Annealing studies of irradiated p-type sensors designed for the upgrade of ATLAS Phase-II Strip Tracker

- Liv Wiik-Fuchs, L. Diehl, R. Mori, M. Hauser, U. Parzefall, S. Kühn, K. Jakobs, A. Affolder, V. Fadeyev, C. Garcia, C. Lacasta, D. Madari, U. Soldevila, Y. Unno

Albert-Ludwigs-Universität Freiburg

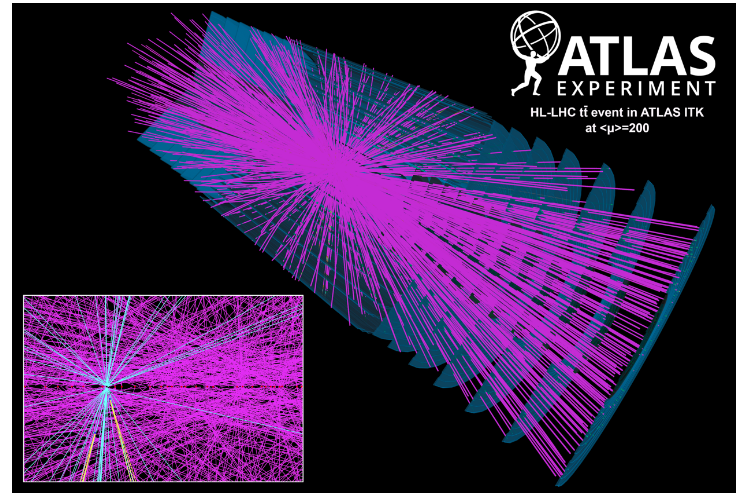
UNI FREIBURG

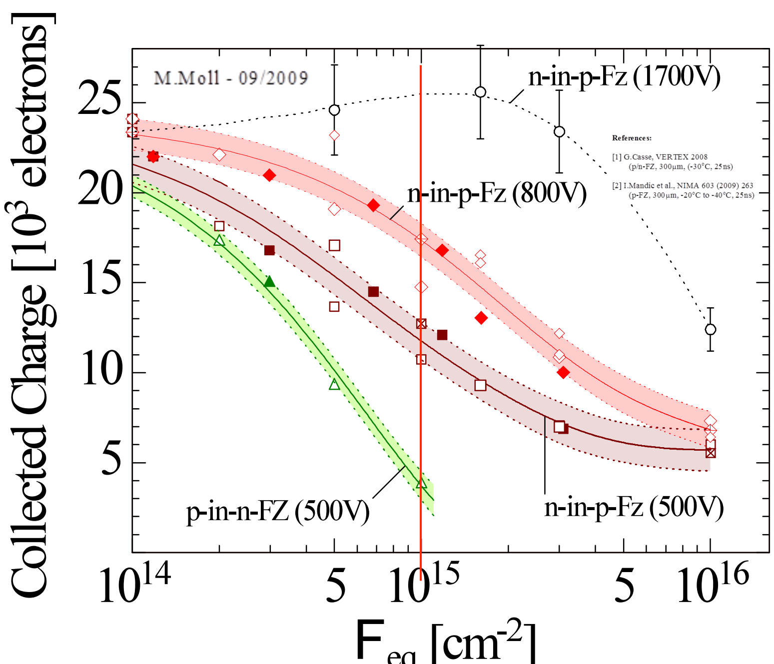
Motivation: HL-LHC / ATLAS Inner Tracker

2024 luminosity upgrade of the LHC to the HL-LHC

ATLAS: replace Inner Detector with all silicon Inner Tracker (ITk) ➜ Challenges:

- Fivefold instantaneous luminosity
- Tenfold increase in integrated luminosity (~3000 fb^{-1}) :
  - Increased particle flux ➜ radiation damage ➜ need more radiation tolerant silicon





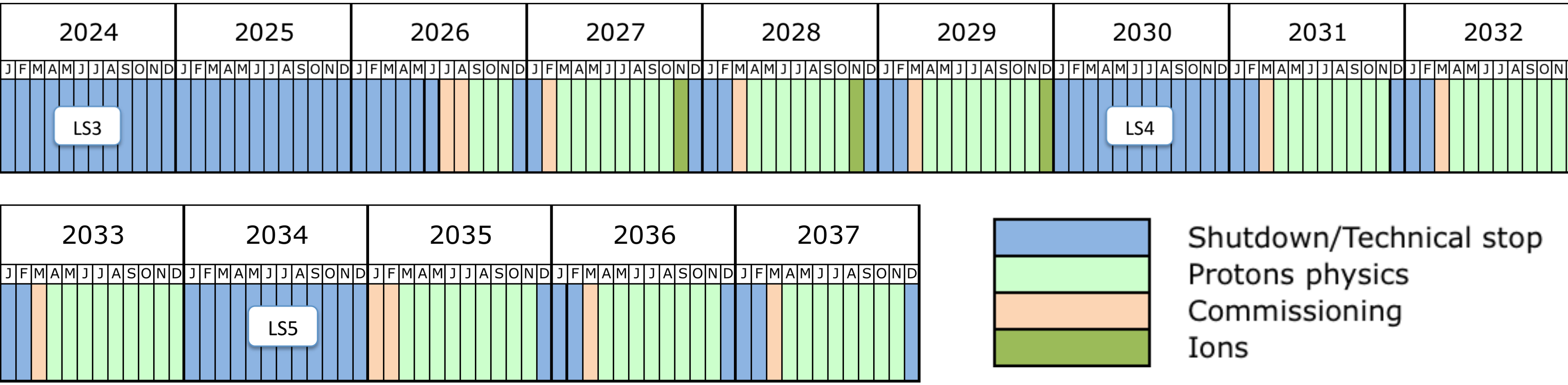
Dose: inner strip layers

Radiation leads to :

