Annealing in n and p-side readout of silicon microstrip detectors after irradiation to LHC and sLHC doses

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CONTEXT:

Two rather recent results from studies performed for preparing high resolution sensors for the future supercolliders (sLHC at CERN) have proven that silicon detectors can be used for tracking minimum ionising particles (mip’s) after doses above 2x10^{16} n_{eq} cm^{-2}. These are the discovery of the charge multiplication mechanism taking place in irradiated **n-in-p** silicon detectors and the *suppression* of the reverse annealing. A discussion of this last feature is here presented with the implications for the running scenario in the actual experiments.

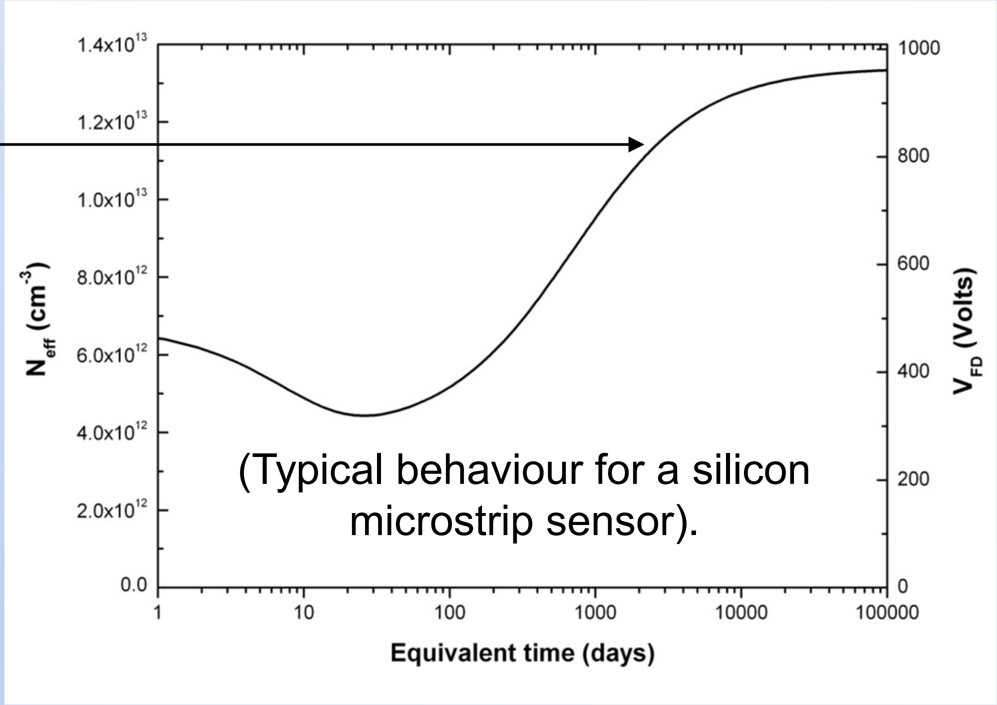
Evolution of Sensor Properties After Irradiation

Sensor **leakage current** (**I_{LEAK}**), **depletion voltage** (**V_{DEP}**) and **charge collection efficiency** (**CCE**) are all affected by irradiation.

Evolution of **V_{DEP}** shows dependence on both temperature and time spent after irradiation.

Require full depletion (and some) of sensor in order to optimise **CCE.**

I_{LEAK} Shows strong temperature.



(Typical behaviour for a silicon microstrip sensor).

Need to avoid the sensors being warm (> 0 °C) for long periods of time!

Comparison of Hamburg Model and ATLAS TDR Parameterisation

The Hamburg parameterisation is believed to best fit the available data to predict V_{DEP}.

However, large differences observed between the predictions of the TDR model and the Hamburg model.

Origin is in **reverse annealing** contribution ΔN_Y to the predicted change in effective doping concentration ΔN_{EFF}:

$$\Delta N_{EFF}(\Phi,T,t) = \Delta N_C(\Phi) + \Delta N_A(\Phi,T,t) + \Delta N_Y(\Phi,T,t) \qquad V_{DEP} = \frac{ed^2|N_{EFF}|}{2\varepsilon}$$

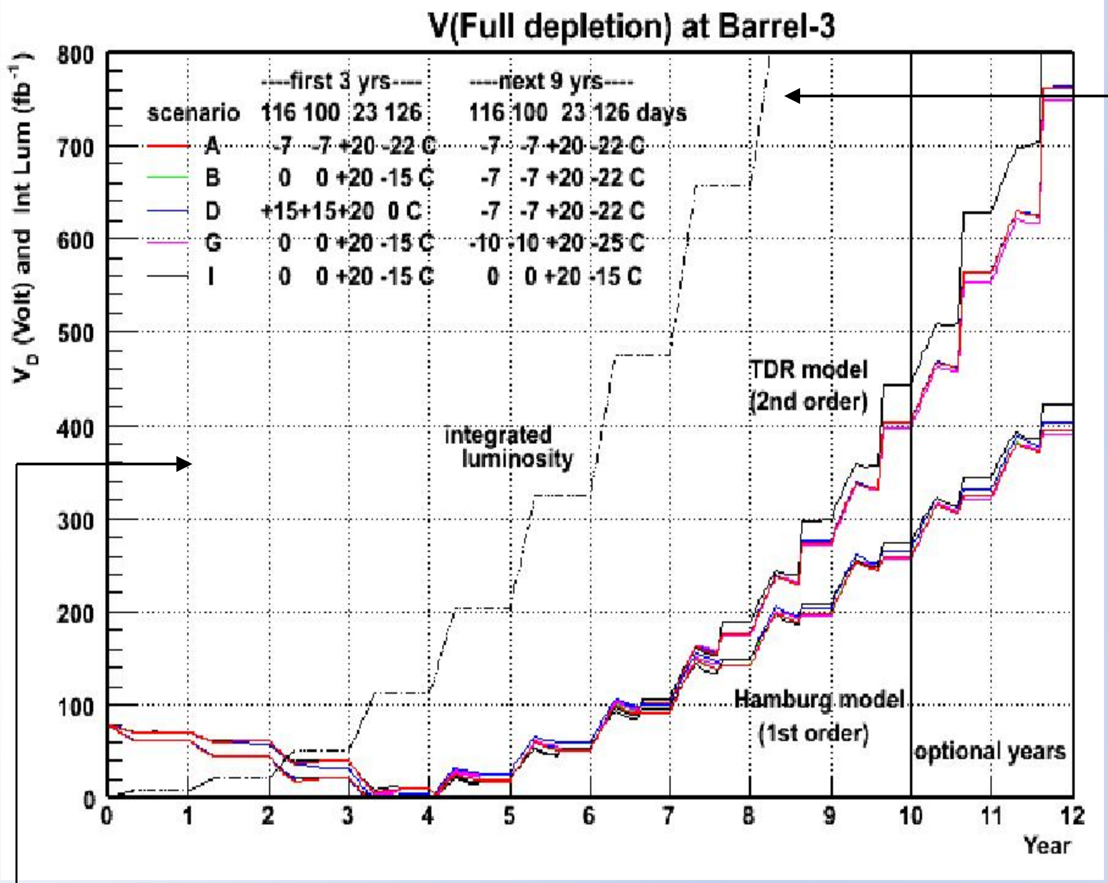
TDR model parameterised reverse annealing as a **second order process**
($dN_Y=-k\cdot dN_X^2\cdot dt$) $N_Y(t)=N_{X,0}(1-(1+k\cdot N_{X,0}\cdot t)^{-1})$.

