Effect of annealing on charge collection in n-on p type silicon strip detectors irradiated with 24 GeV protons

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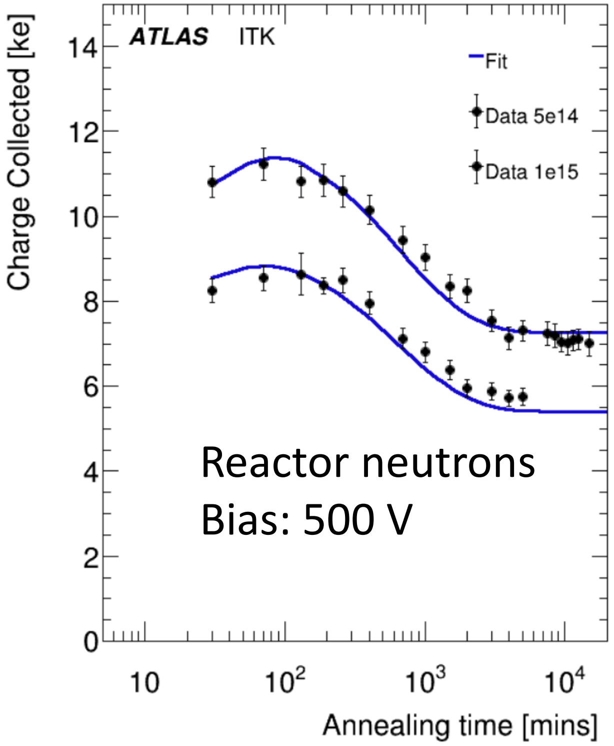
ATLAS ITk

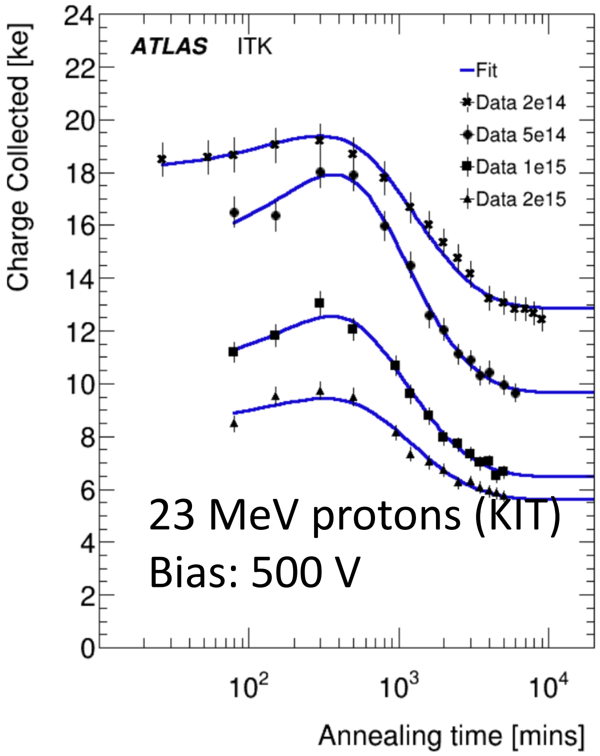
Introduction

- extensive measurements of charge collection and annealing up to Φ_{eq}~ 2e15 n_{eq}/cm^2 during development of strip sensors for the ATLAS Itk

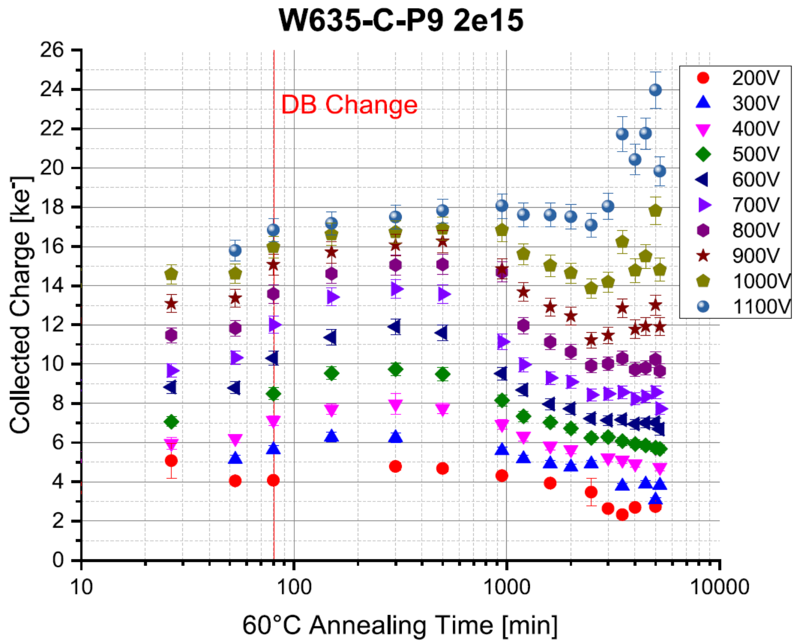
- at 500 V (ATLAS ITk Strips max. operating bias) annealing of collected charge in detectors irradiated with reactor neutrons or low energy protons behaves as expected:
  ➔ beneficial effect of short term annealing followed by loss of CCE because of "reverse" annealing

R. Orr et al., PoS(Pixel2022)043





L. Wiik-Fuchs et al., NIMA 924 (2019) 128-132



23 MeV protons (KIT), Φ: 2e15 n_{eq}/cm^2

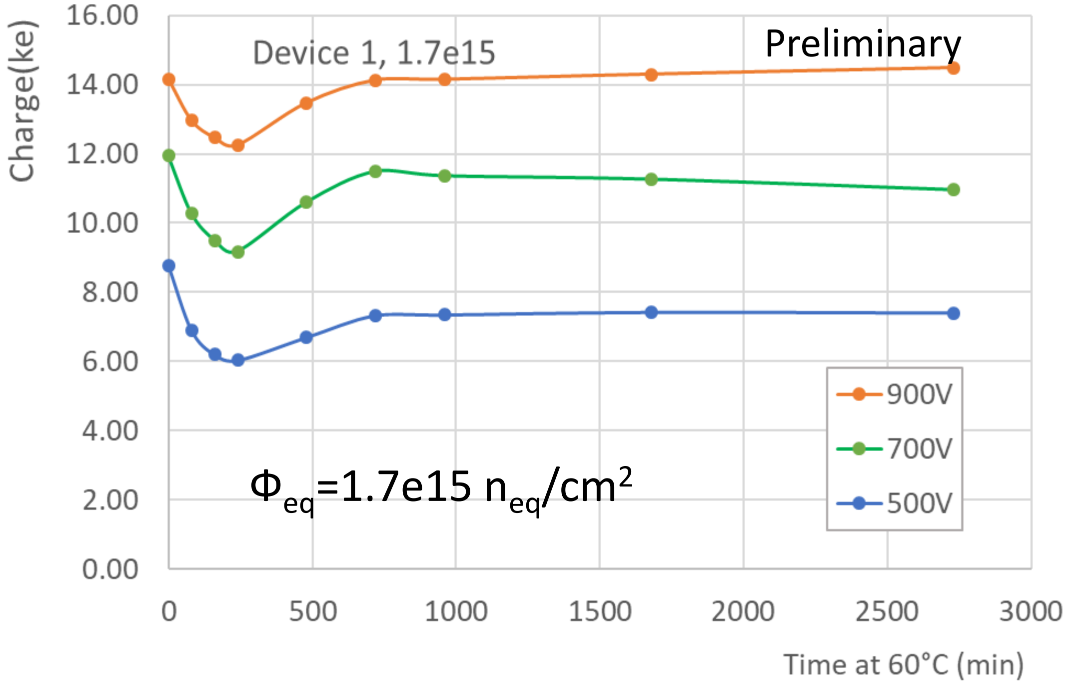
Introduction

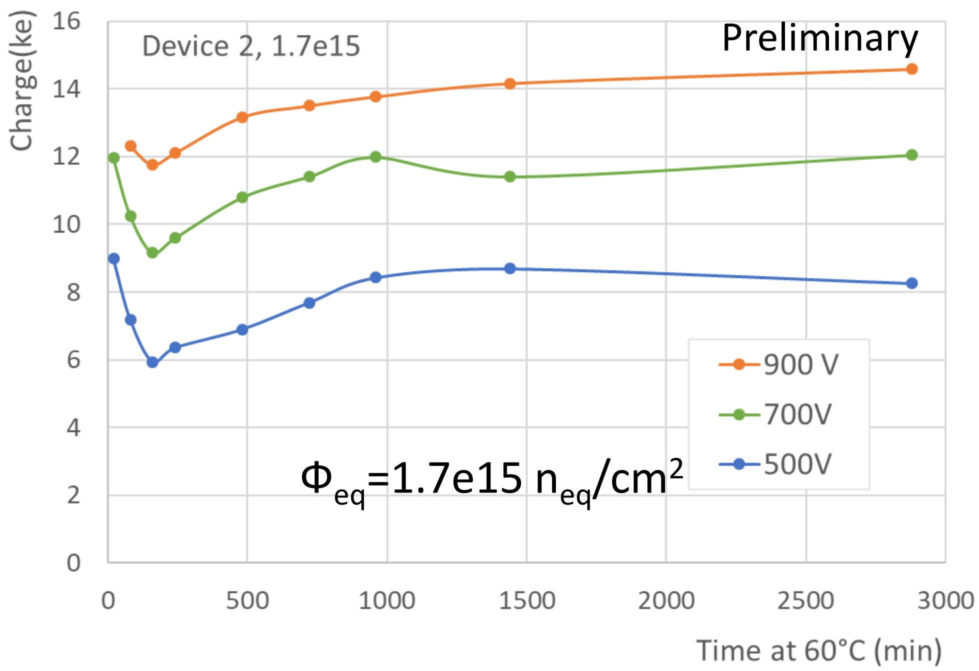
- recently unusual annealing behavior was measured after irradiation with 24 GeV protons at CERN IRRAD facilities:

  ➔ drop of collected charge after short term annealing followed by the increase after longer annealing times
  ➔ no or very small effect of long annealing

- motivation for further investigation, preliminary results reported in this presentation

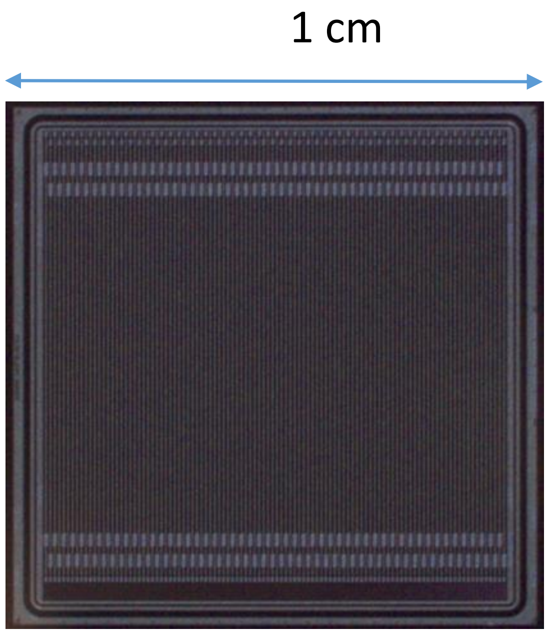
Irradiated with 24 GeV protons in IRRAD shuttle (at normal angle vs. beam)