- Increase in depletion voltage
- Loss of charge carries due to trapping
- Higher leakage current

Move from current n-type bulk silicon p-bulk silicon for upgrade mandatory

Motivation: HL-LHC run-time



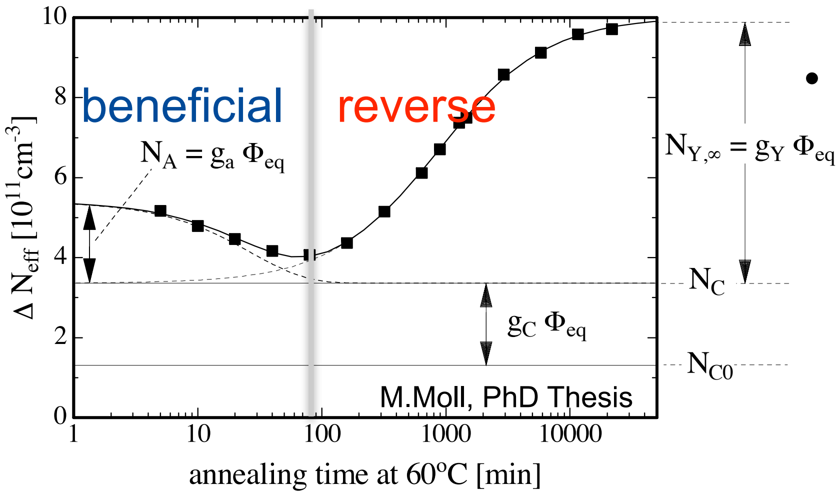
Frederick Bordry

- Expected runtime ~10 years
- Shutdown for machine maintenance on yearly basis
- Detectors will potentially not be cooled during these periods ➜ annealing
- Annealing describes migration of radiation induced defects in silicon
- Measurement standard: 80 min annealing at 60°C
- Current annealing model based on n-bulk
    - Understanding of annealing of p-type silicon bulk mandatory for HL-LHC

UNI FREIBURG

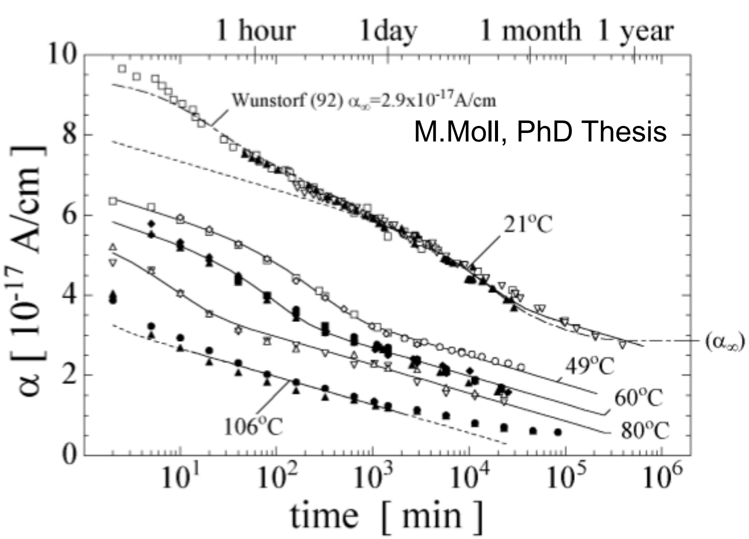
Hamburg Annealing Model

- Temperature and time dependent



- Three annealing terms: constant, beneficial and reverse:

$$\Delta N_{eff} = \boxed{N_0 e^{-\frac{t}{\tau}}} + N_C + \boxed{N_\infty (1 - e^{-kt})}$$



- Damage rate α proportional to leakage current

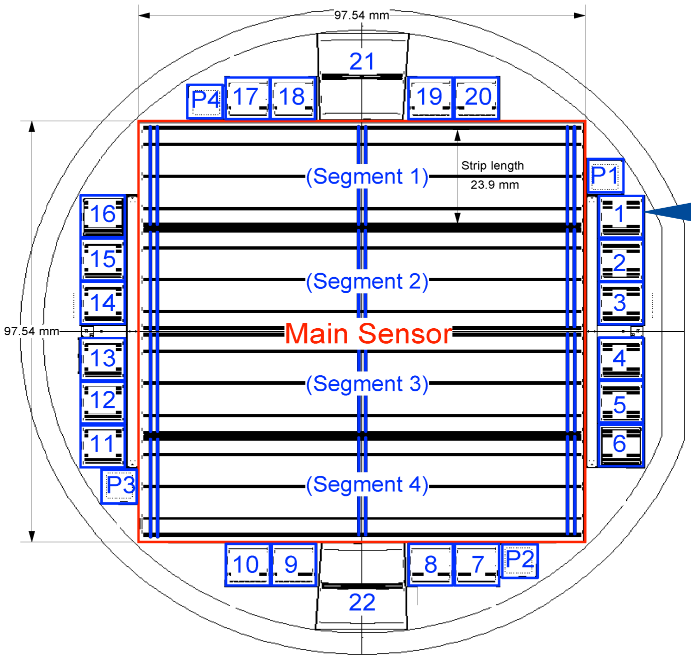
$$\alpha(t) = \alpha_i e^{-\frac{t}{\tau_i}} + \alpha_0 + \beta \ln(t)$$

