Determination of Proton Hardness Factors with Commercial PiN Diodes

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Radiation Hardness Testing Facilities

- Radiation hardness studies are critical for HL-LHC detectors
- Global campaign to characterise sensors and components
- Transnational access granted to 10 European facilities by AIDA-2020

Transnational Access

AIDA-2020 Transnational Access supports small teams to carry out experiments and tests at one of the 10 European facilities listed below. By clicking on the facilities' name you will access a video providing more information on the available equipment.

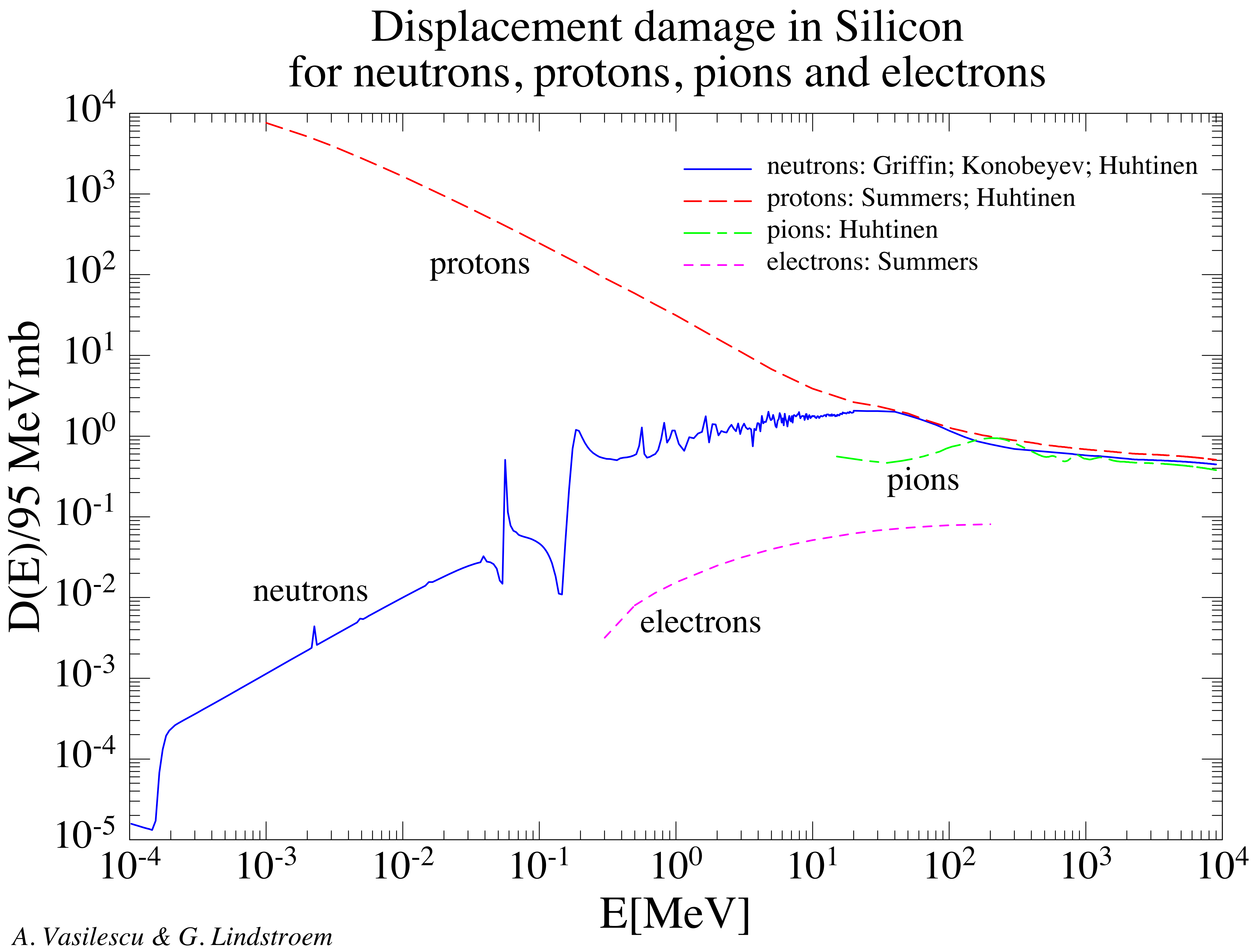
Type of facility	Access provider	Infrastructure	Country	Facility Coordinator Contact
Beam test	CERN	PS&SPS	International Organisation	Henric Wilkens
	DESY	DESY-II	Germany	Marcel Stanitzki
Irradiation test	CERN	IRRAD	International Organisation	Michael Moll
	CERN	GIF++	International Organisation	Michael Moll
	JSI	TRIGA Reactor	Slovenia	Vladimir Cindro
	KIT	KAZ	Germany	Alexander Dierlamm
	UCLouvain	CRC	Belgium	Eduardo Cortina Gil
	UoB	MC40 Cyclotron	UK	David Parker
Detector characterisation	RBI	RBI-AF	Croatia	Stjepko Fazinić
	ITAINNOVA	EMClab	Spain	Fernando Arteche

NIEL and Hardness Factor

- Fluences expressed **in 1 MeV neutron equivalent (n_{eq})** for comparison
- Related by **Hardness Factor** κ
- Usually calculated from **bulk leakage current change ΔI** following irradiation
- Assumption: ΔI scales with Non-Ionising Energy Loss (NIEL)

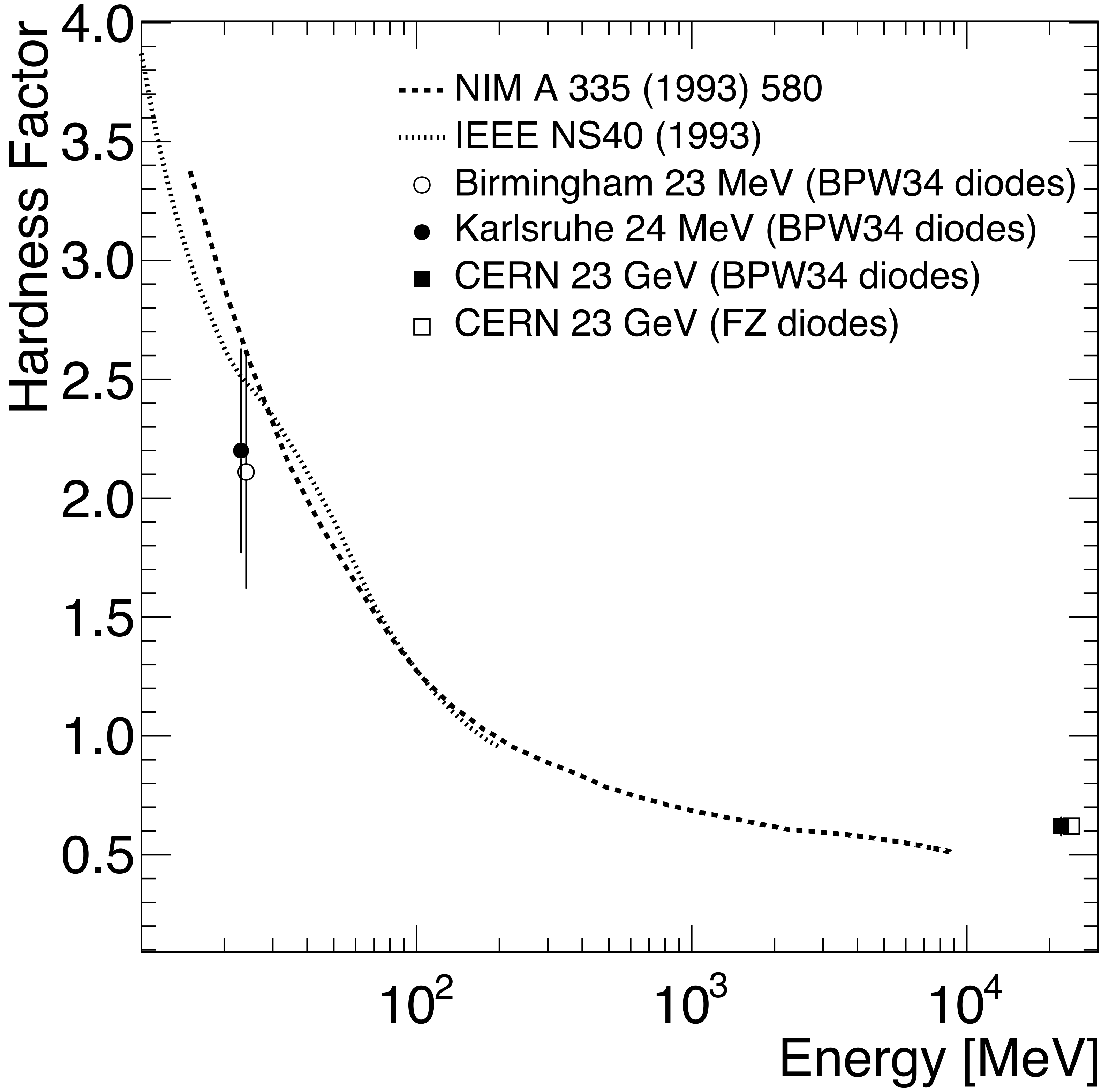
Standard procedure to get κ:

- Measure ΔI after irradiation
- Fit ΔI/(depleted volume) vs fluence to get α
- $\kappa = \alpha/\alpha_{neq}$



Standardisation of Hardness Factor Measurements

- Clear need to standardise hardness factor measurements
- Collaboration between University of Birmingham, Karlsruhe Institute of Technology, CERN
- Consistent methodology between facilities



UNIVERSITY OF BIRMINGHAM

KIT Karlsruher Institut für Technologie

CERN | IRRAD Proton Facility

JINST 14 (2019) p12004

Experimental determination of proton hardness factors at several irradiation facilities

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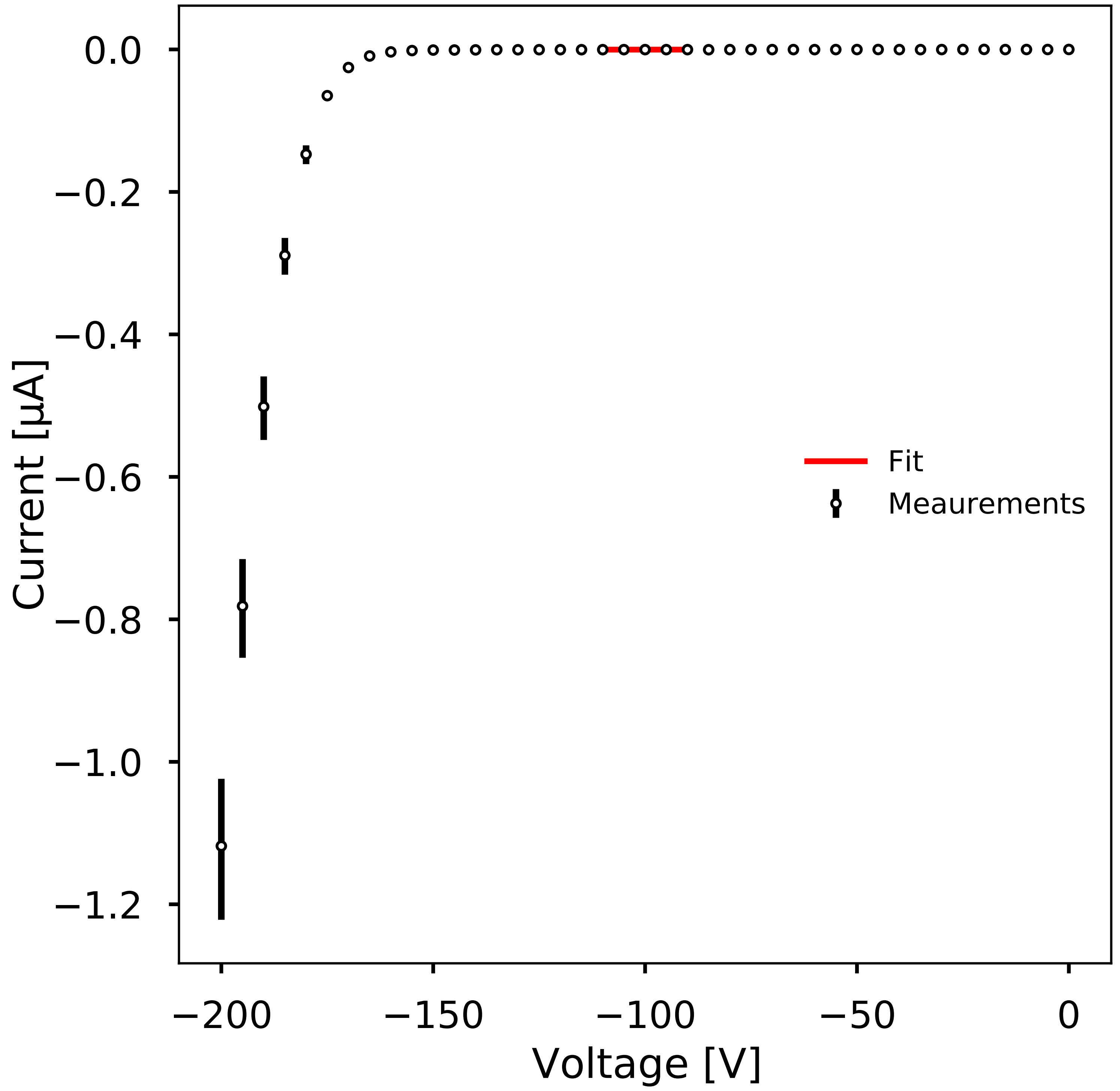
ABSTRACT: The scheduled High Luminosity upgrade of the CERN Large Hadron Collider presents new challenges in terms of radiation hardness. As a consequence, campaigns to qualify the radiation hardness of detector sensors and components are undertaken worldwide. The effects of irradiation with beams of different particle species and energy, aiming to assess displacement damage in semiconductor devices, are communicated in terms of the equivalent 1 MeV neutron fluence, using the hardness factor for the conversion. In this work, the hardness factors for protons at three different kinetic energies have been measured by analysing the I–V and C–V characteristics of reverse biased diodes, pre- and post-irradiation. The sensors were irradiated at the MC40 Cyclotron of the University of Birmingham, the cyclotron at the Karlsruhe Institute of Technology, and the IRRAD proton facility at CERN, with the respective measured proton hardness factors being: 2.1 ± 0.5 for 24 MeV, 2.2 ± 0.4 for 23 MeV, and 0.62 ± 0.04 for 23 GeV. The hardness factors currently used in these three facilities are in agreement with the presented measurements.

Commercial Silicon Sensor: BPW34F

- BPW34F diode used for this study
  - PiN photodiode with daylight blocking filter
  - Produced by OSRAM Opto-Semiconductors
  - Commercially available
  - Extensively studied

BPW34F Diode
Active Area: 2.65x2.65 mm^2
Full Depletion Depth: 300 μm



M.Moll, PhD thesis: Hamburg U., 1999

$$\alpha_{n_{eq}} = (3.99 \pm 0.3) \times 10^{-17}\ \mathrm{A/cm}$$

BPW34 Commercial *p-i-n* Diodes for High-Level 1-MeV Neutron Equivalent Fluence Monitoring

Federico Ravotti, *Member, IEEE*, Maurice Glaser, Michael Moll, and Frédéric Saigné