Hamburg model parameterises reverse annealing as a **modified first order process**.

($dN_Y=-1/\tau\cdot dN_X\cdot dt$) $N_Y(t)=N_{X,0}(1-\exp(-t/\tau))$

Need high fluence + long annealing data to compare to predictions of both models.

Re-Evaluating the Evolution of V_{DEP} and I_{LEAK} in the SCT



An updated LHC luminosity profile now exists.

Maintenance/shutdown time and cooling temperatures reviewed in line with:

Achievable coolant temperatures.

Insertable B-Layer installation.

Possibly longer maintenance.

V_{DEP} predictions suggest 450 V (max for SCT) is sufficient for at least 10 years operation.

Paul Dervan, Joost Vossebeld, Tim Jones (Liverpool), Taka Kondo (KEK), Graham Beck (QMUL), Georg Viehhauser (Oxford), Steve McMahon (RAL), Koichi Nagai (Brookhaven), Kirill Egorov (Indiana), Richard Bates, Alexander Bitadze (Glasgow).

Programme of Accelerated Annealing Measurements

Sensor performance traditionally studied by determining V_{DEP} from CV measurements. The rate of annealing is a function of temperature, therefore it is possible to slow it down or accelerate it relatively to a given temperature. Previous studies have found an Arrhenius relation for temperature dependence of the reverse annealing of V_{DEP} with an activation energy Ea = 1.31 eV. With a reference temperature of 20^{o}C, the acceleration factors are about 540 at 60^{o}C and 7350 at 80 ^{o}C.

In **Liverpool** the focus has been on **measuring the annealing of CCE**

The p-in-n case.

New programme of accelerated annealing measurements on **ATLAS mini sensors**. →

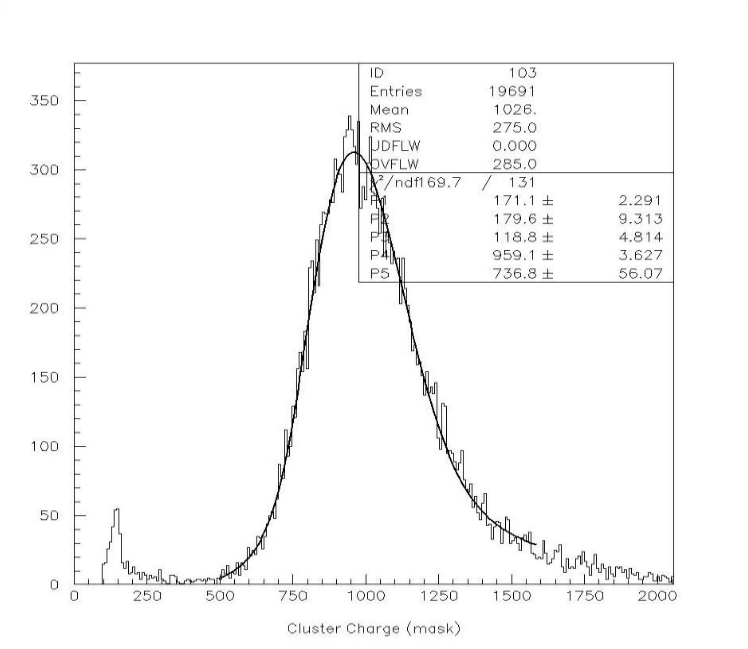
Manufacturer	HPK
Wafer Tech.	FZ
Structure	p-in-n
Size	1 cm x 1 cm
Thickness	285 µm

Pair of sensors irradiated with neutrons at Ljublijana (V. Cindro et al) to **2×10^{14} 1 MeV n_{eq} cm^{-2}**

(new prediction for SCT = **1.6×10^{14} 1 MeV n_{eq} cm^{-2}**).

One sensor used for **CCE** measurements and one sensor used for **V_{DEP}** measurements. Both **sensors annealed together** at same temperature for same length of time.

Experimental Setup and Analysis Procedure



Charge Collection Measurements

^{90}Sr fast electron source used to generate signal. Readout triggered by scintillator.

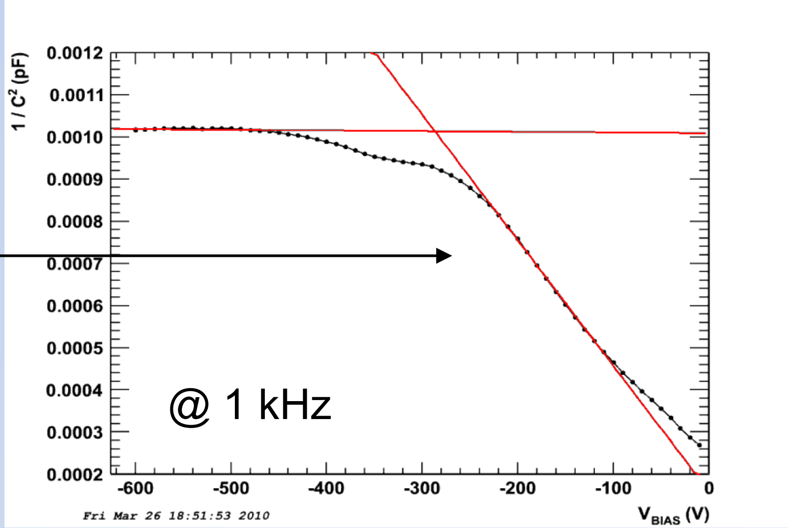
← Charge collection measured using analogue electronics chip (SCT128A or Beetle) clocked at LHC speed (40 MHz clock, 25 ns shaping time).

System calibrated to most probable value of MIP energy loss in non-irradiated 300 μm thick sensor (~ 23000 e).

