UNIVERSITY OF BIRMINGHAM

Irfu - CEA Saclay
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BILPA Birmingham Instrumentation Laboratory for Particle physics and Applications

Determination of Proton Hardness Factors with Commercial PiN Diodes

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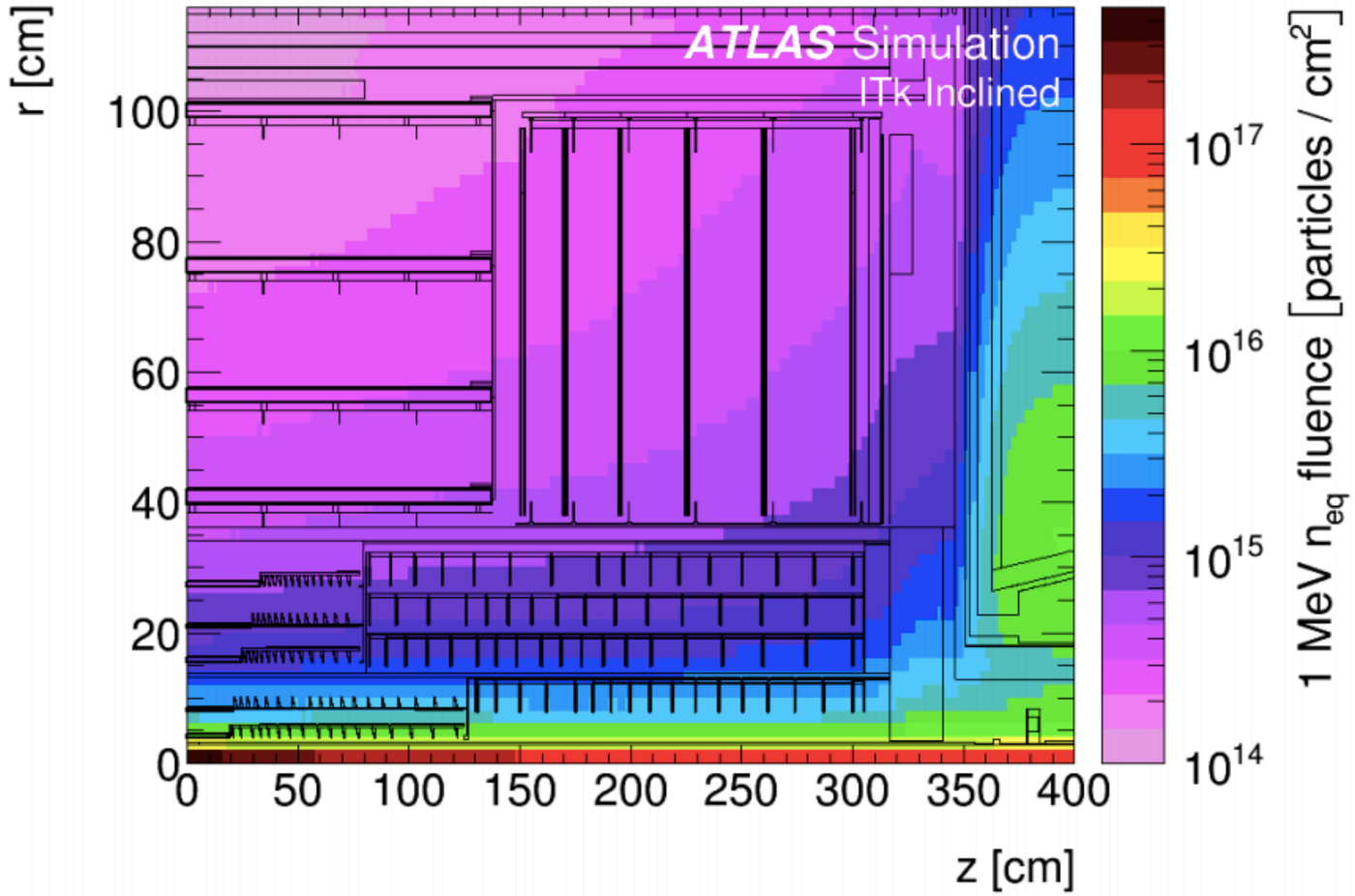
Radiation Hardness Testing

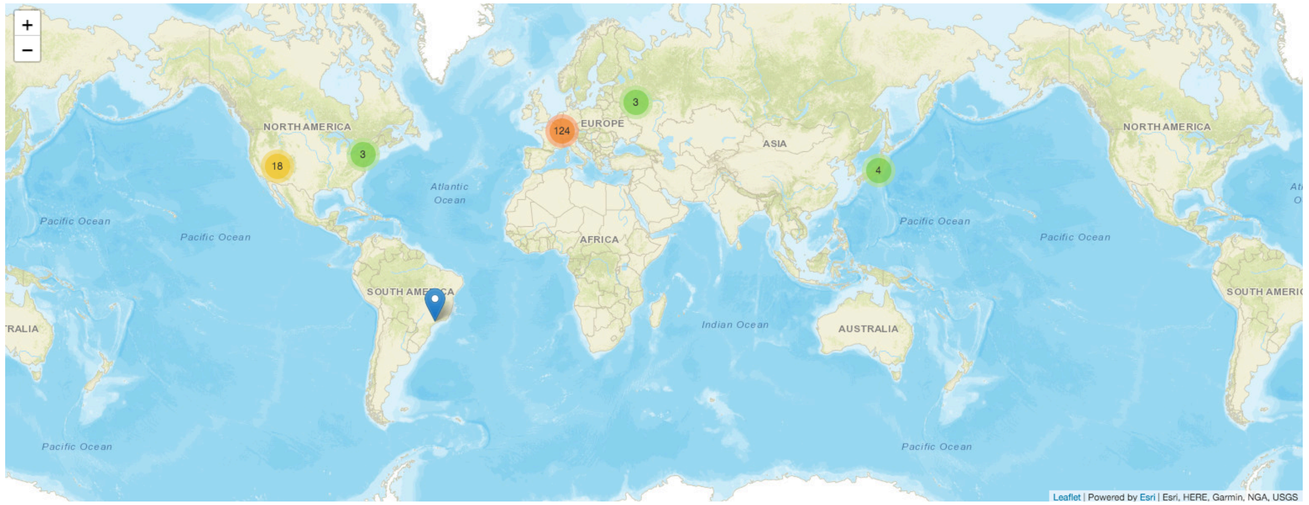
ATI-TDR-025

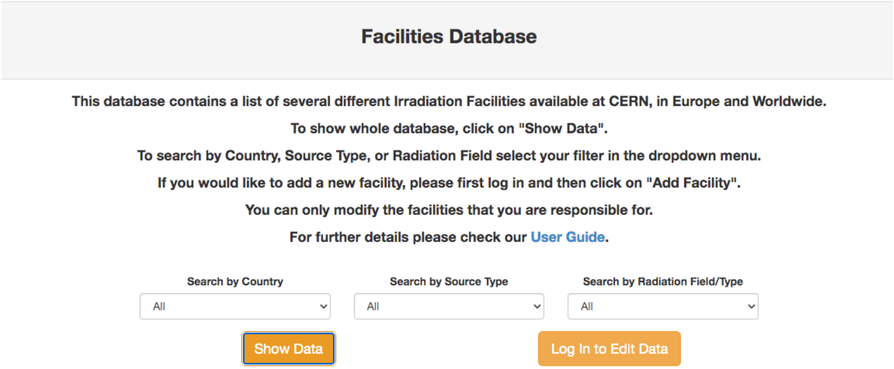


- Radiation hardness of detectors of critical importance to current and future projects; HL-LHC, FCC, …
- Irradiation facilities for characterisation of detectors
- Strip sensors need to withstand 10^{15} 1 MeV n_{eq} cm^{-2} at HL-LHC (3000 fb^{-1})

Radiation Hardness Testing Facilities

- Global campaign to characterise sensors and components
- Irradiation facilities established globally





