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Characterisation of the University of Birmingham Proton Irradiation Facility

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Overview

- Introduction of the University of Birmingham's MC40 cyclotron facility – typical performance in irradiations for detector R&D.

- Characterisation Studies:
  - Geant4 simulation of the irradiation beamline.
  - Proton hardness factor for different beam energies via irradiation of silicon diodes.

The MC40 Cyclotron Facility

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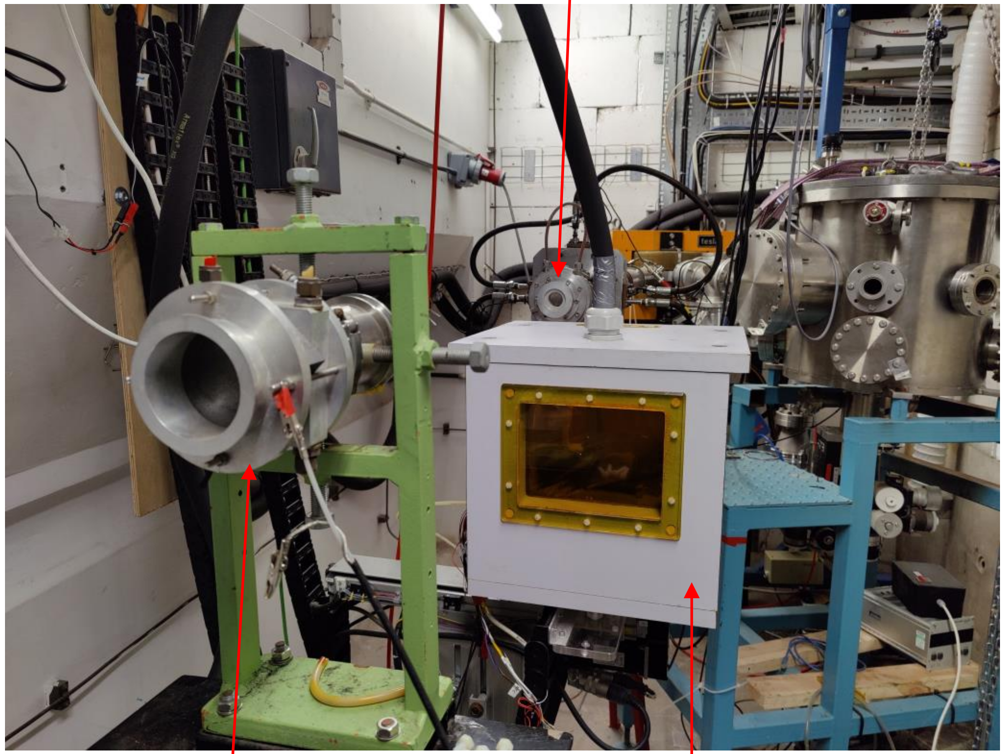
- The MC40 cyclotron facility at the University of Birmingham is primarily used for radioisotope production for medical applications. It is also involved with several research programs.
- Usually proton beams but can deliver deuterons and helium isotopes.
- Proton beam energy ranges from 2 – 38 MeV.
- Proton beam currents up to a few µA.

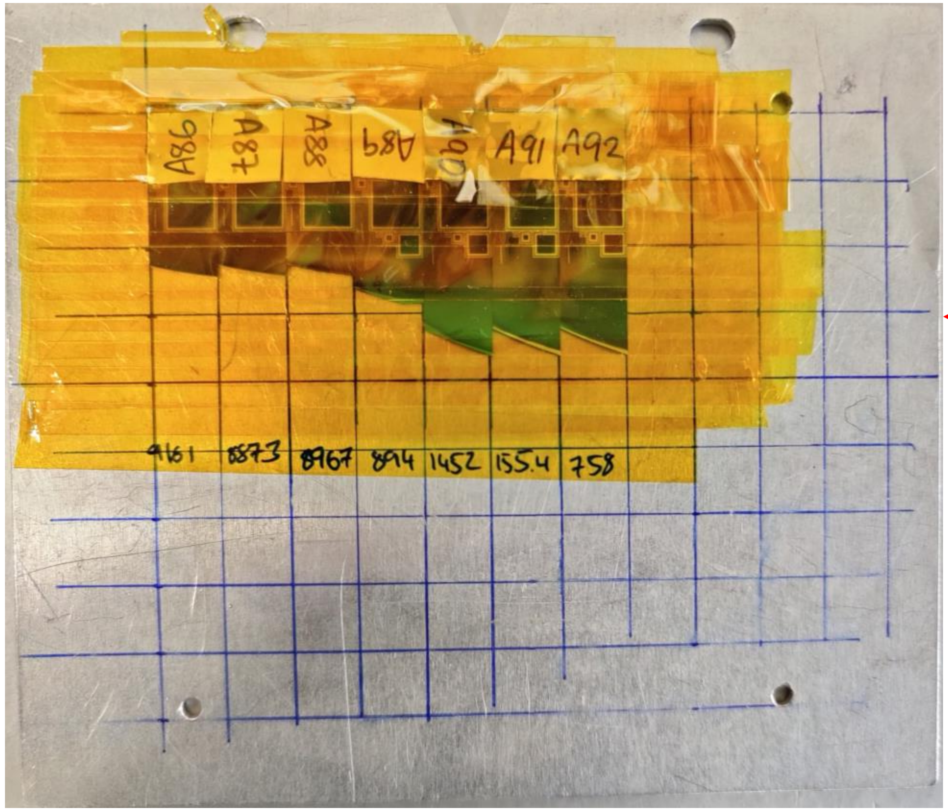
Detector R&D Irradiation Line

- Typically run with **27 MeV** proton beam at a current of **200 nA.**
  - Enables a few $\mathbf{10^{15}\ n_{eq}/cm^2}$ to be delivered to a small area of samples (~ 10 cm^2) in one day.
- Samples are housed in a climate box.
  - Maintained at -27°C via liquid nitrogen evaporative cooling.
  - Relative humidity < 10%.
- Beam is collimated into approximately a 10 x 10 mm^2 square with roughly uniform intensity.
- Box sits on an XY stage. For most irradiations, a **grid scanning pattern** is used to deliver a uniform fluence across the samples.
- During irradiation, beam current is monitored via Faraday cup.
- Offline dosimetry is performed using nickel foil (details in backup).

