Radiation effects of CERN-PS 24 GeV/c protons in ATLAS18 ITk strip sensors

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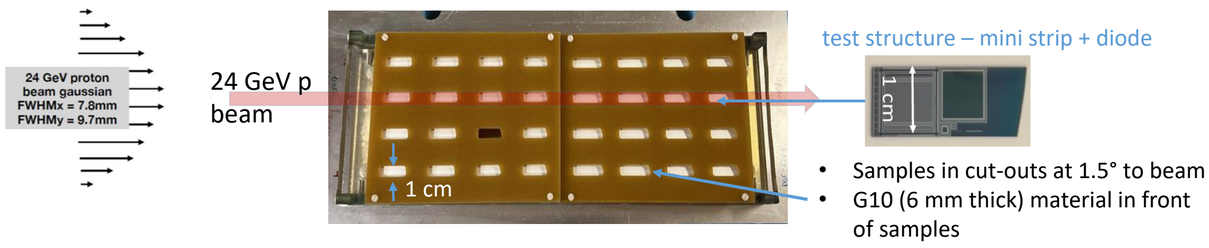
Introduction

- **Strip Sensors in ATLAS ITk requirement:**
  ➔ Collected Charge (***CC***) for a **MIP** at V_{bias} **= 500 V** after irradiation to Φ_{eq} **= 1.6e15 n_{eq}/cm^2 : *CC* > 6350 electrons**

➔ **too low *CC*** measured after irradiation with **24 GeV/c protons at CERN PS** in several experiment



- Samples in cut-outs at 1.5° to beam
- G10 (6 mm thick) material in front of samples

- PS proton beam narrow (FWHMx = 7.8 mm, FWHMy = 9.7 mm) test structures irradiated at shallow angle beam at fixed position, no scanning during irradiation of line of samples ➔ non-uniform irradiation

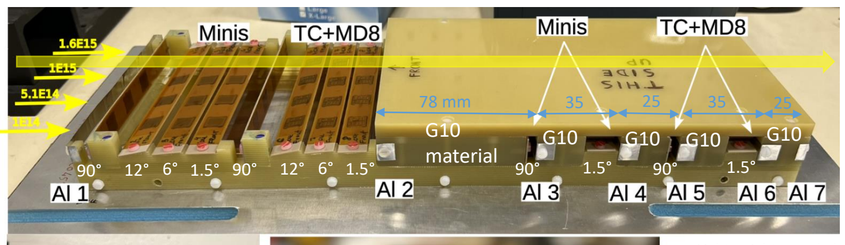
- we suspect two causes: shallow angle and material effects. Simulation indicated that fluences might be larger than planned because of secondaries generated by 24 GeV/c protons in the material of the support structure and in the silicon of test structures due to shallow angle in the beam
  ➔ low CC because true fluences larger than planned

Setup for irradiation in 2023

- test structures (minis, Test Chips and MD8 diodes) cut to 1x1 cm^2
- structures on light weight support at **variable angles** wrt. beam
- G10 (up to ~ 170 mm thickness) material put in front of samples
- 7 layers of aluminium foils ➔ 28 Al pieces cut from the foils for dosimetry
  ➔ proton fluence measured from radioactivity of Na-24 in Al foils after irradiation

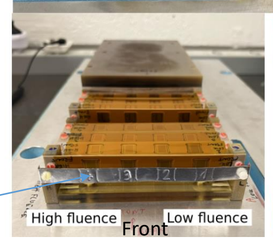
Target fluences:
- 1.0e14 n_{eq}/cm^2
- 5.1e14 n_{eq}/cm^2
- 1.0e15 n_{eq}/cm^2
- 1.6e15 n_{eq}/cm^2

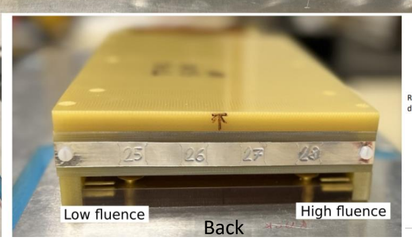
- Beam at fixed positon for each fluence



