Measuring and Comparing the Hardness Factor of the MC40 Cyclotron using BPW34F Photodiodes

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Outline

Motivation

- The **hardness factor** is a quantity that is used to convert from proton fluences to **1 MeV neutron equivalent fluences**.
- The theory states that for 28 MeV protons, the hardness factor has a **value of 2.2**.
- However, facilities with the same beam energy have found differing values. For example, the **Karlsruhe Institute of Technology (KIT) has recorded a value of 2.05 $\pm$ 0.61** [1].

Experimental Aims

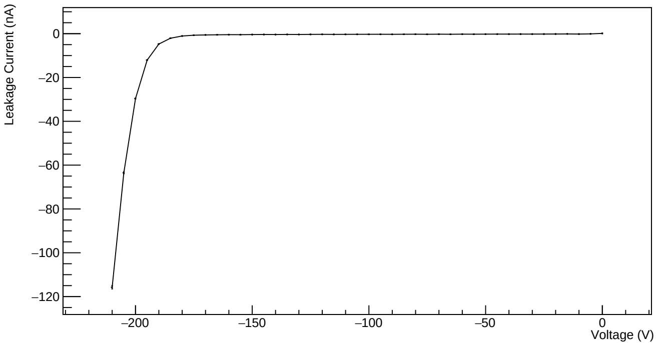
- To analyse the **I–V and C–V characteristics** of BPW34F photodiodes.
- Using this, **experimentally determine the hardness factor** of the MC40 cyclotron.
- Employing the same method, determine the hardness factor of the beam at the **KIT**.

What is a Photodiode?

- Output a current based on the intensity of incoming light.
- Consists mainly of a **silicon P–I–N junction**.
- The **leakage current** under a reverse bias depends on the **radiation damage** the photodiode has incurred.

Example of a wired BPW34F photodiode.

What is a Photodiode?



Reverse bias I–V curve for a non-irradiated diode.

What is a Photodiode?
The Depletion Region

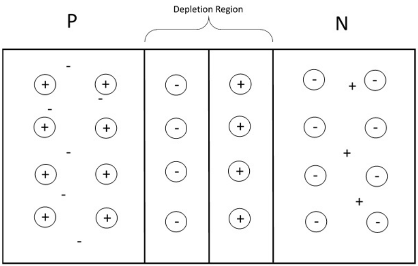
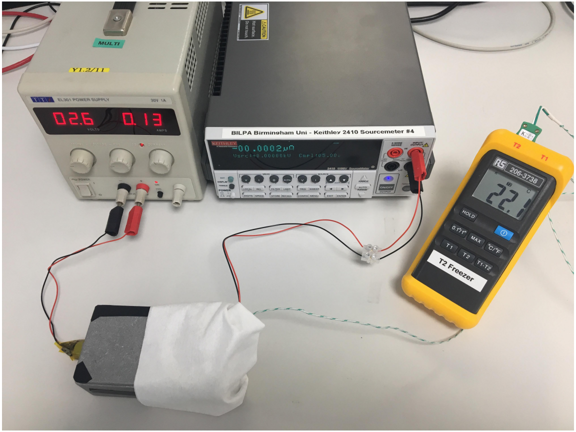


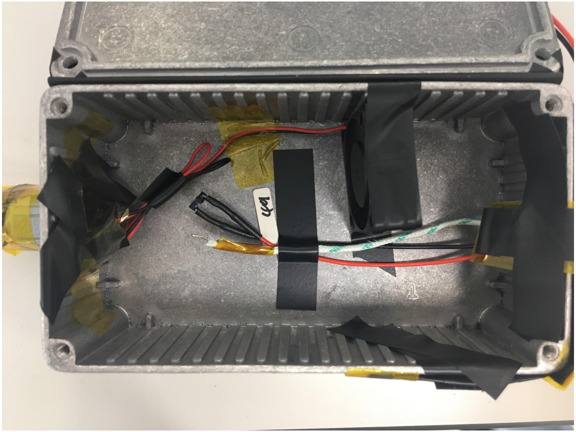
Diagram of a P–I–N junction under reverse bias (positive terminal is on the right).

- Analogous to a parallel plate **capacitor**.
- Size of the **depletion region** grows as higher voltages are applied.
- The depletion region ceases to grow when **maximum depletion voltage** is reached.

I–V Measurements
Setup



Experimental setup for I–V measurements.