Depletion Voltage Measurements

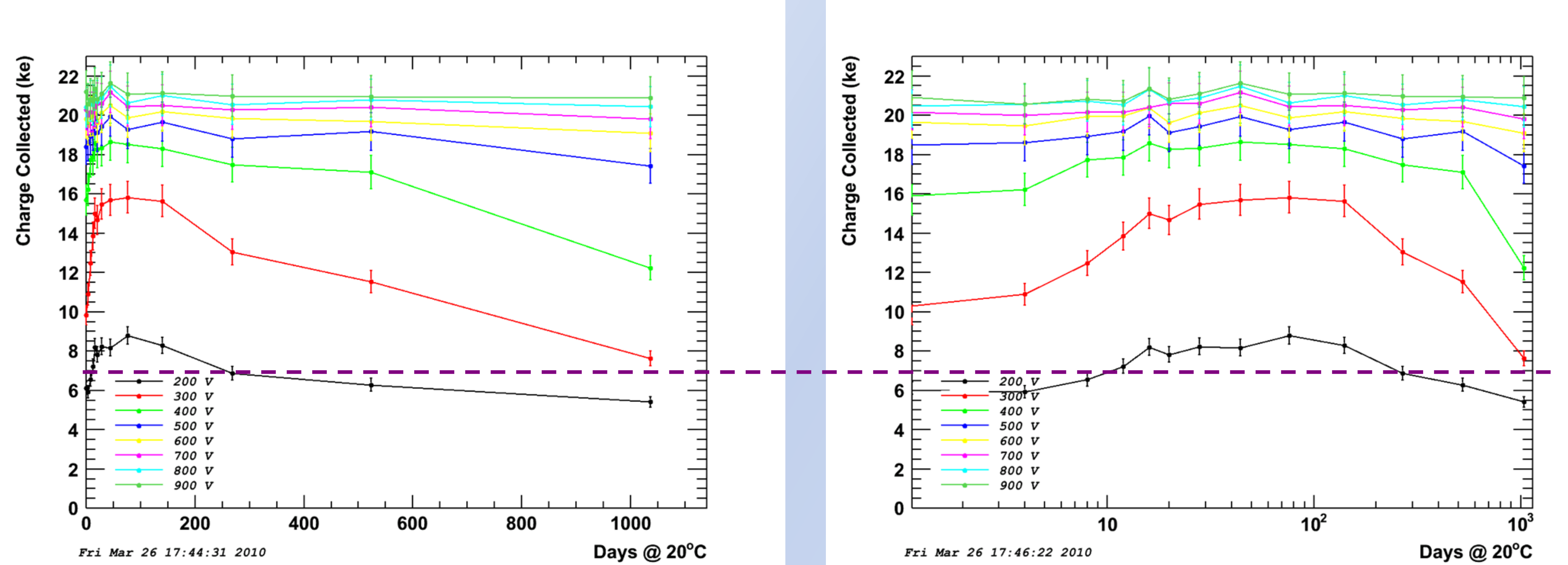
V_{DEP} Determined by standard method of measuring the V_{BIAS} at which $1/C^2$ saturates. →

Both sets of measurements performed in freezer at temperature of ~-25 °C with N^2 flush.



Results of Charge Collection Measurements

Above ~ 500 V collected charge remains almost constant in time

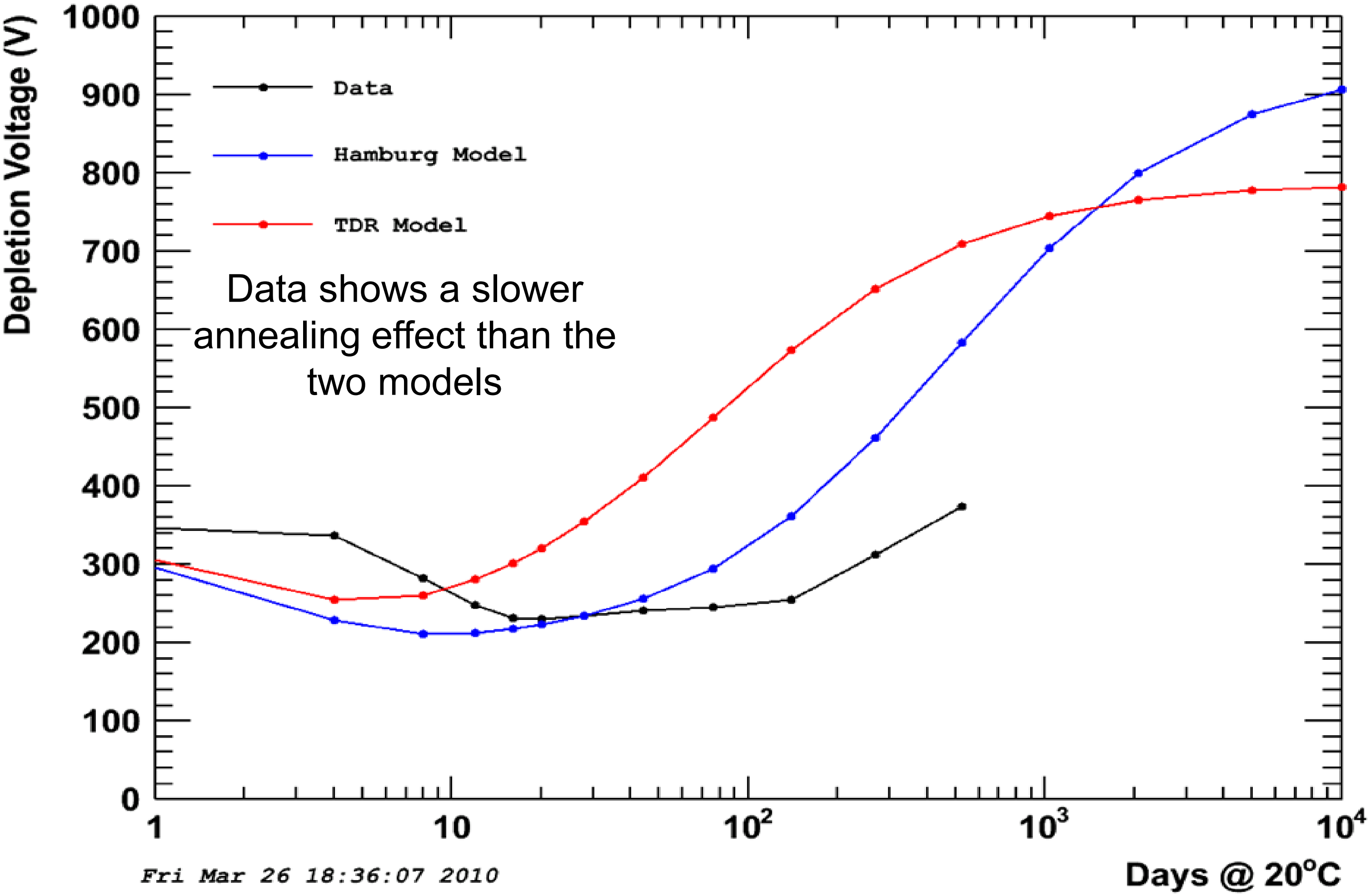


SCT Default threshold 1 fC (~ 6.2 ke)

