Determination of proton related damage on commercial and high-ohmic silicon pad diodes

European Research Council
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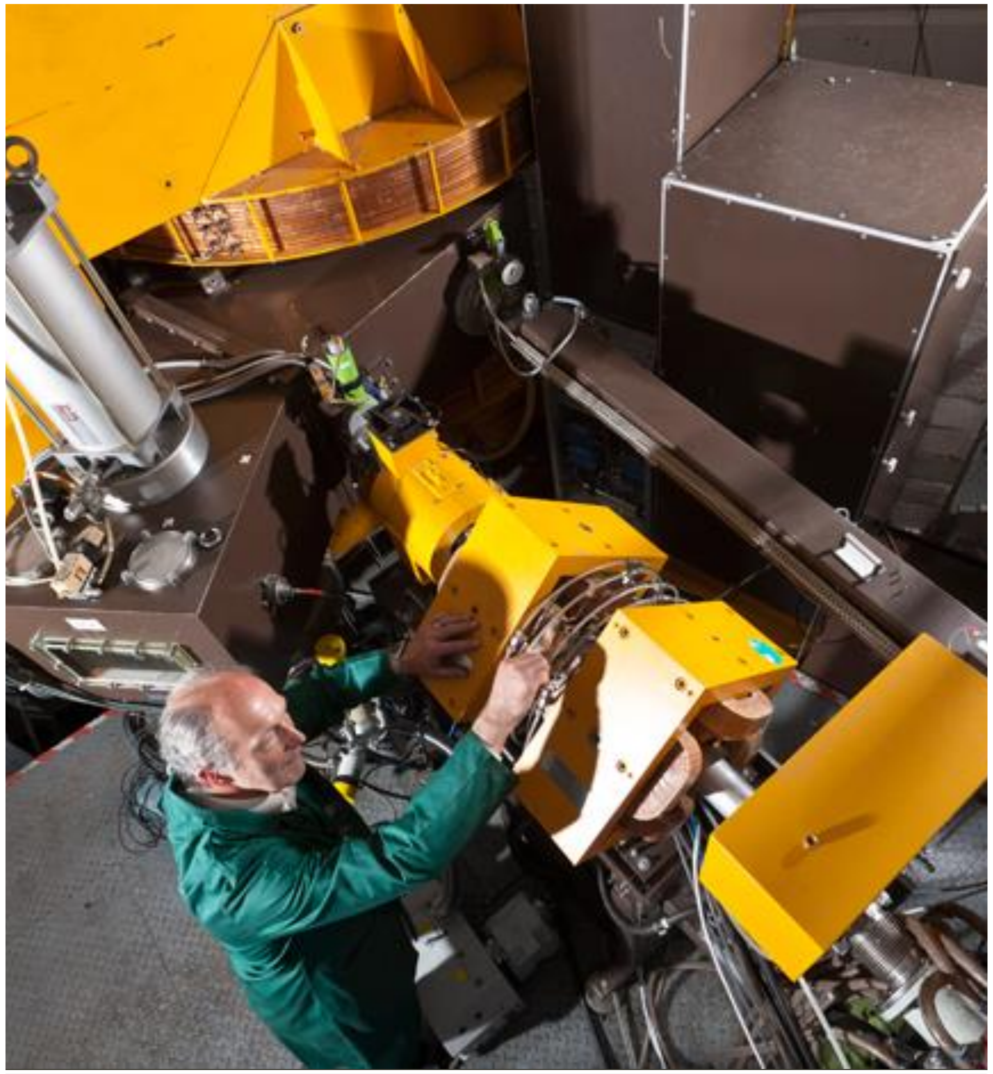
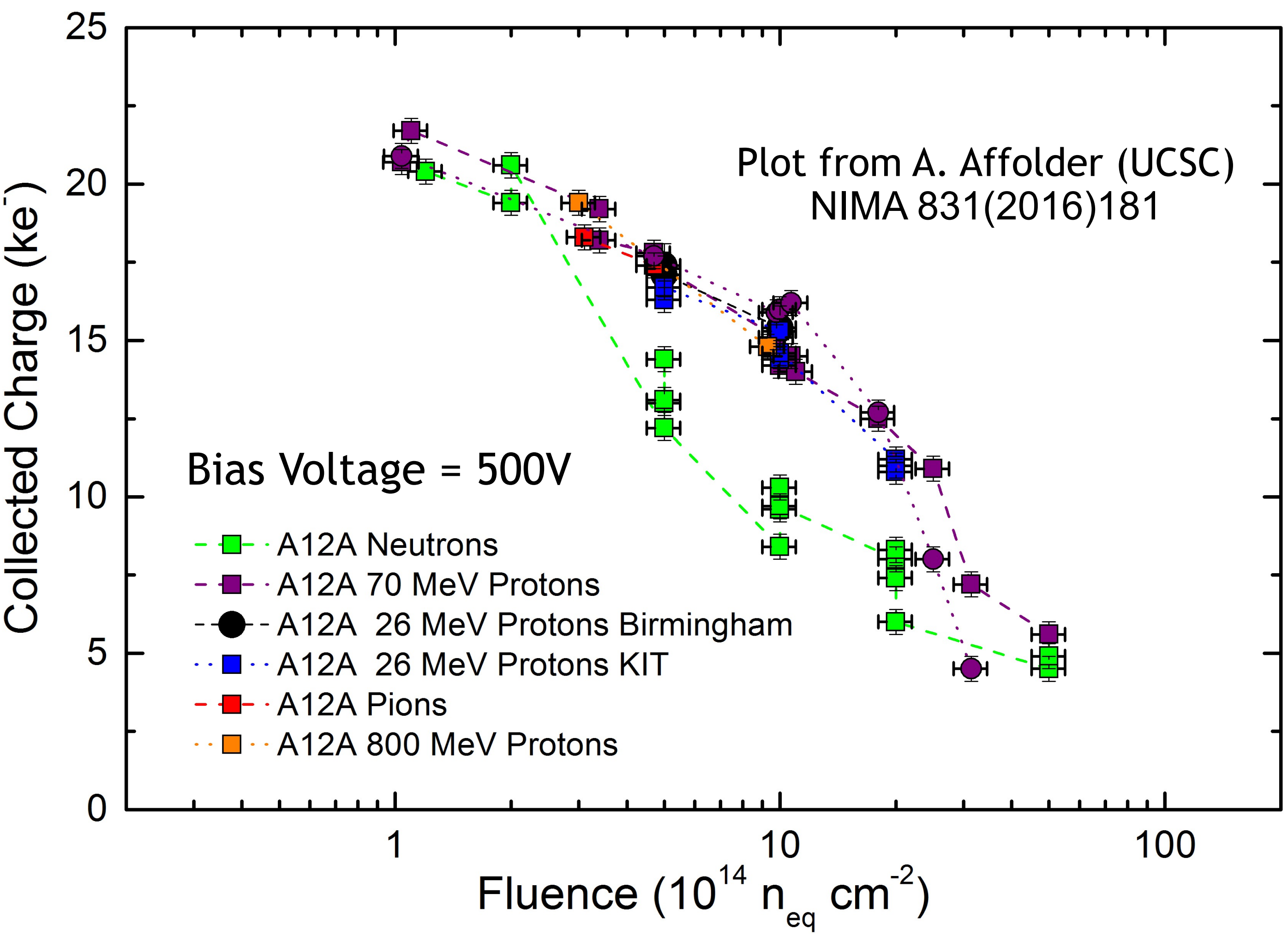


Medical Cyclotron at the University of Birmingham

36th RD50 Workshop
3rd June 2020, online

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme unde
grant agreement no 714893 (ExclusiveHiggs) and grant agreement no 654168 (AIDA-2020).

Comparison between facilities



Transnational Access

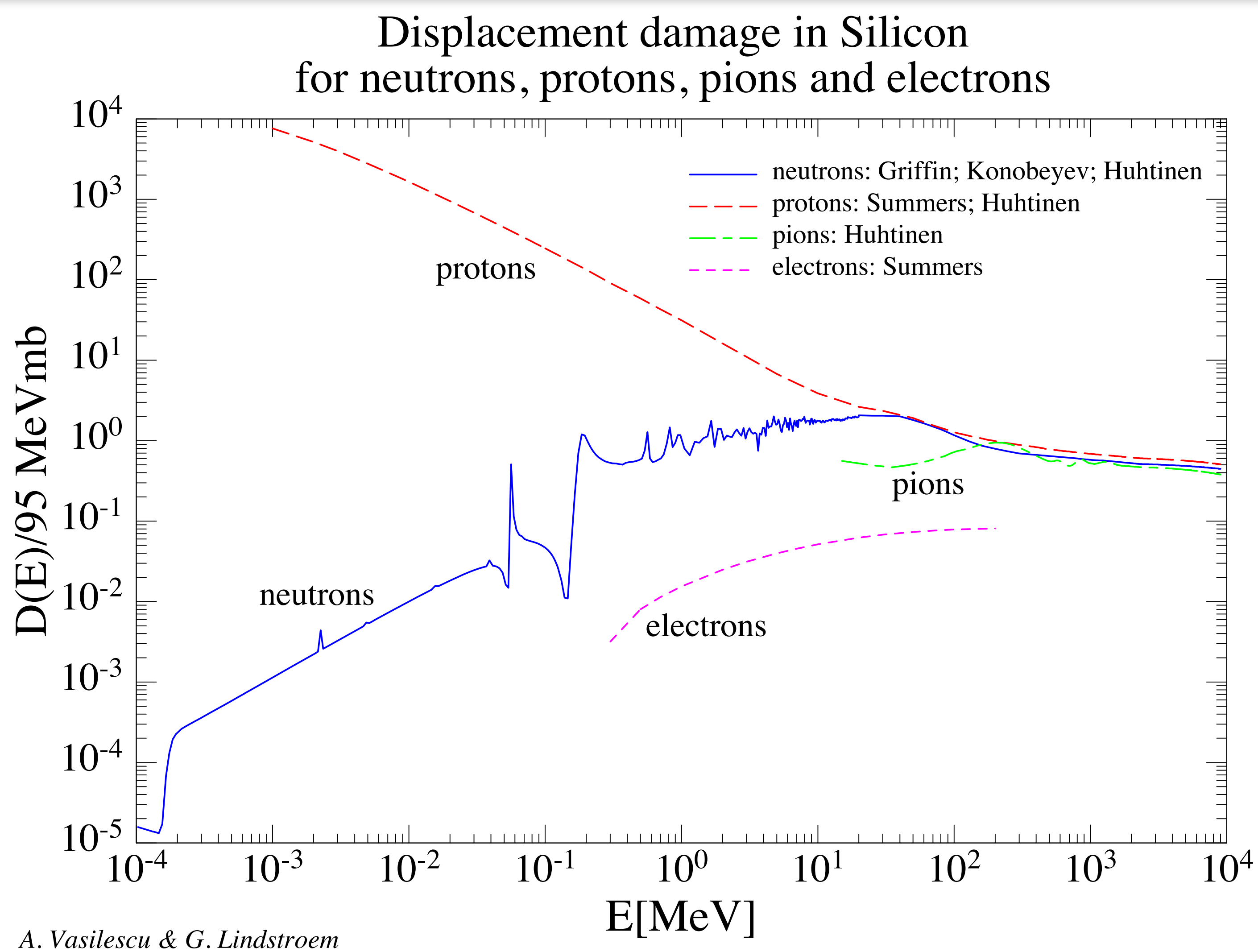
Transnational Access

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

- Radiation hardness critical for HL-LHC detectors and beyond
- World-wide campaigns to characterise radiation hardness of sensors and components
- Within AIDA-2020, transnational access to 10 European Facilities was supported
  - CERN maintains a database with 158 irradiation facilities worldwide
    - https://irradiation-facilities.web.cern.ch/

NIEL and the Hardness factor



A. Vasilescu & G. Lindstroem

- For comparison: fluences expressed in equivalent 1 MeV neutron fluence
  - Conversion via hardness factor
  - Usually derived from leakage current in the bulk of a silicon sensor
    - Assumption: leakage current scales with the non-ionizing energy loss (NIEL)
- In practice, variety of approaches to estimate hardness factors:
  - MC40: κ=2.2 for 23 MeV protons [K. Nikolopoulos, IPRD2016]
  - KIT: κ= 2.05 ± 0.61 for 24 MeV protons (1.85 previously) [A. Dierlamm, RD50 Workshop in Barcelona, 2010]
  - RD50 tables: $\kappa \cong$2.56 for 25 MeV protons [https://rd50.web.cern.ch/rd50/NIEL/default.html]
  - IRRAD: κ=0.62 for 23 GeV protons [NIM B186 (2002) 100]

Hardness factor standardisation

Experimental Determination of Proton Hardness Factors at Several Irradiation Facilities

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arXiv:1908.03049

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.

- Clear need for uniformly derived hardness factors
- Collaboration between
  - University of Birmingham
  - CERN
  - Karlsruhe Institute of Technology
- Measuring and comparing hardness factors with consistent methodology

Silicon sensor: BPW34F

- BPW34F diode was chosen for this study
  - silicon p-i-n photodiode with daylight blocking filter
  - produced by OSRAM Opto-Semiconductors
  - commercially available
  - extensively studied
- For comparison, measurements at CERN also performed with Float Zone pad diodes

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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

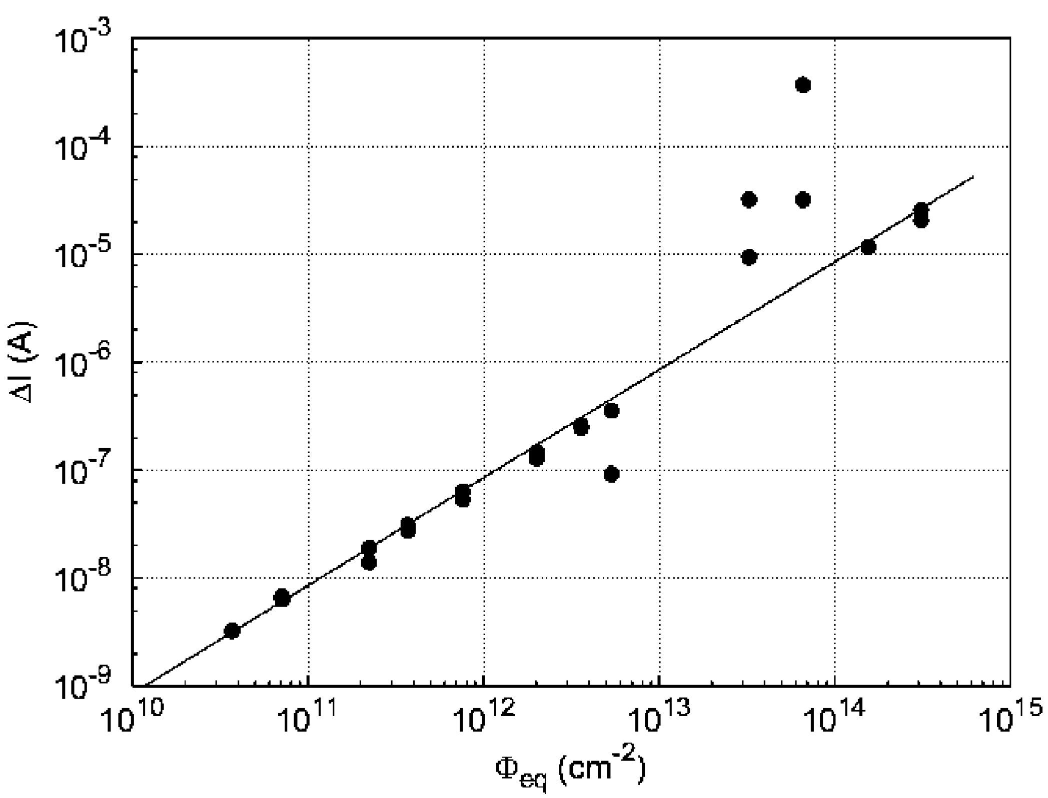
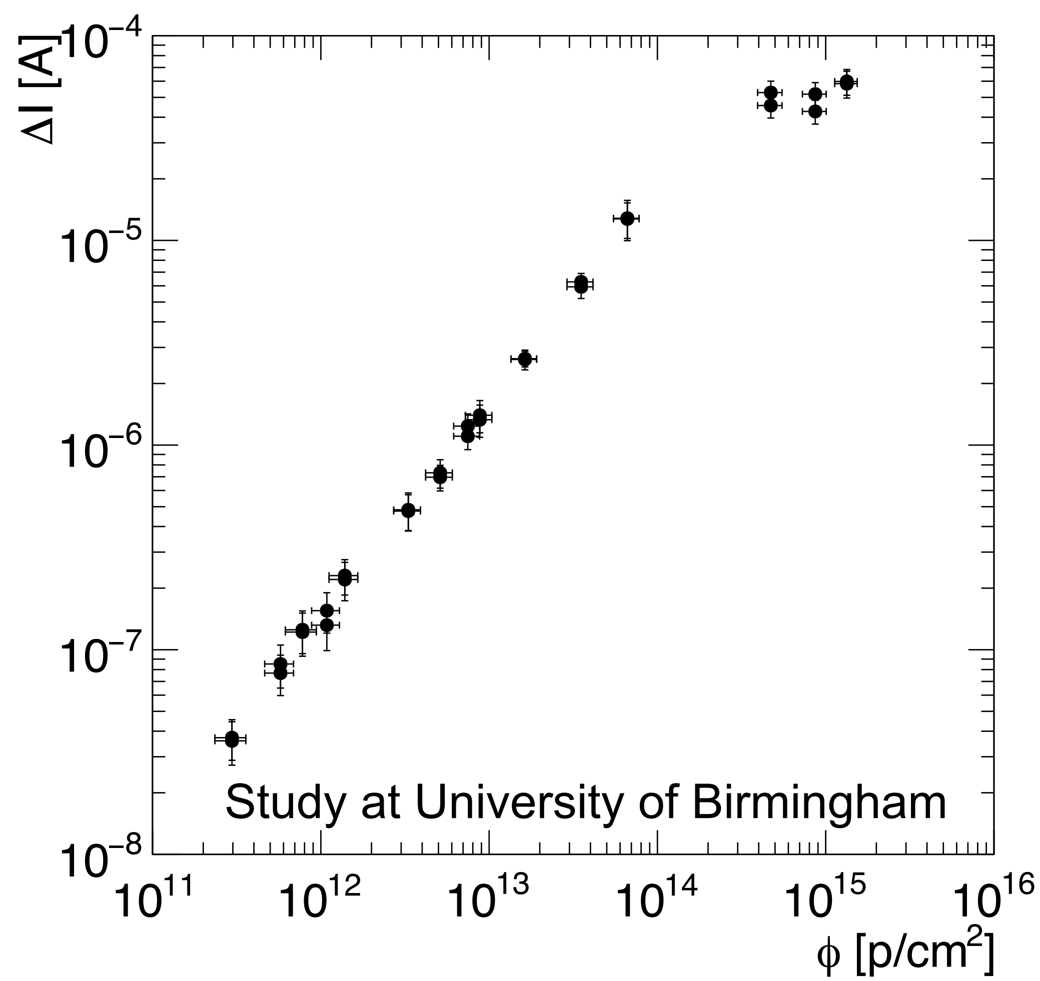
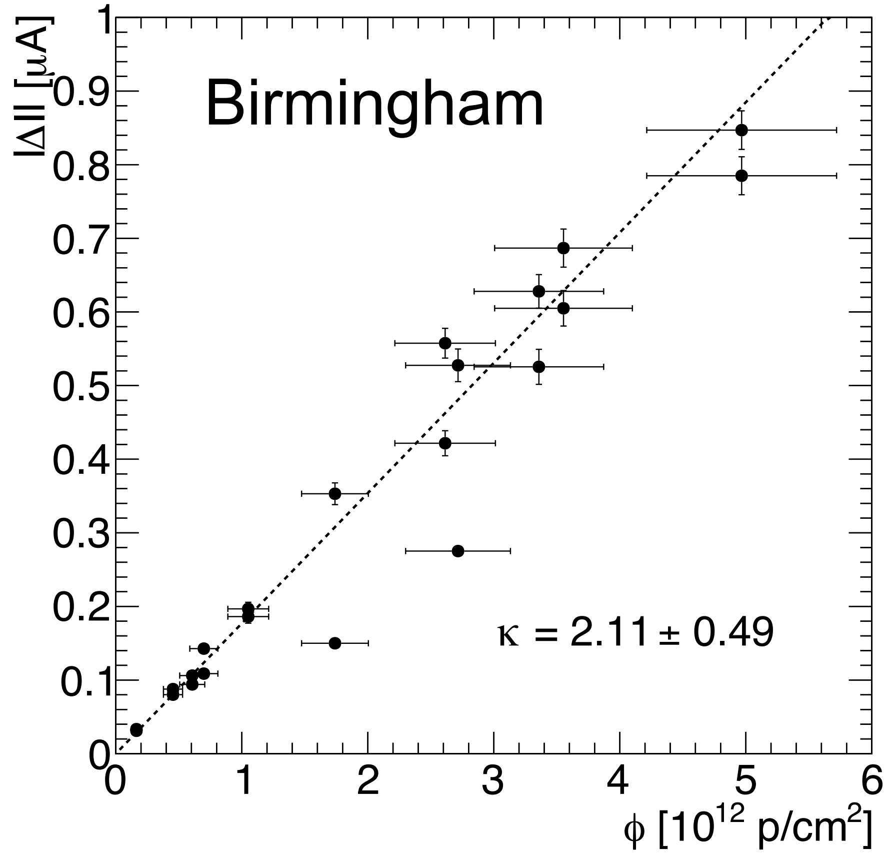
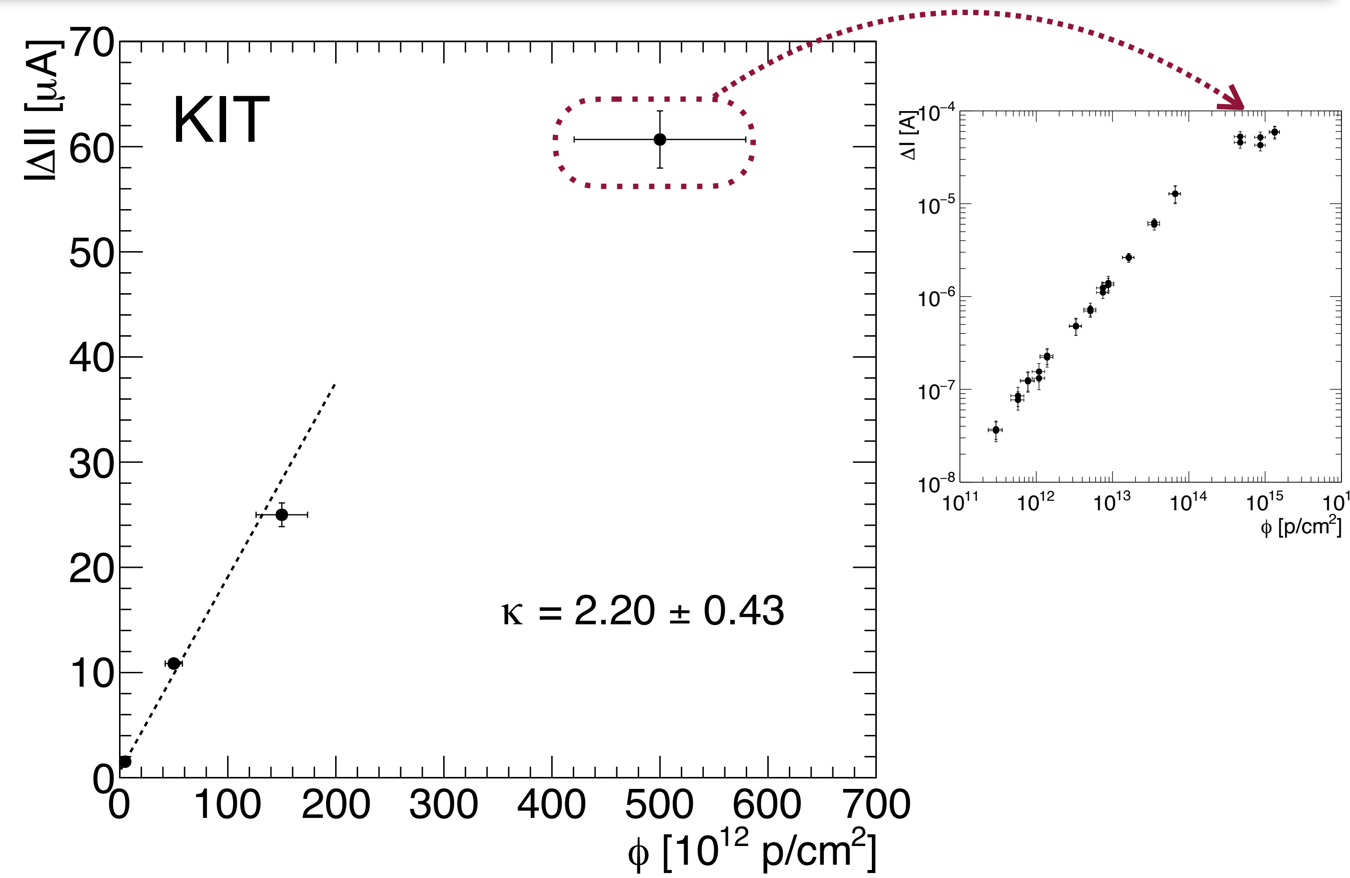


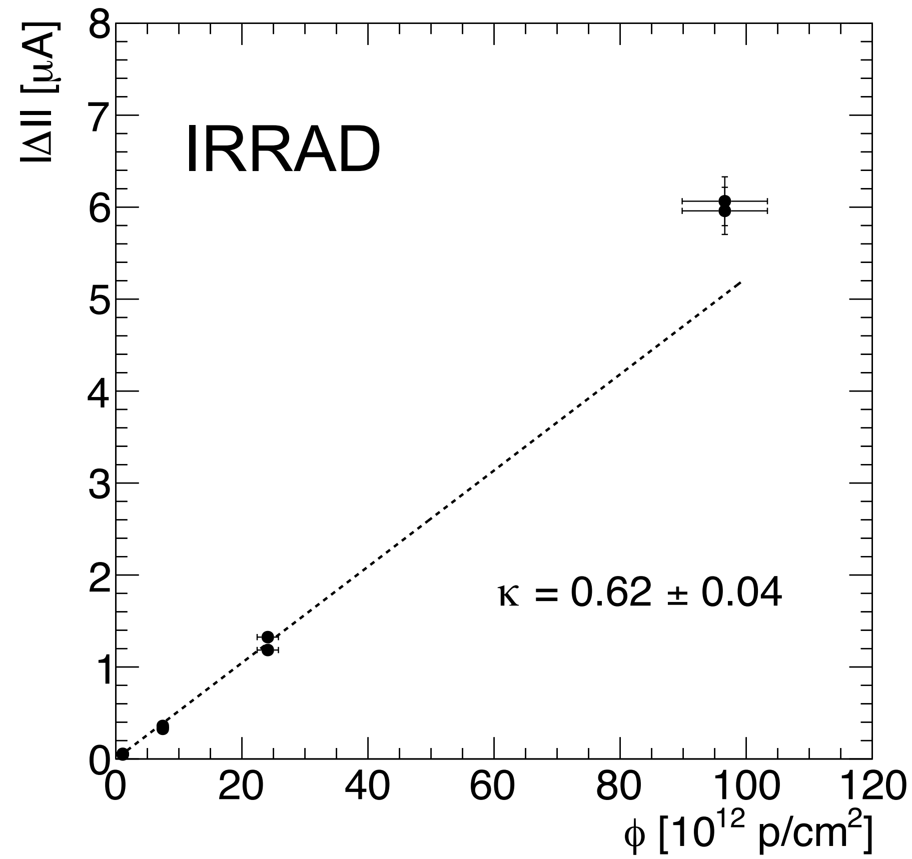
Fig. 3. BPW34F characteristics in reverse bias normalized to 20°C. Leakage current measurement and increasing irradiation levels with 23 GeV protons.

