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 proton beams at various energies have been measured.

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

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

Earlier Studies and Current Hardness Factor Values

- Current **MC40 cyclotron** value: **2.2** for **25 MeV protons**[1].
- **KIT**: **2.05 ± 0.61** for **24 MeV protons**, and an earlier value of **1.85** for **26 MeV protons**[2].
- **RD50 Tabulated values**: $\sim$ **2.56** for **25 MeV protons**[3].
- Studies at **IRRAD facility**: **0.56** (2015), and **0.60** (2016) for **24 GeV protons**[4].

C–V Measurements

Current – Voltage Relation and Maximum Depletion Voltage.

- The **capacitance**, C, of a photodiode, before **maximum depletion** is reached, is related to the **reverse bias**, V, by [5]:

$$C = A\sqrt{\frac{q\epsilon_{Si}N_{eff}}{2}}\frac{1}{\sqrt{V}}$$

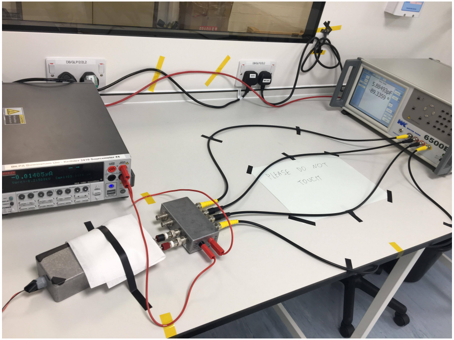
where A is the surface area of the diode, N_{eff} is a parameter related to the resistivity of the material, and all other symbols have their usual meanings.

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

- Plotting **capacitance vs voltage** on a log plot should therefore show a straight line, becoming **flat** for maximum depletion.

C–V Measurements

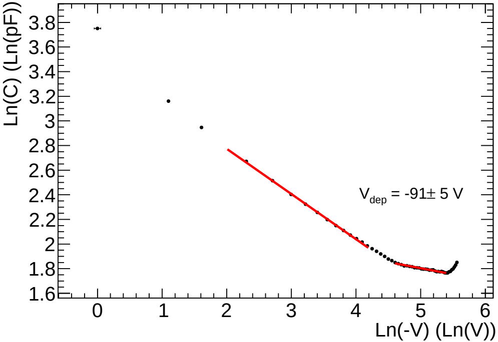
Setup

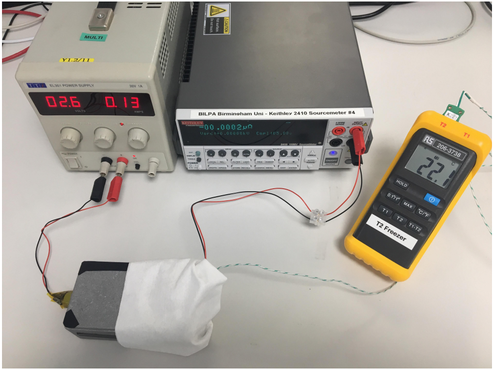


Experimental setup for C–V measurements.

- **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.

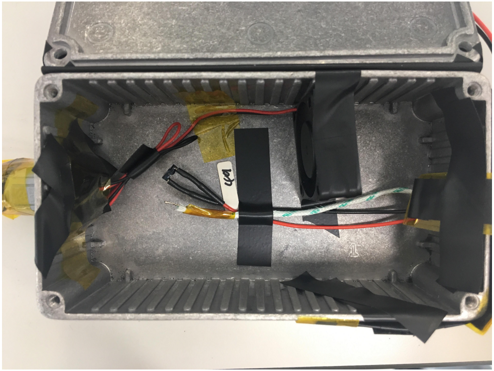
- By calculating the **intercept** of the two fits, **the maximum depletion voltage** could be calculated.
- Applying this method, a maximum depletion voltage value of $\boldsymbol{V_{dep} = -91 \pm 5}$ **V** was inferred.





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.

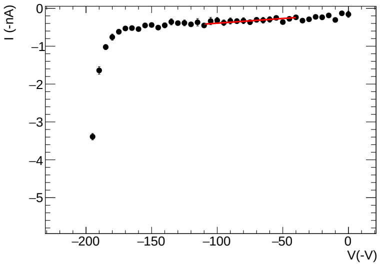


Aluminium shielding box.

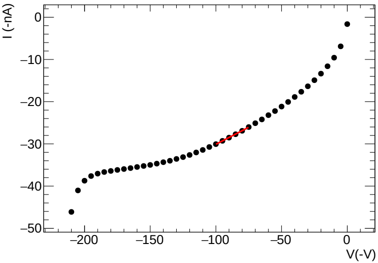
- **Thermocouple** fixed close to the photodiode.
- **Electric fan** for air circulation.
- **Tape** across any gaps in the box to **block out light**.
- The lid of the box could be closed to **shield the system** in Aluminium.

