Studying Displacement Damage in Silicon Detectors with the University of Birmingham MC40 Cyclotron

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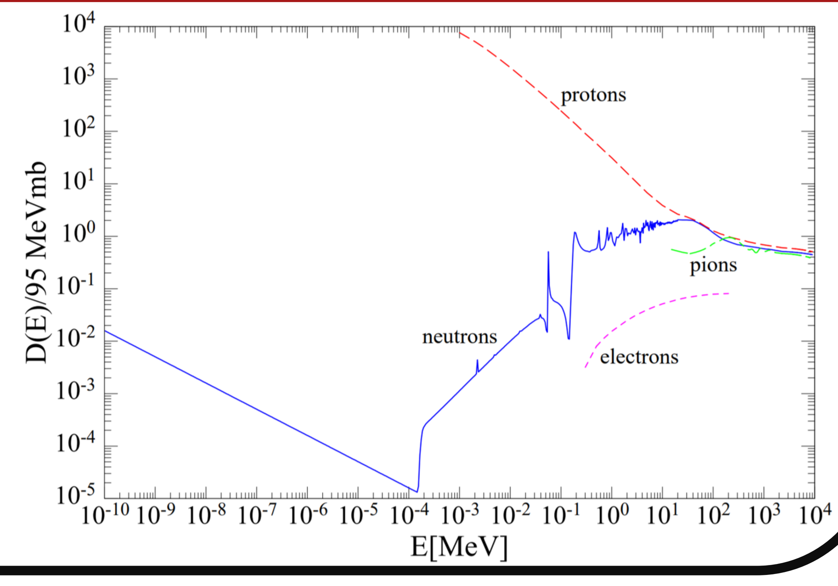
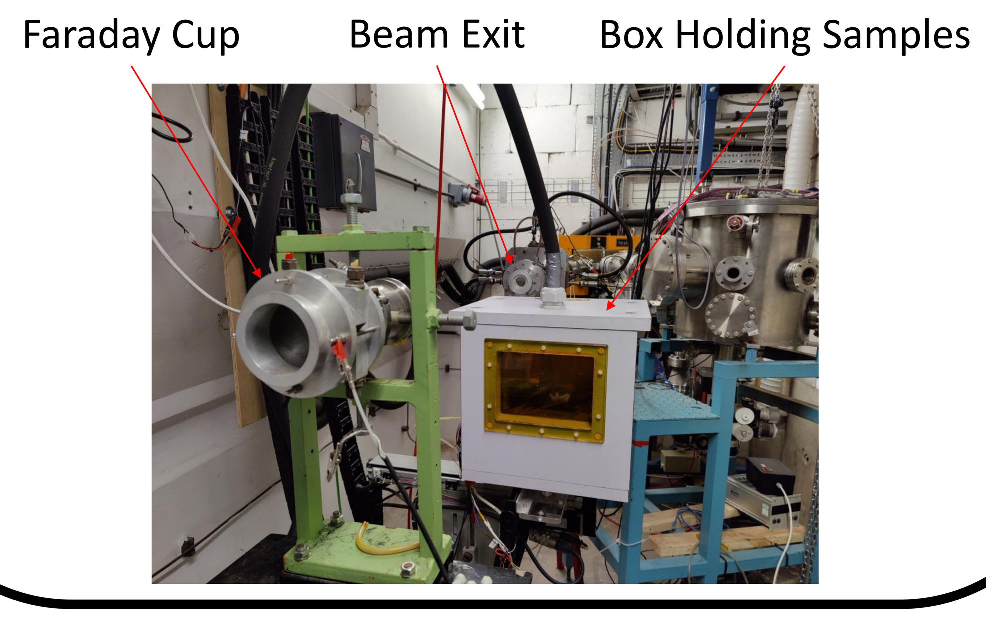
NIEL Scaling Hypothesis

- Non-ionising energy loss (NIEL), or bulk, damage occurs when incoming particles collide with the atoms in the (silicon) lattice, resulting in displacements of these atoms from their lattice sites. NIEL damage is dependent on factors including the incoming particle type and energy.
- Hardness factors, κ, are used to normalise the NIEL damage in a specific material to that of a 1 MeV neutron to facilitate more direct comparisons.
- Right: Normalised displacement damage function (κ) as a function of particle kinetic energy in silicon. These are the values currently adopted by RD50 and are based on theoretical calculations and simulations [1].