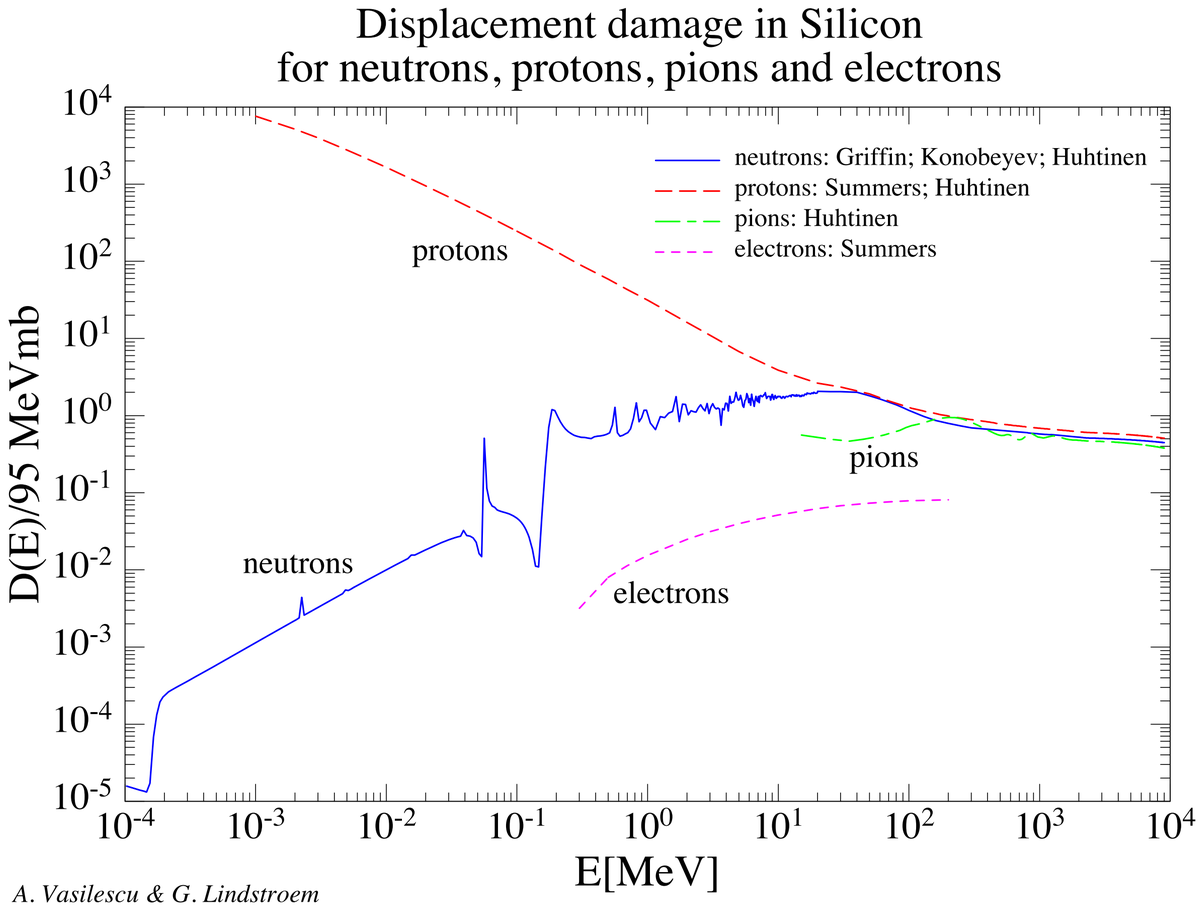
AIDA Irradiation Facilities Database

Details	Institute Name	Country	Facility Name	Source Type	Radiation Field/Type	Funding Details
	A.R.T.E.	Italy		Accelerator	Heavy Ions	
	ADVANCED RADIATION RESEARCH INSTITUTE (JAEA)	Japan	PROTON facility TIARA	AVF Cyclotron (K110), Tandem, Ion Implanter	Proton	
	ADVANCED RADIATION RESEARCH INSTITUTE (JAEA)	Japan	Electron Beam Irradiation Facility	Cockcroft-walton type	Electron	
	ADVANCED RADIATION RESEARCH INSTITUTE (JAEA)	Japan	Gamma-ray Irradiation Facilities	Co-60	Gamma	
	ADVANCED RADIATION RESEARCH INSTITUTE (JAEA)	Japan	HEAVY IONS facility TIARA	AVF Cyclotron (K110), Tandem, Ion Implanter	Heavy Ions	
	Aerial	France	feerix	Rhodotron	Electron	
	Aerial	France	feerix	Rhodotron	X-Ray	
	Aerial	France	feerix	Rhodotron	X-Ray	
	Aerial	France	Van De Graaff	VdG, linear accelerator	Electron	
	Aerial	France	Van De Graaff	VdG, linear accelerator	X-Ray	
	Aerial	France	kV X-rays	X-Ray tube	X-Ray	
	ALTER RADLAB	Spain	ALTER RADLAB	Co-60 / Accelerator	Gamma / Proton	
	ARC-Nucléart	France	ARC-Nucléart Irradiator	Co-60	Gamma	
	ARRONAX	France	Gamma Irradiator	Cs-137	Gamma	
	ATRON Metrology	France	FELIX	Electron beam	Electron	
	ATRON Metrology	France	FELIX	X-Rays from electrons braking	X-Ray	

⋮

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)

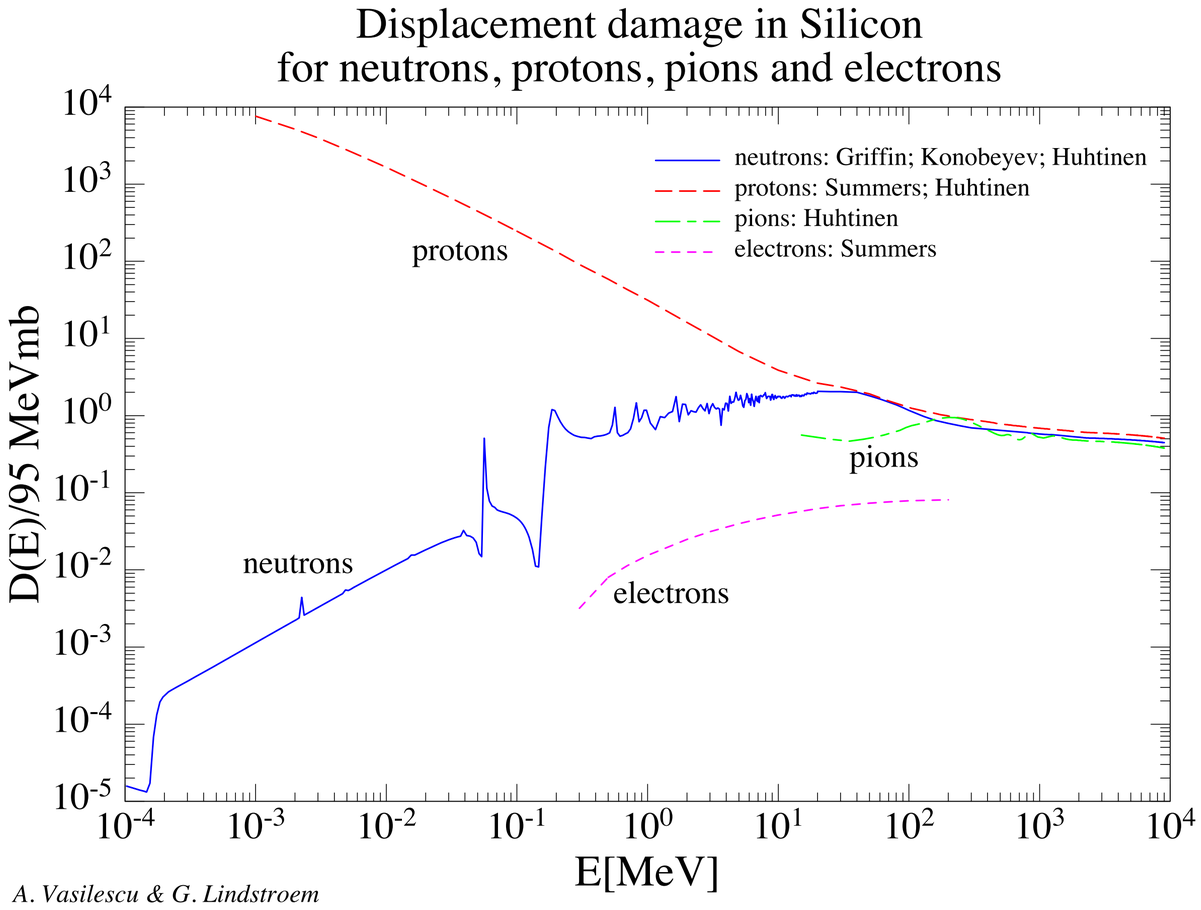


Standard procedure to get κ:

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

Hardness Factors at Different Facilities

- In practise, variety of hardness factors have been used:
  - B'ham MC40: 2.2 for 23 MeV protons [K. Nikolopoulos, IPRD2016]
  - ZAG/KIT: 2.05±0.61 for 24 MeV protons [A. Dierlamm, RD50 Workshop in Barcelona, 2010]
  - RD50 tables: ~2.56 for 25 MeV protons[https://rd50.web.cern.ch/rd50/NIEL/default.html]
  - CERN IRRAD: 0.62 for 23 GeV protons [NIM B186 (2002) 100]



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

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
  - Si PiN photodiode with daylight blocking filter
  - Produced by OSRAM Opto-Semiconductors
  - Commercially available
  - Extensively studied

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

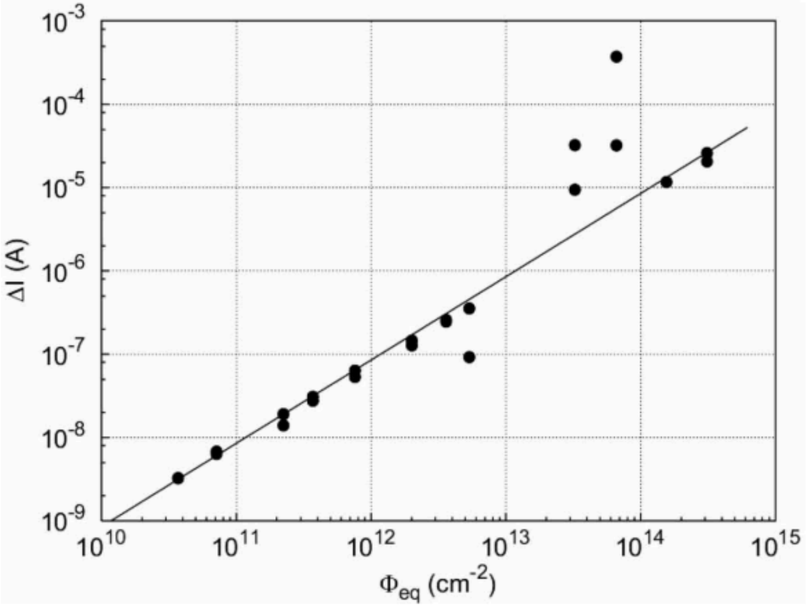
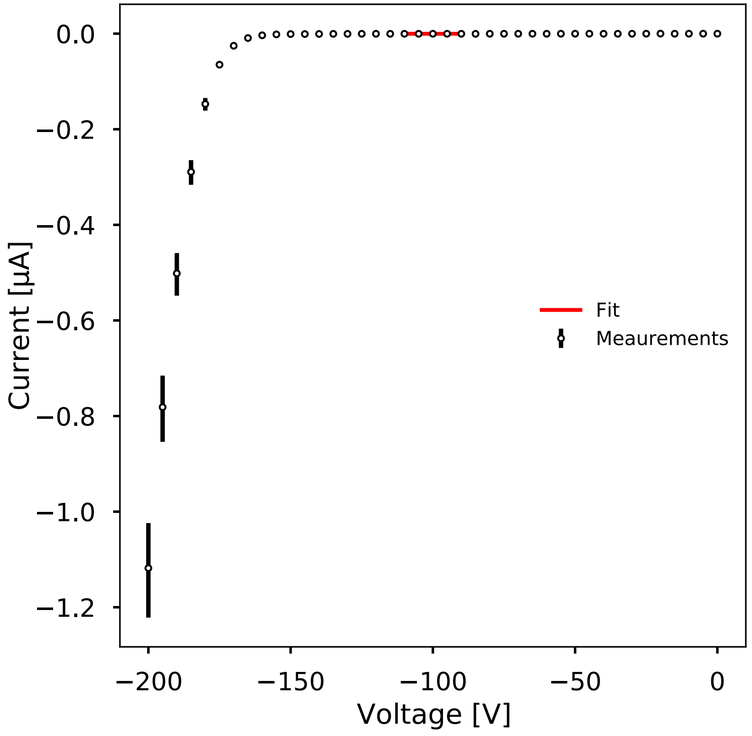


Fig. 3. BPW34F characteristics in reverse bias normalized to 20°C. Leakage current measurement and increasing irradiation levels with 23 GeV protons.