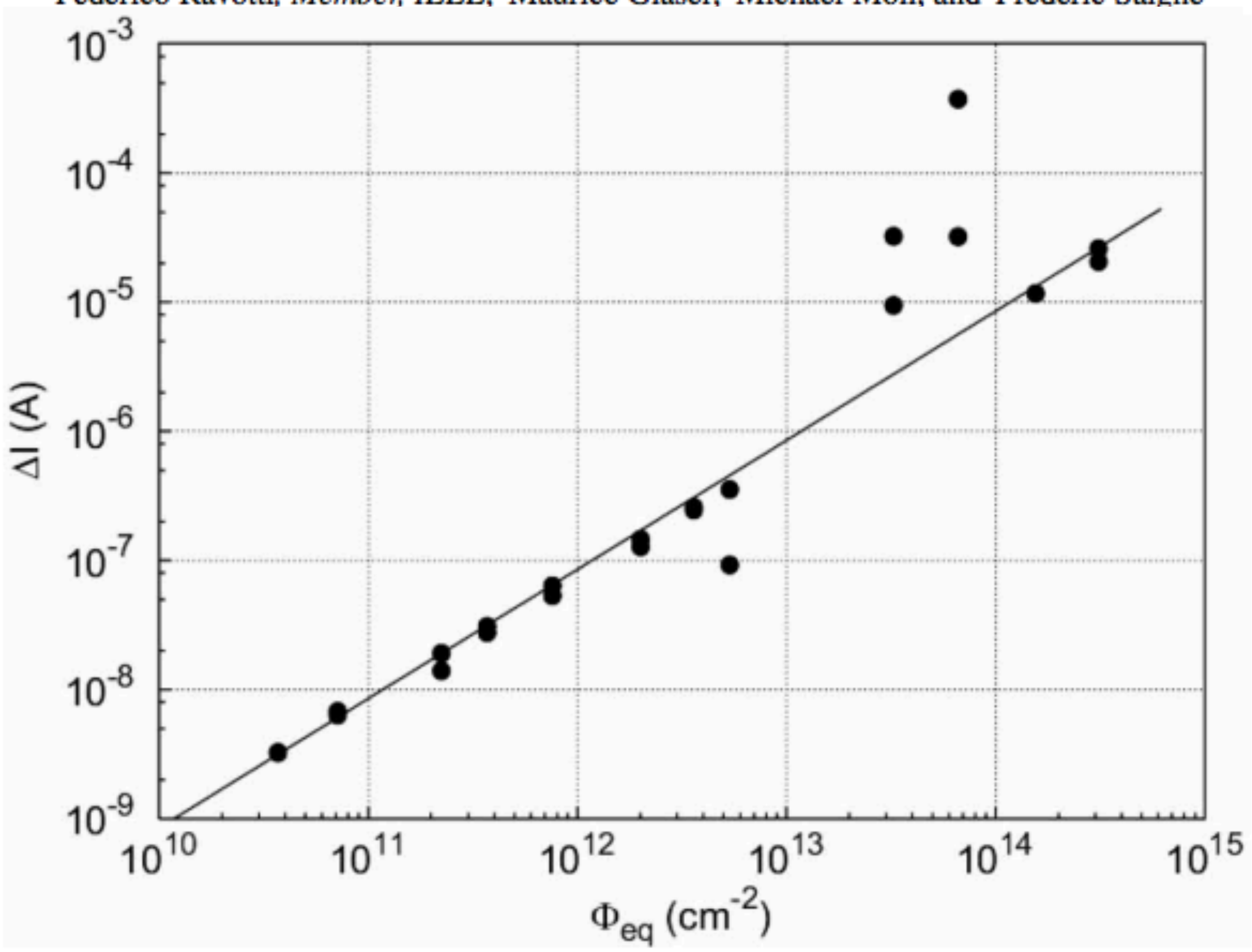
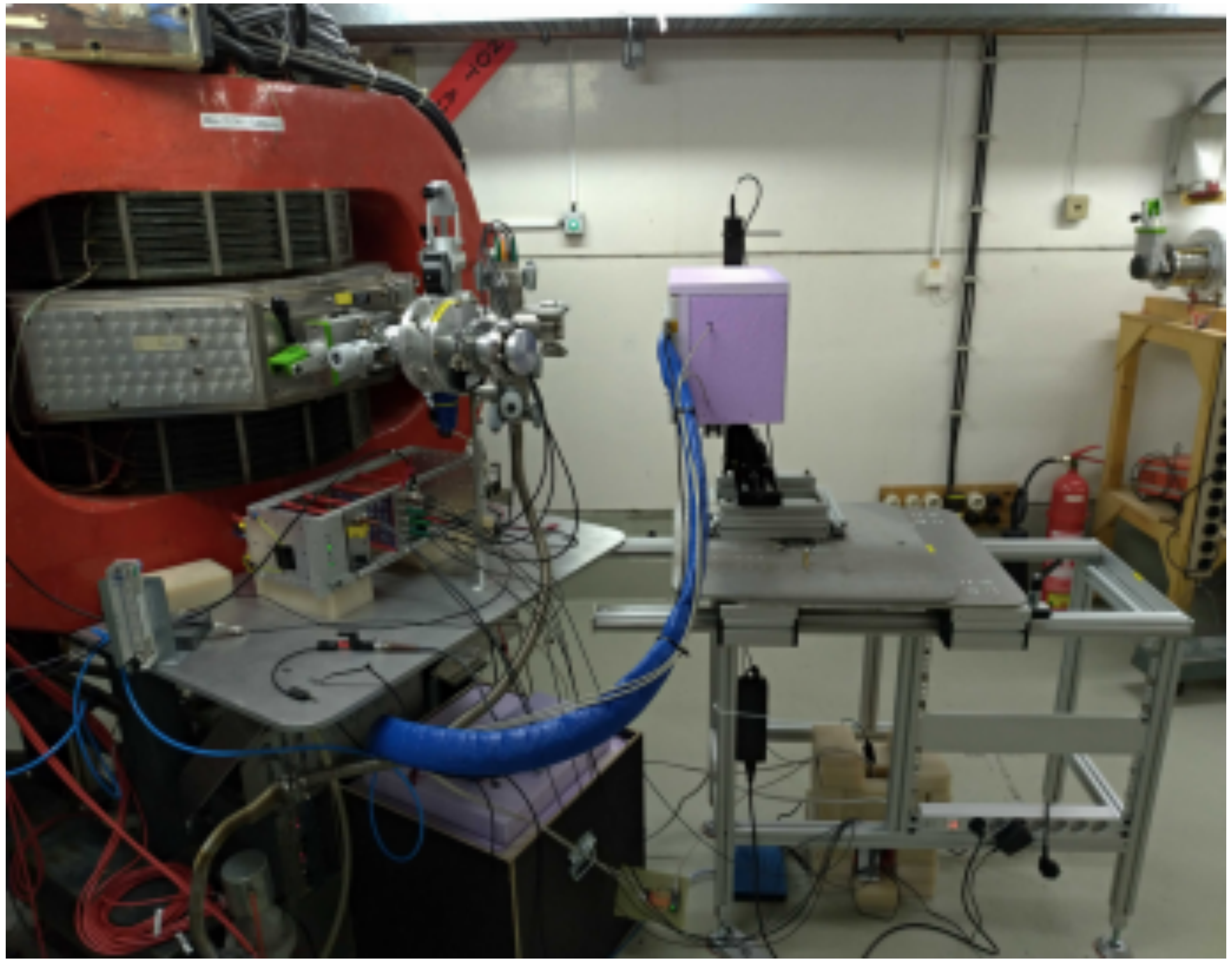


Fig. 3. BPW34F characteristics in reverse bias normalized to 20°C. Leakage current measurement and increasing irradiation levels with 23 GeV protons.

Bonn Isochronous Cyclotron

UNIVERSITÄT BONN

- Electron-Cyclotron-Resonance ion source
  - Protons, deuterons, Alpha, ^{12}C, …
- Kinetic energy 7-14 MeV per nucleon
- Few nA to μA beam current
- Beam profile: mm ≤ ØFWHM ≤ 2 cm
- Flux(1 μA, ØFWHM= 1cm) ≈ 8×10^{12} p/(s·cm^2)
- **S**econdary **E**lectron **M**ultiplier (SEM) to monitor flux
  - $\Delta\phi_p/\phi_p \sim 2\%$

