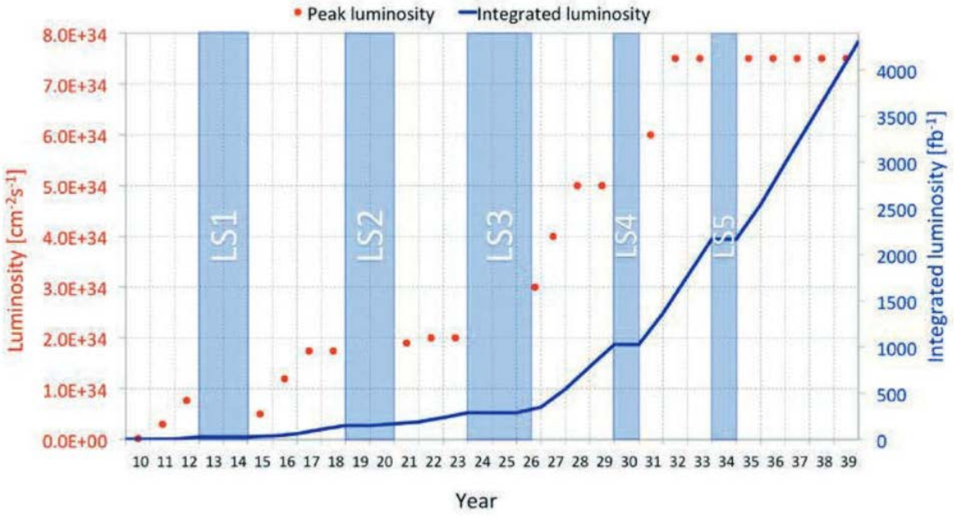
Comparison of model with experiment

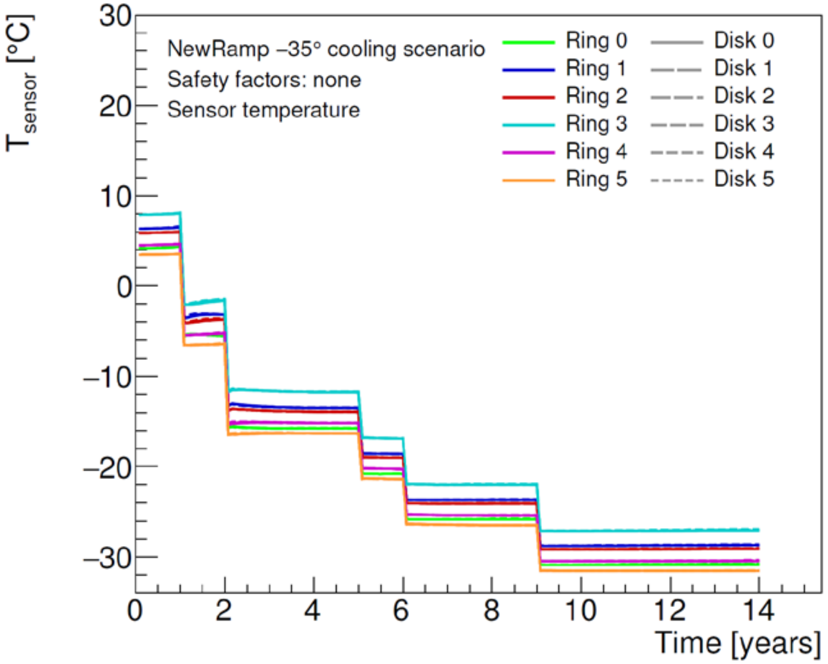
Conclusions

- We have constructed a simple, data driven, model of the dependence of collected charge on annealing time / temperature for the ATLAS18 strip sensors
- It reproduces annealing measurements at end-of-life to better than 5%
- We have used the model in temperature/schedule planning extending over the foreseen lifetime of the ITk
- The model does have shortcomings, viz:
    - Present approximation:
        - Apply fluence as a delta function
        - Run model for time@temp
        - Apply fluence as a delta function
        - Run model for time@temp
        - Force continuity
        - Iterate

  - Empirically this is a good approximation for long cold periods interspersed with short warm ups - See three running scenarios
  - In real running irradiation occurs concurrently with annealing
  - Try to build differential equation with phenomenological parameters

Additional





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- Studies are based on luminosities and shutdown periods of the “ultimate HL-LHC parameters” described in CERN-2017-007-M

- Possible running scenarios have included the “warm start” to exploit the TID bump. Start above 0°. As fluence increases run at progressively lower temp, to reduce leakage current.
- Studies have shown that pre-irradiation of ASICs reduced the TID bump by an order of magnitude.
- Pre-irradiation has been included in the ASIC production procedure.
- It could be that the warm start scenario is no longer necessary.

Alternative Temperature Variation during Running Scenarios

- Irradiated ATLAS 18 miniature R0 sensors at Ljubljana reactor
- Final irradiation corresponds to final integrated luminosity of 4000 fb^{-1} with a safety factor of 1.5
- Annealing is done at 60^{o}, corrected to simulated temperature using activation energy of 1.07 eV

$$T_{eff}(\theta_{eff}) = T_{ann}(\theta_{ann})\exp\left(\frac{E_{act}}{k_B}\left(\frac{1}{\theta_{eff}} - \frac{1}{\theta_{ann}}\right)\right)$$

- Cycled repeatedly through- irradiate, anneal, measure CCE for three operation scenarios:
    - Warm start
        - 2 year fluence, anneal 1 year (equiv) 7^{o} then 1 year at -3^{o}.
        - 3 year fluence, then anneal 4 years at -13^{o} .
        - 4 year fluence, then anneal 3 years at -20^{o} .
        - 5 year fluence, then anneal 5 years at -25^{o} .