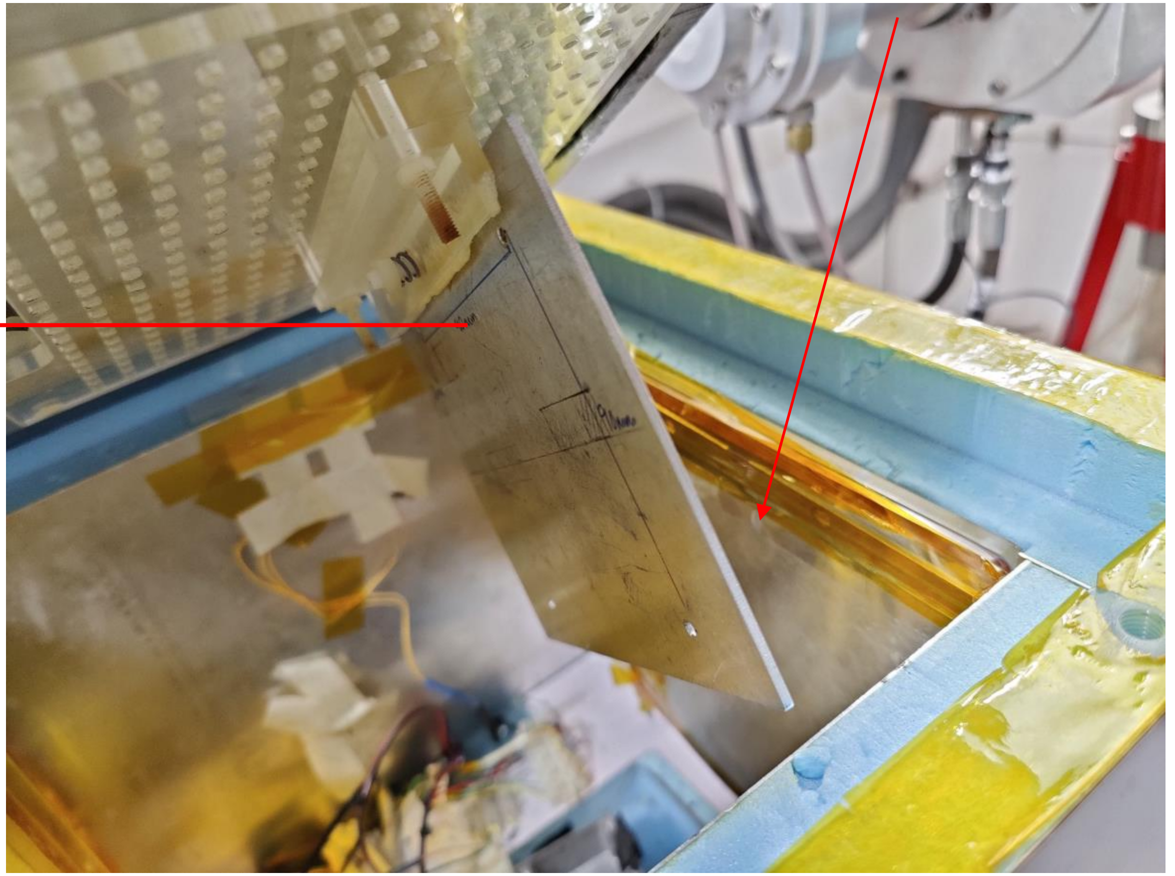


Detector R&D Irradiation Line

Irradiation samples and nickel foils attached to a 2mm thick aluminium plate. A single layer of kapton tape separates the samples from the plate and foils.



A view of the inside of the irradiation box: sample holder attachment point and 0.3 mm thick aluminium plate to filter low energy components.



Characterisation of the Irradiation Line

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- Seek to evaluate the performance of the cyclotron for R&D irradiations and compare to expected performance.

- Two complementary investigations:

1. **Simulation of the Irradiation Line using Geant4**
   - Beam energy attenuation: understand the effects of upstream material on the proton energies before they hit the sample which would otherwise be difficult to compute analytically.
   - Estimate the total ionising dose (TID) delivered to the samples.

2. **Experimental Studies of Delivered Dose**
   - Irradiations performed on silicon sensors to extract the hardness factor for different proton energies accessible at the facility.

Schematic of the Irradiation Line

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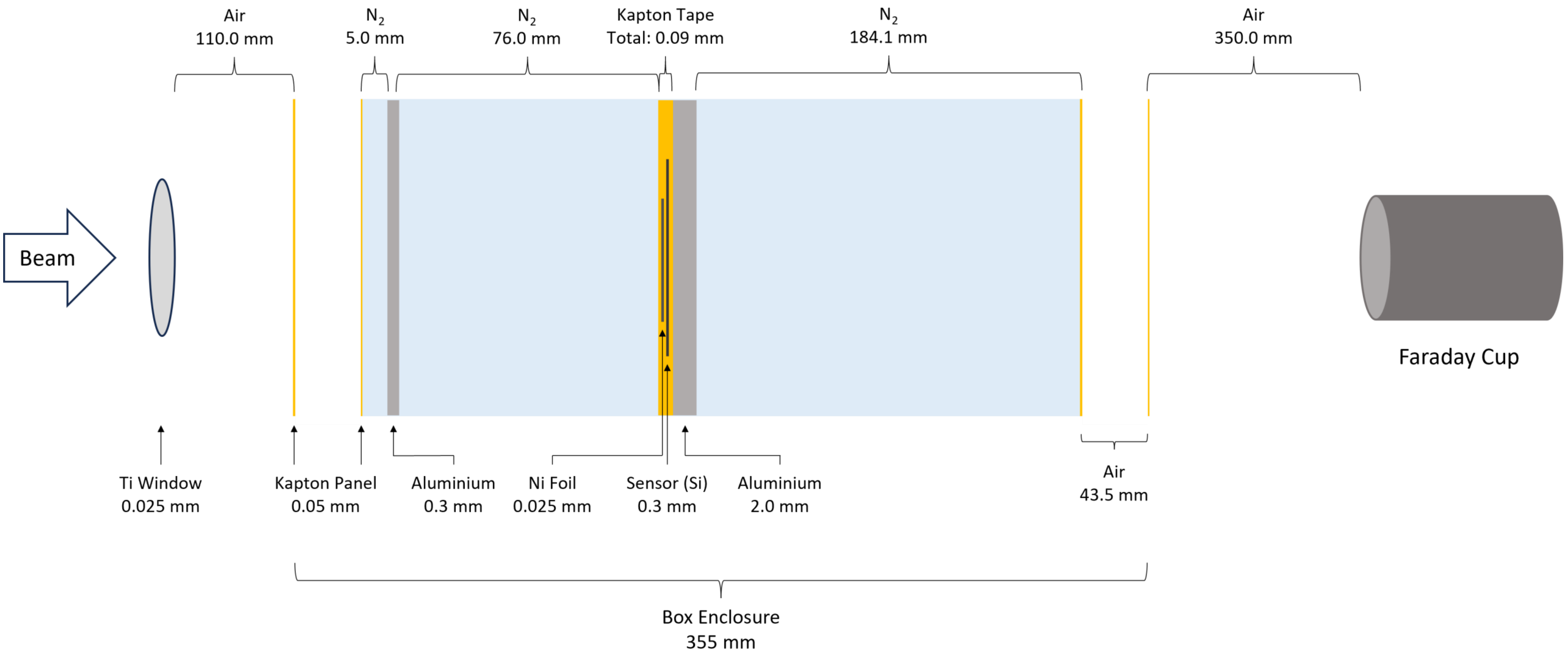

Geant4 Simulation Setup

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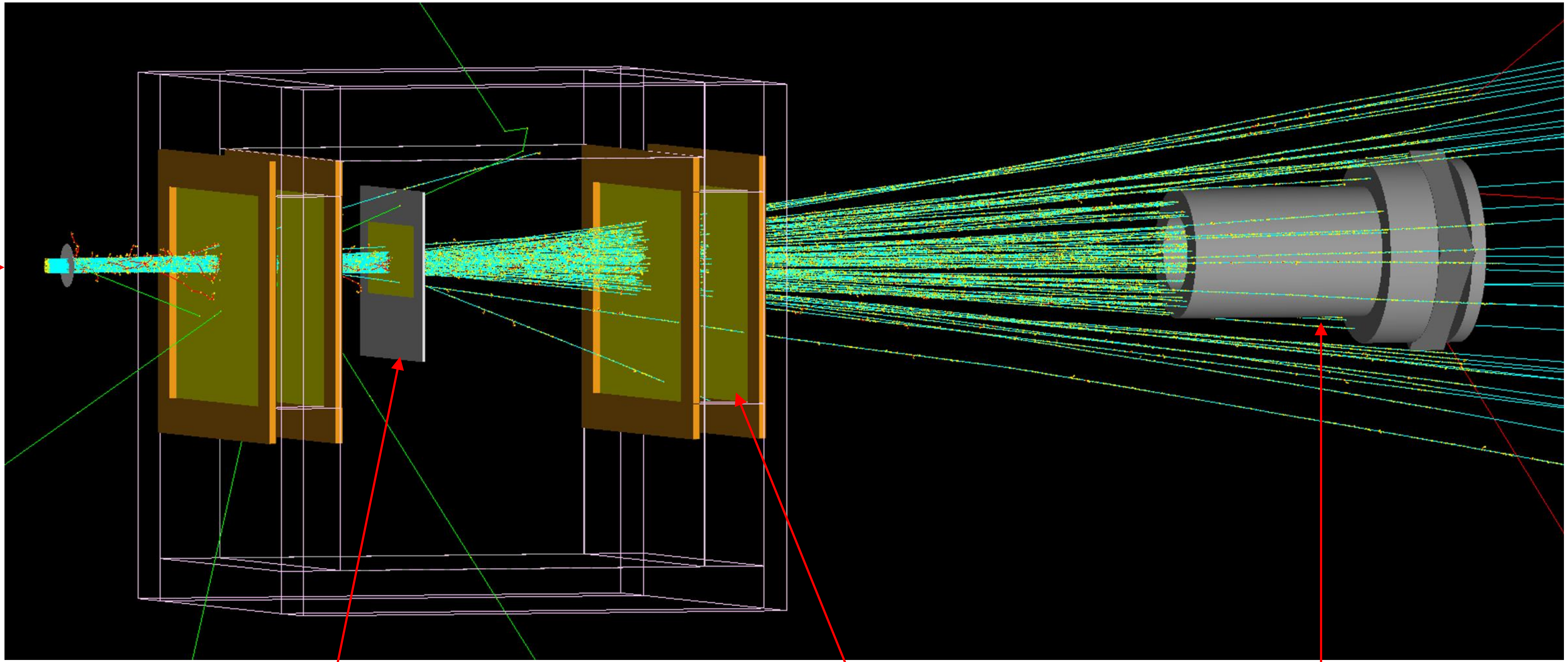
Beam