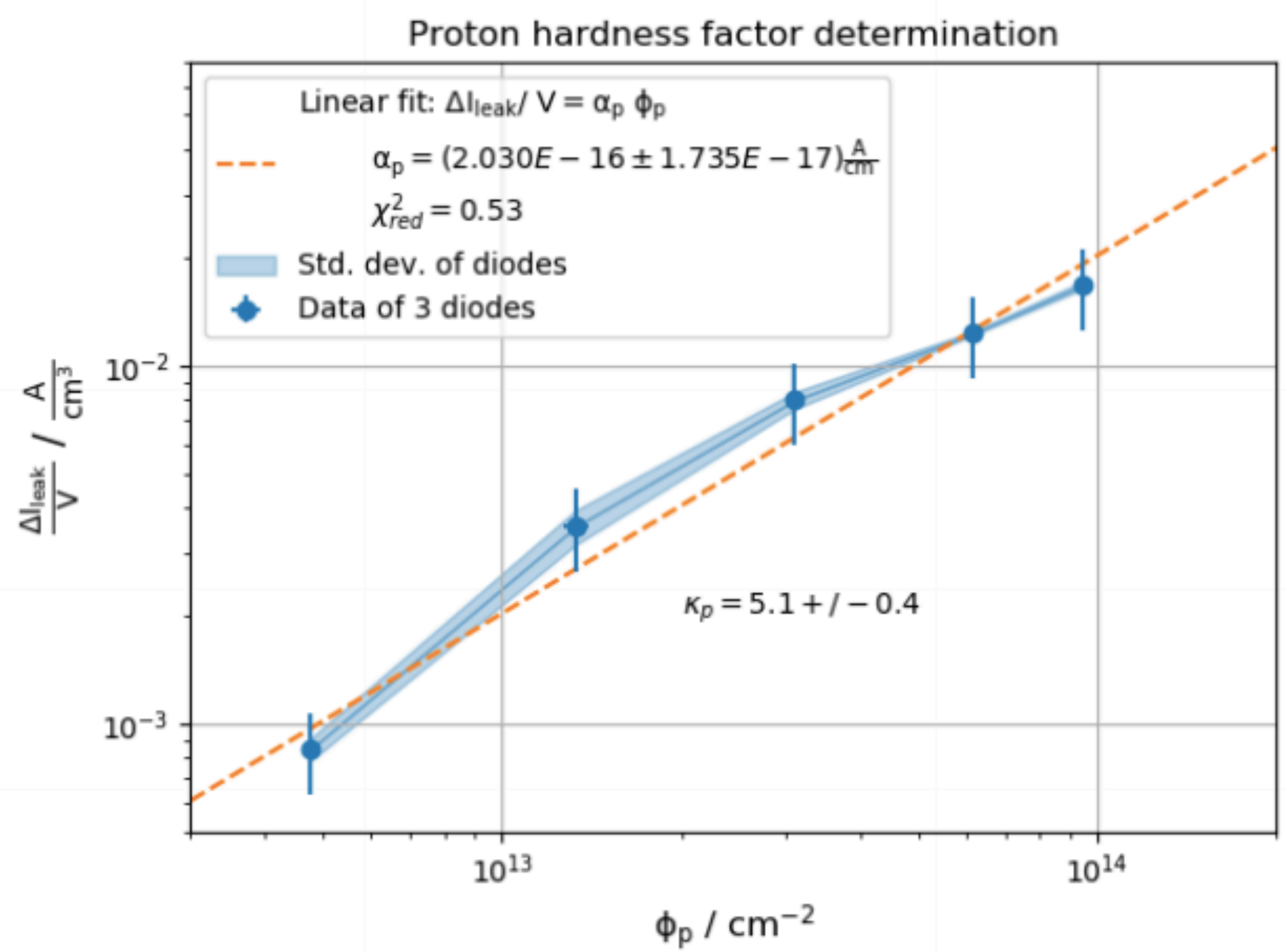


Hardness Factor at Bonn

- Measurements using BPW34F diodes to determine hardness factor
  - Presented at 35th RD50 workshop
- 5 sets of 3 diodes irradiated to fluencies between 4.78E12 p/cm to 9.45E13 p/cm
- Nominal energy at diode: ~12.5 MeV
  - After plastic case: 10.4 MeV (simulation)

Post-irradiation:

- Annealed for 80 minutes at 60°C
- I-V measured at -20°C and scaled to 20°C
  - Leakage current evaluated at 100±10 V
- Found κ = 5.1±0.4
- Diodes sent to Birmingham to be measured with same method as previous study



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BILPA

Birmingham Instrumentation Laboratory for Particle physics and Applications
BILPA

- **B**irmingham **I**nstrumentation **L**aboratory for **P**article physics and **A**pplications - more here
- ISO-14644-1 Class-5 and Class-7 clean room for semiconductor detector system assembly and testing
- Presented measurements conducted in Class-5 cleanroom
- Complemented by on-site proton irradiation facility