I–V Measurements

Results



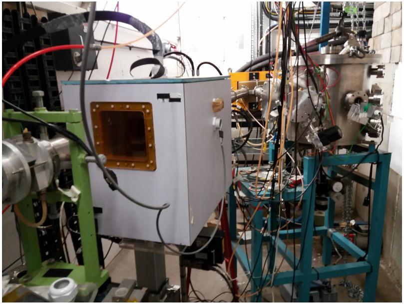
Unirradiated.



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

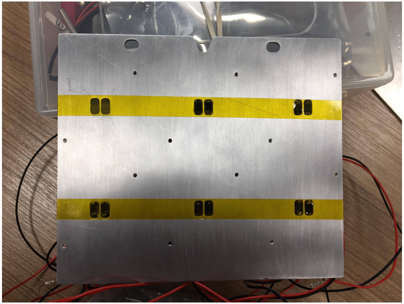
The fits were evaluated at the **maximum depletion voltage**.

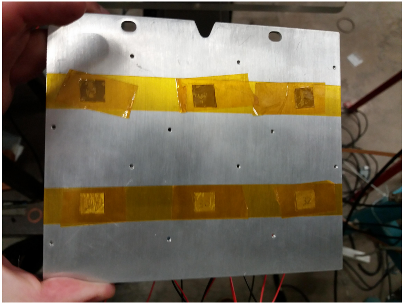
Proton Irradiations
ATLAS Chamber




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

⊗ Beam direction.





Aluminium mount.

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** pre- and post- irradiation is related to **proton fluence** by[6]:

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

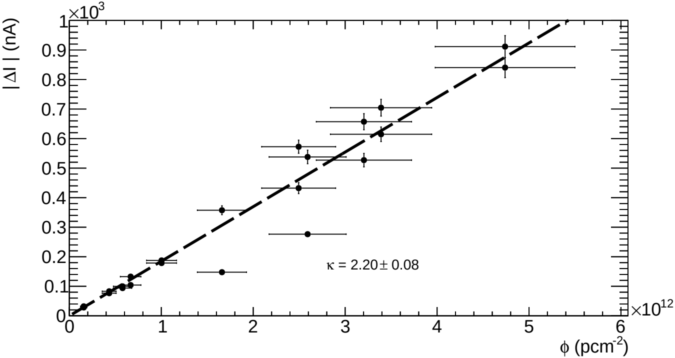
where L^2 is the **active area of the silicon**, w is the **maximum depletion width**, and ϕ is the **incident proton fluence**. The **hardness factor** can be written as:

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

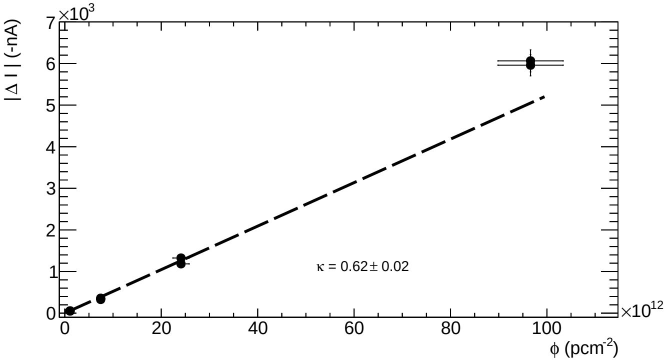
where α is the **current related damage rate** for protons, ϕ_{neq} is the **1 MeV neutron equivalent fluence**, and $\alpha_{neq} = (3.99 \pm 0.03) \times 10^{-17}$ Acm^{-1}[6] (1 MeV neutron equivalent current related damage rate).

Results

Hardness Factor of the MC40 Cyclotron



A value of $\kappa_{MC40} = \mathbf{2.20 \pm 0.08}$ for **25 MeV protons** was inferred, using BPW34F photodiodes.

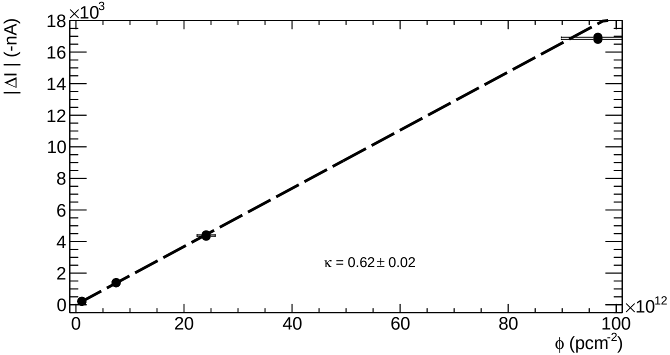


Using the same method, a value of $\kappa_{IRRAD} = \mathbf{0.62 \pm 0.02}$ for **24 GeV protons** was inferred. These data were also obtained with BPW34F photodiodes.

Results

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

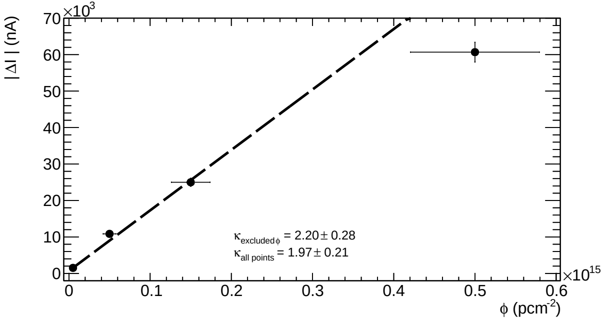
I.Mateu collected data with **FZ pad diodes**. Analysis of their data excluding the points at $\sim 10^{14}$p/cm^2 yielded a value of $\boldsymbol{\kappa = 0.63}$.