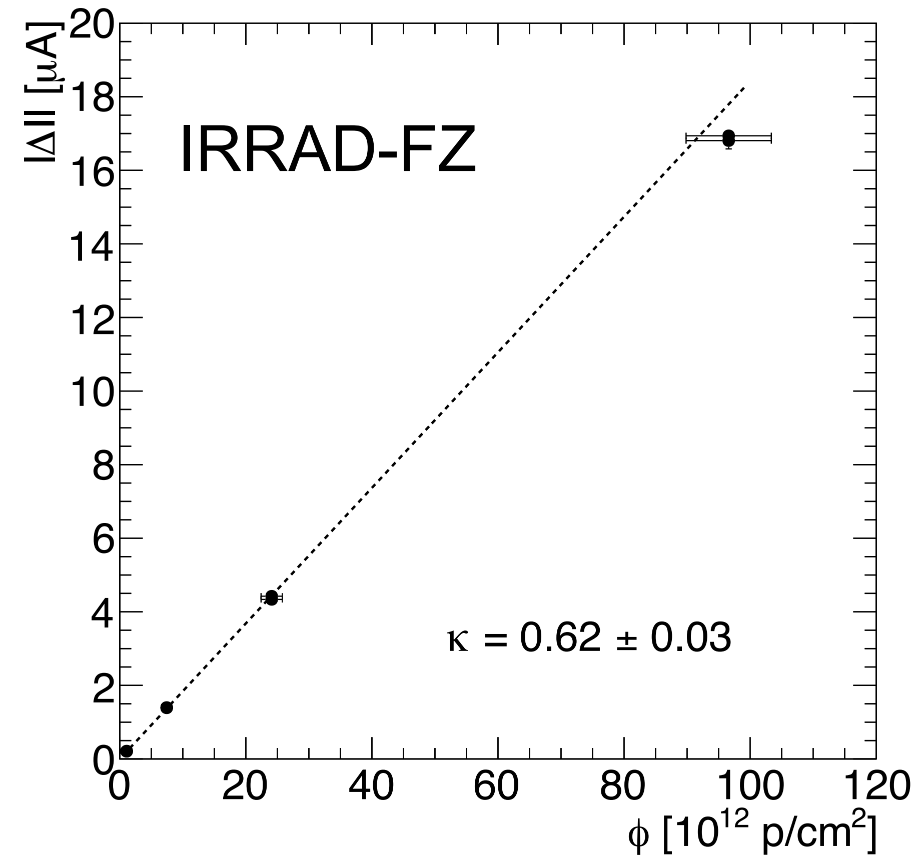


Hardness factors

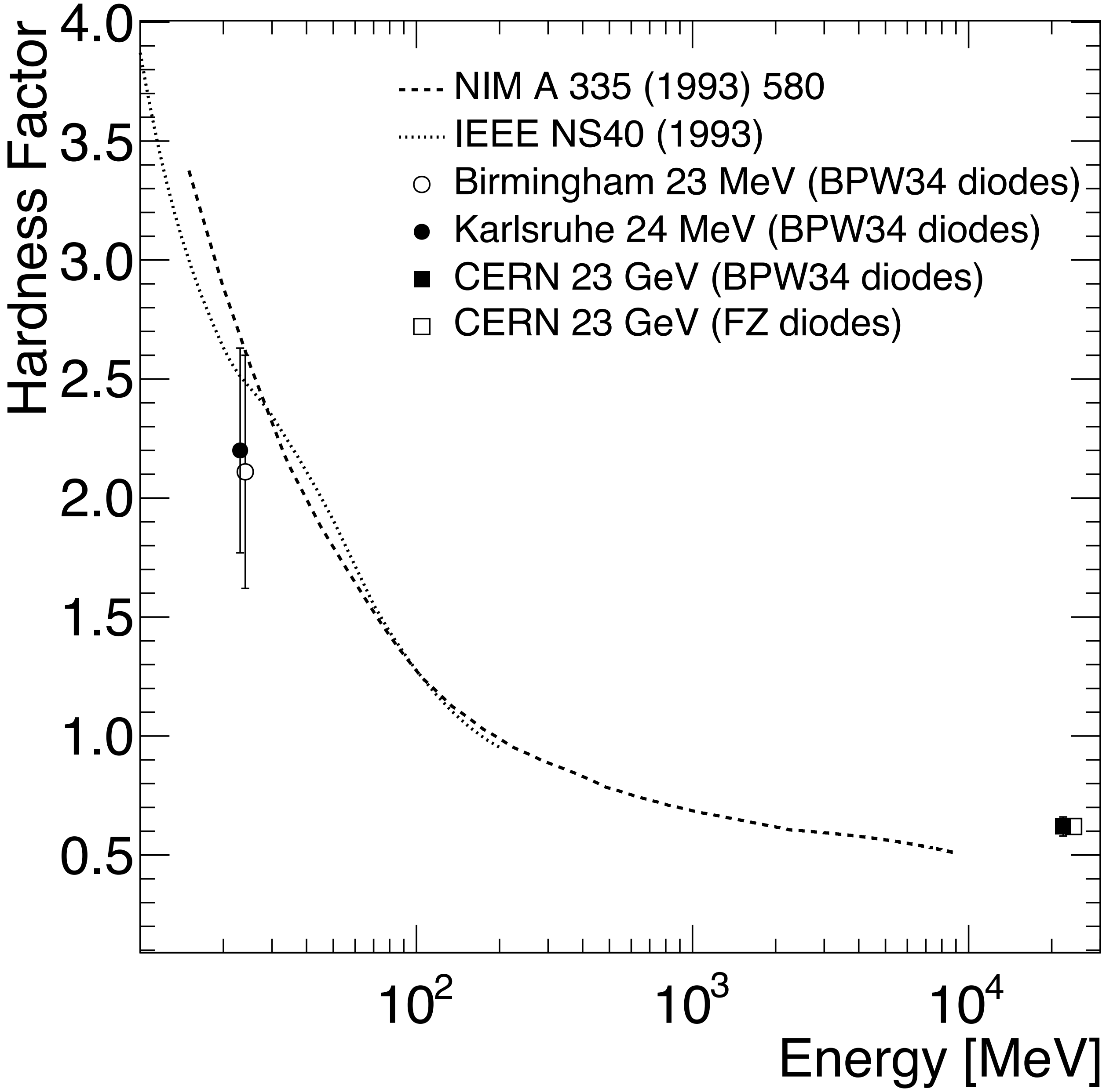


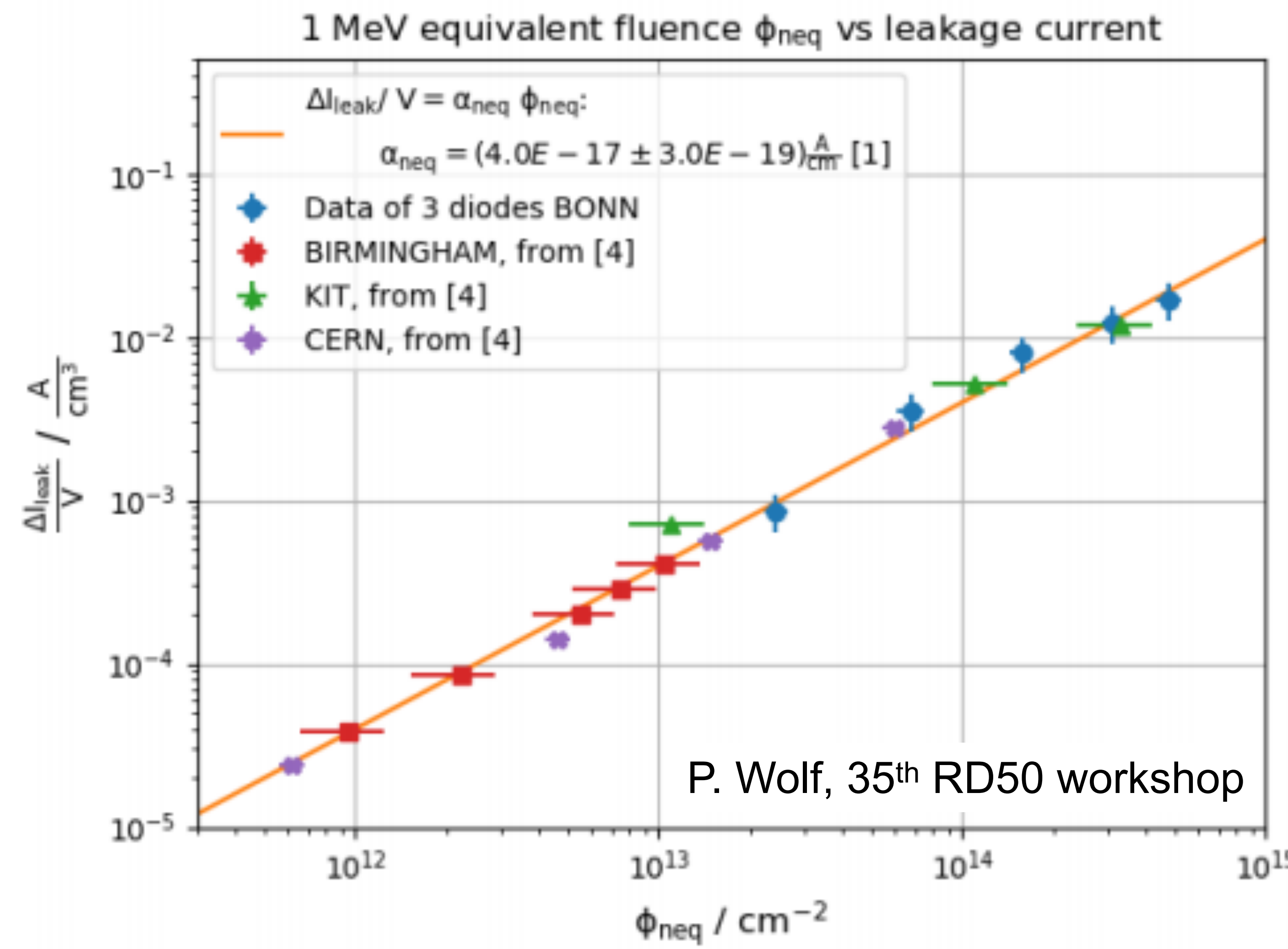






Overview of results



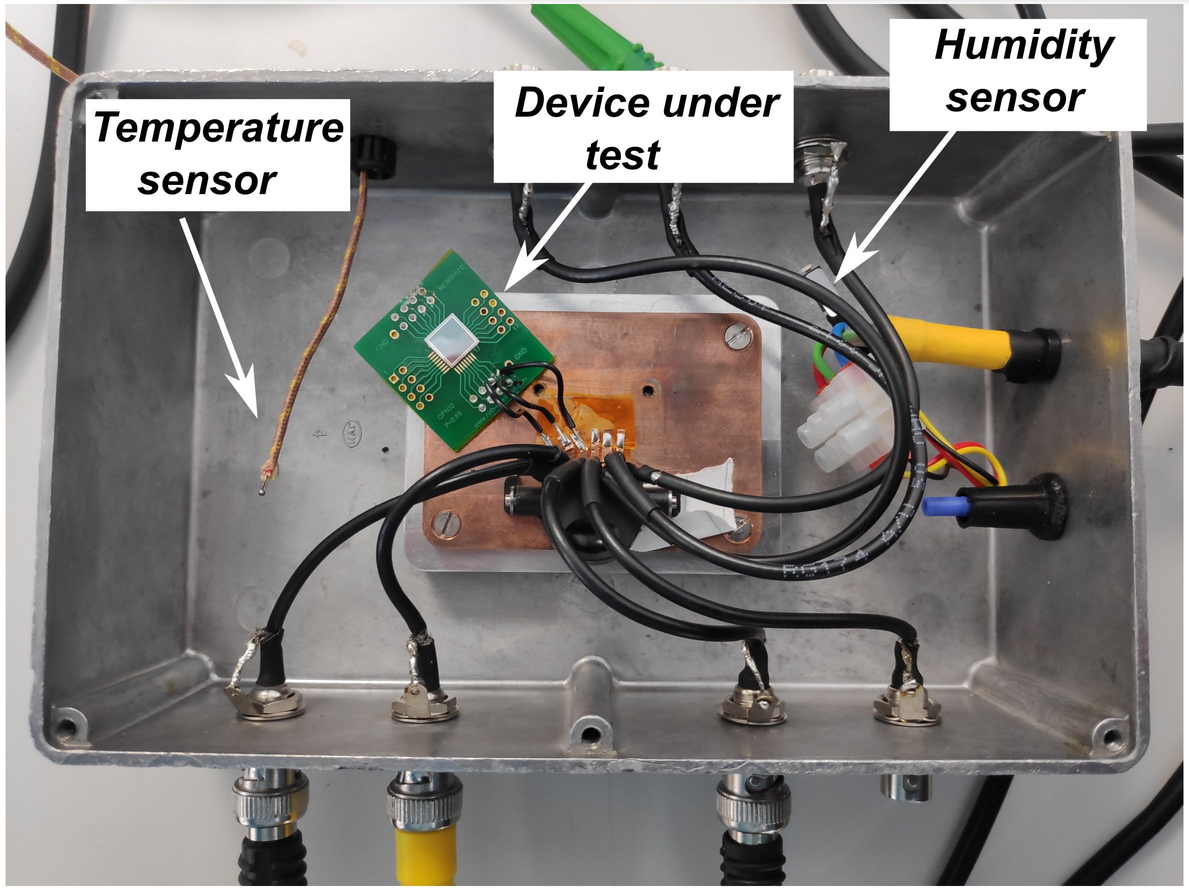


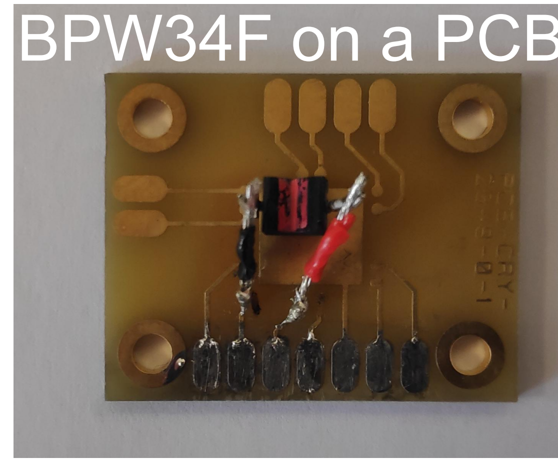
$$\alpha_{neq} = (3.99 \pm 0.03) \times 10^{-17}\ \mathrm{Acm}^{-1}$$

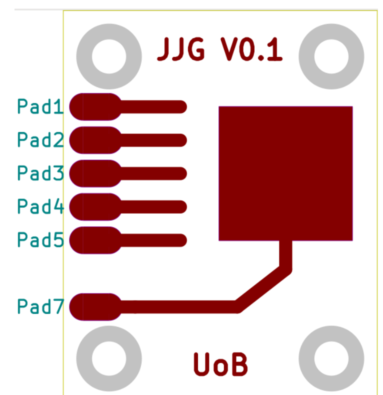
M. Moll, PhD Thesis

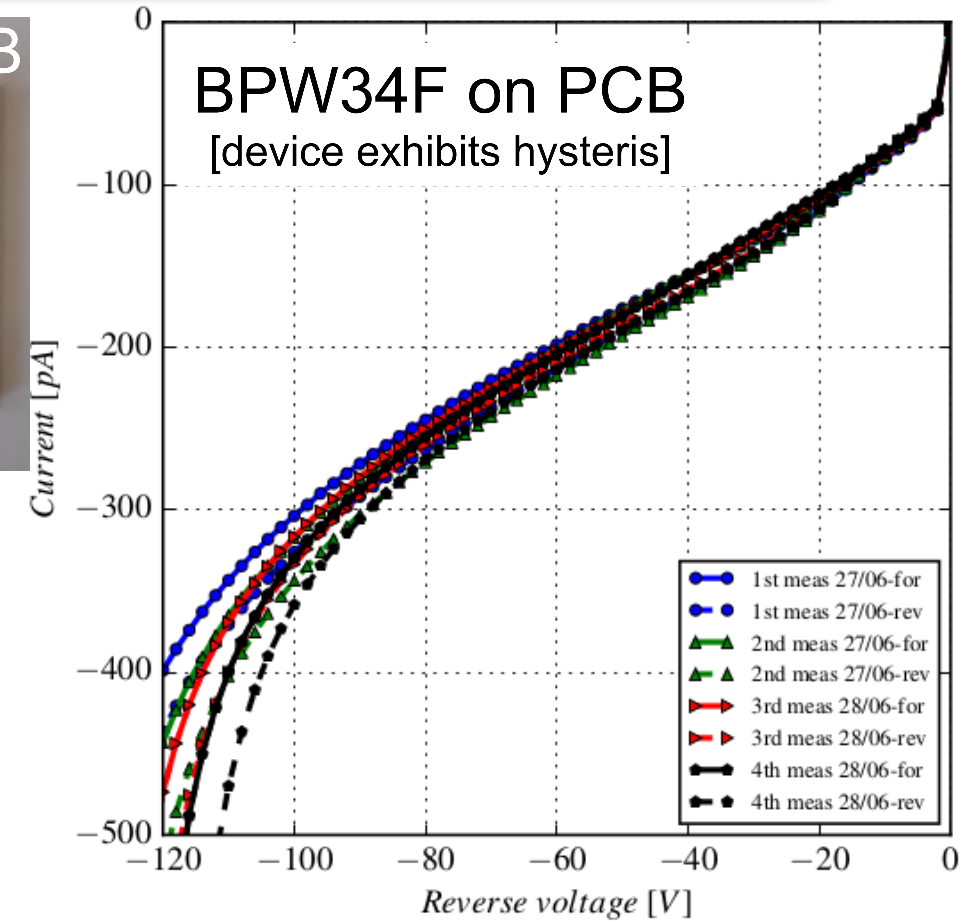
- Common methodology applied to derive consistent set of hardness factors
  - Significant uncertainties still exist: dosimetry and measurement precision
- University of Bonn has now commissioned a proton irradiation facility [P. Wolf, 35th RD50 workshop]
- BPW34F diodes irradiated at Bonn were sent to Birmingham for measurements/comparisons
  - Work to resume once laboratory become accessible again

Set-up for precision electrical measurements

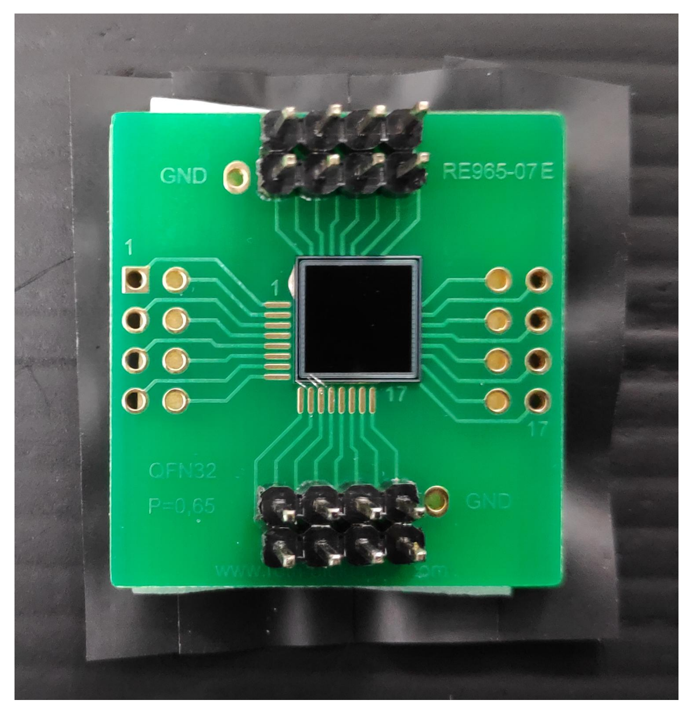


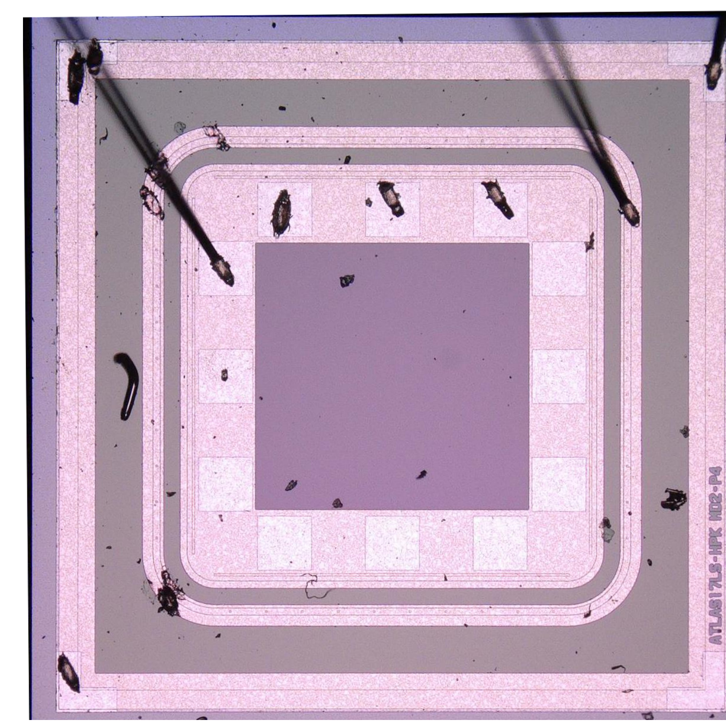






- New PCB with spring loaded connection
- On-line humidity/temperature monitoring
- pA range current measurement precision
  - Keithley electrometers 6517B & 6487
- Capacitance/Resistance measurements:
  - Wayne Kerr 6500B series LCR meter

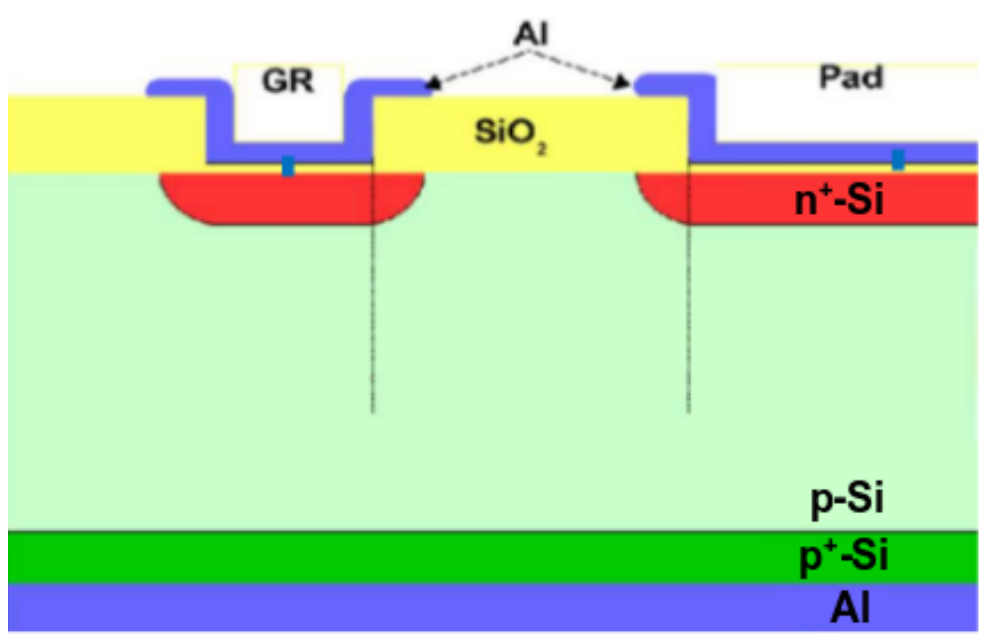




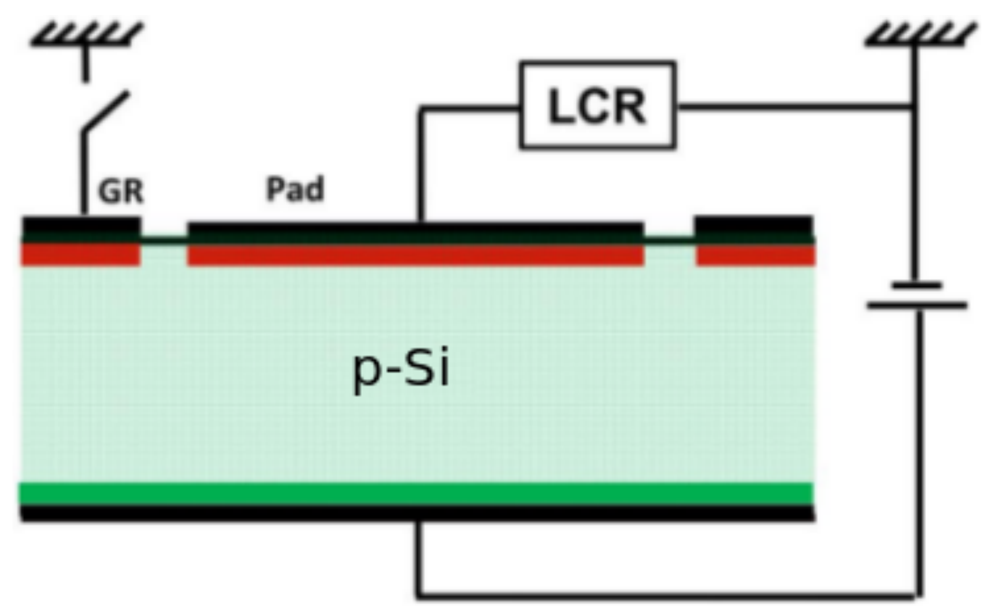
Hamamatsu 8x8mm² diode
(ATLAS17 strip sensor campaign)