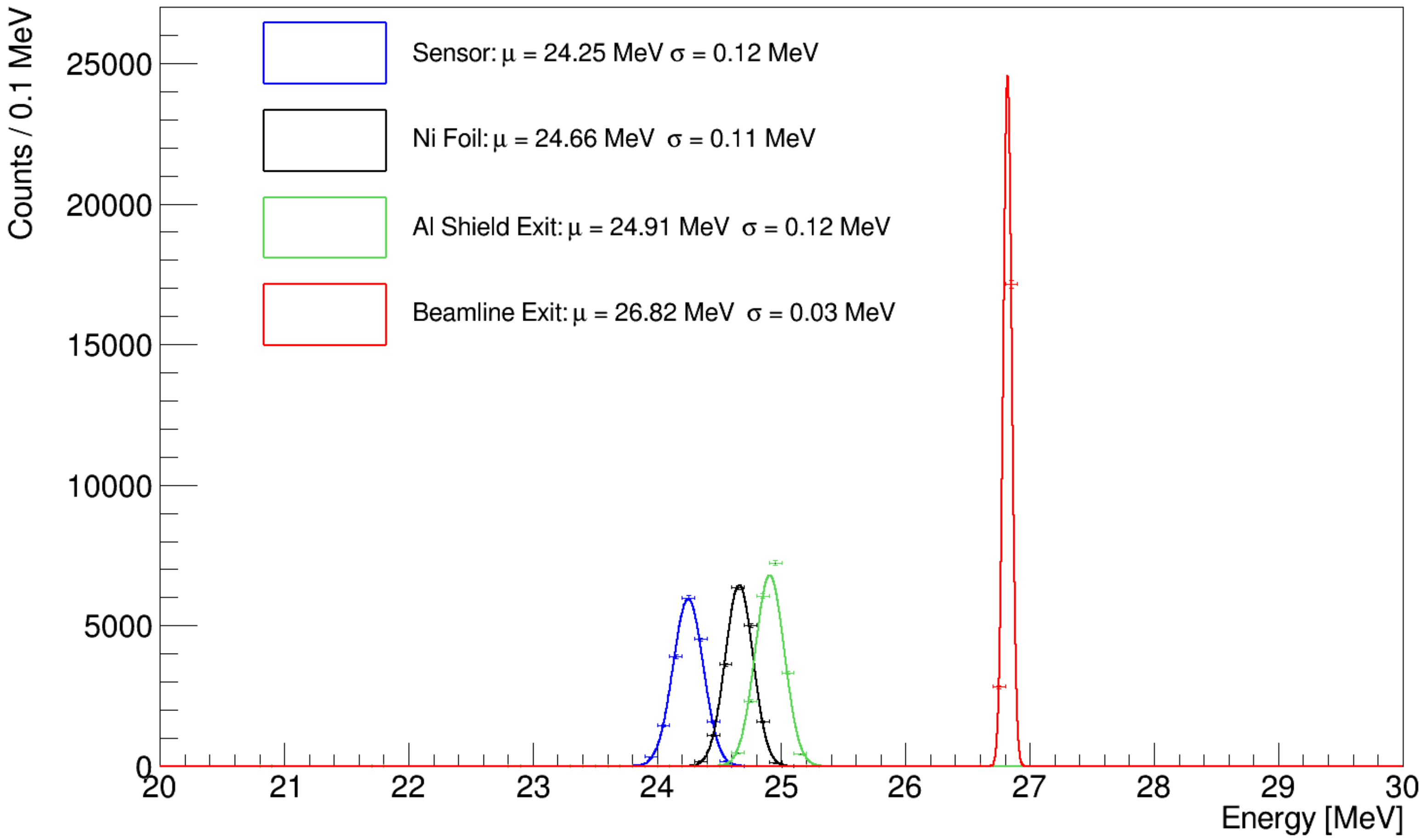
<u>Sample Holder:</u>
Ni Foil
300 µm monolithic Si
(Separated with Kapton Tape)

Kapton Window

Faraday Cup

Beam Energy Profile

- Simulation of 20000 protons passing through setup.
- With an **injection energy of 27 MeV**, the average beam energy seen at the samples is **24.3 MeV** with a spread of **0.1 MeV**.
- The beam energy on the nickel foil, **24.7 ± 0.1 MeV**, is used as an input for the dosimetry calculation.
  - The cross-section for ^{57}Ni production is energy dependent.