Smooth fall off after
~ 100 days @ 20 °C

No sharp drop in the
collected charge

Comparison of Predicted V_{DEP} and Measured V_{DEP}



Data shows a slower annealing effect than the two models

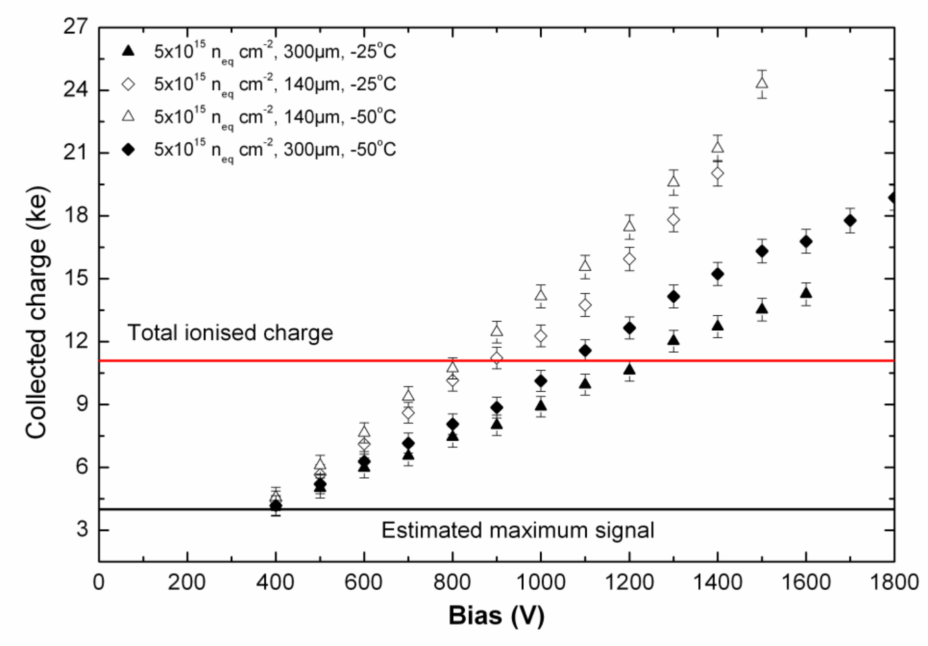
This discussion is relevant to the present tracker sensors in the LHC experiments.

The future experiments on sLHC will make large use of n-side readout sensors, possibly n-in-p.

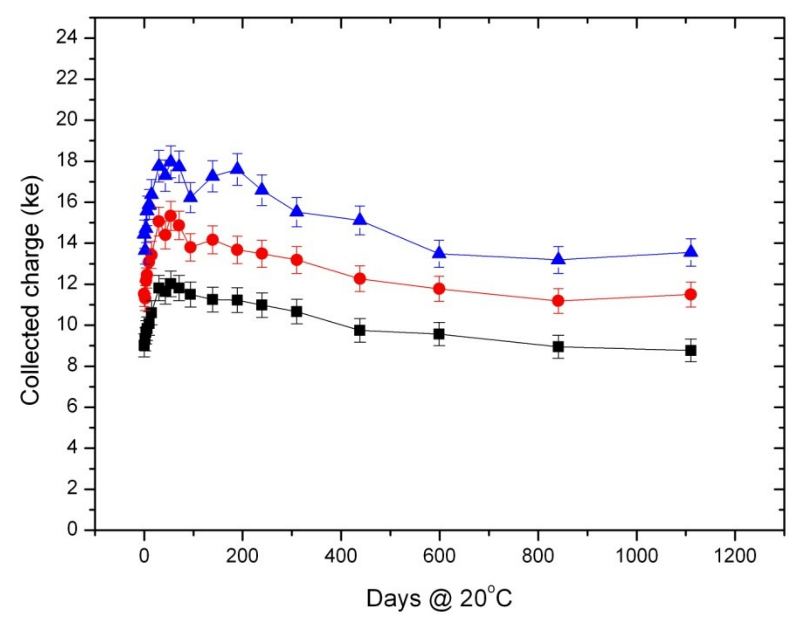
The annealing of n-in-p sensors is different again: the reason is that the effect of charge multiplication plays a role.

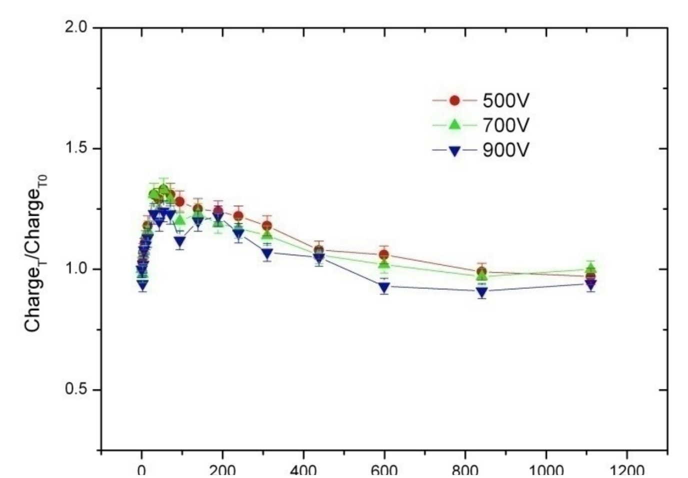
140 and 300 μm n-in-p Micron microstrip sensors after $5x10^{15}$ n_{eq} 26MeV p

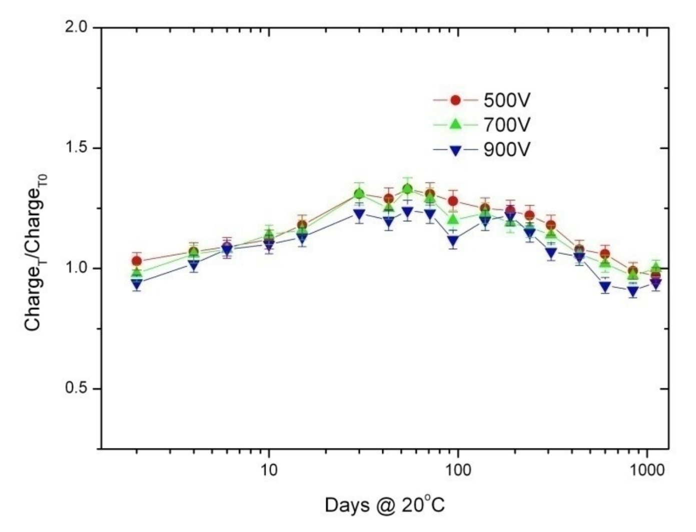
Evidence of a charge multiplication effect: not only the whole charge is recovered, but increased by f = 1.75/2.1



Accelerated Annealing of the collected charge, case of n-in-p sensors. HPK FZ n-in-p, 1E15 n_{eq} cm^{-2}