Pad diode measurements

- Test structure: pad diode with guard rings (gr)
  - fabricated on p-type wafers (FZ320) by Hamamatsu for ATLAS ITk
  - Nominal thickness 320 μm
- Measurements: I-V and C-V for guard ring grounded/floating/connected

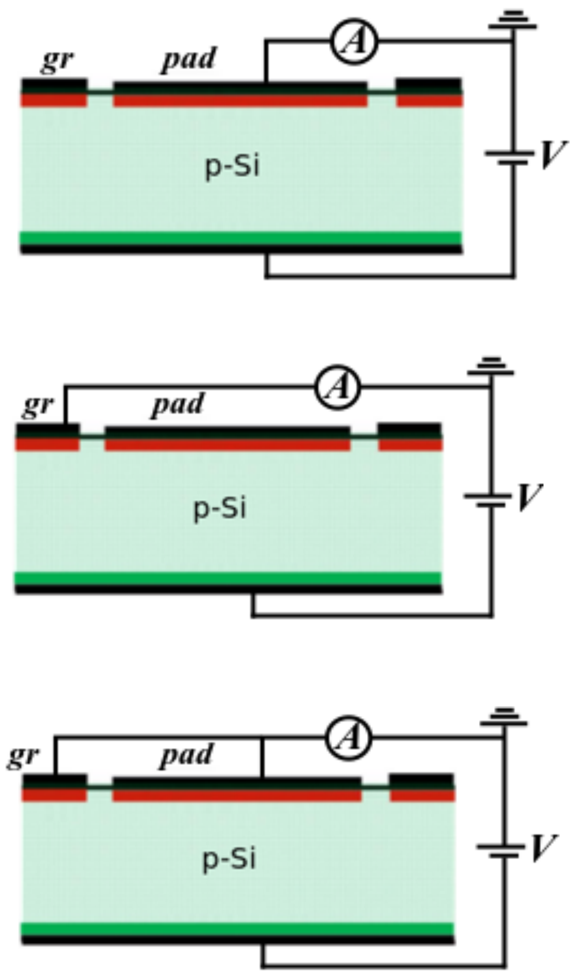


Diode cross section

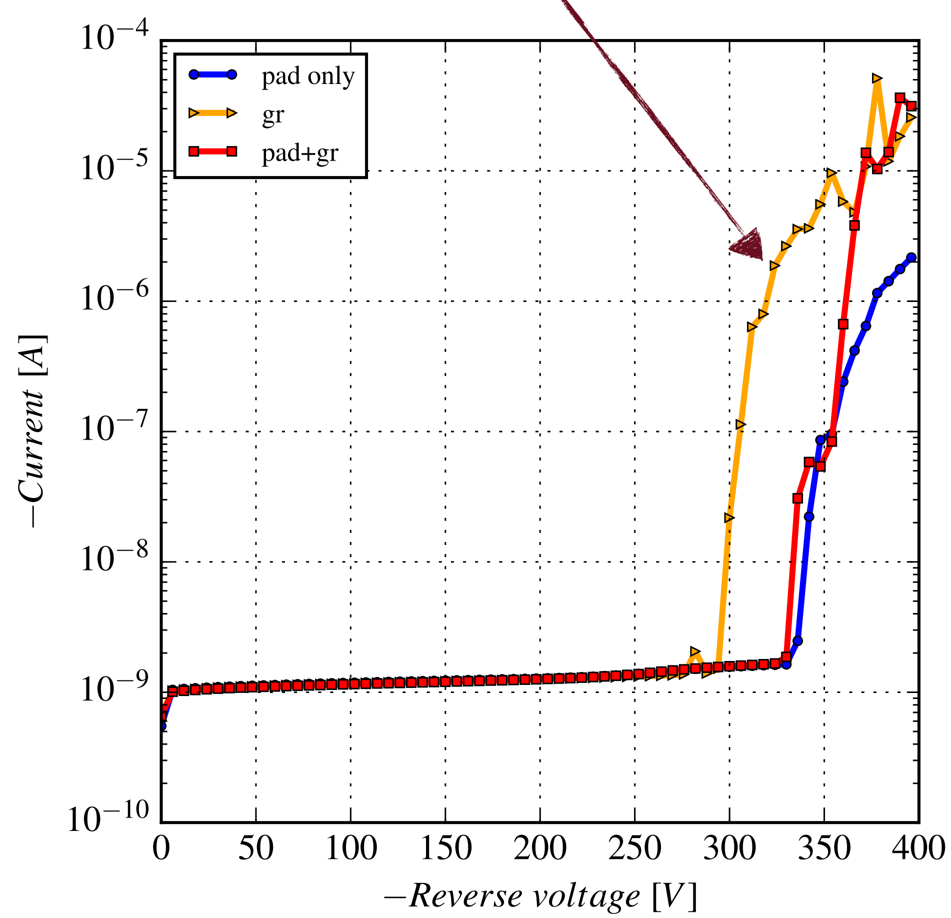


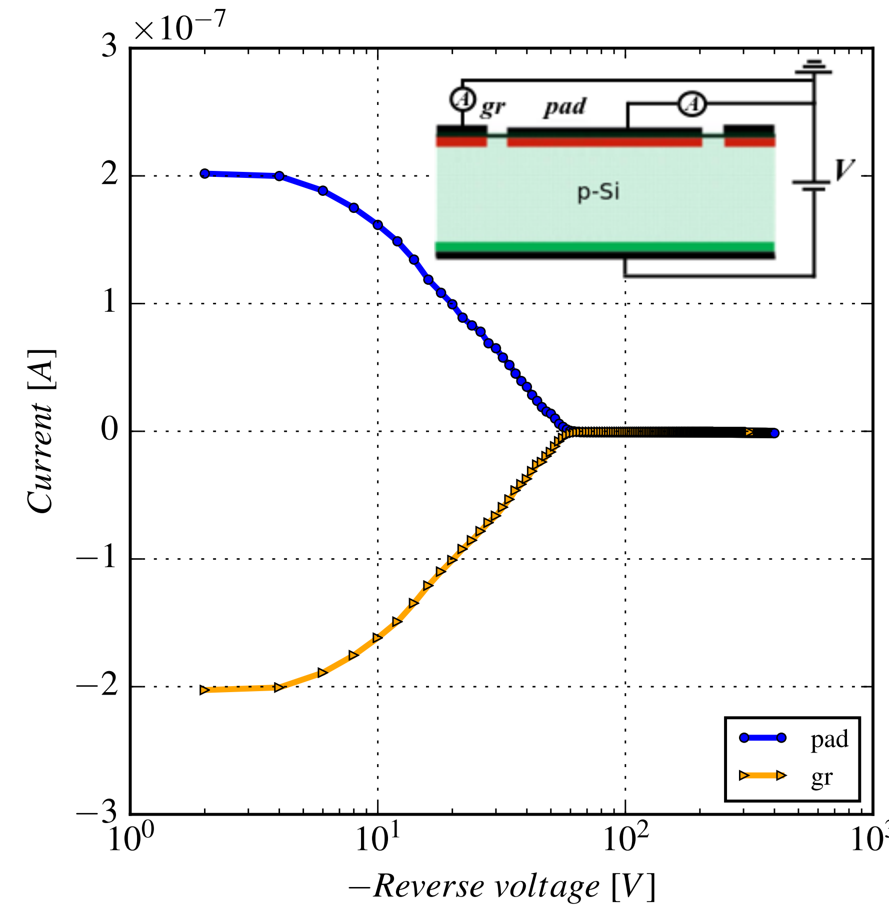
Measurement set-up

I-V measurements



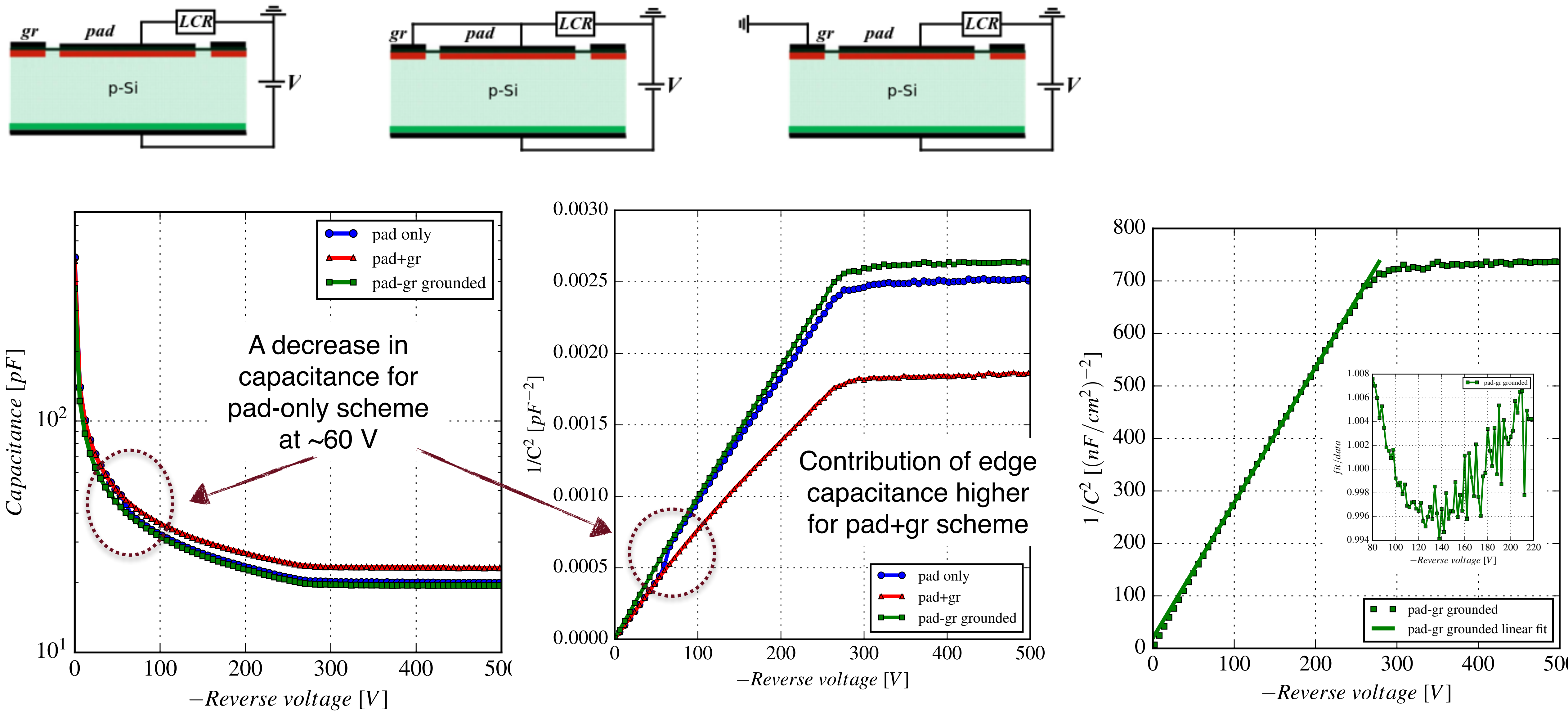
Early breakdown due to humidity





- For pad and guard-ring connected to different ammeters, a channel is observed between pad and guard-ring for all the investigated diodes due to missing p-stop isolation

C-V for different biasing schemes



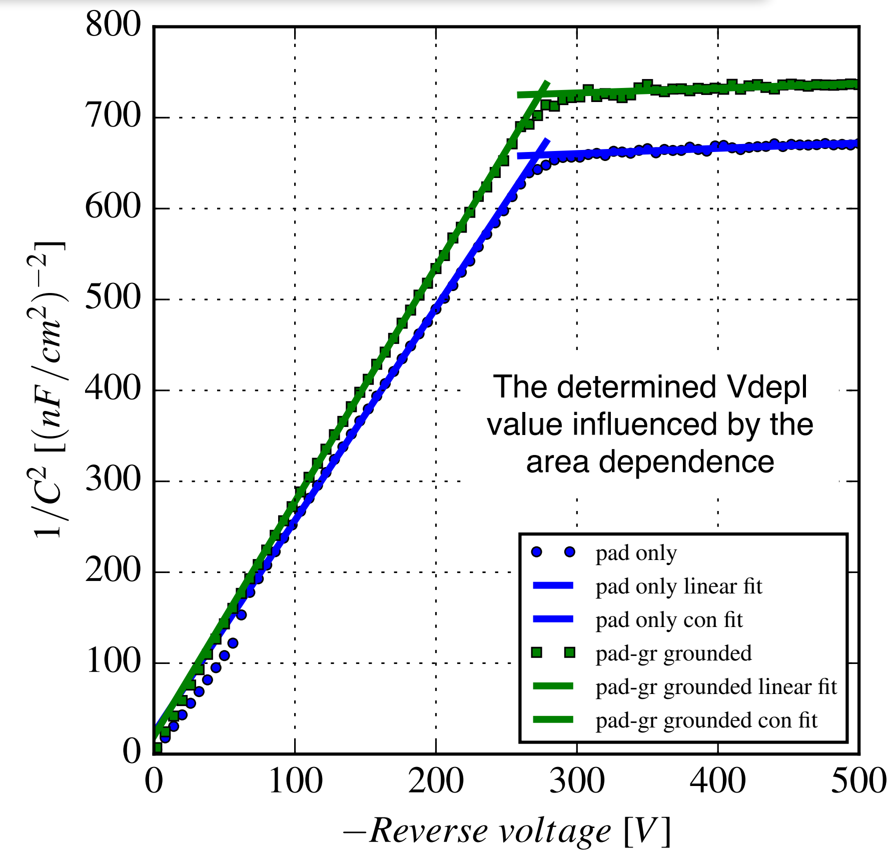
- Doping density N_D determination for pad-gr grounded biasing scheme
  - 1/C² method: $N_D = 2/(\varepsilon_0 \varepsilon_{Si} q_0 b)$ with $1/C^2 = b(V+V_0)$; $V0 \cong V_{bi}$ (built-in voltage)
    - $N_D = 4.6 \cdot 10^{12}$ cm^{-3}, $V_0 = 7.71$ V, $\chi^2/ndof = 56.7/68$
  - Estimate with full depletion method in next slide

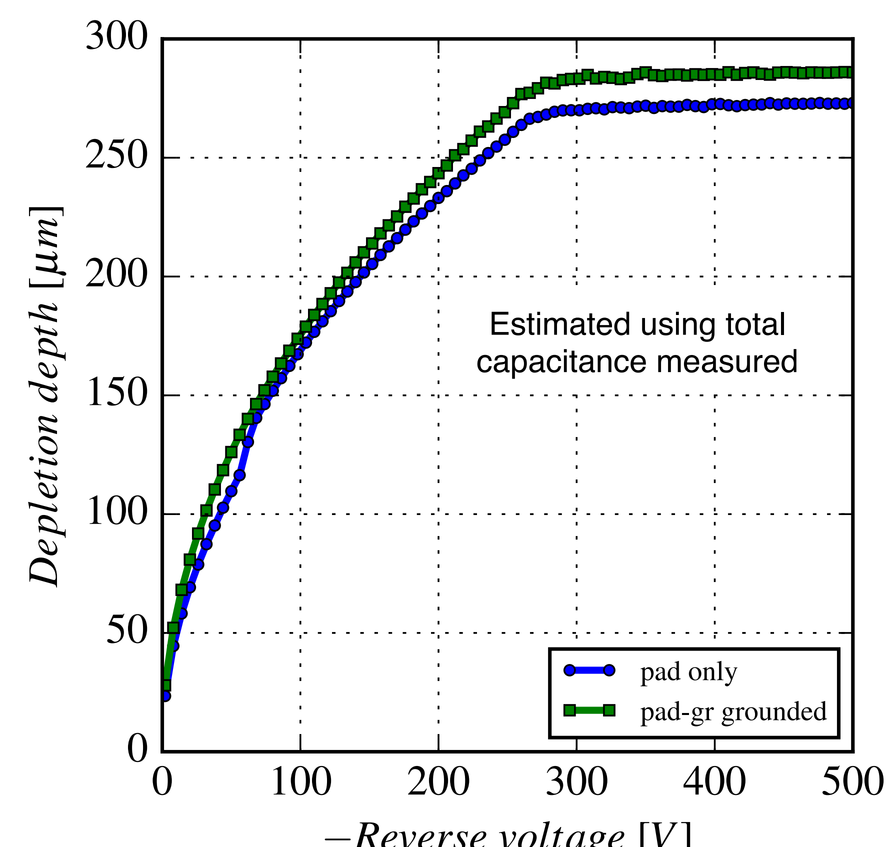
Determination of V_{dep}

- Determination of full depletion voltage V_{dep}
  - pad-only and pad-gr grounded biasing schemes
  - fits for V= 80-218 V and V= 320-478 V
- Intercept of $1/C^2$ fits below and above the full depletion
  - Pad-only V_{dep} = 265.1V
  - Pad+gr V_{dep} = 268.4V
  - $N_D = (2\varepsilon_0\varepsilon_{Si}/q_0 d^2)V_{dep}$

Thickness [μm]	N_D [cm^{-3}] ($1/C^2$)	N_D [cm^{-3}] (V_{dep})
320	$4.6\ 10^{12}$	$3.45\ 10^{12}$
310	$4.6\ 10^{12}$	$3.67\ 10^{12}$

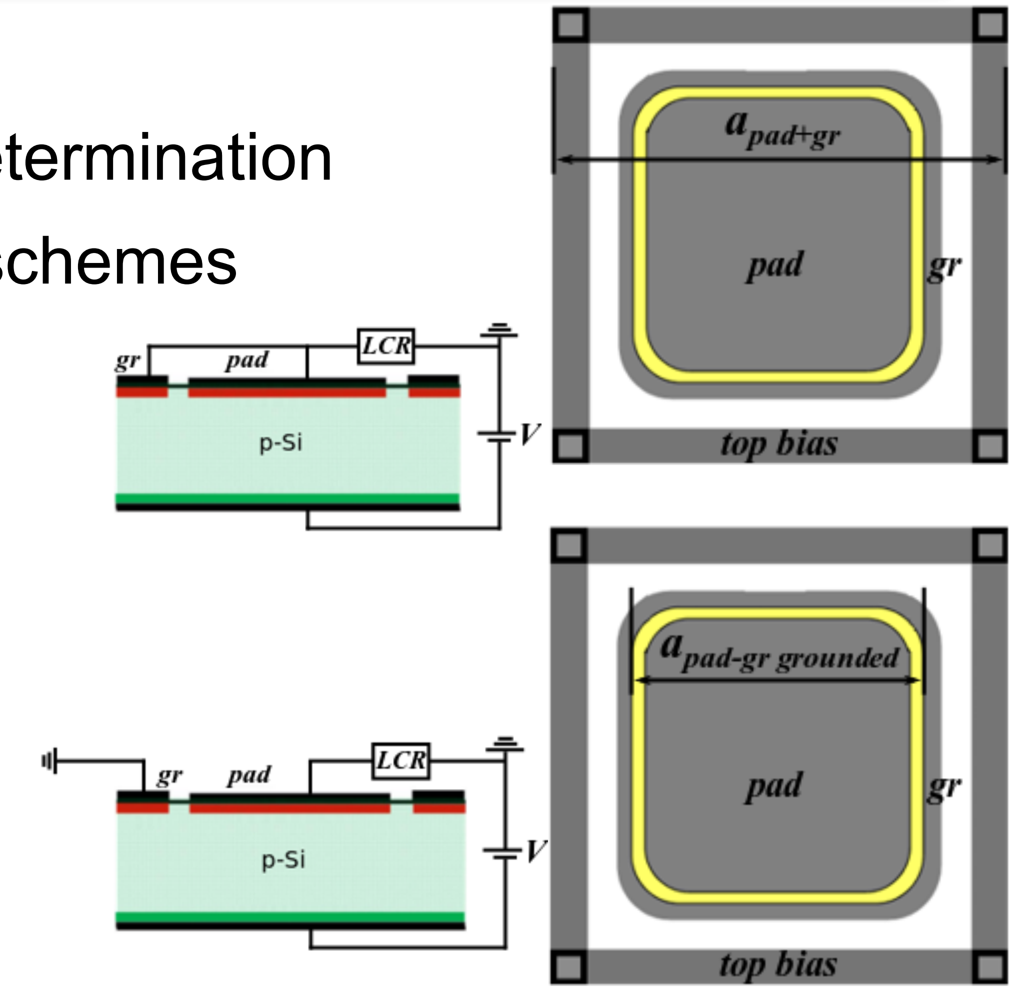
- Depletion depth $w(V) = \frac{\epsilon_0 \epsilon_{Si}}{C(V)}$
  - $V > V_{dep}$ → active thickness for diode
- For effective active thickness need to account for edge capacitance contributions
- Smartscope thickness measured consistent with 320μm





Estimating the planar and edge capacitance

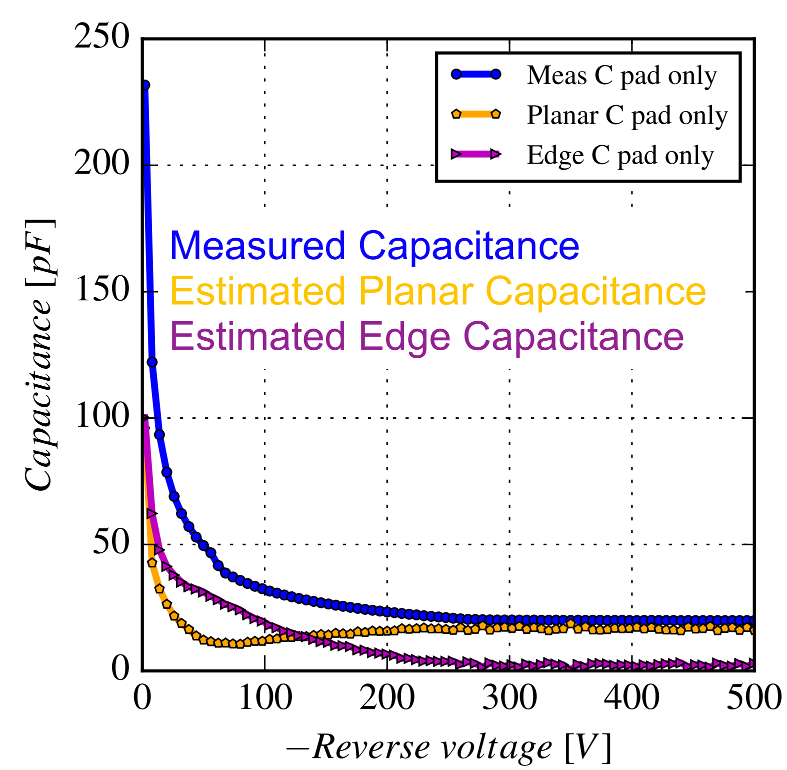
- Used p-type diodes do not have p-stop isolation
  - Estimate edge effects and influence on doping determination
- Method: square pad diode under different biasing schemes
  - smaller diode side: α_S
  - larger diode side: α_L (extended lateral depletion)