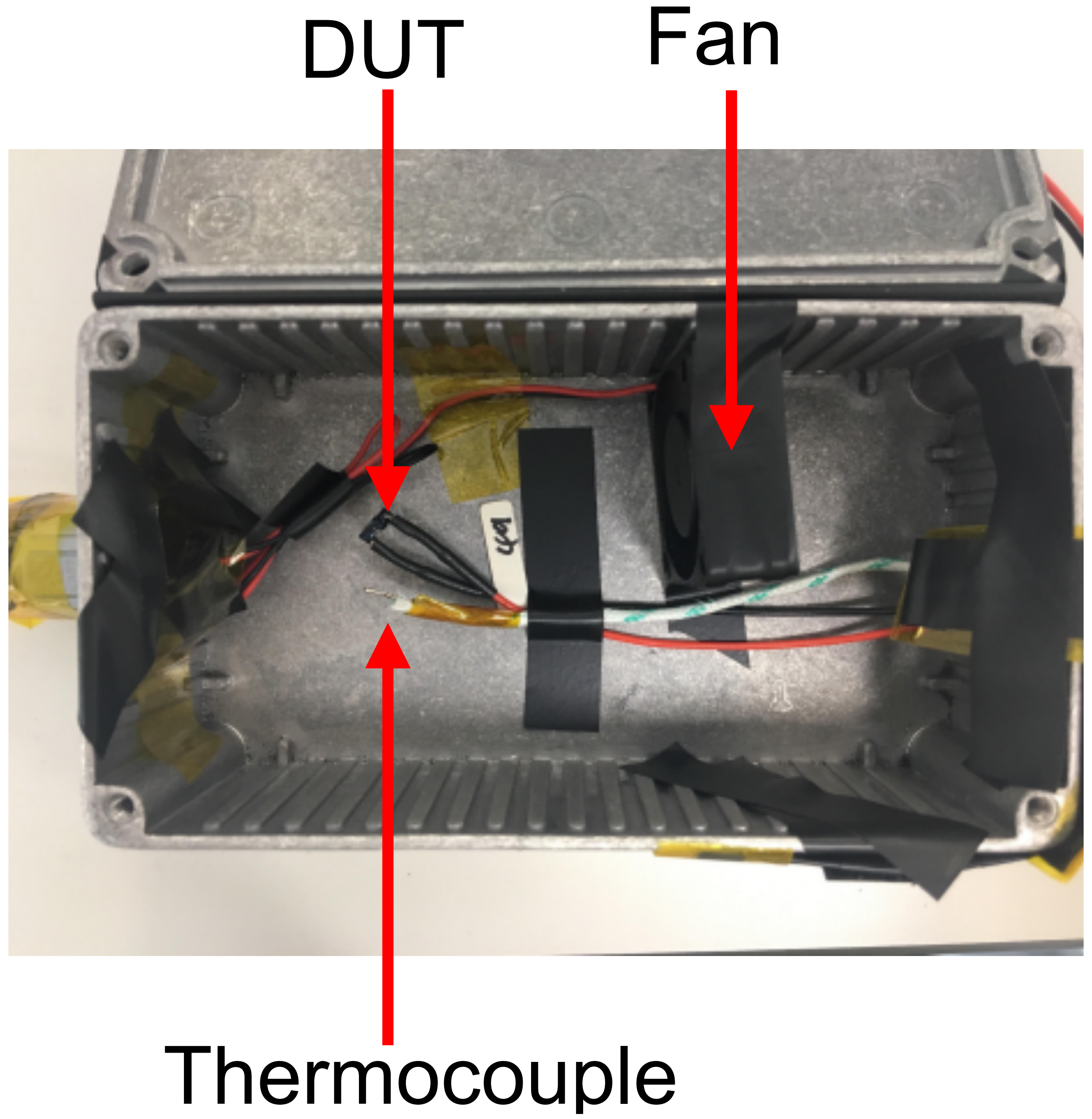
Electrical Measurements

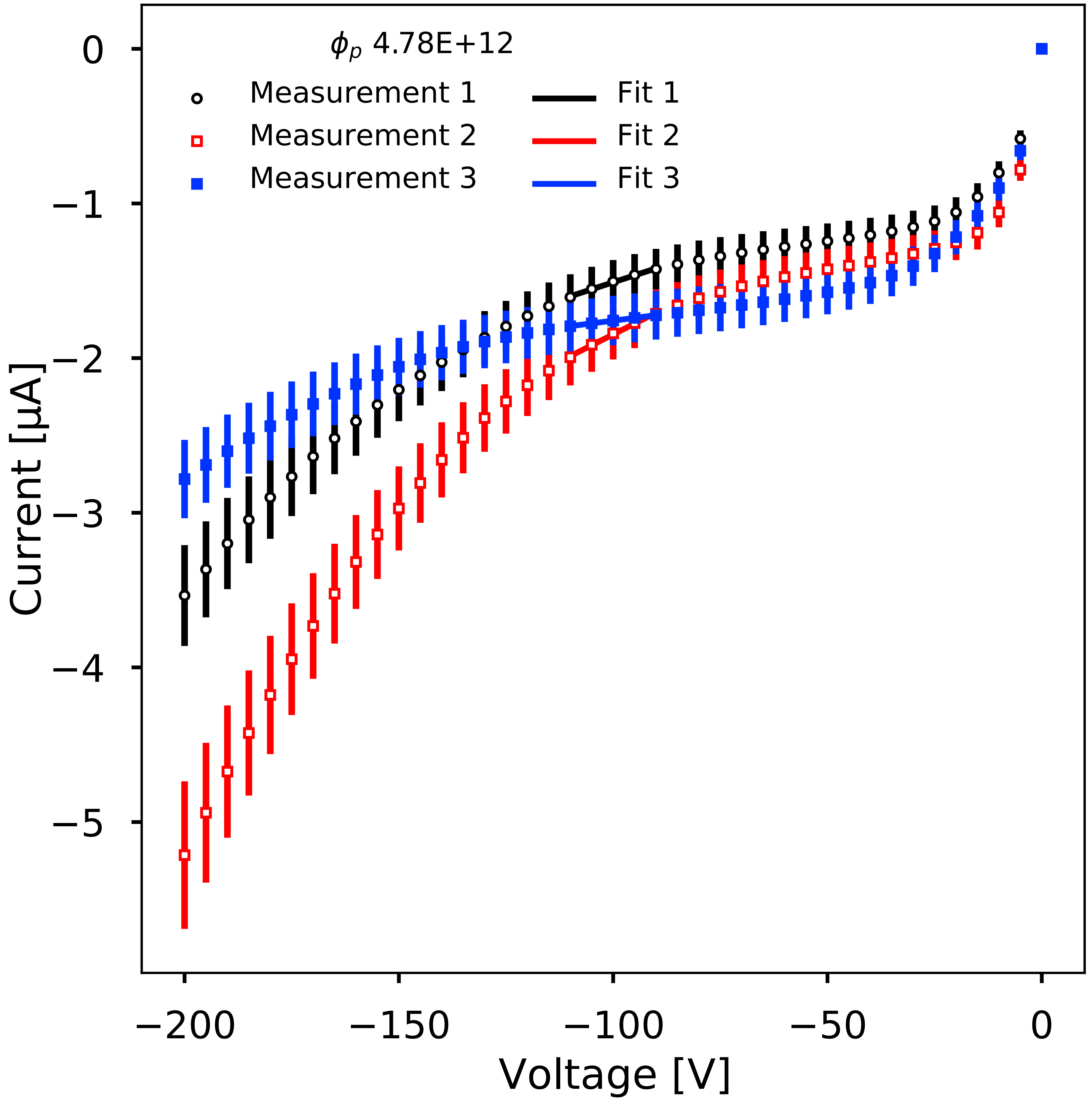
- Measured using procedure described in JINST 14(2019) P12004
- I-V measured with Keithley 2410 source meter
- Measured at room temperature (~22°C) and scaled to 20°C
- Leakage current evaluated at 100±10 V