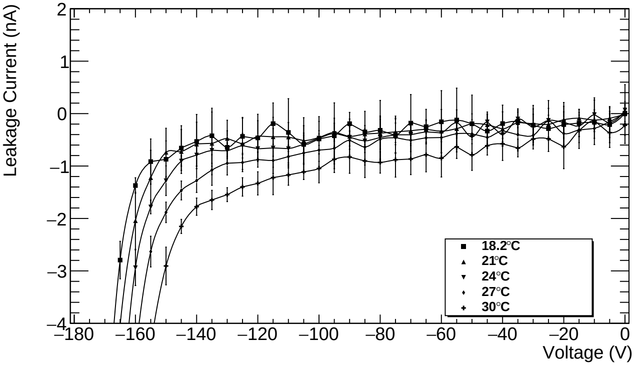
Aluminium shielding box.

- The **leakage current** of a photodiode is dependent on **temperature** by [2]:

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

- Therefore, all I–V measurements were scaled to a **reference temperature** of 21°C.

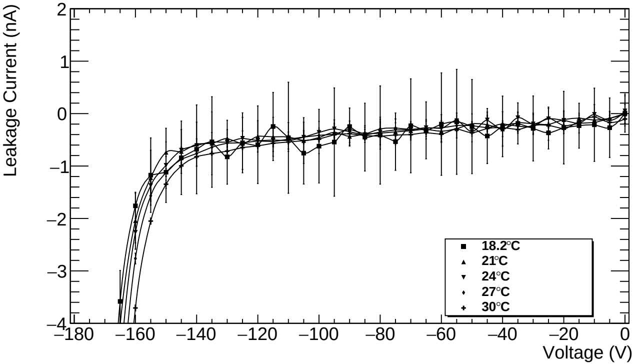
I–V Measurements
Effect of Temperature Scaling



I–V curves before temperature scaling.

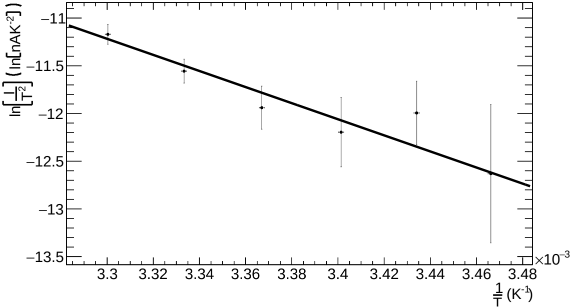
I–V Measurements

Effect of Temperature Scaling



I–V curves after temperature scaling.

- The range of $15^{\circ}\mathrm{C} < T < 30^{\circ}\mathrm{C}$ was investigated.



$\ln\left[\frac{I}{T^2}\right]$ vs $\frac{1}{T}$ in the range $10^{\circ}\mathrm{C} < T < 35^{\circ}\mathrm{C}$.

- This yields a value of $\boldsymbol{E_a = 1.45 \pm 0.33}$ **eV**.

C–V Measurements

Current – Voltage Relation and Maximum Depletion Voltage.

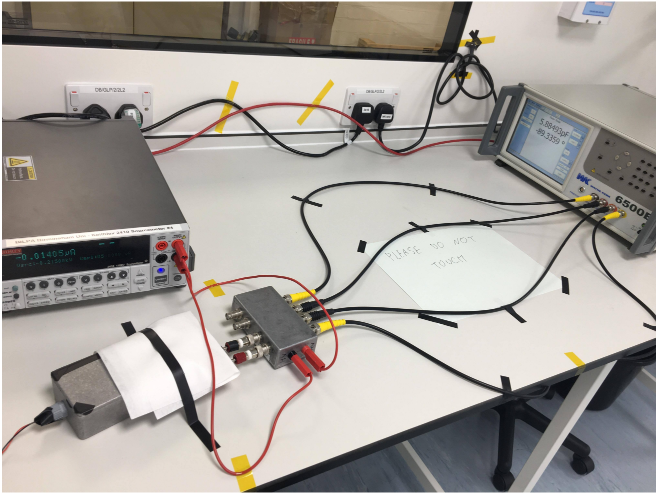
- The **capacitance** of a photodiode is related to the **reverse bias** by [3]:

$$C = \frac{f\sqrt{\epsilon_{Si}\epsilon_0}}{\sqrt{V}}$$

- At **maximum depletion voltage**, capacitance becomes independent of voltage.

- Plotting **capacitance vs voltage** on a log plot should therefore show a straight line, with a **deviation** at maximum depletion.