Assuming: $$C = \alpha^2 C_{planar} + 4\alpha C_{edge}$$

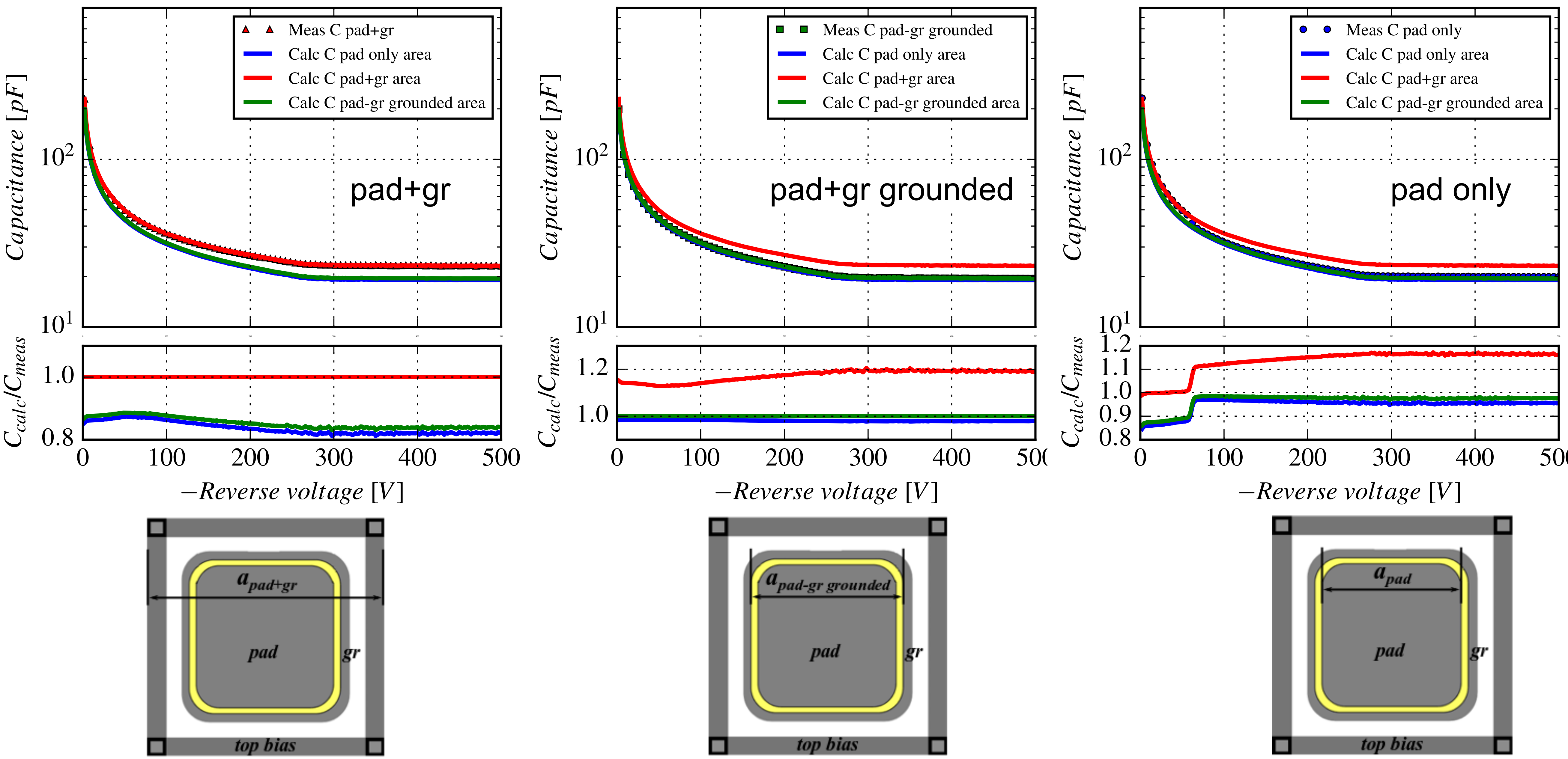
$$C_{planar} = \frac{\frac{C_{\alpha_S}}{\alpha_S} - \frac{C_{\alpha_L}}{\alpha_L}}{\alpha_S - \alpha_L} \qquad C_{edge} = \frac{\frac{\alpha_L}{\alpha_S}C_{\alpha_S} - \frac{\alpha_S}{\alpha_L}C_{\alpha_L}}{4(\alpha_S - \alpha_L)}$$

	pad+gr	pad + gr grounded
Side length [μm]	7980	7267



Estimating the planar and edge capacitance

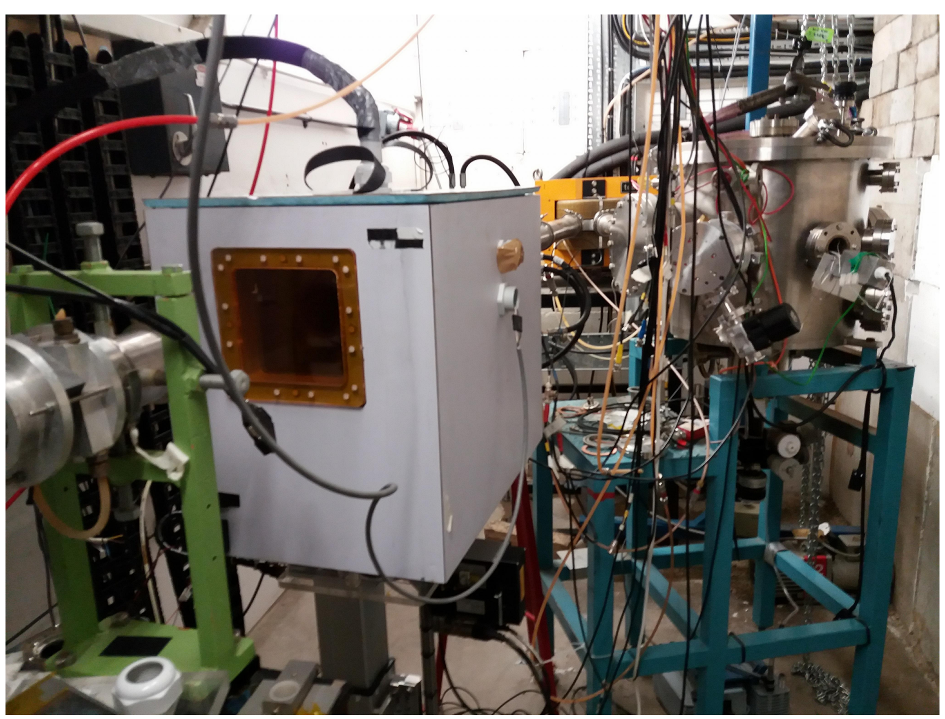
- The model describes well all three biasing schemes
  - For “pad only” after 60V the data are described better by the pad + gr grounded area

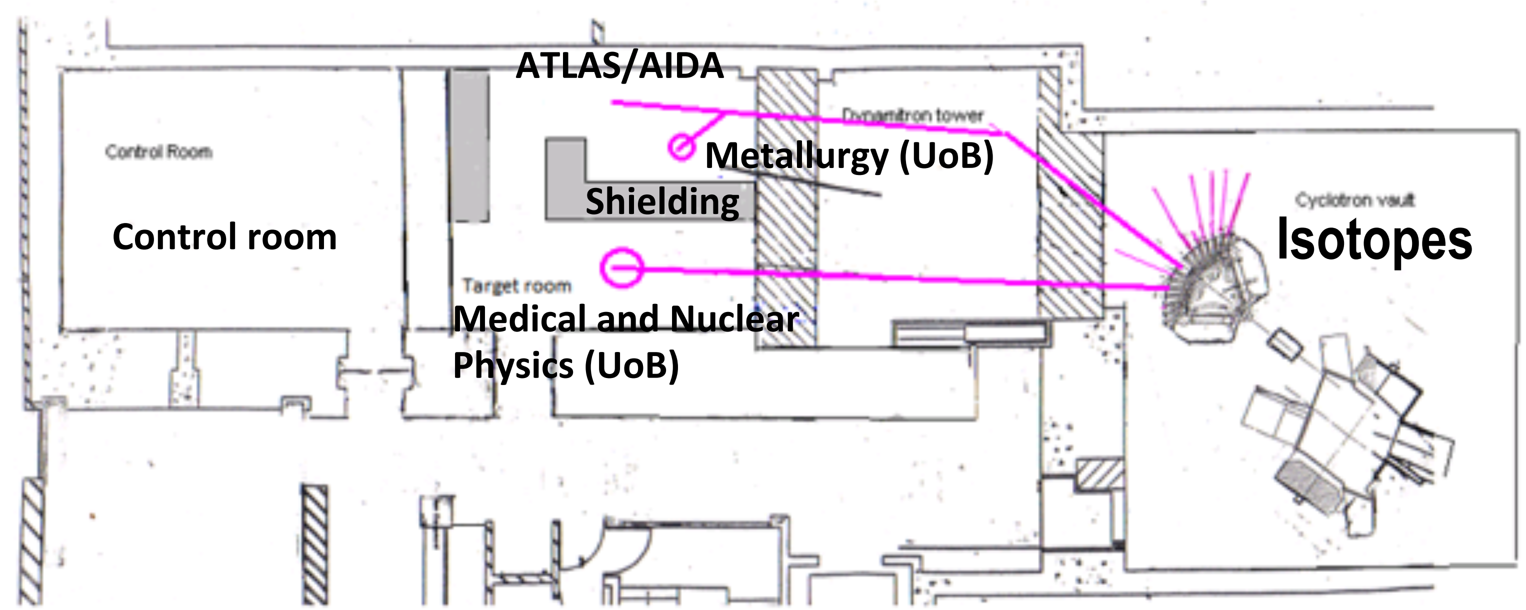


MC40 cyclotron University of Birmingham

- Provides: p, d, ^{3}He, and ^{4}He ~continuous beams
- Second beam-line into specially shielded area (2013)
  - high dose-rate damage studies
- Proton current: up to 2μA
- Beam spot: ~10×10 mm^2
- Flux: up to 10^{13} protons/s/cm^2
- Typical beam parameters:
  - Energy: 27 MeV
  - Current: 0.1-0.5μA

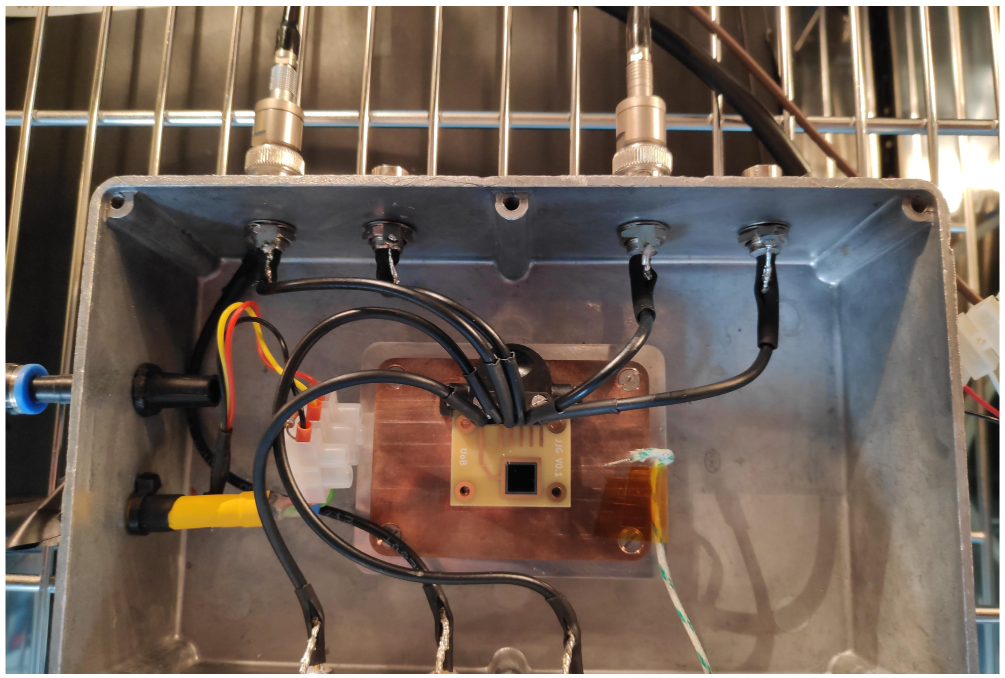
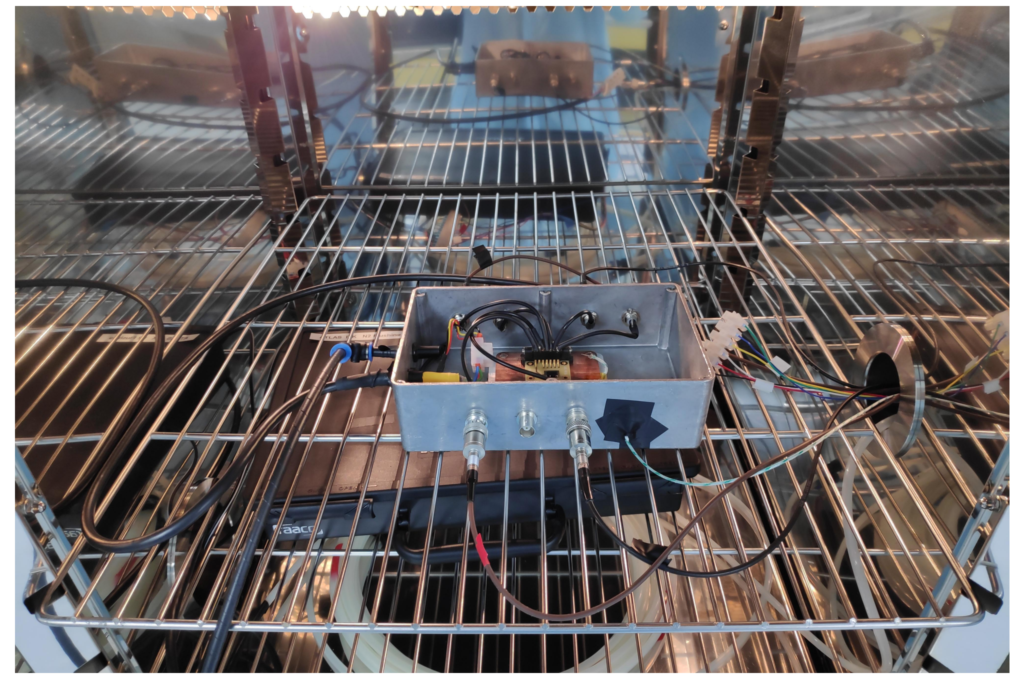
Ion	Energy at Extraction
Proton	11 – 38 MeV (N=1) 3 – 9 MeV (N=2)
Deuteron	5.5 – 19 MeV (N=2)
^{3}He	35 – 53 MeV (N=1) 9 – 27 MeV (N=2)
^{4}He	11 – 37 MeV (N=2)



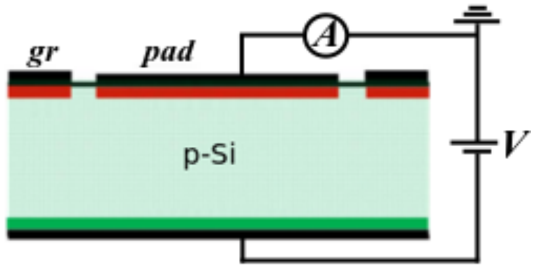


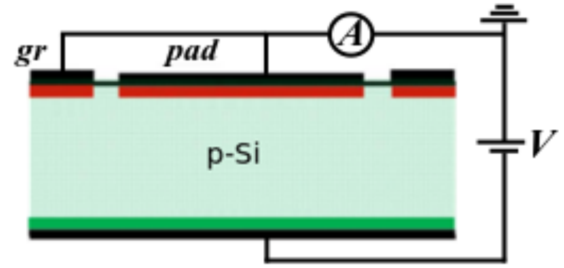
Electrical measurements post-irradiation

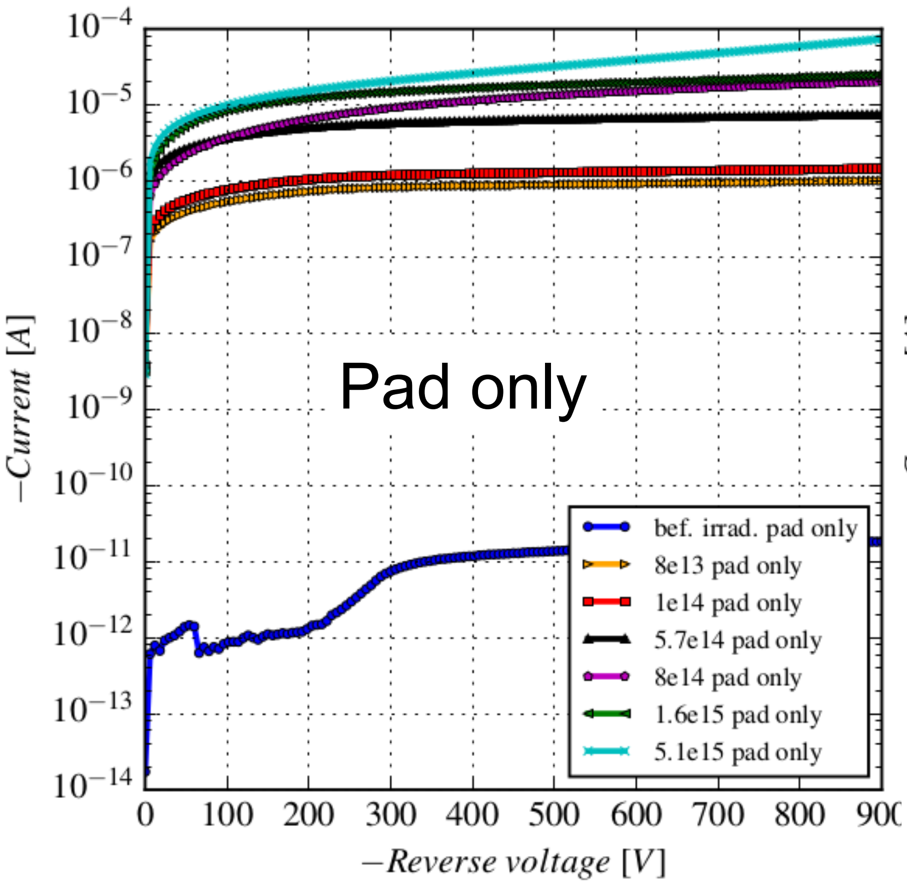
- Standard annealing procedure (80min at 60℃)
- Temperature -20℃ and humidity <5% RH control during measurements (nitrogen flow)

