Unusual annealing of charge collection efficiency of silicon strip detectors, ATLAS18, irradiated to high fluences with 24 GeV/c protons

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Ljubljana, Slovenia

VCI2025 - The 17th Vienna Conference on Instrumentation

ATLAS ITk

Introduction

- extensive studies of effects of annealing on charge collection efficiency were made during development and production of sensors for ATLAS ITk strip detector
 (for details of ATLAS ITk Strip detector see slides by C. Lacasta at this conference)

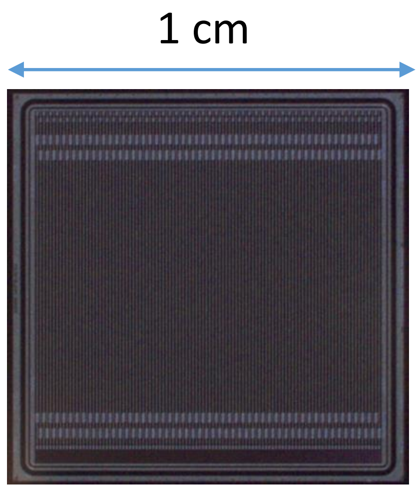
- after irradiation with neutrons or low energy protons, at bias voltages below ~ 900 V, "typical" annealing behaviour was observed: beneficial effect of short term annealing was followed by a drop of charge collection efficiency at longer annealing times

- after irradiation with high energy 24 GeV/c protons, a different "unusual" annealing was observed at high fluences

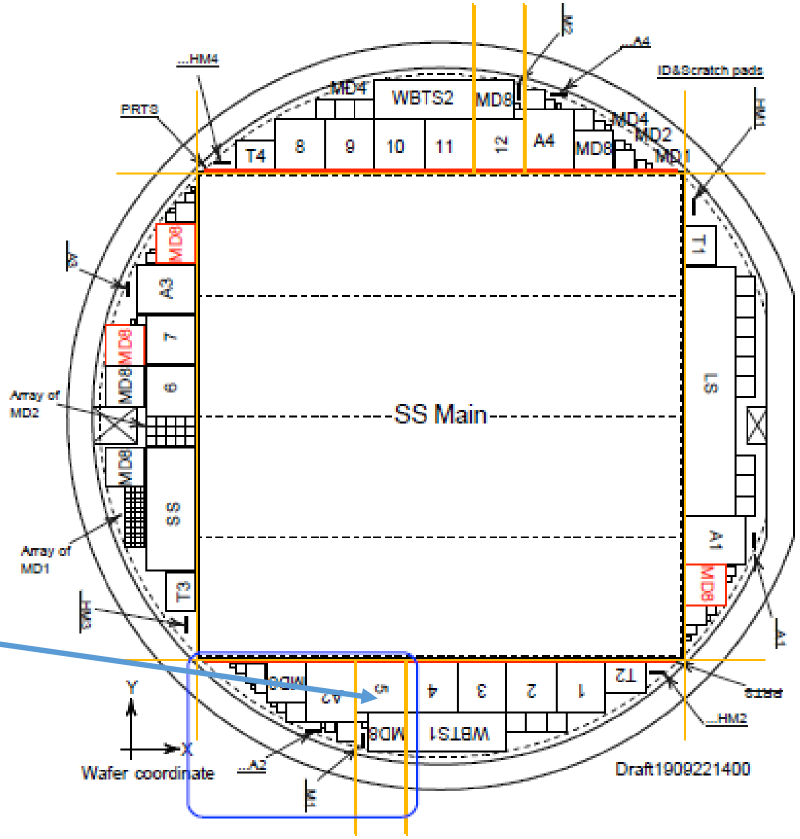
- in this contribution studies of these effects by charge collection and E-TCT measurements will be presented

Samples

- miniature strip detectors from ATLAS18 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} between 200 and 300 V



Mini strip detector



Layout of ATLAS ITk strip wafer ATLAS18
Y. Unno et al.,2023 JINST 18 T03008
https://doi.org/10.1088/1748-0221/18/03/T03008

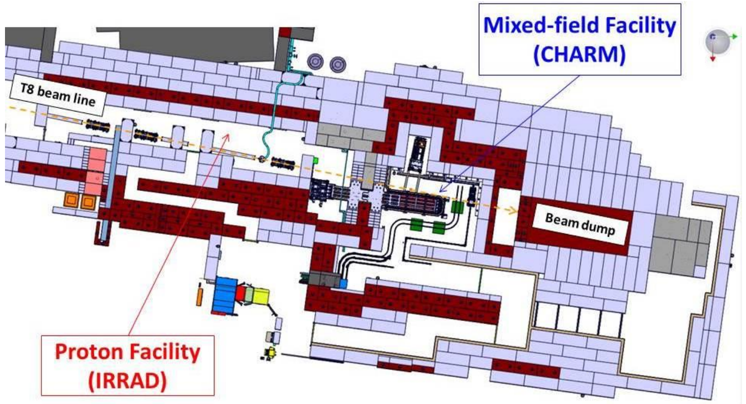
ITk strip detector:

- maximal operating voltage: **500 V**
- maximal fluence (including safety factors): **1.6e15 n_{eq}/cm^2**

Irradiations

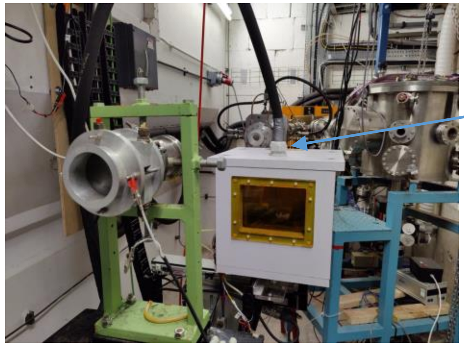
- 24 GeV/c protons

➔ IRRAD facility: 24 GeV/c protons from CERN-PS
- Samples in climate box at -20°C



- 27 MeV protons

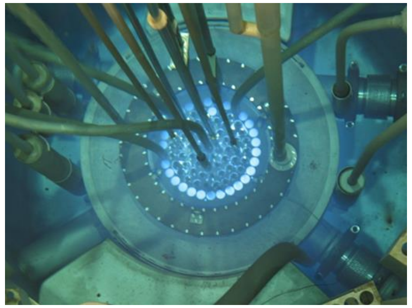
➔ MC40 Cyclotron Facility in Birmingham, UK
- samples in climate box at -27°C

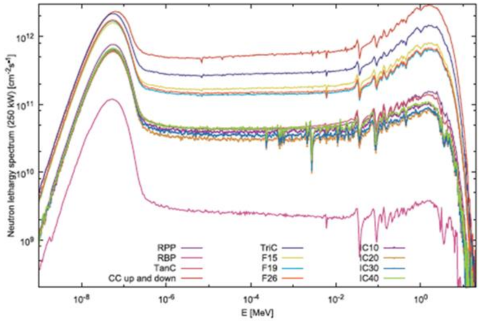


Cold box

- reactor neutrons

➔ TRIGA reactor in Ljubljana, Slovenia
- samples not cooled during irradiation
- temperature of samples ~ 40°C
  - → short irradiation times (max ~15 minutes)
  - → samples in freezer after irradiation

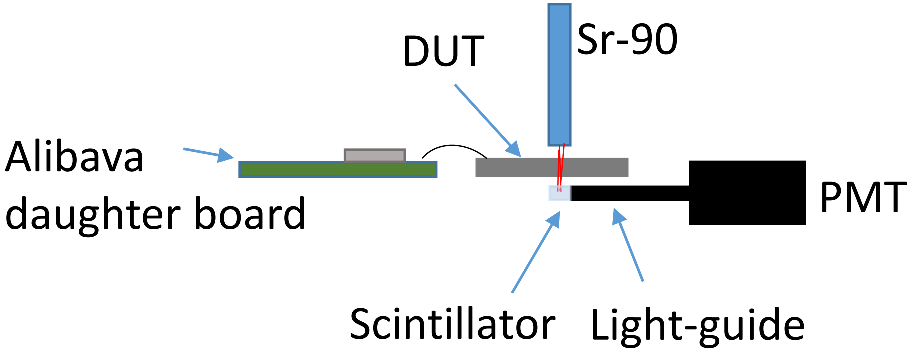




Experimental methods: CCE with Sr-90

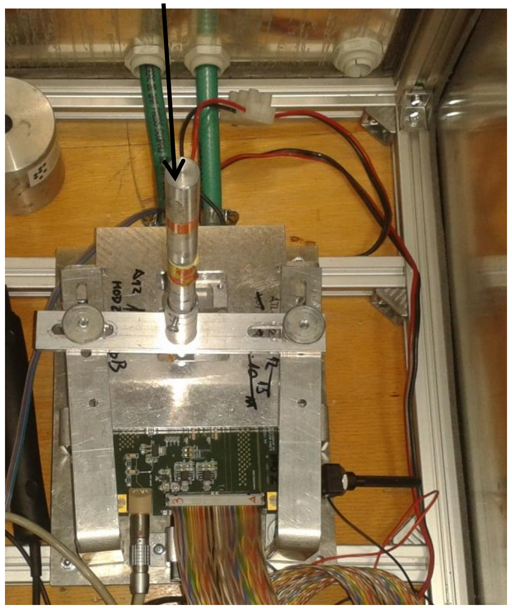
- **Alibava** system based on analogue Beetle chip
  - ➢ https://alibavasystems.com/
- 25 ns peaking time
- 40 MHz clock
- triggering with scintillator
- MPV from fit of Landau + Gauss a measure of collected charge
- convert ADC to electrons via MPV measured with not irradiated detector (77 e-h pairs/µm)

Scheme of the setup:

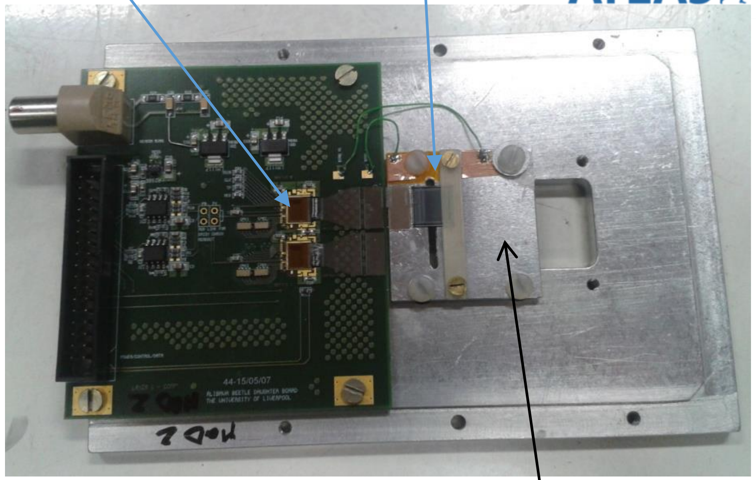


More info about CCE measurements on poster by Y. Huang et al.