C–V Measurements
Setup

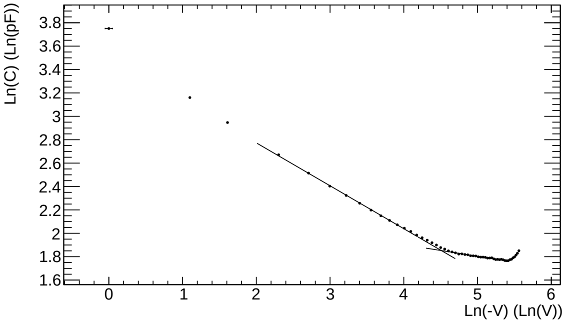


Experimental setup for C–V measurements.

C–V Measurements

Calculating Maximum Depletion Voltage

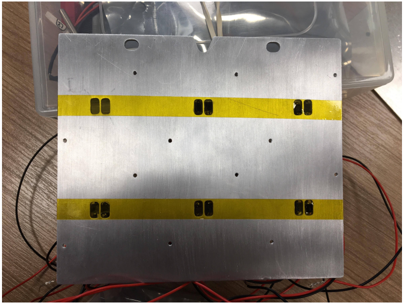
- By calculating the **intersect** of the two fits, the point at which the trend deviates from a straight line can be calculated.
- Applying this method, a maximum depletion voltage value of $\boldsymbol{V_{dep} = -90.8 \pm 5.1}$ **V** was inferred.

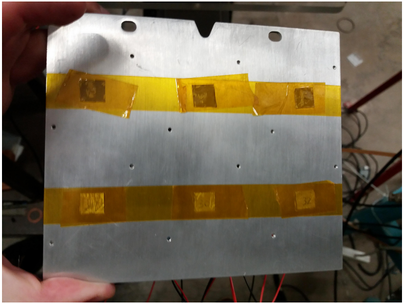


log capacitance vs log voltage.

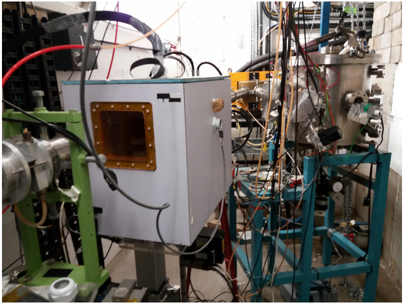
Proton Irradiations
Mounting the Photodiodes

⊗ Beam direction.



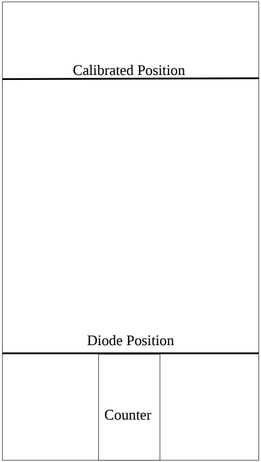


Aluminium mount. The nickel foils were used to measure the incident fluence.



The isolation box within the ATLAS chamber, the box was used to cool the photodiodes to -27°C.

Proton Irradiations
Ni Foil Analysis



Schematic diagram of germanium counter.

- The **irradiated nickel foils** were analyzed using a **germanium counter**.
- Due to the weak activity of the foils, they had to be placed directly on top of the counter.
- A **ratio of counts** was taken between this position and the calibrated position.
- The measured counts from the foils were then converted into **proton fluences**.

Annealing
The Arrhenius Relation

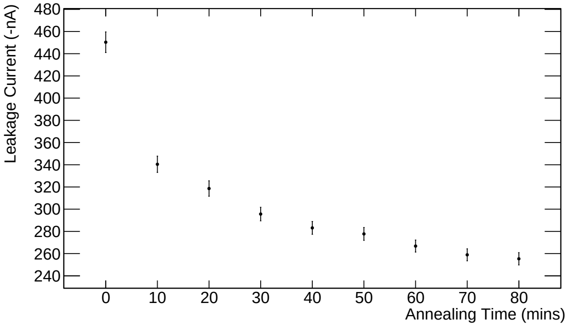
- A radiation damaged photodiode will **repair** itself over time.
- The **rate** of this repair decreases exponentially with **temperature**.
- This process is known as **annealing**, and can be quantified by the equation [2]:

$$\frac{1}{\tau} \propto e^{-\frac{E_a}{k_B T}}$$

- Exploiting this phenomenon, the **thermal history** of a set of radiation damaged photodiodes can essentially be removed.