$$\alpha(t) = \frac{\Delta I}{\Phi_{eq} V}$$

Method and Devices under Test

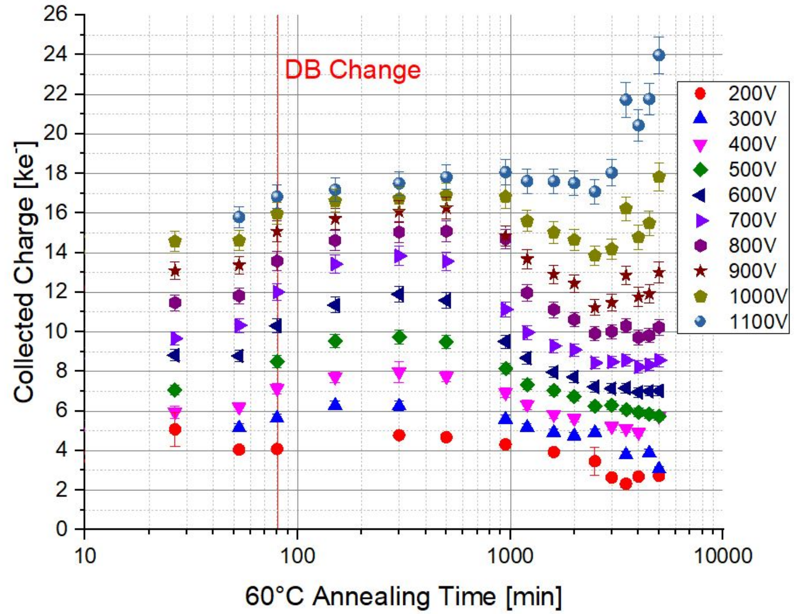
Measurements:

- Charge collection using a ^{90}Sr source
- Leakage current
- Impedance (capacitance)
- Annealing two set of sensors: one room-temperature (23°C) (RT) one at 60°C



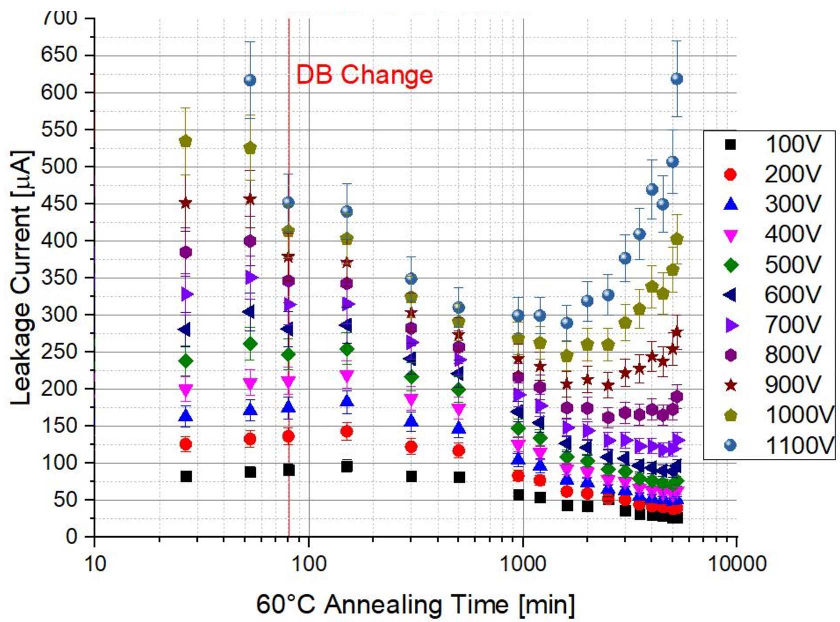
- ATLAS12 Hamamatsu Photonics
- Mini strip sensors (1x1 cm^2)
- p-type with n-type readout strips
- 74.5µm pitch, 320µm thickness
- Float-zone technology
- Irradiated with 24 MeV protons to fluences between 5x10^{13} and 2x10^{15} n_{eq} cm^{-2}

Long Term Annealing at 60°C: 2x10^{15} n$_{eq}$



Charge collection:

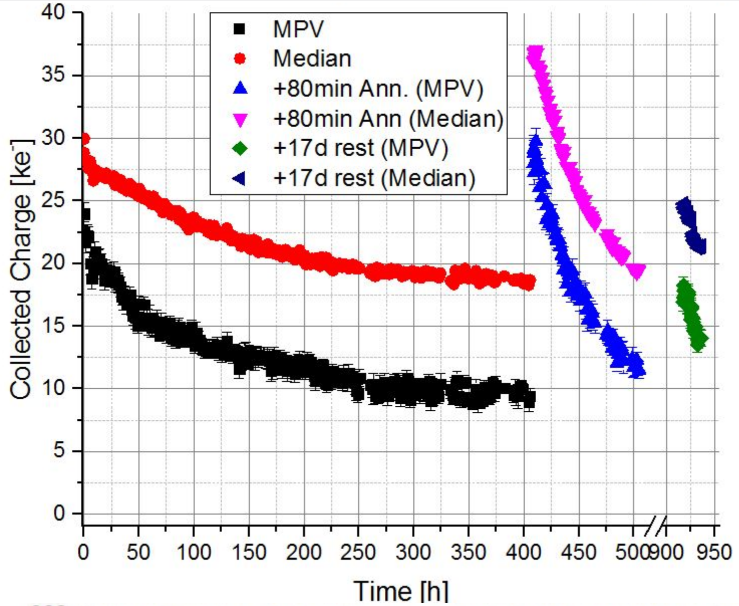
- Increase during beneficial annealing (<300 min)
- Decrease during reverse annealing
- Strong increase for t > 3000 min due to charge multiplication
- corresponding behaviour found in ATLAS07 sensors