Sr-90 Source

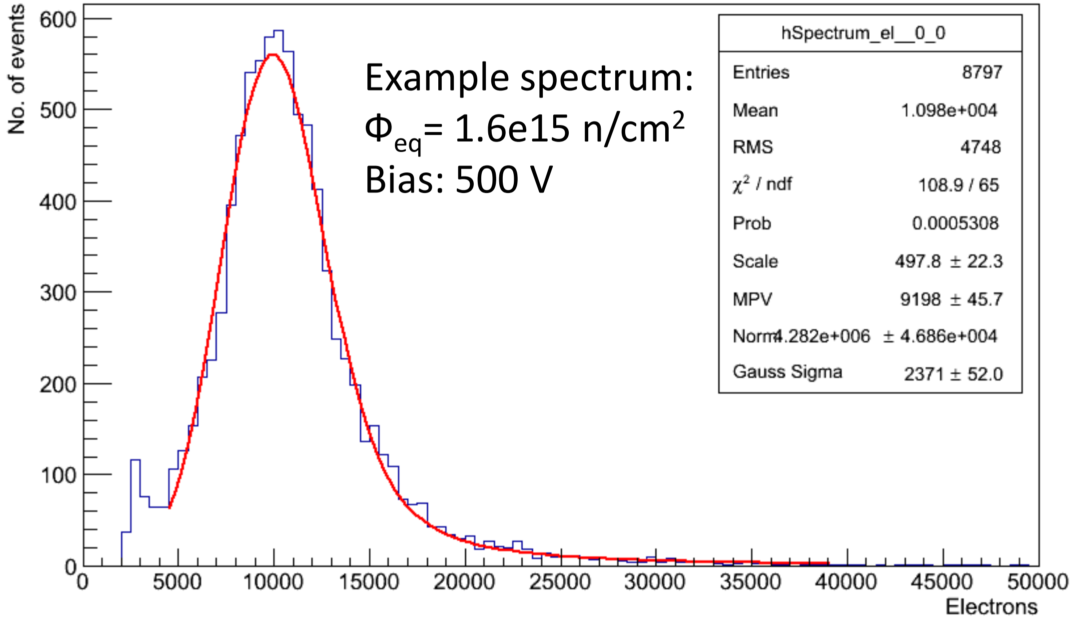


Beetle chip DUT



Al support in thermal contact with cooling block

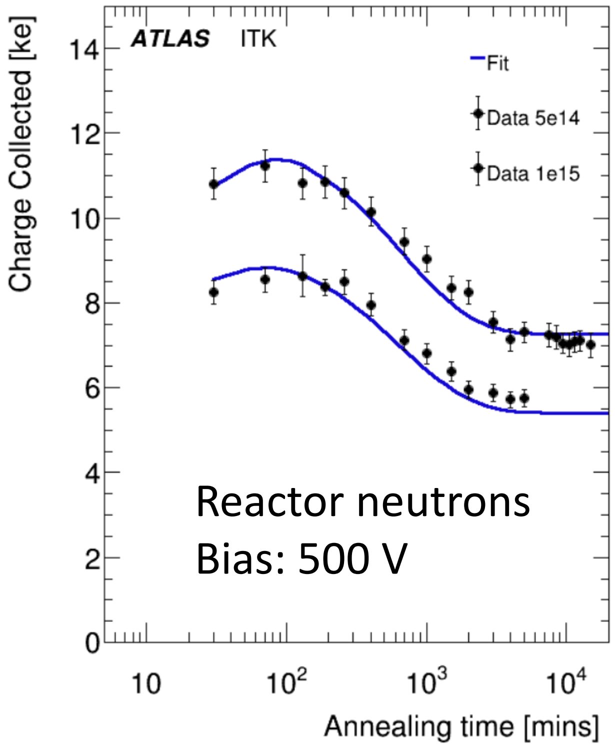
DUT at -20°C

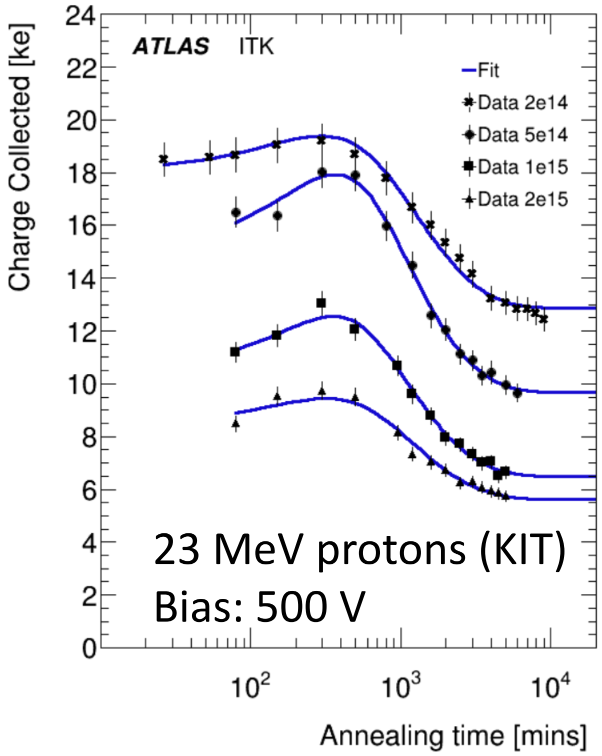


Introduction

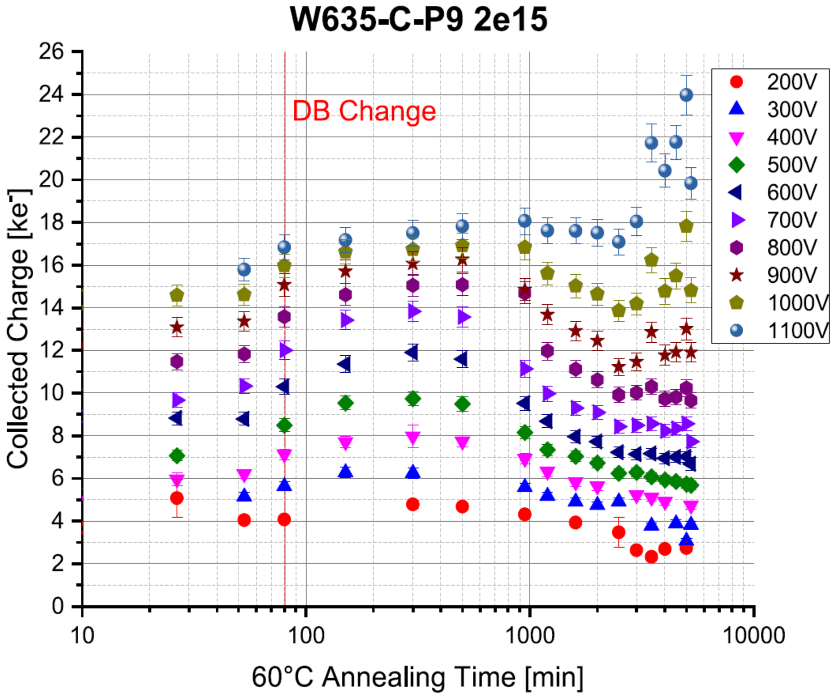
- at bias voltage of 500 V annealing of collected charge in detectors irradiated with reactor neutrons or low energy protons behaves in "usual" way:
  - ➔ beneficial effect of short term annealing followed by loss of CCE because of "reverse" annealing

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





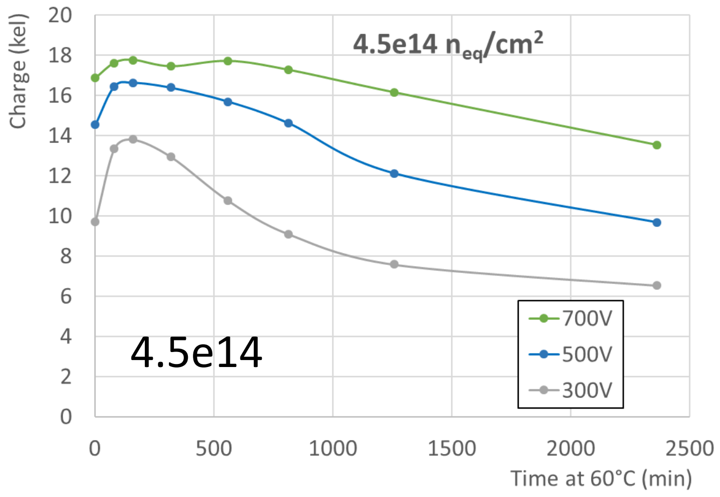
L. Wiik-Fuchs et al., NIMA 924 (2019) 128-132