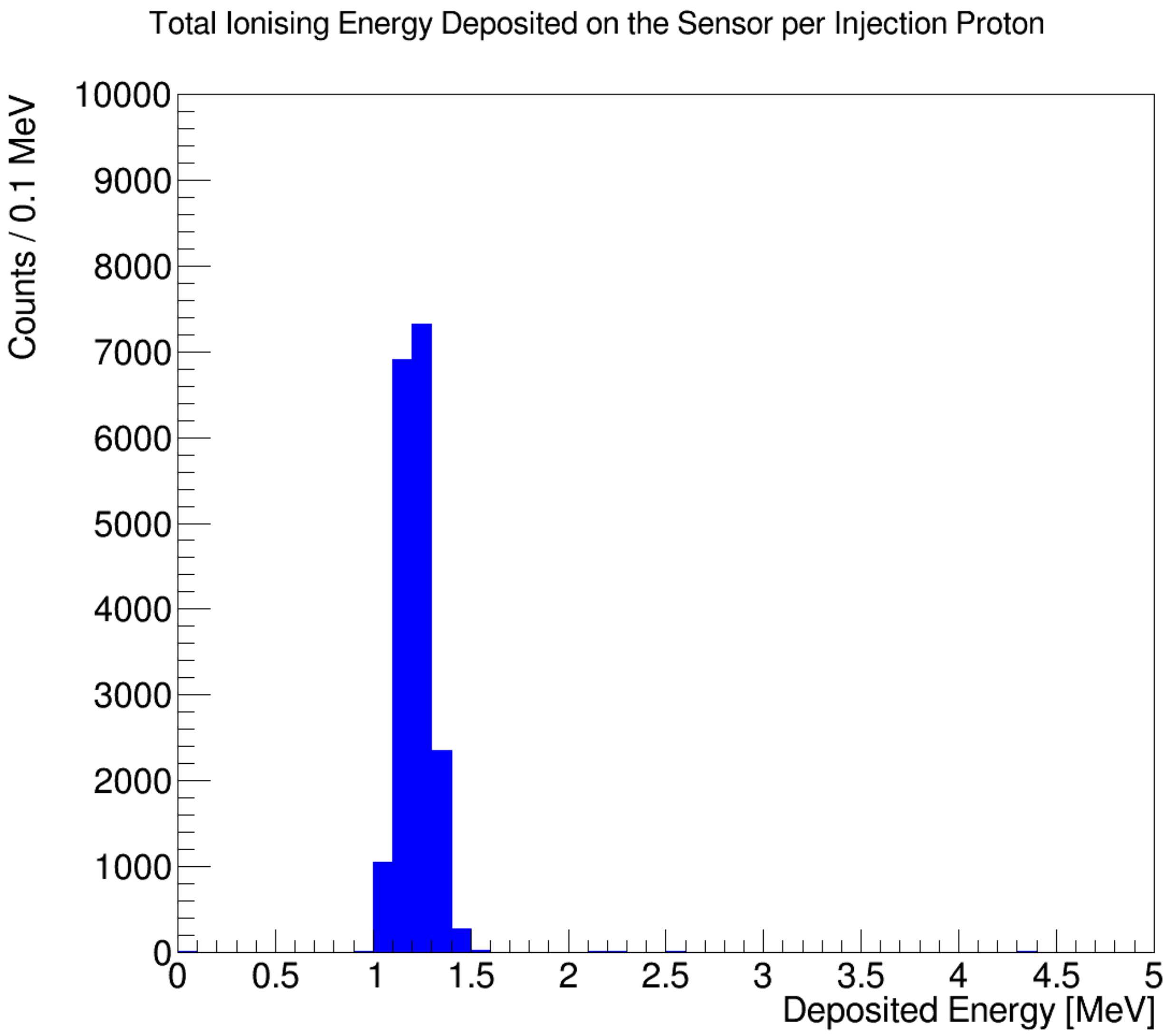
Total Ionising Dose Delivered

- Estimating the total ionising energy deposited by a 27 MeV proton (24.3 MeV at sample) in silicon.

- For the simulated silicon sensor:
  - $\frac{dE}{dx}$ = 16.95 MeV g^{-1} cm^2 (for proton energy 25 MeV)
  - t = 300 x 10^{-4} cm
  - ρ = 2.33 g cm^{-3}

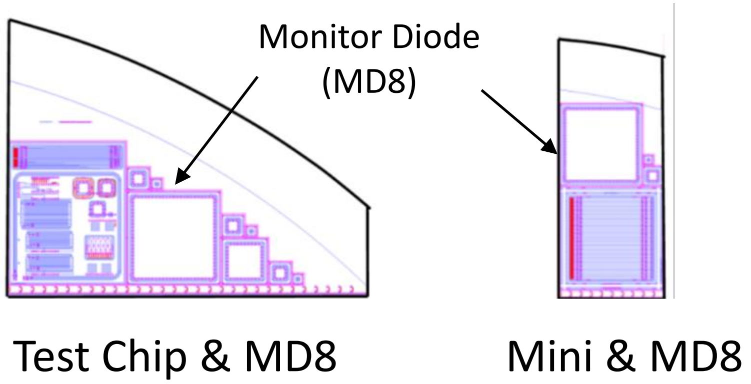
  ➢ E_{dep} ~ 16.95 · 300 x 10^{-4} · 2.33 = 1.18 MeV

- From plot, <E_{dep}> ~ 1.2 MeV

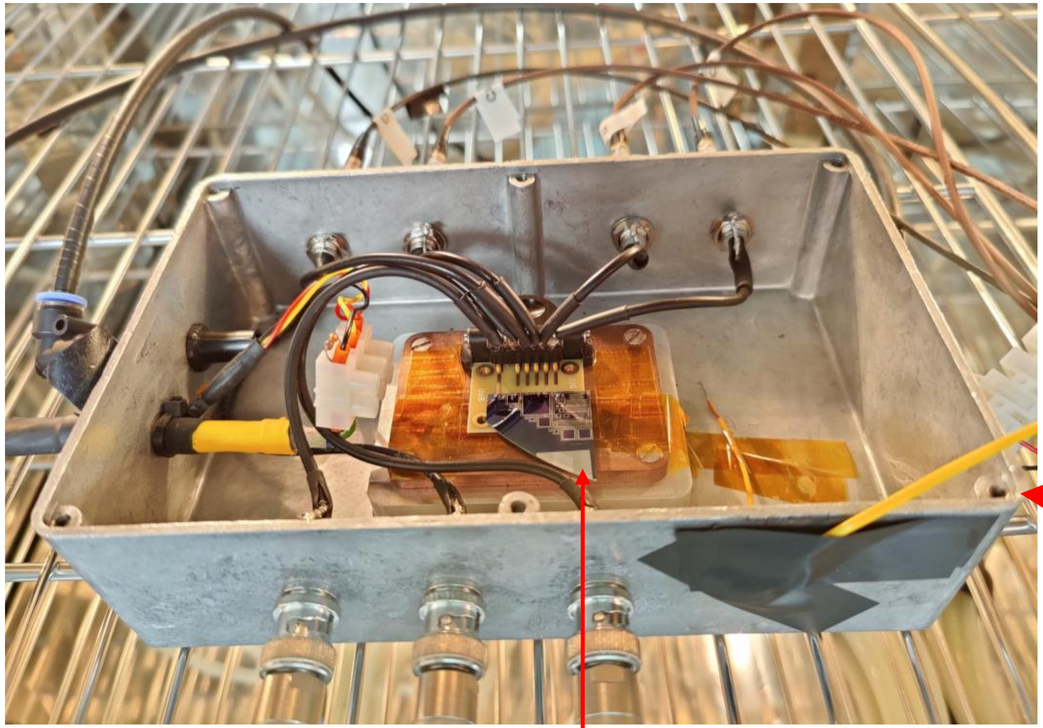


Hardness Factor Measurement

- Past measurement of the 27 MeV hardness factor by Allport et al. [JINST 14 (2019) P12004] was performed using BPW34F photodiodes and FZ pad diodes → $\kappa = 2.11 \pm 0.49$
- Since then, the irradiation setup has been recommissioned, and the majority of the samples irradiated are n^+-in-p silicon devices.
- Remeasure the hardness factor for the new setup using the commonly irradiated sensors.
- Monitor Diodes (MD8) on ATLAS ITk QA test chips and mini sensors were irradiated to various fluence points at both **20 MeV** and **27 MeV**.
- Samples were annealed before measurement at 60°C for 80 minutes as per the RD50 standard.
- IV Measurements were performed at temperatures around -20°C and RH < 10%.
- Hardness factor acquired from leakage current/fluence plots via extraction of the current-related damage factor (details in backup).
- Currents were normalised to 20°C for comparison to the 1 MeV n_{eq} current-related damage factor.
  - $\alpha_{neq} = 3.99 \times 10^{-17}$ A/cm^2