I. Mateu's data were **reanalysed** at the University of Birmingham, consistent results were obtained. From including all data points, $\boldsymbol{\kappa = 0.62 \pm 0.02}$.

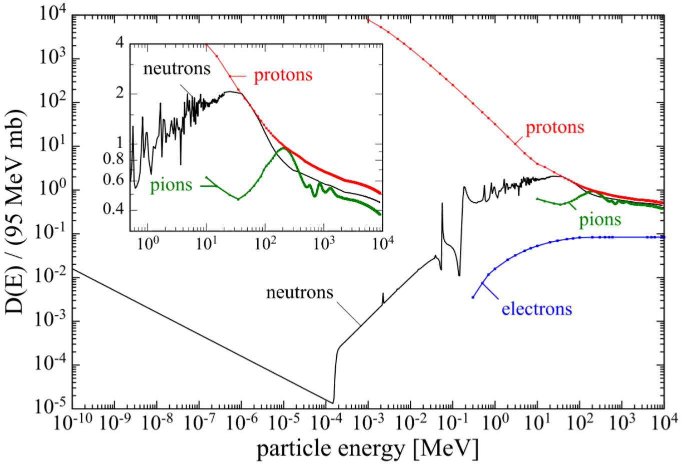
Hardness Factor of the KIT Irradiations Facility

For KIT, with BPW434F photodiodes, a value of $\kappa_{KIT} = \mathbf{1.97 \pm 0.21}$ for **23 MeV protons** was obtained.



However, based on [7], for fluences greater than $\sim \mathbf{5 \times 10^{13} n_{eq}/cm^2}$, there is a **non-linear response**. Hence, excluding the highest fluence point, a value of $\kappa_{KIT} = \mathbf{2.20 \pm 0.28}$ was determined.

Displacement Damage Function



Displacement Damage as a Function of Energy[8].

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 earlier studies.

Facility	Hardness Factor	Energy
MC40 Cyclotron	2.20 ± 0.08	25 MeV
IRRAD	0.62 ± 0.02	24 GeV
KIT	2.20 ± 0.28	23 MeV

- 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

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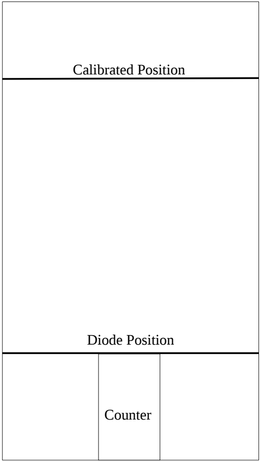
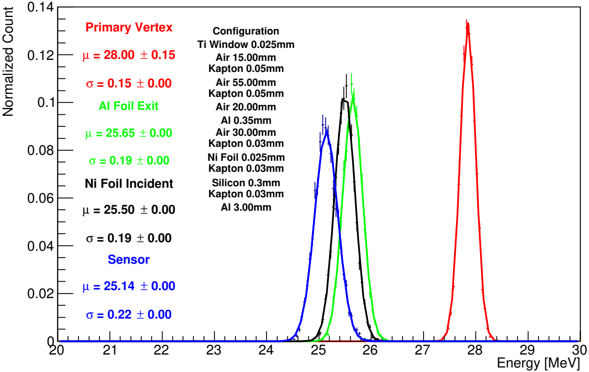


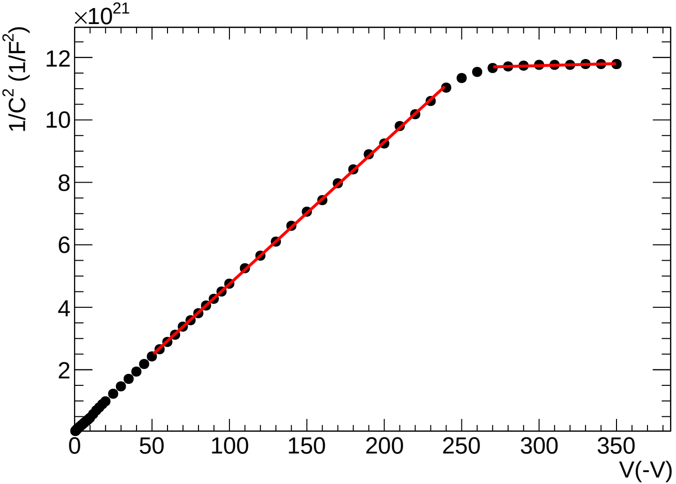
Schematic diagram of germanium counter.

- 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 T. Price).

For I. Mateu's data, the **maximum depletion voltage** was calculated for each sensor, as opposed to keeping a constant value.



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.