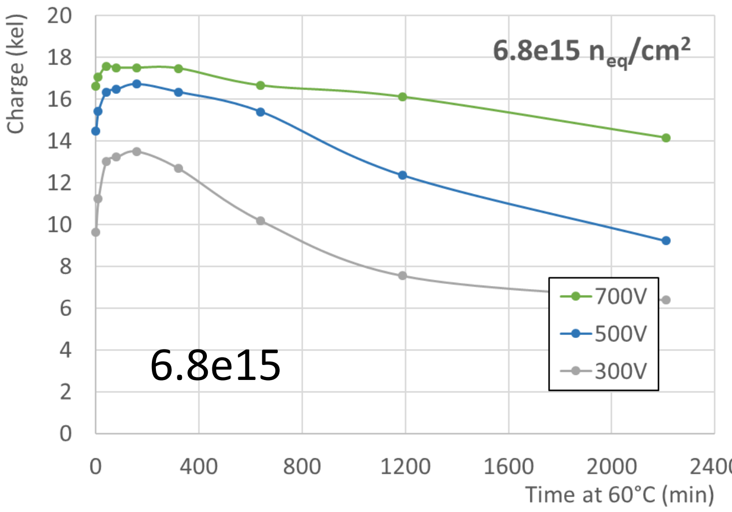


23 MeV protons (KIT), Φ: 2e15 n_{eq}/cm^2

Irradiation with 24 GeV/c protons

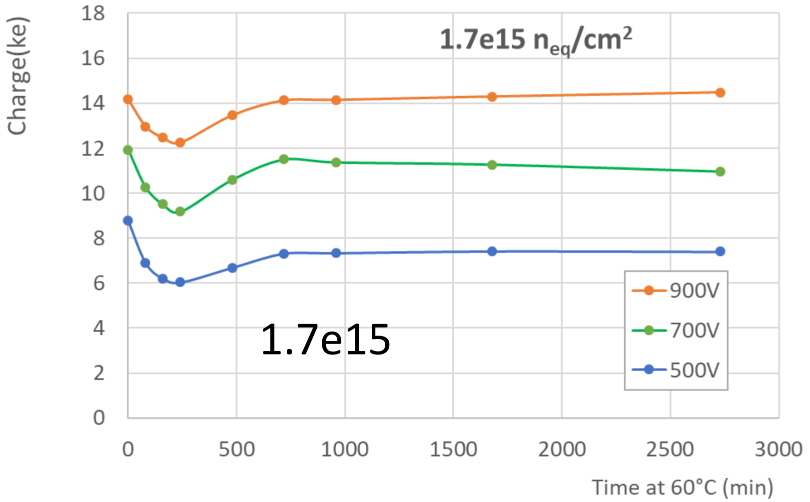
- fluences **4.5e14** and **6.8e15 n_{eq}/cm^2**:
  ➔ "**usual**" annealing behavior

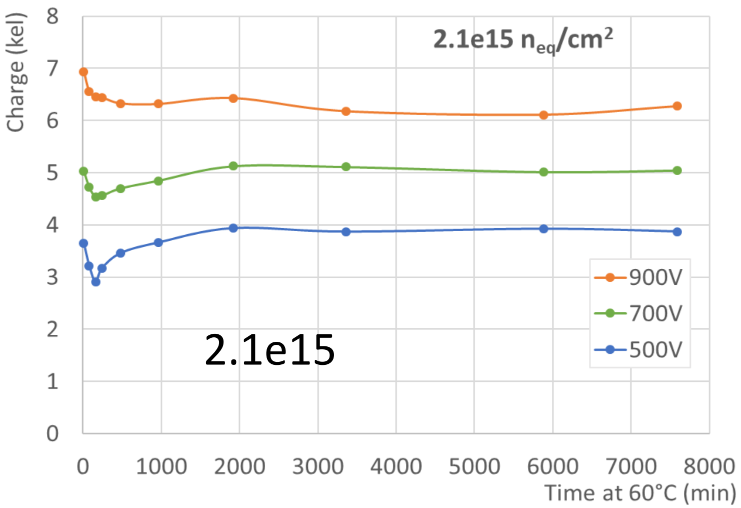




- **1.7e15** and **2.1e15 n_{eq}/cm^2** :
  ➔ **"unusual"** drop of charge after short annealing times

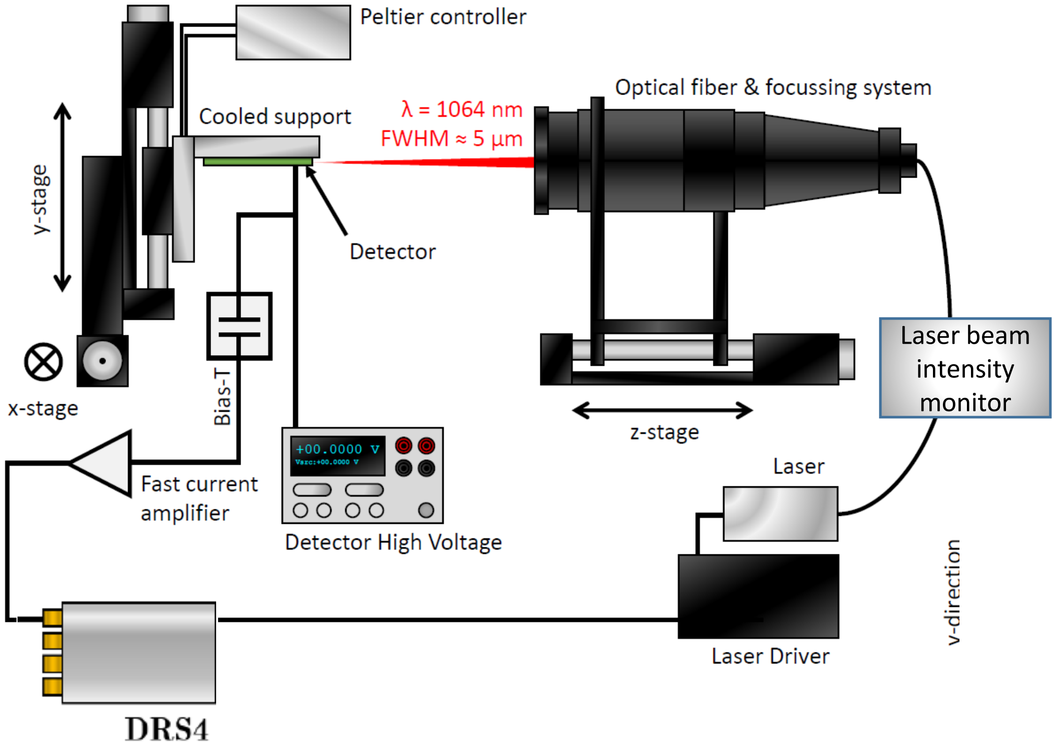
➔ **investigate with E-TCT!**



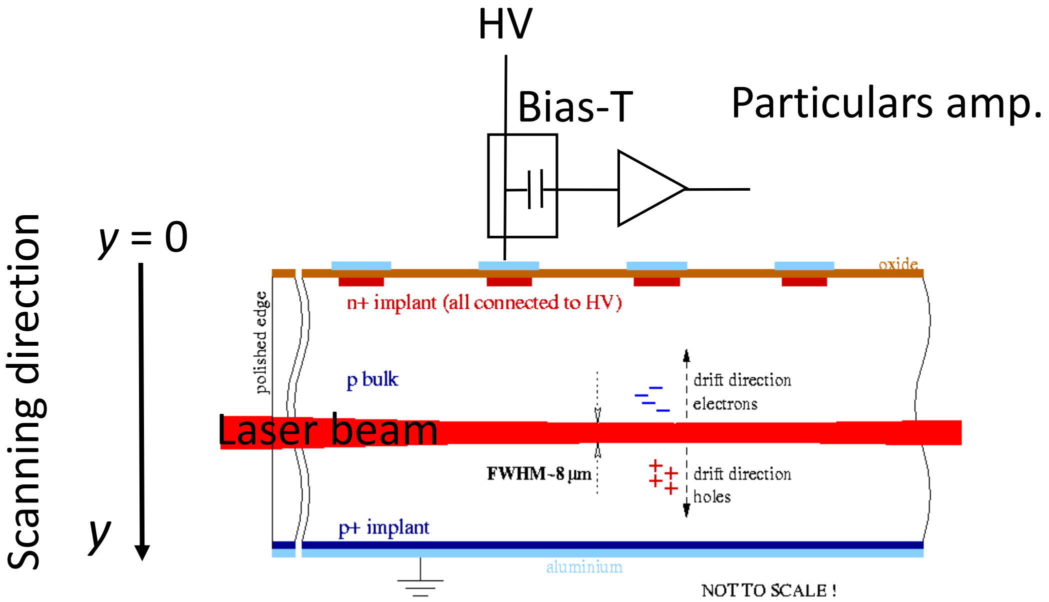


Experimental methods: E-TCT

- short pulses of IR laser (1084 nm) light
- System by www.particulars.si



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



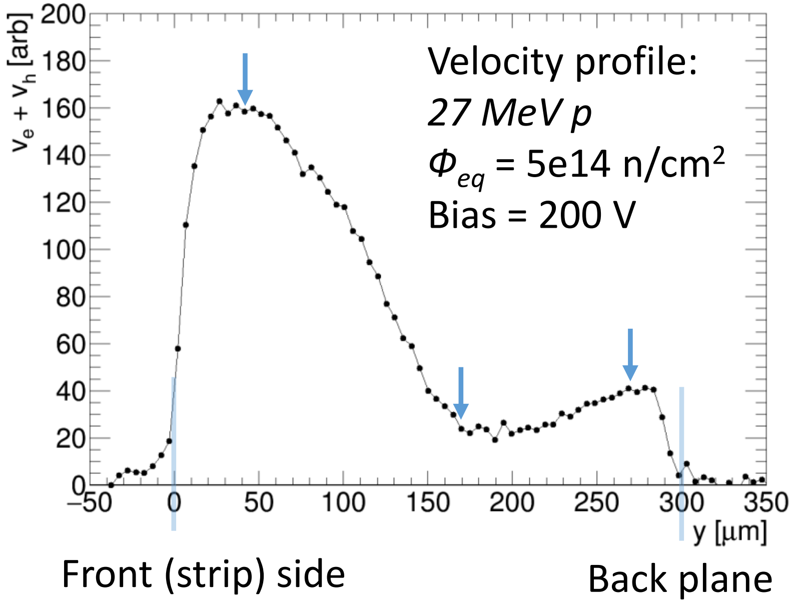
E-TCT velocity profile:

- induced current at $t \sim 0$ (**prompt current**) is proportional to carrier velocity at the location (depth - coordinate y) of laser beam:

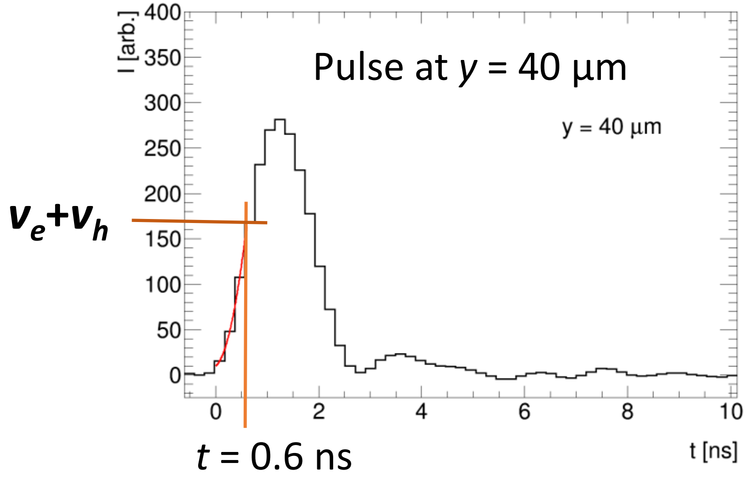
$$I(y,t\sim 0) \approx qE_w\left[\bar{v}_e(y)+\bar{v}_h(y)\right]; \quad \bar{v}_e(y)+\bar{v}_h(y) \propto E$$

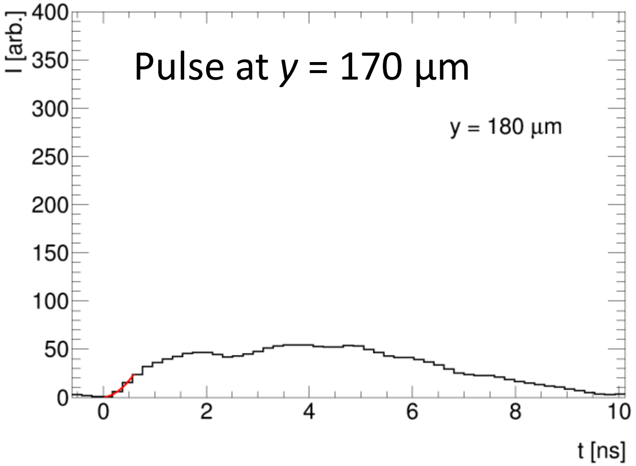
- E_w ~ constant (see: [G. Kramberger, et al.,IEEE Trans. Nucl. Sci. NS-57 (2010) 2294](#).) [R. Klanner , et al., Nulc. Instr. and Meth. A 951 (2020) 162987](#).
- if ***E*** not too high, prompt current ***I*** roughly proportional to ***E***

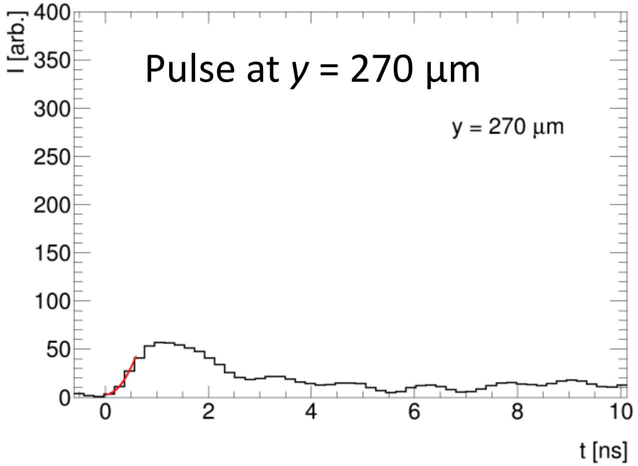
➔ in this work: $\boldsymbol{v_e+v_h\ (y) = I\ (0.6\ \text{ns})}$ **[arb. units]**



Induced current pulses:





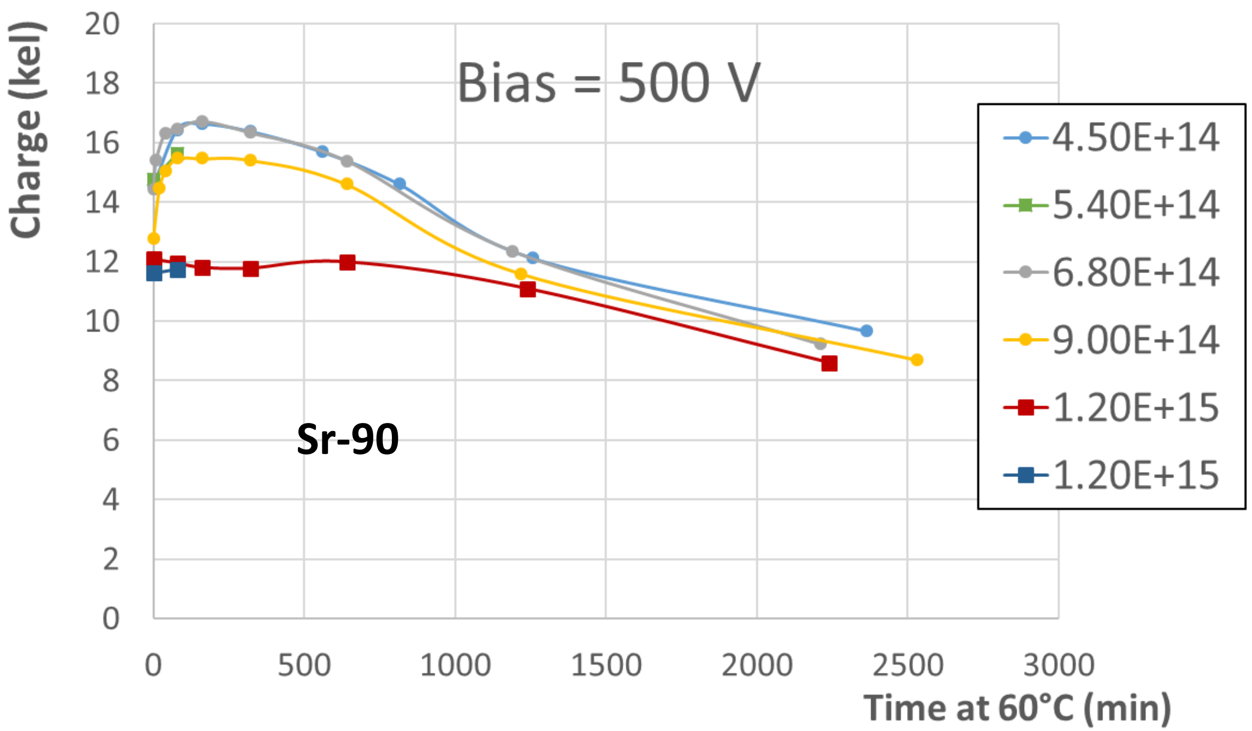


CCE, 24 GeV/c protons

- E-TCT measurements made with samples irradiated at IRRAD in 2023
- more details about irradiation setup in: ATL-ITK-PROC-2025-002, submitted to NIMA

- **fluence < 1.2e15 n_{eq}/cm^2** : annealing at 60°C up to few hundred minutes beneficial for CCE followed by drop of CCE at longer annealing times ➔ **"usual"** annealing

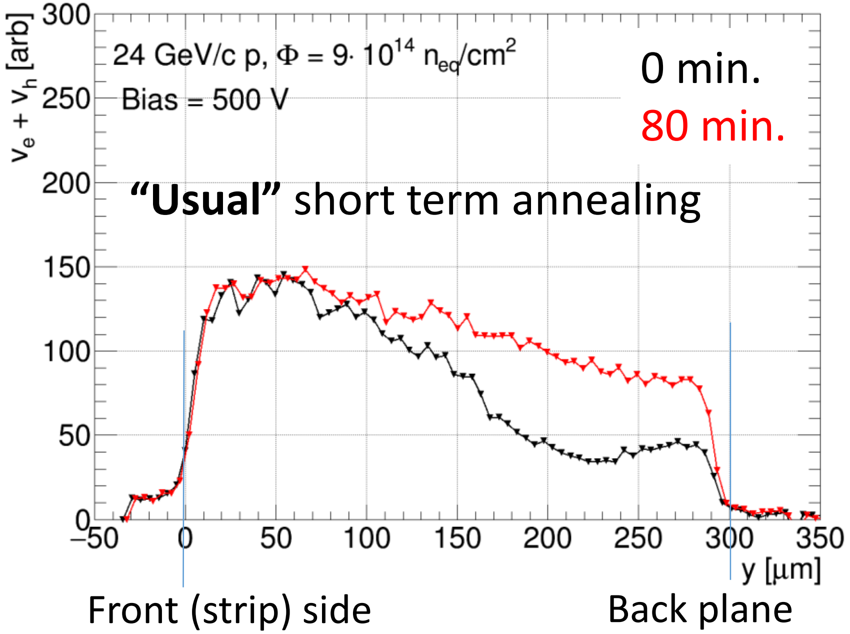
- **fluence ~ 1.2e15 n_{eq}/cm^2** : no beneficial effect of annealing at 60° ➔ **"unusual"** annealing