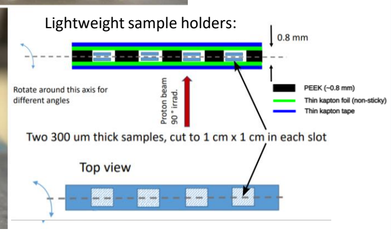
Samples aligned in the 24 GeV p beam

When fluence reached next line of samples moved into the beam



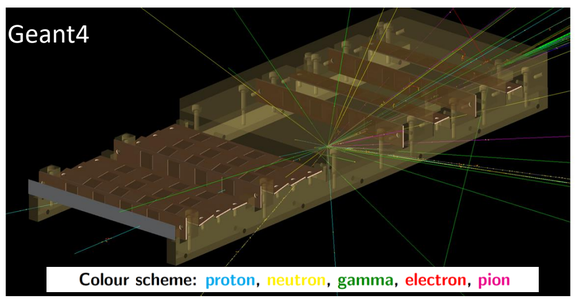


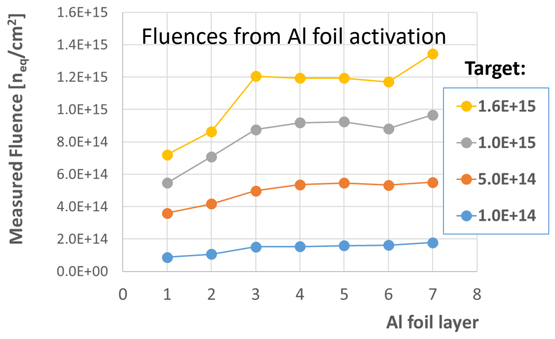
Aluminium pieces cut from the foil

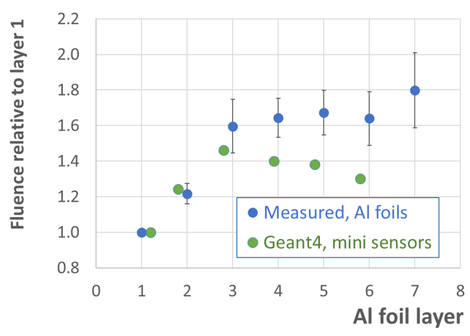


Dosimetry and simulation

- delivered fluence lower than targeted
- **significant increase of fluences by G10 material**
  ➔ leakage current in MD8 diodes confirms the effect
- **Geant4** simulation to calculate NIEL in 6 layers of mini sensors for primary protons and secondary particles
  ➔ increase of NIEL by scattering material confirmed by simulation
  ➔ studies ongoing to understand discrepancies with measurements

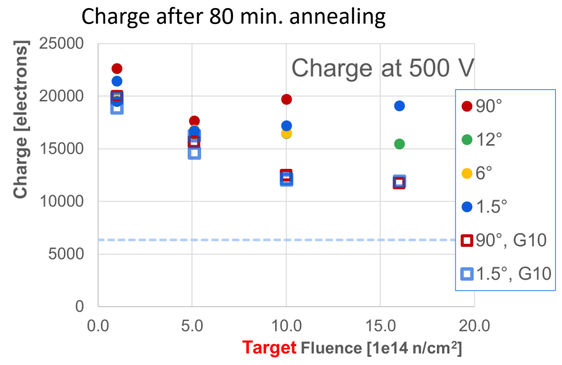


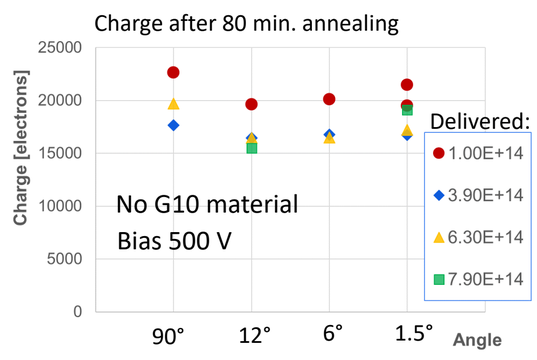




Collected charge

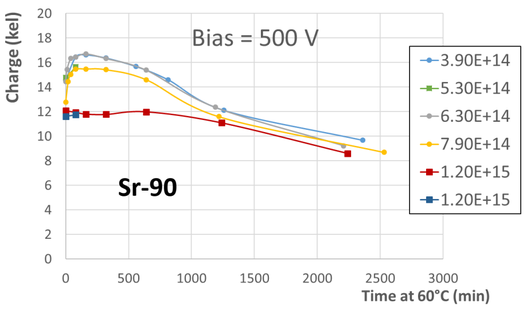
- collected charge measured with Sr-90 source on Alibava system
- charge **well above the QA acceptance level** (6350 el. @500 V)
- significant effect of G10 material ➔ increase of effective fluence
  ➔ lower collected charge than samples at same target fluence but without G10
- effect of angle visible for samples without G10 material around