Annealing

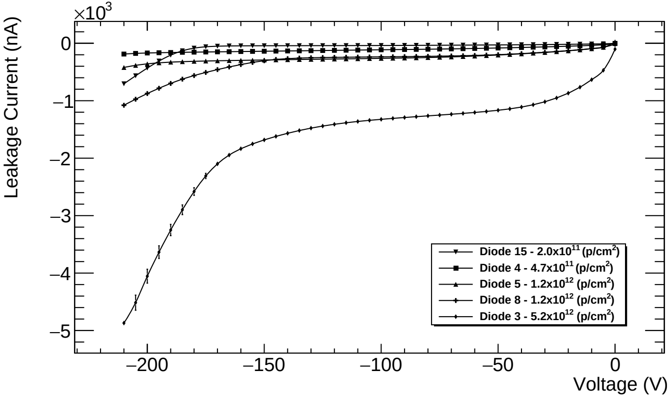
The Effect on Leakage Current



Change in leakage current due to annealing

After **80 minutes of annealing at 60°C**, it can be seen that any thermal history has effectively been removed.

Annealing
The Effect on Leakage Current



Leakage current changes after irradiations and annealing.

- The **change in leakage current** before and after irradiation is related to **proton fluence** by [2]:

$$\Delta I = \alpha L^2 w \phi$$

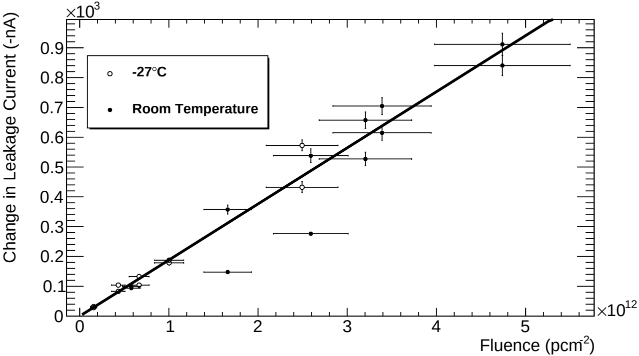
- The **hardness factor** can be written as:

$$\kappa = \frac{\alpha}{\alpha_{neq}} \quad \text{since} \quad \kappa = \frac{\phi_{neq}}{\phi}$$

Where $\alpha_{neq} = (3.99 \pm 0.03) \times 10^{-17}$ Acm^{-1} [2].

- Therefore, **plotting change in leakage current vs fluence** should give a straight line graph with $\boldsymbol{\alpha L^2 w}$ as the gradient.

Determining the Hardness Factor
Results for MC40 Cyclotron



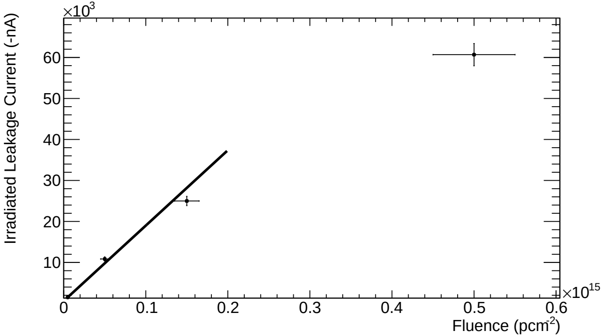
Change in leakage current vs proton fluence.

This gave a combined value of $\alpha = (8.93 \pm 0.34) \times 10^{-17}$ Acm^{-1}.

Hence, the hardness factor was found to be:

$$\boxed{\kappa_{MC40} = 2.24 \pm 0.09}$$

Determining the Hardness Factor
Results for KIT



Irradiated leakage current vs proton fluence for KIT photodiodes.

This gave a value of $\alpha = (8.77 \pm 1.06) \times 10^{-17}$ Acm^{-1}. Hence, the hardness factor for KIT was found to be:

$$\boxed{\kappa_{KIT} = 2.20 \pm 0.27}$$

Which is in agreement with our result, and the quoted value of 2.05 ± 0.61.