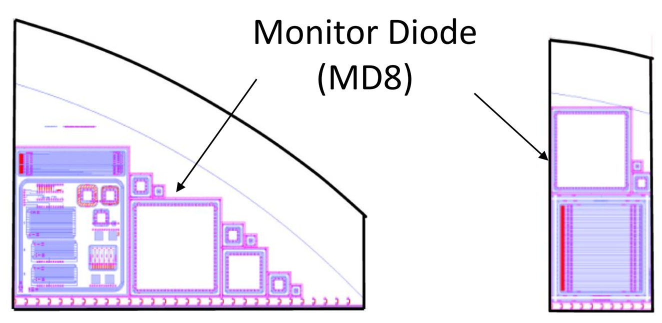
MC40 Cyclotron

The MC40 cyclotron can deliver proton beams in the energy range 2 – 38 MeV, with beam currents up to a few µA. This enables a fluence of a few 10^{15} n_{eq}/cm^2 to be delivered to a small area of samples in one day.



Test Structures

The hardness factor is extracted by measuring the change in the leakage current of silicon sensors post-irradiation. The sensors for this study are the n⁺-in-p monitor diodes from the ATLAS ITk strip wafers.



Properties:

- Active Area: 0.5095 cm^2
- Bulk Thickness: 300 µm

Irradiation

Irradiations are performed cold (-27°C) and dry (RH < 10%) to prevent potential annealing from the beam. The dosimetry is performed offline with metal foils.

Geant4 simulations are used to estimate the proton beam energy at the sensor after attenuation in upstream material.

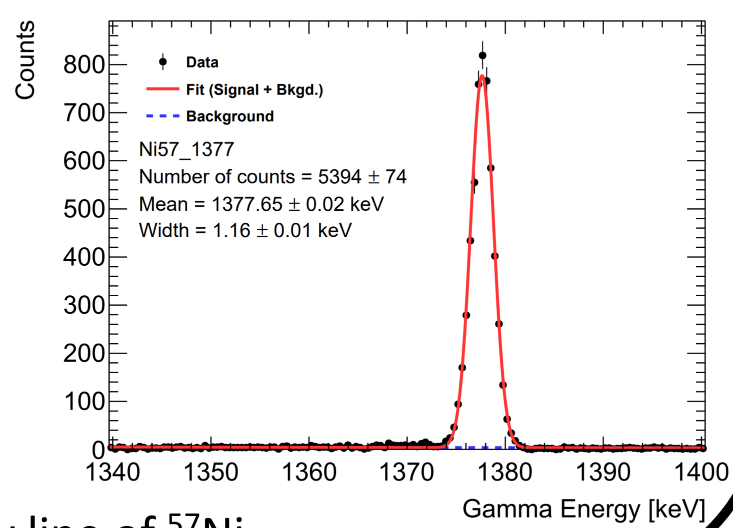
Proton Energy from Cyclotron [MeV]	Proton Energy on Sensor [MeV]
27.0	24.3 ± 0.1
20.0	16.4 ± 0.1
15.0	10.6 ± 0.1

Dosimetry

The dosimetry foil is chosen to maximise the production cross-section for a target beam monitor reaction and for a high gamma branching ratio for the active nuclide.

Cyclotron Energy	Foil	Monitor Reaction
20 and 27 MeV	^{nat}Ni	$^{nat}Ni(p, x)^{57}Ni$
15 MeV	^{nat}Ti	$^{nat}Ti(p, x)^{48}V$