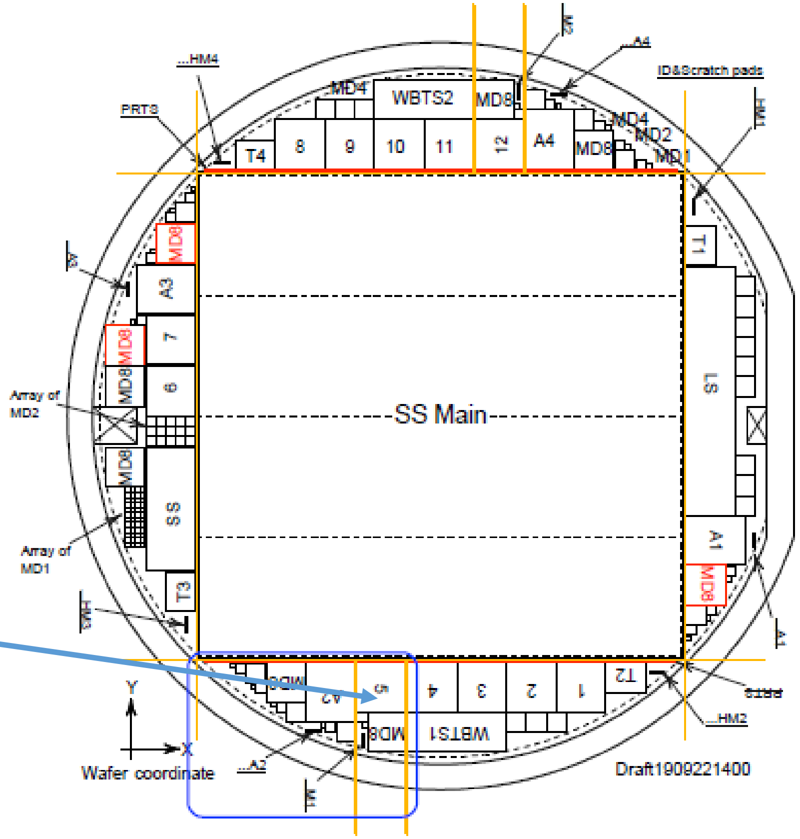


Samples

- miniature strip detectors from production wafers for ATLAS ITk strip detector
- producer: HPK
- n+ strips in p-type bulk, FZ
- AC coupled
- strip pitch 75.5 µm
- active thickness 300 µm , (physical thickness 320 um)
- V_{fd} ~ 300 V



Mini strip detector

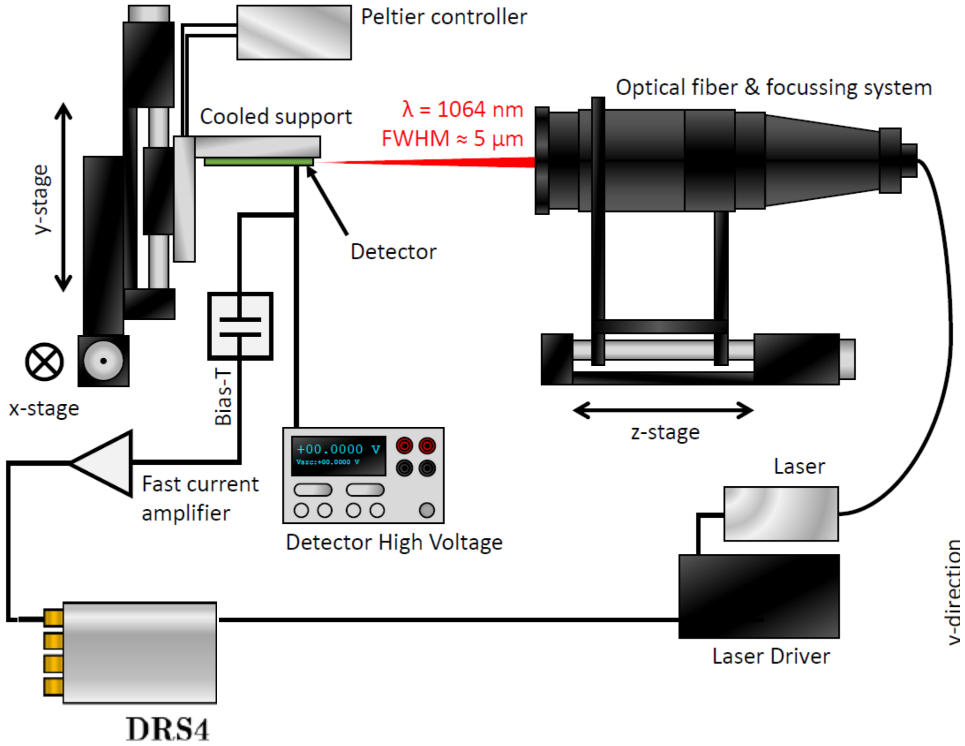


Layout of Atlas ITk strip wafer from Y. Unno et al.,2023 JINST 18 T03008 https://doi.org/10.1088/1748-0221/18/03/T03008

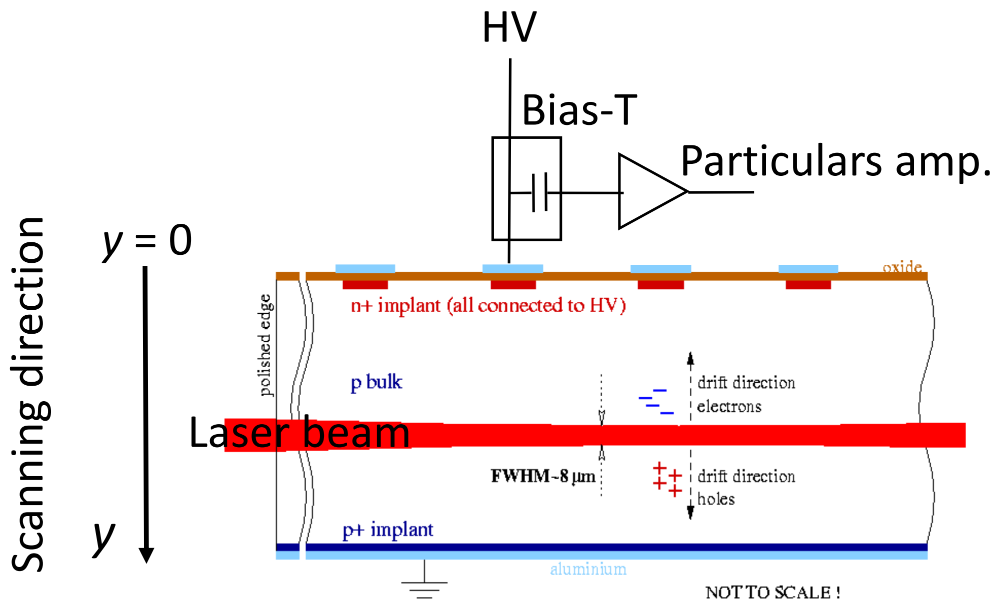
Experimental methods

Edge TCT

- IR laser methods
- System by www.particulars.si



Drawing by M. Franks et al., 36th RD50 workshop



Velocity profiles:

$$I(y,t\sim 0) \approx qE_w\left[\bar{v}_e(y)+\bar{v}_h(y)\right]; \quad \bar{v}_e(y)+\bar{v}_h(y) \propto E$$

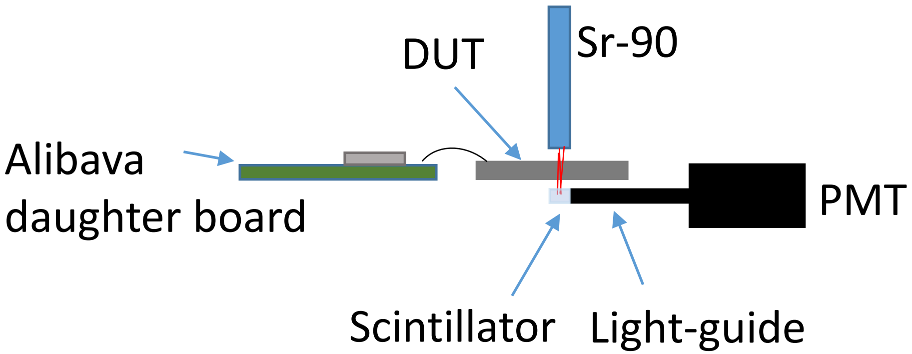
- induced current at $t \sim 0$ proportional to carrier velocity at laser location
- if E not too large, I proportional to E ($\boldsymbol{E_w}$ ~ constant (see: G. Kramberger, et al.,IEEE Trans. Nucl. Sci. NS-57 (2010) 2294.))

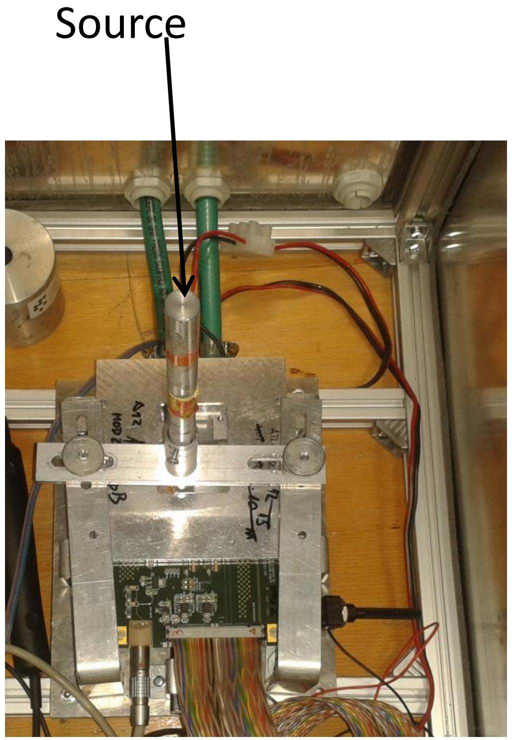
Charge: $Q = \int_0^{25ns} I(t)dt$

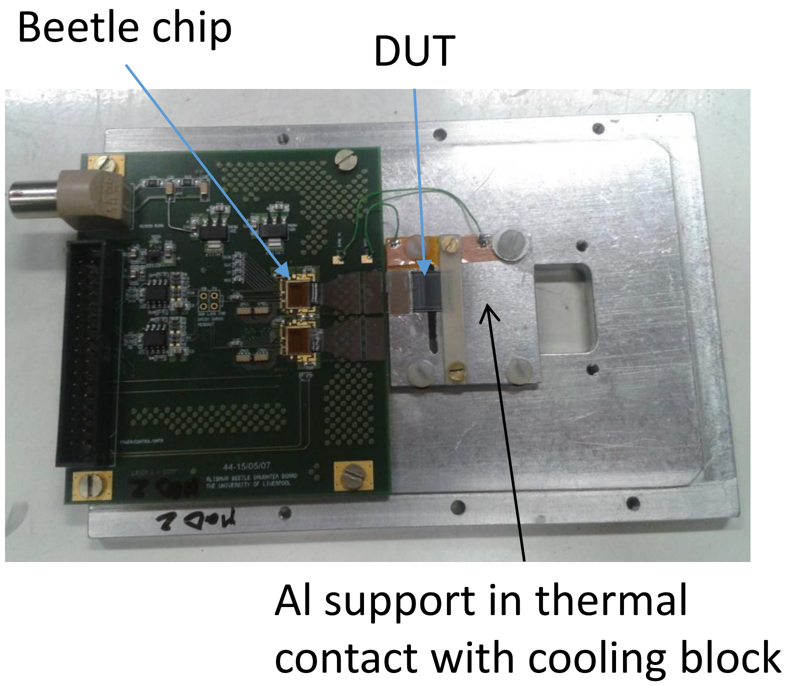
Experimental methods

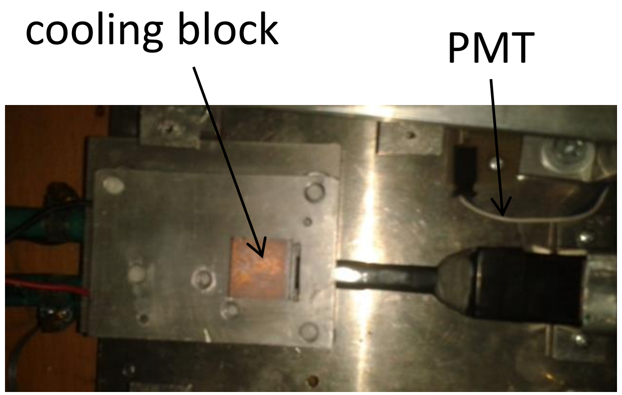
- CCE with Sr-90
- Alibava system based on analogue Beetle chip
  - ➢ alibavasystems.com
- 25 ns peaking time
- 40 MHz clock
- DUT cooled by Peltier cooling
- triggering with scintillator
- normalization to MIP MPV – 23100 e-h pairs in 300 µm of depleted unirradiated silicon (77 e-h pairs/µm)