E-TCT 24 GeV/c protons

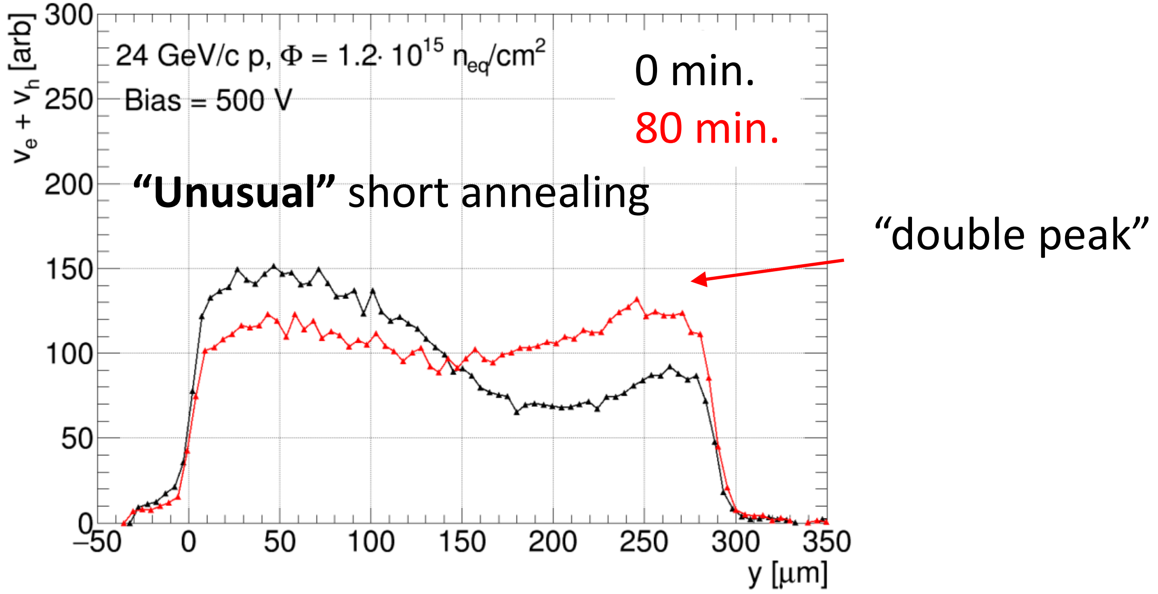
- **"usual" annealing →** increase of "depletion" depth (front peak width) after 80 minutes at 60°C
- **"unusual" annealing** → "**double peak"** velocity profile
  → after annealing for 80 minutes at 60°C: lower front peak and increased back peak

E-TCT 24 GeV/c, **9e14 n_{eq}/cm^2**, 500 V



- annealing beneficial for CCE measured with ^{90}Sr

E-TCT 24 GeV/c, **1.2e15 n_{eq}/cm^2**, 500 V



- annealing may result in lower CCE

Double peak

- double peak electric field profile in Si detectors after irradiation is a known phenomenon:

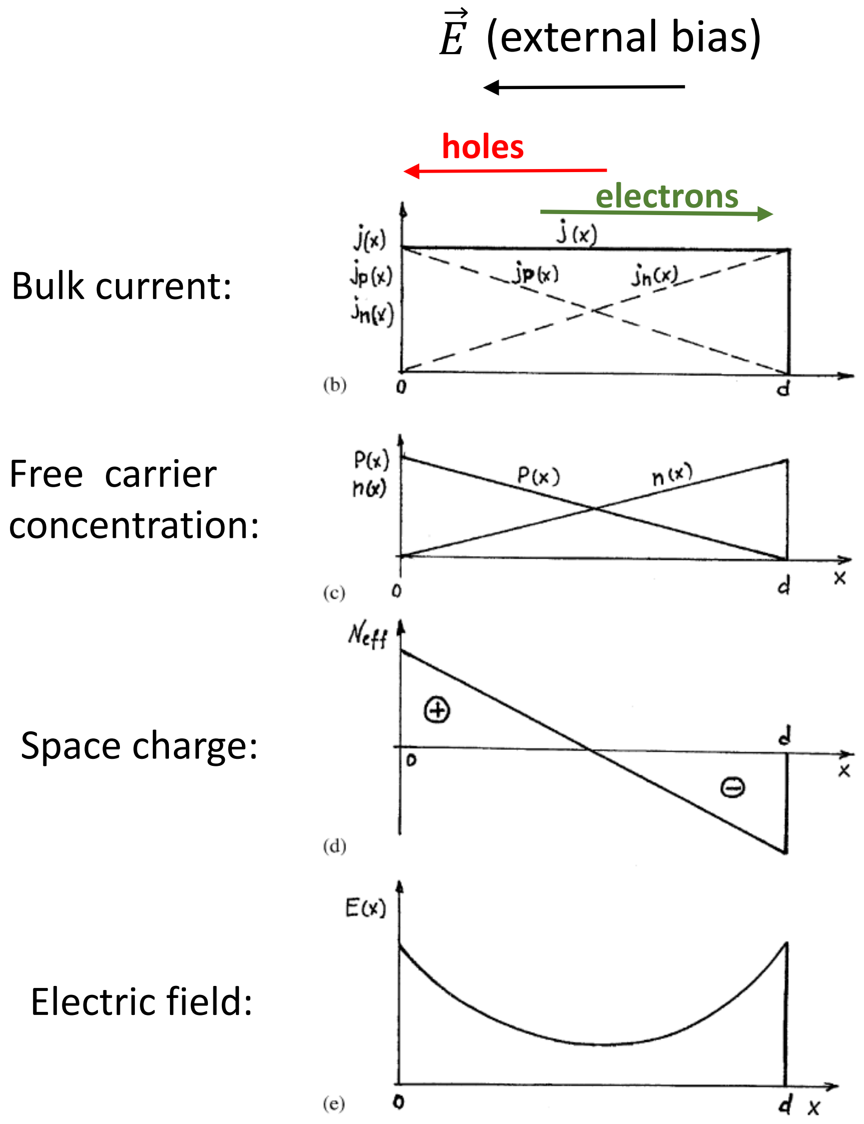
  [1] V. Eremin, E. Verbitskaya, Z. Li, NIM A 476 (2002) 556–564
  [2] V. Chiochia et al., NIM A 568 (2006) 51–55
  [3] G. Kramberger et al. 2014 JINST 9 P10016
  [4] several other publications…

Origin of double peak as explained in [1]:

- free carriers thermally generated uniformly in depleted region

- because of external bias electrons and holes drift in opposite directions → distribution of free electrons and holes not uniform

- electrons and hoes get trapped on radiation induced energy levels
  → space charge not uniform
  → space charge in depleted silicon polarized
  → shape of space charge depends on concentrations and properties of electron and hole traps

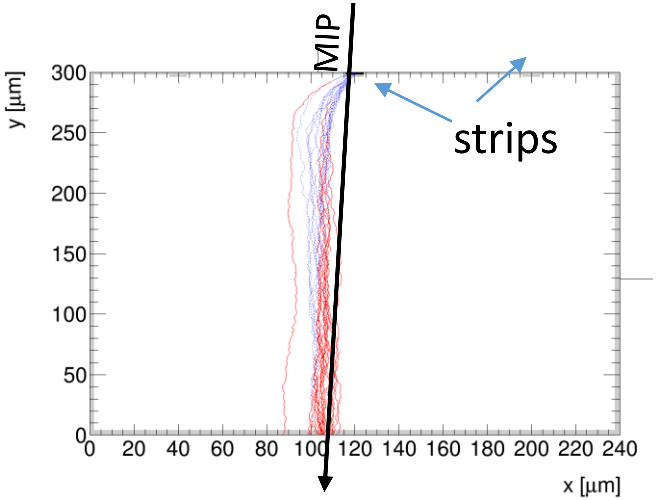


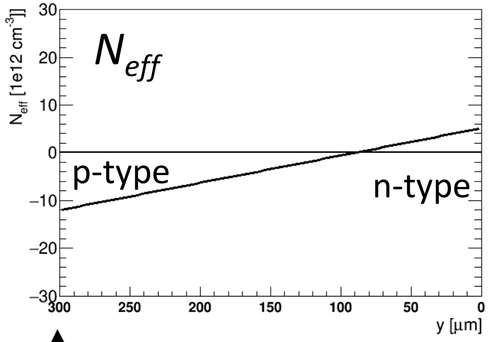
Simple simulation exercise (kDetSim)

- U = 500 V
- Φ_{eq} = 1.2e15 n_{eq}/cm^2
- β = 3.4e-16 cm^2/ns (trapping constant)
- $\tau_{eff} = 1/\beta \cdot \Phi_{eq}$ = 2.5 ns (effective trapping time)
- g_c = 0.01 cm^{-1}