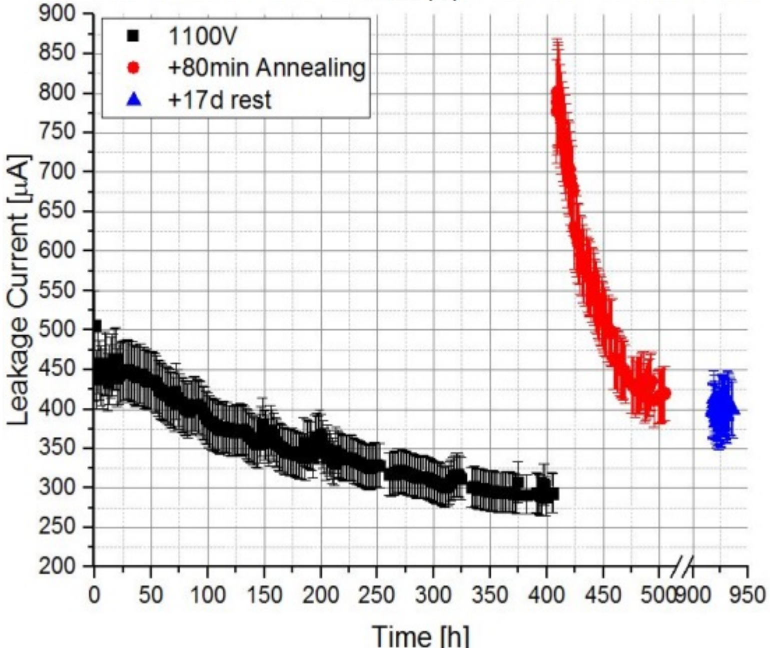


Leakage current:

- Decrease during beneficial and reverse annealing
- Strong increase in charge multiplication regime

Long Term Stress : Signal Stability @ 1100V





$2x10^{15}$ n_{eq} cm^{-2}, 5000 min annealing at 60°C, sensor in charge multiplication

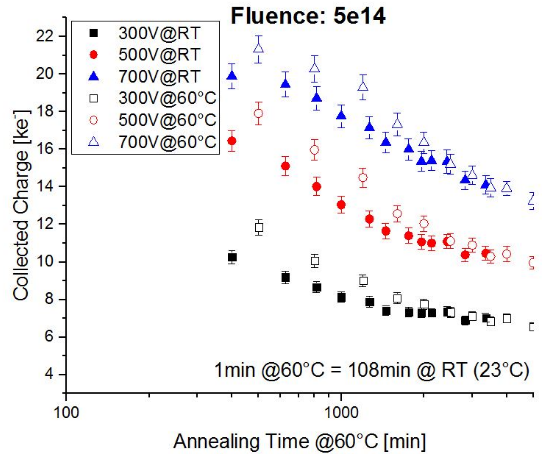
Charge multiplication under long term bias:

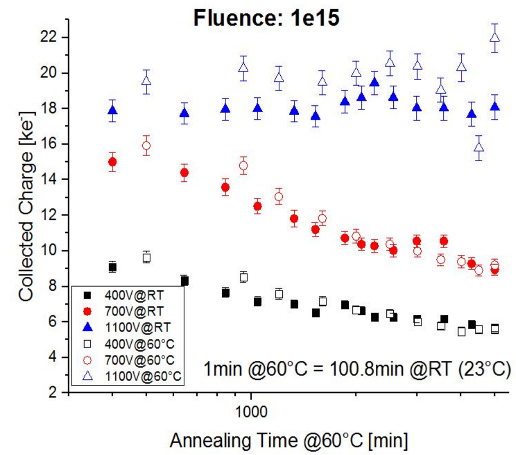
- Signal declines under permanent bias
- Annealing: 80 min at 60°C recuperates CM
- Stronger decline in following measurement
- Resting of sensor only recuperates a fraction of signal
- Leakage current and noise measurement follow the trend