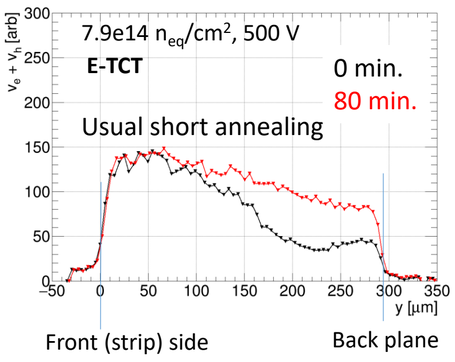


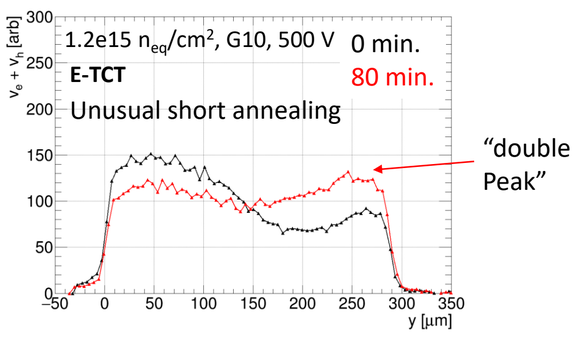


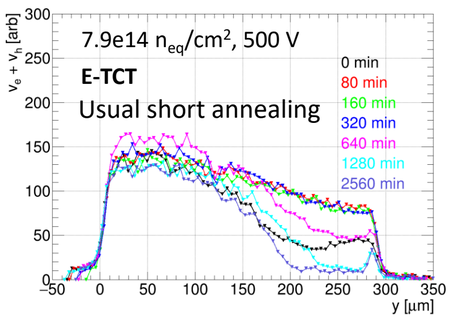
Annealing

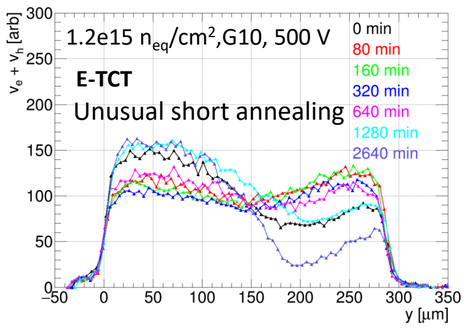
- fluences < 1.2e15 n_{eq}/cm^2 : significant beneficial annealing until up to ~ 200 minutes at 60°C
  ➔ **"usual"**
- fluence ~ 1.2e15 n_{eq}/cm^2 : no beneficial annealing
  ➔ **"unusual"**
- related to "**double peak**" velocity profile measured with **E-TCT**







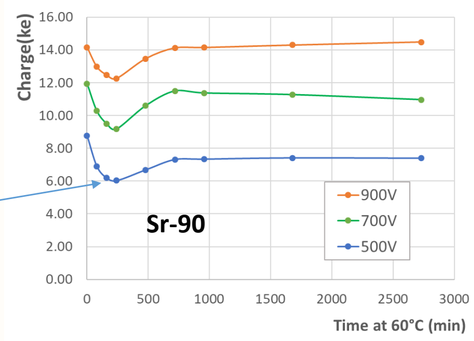




- effects of **long** annealing at 60°C similar for high and low proton fluences
  ➔ depletion depth drops with annealing time