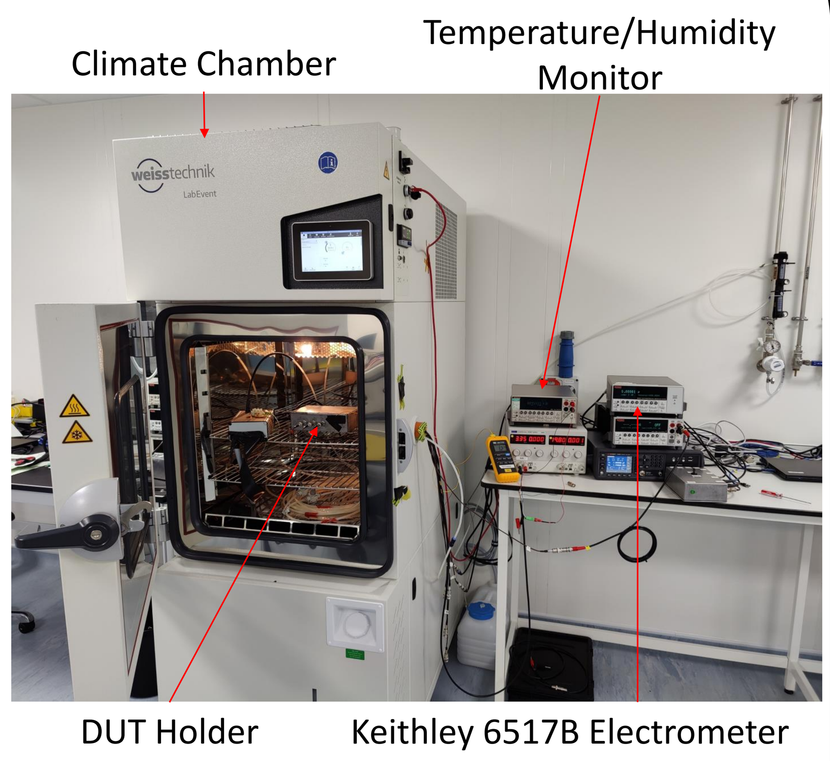
The gamma rays from the decay of the active nuclide are measured using a HPGe detector. The measured activity along with the cross-section and physical parameters of the foil are used to estimate the proton fluence delivered to the samples.



- Right: Example of the desired gamma decay line of ^{57}Ni.

IV Measurements

All irradiated sensors undergo annealing for 80 minutes at 60°C as per the RD50 standard. Leakage IV measurements are performed at -20°C in a climate chamber. This suppresses the currents which may otherwise contribute to sensor self-heating. The leakage current is extracted from the IV curves at a bias voltage 500 V, where the sensors are expected to be fully depleted. Analysis is performed to a reference temperature of 20°C, hence the currents are scaled according to:



$$I(T_R) = I(T) \cdot \left(\frac{T_R}{T}\right)^2 \cdot e^{-\frac{E_a}{2k_B}\left(\frac{1}{T_R} - \frac{1}{T}\right)}$$

- T - Measurement temperature
- T_R - Reference temperature
- E_a - Activation energy of silicon (1.21 eV for this study [2])

Analysis

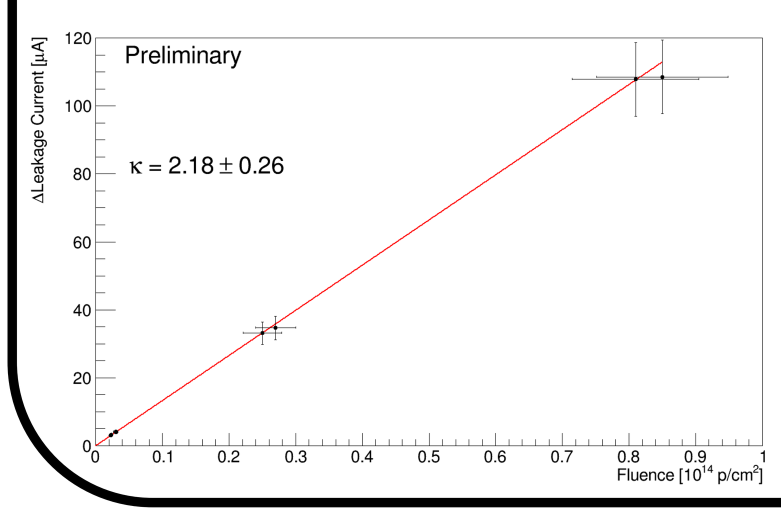
The change in leakage current post-irradiation is expected to follow:

$$\Delta I = \alpha A w \phi$$

- α - Current-related damage factor
- A - Sensor active area
- w - Sensor bulk thickness
- ϕ - Proton fluence