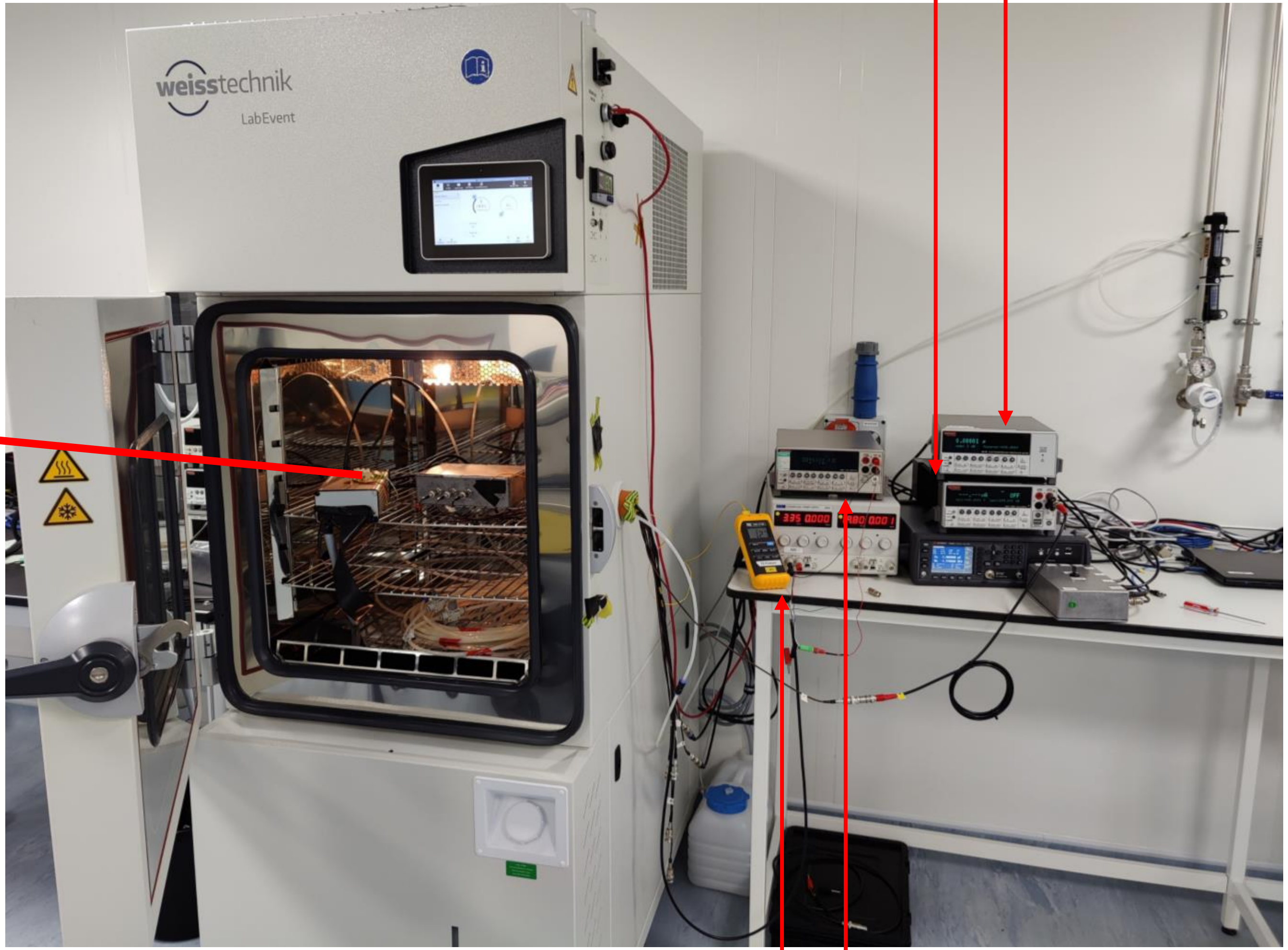
Measurement Setup



MD8 (ITk QA test chip on PCB)

Climate Chamber

Keithley 6517b + 2410



Humidity and Temperature Monitor

Example MD8 IV Curves

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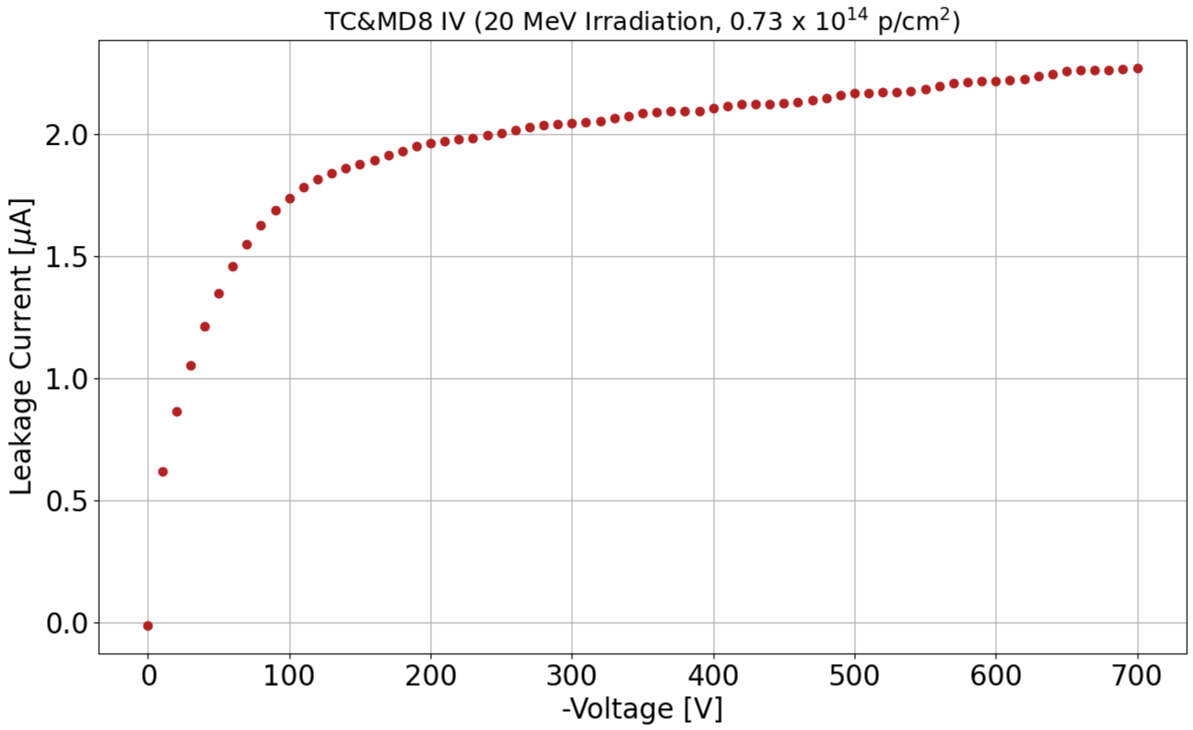
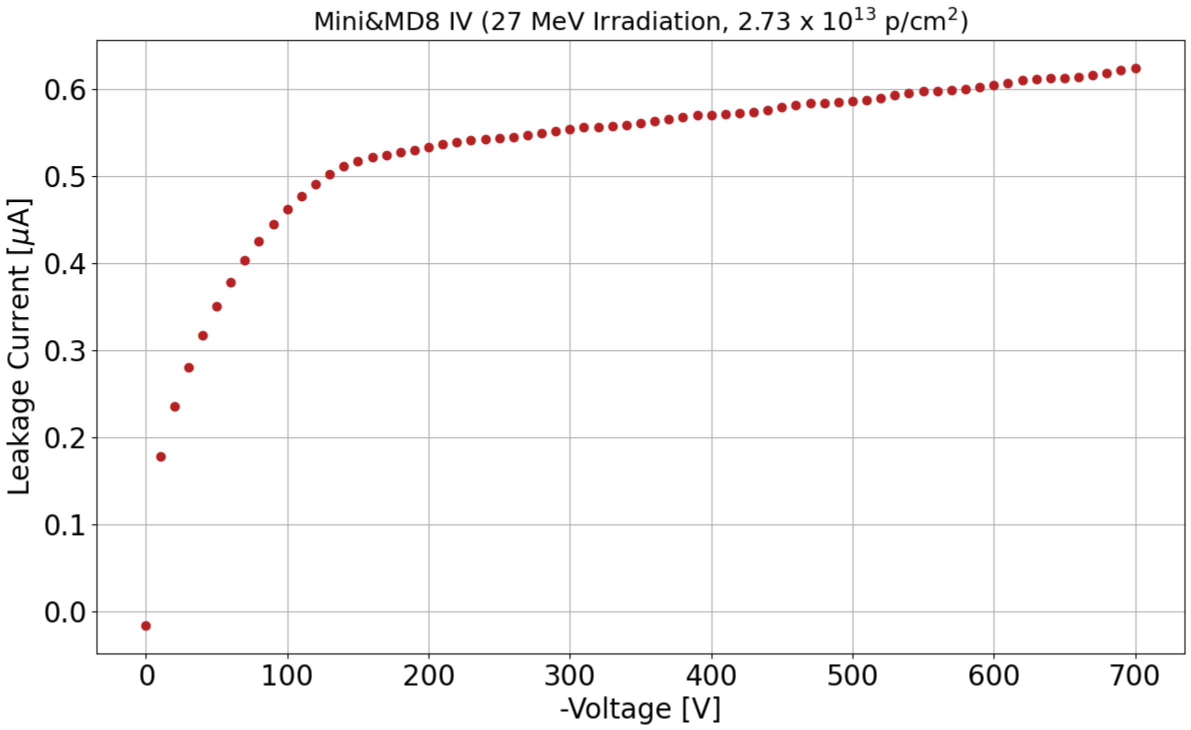