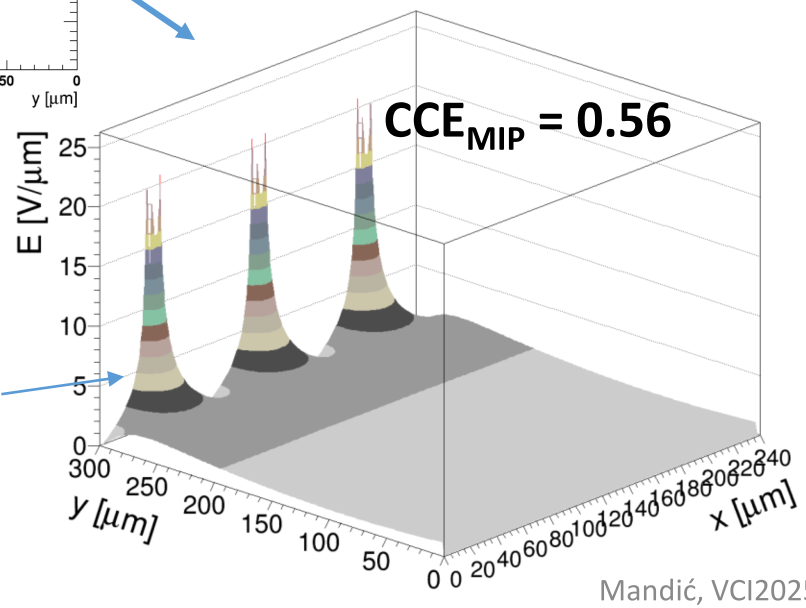
→ shape of ***N_{eff} (y)*** is the input to the simulation
(note: **N_{eff} parameters are arbitrary, only to illustrate the effect!)**

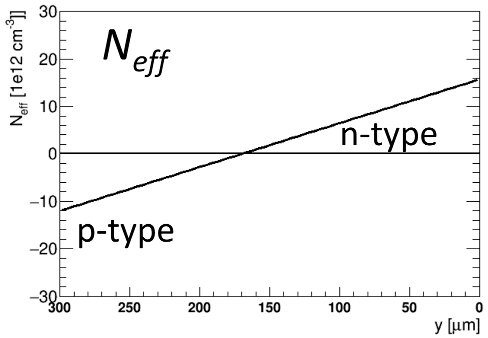
- kDetSim simulation of a MIP crossing 300 µm thick Si strip detector



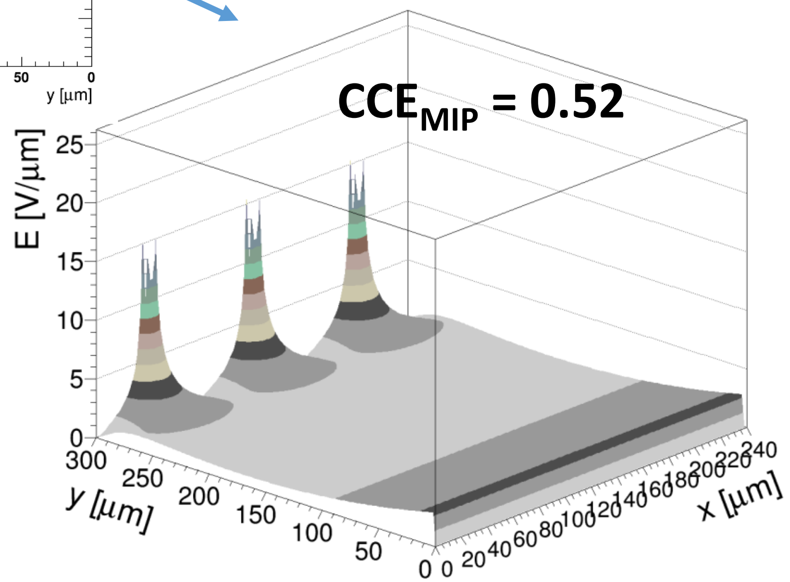


strip side





➔ **higher field at the back may result in lower CCE**

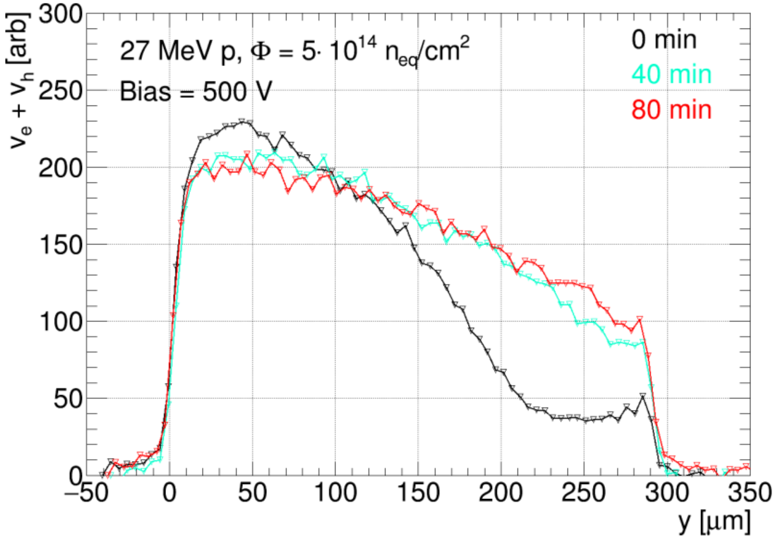


E-TCT 27 MeV protons

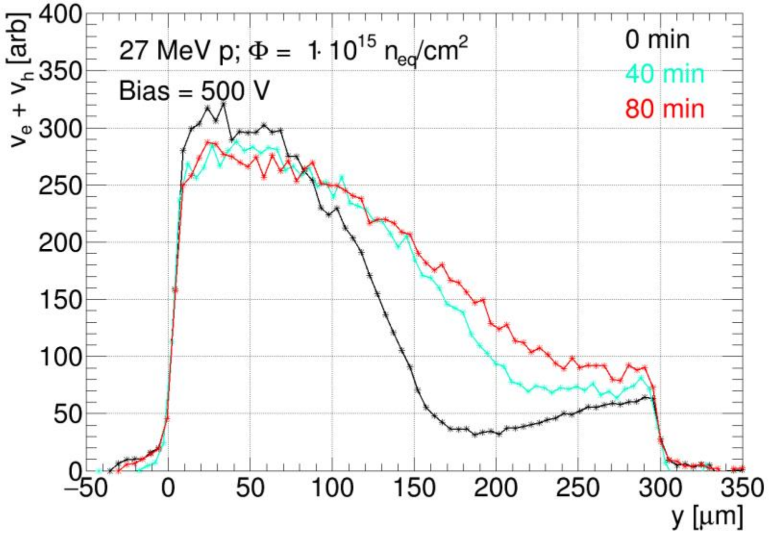
- significant beneficial effect of short term annealing ("usual" increase of depletion depth)
- most of annealing effect already after 40 minutes at 60°C

➔ double peak is seen before annealing but back peak much smaller than for 24 GeV/c protons
➔ beneficial short term annealing of charge collection is measured also with ^{90}Sr

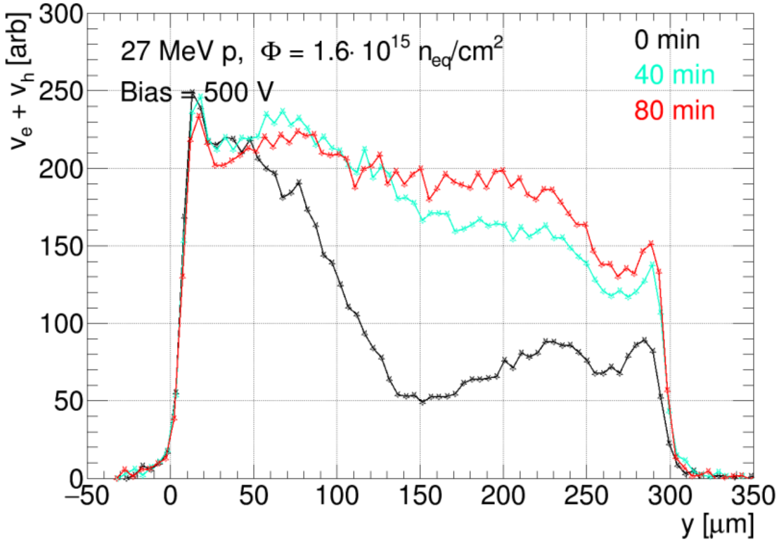
5e14 n_{eq}/cm^2



1e15 n_{eq}/cm^2



1.6e15 n_{eq}/cm^2



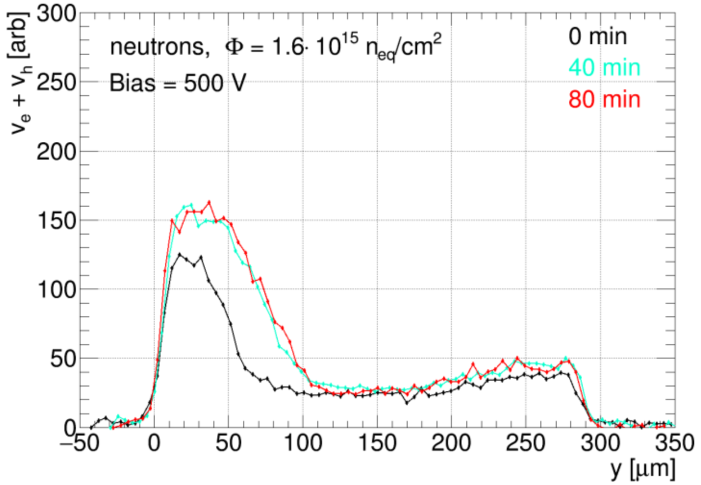
Neutrons and mixed irradiation

- **neutrons, Φ_{eq} = 1.6e15 n/cm^2**

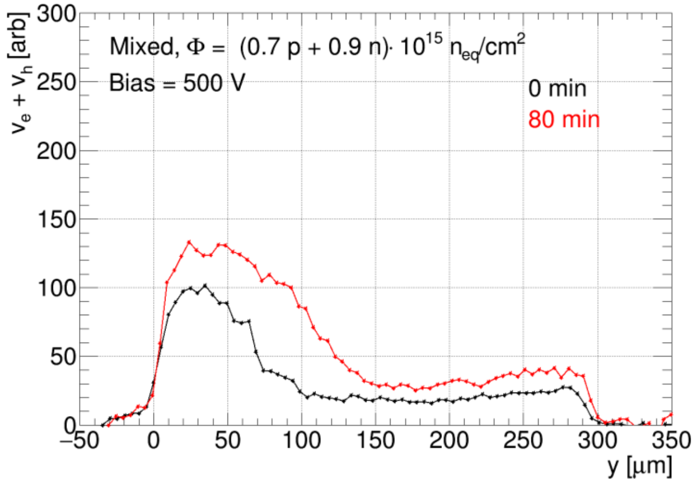
- **mixed irradiation**:
  - sample irradiated with **7.2e14 n$_{eq}$/cm^2 24GeV/c protons** was irradiated with **8.8e14 n$_{eq}$/cm^2 neutrons** in the reactor:
    ➔ total fluence **Φ_{eq} = 1.6e15 n$_{eq}$/cm^2**
  - more than 50% of bulk damage in ATLAS ITk strip detector will be caused by neutrons, the rest by charged hadrons
  - the largest expected fluence of charged hadrons: **~ 7e14 n$_{eq}$/cm^2**