BPW34F Diode
Active Area: 2.65x2.65 mm^2

Full Depletion Depth: 300 μm

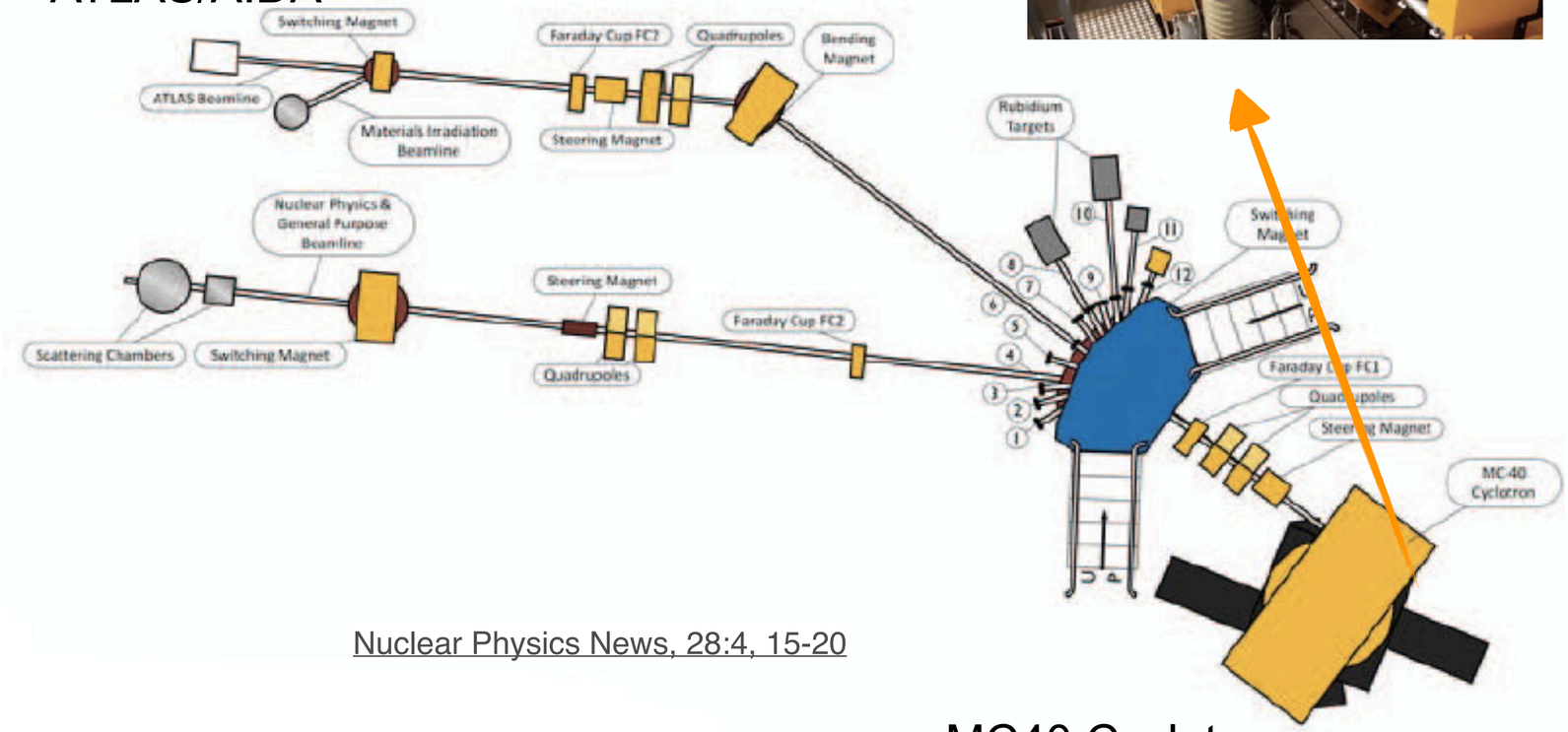


University of Birmingham MC40 Cyclotron

- p, d, ^{3}He, ^{4}He ~continuous beam
- Dedicated high-dose rate beam line
- Proton current: ≲2 μA
  - Typically use: 0.1-0.5 μA
- Beam profile: ~10x10 mm^2
- Flux: ≲10^{13} p/s/cm^2
- Proton energy (extraction): 3-38 MeV
  - Typically use 27 MeV

Beam ion	Energy [MeV]
Protons	10.8–40 (N=1) 2.7–10 (N=2)
Deuterons	5.4–20 (N=2)
Helium-3	33–50 (N=1) 8–28 (N=2)
Helium-4	10.8–40 (N=1)

ATLAS/AIDA

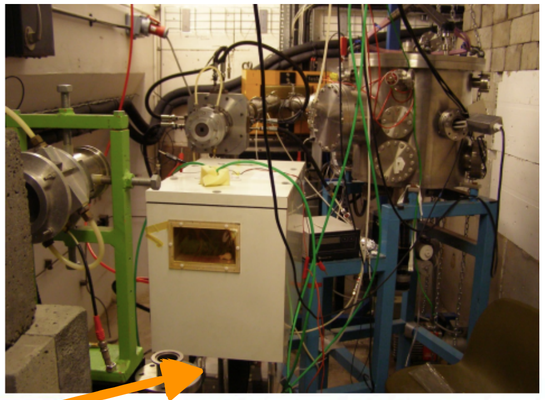


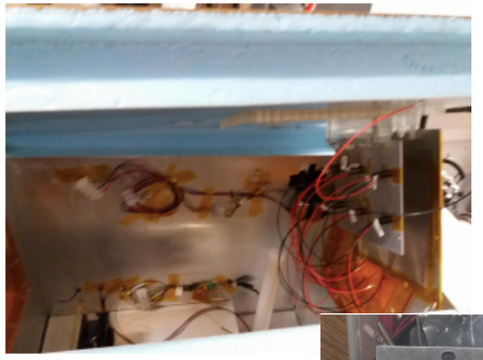
Nuclear Physics News, 28:4, 15-20

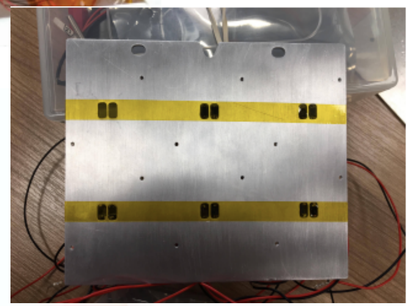
MC40 Cyclotron

University of Birmingham MC40 Cyclotron

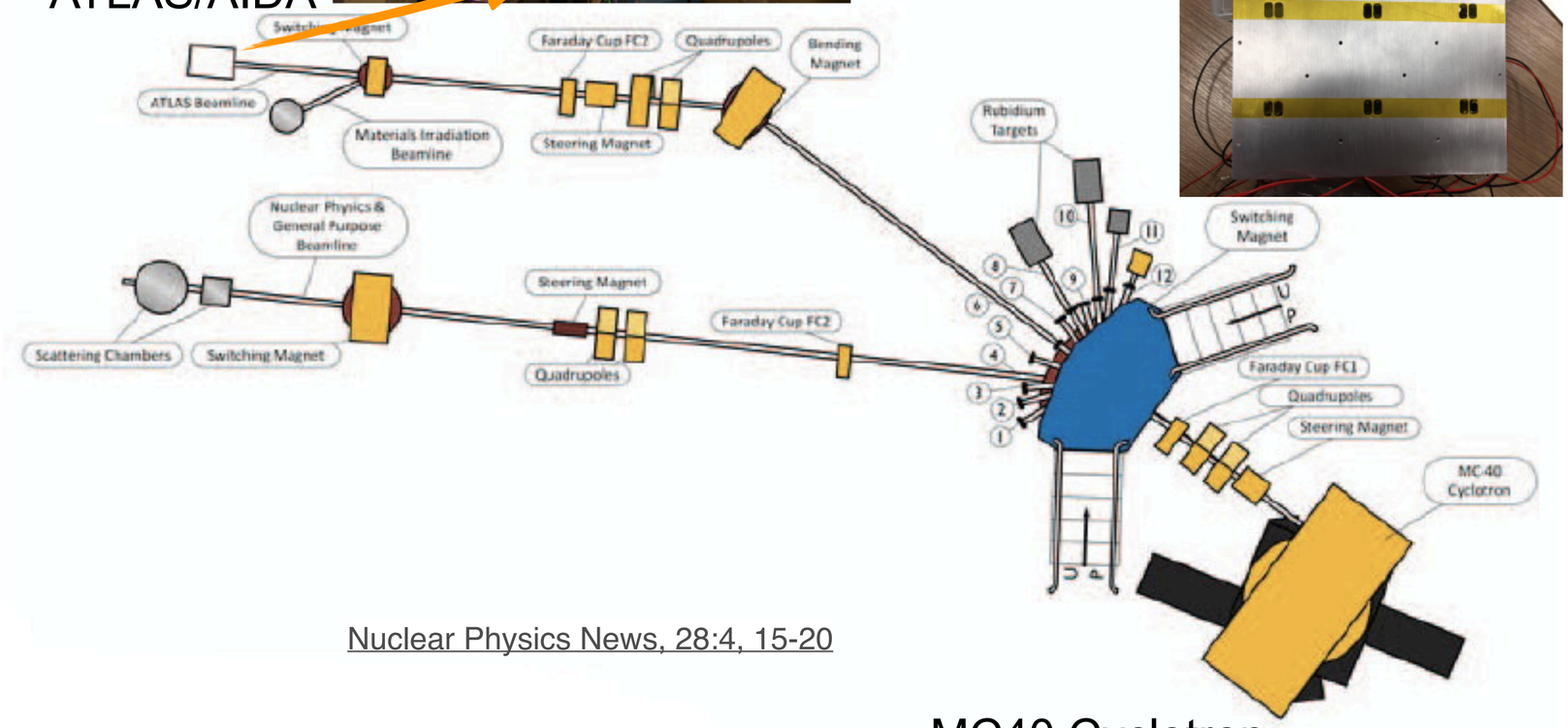
- Environmental control box
  - Liquid N evaporative cooling ~-25°C
  - Relative humidity~10%
  - Both continually logged
- XY-axis robotic scanning
  - 4 mm/s
- Feed-though for read-out monitoring
- Ni-foil activation dosimetry
  - $^{28}Ni(p,X)^{28}Ni^{57}$
  - $\Delta\phi_p/\phi_p \sim \pm 20\%$