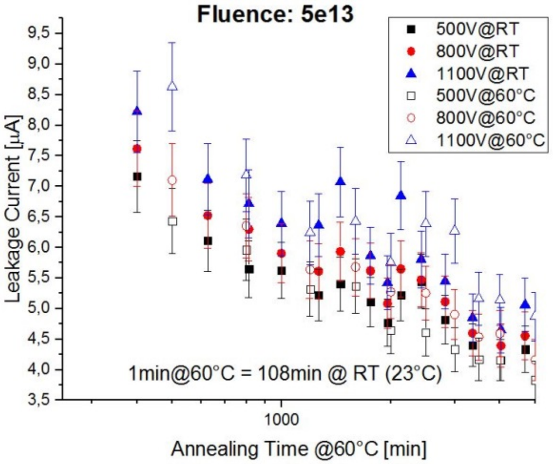
→ No reliable operation mode

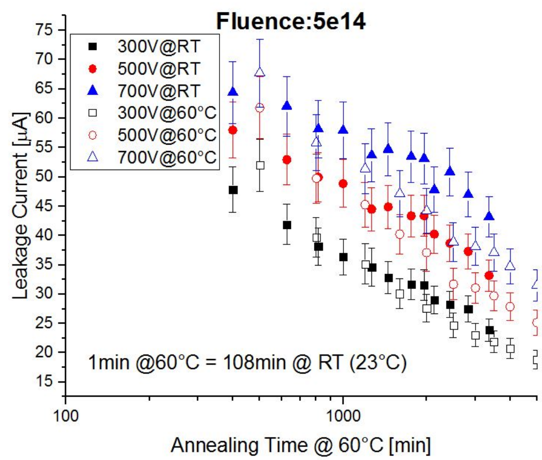
UNI FREIBURG

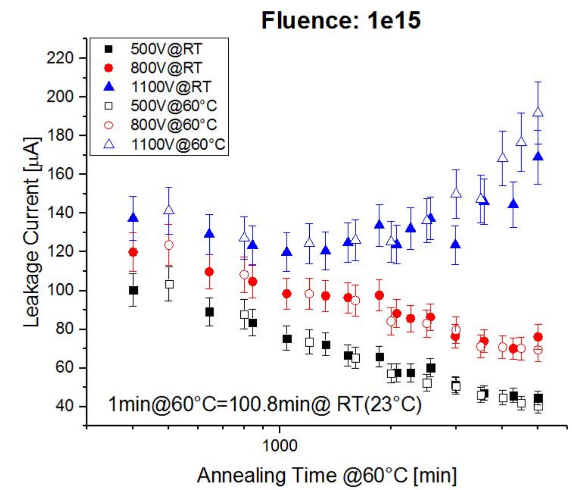
Temperature Scaling Factor: RT vs 60°C











- Determine scaling factor between RT and 60°C annealing
- Scaling factors between k=100/110
- Literature value is k=325,
- This indicates different annealing behaviour of p-type sensors

UNI FREIBURG

Temperature Scaling Factor: RT vs 60°C

Fluence[$\frac{n_{eq}}{cm^3}$]	5e13	1e14	5e14	1e15	2e15
Scaling Factor k	$108 \pm 8^*$	$101 \pm 15^*$	108 ± 12	101 ± 9	108 ± 8

- Smaller temperature factor may be attributed to:
  - Different oxygen concentration
  - Effect of moving from n-type to p-type leads to changes in defect annealing
  - Change in sensor properties

Measure effective doping concentration using impedance measurements

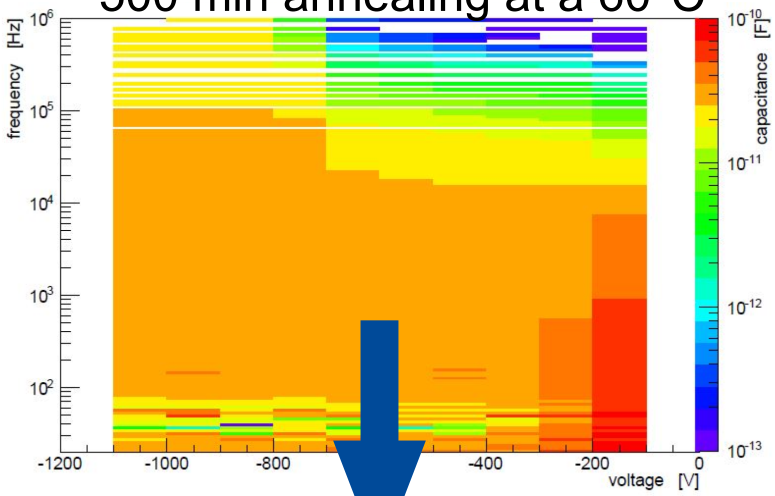
$$\frac{1}{C^2} = \frac{1}{A^2}\frac{2V}{\epsilon q N_{eff}}$$