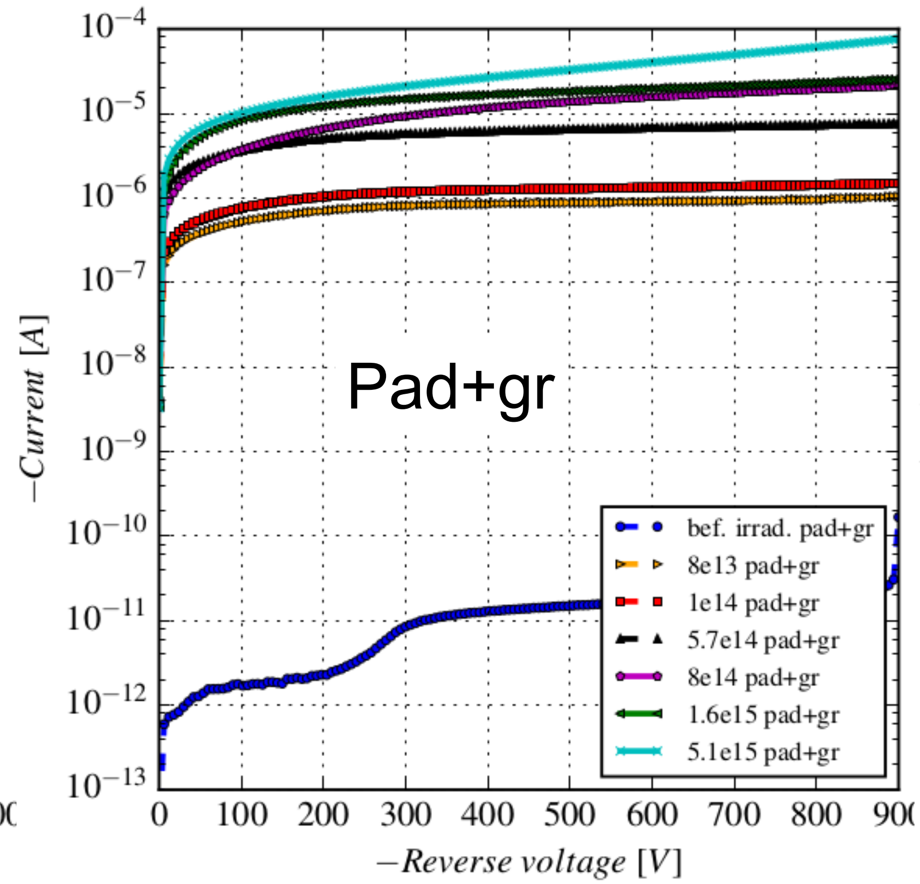



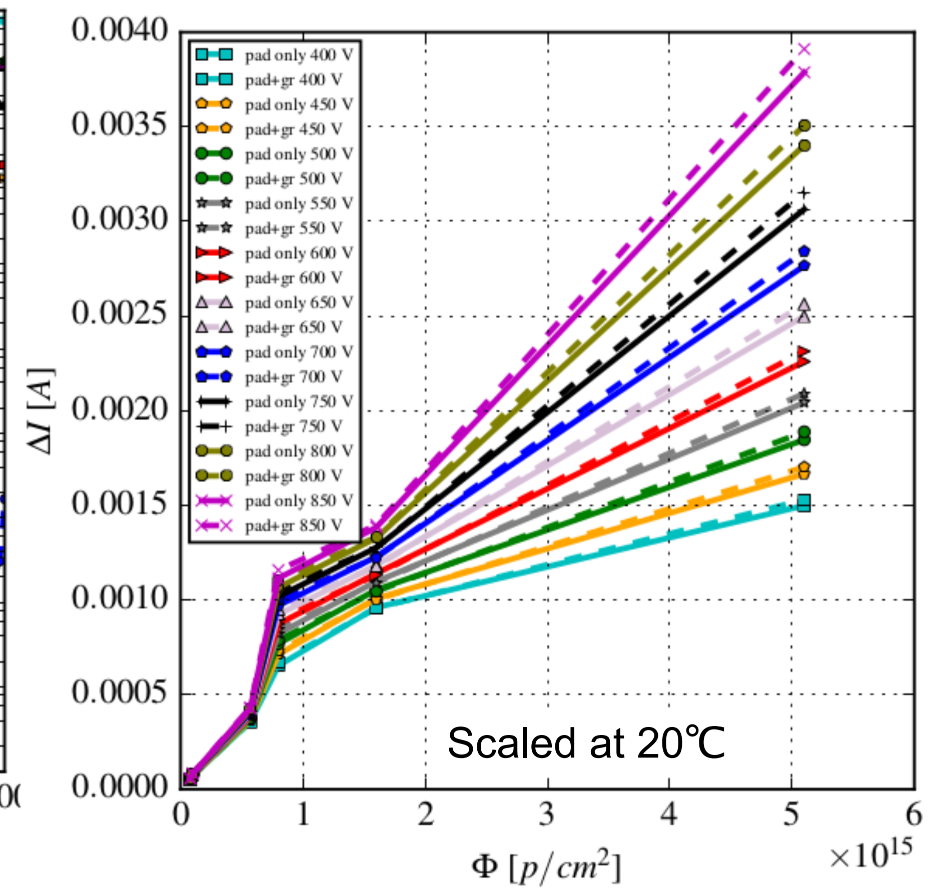
I-V post irradiation and annealing





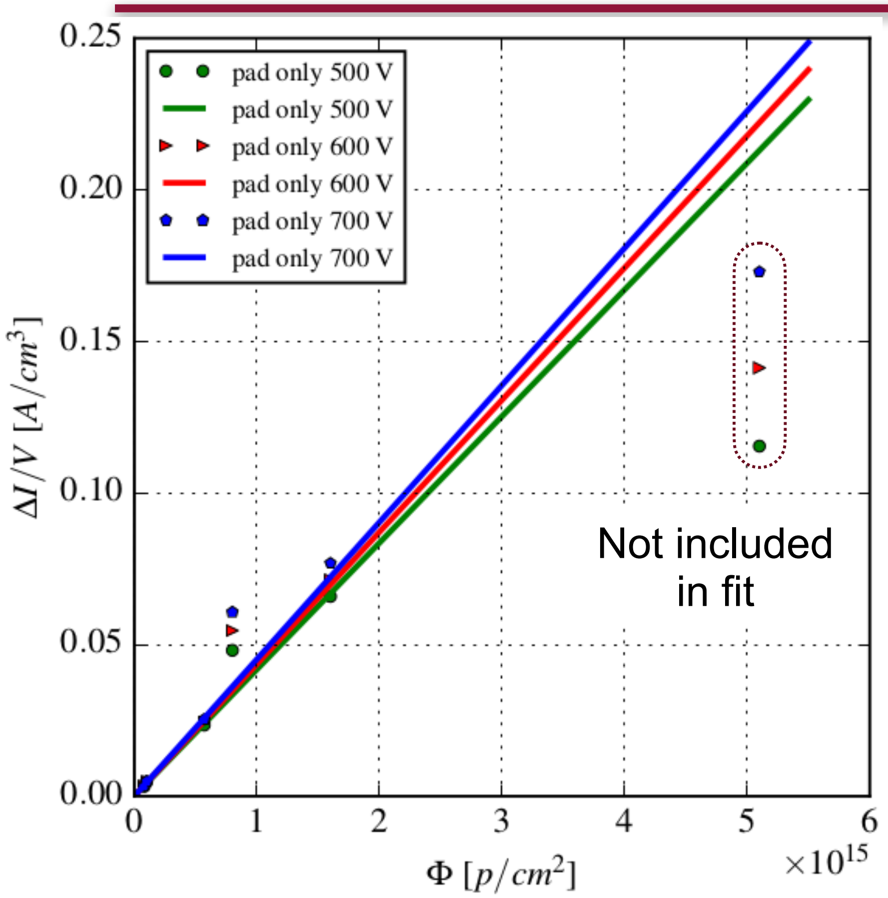


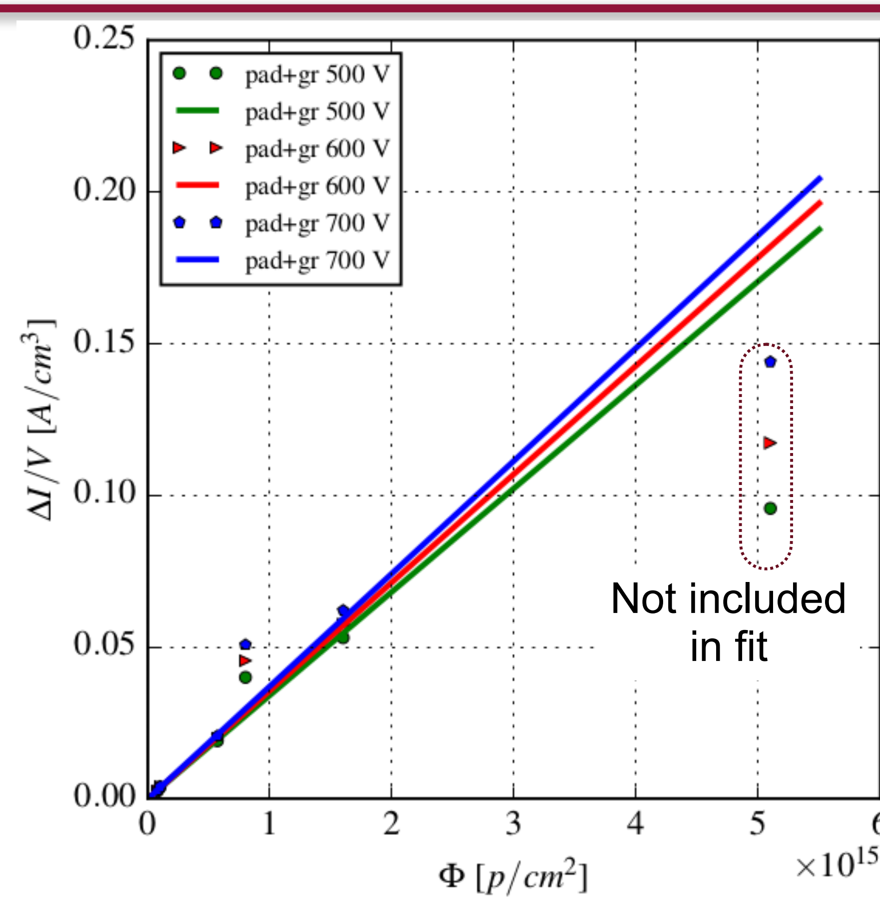


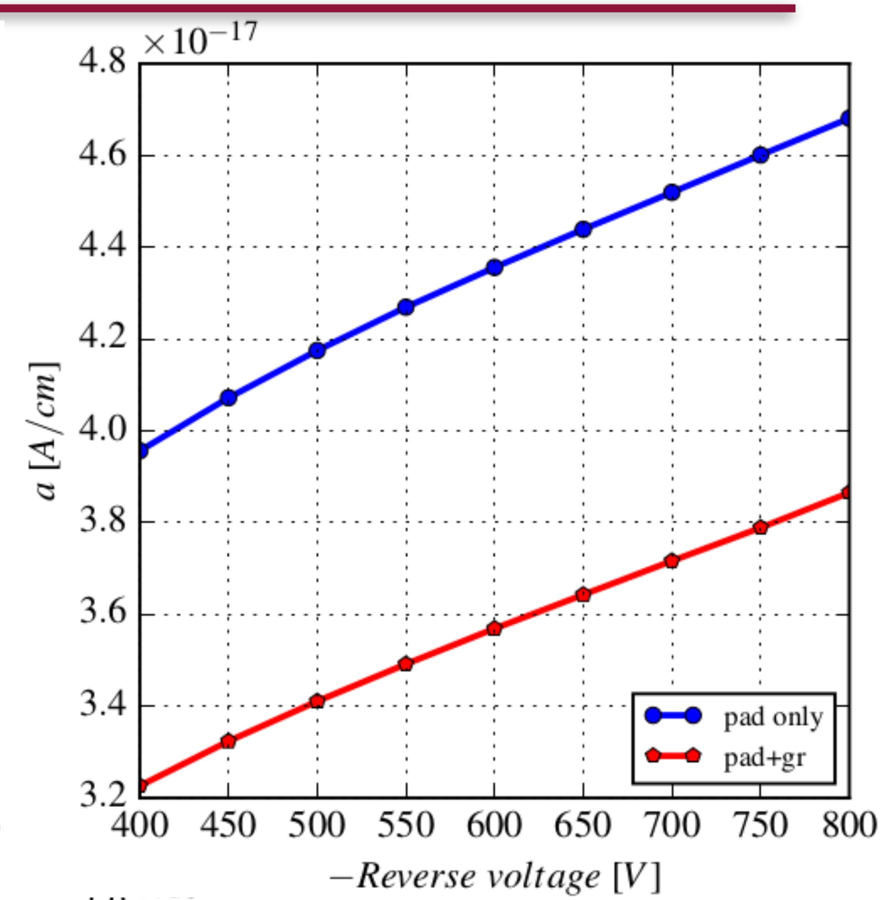


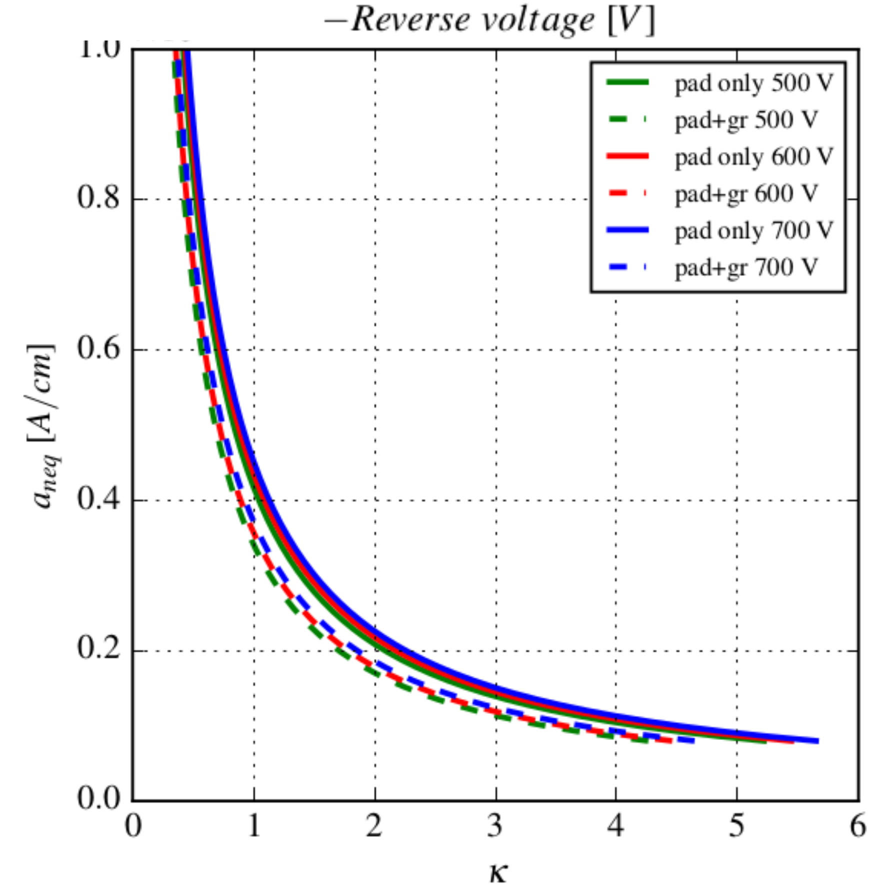
- Diodes irradiated at the cyclotron in proton fluences 0.8, 1, 5.7, 8, 16 and 51 $\times 10^{14}$ p/cm^2

Current related damage factor





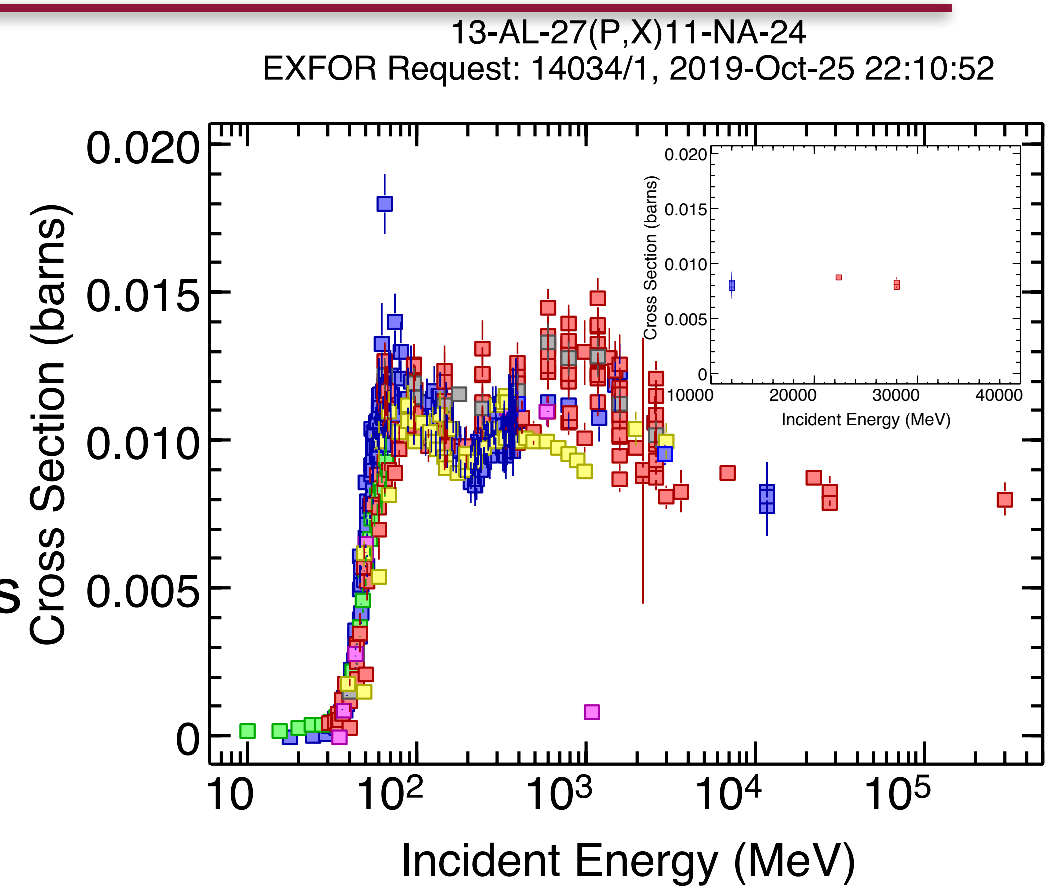


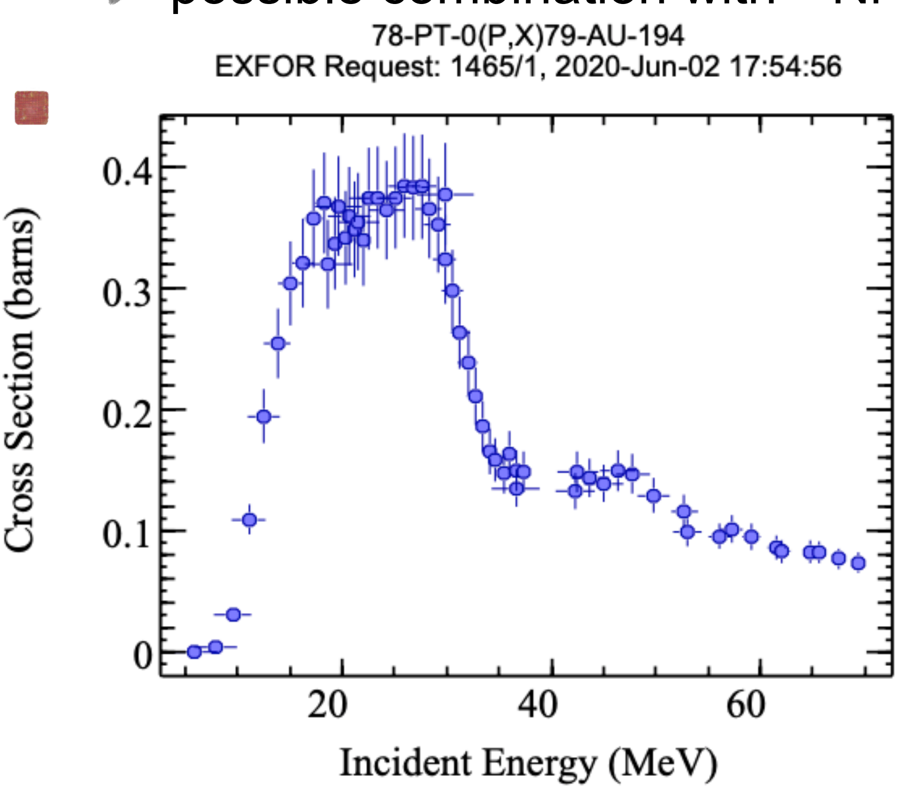


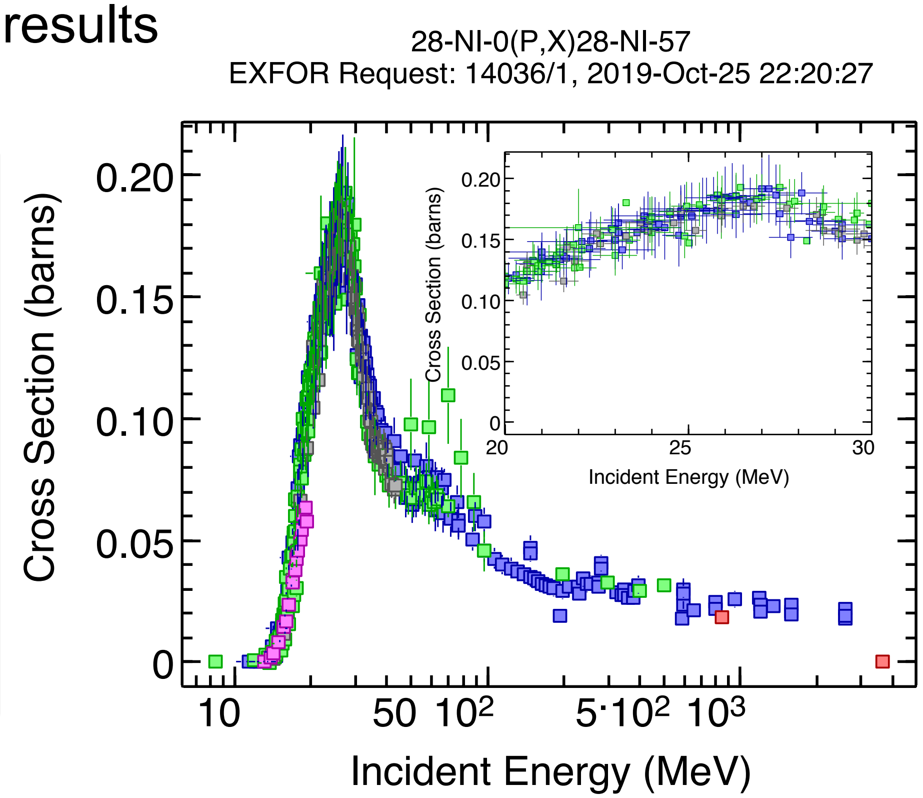
- Calculate slope α, from $\Delta I/V = \alpha \cdot \Phi$, where $V = \text{area} \cdot d_{active}$
- Measurements up to 900V performed
- Extracted α at 600V
  - pad only: $\alpha = 4.36 \cdot 10^{-17}$ A/cm
  - pad+gr: $\alpha = 3.57 \cdot 10^{-17}$ A/cm
- To estimate hardness factor κ, $\kappa = \alpha/\alpha_{neq}$, α_{neq} required
- Effective volume chosen after irradiation influences results
  - Under investigation

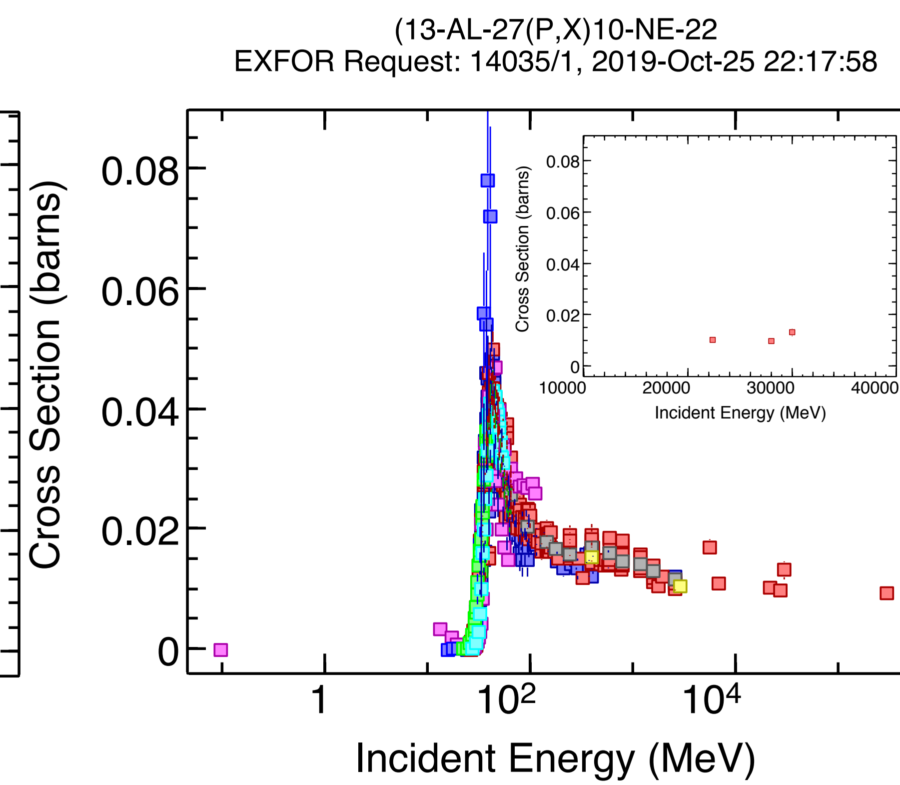
Dosimetry

- Dominant uncertainty on hardness factors: dosimetry
- Isotope activity measured with HPGe spectrometer
  - For ^{57}Ni isotope activity 1377.6 keV line used
  - ^{57}Ni to ^{57}Co: 81.7% intensity
- Uncertainty from nuclear cross-sections
  - for nickel foils uncertainty ~20%
  - for aluminium foils uncertainty ~7%
- Possibility to use alternative foils to reduce uncertainties
  - Promising candidate Pt: Pt(p,X)^{194}Au
    - ^{194}Au half-life of 37.92h
    - 328.46keV γ-ray
    - uncertainty from nuclear cross-sections ~11%
    - somewhat more expensive than nickel
    - possible combination with ^{57}Ni results



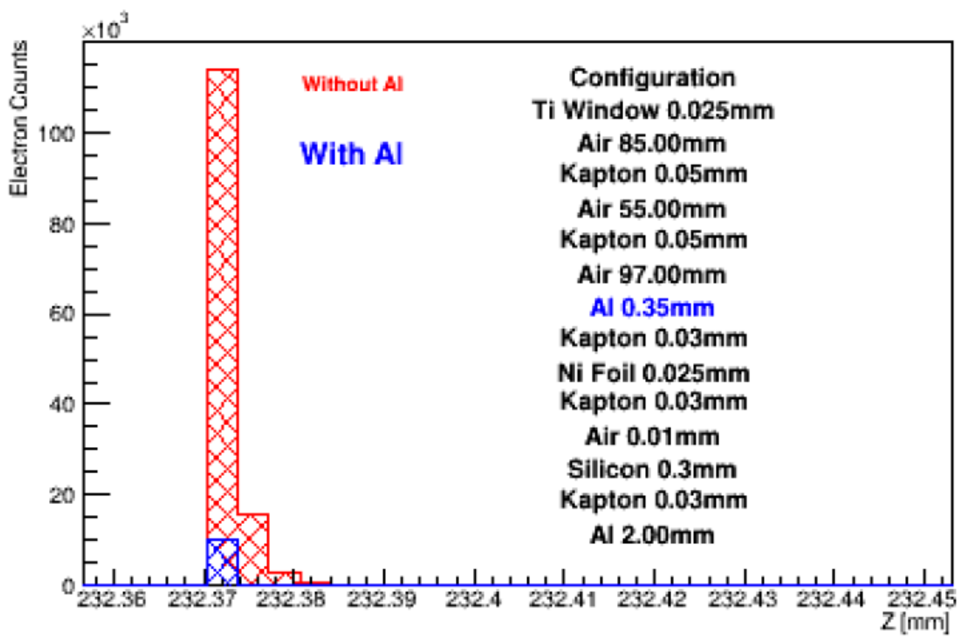


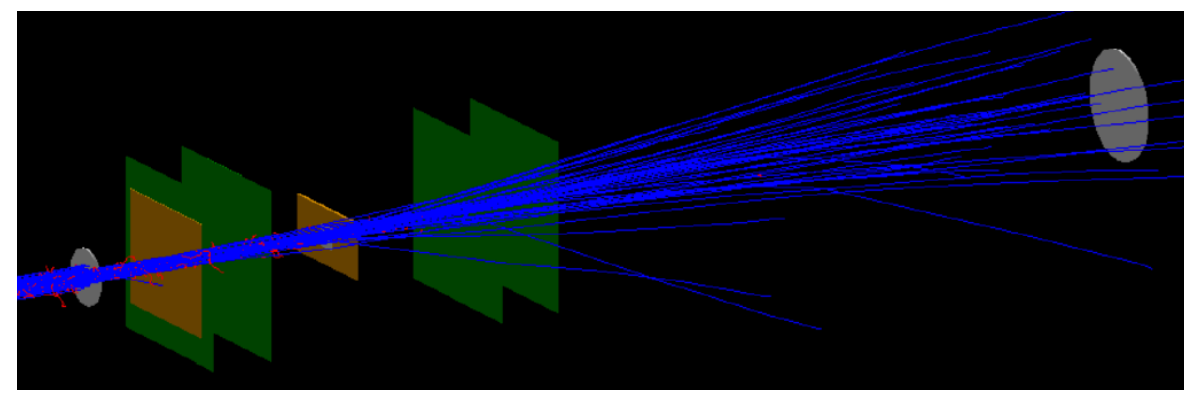


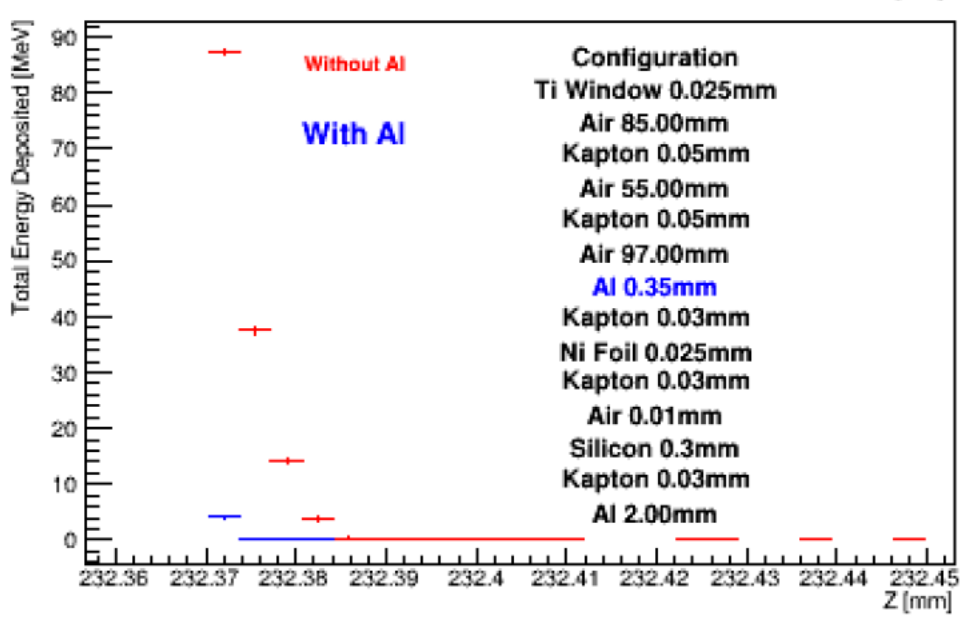


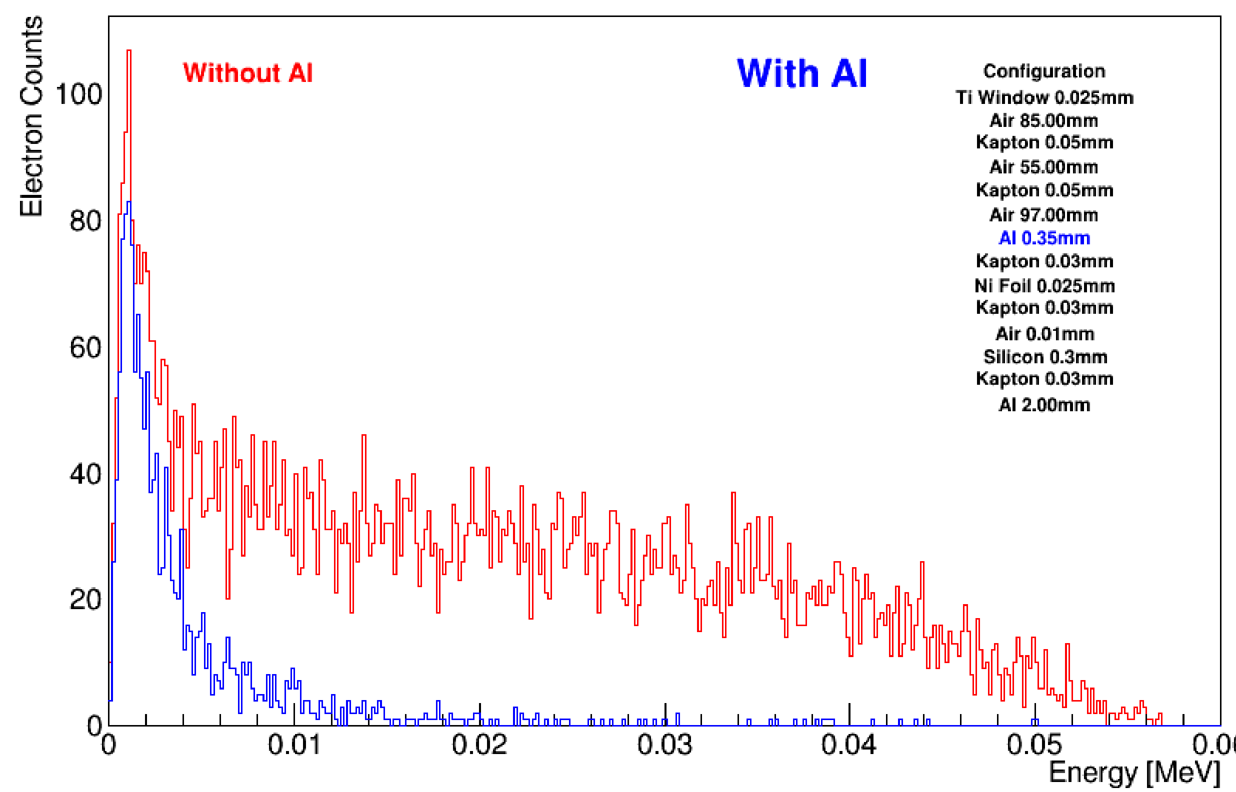
Investigation of low energy component

- Full beam line Geant4 simulation implemented to understand beam composition at sample
- Previous results/investigations indicated presence of low energy component in the beam
  - Led to inclusion of an upstream 350μm-thick Al plate
- Simulations suggest low energy electron component generated by proton interactions in air
- Addition of 350μm-thick Al plate upstream absorbs electrons before reaching sensor