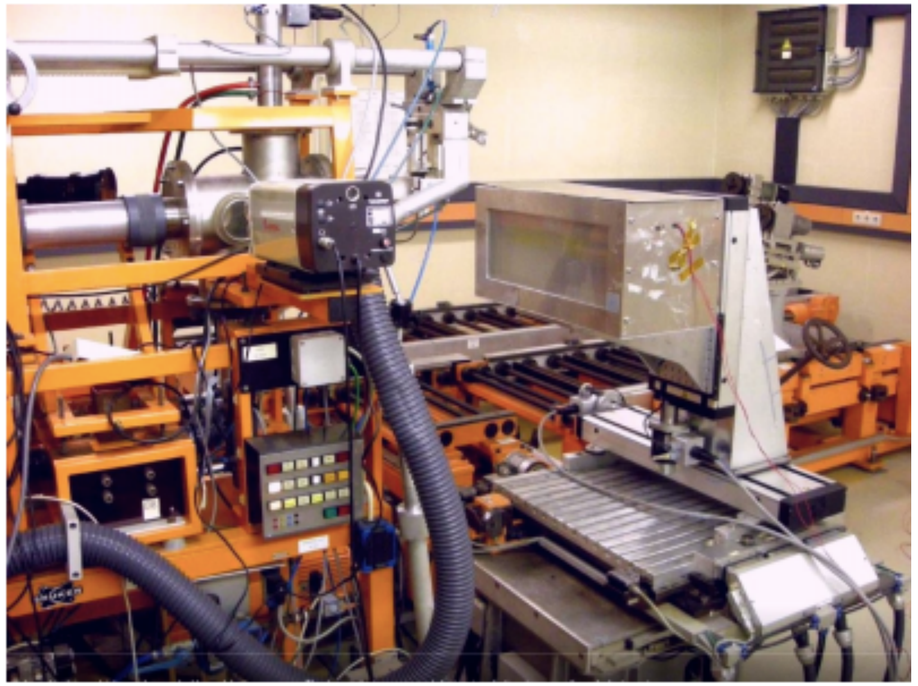
ATLAS/AIDA



Nuclear Physics News, 28:4, 15-20

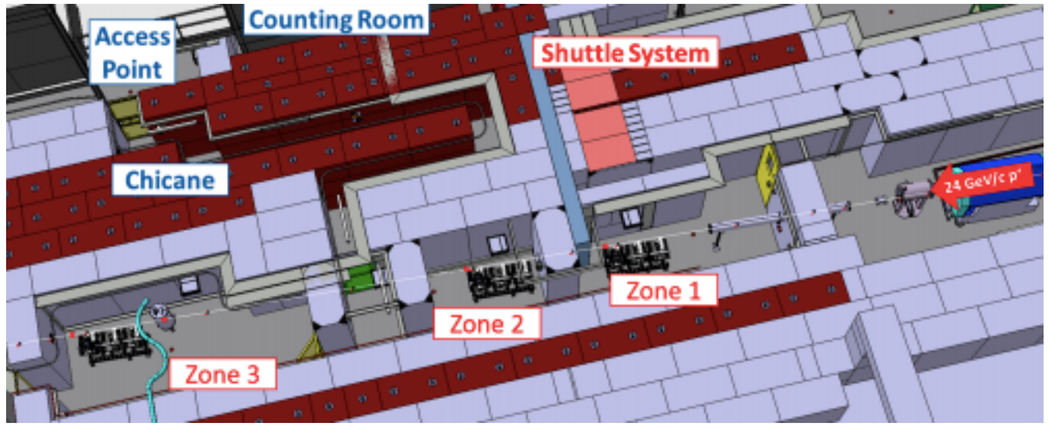
MC40 Cyclotron

ZAG/KIT

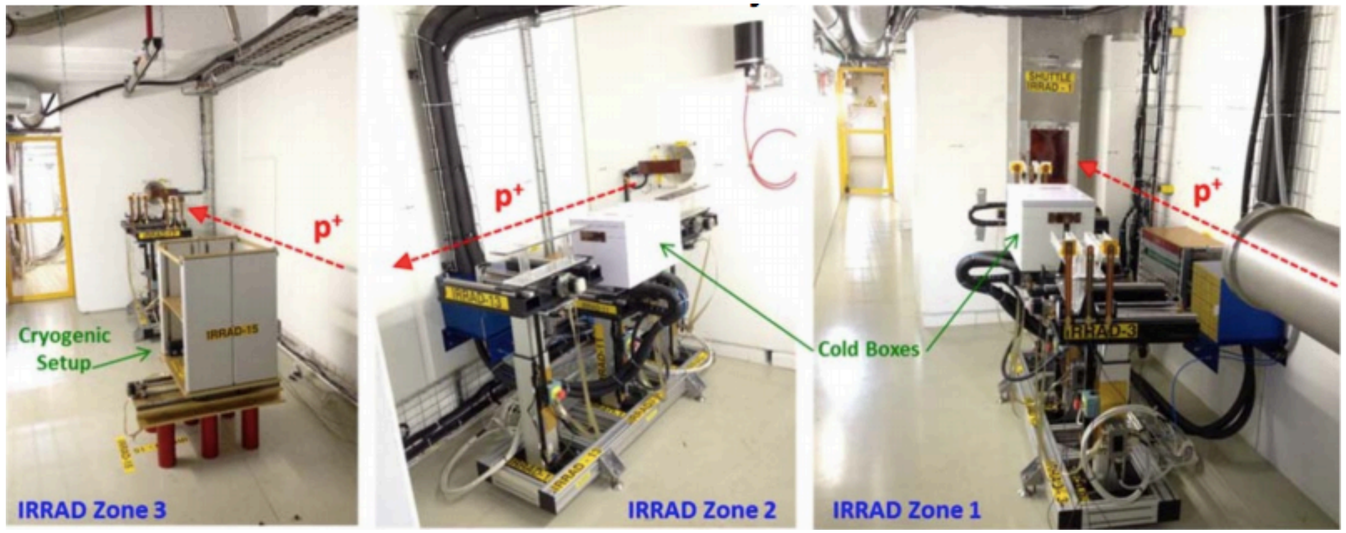


- The Irradiation Center Karlsruhe accesses a compact cyclotron operated by ZAG Zyklotron AG
- Typical proton current: 1.5 μA
- Beam spot: ~ 7 mm
- Flux: ~ 2.5 $\times 10^{13}$ p/(s·cm2)
- Proton energy (extraction): 25.3 MeV
- Insulated box, cooled by cold nitrogen gas
  - Temperature in box: -30°C
  - Goose-necks lead gas to individual samples
- Graphite plate to stop protons at the back Window with two Kapton foils for insulation
- Samples fixed to Al-frames frames with Kapton tape and fixed in the box
- Mounted on movable XY-stage
- Horizontal speed at nominal current 115 mm/s
- Dosimetry using Ni foil activation