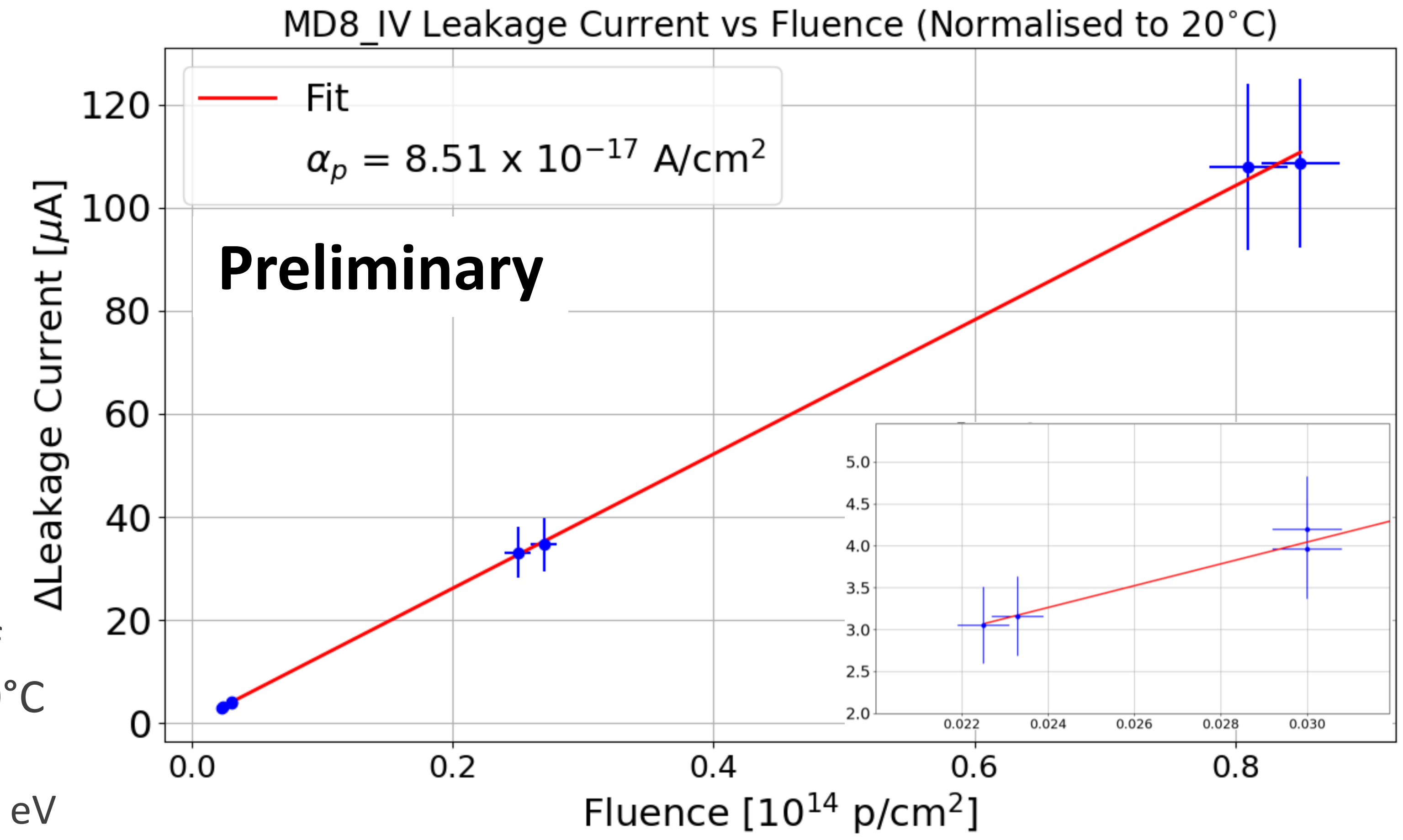


- MD8_IV leakage current IV measurement curves for a 20 MeV and 27 MeV irradiated sample.

- Leakage current for hardness factor extracted at V_{bias} = -500 V.
  - Expect that the diodes are fully depleted by this voltage.

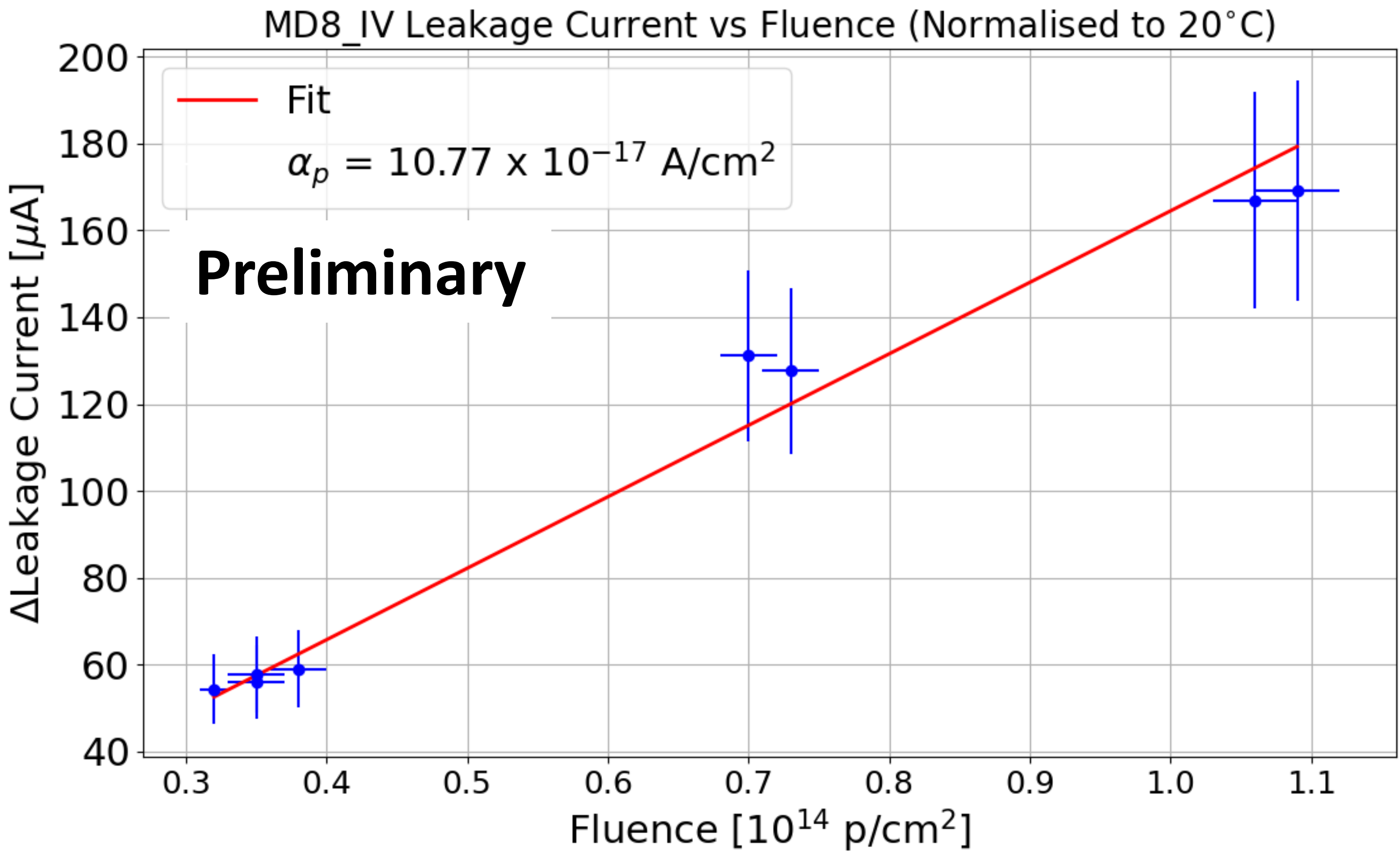
Proton Hardness Factor at 27 MeV (24.3 MeV on Sensor)