Scheme of the setup:



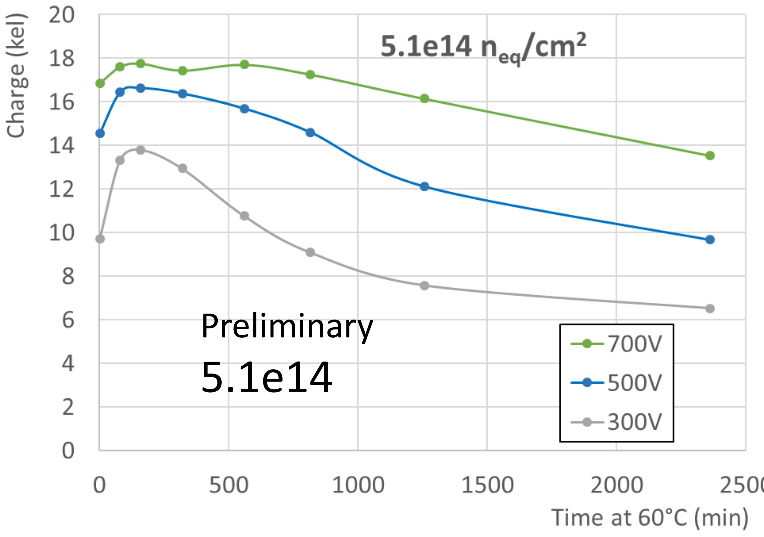


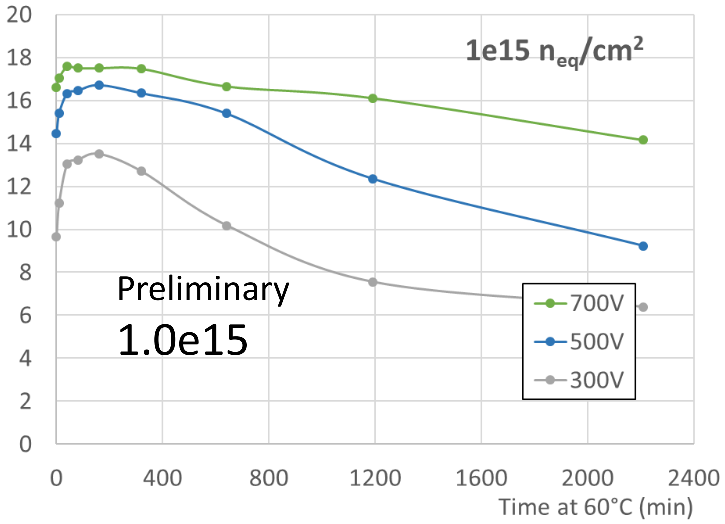


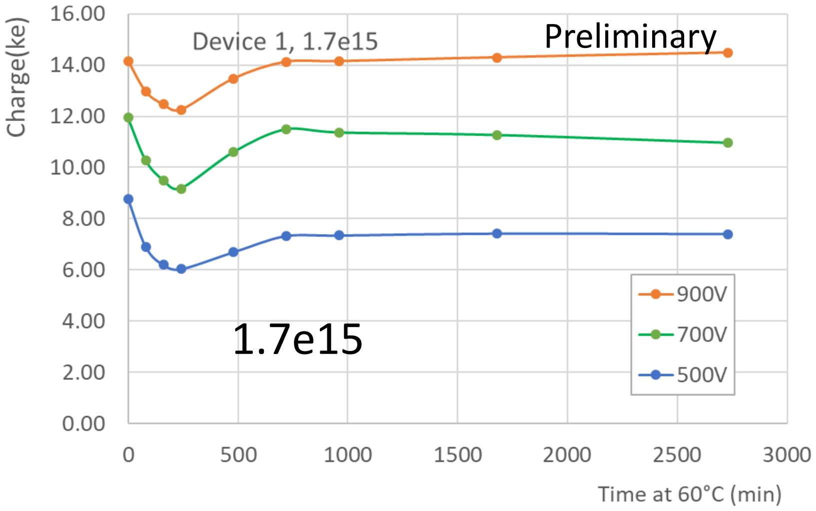


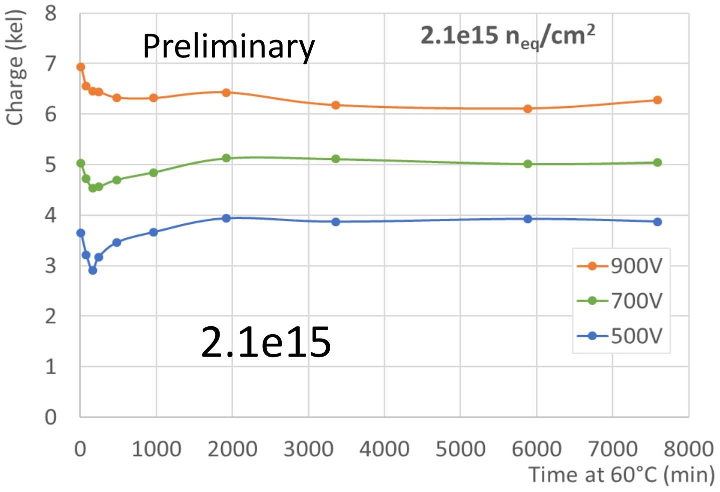
Results

- mini detectors irradiated with 24 GeV protons
- collected charge measured with Alibava setup
- Fluences **5e14** and **1e15**: (irradiated in the cold box at 12 deg. vs beam)
  ➔ usual annealing behavior
- Fluences **1.7e15** and **2.1e15**: (irradiated in the shuttle at normal angle)
  ➔ drop of charge after short annealing times





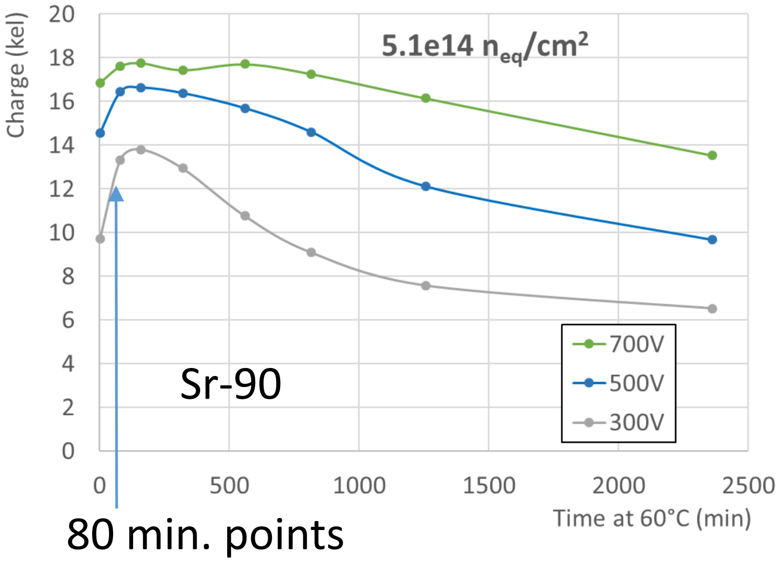




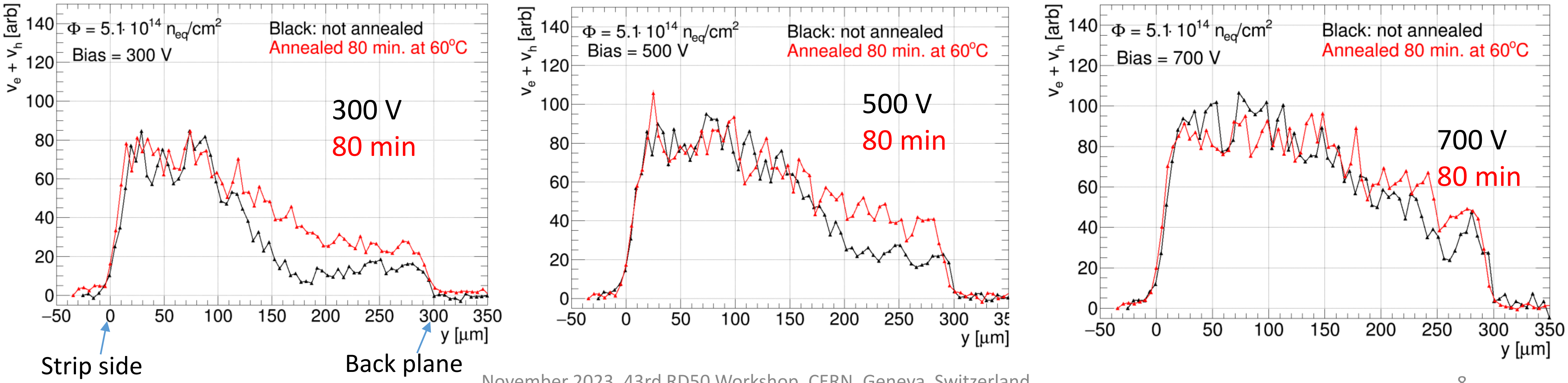
E-TCT

- **24 GeV protons, Fluence: 5e14 n_{eq}/cm^2**

- usual annealing behavior:
- ***N_{eff}*** (effective acceptors) decreases during short term annealing:
  - depleted depth increases at bias below V_{fd}
  - V_{fd} decreases



E-TCT velocity profiles:

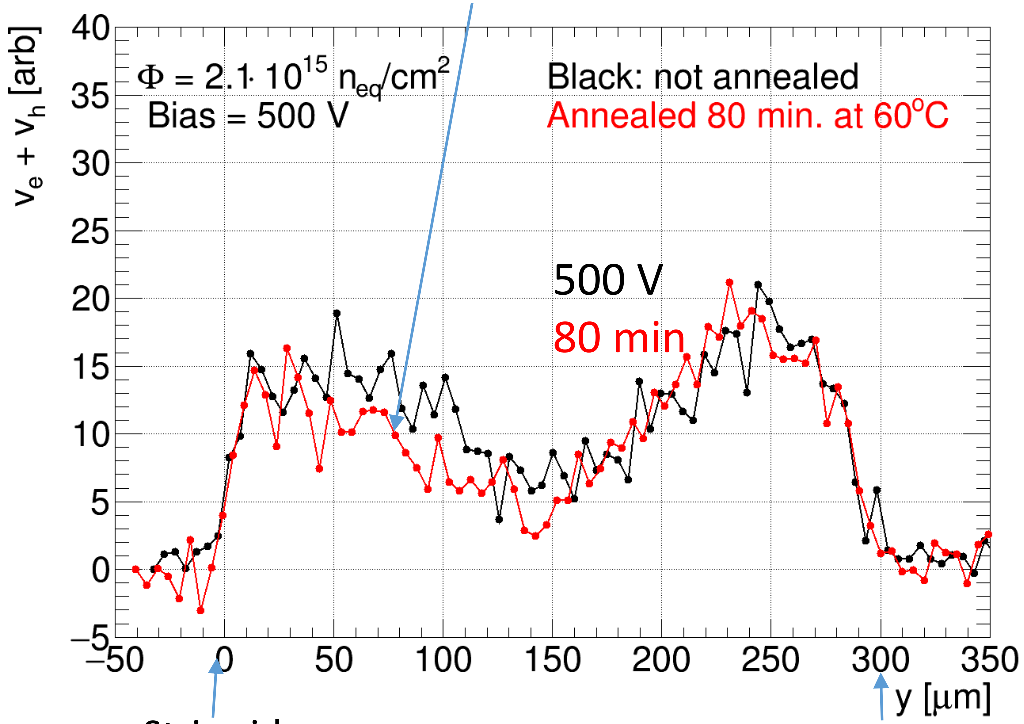


E-TCT

High fluence: 2.1e15 n_{eq}/cm^2

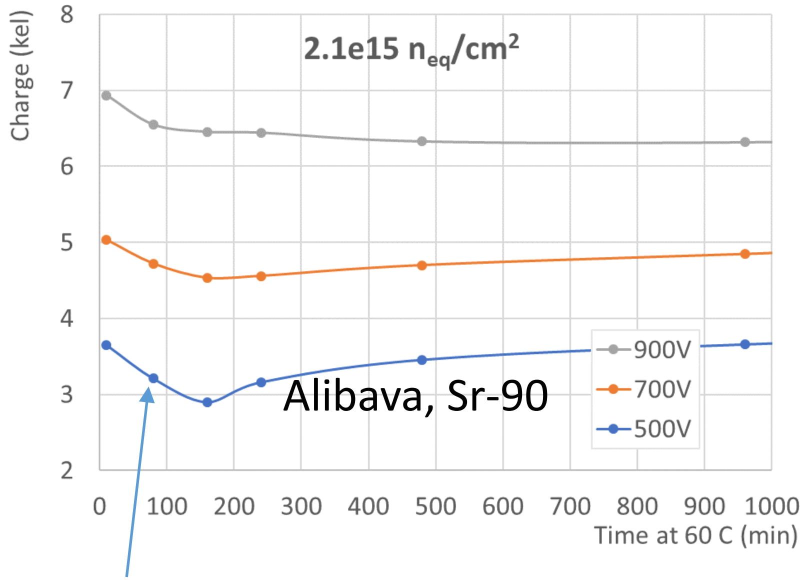
- double peak velocity profile
- carrier velocity (Electric field) near strips reduced by short annealing
  ➔ not beneficial for charge collection when trapping times short → CCE drops

Lower carrier velocity on strip side after annealing



Strip side

Back plane

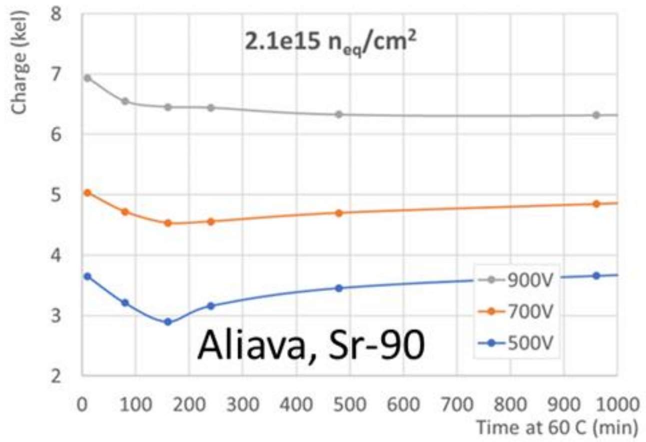


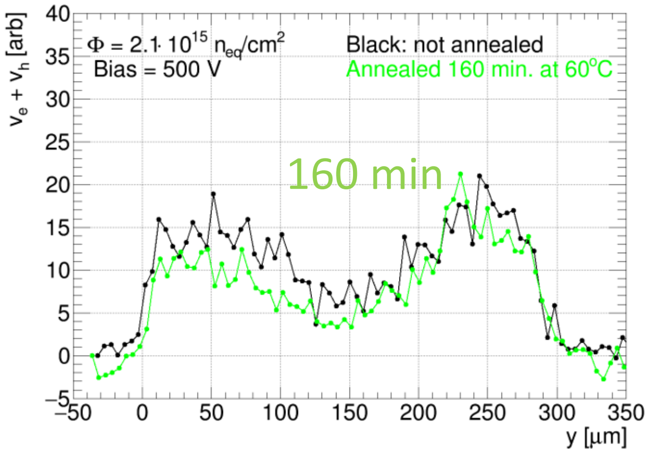
80 minutes annealing point

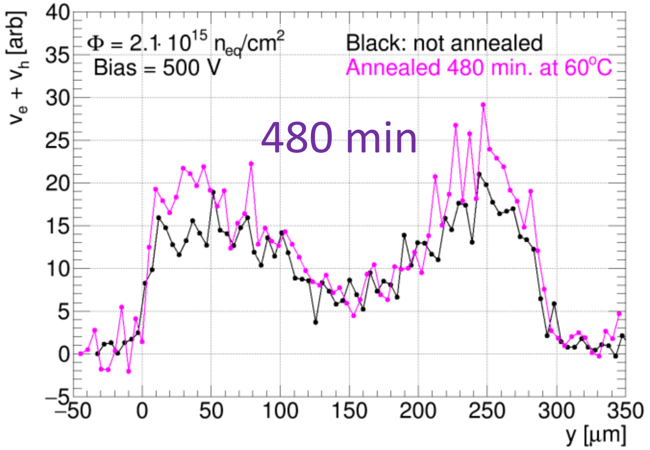
E-TCT

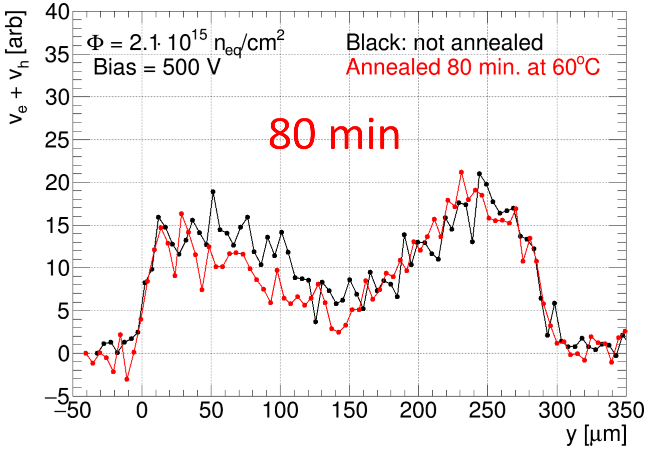
- **High fluence Φ_{eq} = 2.1e15 n_{eq}/cm^2**

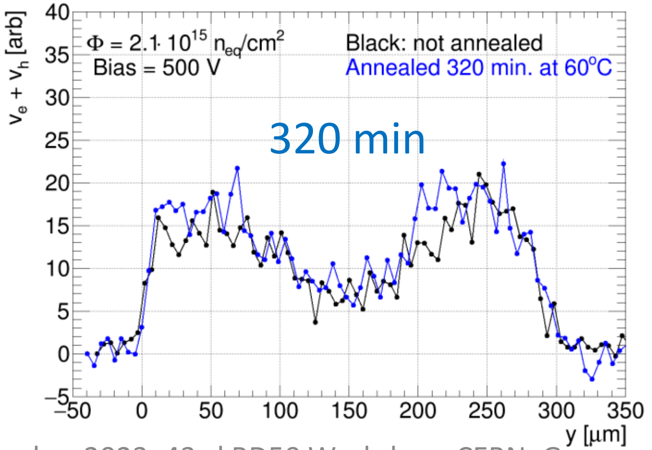
- drop of negative N_{eff} by short term annealing → smaller carrier velocity in the first peak → drop of CCE
- increase of negative N_{eff} by longer (reverse) annealing → carrier velocity in the first peak increases → rise of CCE

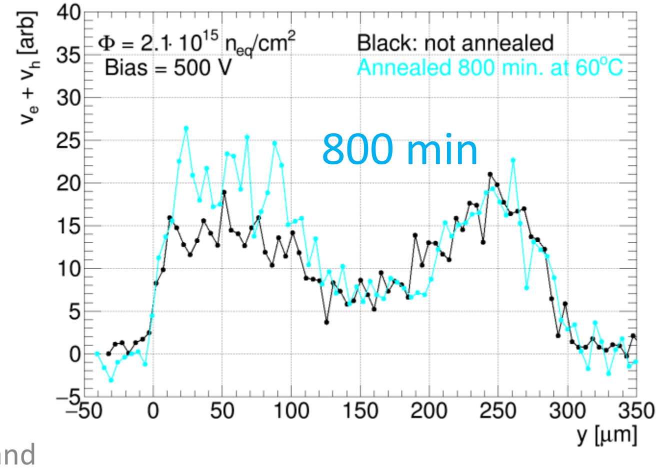








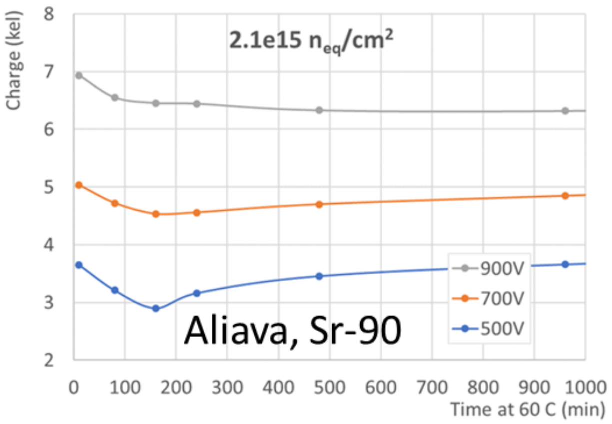


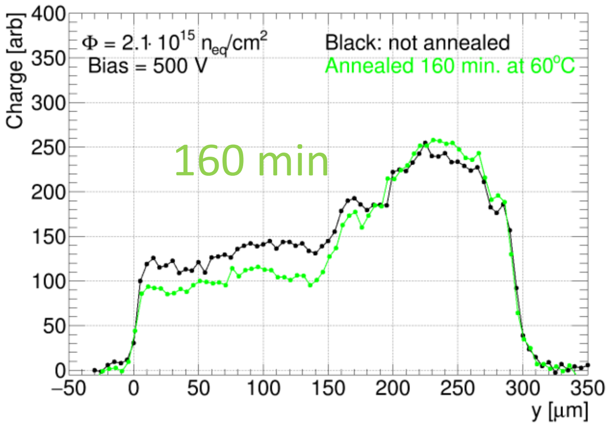


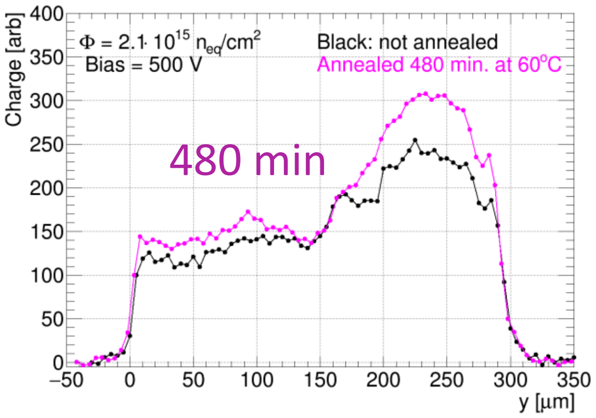
E-TCT, Charge collection profiles

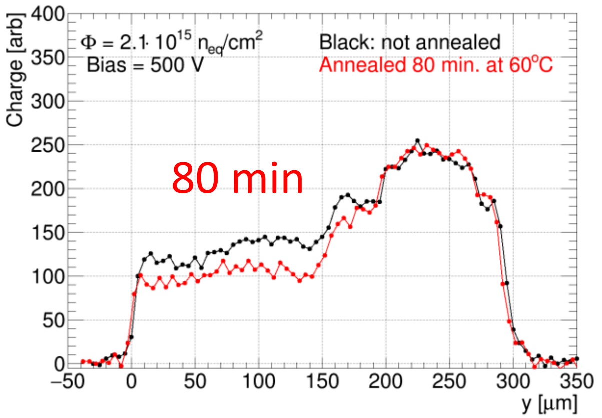
- Charge: integral of current pulse from 0 – 25 ns
- lower charge collection on strip side after up to 160 minutes annealing