CERN IRRAD



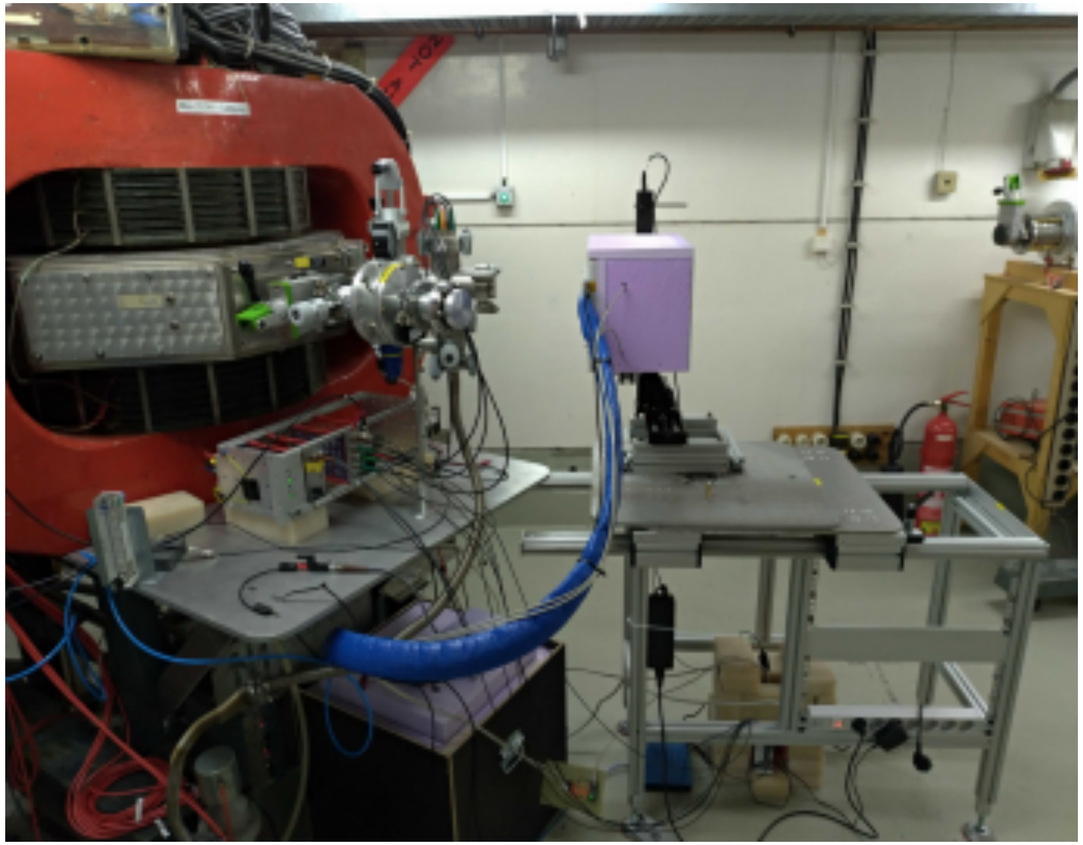
- CERN Irradiation: protons from the Proton Synchrotron
- Beam momentum: 24 GeV/c
- Beam profile: ~6x6 mm^2 to ~20x20 mm^2 (FWHM)
  - Standard: ~12x12 mm2 (FWHM) spot size
- Beam intensity: ~5×10^{11} protons/spill on cycles of 30-37 s
  - Typically: 3 spills per CPS
- ~0.7-1 x 10^{14} p cm^{-2} h^{-1} (on 5x5 mm2 sample)



- Samples placed in environmental controlled box
  - Possible temperature down to -20°C
  - Room temperature in this study
- Mounted on movable XY-stage
- Dosimetry using Al foil
  - $^{27}Al(p,3pn)^{24}Na$ and $^{27}Al(p,3p3n)^{22}Na$
  - $\Delta\phi_p/\phi_p \sim \pm 7\%$

Bonn Isochronous Cyclotron

- 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
  - $\Delta\phi_p/\phi_p \sim 2\%$
- Irradiated diodes measured with standard methodology and independently at Bonn with consistent results



BILPA

Birmingham Instrumentation Laboratory for Particle physics and Applications

- **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-7 cleanroom

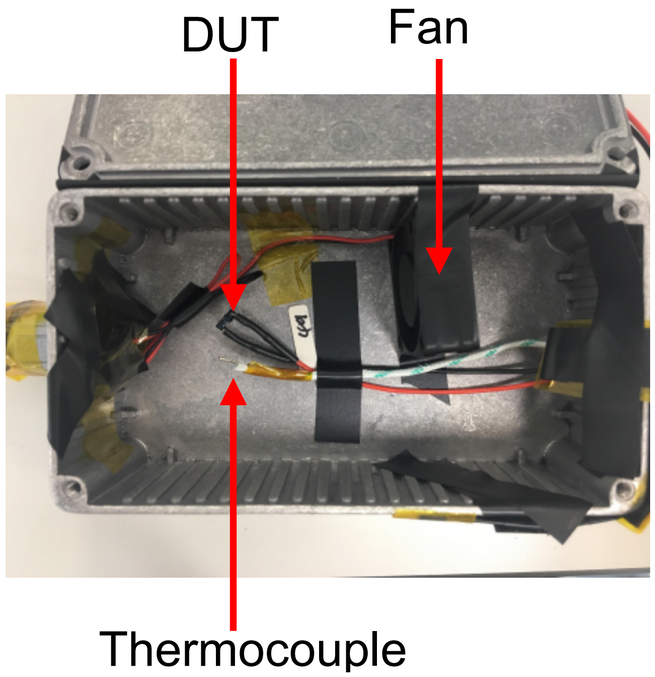
Measurements: I-V

- Devices annealed for 80 minutes at 60°C
- 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

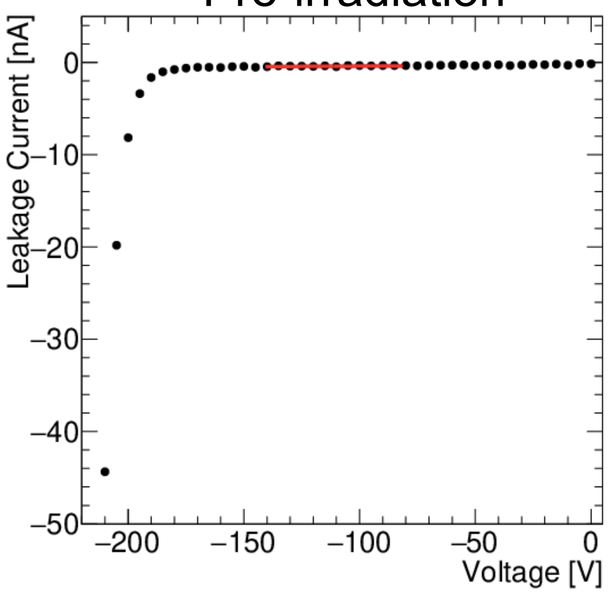
$$I \propto T^2 \exp\left(\frac{-E_a}{2k_B T}\right)$$

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

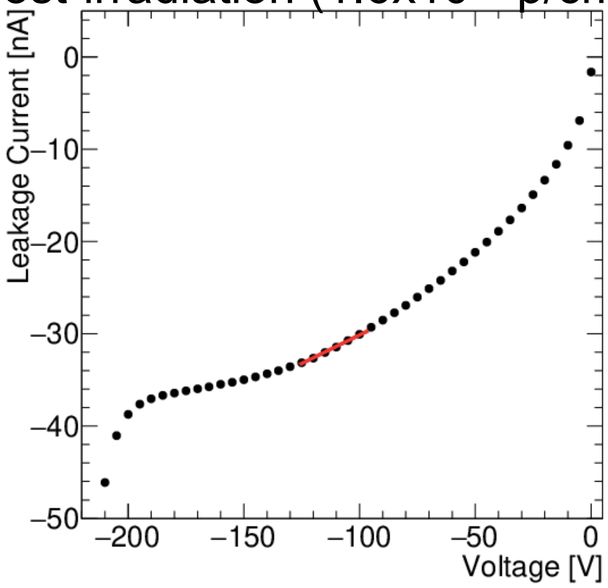
JINST (2013)P10003



Pre-irradiation

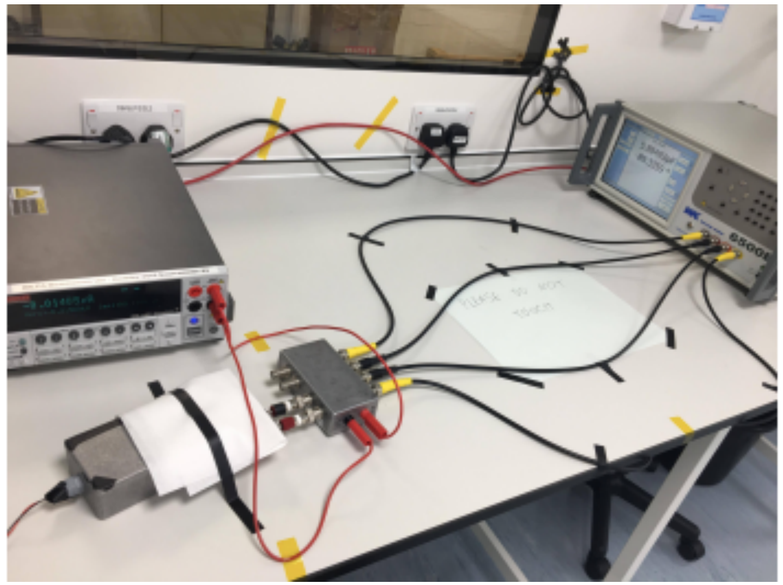


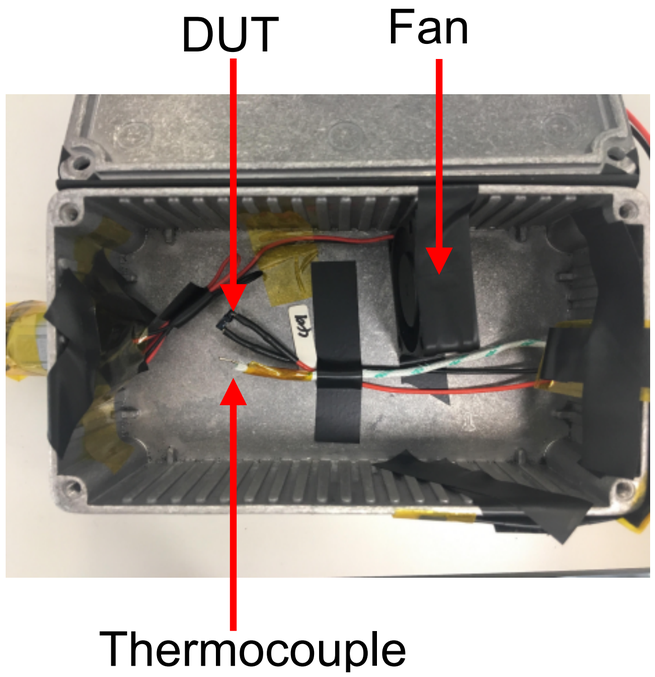
Post-irradiation (1.6×10^{11} p/cm^2)