$$I \propto T^2 \exp\left(\frac{-E_a}{2k_B T}\right)$$

$$E_a = 1.21 \text{ eV}$$

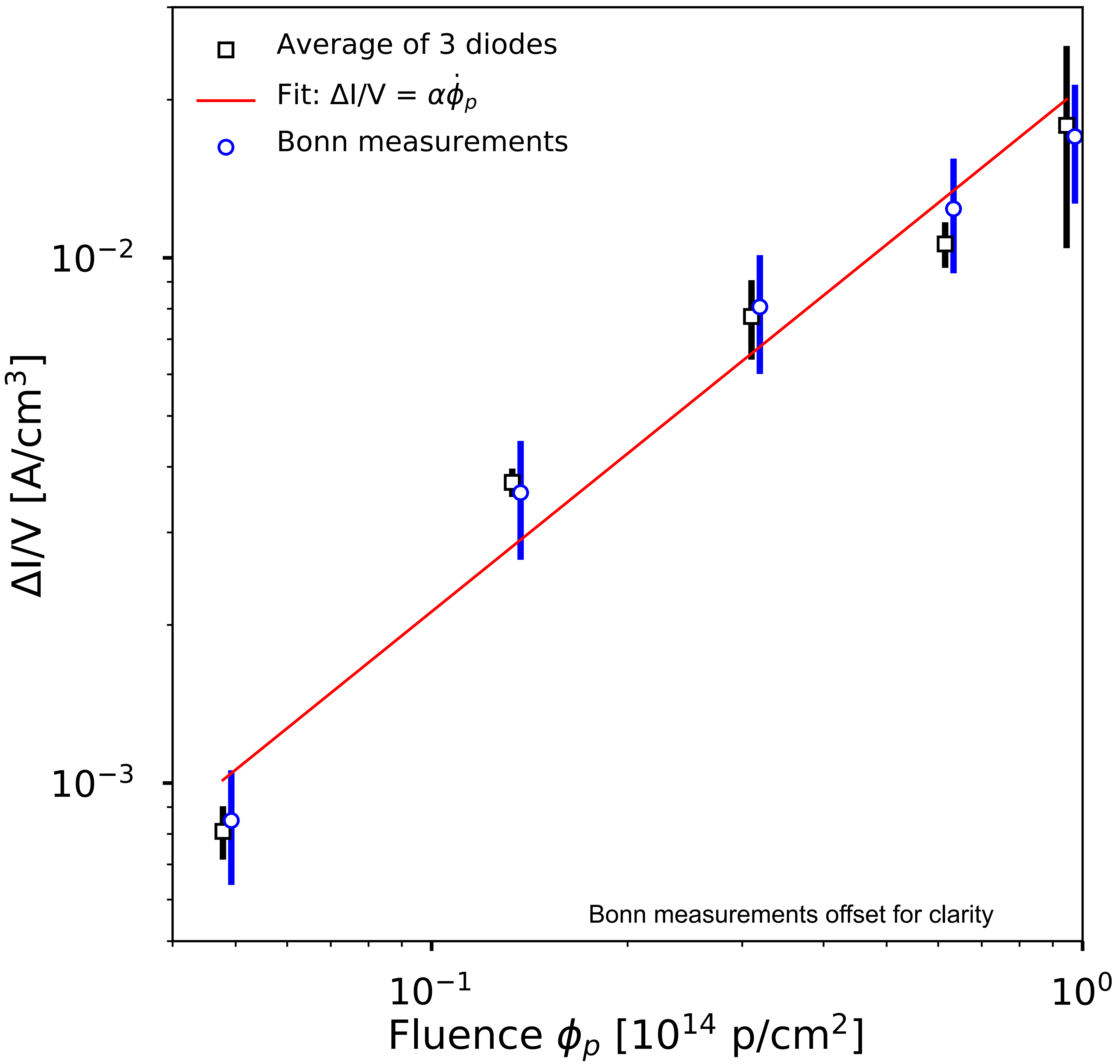
JINST (2013)P10003



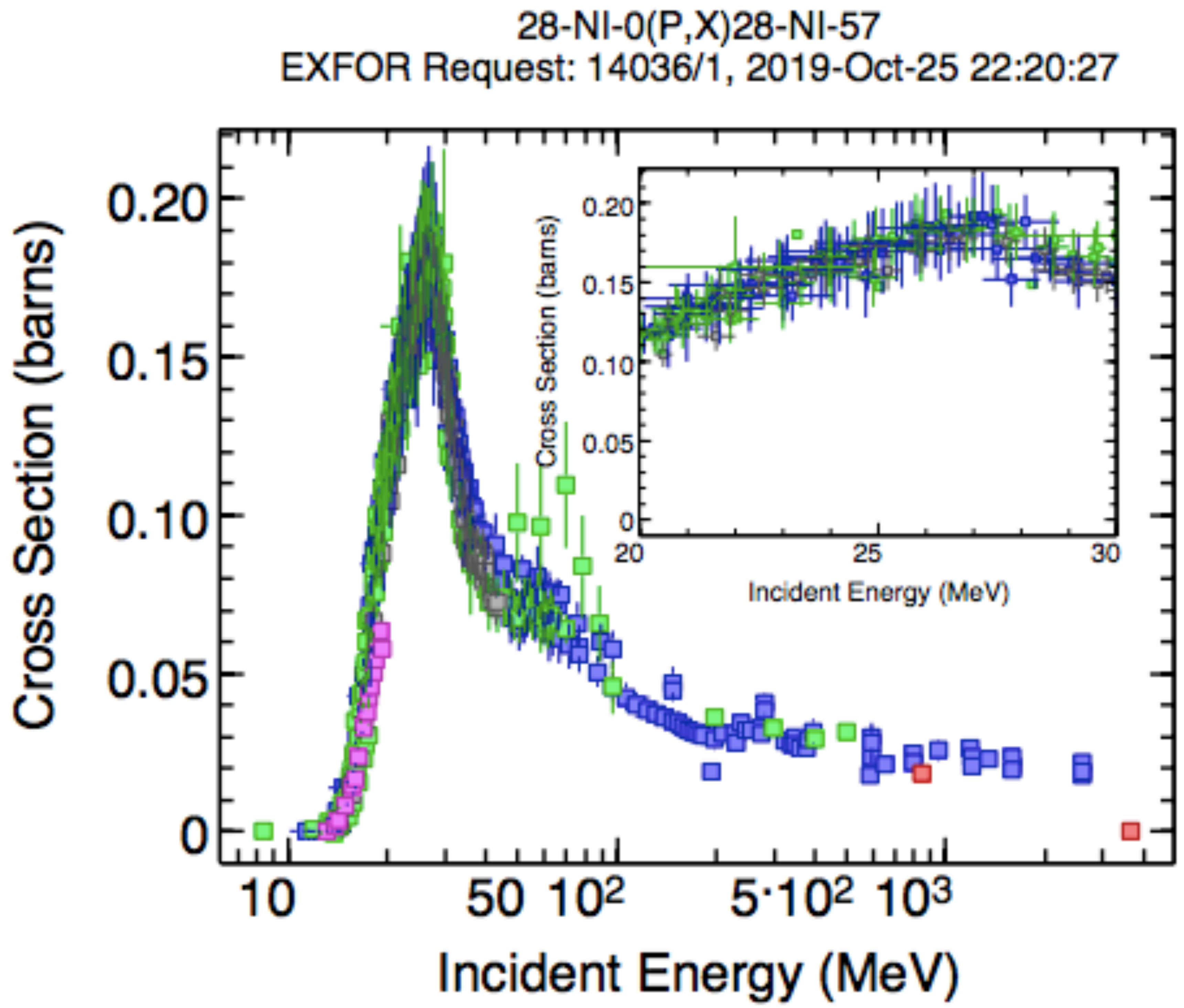


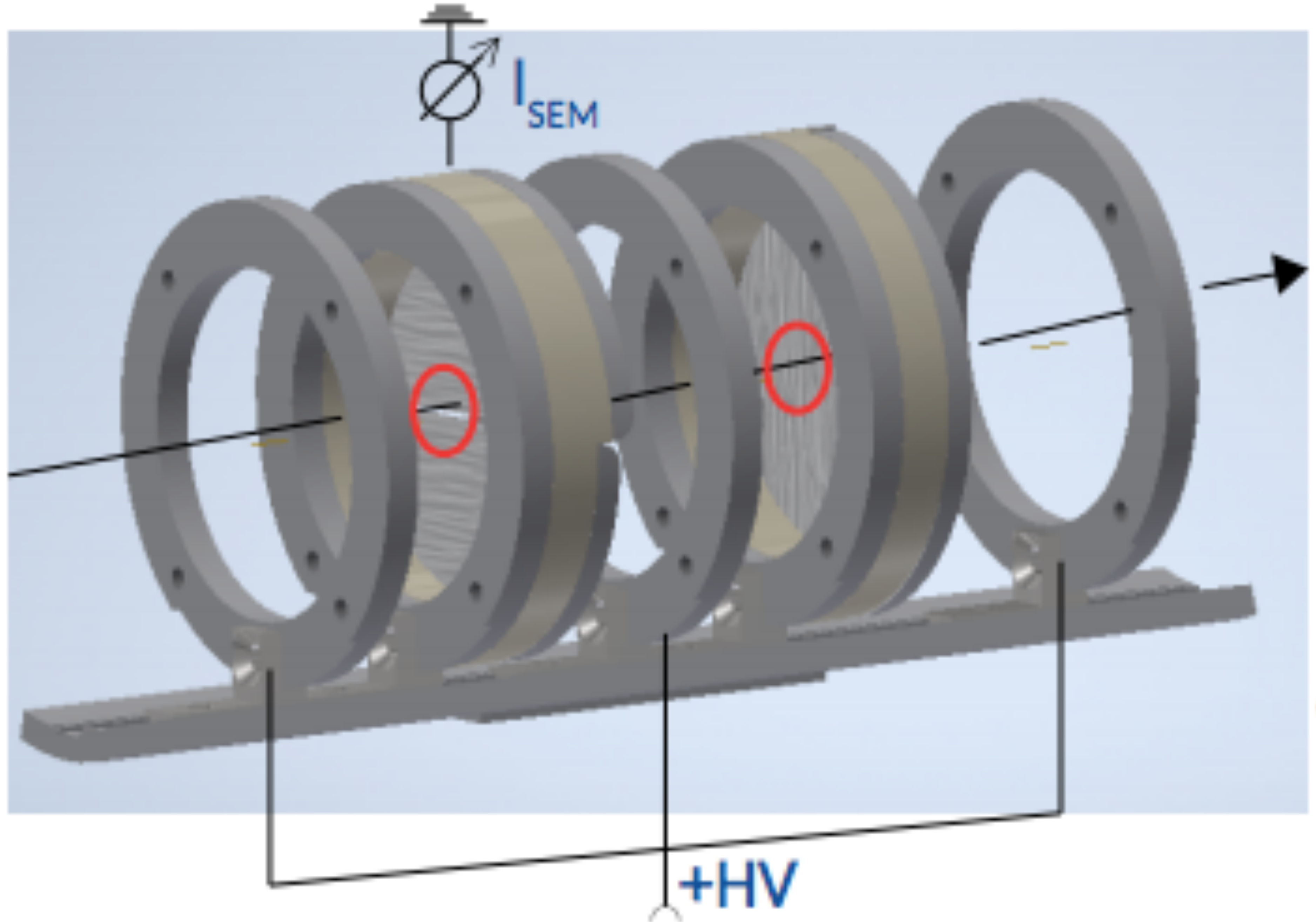
Comparison

- For Birmingham measurements:
  - Linear fit yields α = (2.1 ± 0.3)x10^{-16} A/cm
  - κ = 5.3 ± 0.6
- Good agreement with measurements from Bonn
  - α = (2.0 ± 0.2)x10^{-16} A/cm
  - κ = 5.1 ± 0.4