    - Cold start – short warm ups
        - Operation at -25^{o} , 10 days at room temp during LS4 and LS5
    - Cold start – long warm ups
        - Operation at -25^{o} , 100 days at room temp during LS4 and LS5

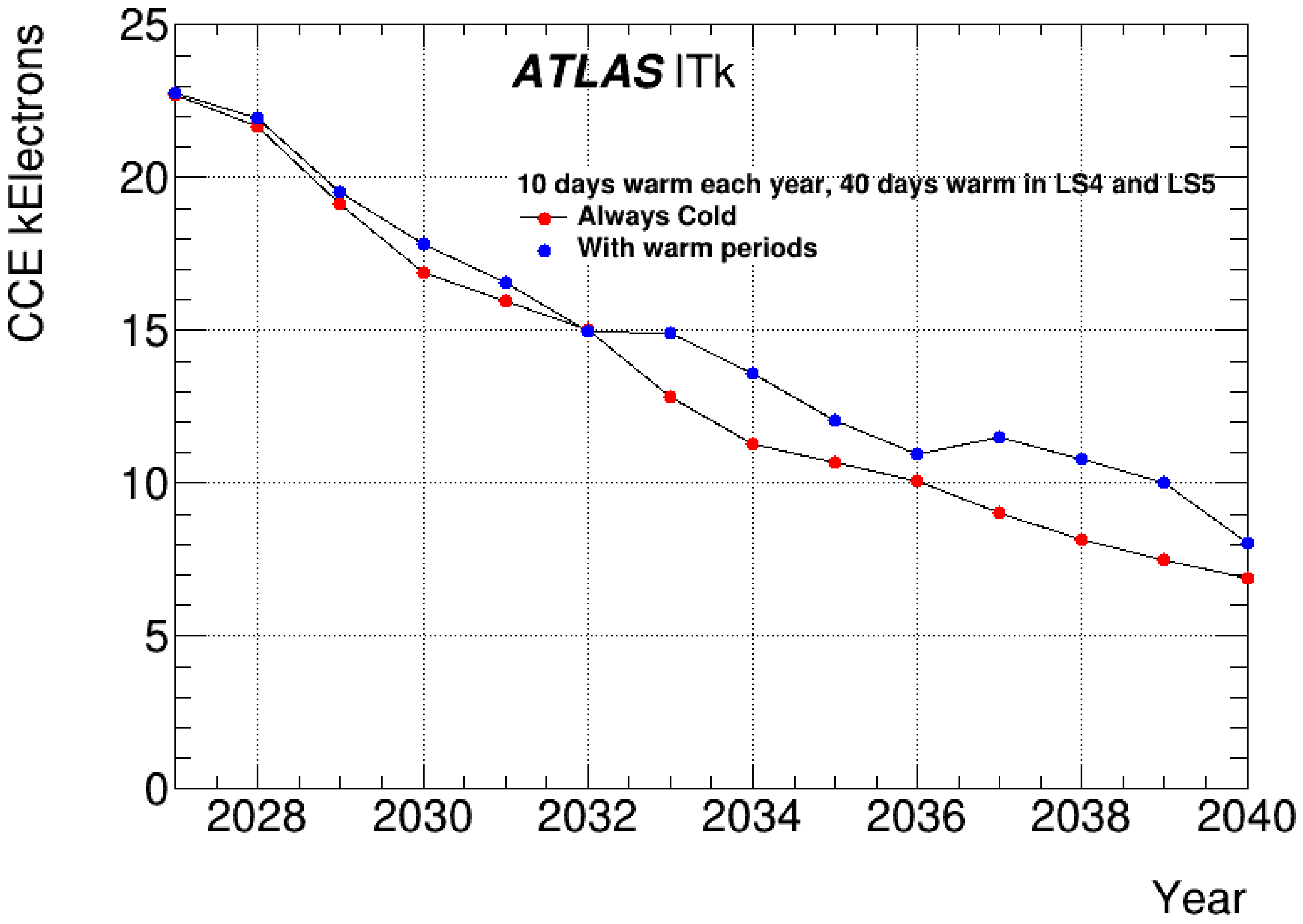
Proposed Staging of Pixels

- Assumed 13 month warmup in LS4, addditonal 100 days warm in LS5
- Ran Model for two fluence scenarios
  - Used tool https://atlas-service-radsim.web.cern.ch/radsim_noerrs
  - Radius = 40 cm, z =150. This is inner edge of strip endcap closest to interaction point
  - Phase 2 ITk Step3.1Q6 geometry model
  - Si 1 MeV neutron equivalent (NIEL)
  - GEANT4
  - Twice this fluence – More or less strip "nominal safe"
- In reality neutrons only contribute 50% of fluence
  - Other 50% is protons – which are less damaging – further "safety" factor

Total Fluence	LS4	LS4->LS5	LS5	End of Life
8e14	14.8	14.9	12.9	10.
16e14	11.5	11.6	10.2	6.6

cf. 6.350

Use in Scheduling Studies II – Proposed CO2 Cooling line WarmUp



Lines are just root joining the dots

cf. 6.350