Summary

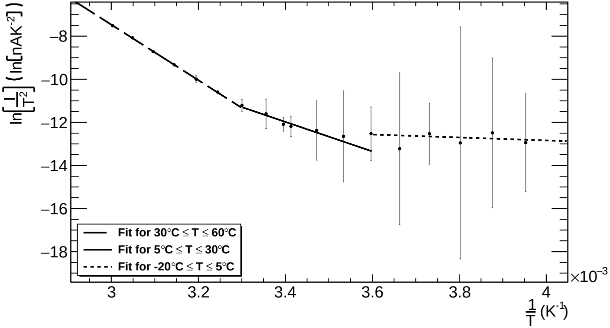
- The **I–V** and **C–V** characteristics of **BPW34F photodiodes** have been analysed.
- Using this, we have obtained a value of $\kappa_{MC40} = \mathbf{2.24} \pm \mathbf{0.09}$ for the MC40 Cyclotron.
- Applying the same method to photodiodes from **KIT**, a value of $\kappa_{KIT} = \mathbf{2.20} \pm \mathbf{0.27}$ was obtained.
- Our value **agrees** with the value obtained from **KIT** photodiodes.

References

- A. Dierlamm. *Proton Irradiation in Karlsruhe*. 16th RD50 Workshop. 2010. URL: https://indico.cern.ch/event/86625/contributions/2103519/attachments/1080676/1541436/Irradiations_Ka.pdf.
- M. Moll. "Radiation Damage in Silicon Particle Detectors". PhD thesis. University of Hamburg, 1999.
- G. Casse. "The effect of hadron irradiation on the electrical properties of particle detectors made from various silicon materials". PhD thesis. Universite Joseph Fourier-Grenoble, 1998.
- A. Chilingarov. "Temperature dependence of the current generated in Si bulk". In: *Journal of Instrumentation* (2013).

Appendix: I–V Measurements

Calculating the Activation Energy



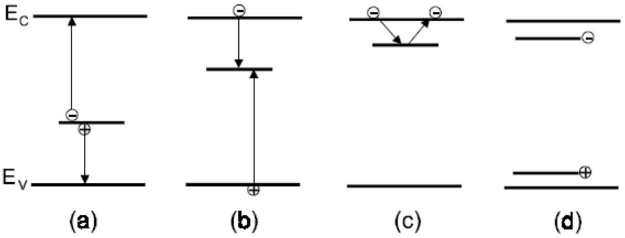
$\ln\left[\frac{I}{T^2}\right]$ vs $\frac{1}{T}$. The leakage current is evaluated at maximum depletion.

$$\ln\left[\frac{I}{T^2}\right] = -\frac{E_a}{2k_B}\frac{1}{T}$$

$E_a^{high} = 2.22 \pm 0.03$ eV; $E_a^{mid} = 1.18 \pm 0.50$ eV; $E_a^{low} = 0.12 \pm 1.84$ eV.

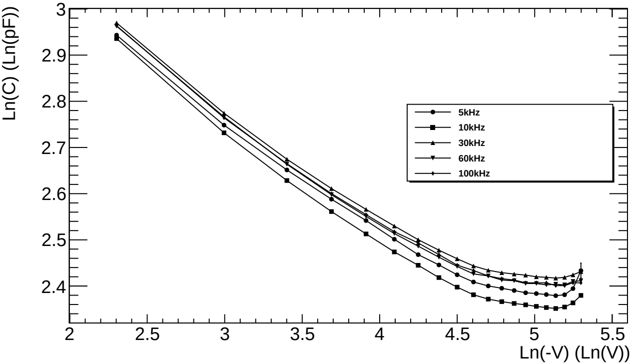
- The accepted value is $\boldsymbol{E_a^{accepted} = 1.21}$ **eV** [4].
- E_a^{low} is unreliable since the **noise floor** of the Keithley becomes a problem at lower temperatures.

- For **radiation damaged** photodiodes, the AC frequency applied to the system will have an affect on capacitance.
- As higher frequencies are reached, varying modes of radiation damage will activate.



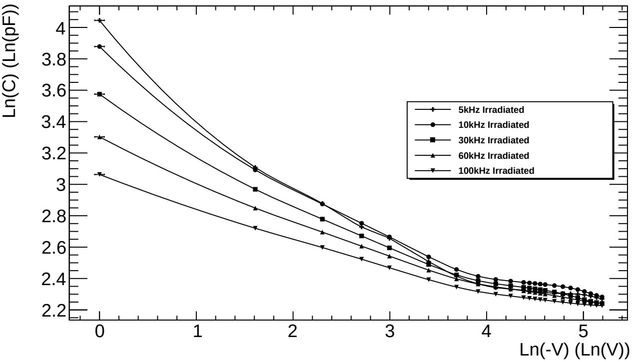
Radiation damage processes: (a) generation, (b) recombination, (c) trapping, (d) compensation [3].