Fluence Measurements





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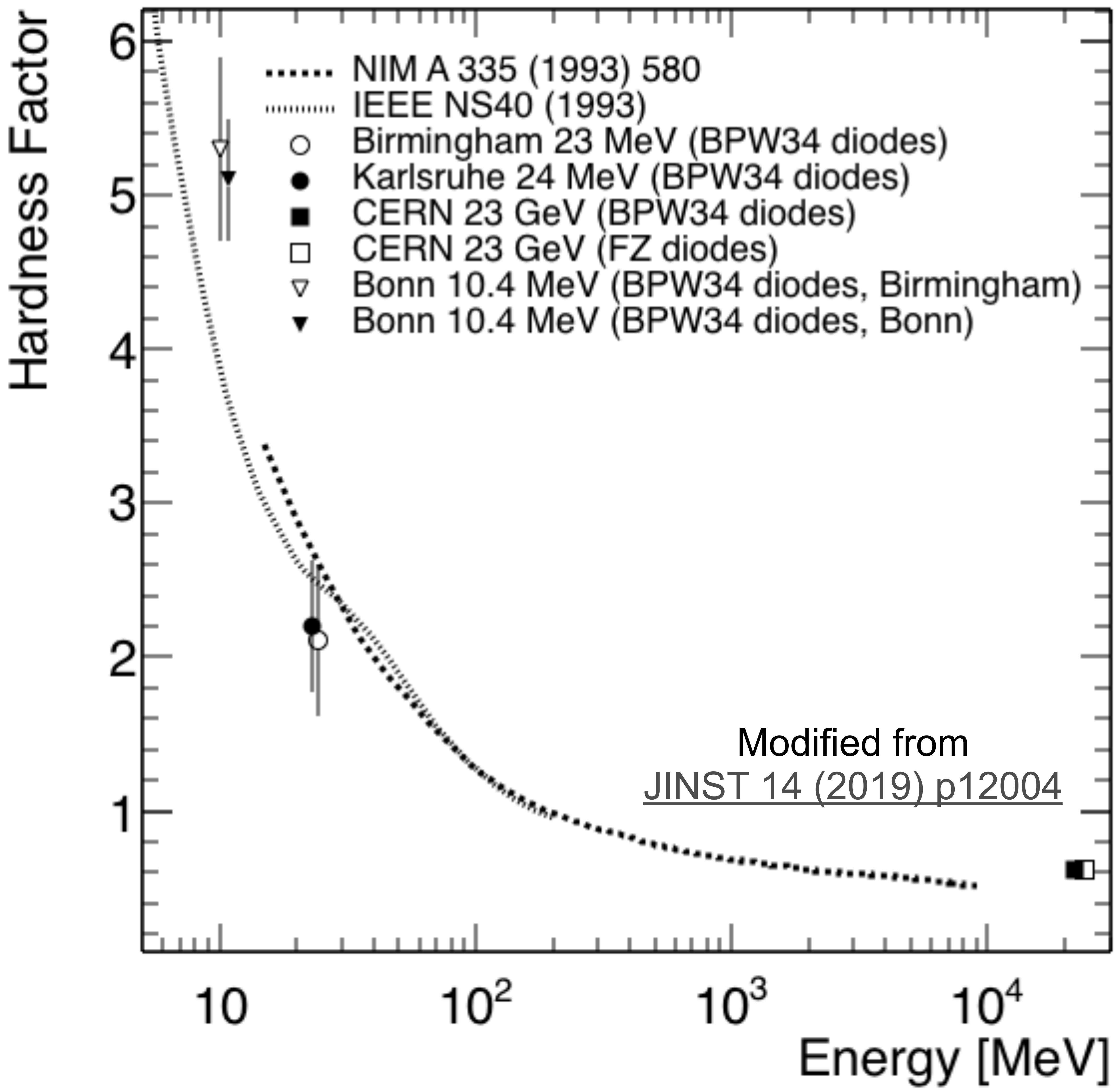
- Fluence uncertainty dominant in previous measurements
- University of Birmingham and KIT use Ni foils dosimetry; ^{28}Ni(p,X)^{28}Ni^{57}
  - Uncertainty on cross-section results in **~20% uncertainty** on fluence measurements
- IRRAD is higher energy - can use Al foils - ~7% uncertainty
- Bonn uses SEM - **~2% uncertainty** - promising development
  - Dominant uncertainty now from difference between repeat measurements and temperature scaling

Results in Context with Other Facilities



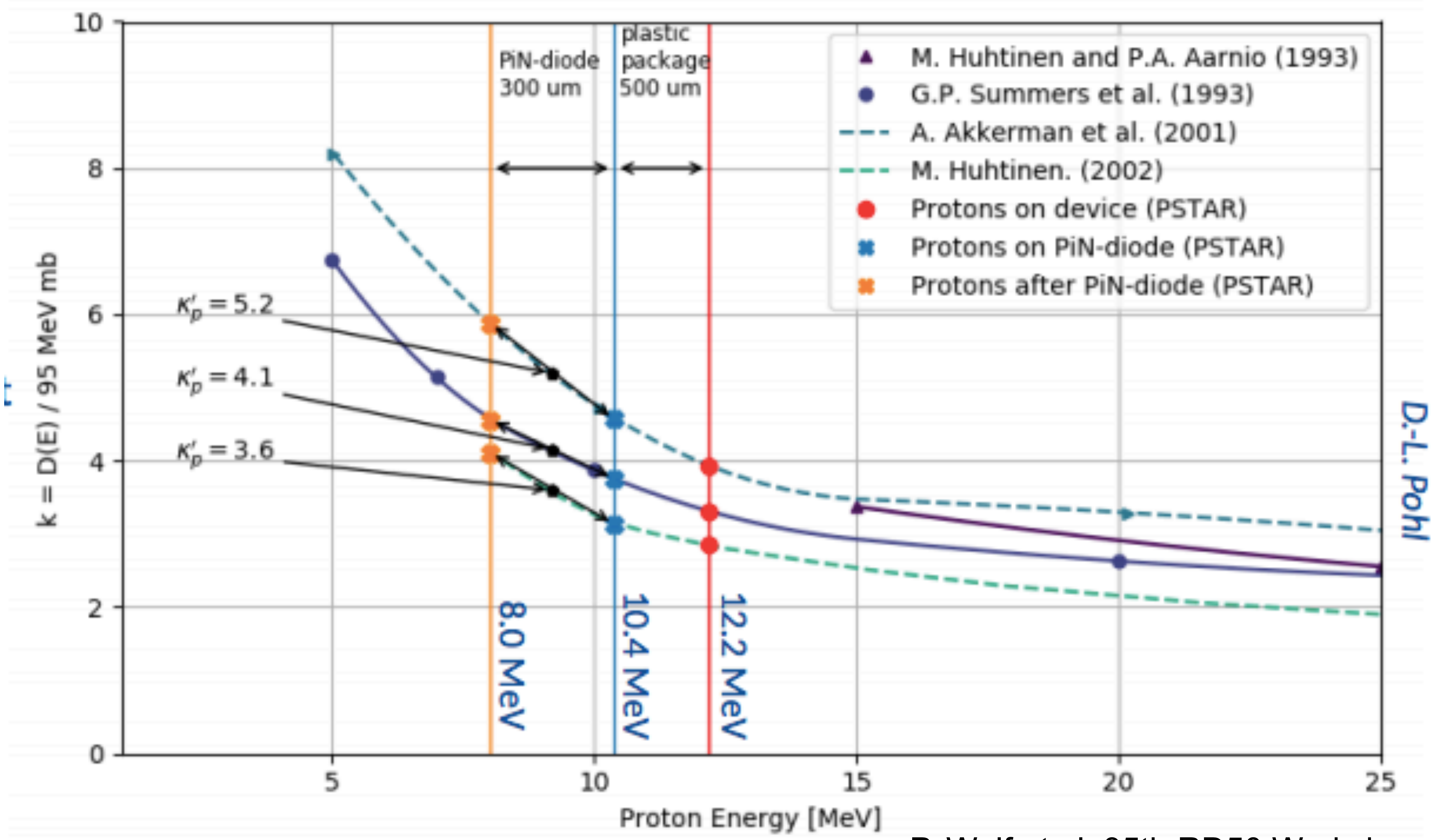
- Common methodology applied in all measurements
- Good agreement overall between measurements

Summary

- Hardness factor determined using same method at 4 institutes
- Diodes from Bonn measured in two different methods yield consistent results
  - Discussions ongoing to clarify details
- Good agreement between all facilities
- Second method using high-resistivity Hamamatsu diodes for ATLAS ITk at Birmingham cyclotron obtains results consistent with BPW34F diodes
  - Precision set-up used
  - See K. Nikolopoulos' presentation 36th RD50 workshop
- SEM fluence monitoring to be used by University of Birmingham irradiation facility in the future