➔ double peak not significant
➔ increase of front peak width ("depletion" depth) after short term annealing
➔ short term annealing beneficial for CCE measured with ^{90}Sr

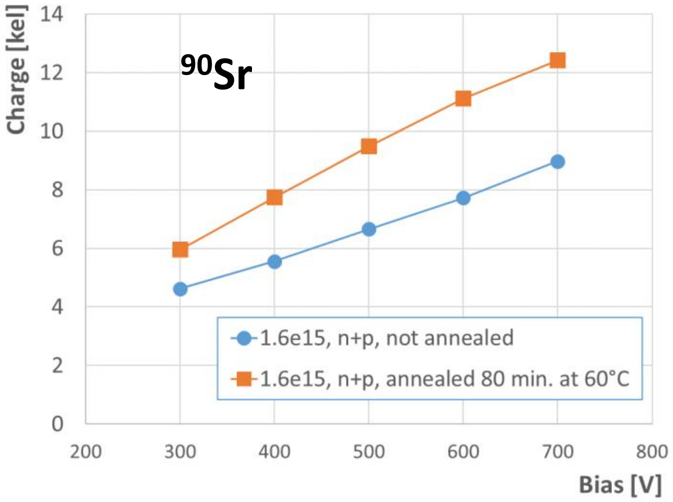
Neutrons 1.6e15



Mixed p+n, 1.6e15

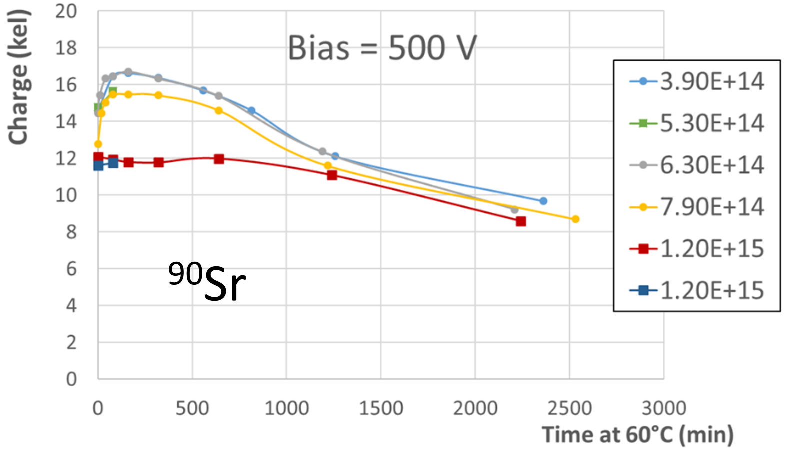


Mixed p+n, 1.6e15

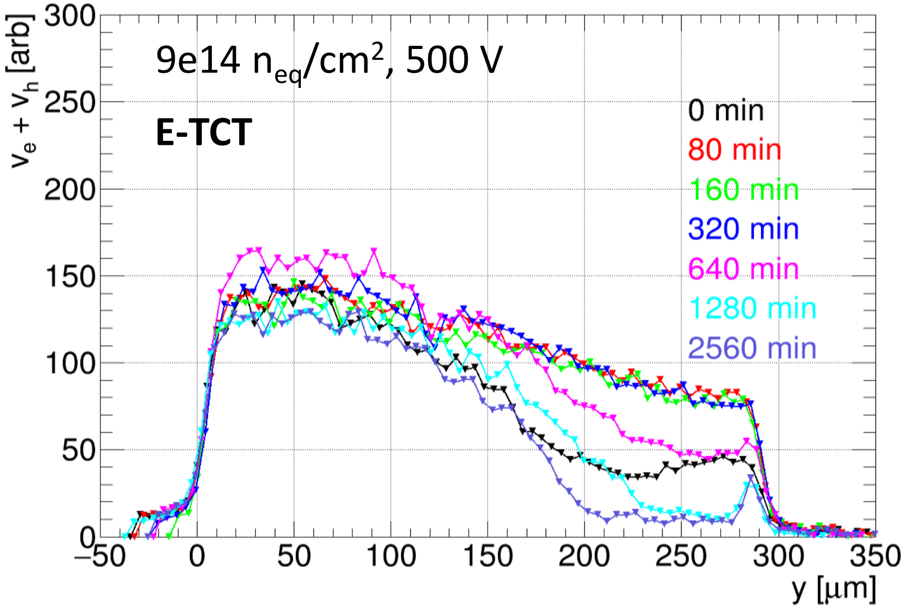


Longer annealing times: 24 GeV/c protons

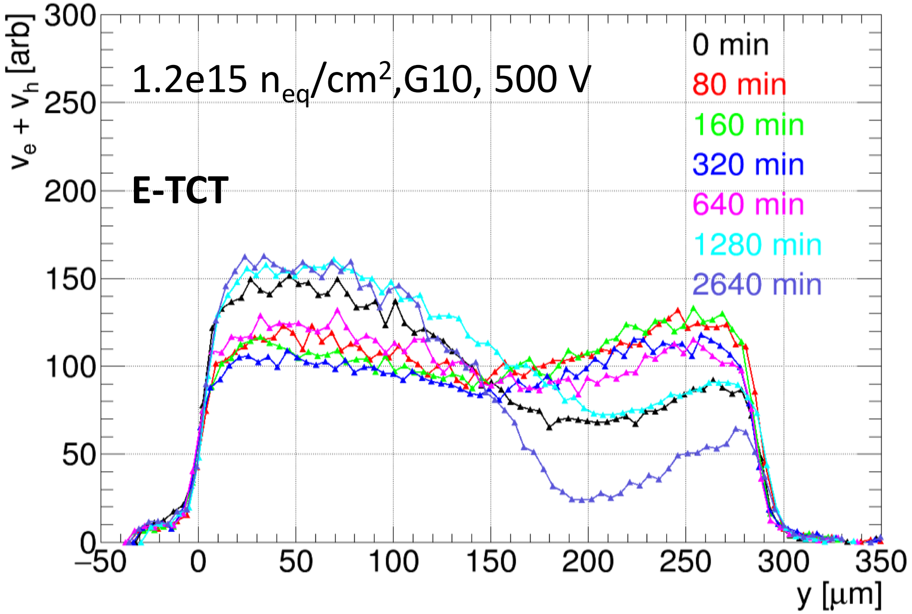
- annealing times longer than ~ 600 minutes at 60°C
  → field at the back starts to drop
- CCE measured with ^{90}Sr also starts to fall at about this annealing time



Low fluence (usual short term annealing)



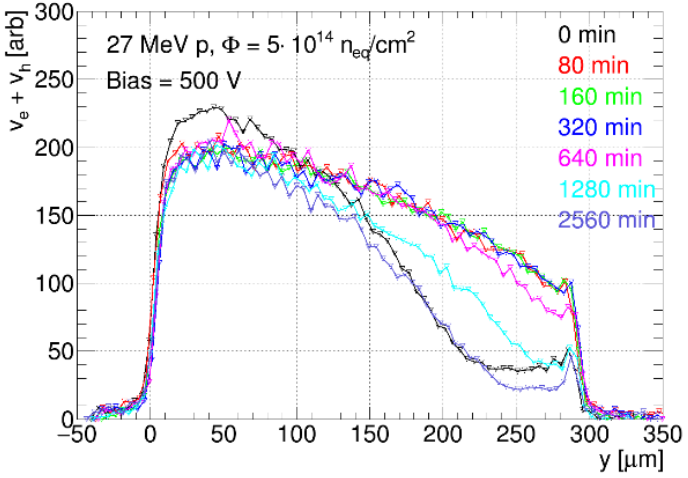
High fluence (unusual short term annealing)



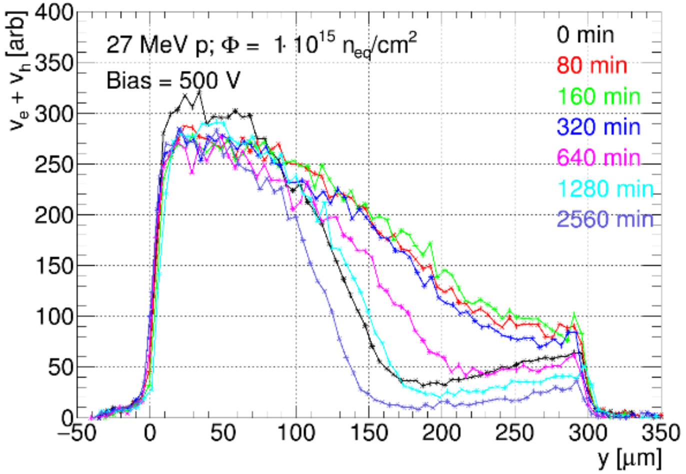
Longer annealing times: 27 MeV p, neutrons, mixed n+ 24 GeV/c p