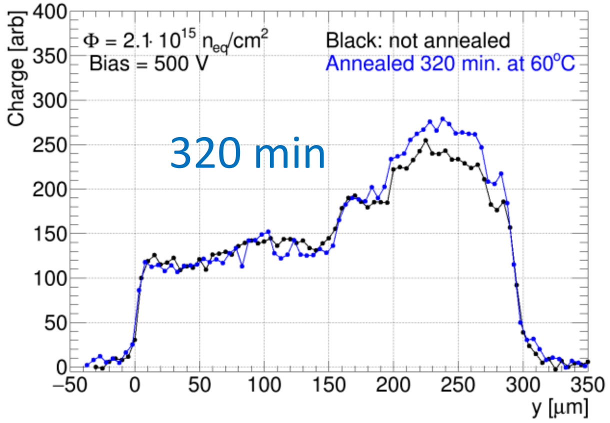
➔ note: increase of charge at back side after annealing seen in E-TCT has smaller effect on CCE with Sr-90 because of different weighting field

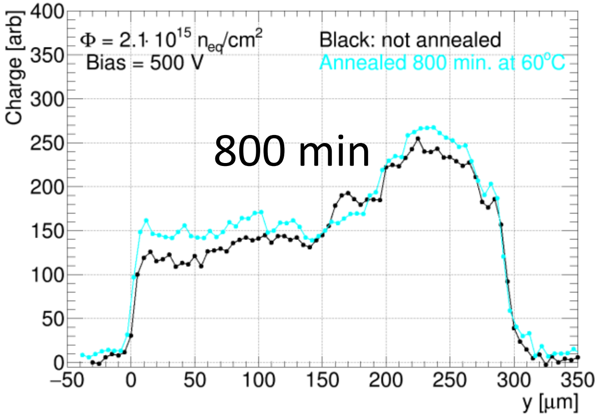












Double peak electric field profile in Si detectors after irradiation is a long known phenomenon:

[1] Z. Li, H.W. Kraner, IEEE TNS 39 (1992) 577
[2] V. Eremin, E. Verbitskaya, Z. Li, NIM A 476 (2002) 556–564
[3] E. Verbitskaya et al., NIM A 583 (2007) 77–86
[4] G. Kramberger et al. 2014 JINST 9 P10016
[5] several more publications…

Origin of double peak as explained in [2]:

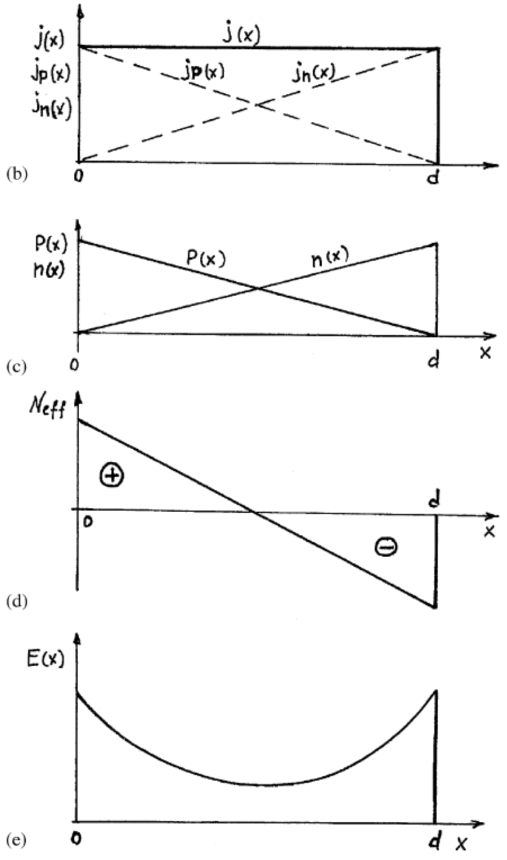
- thermally generated equilibrium carriers trapped on the radiation induced localized energy levels polarize space charge

Current:

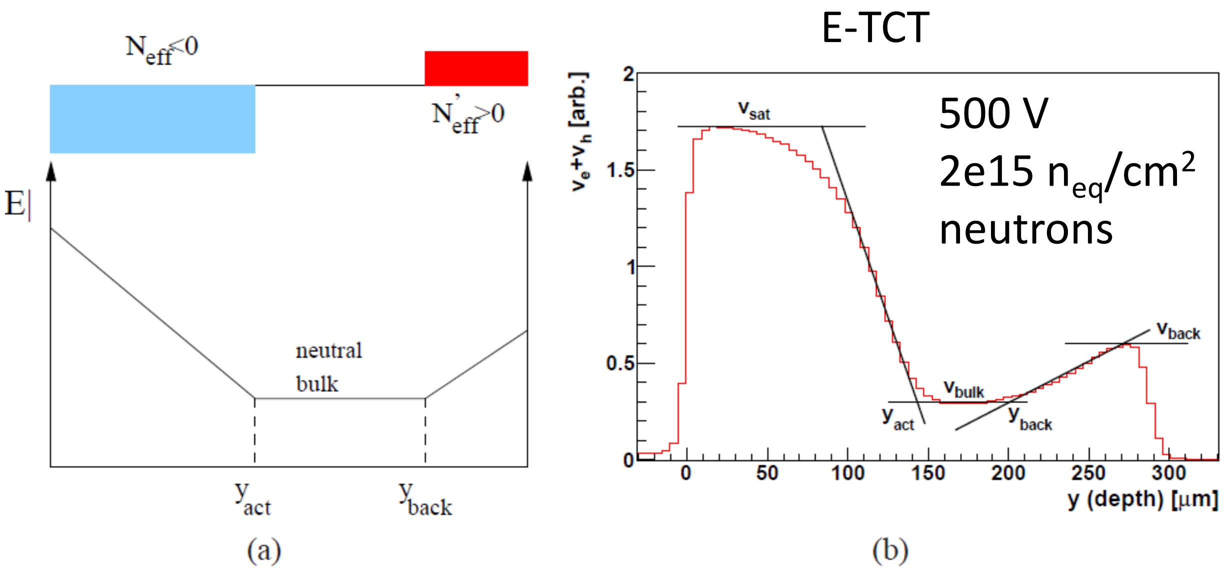
Free carrier concentration:

Space charge:

Electric field:



From [4]:
Approximation of electric field:



E-TCT

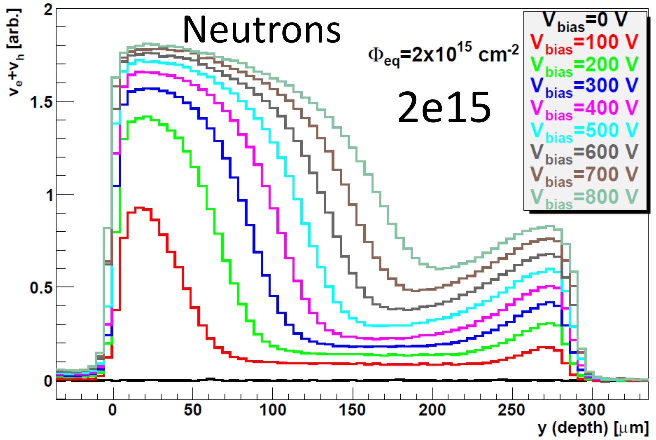
- shape of velocity profile depends on irradiation particle type at high fluences
- neutron irradiation: front peak dominant, back peak much smaller than in case of 24 GeV protons at same Φ_{eq}
- PSI pions (190 MeV), 24 GeV protons: symmetric

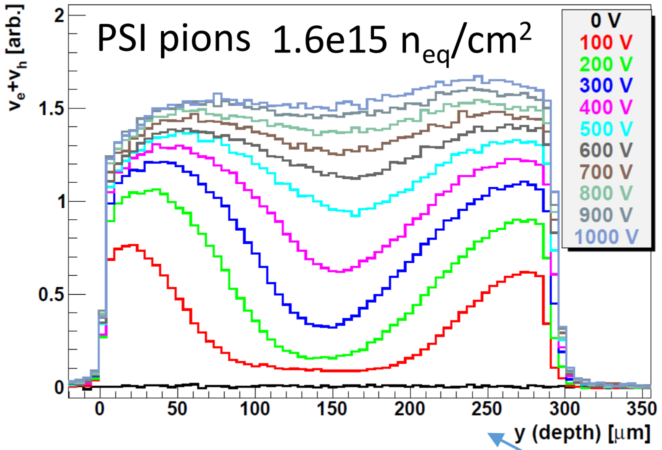
➔ annealing can have different effects on CCE measured with Sr-90 for different shapes of velocity profiles

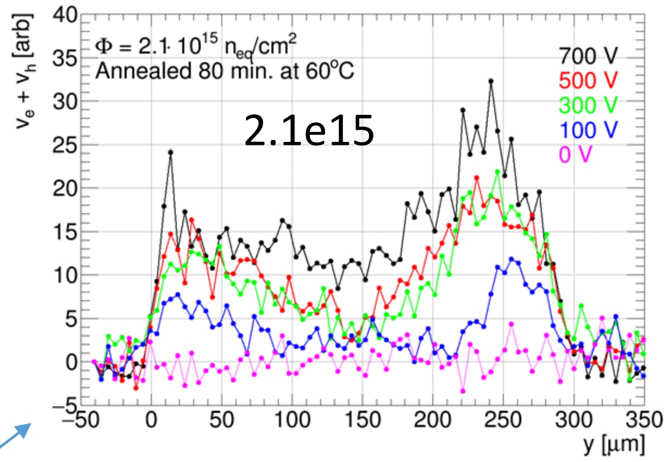
Mini detectors from A07 series

[G. Kramberger et al. 2014 JINST 9 P10016](#)

