Experimental Determination of Proton Hardness Factors at Various Irradiation Facilities

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Outline

Introduction

Utilizing the **I–V** and **C–V** characteristics of **BPW34F photodiodes**, the **hardness factors**, κ, of three different proton beams have been measured.

- The **MC40 Cyclotron** at the **University of Birmingham** (25 MeV).
- The **IRRAD Proton Facility** at **CERN** (24 GeV).
- The **Irradiations Facility** at the **Karlsruhe Institute of Technology** (23 MeV).

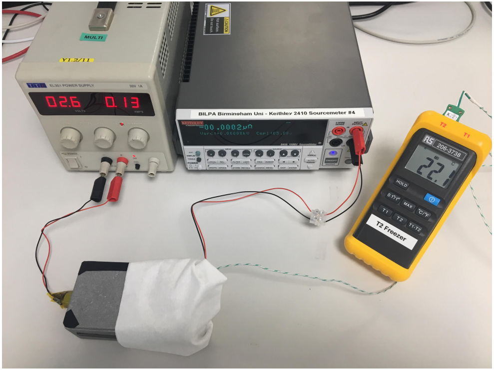
For **IRRAD**, the Results were compared to a similar study undertaken by **I. Mateu** this year.

Other Studies and Current Values

- Current **MC40 cyclotron** value: **2.2** for **25 MeV protons** [1].
- **KIT**: $\mathbf{2.05 \pm 0.61}$ for **24 MeV protons**, with a previous assumption of **1.85** for **26 MeV protons** [2].
- **Tabulated values** from RD50: $\sim$ **2.56** for **25 MeV protons** [3].
- Studies at the **IRRAD facility**: **0.56** (2015), and **0.60** (2016) for **24 GeV protons** [4].

I–V Measurements

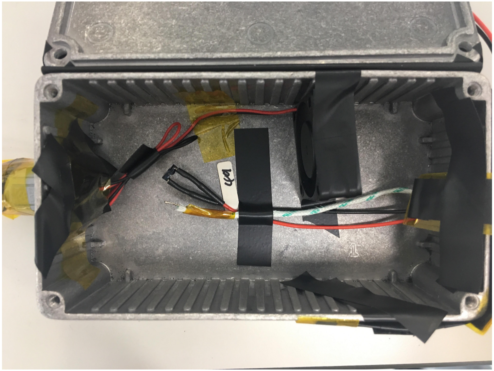
Setup



Experimental setup for I–V measurements.

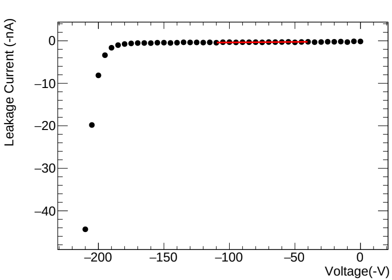
- Aluminium shielded box containing the photodiode.
- Keithley 2410 Source Meter for I–V measurements of the photodiode.
- Thermocouple to monitor temperature.
- Power supply for a fan within the box.

I–V Measurements
Setup

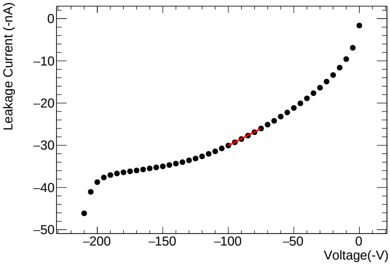


Aluminium shielding box.

- Thermocouple fixed close to the photodiode.
- Electric fan for air circulation.
- Tape across any gaps in the box to block out light.
- The lid of the box could be closed to shield the system in Aluminium.



Unirradiated.



Irradiated, post-annealing $(1.56 \pm 0.34) \times 10^{11}\mathrm{p/cm^2}$.

C–V Measurements

Current – Voltage Relation and Maximum Depletion Voltage.