- significant drop of depletion depth at annealing times longer than 600 minutes at 60°C

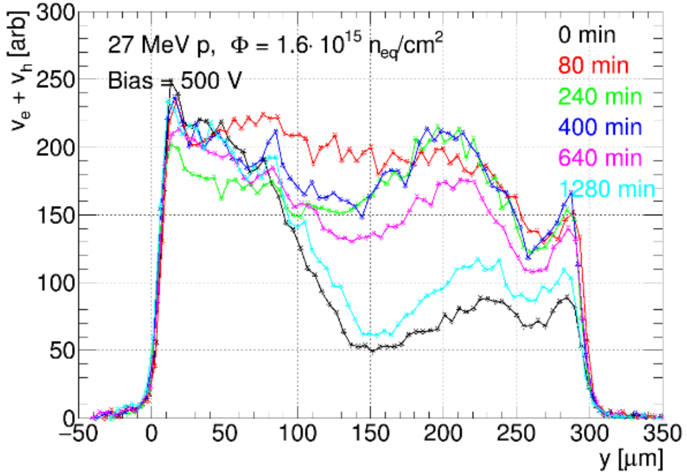
27 MeV p, 5e14



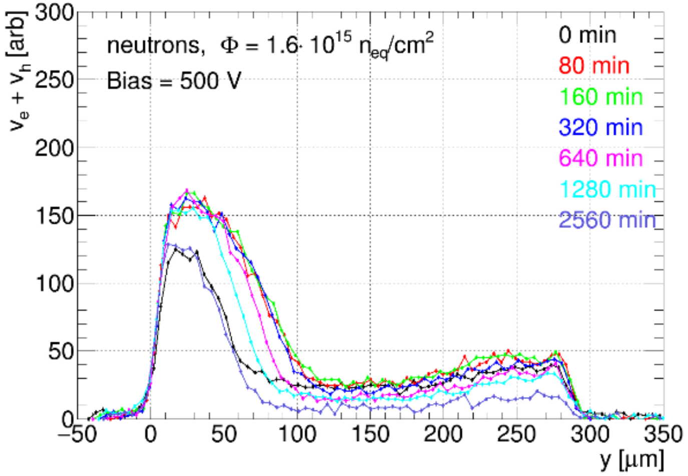
27 MeV p, 1e15



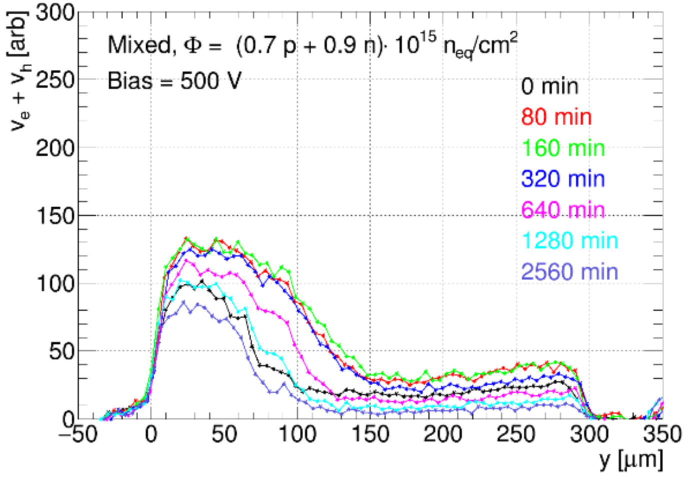
27 MeV p, 1.6e15



Neutrons, 1.6e15



Mixed n+p, 1.6e15



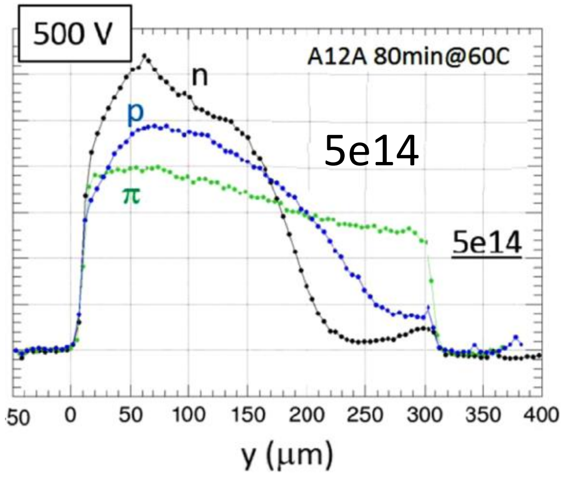
- CCE measured with ^{90}Sr starts to fall after about 600 min at 60°C
  ➔ consistent with E-TCT

Discussion

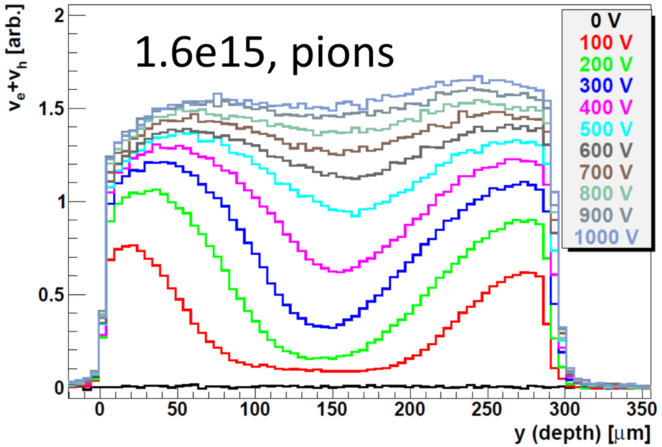
- shape of velocity profile depends on irradiation particle type
  - neutrons, low energy protons: front peak dominant, back peak smaller
  - higher fluences of 24 GeV/c protons or 190 MeV pions: double peak

- shape of velocity profile depends on composition of space charge (concentrations of donors and acceptors)
  - ➔ introduction rates of donors and acceptors depend on irradiation particle type
  - ➔ shape of space charge and electric field depends on free carrier concentration (bulk current)
  - ➔ different defects anneal at different rates
    - → annealing behavior of velocity profiles and CCE depends on irradiation particle type, energy and fluence

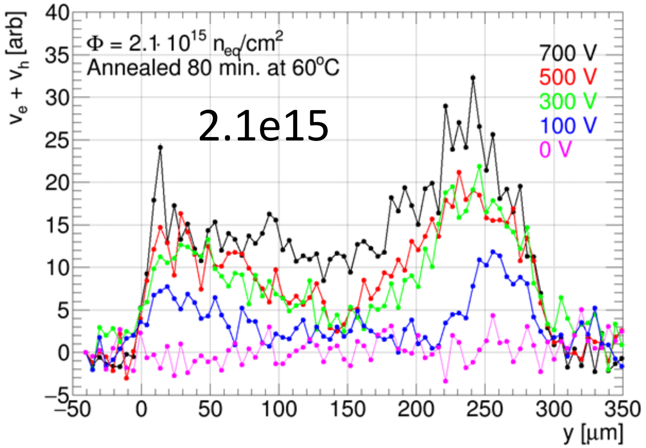
Hara et al., NIMA 831 (2016) 181–188
ATLAS12,
neutrons, 23 MeV p, 190 MeV pions:



G. Kramberger et al. 2014 JINST 9 P10016
ATLAS07, 190 MeV pions:



This work
ATLAS18 24 GeV/c protons



Discussion

ATLAS ITk

- neutrons and protons cause different damage in silicon, differences depend on material type (FZ, DOFZ, MCz, Epi ..)
  - see e.g.: I. Pintilie et al., NIMA 611 (2009) 52

- damage can depend also on energy of protons:
  - A. Junkes et al., 2014 IEEE NSS/MIC

- DLTS with samples from **ATLAS18** wafers after irradiation with low and high energy protons
  - differences are observed
    - ➔ see poster by **C. Klein**

- annealing of V_{fd} and CCE depend on detector material and irradiation particle and type:
  - W. Adam et al. 2020 JINST 15 P04017
  - G. Kramberger et al. NIMA 609 (2009) 253

➔ **“unusual” annealing effects measured with ATLAS18 (FZ, p-type) samples presented in this contribution not reported in literature**

➔ **important to perform irradiation tests with particle of types and energies closest to those in the experiment**

Conclusions

- effects of irradiation of **ALTAS18** detectors with high energy protons are different than effects of irradiation with low energy protons or neutrons to same 1 MeV n equivalent fluence

- after irradiation with neutrons, low energy protons or low fluences of 24 GeV/c protons
  ➔ short term annealing (~ 80 min@60°C) results in increased front peak width in E-TCT velocity profile
  ➔ CCE measured with ^{90}Sr increases after short term annealing

- after irradiation with 24 GeV/c protons to fluences higher than **~ 1.2e15 n_{eq}/cm^2** we observe:
  ➔ double peak velocity profile, after short term annealing front peak lower, back peak higher
  ➔ short annealing not beneficial for CCE measured with ^{90}Sr

- long term annealing behavior has similar effect on velocity profiles for all irradiation particle types

- in upgraded **ATLAS** experiment ITk strips will be exposed to **charged hadrons** and **neutrons**
  ➔ max. expected fluence of **charged hadrons** (including safety factors) **~ 7e14 n_{eq}/cm^2**
  ➔ mixed irradiation with **7.2e14 n_{eq}/cm^2 (p)** + **8.8 n_{eq}/cm^2 (n)** = **1.6e15 n_{eq}/cm^2**
    ➔ no significant double peak, usual annealing behavior

- **charge collection of ATLAS ITk strip sensors OK up to highest expected fluences!**

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