Appendix: C–V Measurements
AC Frequency Dependence



AC frequency effect on capacitance (non-irradiated).

Appendix: C–V Measurements
AC Frequency Dependence

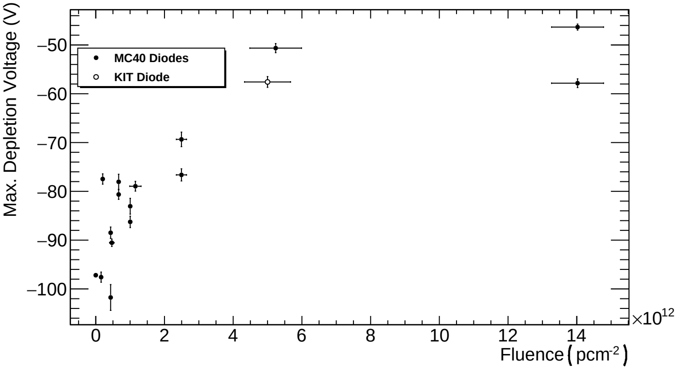


AC frequency effect on capacitance (irradiated).

Appendix: C–V Measurements

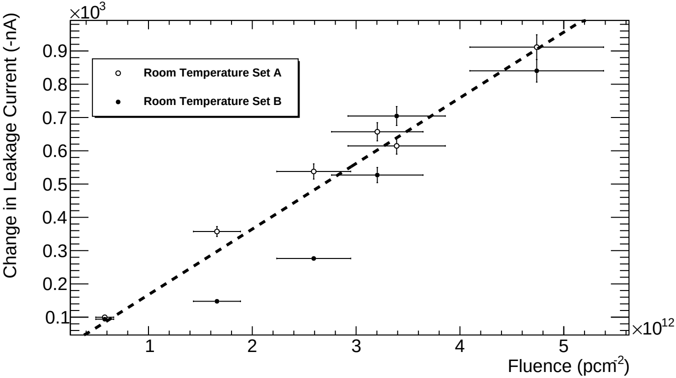
Fluence Dependence of Maximum Depletion Voltage.

- During C–V measurements on an irradiated photodiode, it was found that the **maximum depletion voltage depends upon the degree of radiation damage**.



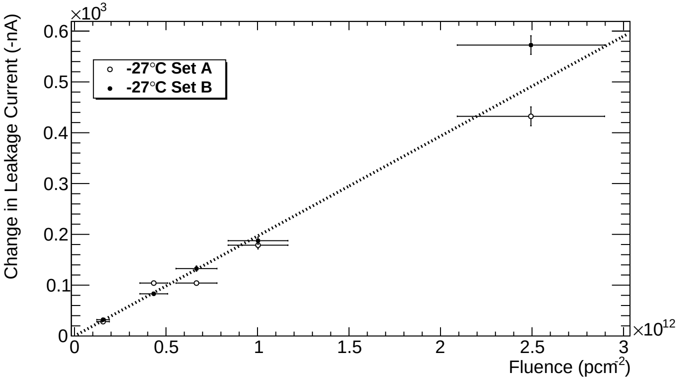
Maximum depletion voltage as a function of fluence.

Appendix: Determining the Hardness Factor
Room Temperature Data



Change in leakage current vs proton fluence for room temperature data.

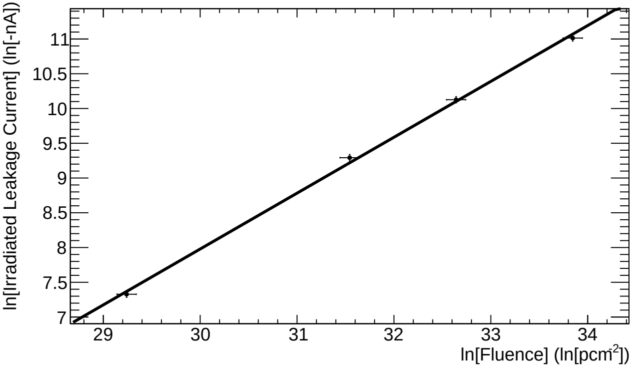
Appendix: Determining the Hardness Factor
-27°C Temperature Data



Change in leakage current vs proton fluence for -27°C data.

Appendix: Determining the Hardness Factor

Results for KIT



Log of irradiated leakage current vs log of proton fluence for KIT photodiodes.