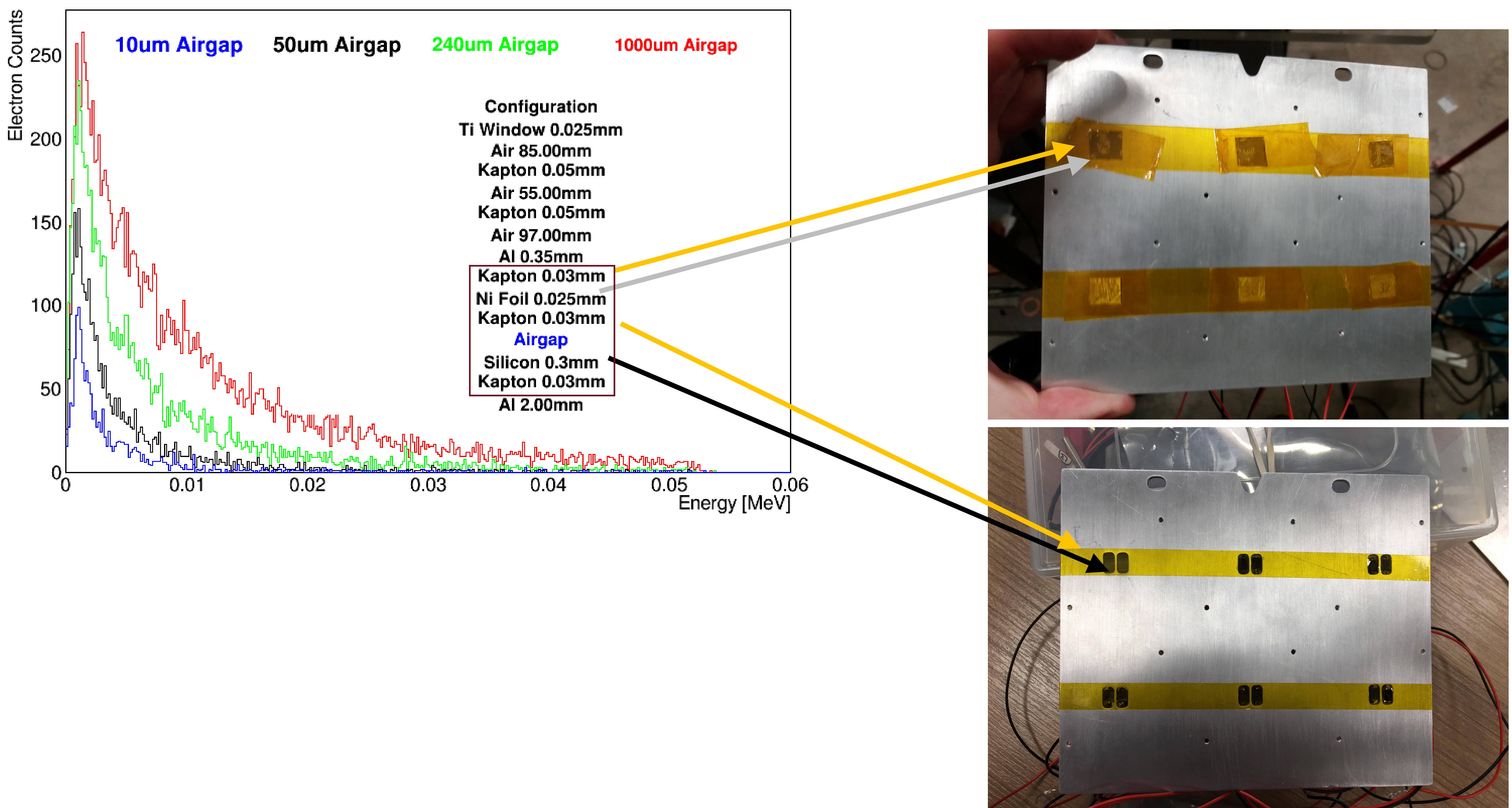






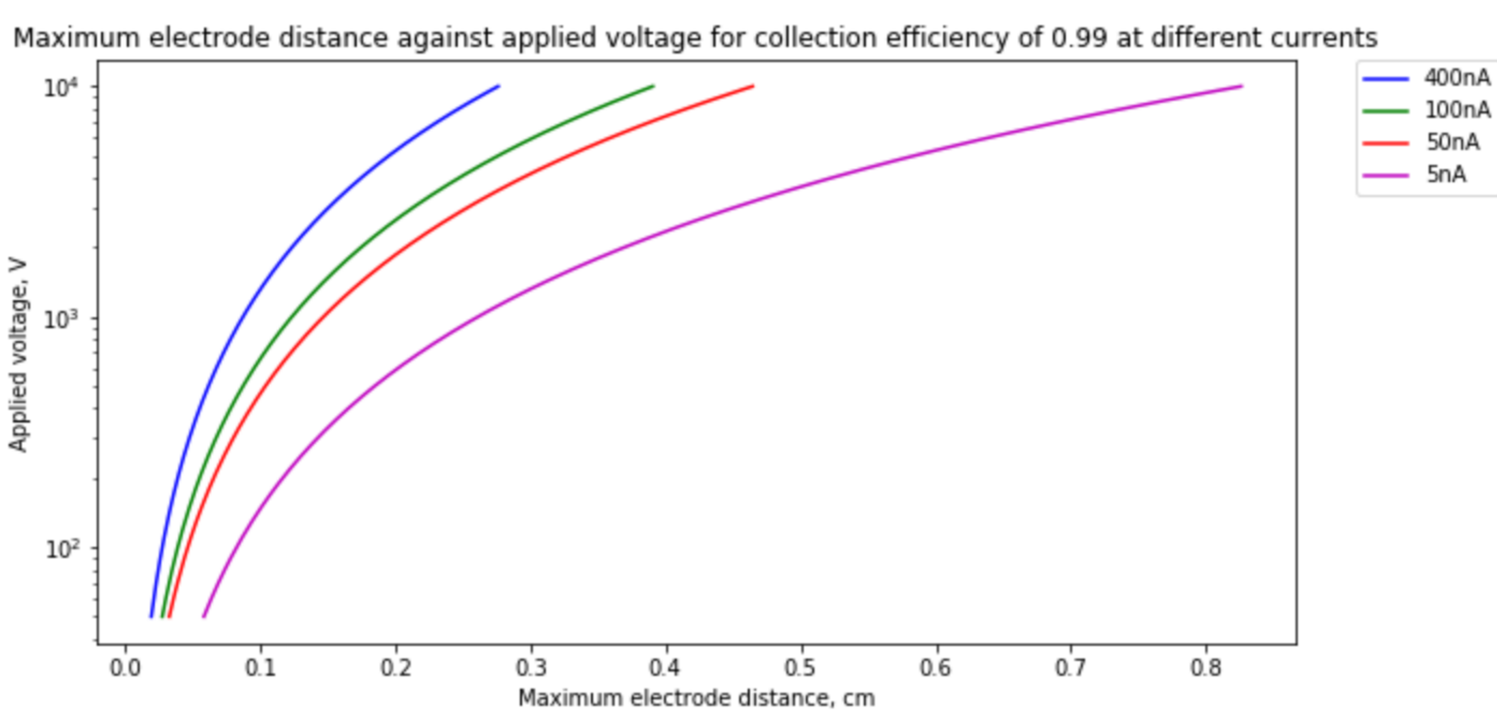
Investigation of low energy component

- Having added the Al plate other sources of low-energy electrons may become relevant
- Given short range, airgap between sensor and kapton critical

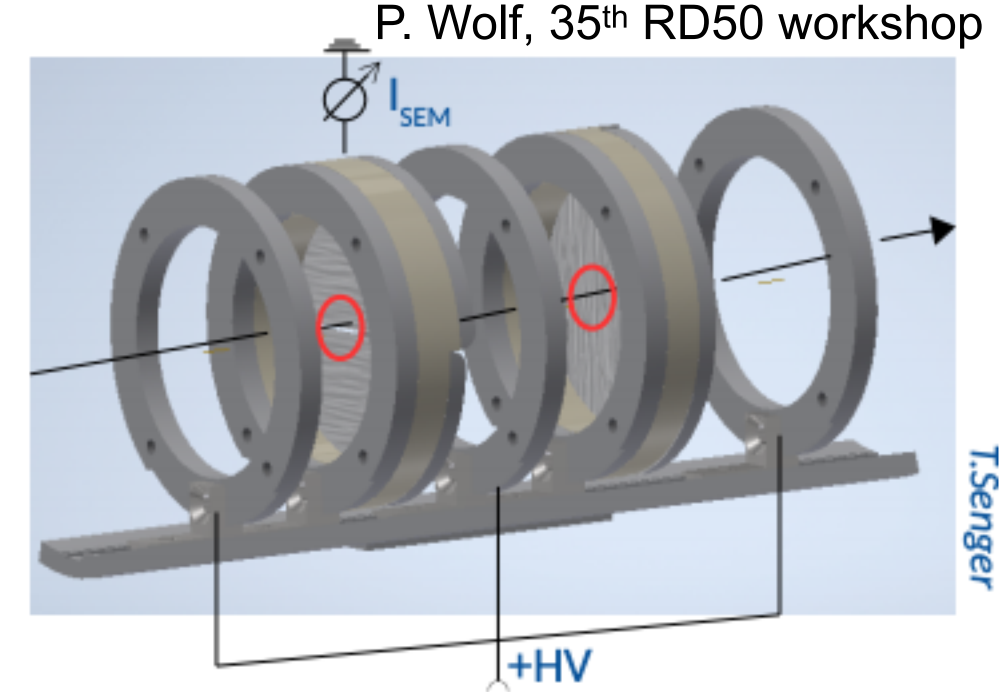


Ionisation chamber for beam monitoring

- Ionisation Chamber current saturates for large currents
  - general (volume) recombination (air-filled)
  - due to space charge effects (argon-filled)
- For the beam currents used the distance between the plates of an Ionisation Chamber would need to be impractically small
- Bonn uses a Secondary Electron Monitor (SEM) with very promising results
  - discussions on-going for further collaboration on improving hardness factor measurements



P. Wolf, 35th RD50 workshop



Summary

- Collaborative effort to standardise hardness factor measurements [JINST 14 (2019) P12004]
  - Birmingham, KIT and CERN using commercial BPW34F diodes
  - Comparisons with irradiations in Bonn on-going
  - BPW34F has several limitations when high precision is required
- High resistivity Hamamatsu diodes 8x8 mm^2 (ATLAS strip sensor campaign) investigated
  - Updated set-up for precision electrical measurements at Birmingham
  - I-V and C-V properties study before/after irradiation
  - Lack of p-stop isolation complicates calculation of active volume
    - Effect more pronounced following irradiation
    - Model developed to estimate the effective depletion depth
  - From estimated C_{planar} = 33.9 pF/cm^2 after depletion, active thickness 310±5μm determined
  - Diodes with p-stop isolation useful to control active volume
- Dosimetry largest uncertainty in hardness factor determination
  - Particle fluxes are too high for Ionisation Chambers
  - Use different foils for isotope activity: Pt foils promising
  - The Secondary Electron Monitor used by Bonn seems promising

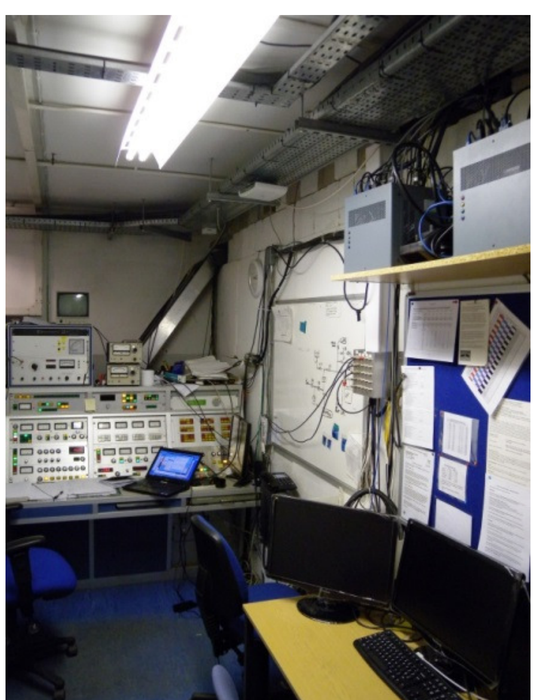
Additional Slides

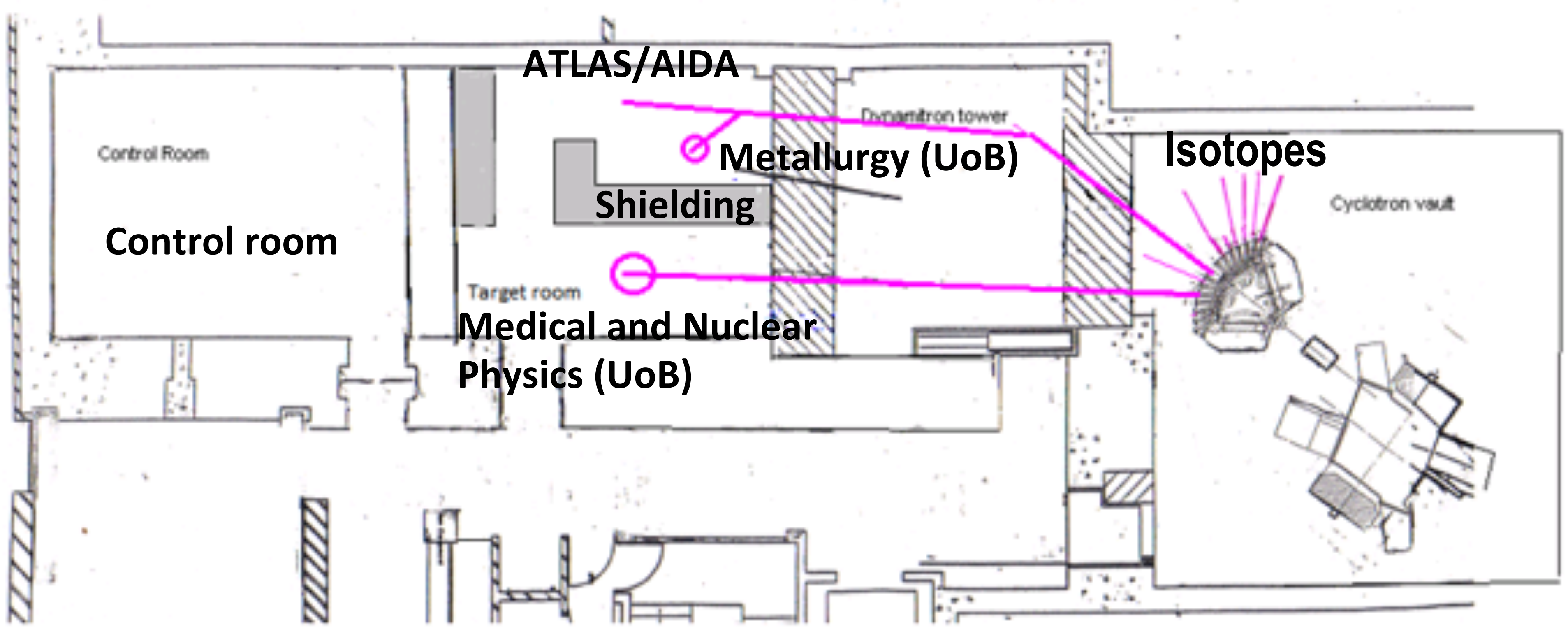
MC40 cyclotron University of Birmingham

- Provides: p, d, ^{3}He, and ^{4}He ~continuous beams
- Second beam-line into specially shielded area (2013)
  - high dose-rate damage studies
- Proton current: up to 2μA
- Beam spot: ~10×10 mm^2
- Flux: up to 10^{13} protons/s/cm^2
- Typical beam parameters:
  - Energy: 27 MeV
  - Current: 0.1-0.5μA

Ion	Energy at Extraction
Proton	11 – 38 MeV (N=1) 3 – 9 MeV (N=2)
Deuteron	5.5 – 19 MeV (N=2)
^{3}He	35 – 53 MeV (N=1) 9 – 27 MeV (N=2)
^{4}He	11 – 37 MeV (N=2)

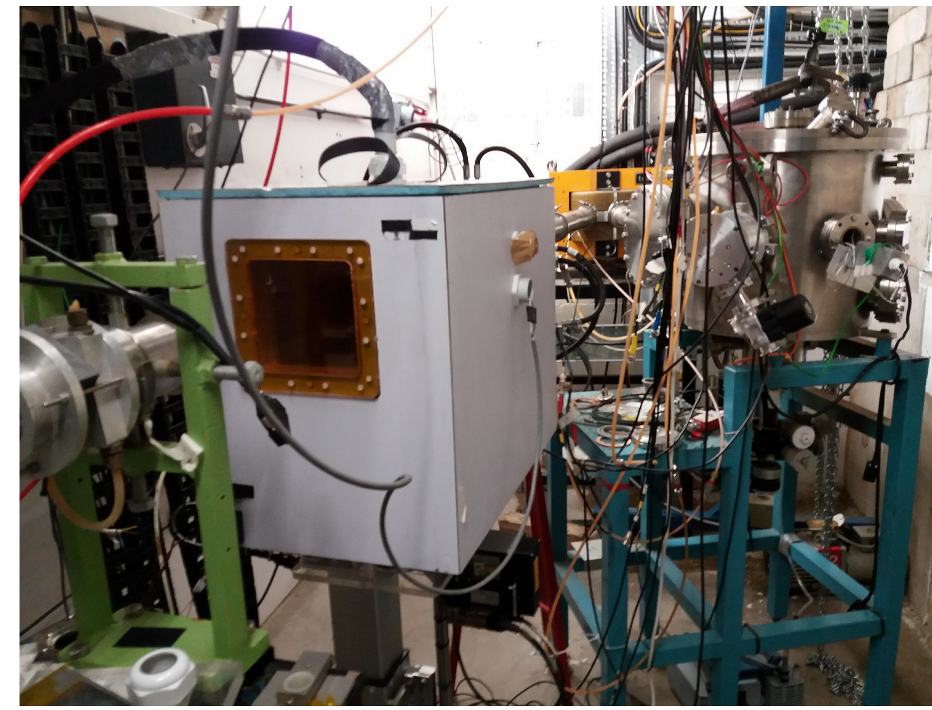
10^{15} 1MeV-n$_{eq}$ cm^{-2} in 80s at 1μA
Fluence strip sensors need to withstand at HL-LHC (3000 fb^{-1})

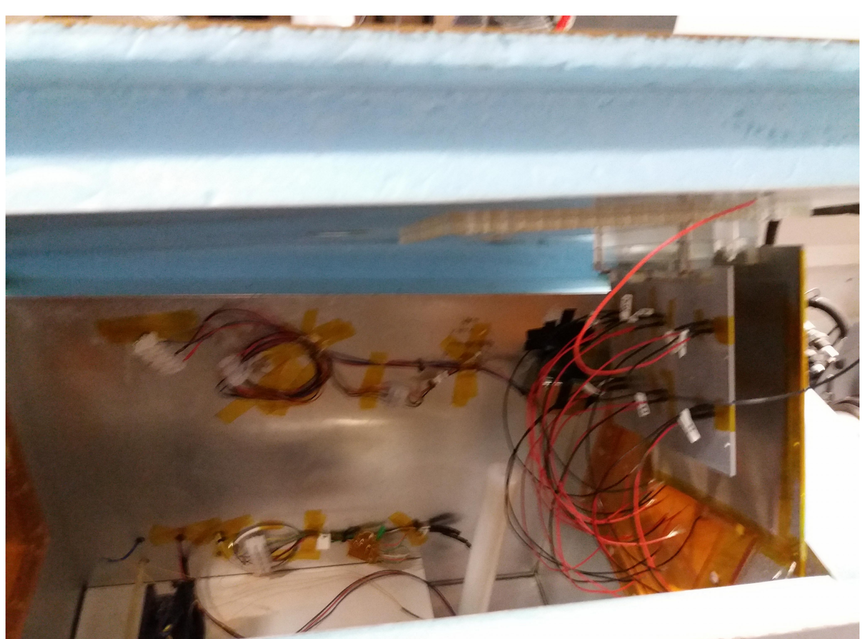


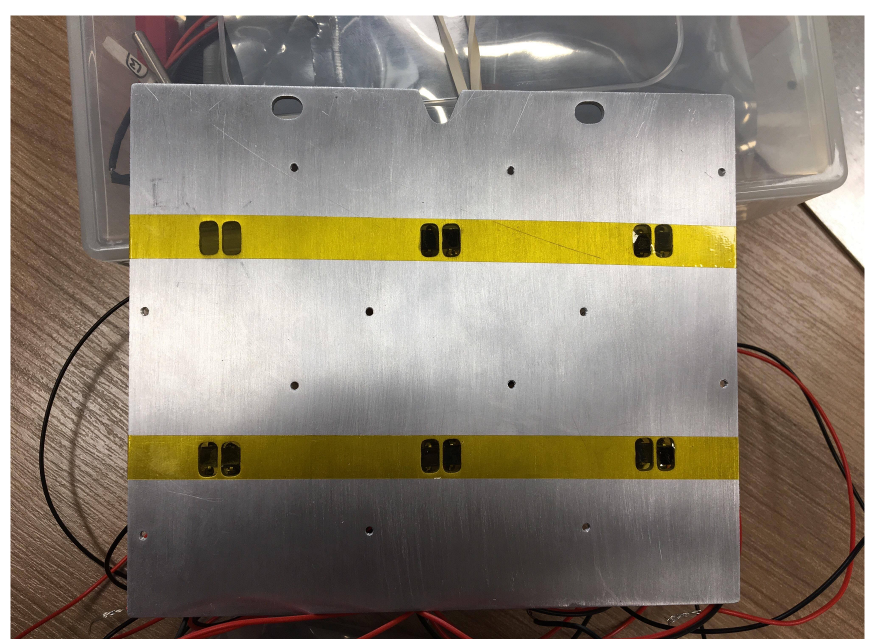


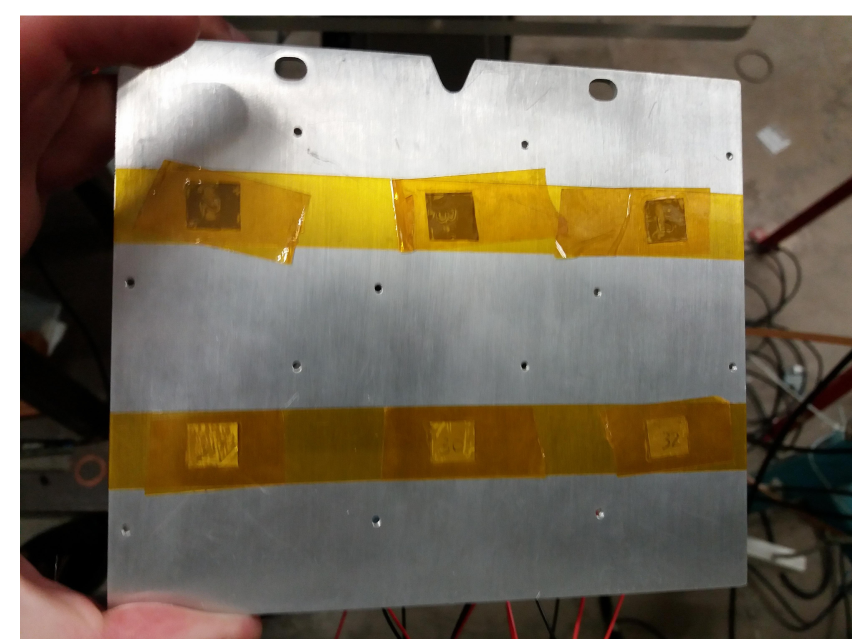
Irradiation set-up

- Samples placed in **temperature controlled box**
  - Liquid nitrogen evaporative cooling typically -25°C during irradiation
  - Dry N_2 flow in box, typical RH~10% during irradiation
  - Temperature/humidity logged
- Feed-through for external read-out/monitoring
- Diodes mounted on Al-plate suspended from box lid
- Ni-foils front of sample for fluence measurement
- Box mounted on XY-axis robotic scanning system
  - Typical horizontal scan speed 4 mm/s
- Gafchromic film used before irradiation to obtain beam position/profile