- 8 MD8s irradiated to fluences in the range 1.0×10^{12} protons/cm^2 to 1.0×10^{14} protons/cm^2.
- Hardness Factor: κ = **2.13 ± 0.20**
- Uncertainty on fluence ~5% from the ^{57}Ni dosimetry.
- Uncertainty on the current from a study of the precision of extrapolation of I from -20°C to 20°C.
  - Motivates ~15% uncertainty for an E_a = 1.21 eV [JINST 8 (2013) P10003]



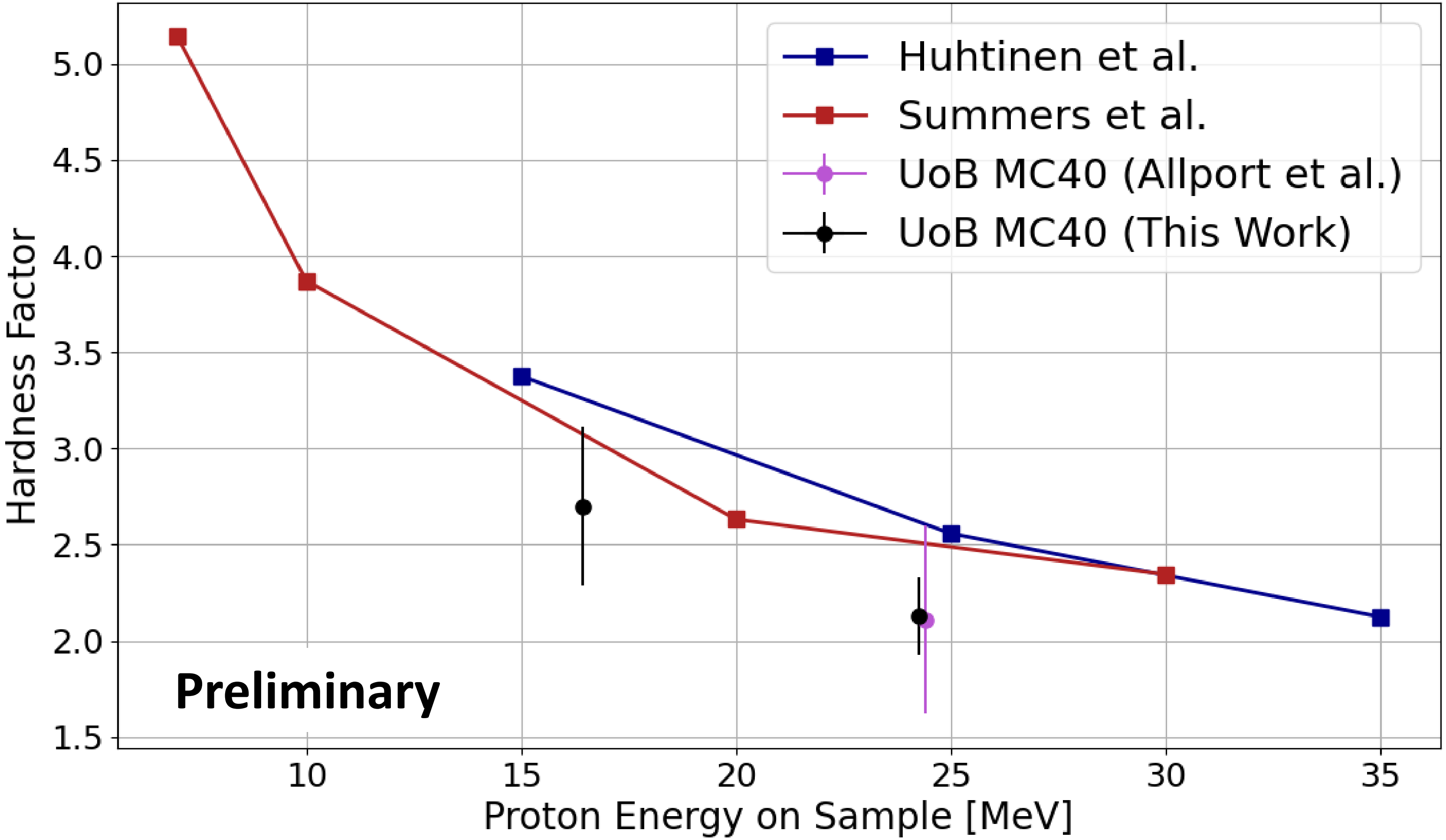
Proton Hardness Factor at 20 MeV (16.4 MeV on Sensor)

- 8 MD8s irradiated to fluences in the range (0.3 - 1.1) x 10^{14} protons/cm^2.
- Hardness Factor: κ = **2.70 ± 0.41**
- Uncertainty on fluence ~5% from the ^{57}Ni dosimetry.
- Uncertainty on the current from a study of the precision of extrapolation of I from -20°C to 20°C.
  - Motivates ~15% uncertainty for an E_a = 1.21 eV [JINST 8 (2013) P10003]



Hardness Factor Summary

- Results from the UoB MC40 investigation alongside the tabulated values from Huhtinen et al. [NIM A 335 (1993) 580] and Summers et al. [IEEE NS 40 (1993) 1372] – Values taken from the RD50 displacement damage factor site.



Summary

- The University of Birmingham MC40 cyclotron facility is involved with detector R&D, being able to deliver a few 10^{15} n_{eq}/cm^2 in one day.

- A detailed reconstruction of the irradiation setup has been performed in Geant4.
  - Beam energy at the Ni foil used for dosimetry calculations.
  - The simulated TID agrees with the theoretical value for a given proton energy.

- Preliminary hardness factor measurement using silicon monitor diodes at proton energies of 20 MeV and 27 MeV.
  - For 20 MeV: 2.70 ± 0.41
  - For 27 MeV: 2.13 ± 0.20

- Planned irradiation at the highest possible proton beam energy at the facility and measure another hardness factor.

- Aim to further investigate interplay between fluence and TID effects on silicon sensors.