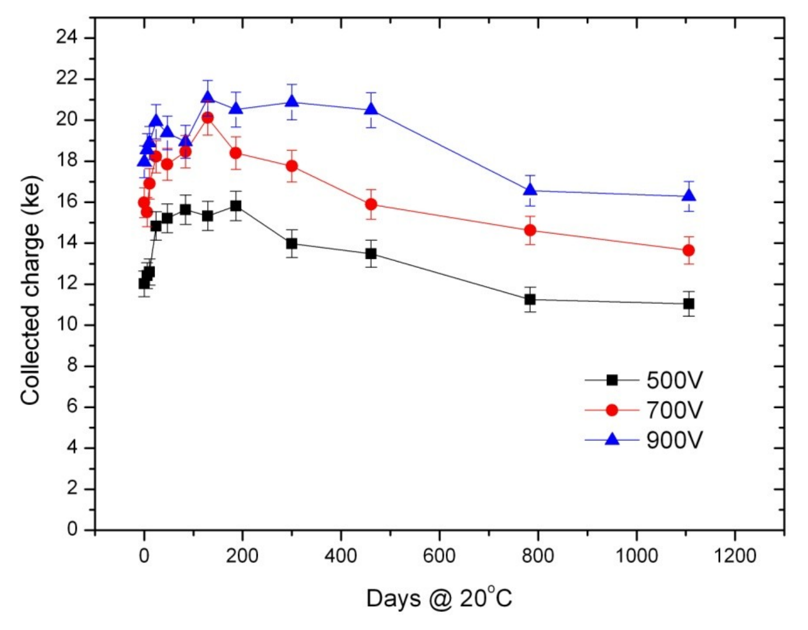


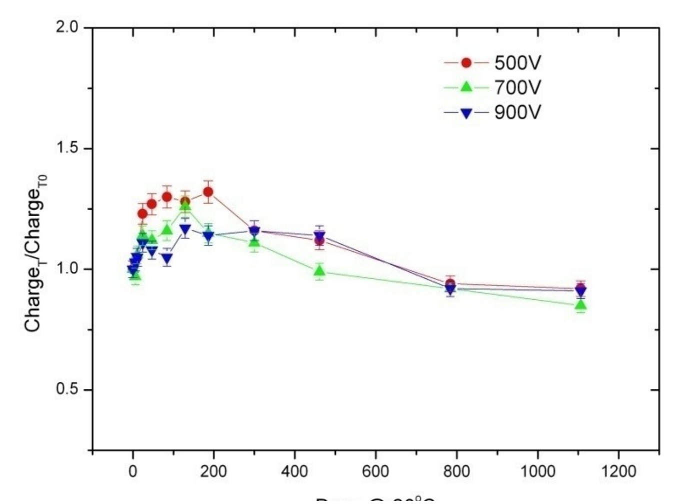


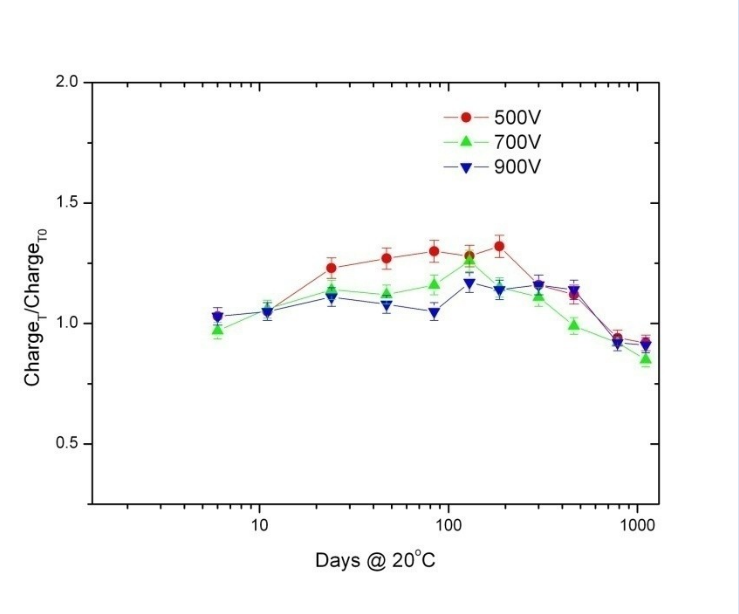


Neutron irradiations in Ljubljana, neutrons are dominating the radiation damage > 25 cm radius.

Annealing of the colleted charge, Micron FZ n-in-p, 1E15 n cm^{-2} (26MeV p irradiation)