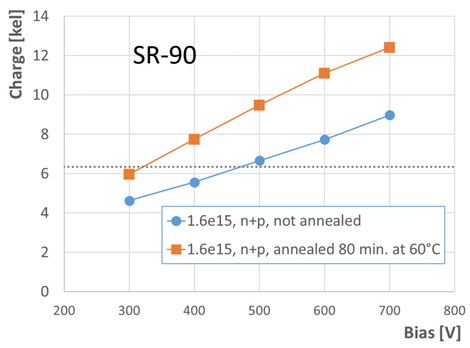
- unusual annealing seen before, irradiation with 24 GeV/c in year 2022 (in IRRAD shuttle)
- 24 GeV/c protons at PS, Φ_{eq} = 1.7e15 n_{eq}/cm^2
- irradiated at **90°**, **no G10** material

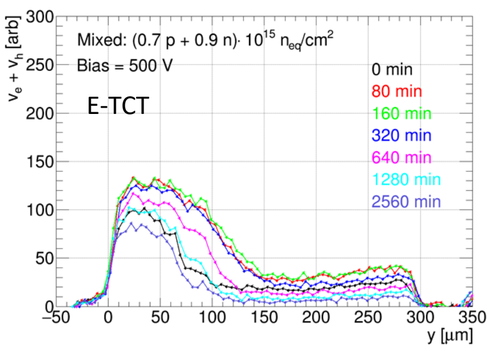
➔ charge **drops** after short annealing
➔ effect may be larger than in the above measurements due to higher fluence



Mixed irradiation

- more than 50% of bulk damage in ATLAS ITK strip detector will be caused by neutrons and the rest by charged hadrons
- the largest fluence of charged hadrons in the most exposed part of detector is **~ 7e14 n_{eq}/cm^2**
  ➔ sample irradiated with **7.2e14 n_{eq}/cm^2 PS protons** was irradiated with **8.8e14 n_{eq}/cm^2 neutrons** in reactor in Ljubljana
  ➔ total fluence Φ_{eq} **= 1.6e15 n_{eq}/cm^2 ,** max. fluence for ATLAS ITk strips after 4000 fb^{-1} (including safety factor of 1.5)





- collected charge above QA acceptance level, charge increases with annealing
  ➔ E-TCT: usual annealing behavior, no significant double peak
  ➔ double peak and unusual annealing related to **proton** fluence , not **total** fluence

Conclusions

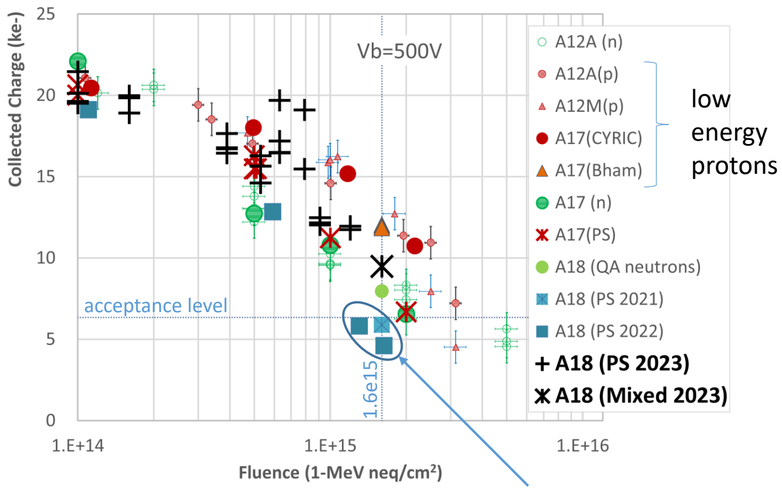
- scattering in the material of irradiation support structure and geometrical effect in narrow beam can significantly increase effective fluences to which samples are exposed

- effects of irradiation with fast charged hadrons different than neutrons, so at high fluence we observe:
  ➔ double peak electric field profile seen with E-TCT ➔ lower collected charge
  ➔ unusual annealing behavior
  ➔ effects significant at 24 GeV proton fluence above **~ 1.2e15 n_{eq}/cm^2**

- in ATLAS 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**
  ➔ high charge collection and usual annealing behavior
  ➔ double peak and unusual annealing related to **proton** fluence, not **total** fluence

- charge collection of ATLAS ITk strip sensors good up to highest fluences



Points added to the plot from
K. Hara et al., NIMA 983 (2020) 164422

low charge because of:
- uncertain fluences due to support material and shallow angle,
- effects of 24 GeV/c protons (PS) at high fluences

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