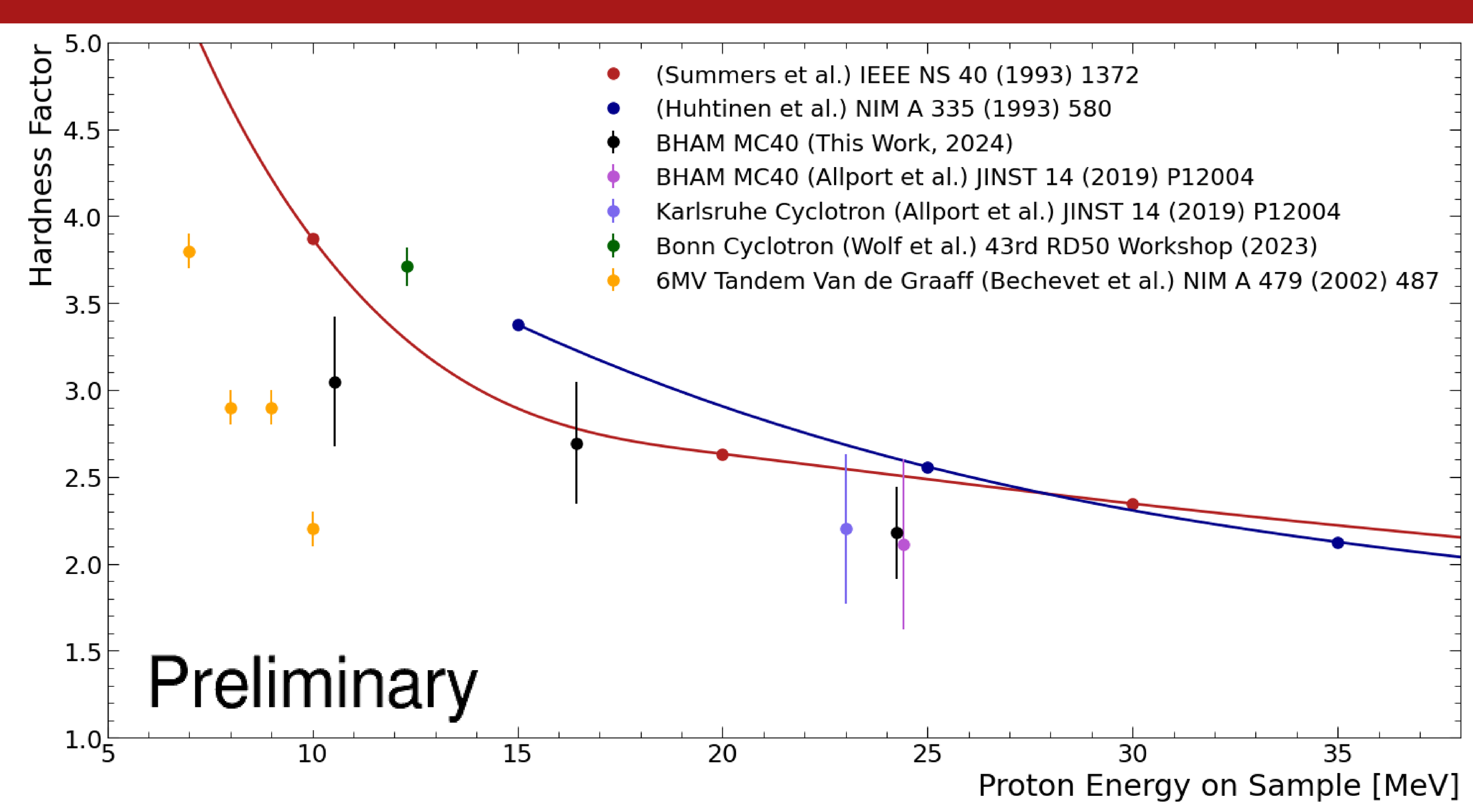
- α is given for a sensor that has undergone controlled annealing and currents measured at 20°C.

The hardness factor is given as the ratio of α to α_{neq}, the current-related damage factor from 1 MeV neutrons under the same annealing and measurement conditions.



An example of the change in leakage current versus fluence points (27 MeV). The uncertainty on κ is dominated by the current scaling extrapolation and the fluence uncertainty (cross-section measurements and our understanding of the HPGe detector efficiency).

Results



A summary of the three hardness factor measurements from this study, along with other experimental data in the energy range. The theoretical curves by Summers and Huhtinen have been interpolated from the discrete predictions.

Summary

- Experimental measurements of proton hardness factors in silicon using the energies available at the University of Birmingham's MC40 cyclotron.
- Results suggest that the NIEL damage is lower than the theoretical values.
- Ongoing work to better understand the uncertainties in the current and fluence measurements.

References

[1] A. Vasilescu (INPE Bucharest) and G. Lindstroem (University of Hamburg), Displacement damage in silicon, on-line compilation

[2] A. Chilingarov, Temperature dependence of the current generated in Si bulk, Journal of Instrumentation 8 (2013) P10003