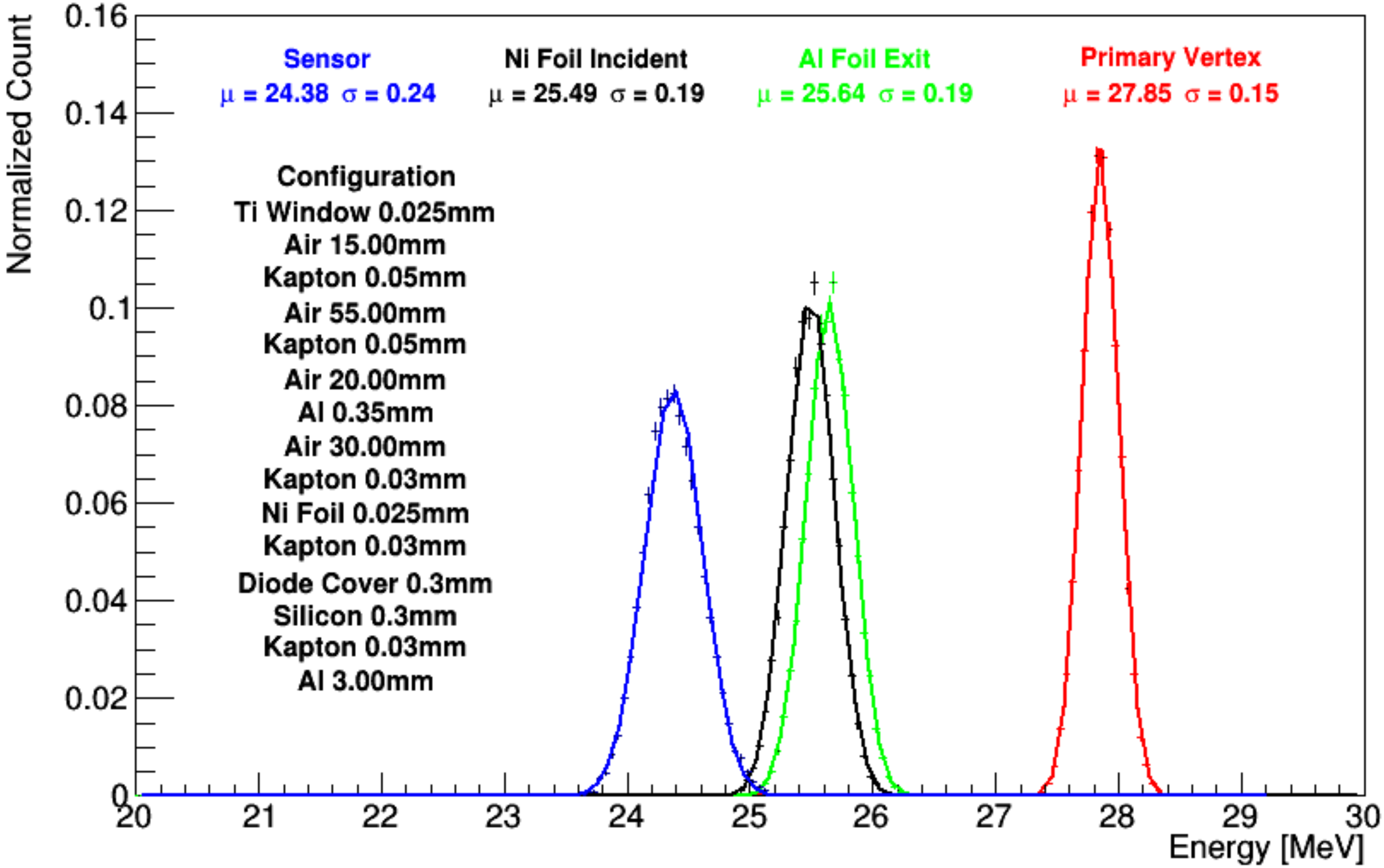






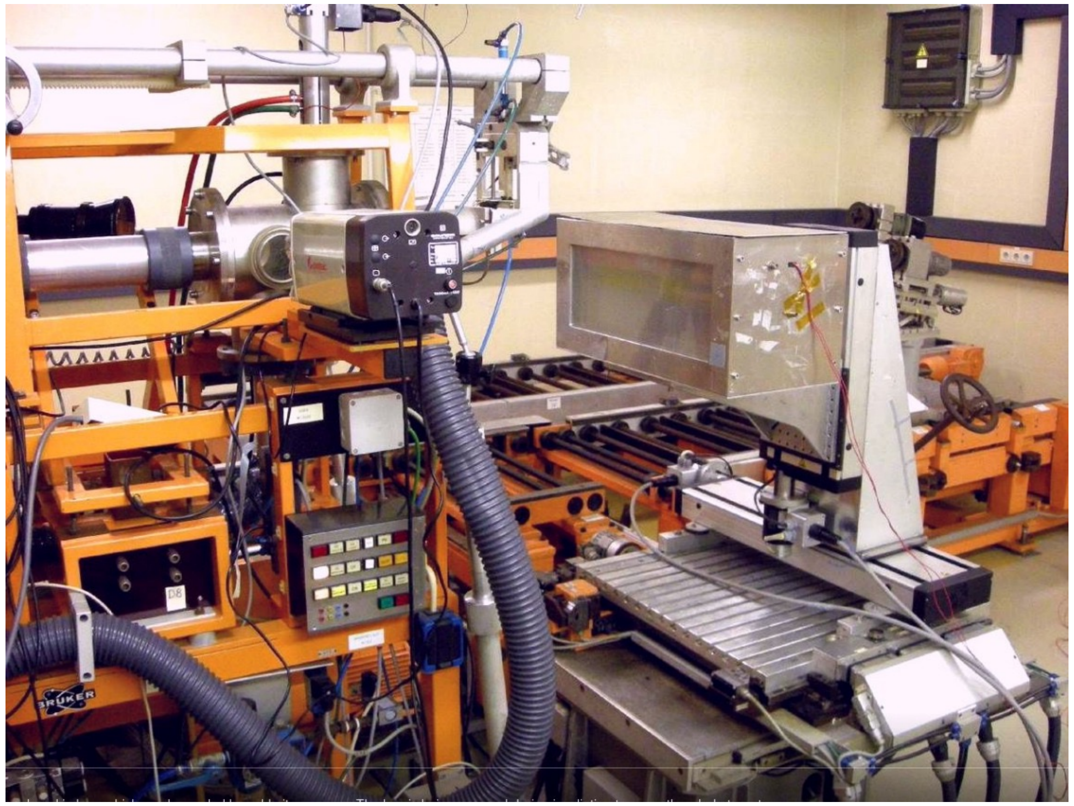


Beam energy on sample

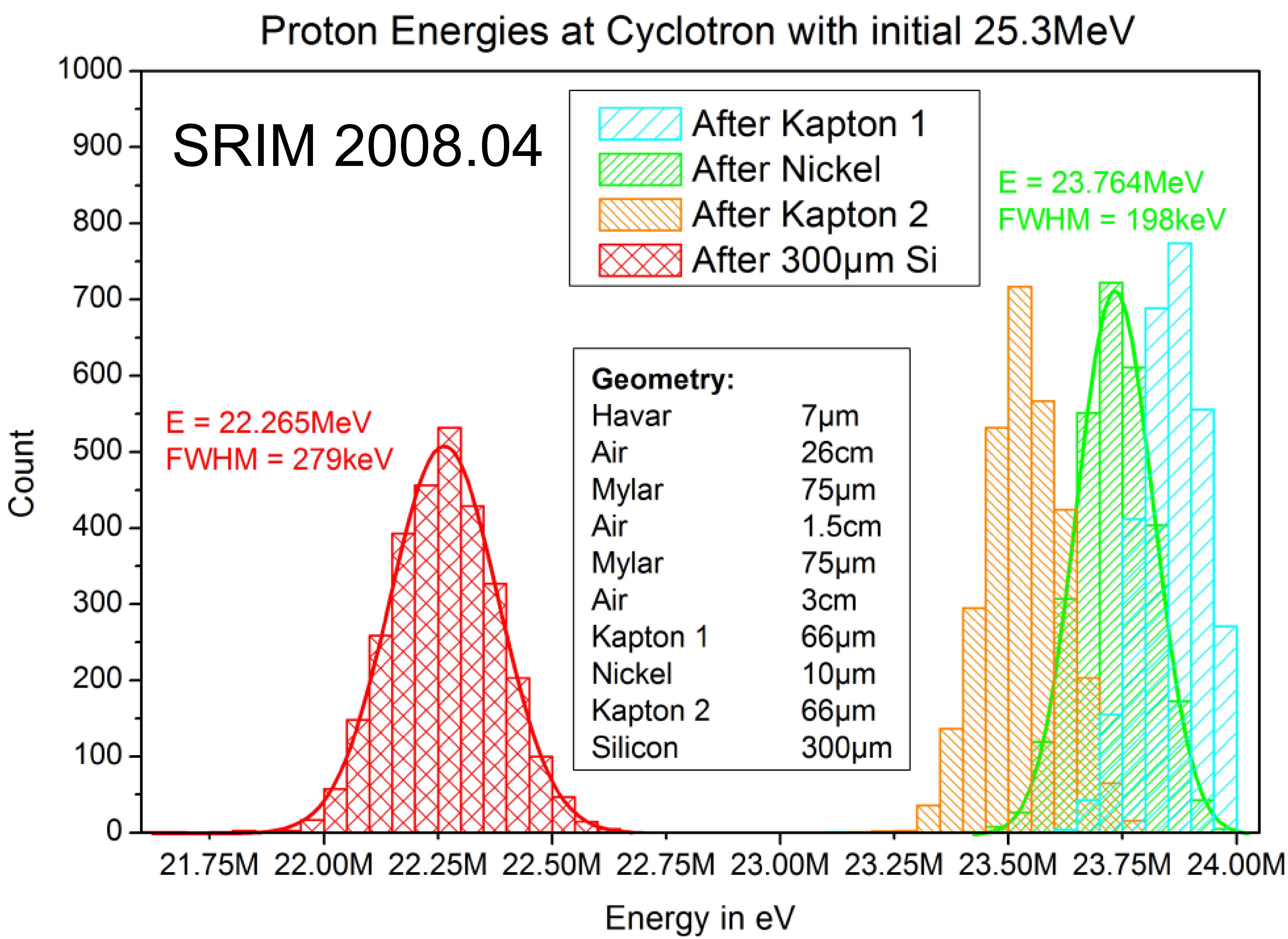


ZAG at KIT

- The Irradiation Center Karlsruhe accesses a compact cyclotron operated by ZAG Zyklotron AG
  - Proton energy at extraction: 25.3 MeV
  - Typical proton current: 1.5 μA
  - Temperature in box: -30°C
  - Beam spot: ~ 7 mm (varying)
  - Flux: ~ 2.5×10^{13} p/(s·cm^2)
- Insulated box, cooled by cold nitrogen gas
  - Goose-necks lead gas to individual samples
  - Graphite plate to stop protons at the back
  - Window with two Kapton foils for insulation
- Samples glued on Kapton tape fixed to Al-frames
  - Frames fixed in the box
- Mounted on movable XY-stage
  - Horizontal speed at nominal current 115 mm/s
- Dosimetry using Nickel foils

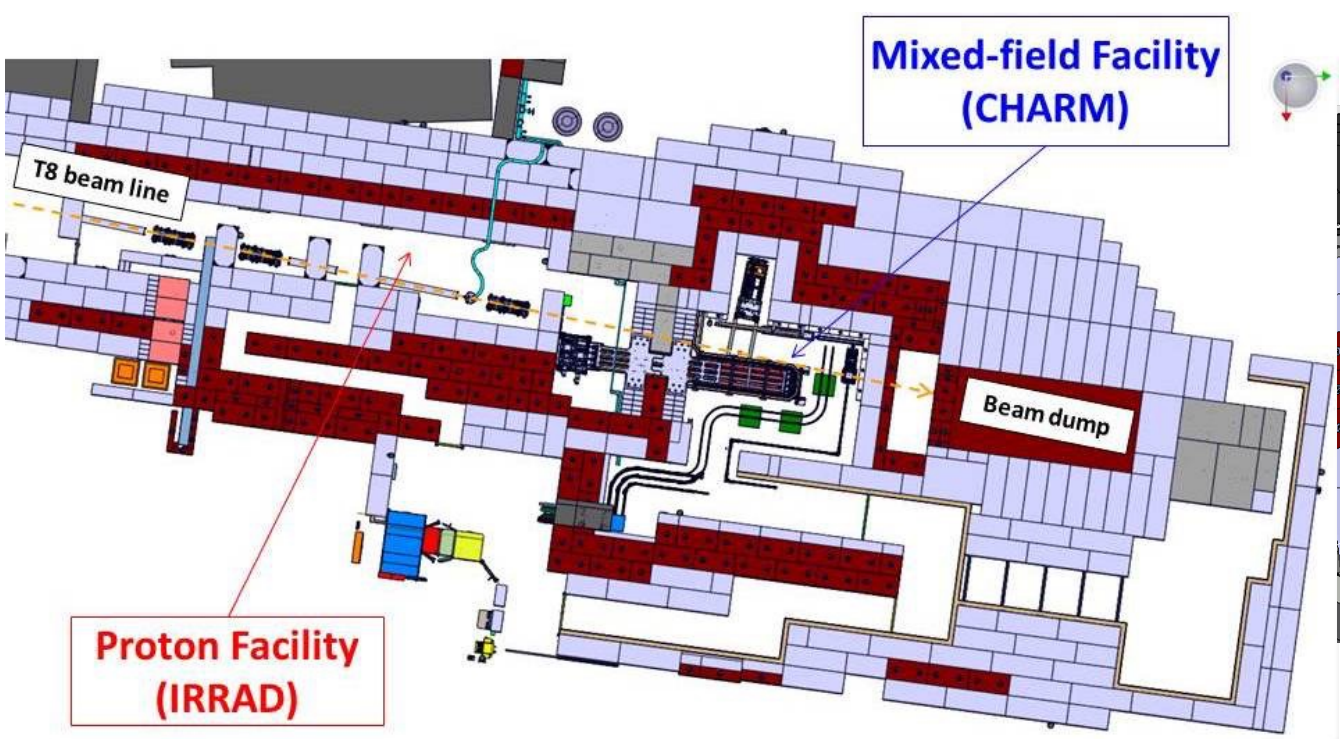


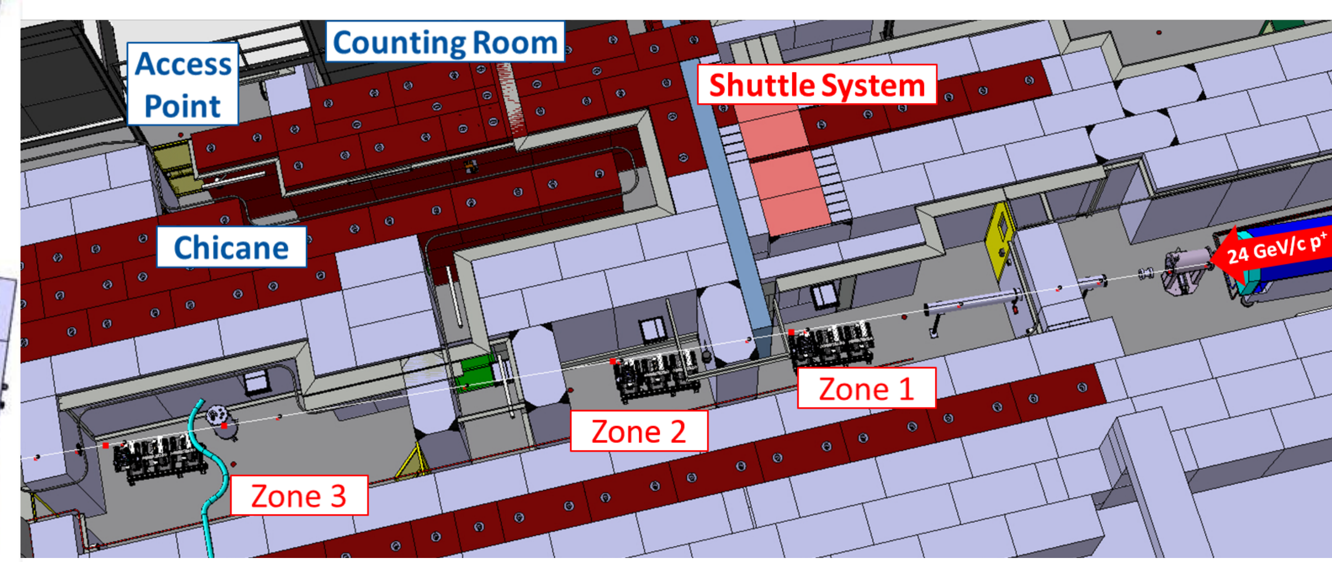
Beam energy on sample



CERN IRRAD

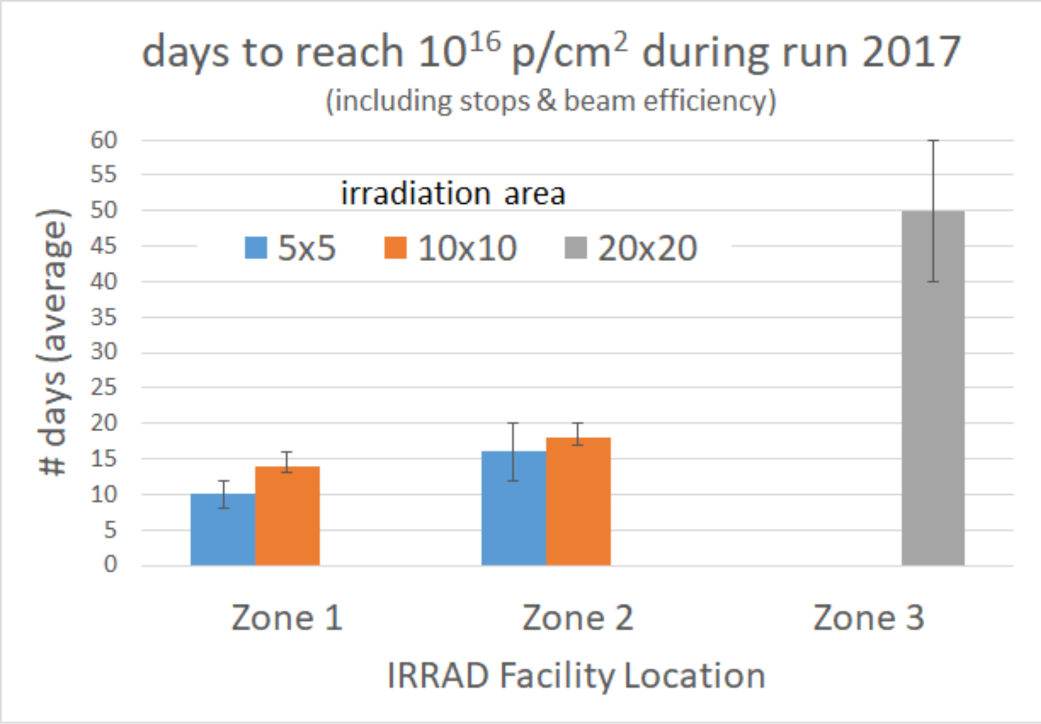
- CERN Irradiation facility provided with protons from the Proton Synchrotron
- Beam momentum: 24 GeV/c
- Beam dimensions standard size: ~12x12 mm^2 (FWHM)
  - spot size from ~6x6 mm^2 to ~20x20 mm^2 (FWHM)
- Beam intensity: ~5×10^{11} protons/spill on cycles of 30-37 s
  - Typically: 3 spills per CPS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

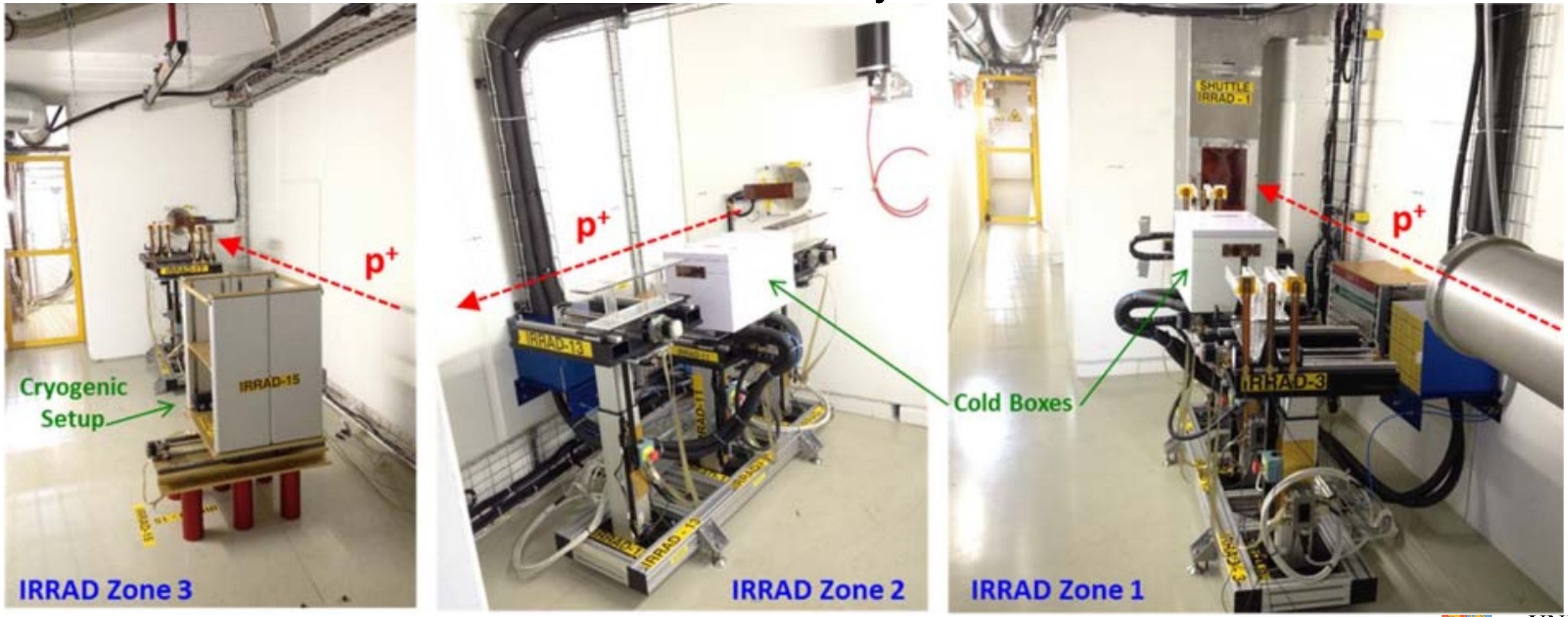




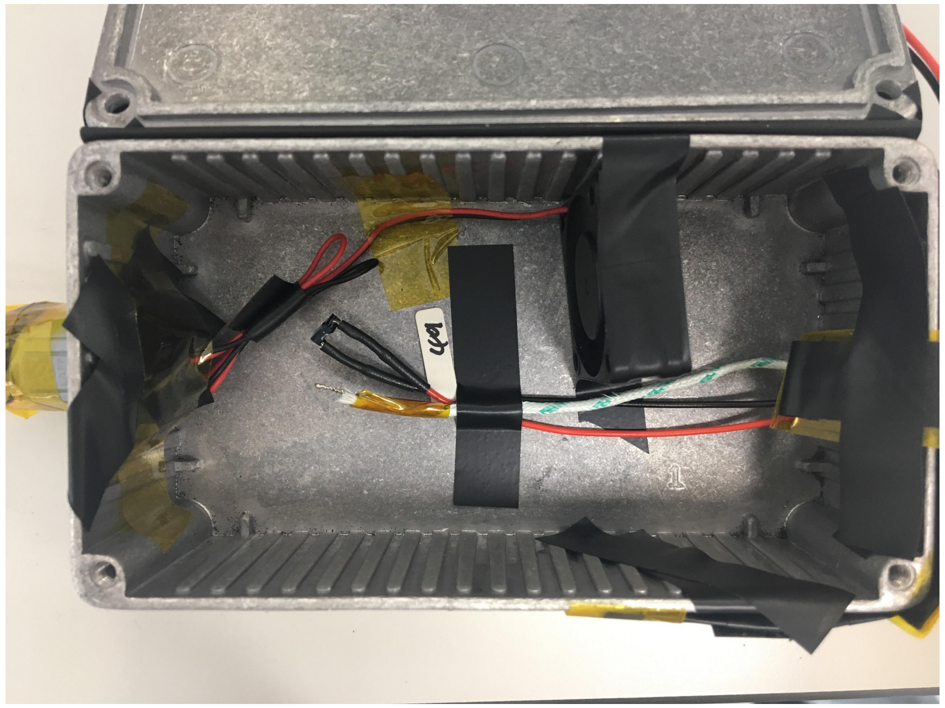
CERN IRRAD Zones

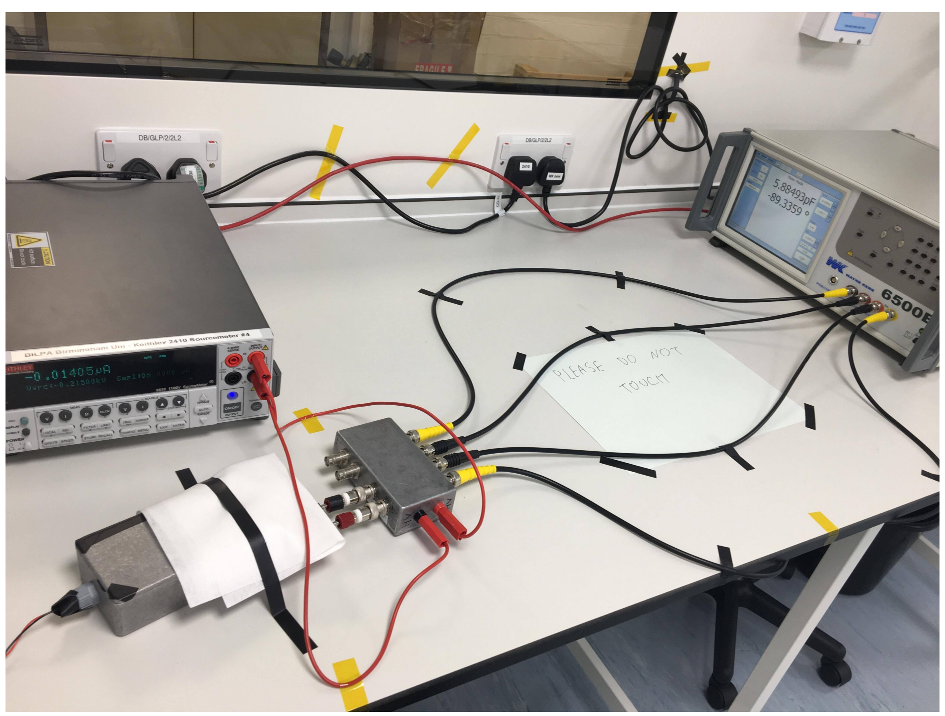
- Samples are placed in temperature controlled box
  - possible temperature down to -20°C
  - for this study irradiations at room temperature
- Box mounted on remotely controlled stage
  - sample alignment
  - beam scanning
- Dosimetry using aluminium foil
  - Reactions: $^{27}Al(p,3pn)^{24}Na$ and $^{27}Al(p,3p3n)^{22}Na$
  - Fluence measurements obtained with accuracy of ±7%



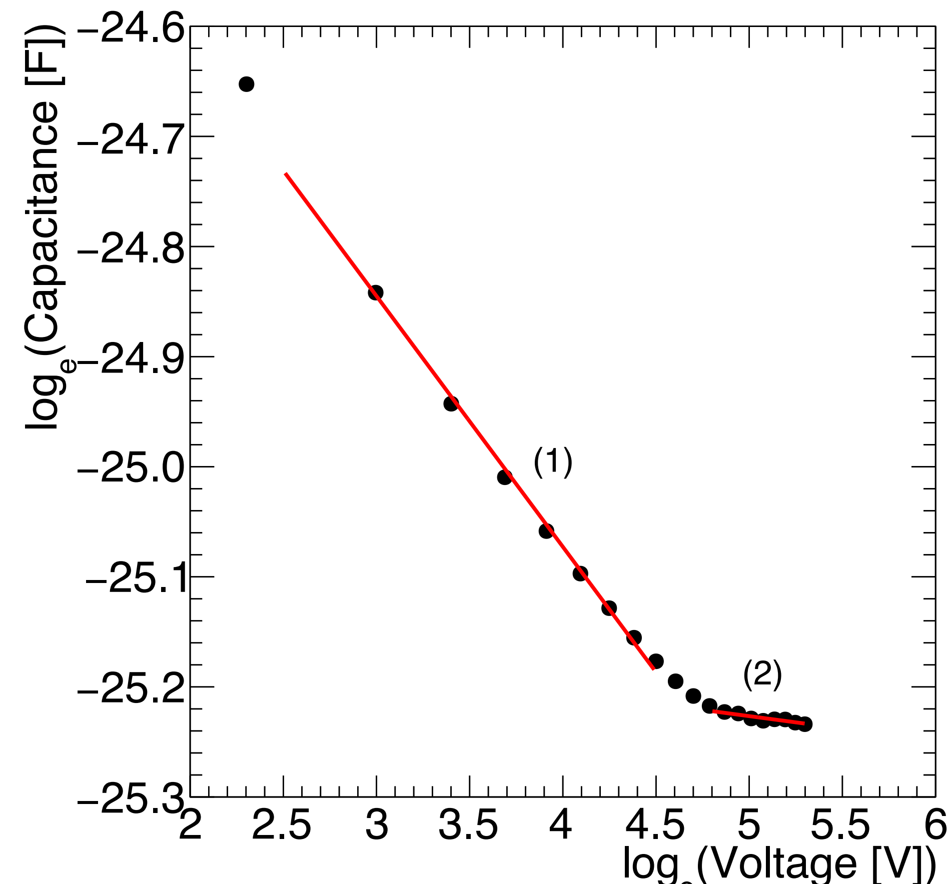


Measurement setup: Depletion Voltage

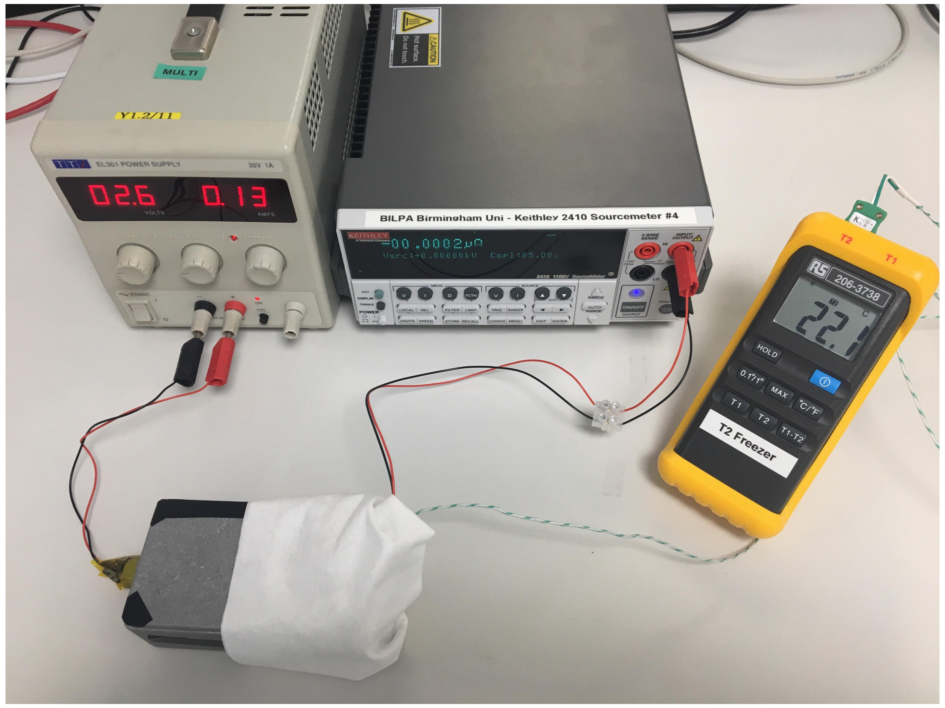




- Measurements performed in aluminium box
  - small fan for air circulation
- Capacitance readings at 10 kHz
  - Wayne-Kerr 6500B Precision Impedance Analyser
  - junction box and four coaxial cables
  - Keithley 2410 Source meter for external bias
- Post-Irradiation all diodes thermally annealed
  - 80 mins at 60˚C