- The **capacitance** of a photodiode is related to the **reverse bias** by [5]:

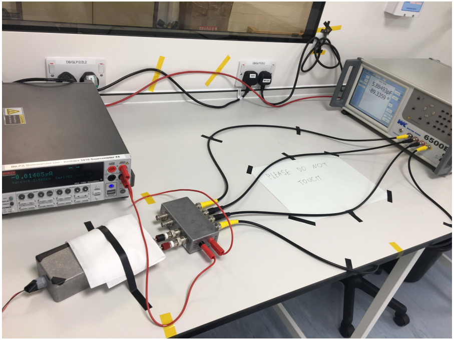
$$C = \frac{f\sqrt{\epsilon_{Si}\epsilon_0}}{\sqrt{V}}$$

- 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

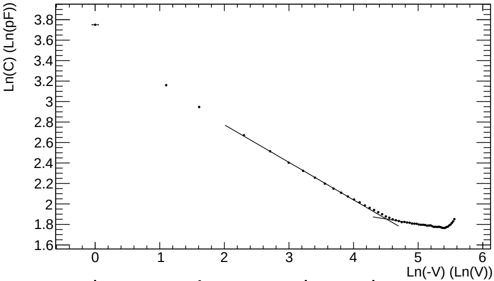
Setup



Experimental setup for C–V measurements.

- Keithley 2410 Source Meter, Wayne Kerr Component Analyser and photodiode setup connected to a junction box.
- Keithley used to apply bias across the photodiode.
- Wayne Kerr used to measure capacitance across the photodiode at the bias set by the Keithley.

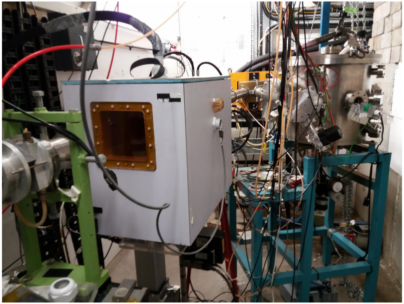
- By calculating the **intersect** of the two fits, the point at which the trend deviates from a straight line could be calculated.
- Applying this method, a maximum depletion voltage value of $\boldsymbol{V_{dep} = -90.8 \pm 5.17}$ **V** was inferred.



log capacitance vs log voltage.

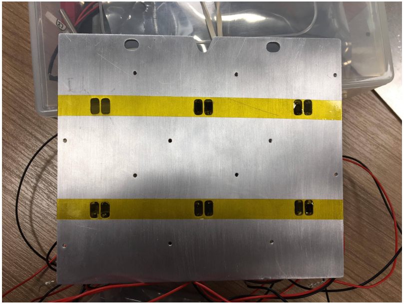
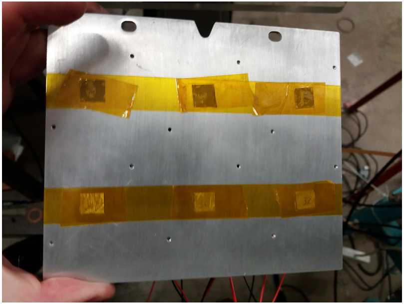
Proton Irradiations

ATLAS Chamber



The environmental chamber at the MC40 high intensity irradiation facility. The photodiodes were installed in the chamber using dedicated aluminium mounts, and then irradiated at -27°C.

$\otimes$ Beam direction.

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

Computing Hardness Factors

Leakage Current Variation with Fluence

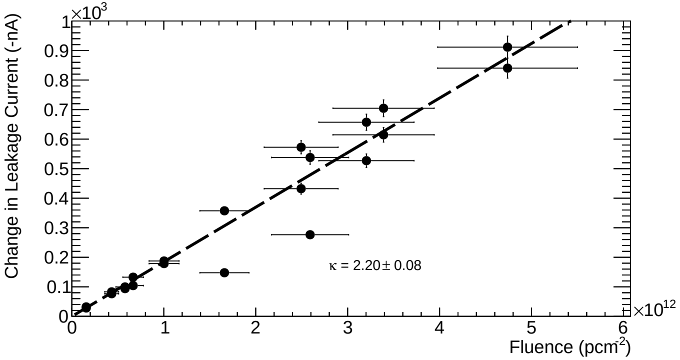
- Post irradiation, all photodiodes were annealed for 80 minutes at 60°C.
- The **change in leakage current** before and after irradiation is related to **proton fluence** by [6]:

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

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

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

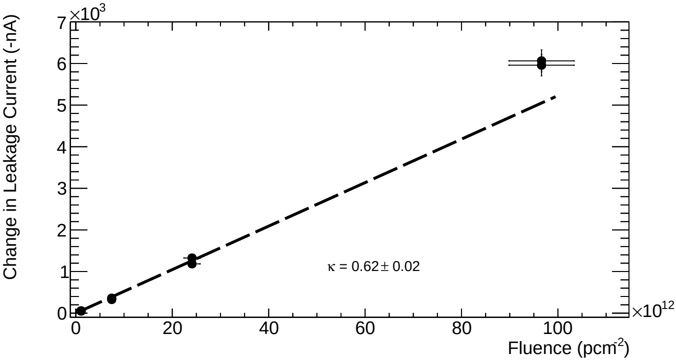
Where $\alpha_{neq} = (3.99 \pm 0.03) \times 10^{-17}$ Acm^{-1} [6].



From this, a value of $\kappa_{MC40} = \mathbf{2.20 \pm 0.08}$ for **25 MeV protons** was inferred. These data were obtained with BPW34F photodiodes.

Results

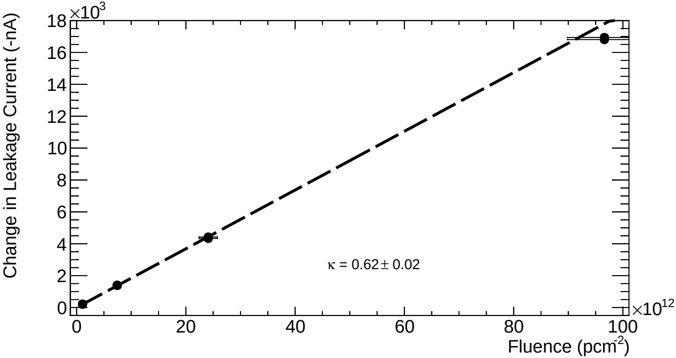
Hardness Factor of the IRRAD Proton Facility



Using the same method as for the MC40 Cyclotron, a value of $\kappa_{IRRAD} = \mathbf{0.62 \pm 0.02}$ for **24 GeV protons** was inferred. These data were also obtained with BPW34F photodiodes.

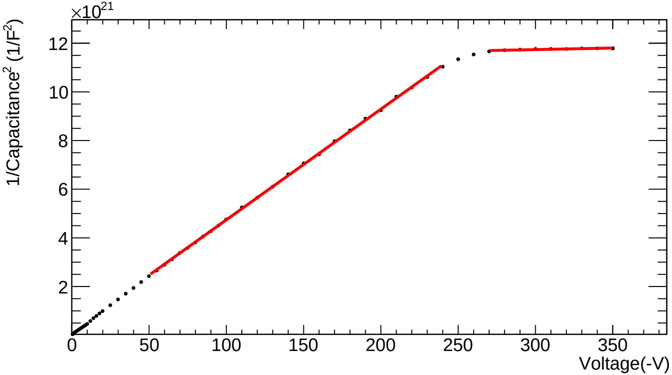
Results

Hardness Factor of the IRRAD Proton Facility - Comparison with I. Mateu's Data



Analysis of I. Mateu's data yields a value of $\kappa_{Mateu} = \mathbf{0.62 \pm 0.02}$ with all points included, which is in agreement with his own analysis and our result. These data were obtained with FZ pad diodes.

For I. Mateu's data, the **maximum depletion voltage** was calculated for each sensor, and so **was not kept constant** across all data points.