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Backup

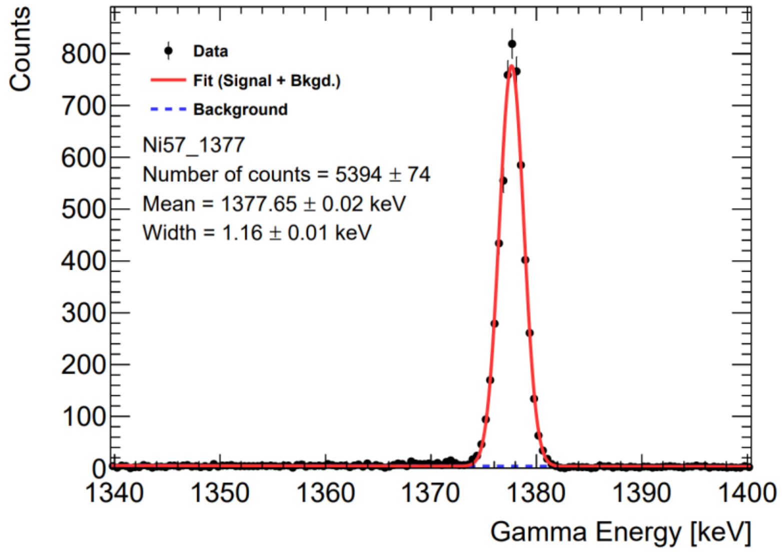
Dosimetry via Nickel Foil

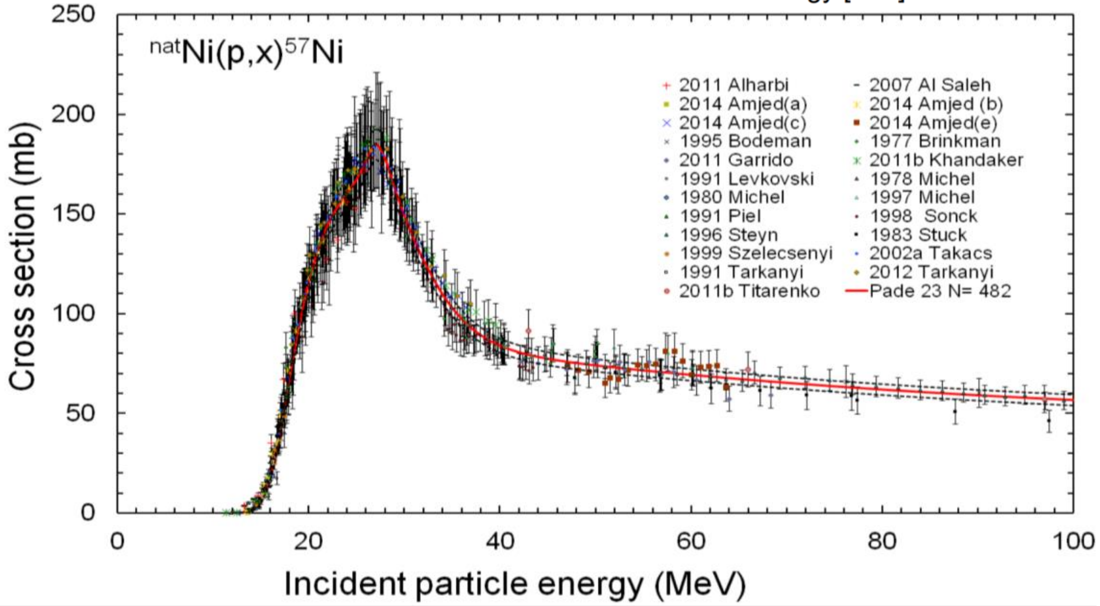
- The proton dosimetry is performed using natural nickel foils.

- Several isotopes are produced, but main reaction of interest is **^{nat}Ni(p, x)^{57}Ni**

- The ^{57}Ni undergoes γ-decay – activity measured using a calibrated high purity Ge detector.
    - Main characteristic peak is the **1377 keV** line.

- The peak intensity along with the ^{57}Ni production cross-section gives the number of protons incident on the foil, from which the **proton fluence** can then be acquired.





https://www-nds.iaea.org/medical/nip57ni0.html

Gafchromic Film Validation

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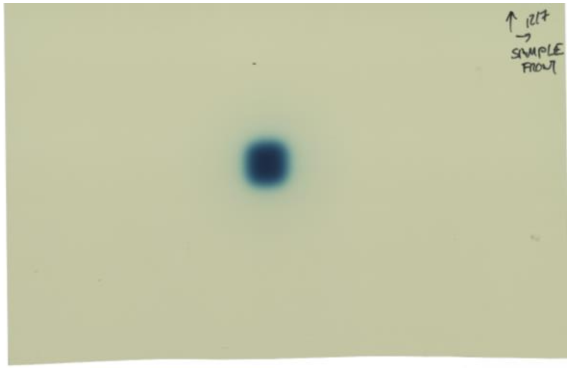
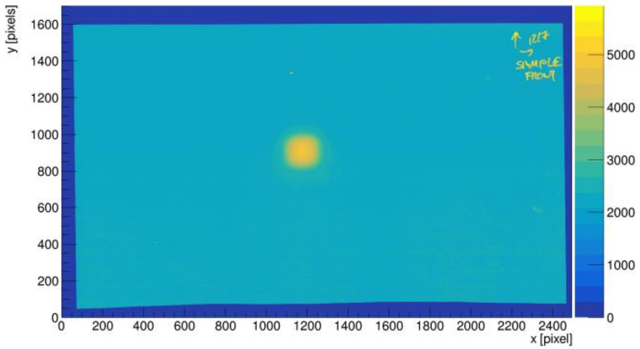
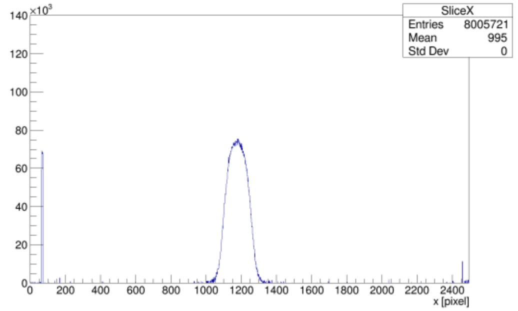
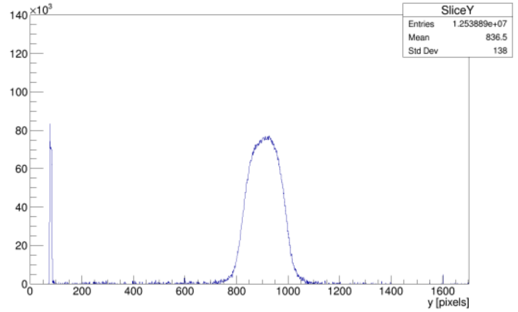


Acquire film

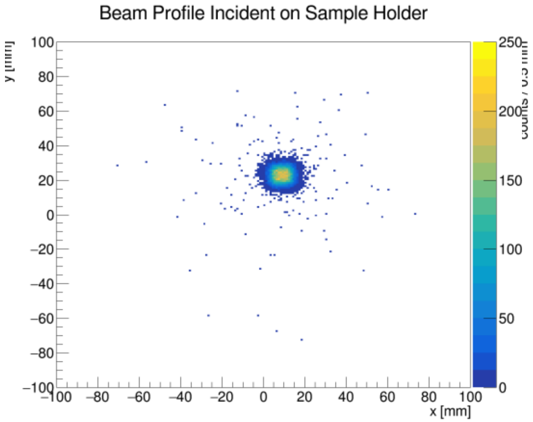


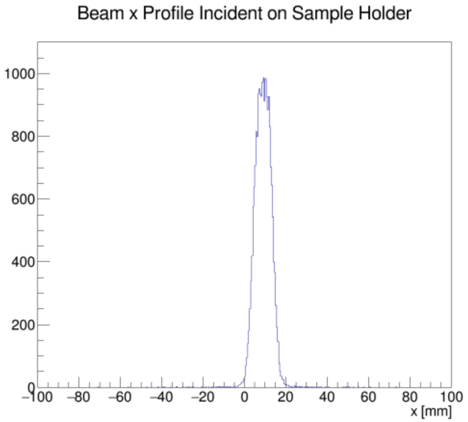
Convert to ROOT file

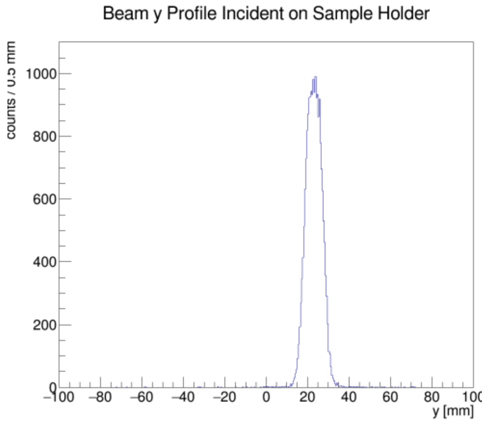




Project along x, y axis







Compare to simulated beam profile

- Work in progress – the set of Gafchromic film further upstream were too saturated

Analysis of Results

- Currents temperature scaled via: $I(T_R) = I(T) \cdot \left(\frac{T}{T_R}\right)^2 \cdot e^{-\frac{Ea}{2k_B}\left(\frac{1}{T_R} - \frac{1}{T}\right)}$

- The change in leakage current post-irradiation related by: $\Delta I = \alpha A w \phi$
  - A = active area of sensor (0.5095 cm^2 for the MD8s in this study)
  - w = width of depletion region (300 µm for fully depleted MD8s)
  - α = current-related damage factor after annealing for 80 min/60°C for currents scaled to +20°C.

- Hardness factor is given by $\kappa = \alpha/\alpha_{neq}$

- α_{neq} = current-related damage factor for 1 MeV n_{eq} after annealing for 80 min/60°C for currents scaled to +20°C.

  - $\alpha_{neq} = 3.99 \times 10^{-17}$ A/cm^2 [1]

[1] Radiation Damage in Silicon Particle Detectors – microscopic defects and macroscopic properties, M. Moll, PhD Thesis, University of Hamburg, 1999

Simulated Beam Energy Profile for 20 MeV Protons