differences in the activation energy and half-life time of annealing process

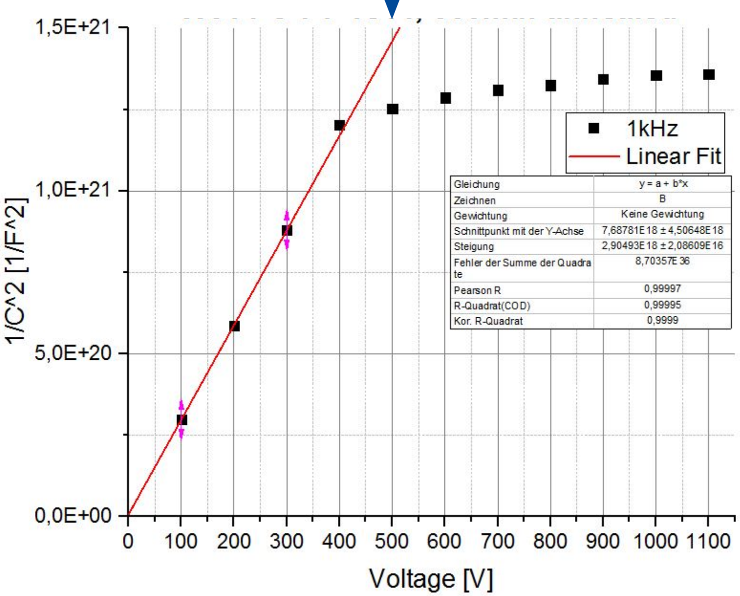
UNI FREIBURG

Impedance Measurements: $1x10^{14}\, n_{eq}$

500 min annealing at a 60°C



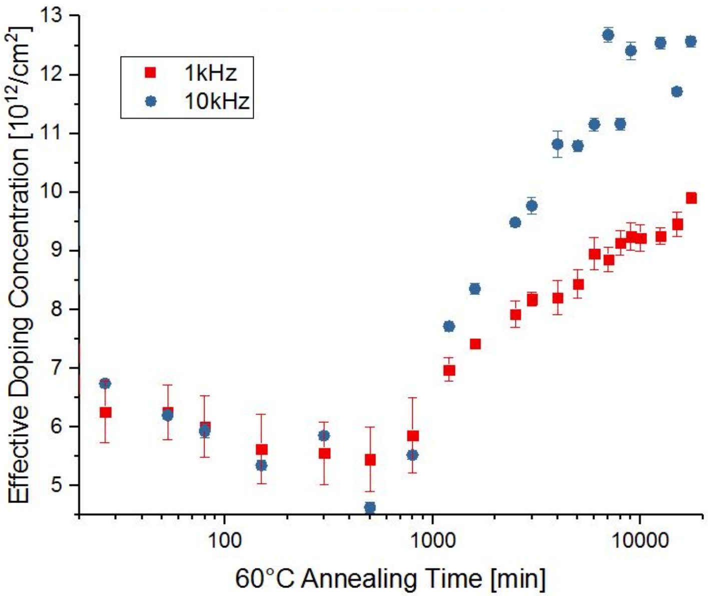
f=1000 Hz

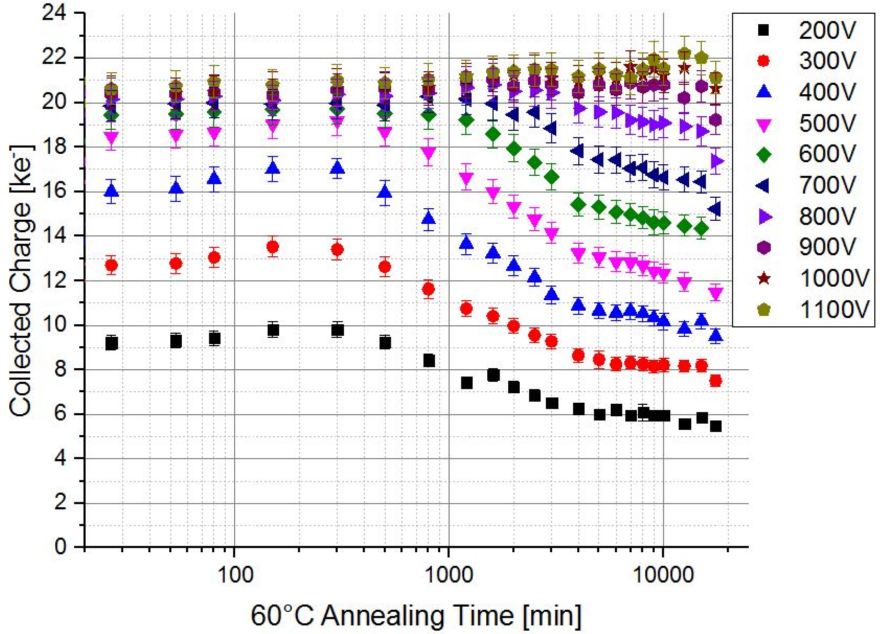


- C/V profiles only accessible for low fluences
- At higher fluences a strong dependency on frequency is found
- Measure N_{eff} after each annealing step for RT and 60°C sensors
- Access to annealing parameters k and τ

UNI FREIBURG

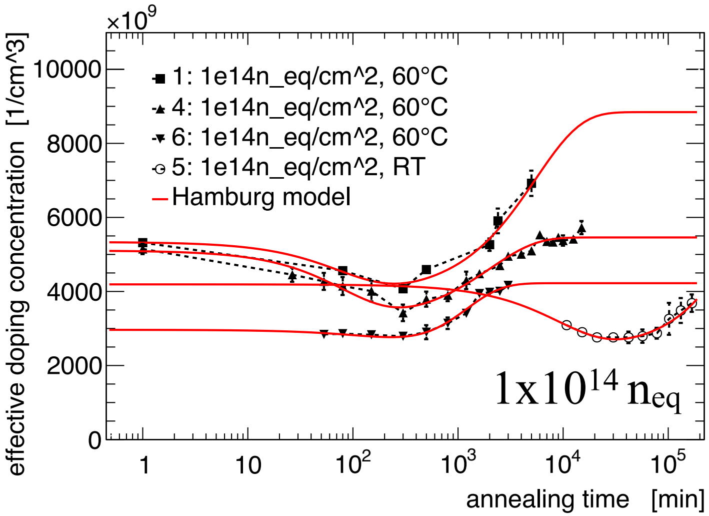
N_{eff} and Charge Collection: $2x10^{14}$ n_{eq}

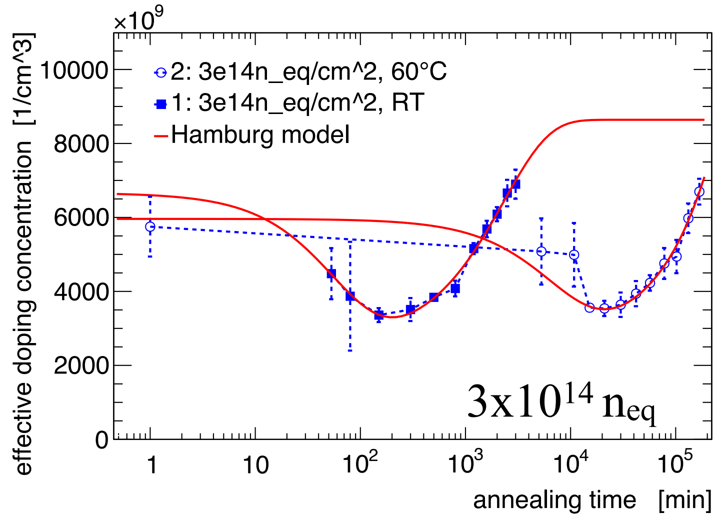


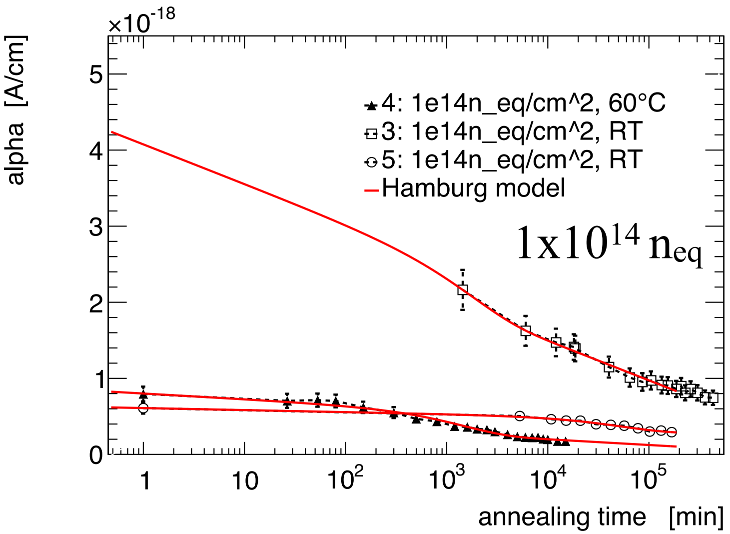


- Correlation between charge collection and N_{eff}
- Decrease of effective doping concentration during beneficial annealing, increase during reverse annealing (meaureument still ongoing)
- More than 14 d of annealing at 60°C (4 years at RT)
- No clear sign of charge multiplication yet