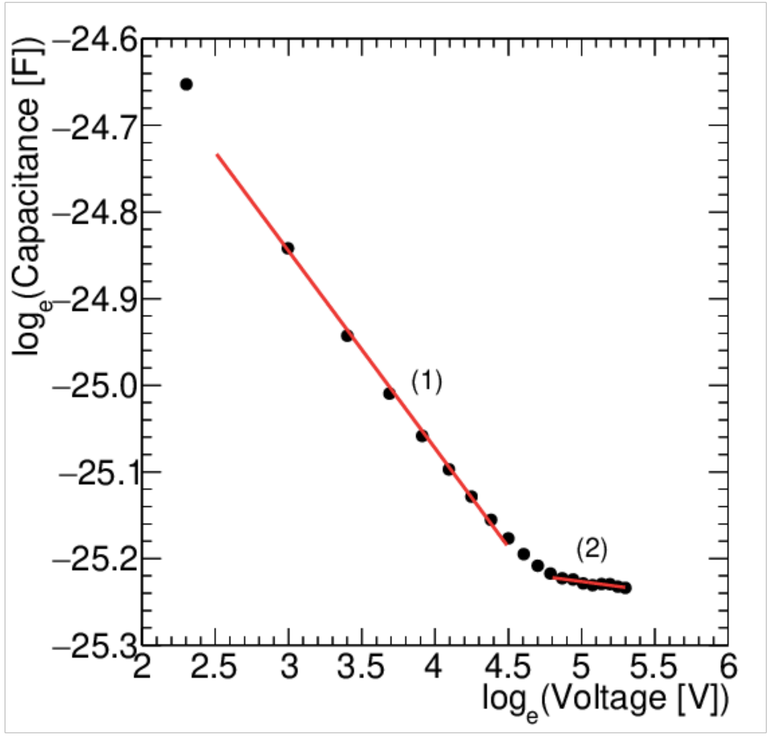


Measurements: Depletion Voltage

- Capacitance reading at 10 kHz
  - Wayne-Kerr 6500B precision Impedence Analyser
  - Keithley 2410 Source meter for external bias
    - Biased through junction box







Hardness Factors

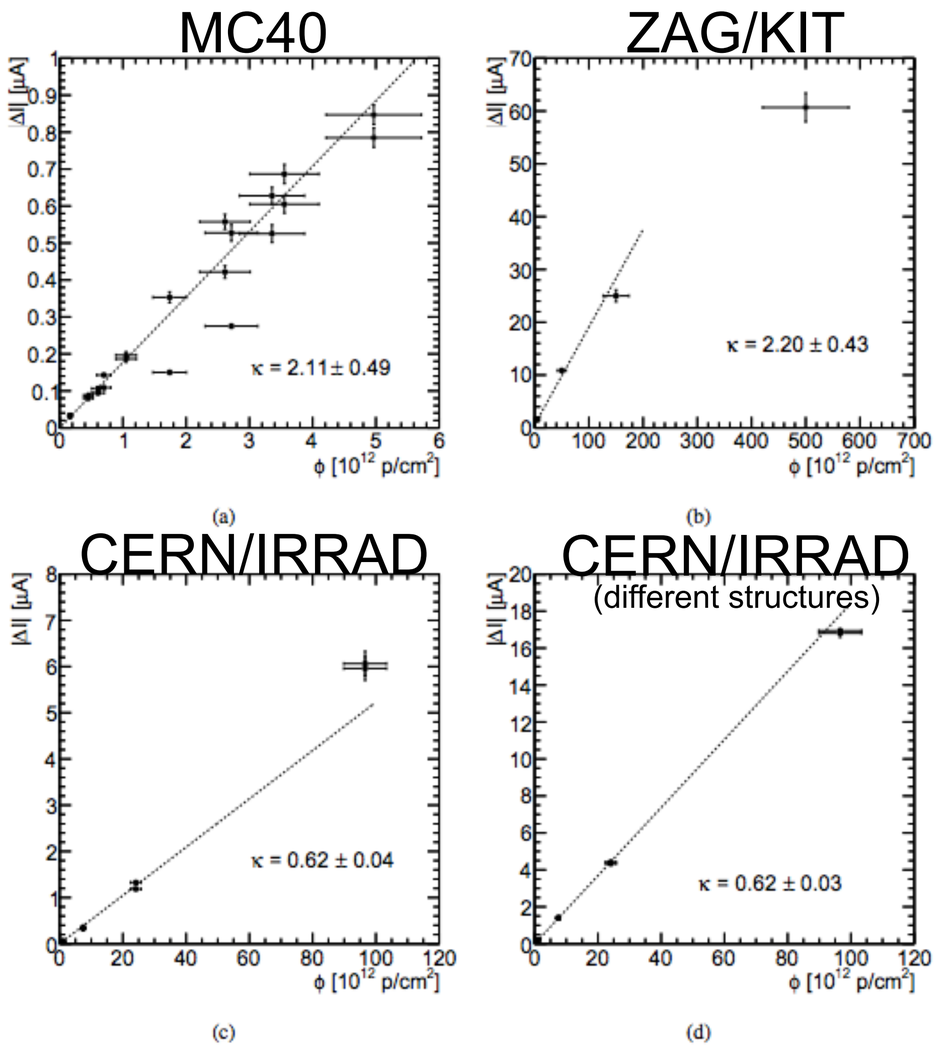
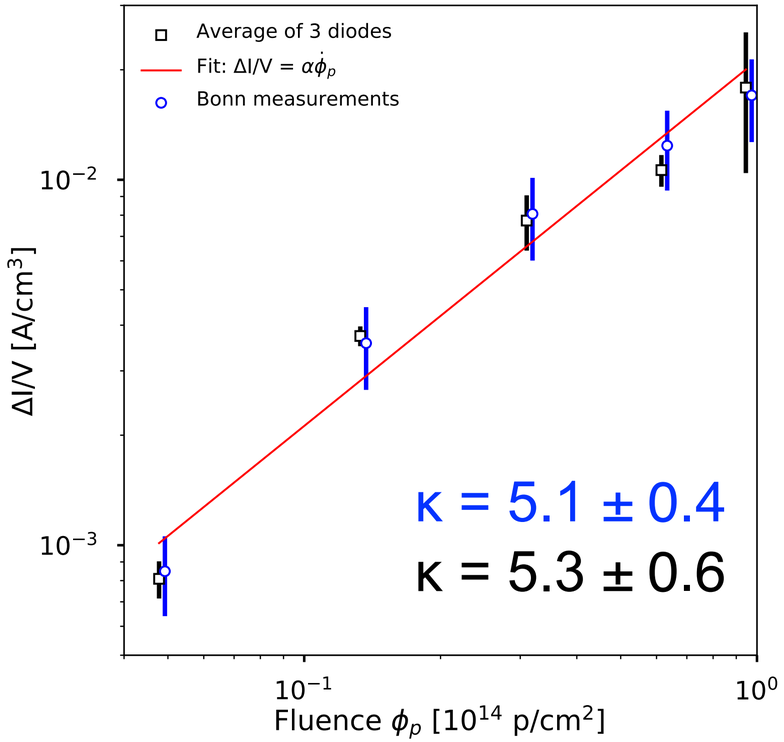
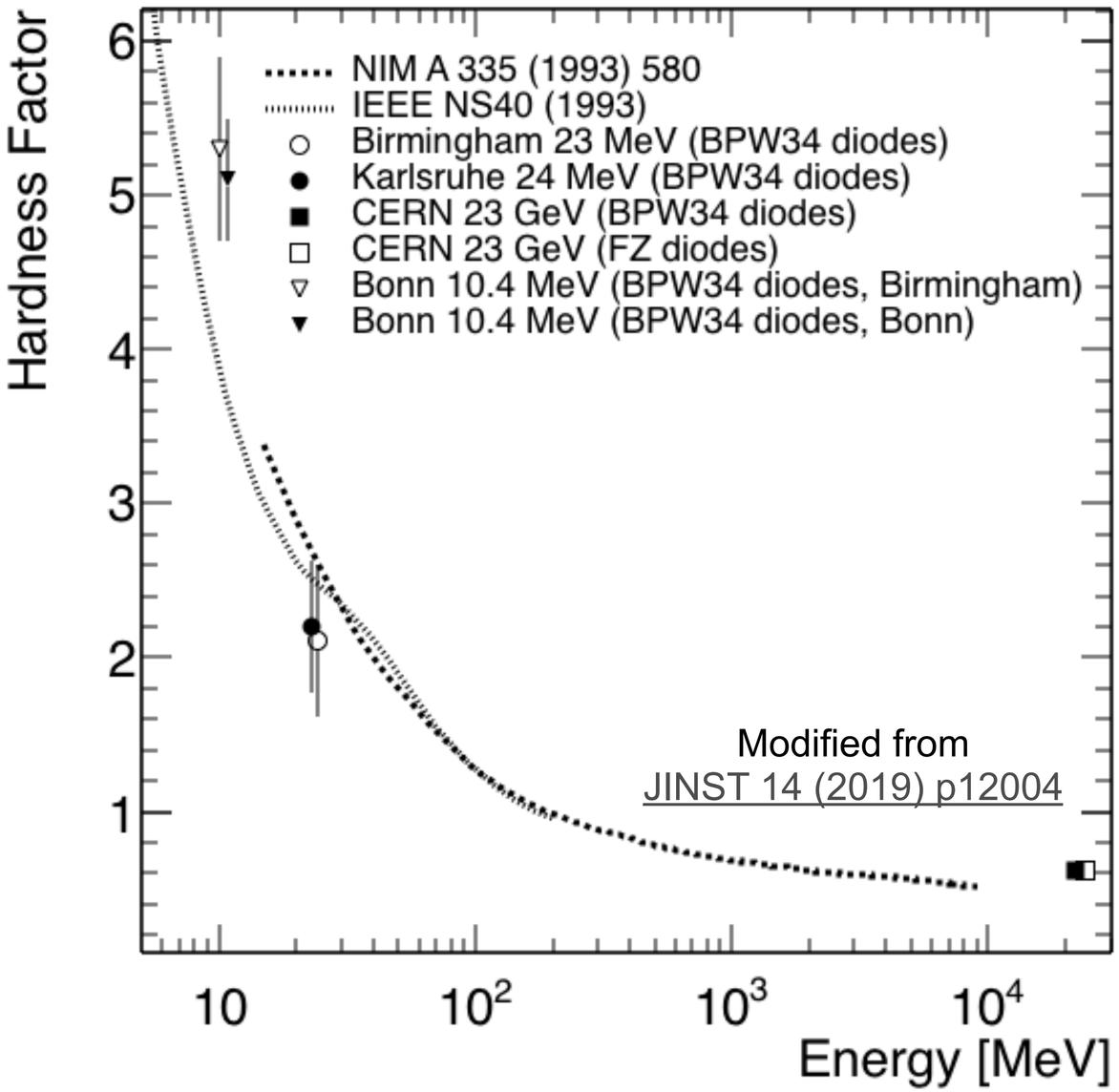