This work: A18, 24 GeV protons







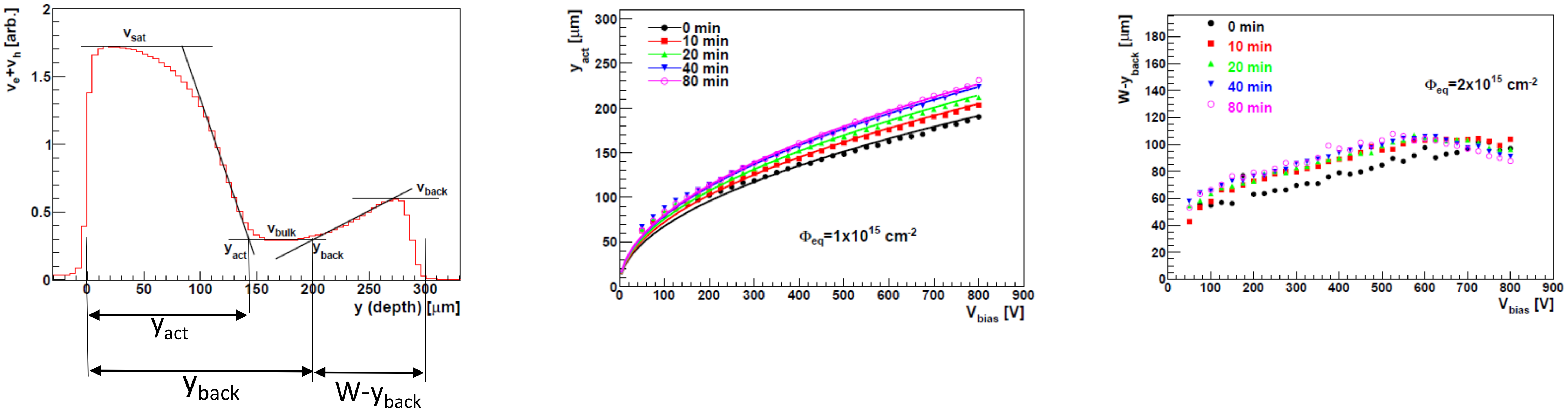
Symmetric profile

E-TCT neutrons

- effects of annealing on E-TCT profiles was measured for neutron irradiated strip detectors to ~ 1e15 n_{eq}/cm^2 in G. Kramberger et al. 2014 JINST 9 P10016
- y_{act} increases with short annealing → concentration of negative space charge (effective acceptors) decreases
- y_{back} doesn't change much with short annealing

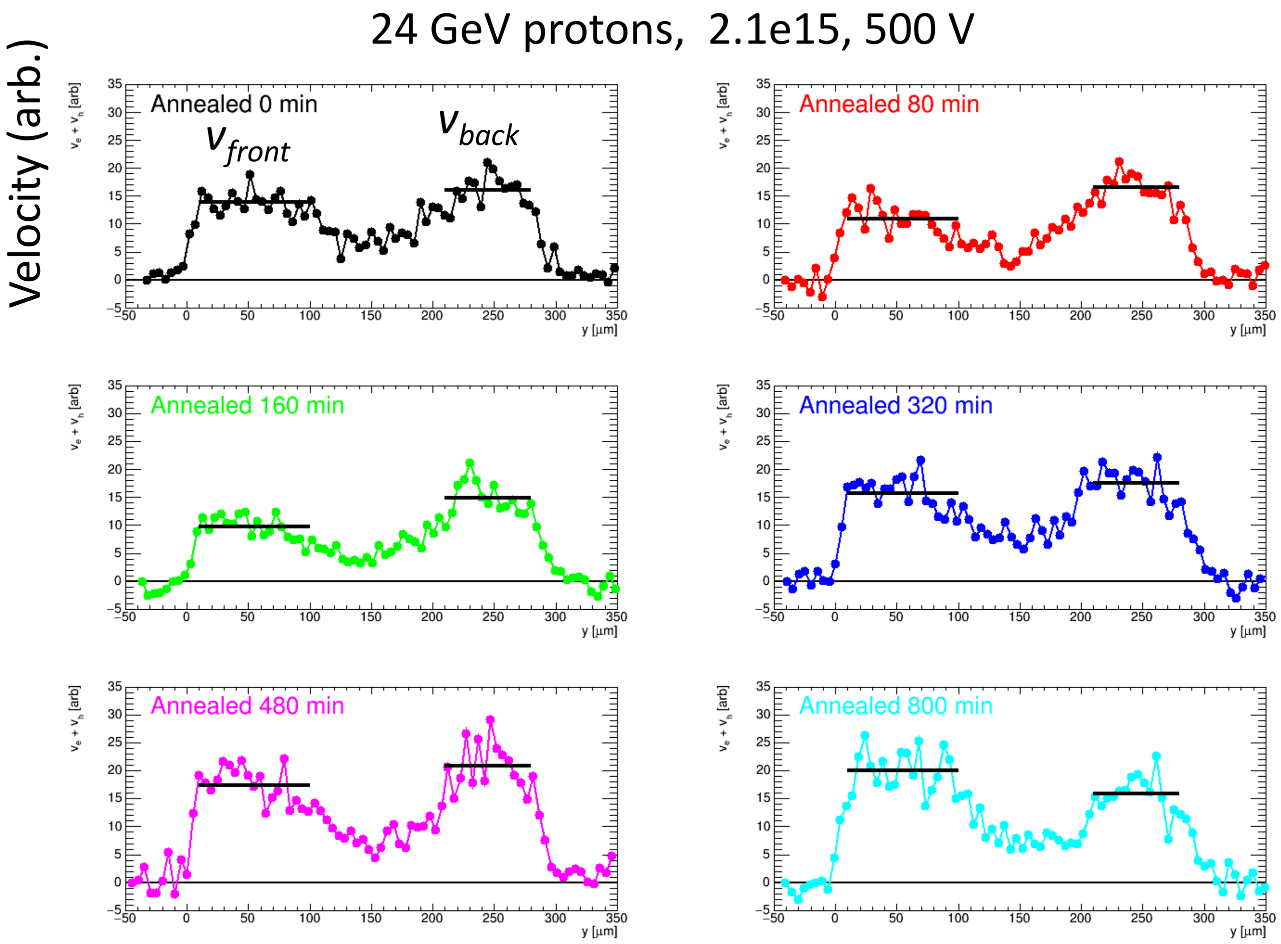
→ neutrons: front peak dominant, decrease of acceptor concentration N_a increases the width of the front peak
→ CCE increases

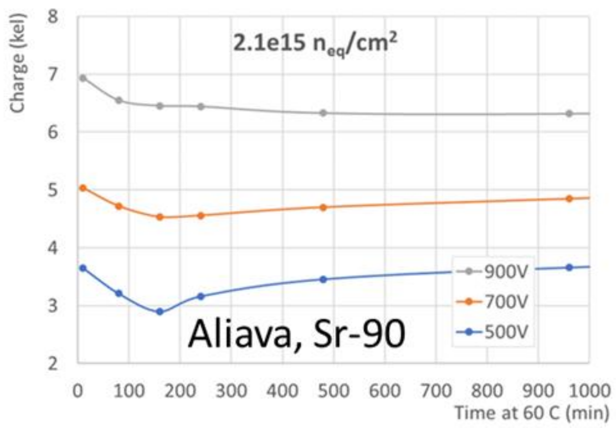
G. Kramberger et al. 2014 JINST 9 P10016

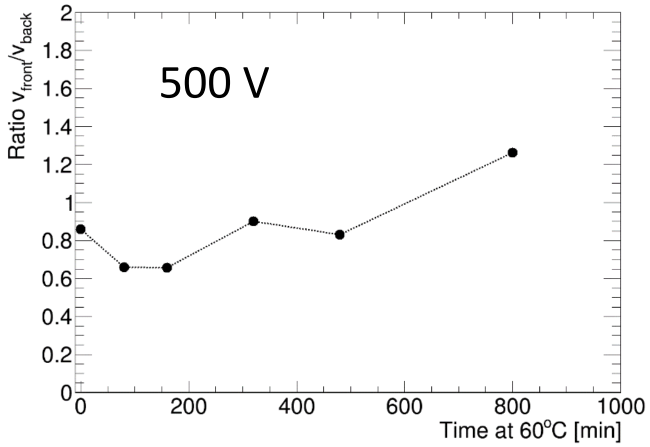


E-TCT, 24 GeV protons

- symmetric velocity profile
- decrease of effective acceptor concentration by short term annealing reduces the electric field in the first peak and consequently increases the field in the second peak (if N_{eff} at the back unchanged) ➔ CCE decreases
- it can be expected that CCE vs. annealing time would behave similar as the ratio v_{front}/v_{back}



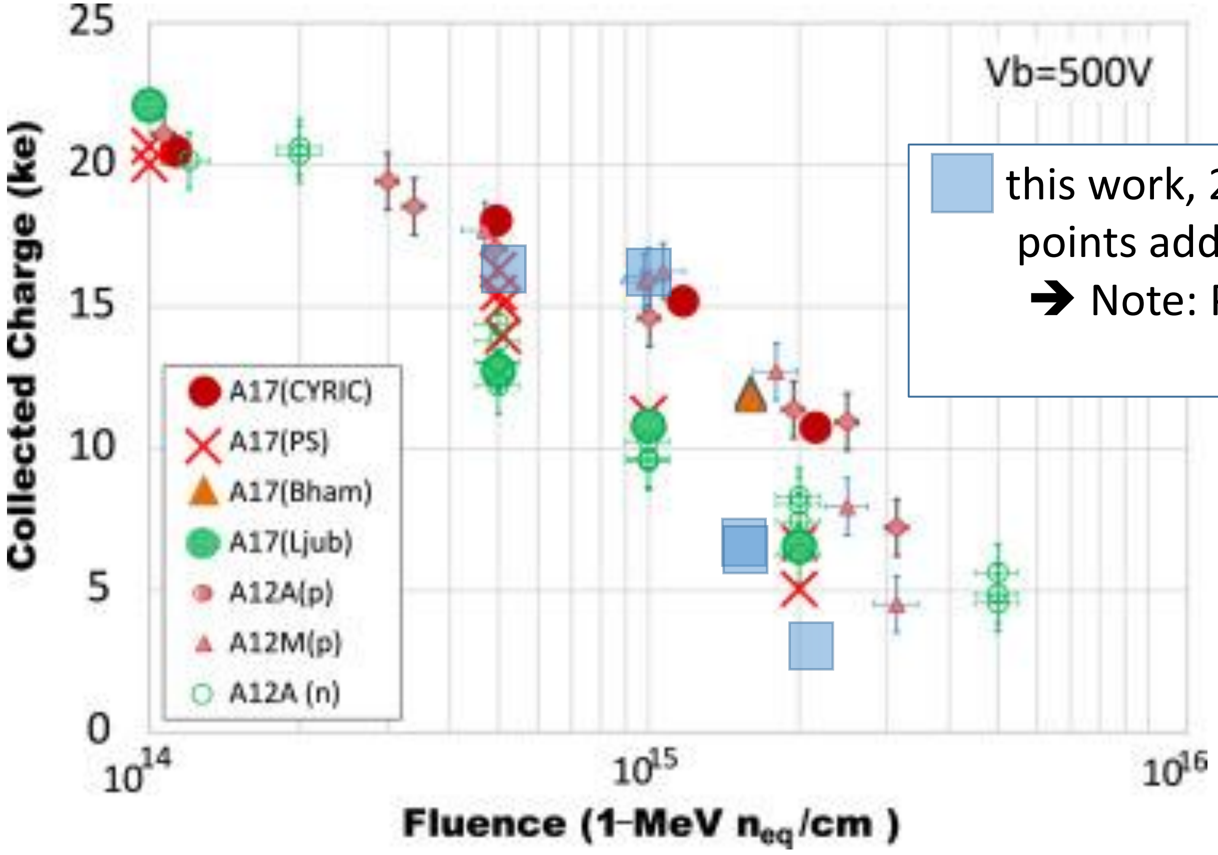




Charge Collection

- double peak electric field not optimal for CCE at high fluences → voltage drop at back side contributes less than the front side
- at 500 V and at $\Phi_{eq} > 1e15\ n_{eq}/cm^2$ collected charge after irradiation with 24 GeV protons lower than after irradiation with low energy protons → double peak electric field may be the reason
- ATLAS ITk Strip sensor community started extensive measurement campaign to study the effect of irradiation with 24 GeV proton, even if at higher proton fluences than expected in the ITk strips after 4000 fb^{-1} at HL-LHC

K. Hara et al., NIM A 983 (2020) 164422



this work, 24 GeV protons, points added to the plot by Hara et al.
→ Note: Preliminary!
Fluences values uncertain!