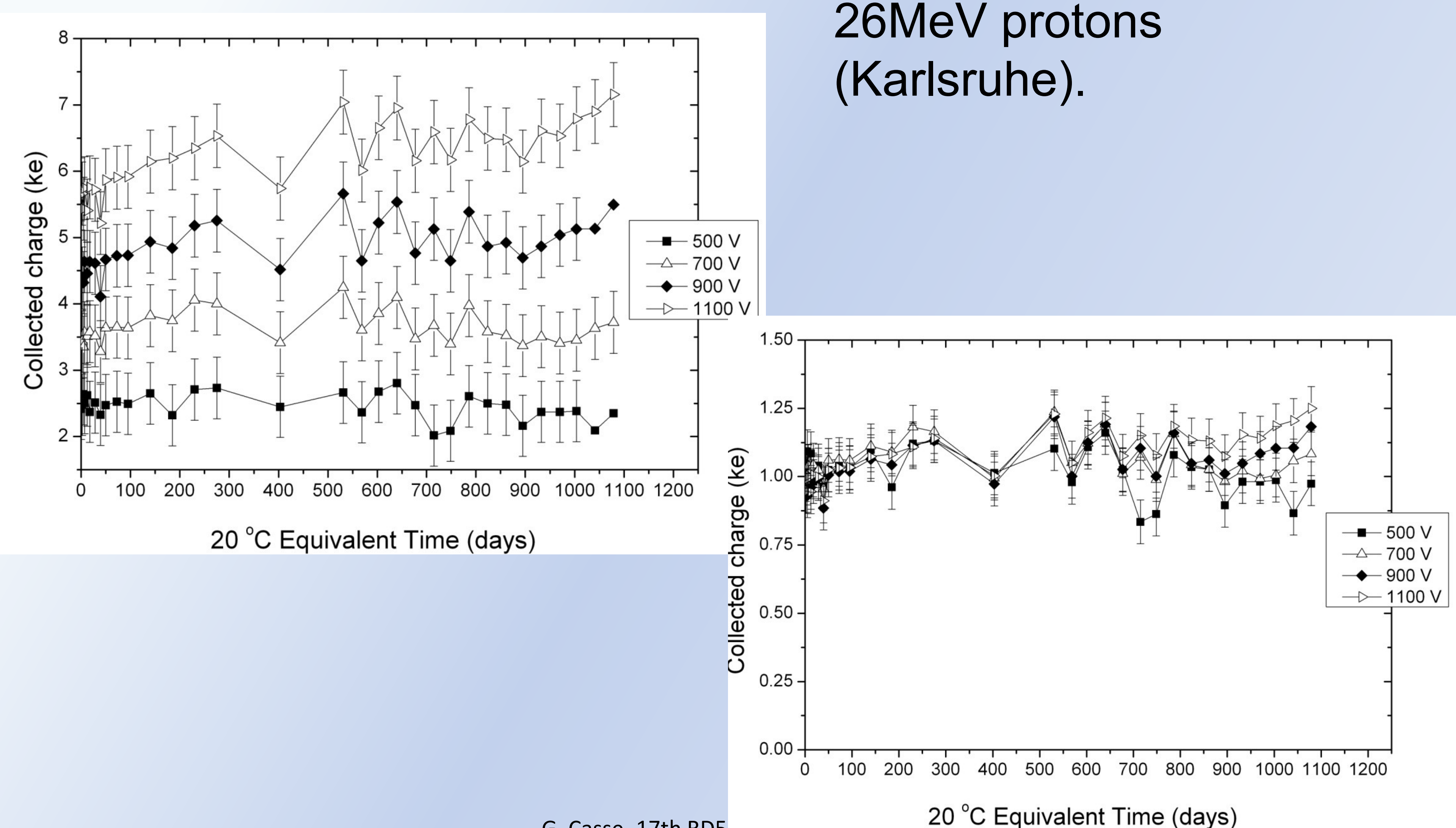




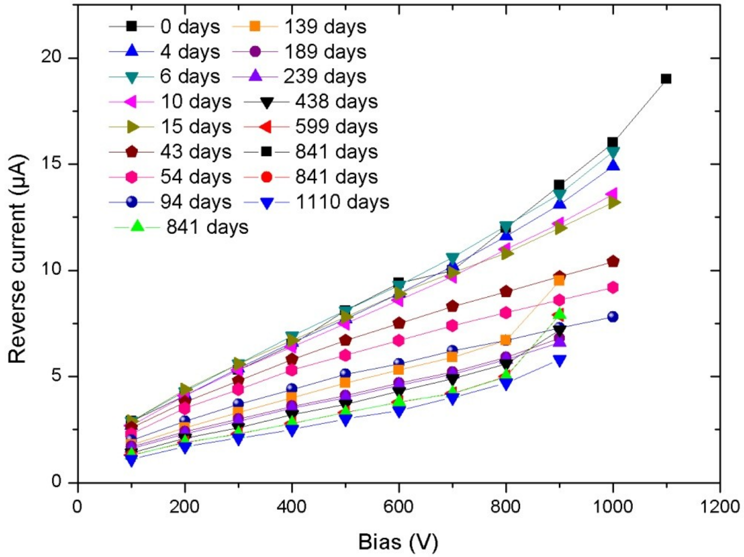


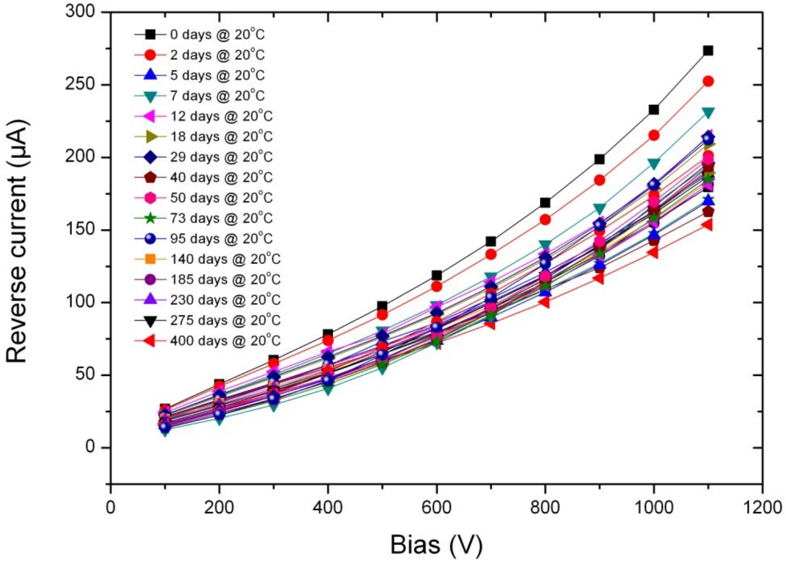
Accelerated CCE Annealing 1.5E16 n_{eq} cm^{-2} (Micron sensors)

Irradiated with 26MeV protons (Karlsruhe).