Figure 11. Change in leakage current as a function of proton fluence for BPW34F photodiodes irradiated at (a) the MC40 cyclotron; (b) the Irradiation Center Karlsruhe; and (c) at the IRRAD proton facility; (d) FZ pad diodes irradiated at the IRRAD proton facility.



- Diodes from Bonn measured first in Bonn and then independently in Birmingham
  - Consistent results between two method

Results Overview

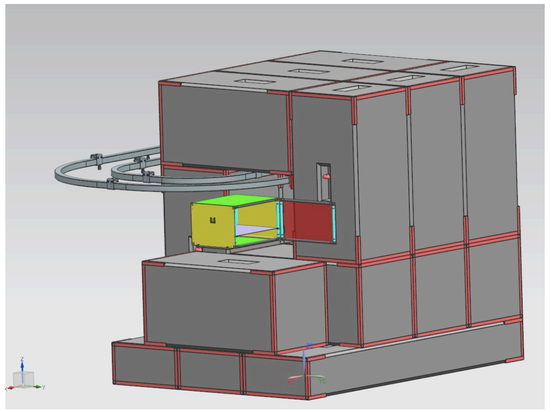


- Common methodology applied in all measurements
  - Bonn and Birmingham independent measurements shown
- Good agreement overall between measurements

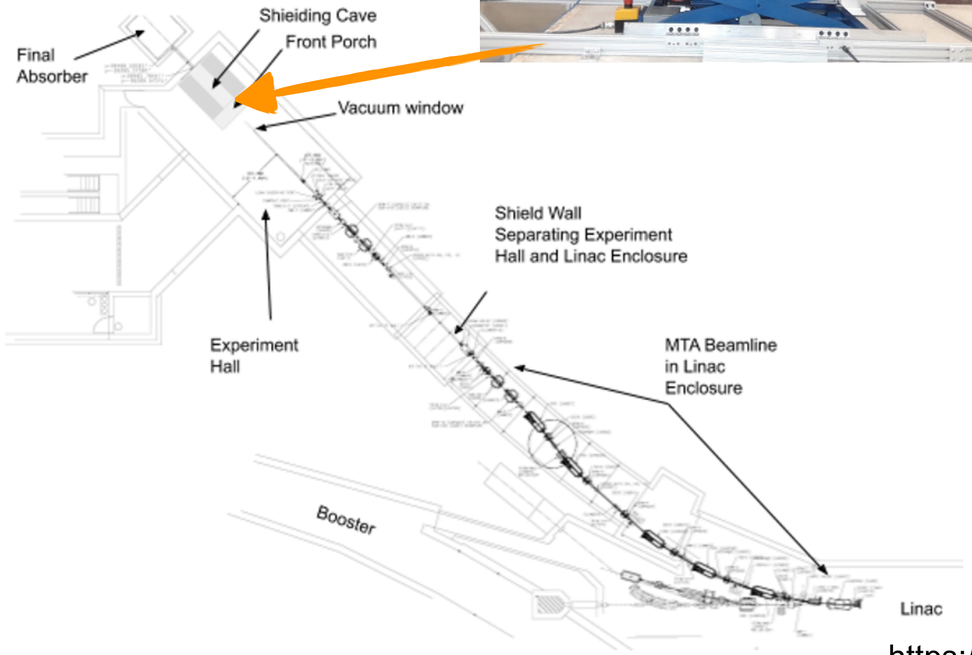
- Future steps:
  - Improve fluence measurement - dominates uncertainty
  - Potential for improvement with more sophisticated test structures
  - Expand measurements to more facilities

Fermilab Irradiation Test Area

- Fermilab ITA began irradiating user samples Jan 2021
  - https://news.fnal.gov/2021/02/first-experiments-receive-beam-in-the-new-irradiation-test-area/
- Protons from LINAC
- ~5x10^{12} proton per pulse
  - ~35 µs pulse
- Beam profile: ~1-7 cm^2
- Energy: 400 MeV
- Movable staging platform
  - Cold box being developed
- Dosimetry:
  - Up-stream toroid: **~1% uncertainty**
    - Live monitoring
  - P-i-N diode array
  - Al foil
- Currently planning measurements