Measurement setup: Leakage Current



- Leakage current measurements at full depletion voltage
  - Using the aluminium box
- Keithley 2410 Source meter provides reverse bias
- All temperature measurements expressed at 21°C
  - Temperature during measurements stable

$$I(T_R) = I(T)\left(\frac{T_R}{T}\right)^2 e^{-\frac{E_a}{2k_B}\left[\frac{1}{T_R}-\frac{1}{T}\right]} \qquad E_a = 1.21\ \mathrm{eV}$$

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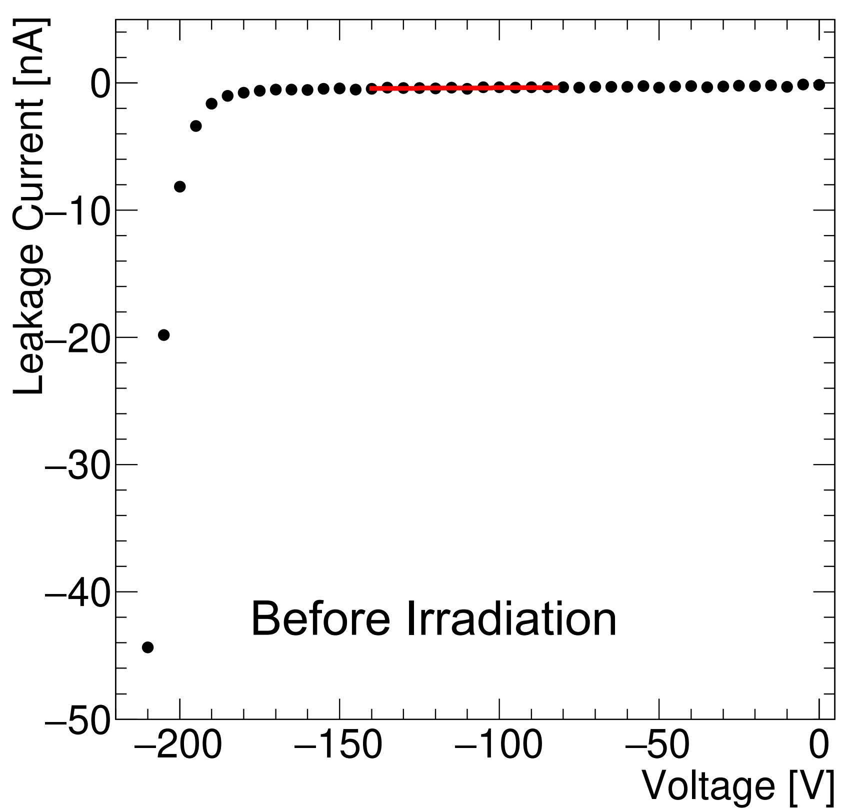
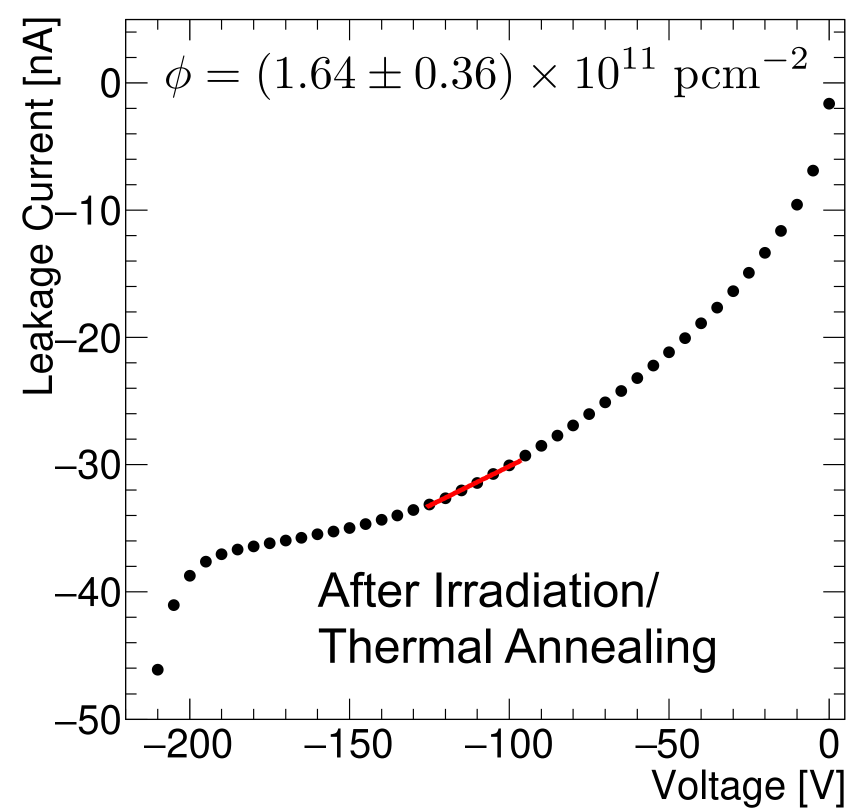
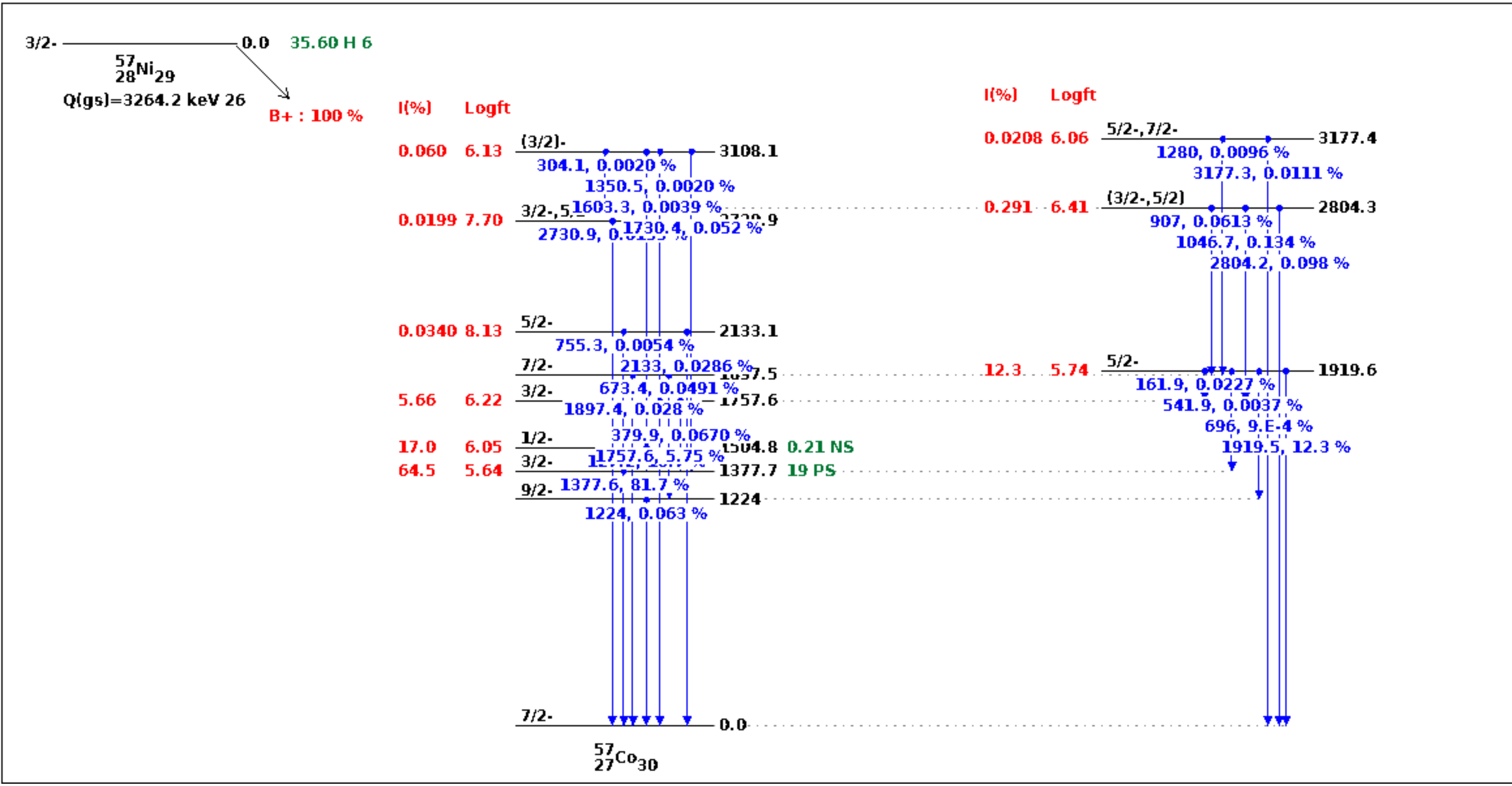


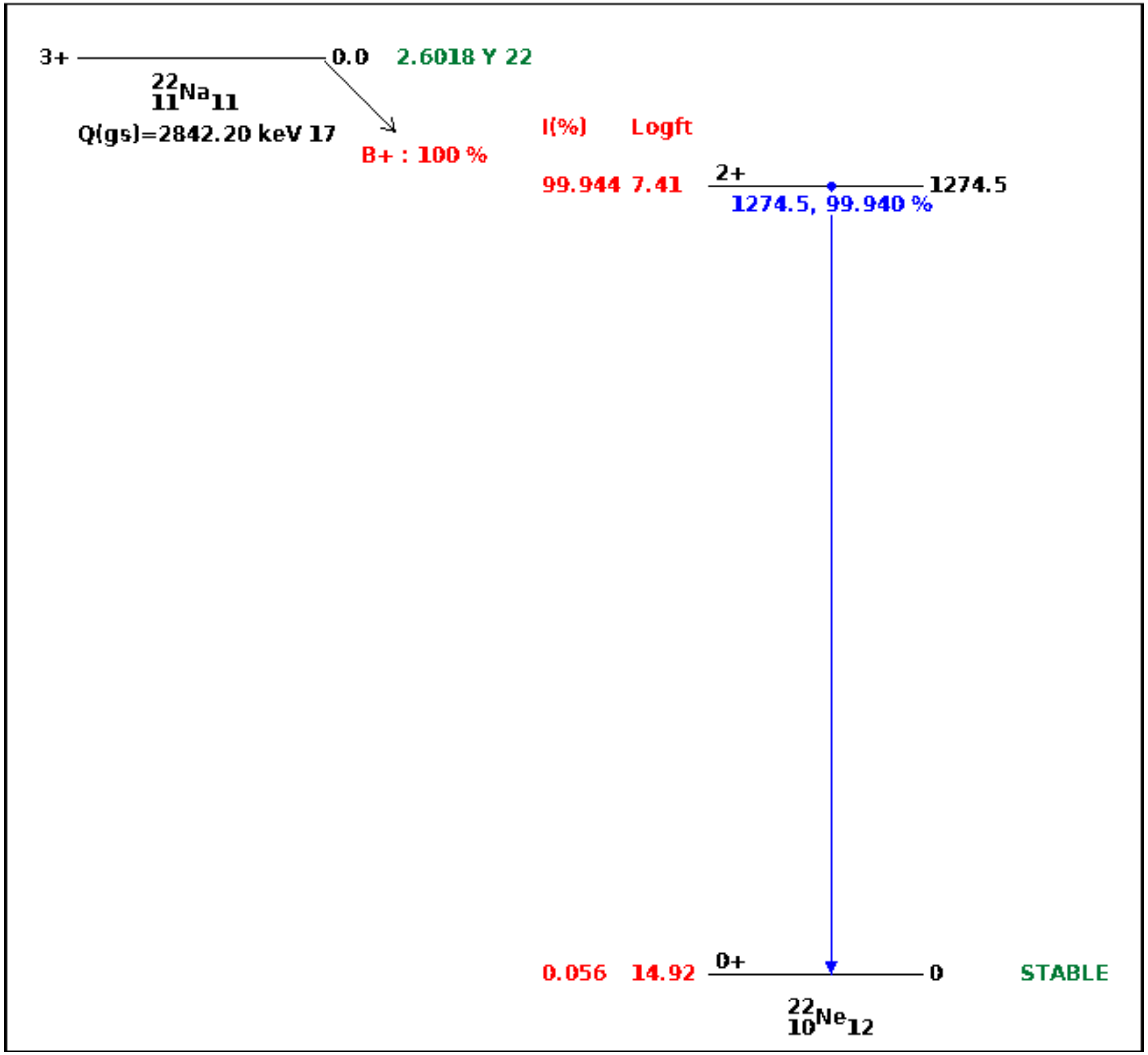


^{57}Ni



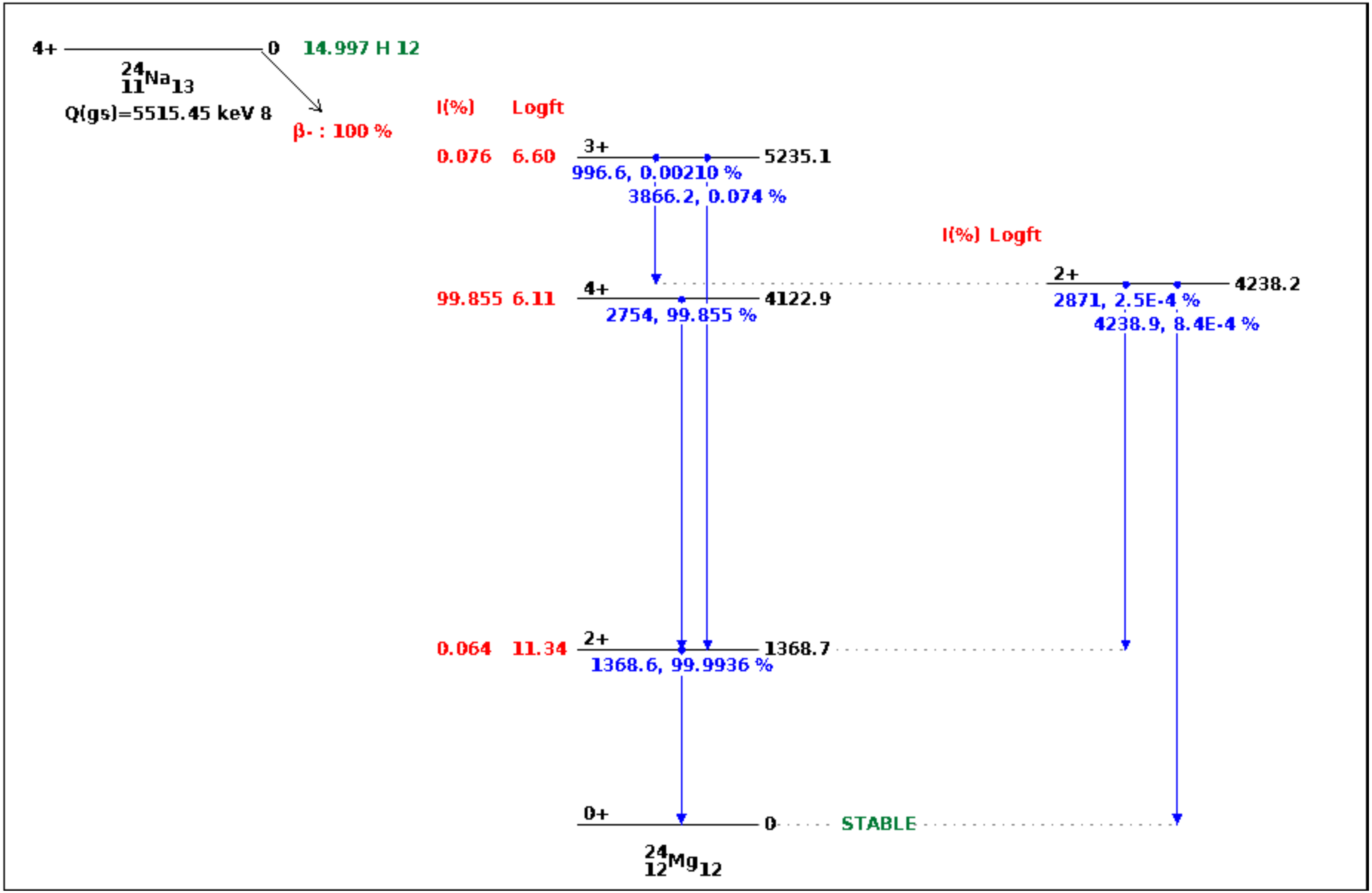
3/2-
0.0
35.60 H 6
57 28 Ni 29
Q(gs)=3264.2 keV 26
B+ : 100 %
I(%)
Logft
0.060 6.13
(3/2)-
3108.1
304.1, 0.0020 %
1350.5, 0.0020 %
1603.3, 0.0039 %
0.0199 7.70
1730.4, 0.052 %
2730.9,
0.0340 8.13
5/2-
2133.1
755.3, 0.0054 %
7/2-
2133, 0.0286 %
3/2-
673.4, 0.0491 %
5.66 6.22
1897.4, 0.028 %
379.9, 0.0670 %
1/2-
17.0 6.05
0.21 NS
3/2-
1757.6, 5.75 %
64.5 5.64
1377.7 19 PS
9/2-
1377.6, 81.7 %
1224
1224, 0.063 %
7/2-
0.0
57 27 Co 30
I(%)
Logft
0.0208 6.06
5/2-,7/2-
3177.4
1280, 0.0096 %
3177.3, 0.0111 %
0.291 6.41
(3/2-,5/2)
2804.3
907, 0.0613 %
1046.7, 0.134 %
2804.2, 0.098 %
12.3 5.74
5/2-
1919.6
161.9, 0.0227 %
541.9, 0.0037 %
696, 9.E-4 %
1919.5, 12.3 %

^{22}Na



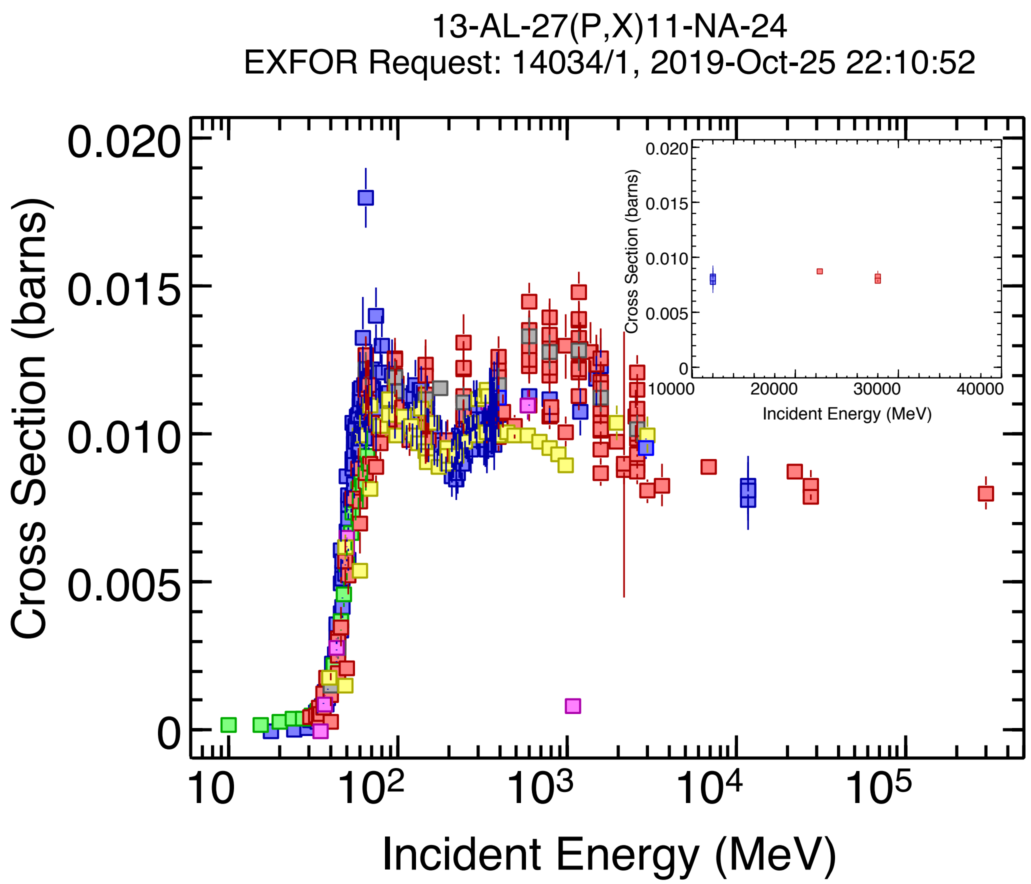
3+
0.0
2.6018 Y 22
$^{22}_{11}Na_{11}$
Q(gs)=2842.20 keV 17
B+ : 100 %
I(%)
Logft
99.944 7.41
2+
1274.5
1274.5, 99.940 %
0.056
14.92
0+
0
STABLE
$^{22}_{10}Ne_{12}$

^{24}Na

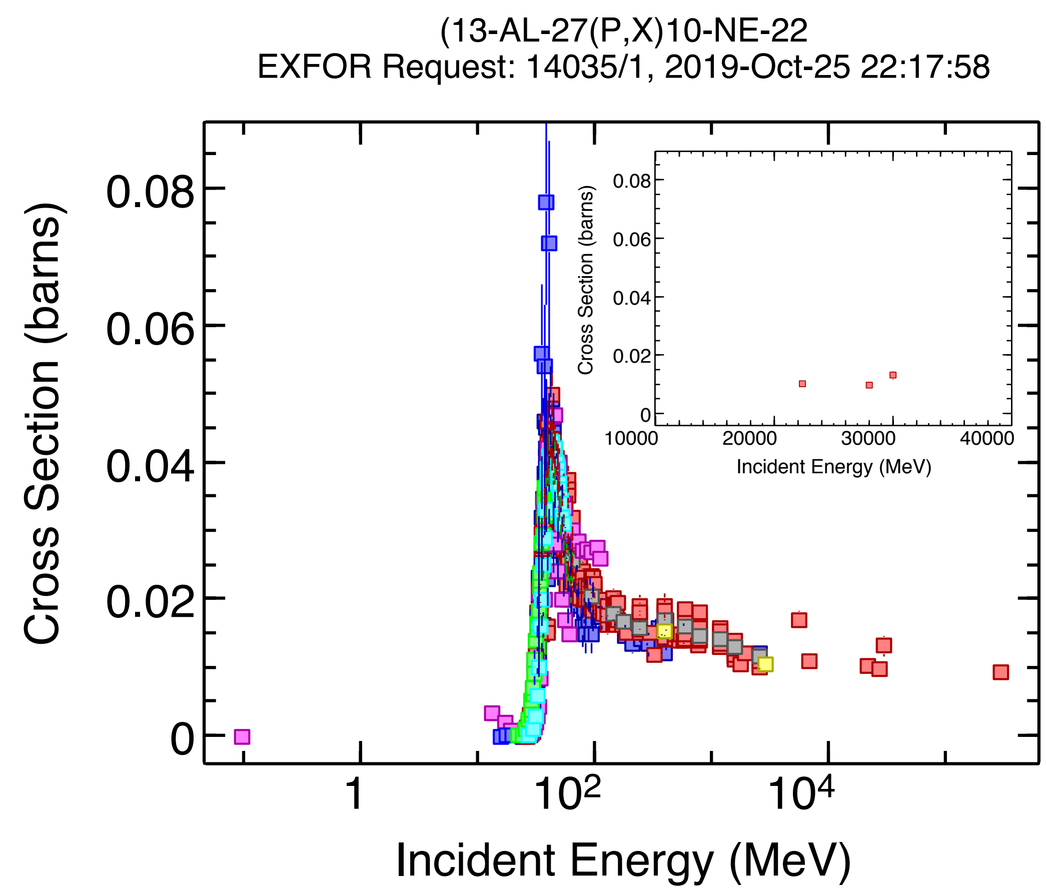


4+
0
14.997 H 12
$^{24}_{11}Na_{13}$
Q(gs)=5515.45 keV 8
β- : 100 %
I(%)
Logft
0.076
6.60
3+
5235.1
996.6, 0.00210 %
3866.2, 0.074 %
I(%) Logft
2+
4238.2
2871, 2.5E-4 %
4238.9, 8.4E-4 %
99.855
6.11
4+
4122.9
2754, 99.855 %
0.064
11.34
2+
1368.7
1368.6, 99.9936 %
0+
0
STABLE
$^{24}_{12}Mg_{12}$

Dosimetry



13-AL-27(P,X)11-NA-24
EXFOR Request: 14034/1, 2019-Oct-25 22:10:52
Cross Section (barns)
Incident Energy (MeV)
0.020
0.015
0.010
0.005
0
10
10^2
10^3
10^4
10^5
10000
20000
30000
40000



(13-AL-27(P,X)10-NE-22
EXFOR Request: 14035/1, 2019-Oct-25 22:17:58
Cross Section (barns)
Incident Energy (MeV)
0.08
0.06
0.04
0.02
0
1
10^2
10^4
10000
20000
30000
40000