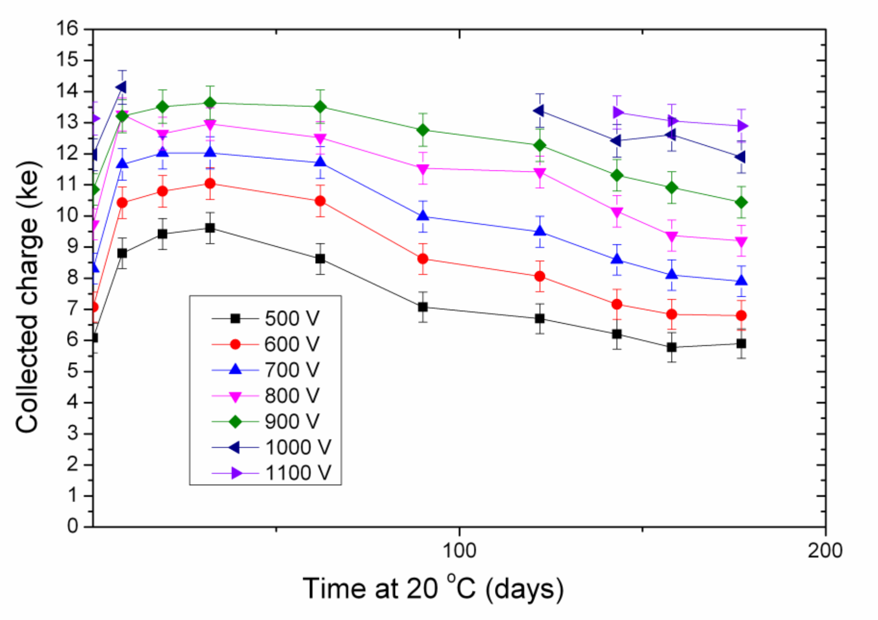


Annealing of the reverse current, n-in-p sensors, 1E15 and 1.5E16 n cm^{-2}

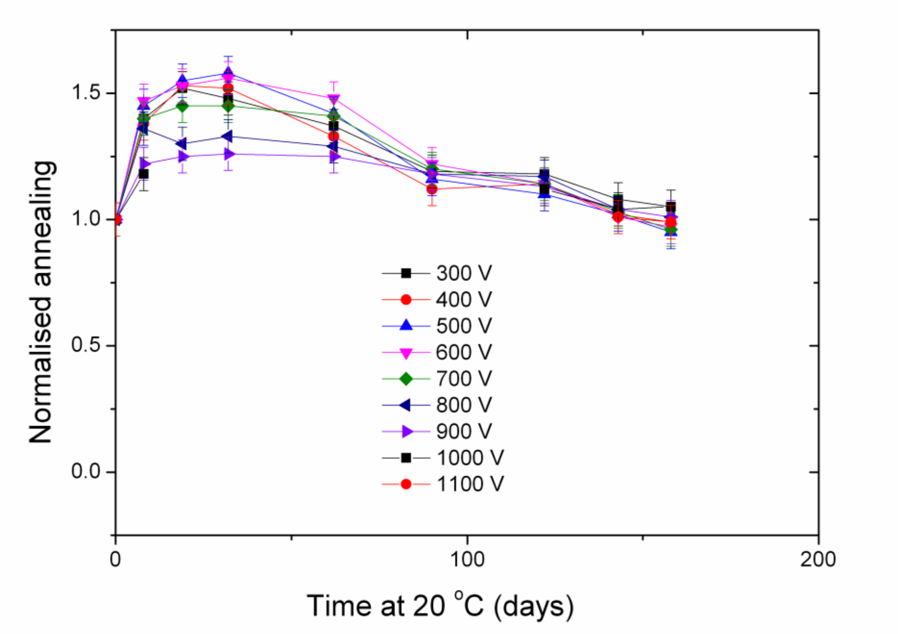




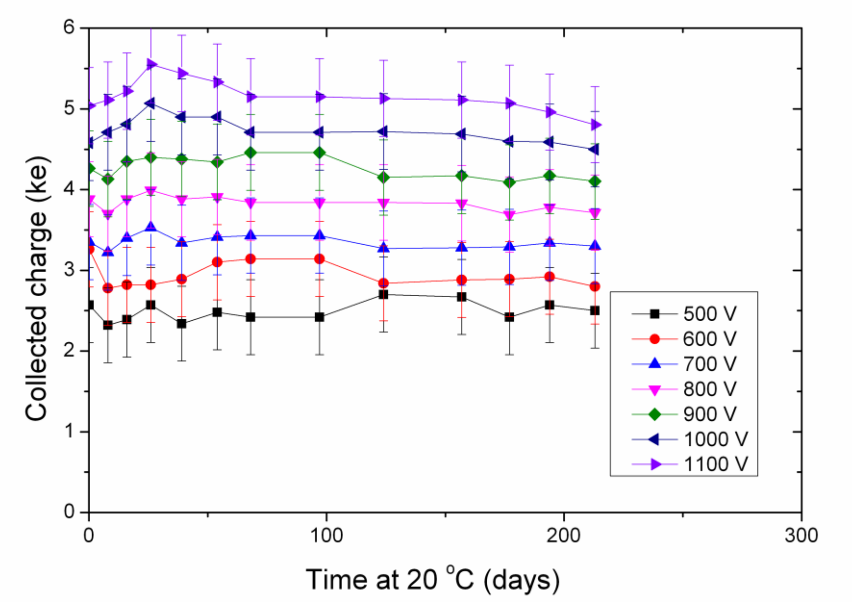
Room Temperature Annealing of the collected charge, HPK FZ n-in-p, 2E15 n cm^{-2} (26MeV p irradiation)



We make large use of accelerating annealing: is this a safe and correct approach?



Room Temperature Annealing of the collected charge, HPK FZ n-in-p, 1E16 n cm^{-2} (26MeV p irradiation)



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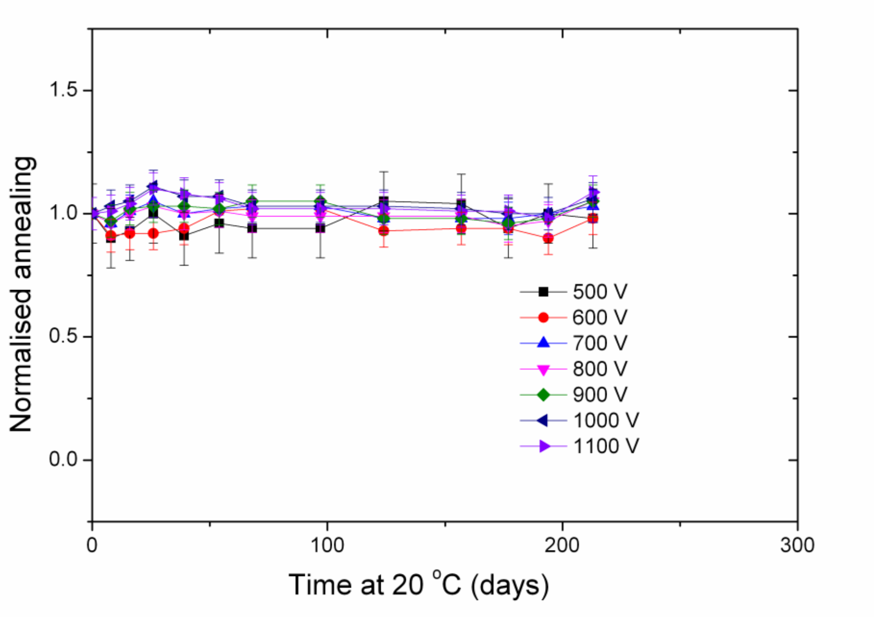
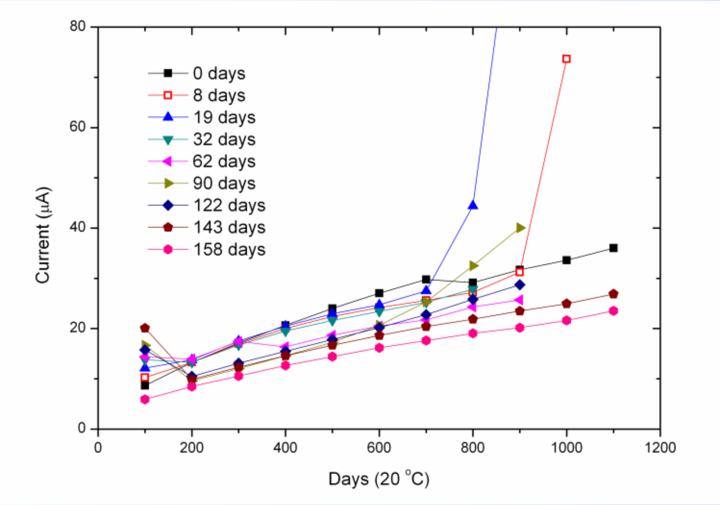
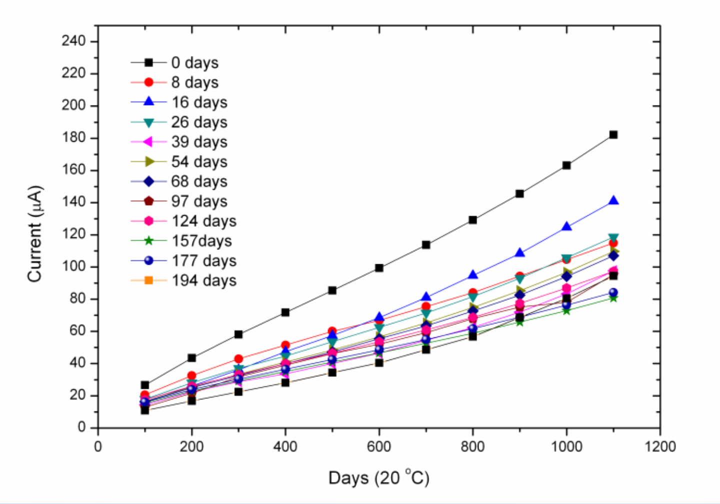