Summary

- dependence of charge collection in irradiated silicon strip detectors on annealing time at 60°C was studied

- it was observed that for samples irradiated to fluences above 1.e15 n_{eq}/cm^2 with 24 GeV protons dependence on annealing time is different than for samples irradiated to lower fluences:

  ➔ at low fluences initial increase of collected charge is followed by decrease at longer annealing times
  ➔ at high fluences collected charge decreases during short term annealing

- E-TCT measurements indicate that the effect could be attributed to the double-peak electric field profile observed in Si detectors irradiated with 24 GeV protons to high fluences

- double-peak electric field may be the reason for lower charge collected measured after 24 GeV protons compared to low energy protons at fluence higher than 1e15 n_{eq}/cm^2

- ATLAS ITk strips community started extensive study of the effects of 24 GeV protons on tests structures from production wafers

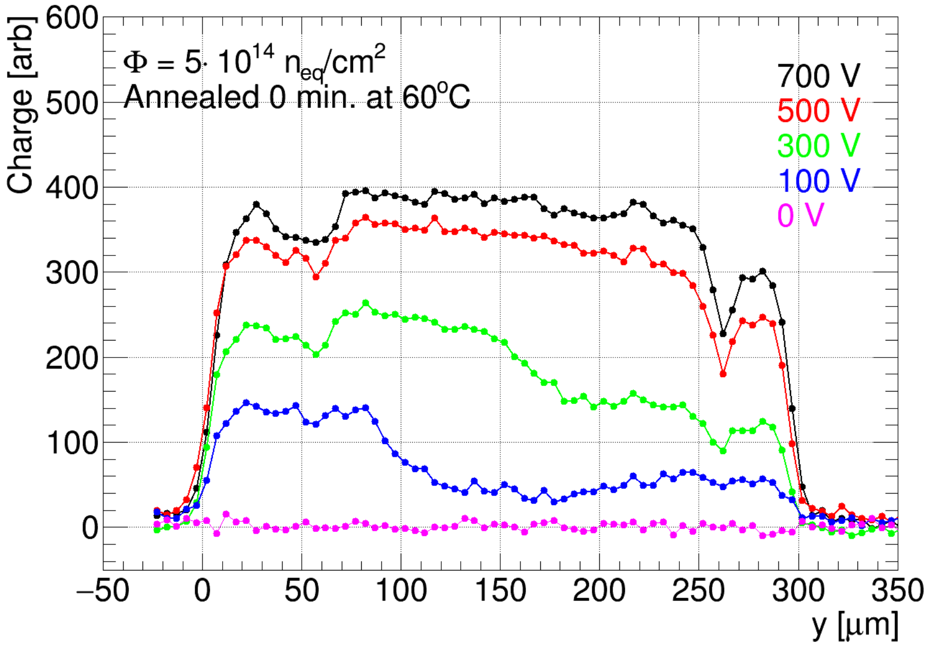
- first preliminary results are shown here, we are looking forward to new results in next months

Backup slides

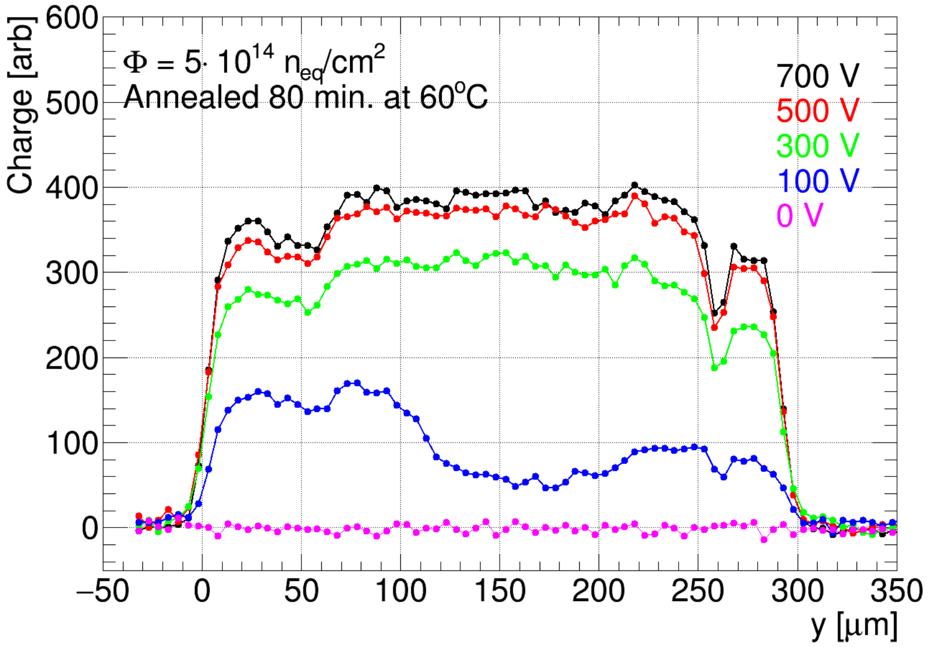
E-TCT

- **24 GeV protons, Fluence: 5e14 n_{eq}/cm^2**
- Charge collection (integral of current pulse 0 – 25 ns) profiles

V_{fd} > 300 V

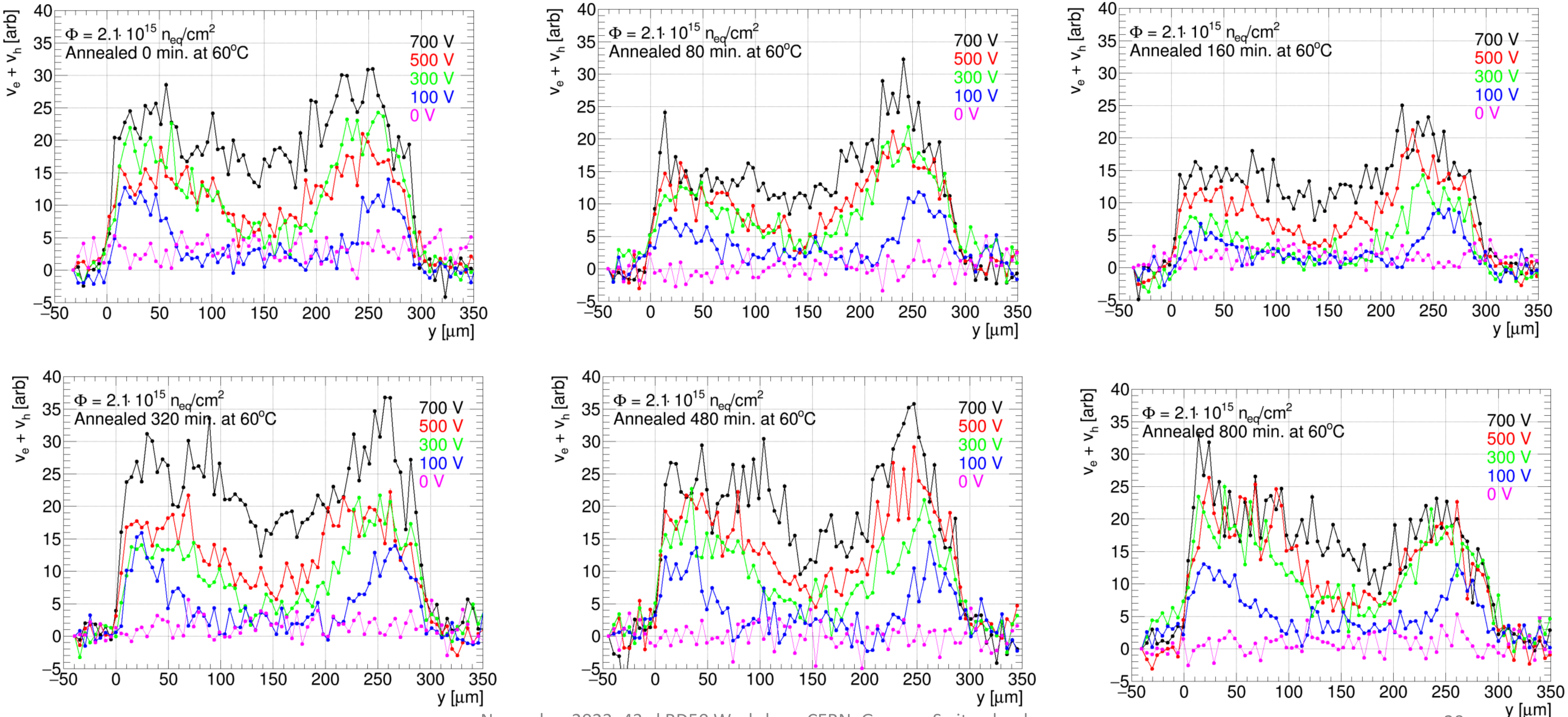


Fully depleted at 300 V



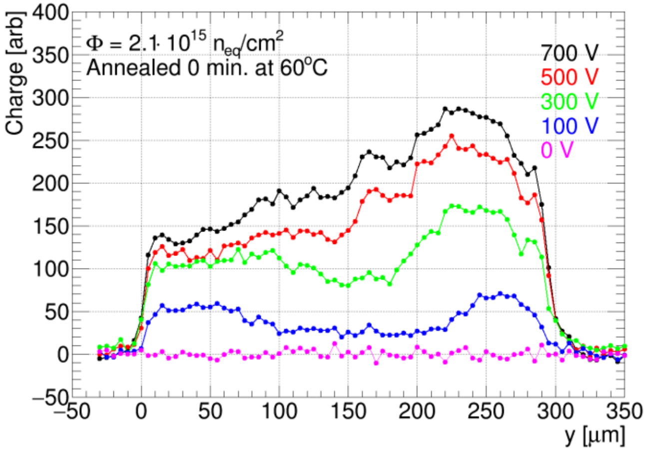
E-TCT

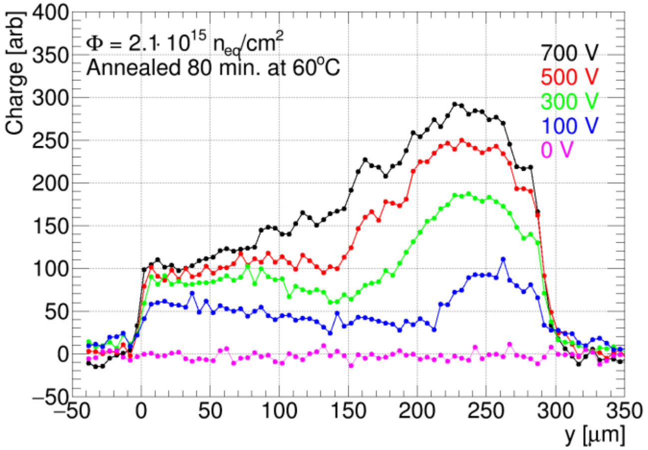
- 2e15, velocity scans at different voltages and annealing times