Example $\frac{1}{C^2}$ –V curve for I. Mateu's data analysis.

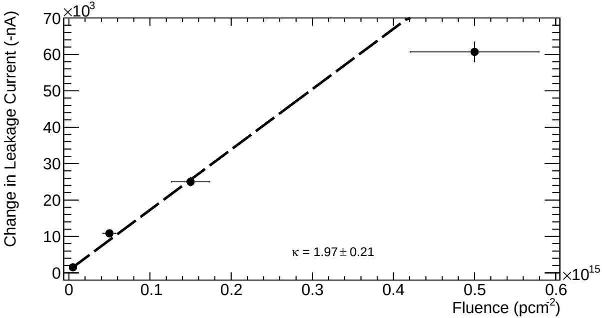
Results

Hardness Factor of the IRRAD Proton Facility - Comparison with I. Mateu's Data

Sensor Name	Max. Dep. Voltage (-V)	Fluence (p/cm^2)
W332-C4	249.52 ± 0.09	7.44×10^{12}
W332-F2	83.13 ± 0.52	9.66×10^{13}
W332-F8	190.97 ± 1.44	2.41×10^{13}
W332-M10	281.09 ± 0.13	1.09×10^{12}
W332-M12	80.74 ± 0.35	9.66×10^{13}
W332-M4	281.68 ± 0.13	1.09×10^{12}
W332-M6	207.36 ± 0.89	2.41×10^{13}
W332-M7	252.41 ± 0.15	7.44×10^{12}

Table: Obtained maximum depletion voltages for I. Mateu's data.

Hardness Factor of the KIT Irradiations Facility



For KIT, a value of $\boldsymbol{\kappa_{KIT} = 1.97 \pm 0.21}$ for **23 MeV protons** was obtained. These data were obtained with BPW34F photodiodes.

Conclusion and Outlook

- The **I–V** and **C–V characteristics** of **BPW34F photodiodes** have been analysed.
- Using these characteristics, **hardness factors** for various **proton beams** have been determined.
- The results are in good agreement with other studies.
- In the future, it is suggested that studies are done to determine the **current related damage rate** for **neutrons** (This study assumed a value of $\alpha_{neq} = (3.99 \pm 0.03) \times 10^{-17}$ Acm^{-1} [6]), and therefore, determine **independent hardness factor values**.

References I

- T. Price. *Experimental Determination of the Hardness Factor for the Birmingham Irradiation Facility*. 30th RD50 Workshop (Krakow). June 2017. URL: https://indico.cern.ch/event/637212/contributions/2608664/.
- 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.
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References II

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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.

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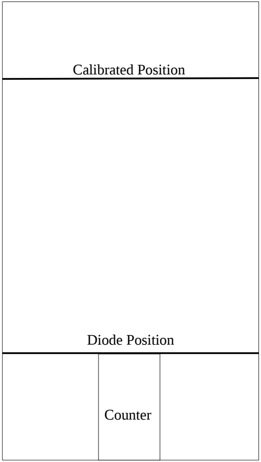
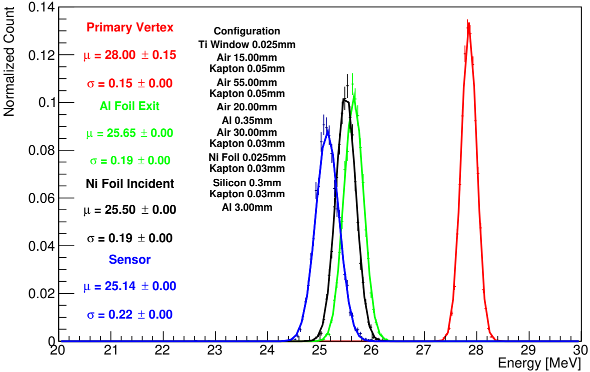


Schematic diagram of germanium counter.

- 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**.



Geant4 simulation revealing the incident beam energy, the energy at the nickel foils, and the energy at the sample (Courtesy of Dr. T. Price).