N_{eff} and damage parameter







- Hamburg model describes N_{eff} and damage factor α
- ATLAS12 anneal slower minimum at about t=150 min (was 80 min in Hamburg Model)
- Factor k=100 between RT and 60°C is reproduced

UNI FREIBURG

Conclusion and Outlook

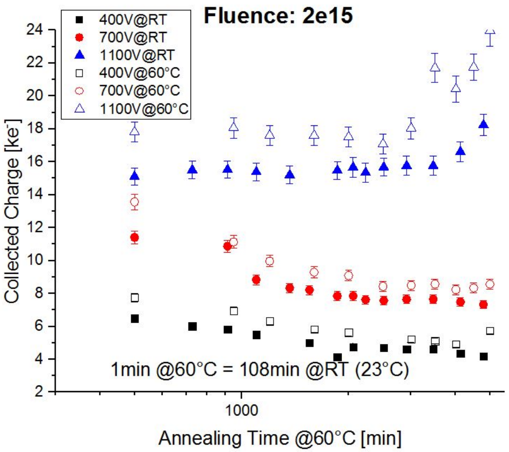
- Long term study on annealing behaviour of p-type silicon up to 4d at 60°C
- Hamburg Model with slight alterations describes sensor behavior
- Smaller temperature scaling factor (O(100) vs. 325) between RT and 60°C annealing is found
- This means sensors anneal faster at 60°C than predicted
- Can not simply use measurement standard of 80 min at 60°C annealing
- Extension: annealing sensors at 40°C and 80°C

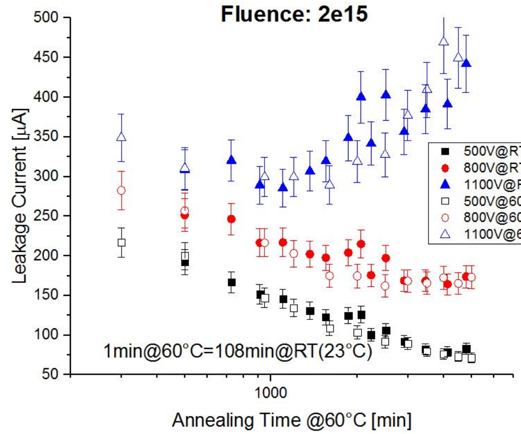
- Charge multiplication effect appears in long term annealing
- CM signal dissapers over time, some recovery after further annealing

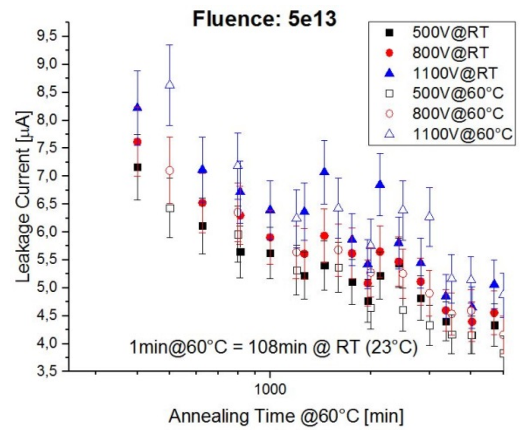
Acknowledgement: The irradiations were performed at Karlsruhe Institute of Technology (KIT) by A. Dierlamm, supported by the Initiative and Networking Fund of the Helmholtz Association, contract HA-101 (Physics at the Terascale) and the European Commission under the FP7 Research Infrastructures project AIDA, Grant agreement no. 262025,