Additional Material

BPW34F



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I-V Curves

Temperature Scaling Uncertainty

- Scaling to 20°C, E_a = 1.214 eV
  - At T = (-20±0.5)°C, $I_{20}/I = 59.75^{+6.1\%}_{-5.7\%}$
  - At T = (23±0.5)°C, $I_{20}/I = 0.77^{+4.5\%}_{-4.3\%}$
  - At T = (-20±1)°C, $I_{20}/I = 59.75^{+12.6\%}_{-11.1\%}$
  - At T = (23±1)°C, $I_{20}/I = 0.77^{+9.1\%}_{-8.3\%}$
- If instead E_a = 1.3 eV
  - At T = -20°C, I_{20}/I = 78.19 (= 30.1% higher)
  - At T = 23°C, I_{20}/I = 0.76 (= 1.3% lower)
- Same uncertainties on T and Ea, have a smaller effect in the scaling when performing measurements at a higher temperature

$$I \propto T^2 \exp\left(\frac{-E_a}{2k_B T}\right)$$

Previous Measurements

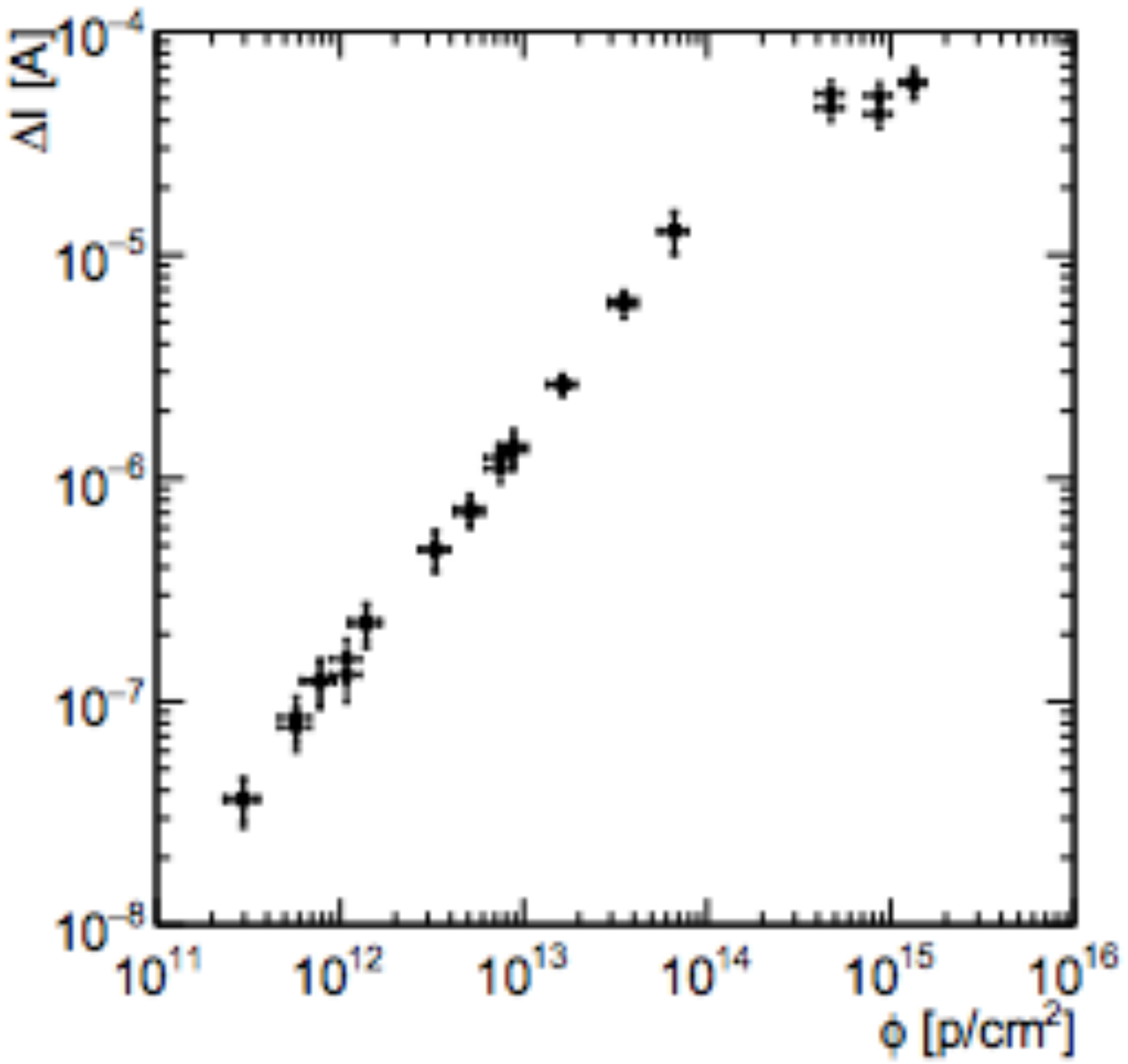

Figure 10. Change in leakage current as a function of fluence for the BPW34F diodes. The linearity of response up to approximately 10^{14}p/cm^2 is demonstrated.

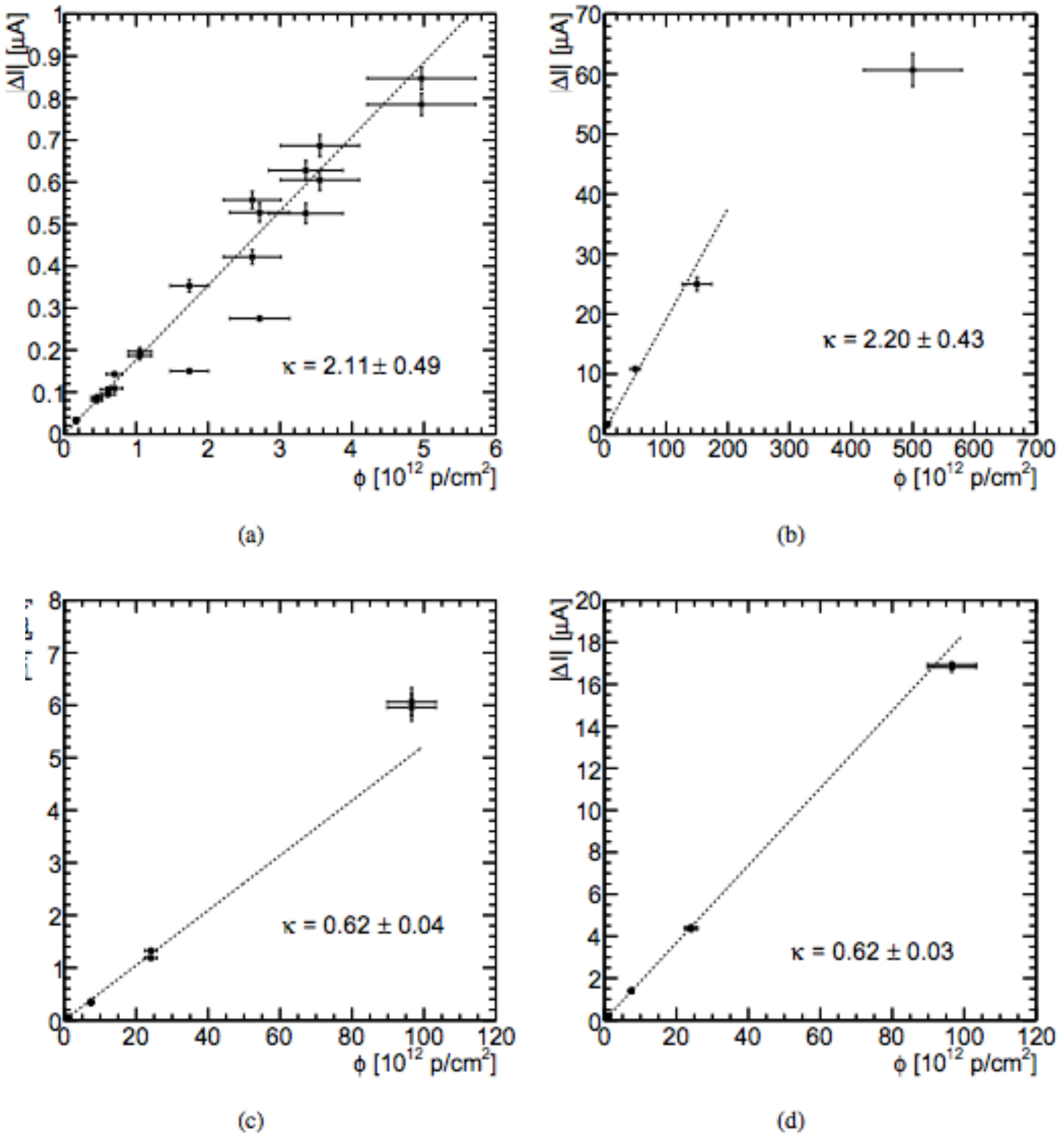

Figure 11. Change in leakage current as a function of proton fluence for BPW34F photodiodes irradiated at (a) the MC40 cyclotron; (b) the Irradiation Center Karlsruhe; and (c) at the IRRAD proton facility; (d) FZ pad diodes irradiated at the IRRAD proton facility.