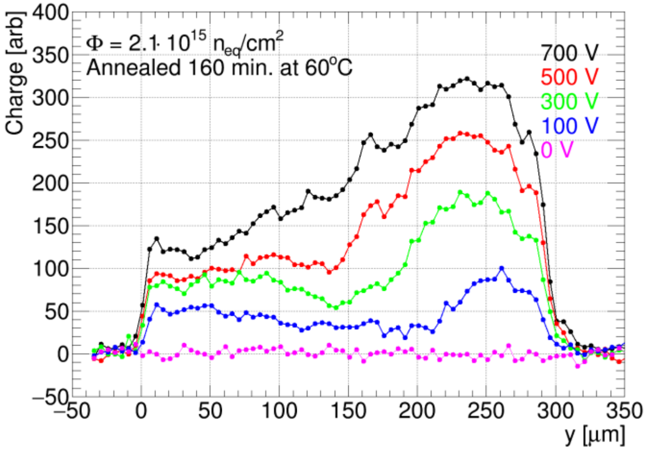


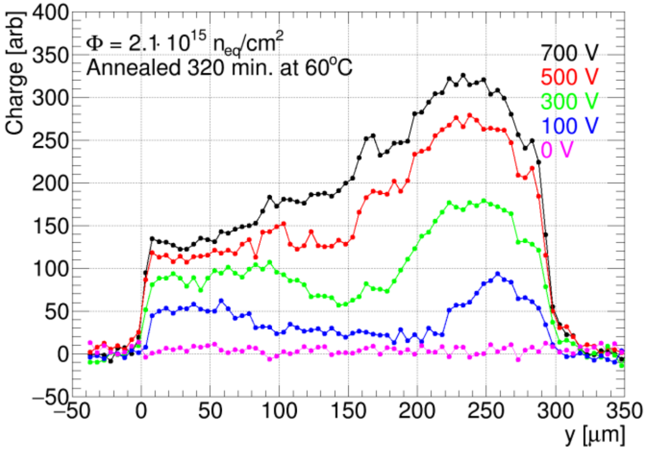
E-TCT

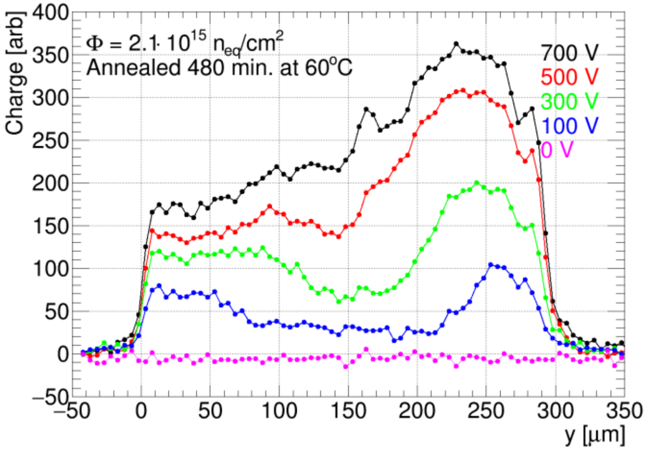
- charge profiles at different voltages and annealing times

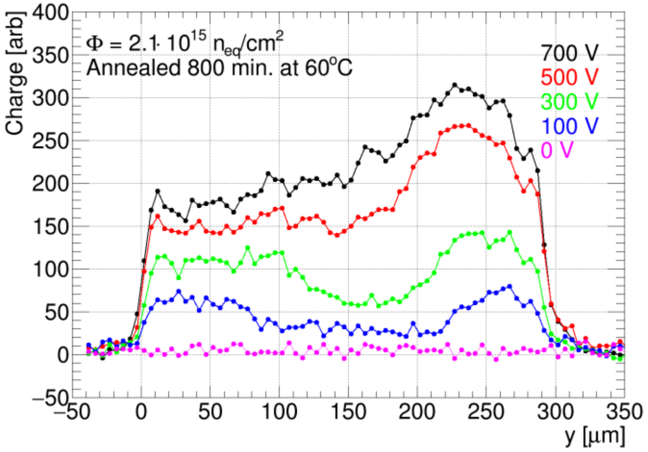






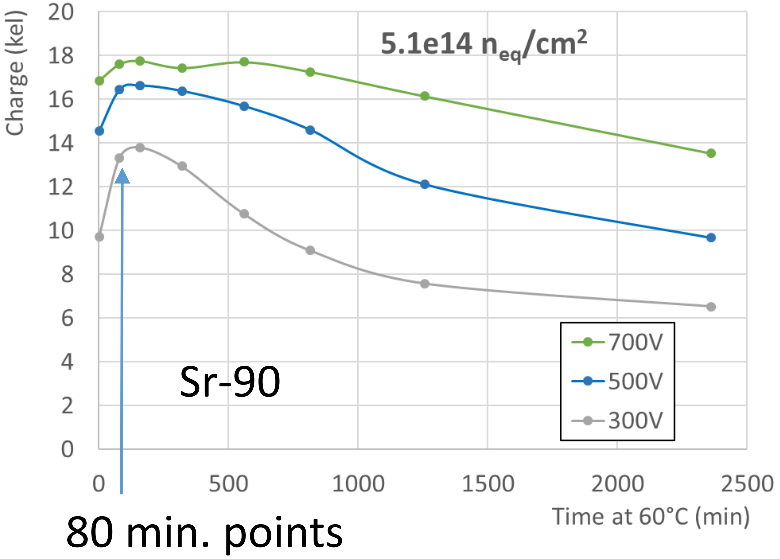


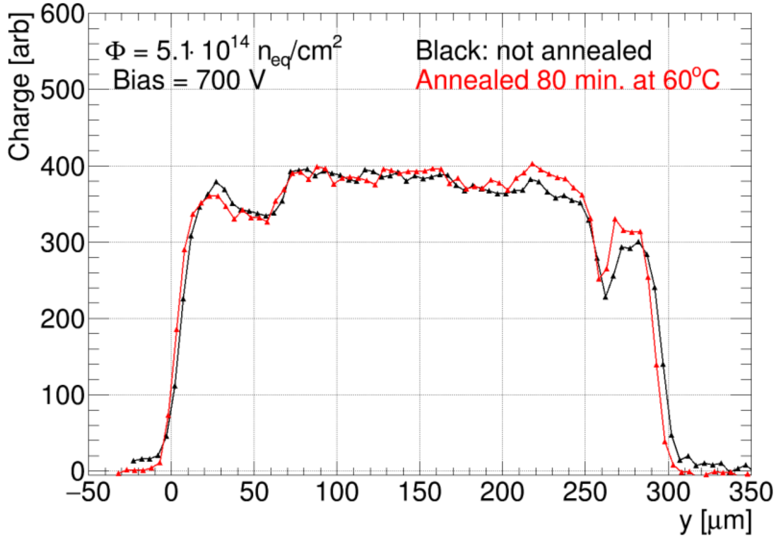


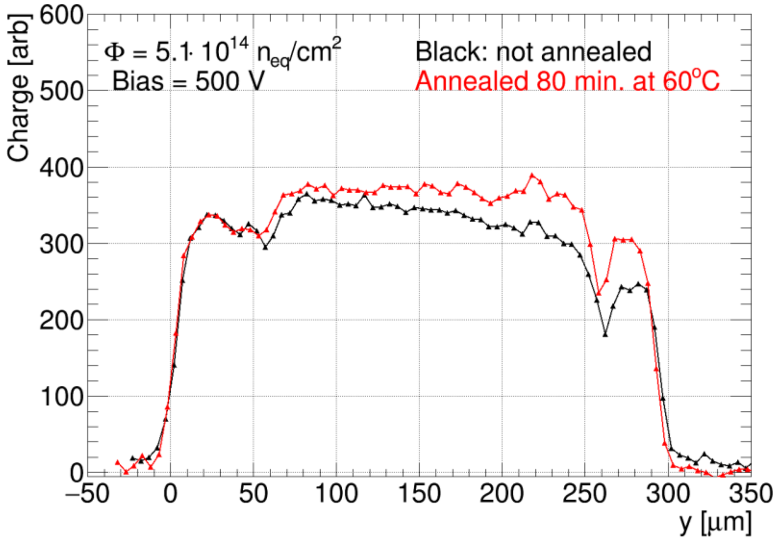


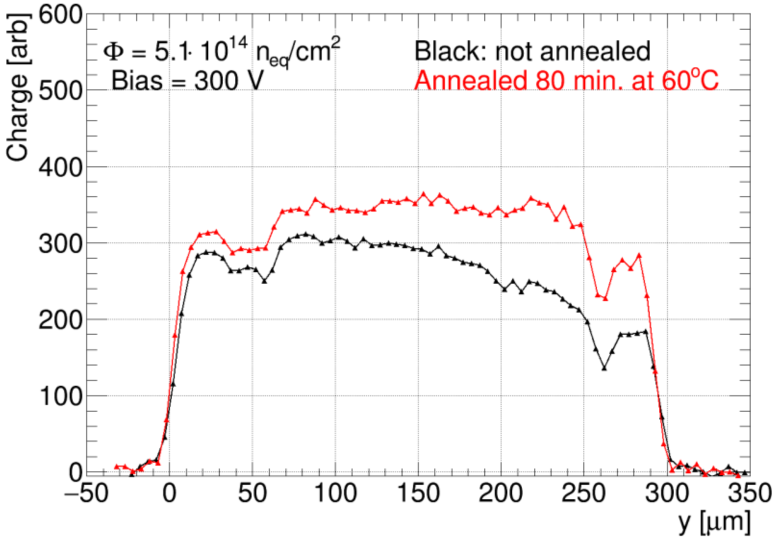
E-TCT

- 5e14
- charge profiles at different voltages before and after 80 min. annealing



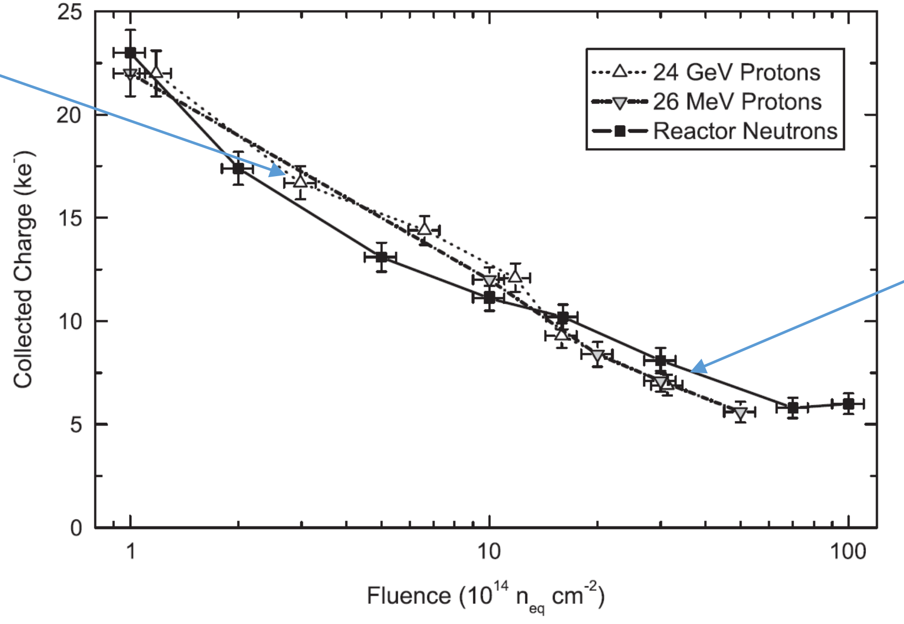






A. Affolder et al., Nuclear Instruments and Methods in Physics Research A 612 (2010) 470–473

Charged particles higher than neutrons



Neutrons higher than charged particles

Fig. 6. Collected charge at 500 V bias as a function of fluence for n-in-p FZ sensors irradiated with 26 MeV protons, 24 GeV protons and reactor neutrons up to 1.6×10^{16} n_{eq} cm^{-2}.