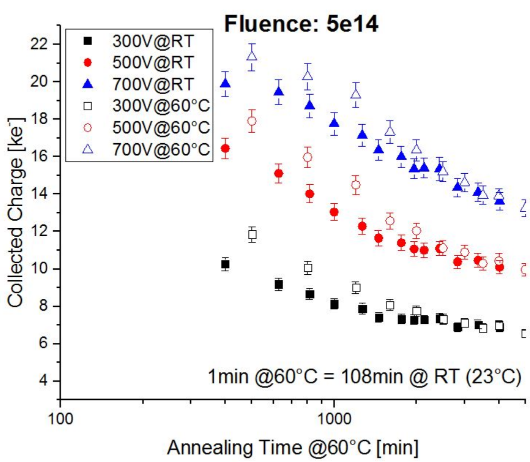
UNI FREIBURG

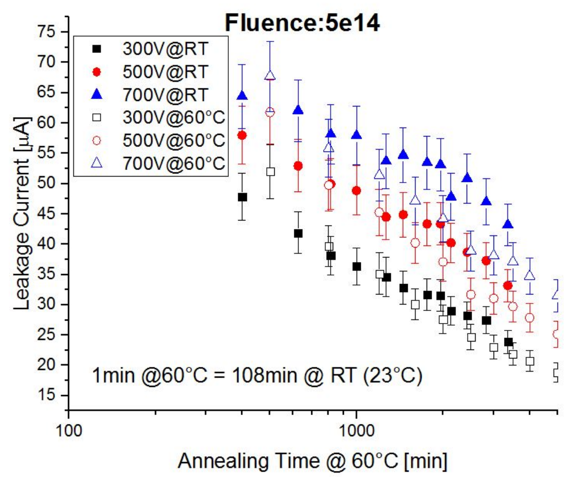
Backup slides

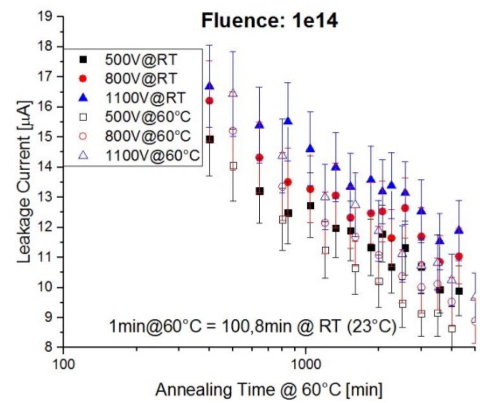

Fluence: 2e15
400V@RT
700V@RT
1100V@RT
400V@60°C
700V@60°C
1100V@60°C
Collected Charge [ke⁻]
1min @60°C = 108min @RT (23°C)
Annealing Time @60°C [min]


Fluence: 2e15
500V@RT
800V@RT
1100V@RT
500V@60°C
800V@60°C
1100V@60°C
Leakage Current [µA]
1min@60°C=108min@RT(23°C)
Annealing Time @60°C [min]


Fluence: 5e13
500V@RT
800V@RT
1100V@RT
500V@60°C
800V@60°C
1100V@60°C
Leakage Current [µA]
1min@60°C = 108min @ RT (23°C)
Annealing Time @60°C [min]

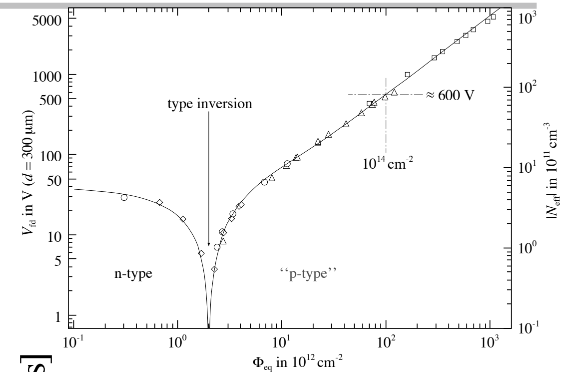

Fluence: 5e14
300V@RT
500V@RT
700V@RT
300V@60°C
500V@60°C
700V@60°C
Collected Charge [ke⁻]
1min @60°C = 108min @ RT (23°C)
Annealing Time @60°C [min]


Fluence:5e14
300V@RT
500V@RT
700V@RT
300V@60°C
500V@60°C
700V@60°C
Leakage Current [µA]
1min @60°C = 108min @ RT (23°C)
Annealing Time @ 60°C [min]

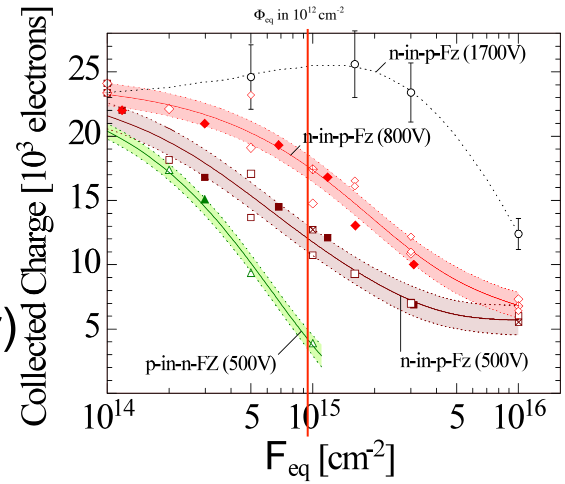

Fluence: 1e14
500V@RT
800V@RT
1100V@RT
500V@60°C
800V@60°C
1100V@60°C
Leakage Current [µA]
1min@60°C = 100,8min @ RT (23°C)
Annealing Time @ 60°C [min]

Radiation Damage in Silicon Sensors

Higher depletion voltage
Due to change in doping concentration
After high fluences: no full depletion possible
Solution: different silicon material, modified detector geometry (3D, thin detectors)

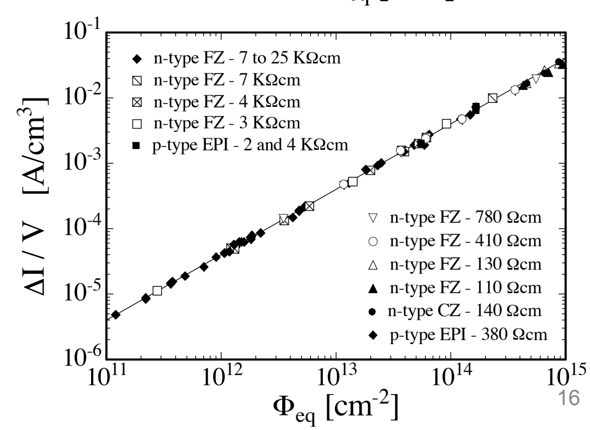


Higher trapping
Liberated charge carriers get trapped at crystal defects
Measured signal decreases
Solution: modify detector geometry (3D, thinner)



inner strip dose

Higher leakage current
More generation-recombination centres
Higher noise, higher power consumption, thermal runaway
Solution: cooling of detector



Dose: inner strip layers

Motivation: Phase-II Radiation Environment