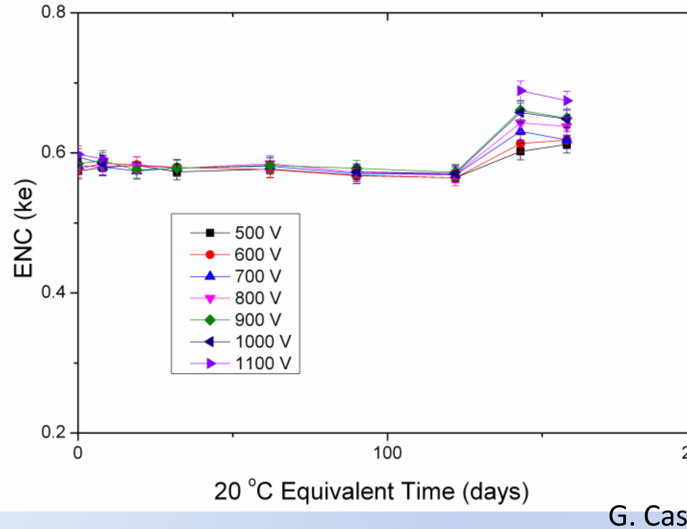
G. Casse, 17th RD50 Workshop, CERN 17-19 Nov.2010

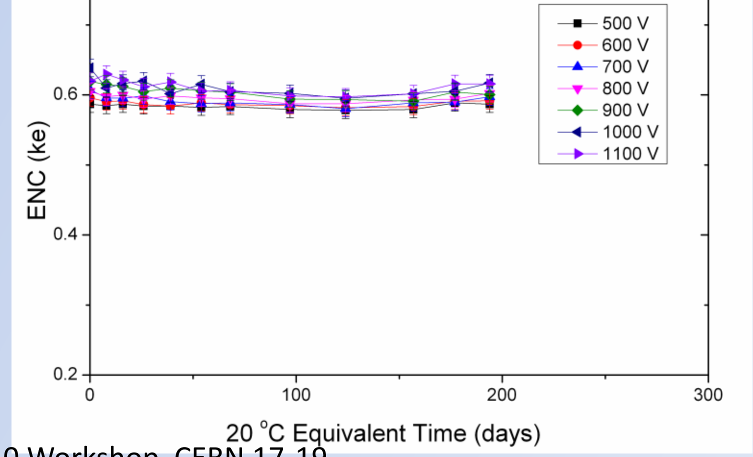
Room Temperature Annealing of the reverse current, n-in-p sensors, 2 and 1E16 n cm^{-2} (26MeV p irradiation)



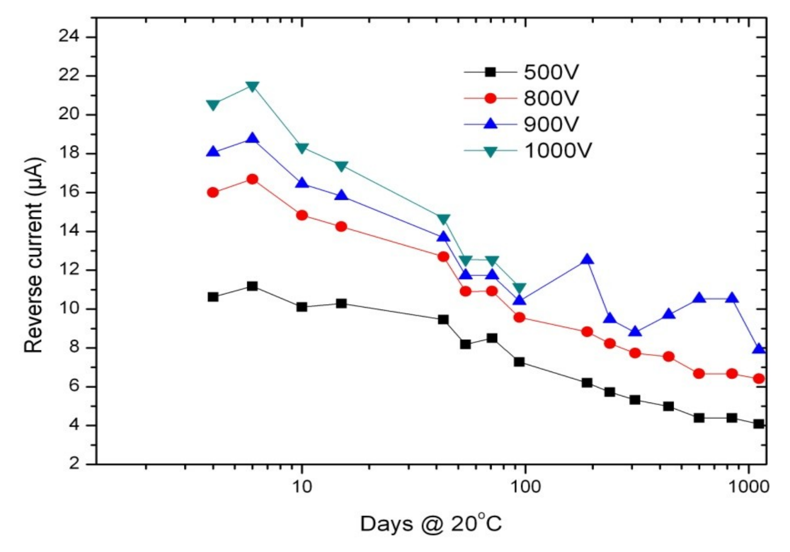


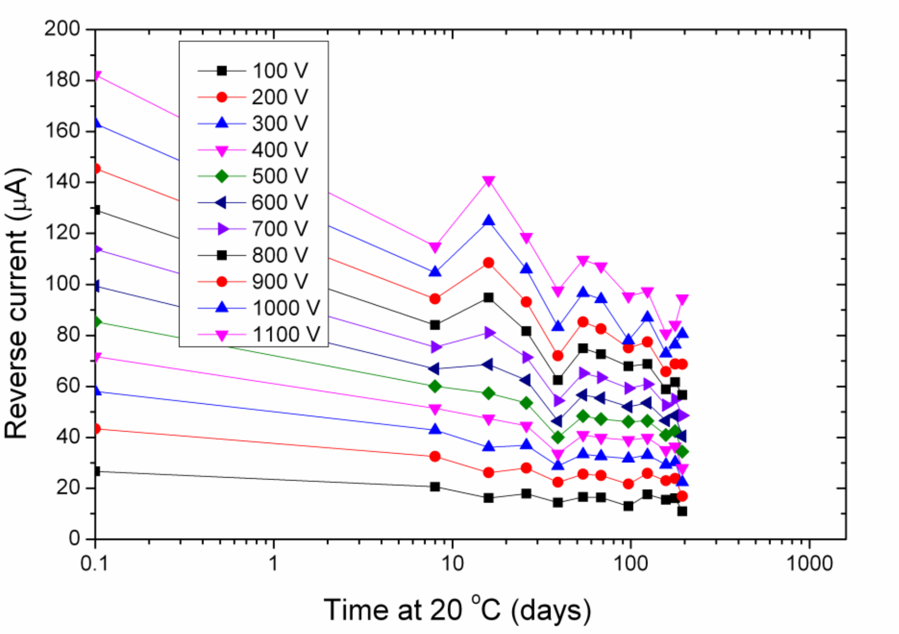
NOISE





Comparison of the Accelerated and Room Temperature Annealing of the reverse current, HPK FZ n-in-p, 2E15 and 1E16 n_{eq} cm^{-2}





CONCLUSIONS

The CCE measurements with both p-in-n and n-in-p sensors show discrepancies with accepted annealing features as measured with CV methods and as predicted by widely accepted parameterisations. In practical terms, the changes with annealing of the CCE sensors after LHC doses (microstrip sensors) are less severe than anticipated.

With n-in-p sensors the reverse annealing seems suppressed when the study is performed by accelerating the annealing at 60 and 80 ^{o}C (maximum voltage 1100V). Nonetheless the rescaling of the accelerated annealing to RT could be wrong at least when applied to the CCE. The reason could be the rescaling criterion itself, or a different evolution of the effective space charge triggered by temperatures between 20 and 60-80 ^{o}C.

Controlled annealing (at 20^{0}C) is still a very useful tool to reduce power dissipation and recover fraction of S/N in heavily irradiated silicon detectors. The discrepancies between the accelerated and RT annealing need to be studied to base the prediction for the changes of CCE with time according to the real operation and maintenance temperatures in the experiments.