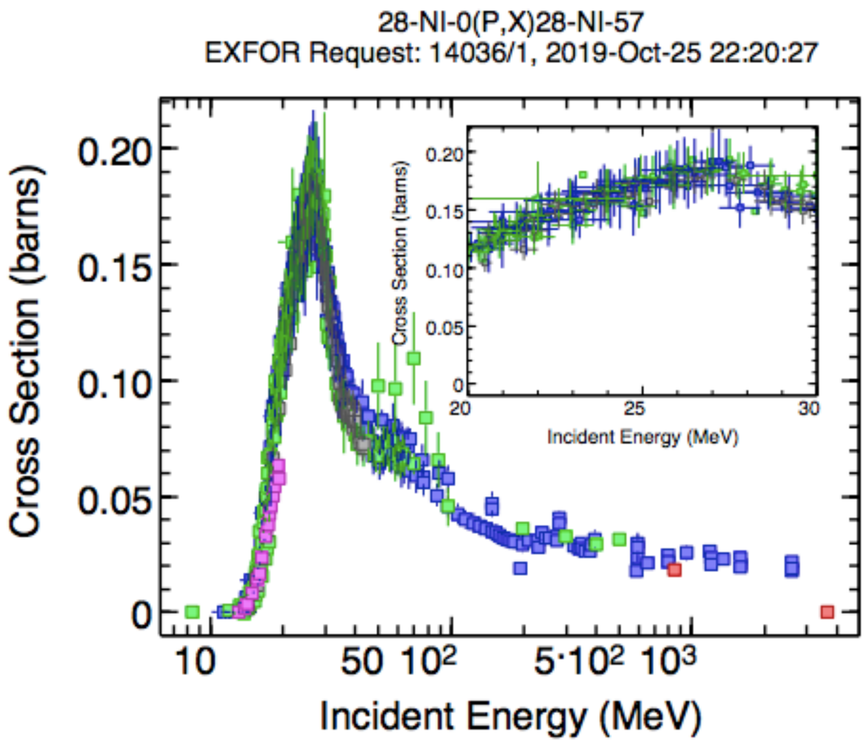


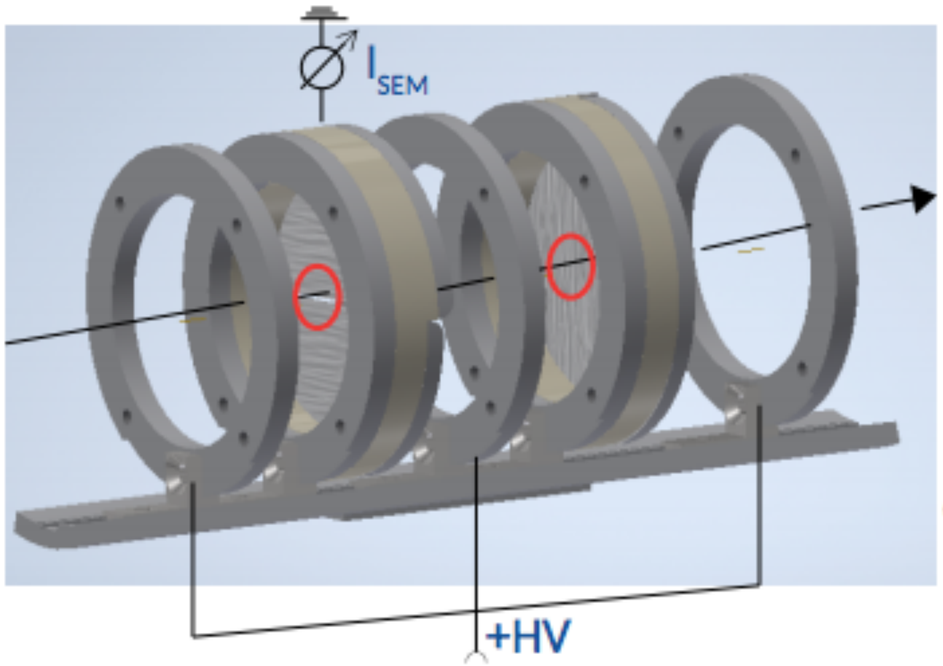
https://ita.fnal.gov/sample-holder/



https://ita.fnal.gov/beam-overview/

Fluence Measurements



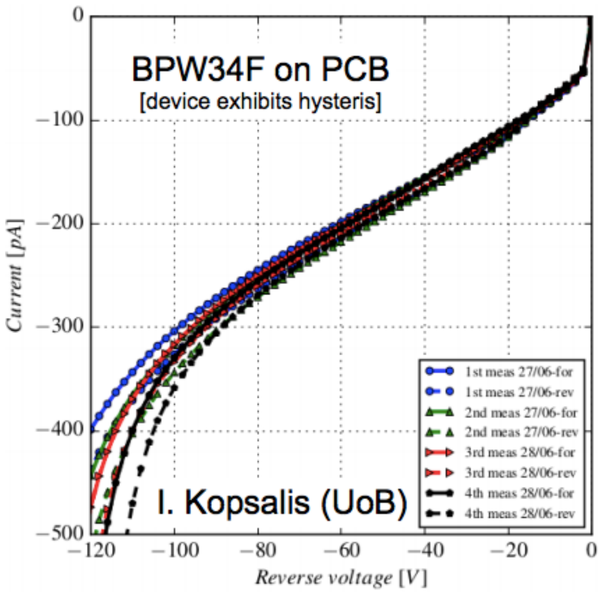


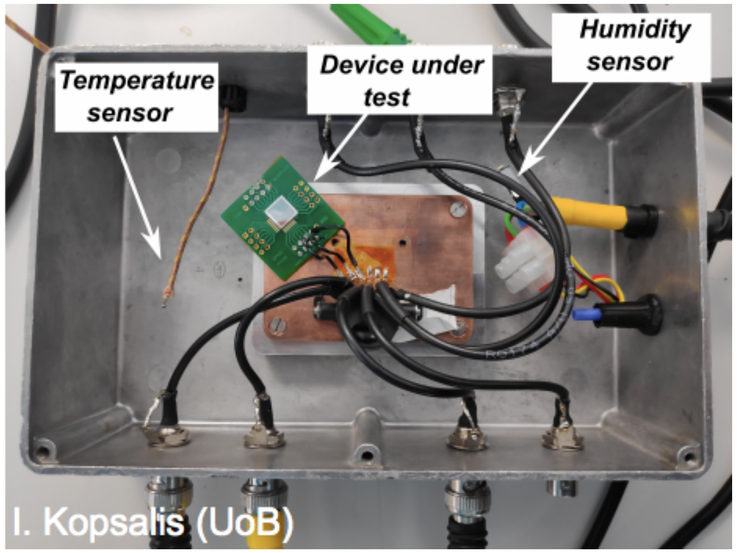
P. Wolf et al. 35th RD50 Workshop, CERN 18/11/2019

- Fluence uncertainty dominant in measurements
- University of Birmingham and KIT use Ni foils dosimetry; $^{28}Ni(p,X)^{28}Ni^{57}$
  - Uncertainty in cross-section results in **~20% uncertainty** on fluence measurements
- IRRAD is higher energy - can use Al foils - **~7% uncertainty**
- Bonn uses **S**econdary **E**lectron **M**ultiplier (**SEM**) - **~2% uncertainty** - promising development
  - Dominant uncertainty from difference between repeat measurements and temperature scaling
- FNAL ITA uses up-stream toroid - **~1% uncertainty**

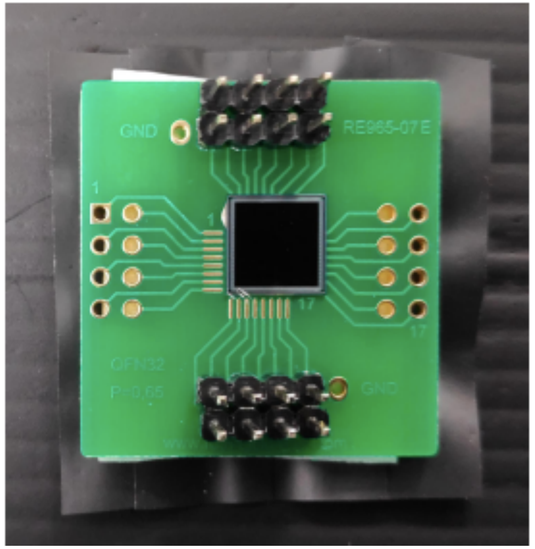
Alternative Devices

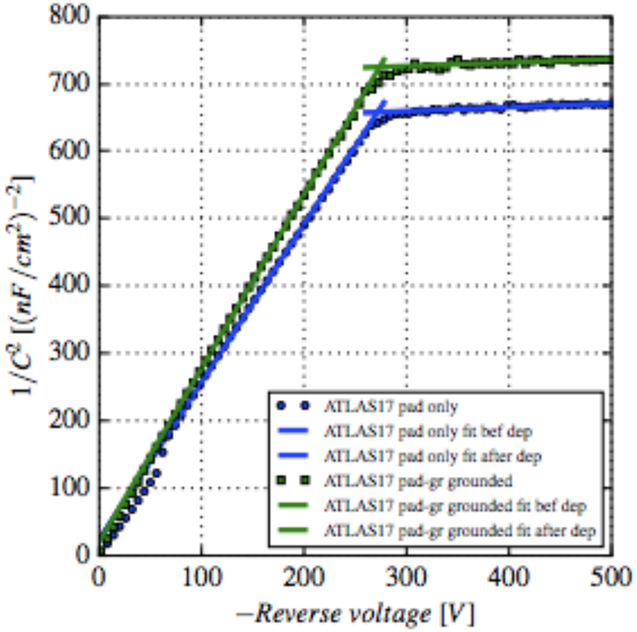
- BPW34F have some limitations:
  - Energy uncertainty due to daylight filter material
  - No guard ring - lateral depletion
  - Hysteresis in I-V





- Exploring use of different structures
  - Hamamatsu 8x8 mm^2 ATLAS17 strip sensors
- Improvements in dosimetry make temperature/current measurement uncertainties more important
  - Improved measurement box
    - pA precision in I
    - Improved reproducibility



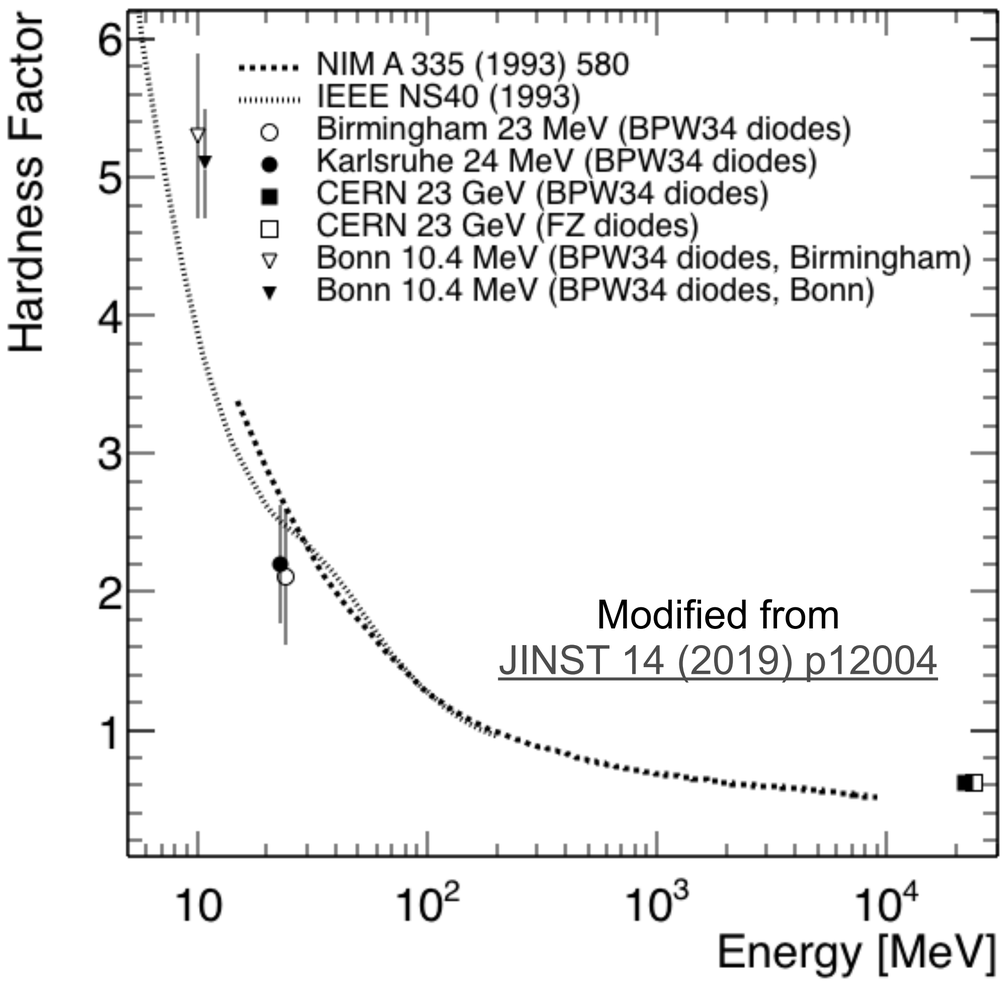


Summary

- Radiation hardness testing critical for future projects
  - Consistency between irradiation facilities is key
- Hardness factor determined using same method at 4 institutes
  - Overall, good agreement between facilities
- Will perform measurements at FNAL ITA this year

Improving technique for future measurements:

- Dosimetry is main source of uncertainty
  - Improvement through up-stream toroid (FNAL ITA) and SEM (Bonn)
  - SEM fluence monitoring to be used by University of Birmingham irradiation facility in the future
- Second method using high-resistivity Hamamatsu diodes for ATLAS ITk → results consistent with BPW34F diodes
- Improving set-up for greater temperature/humidity control and improved current measurement precision



Additional Material