A PROTON IRRADIATION SITE FOR SILICON DETECTORS AT BONN UNIVERSITY

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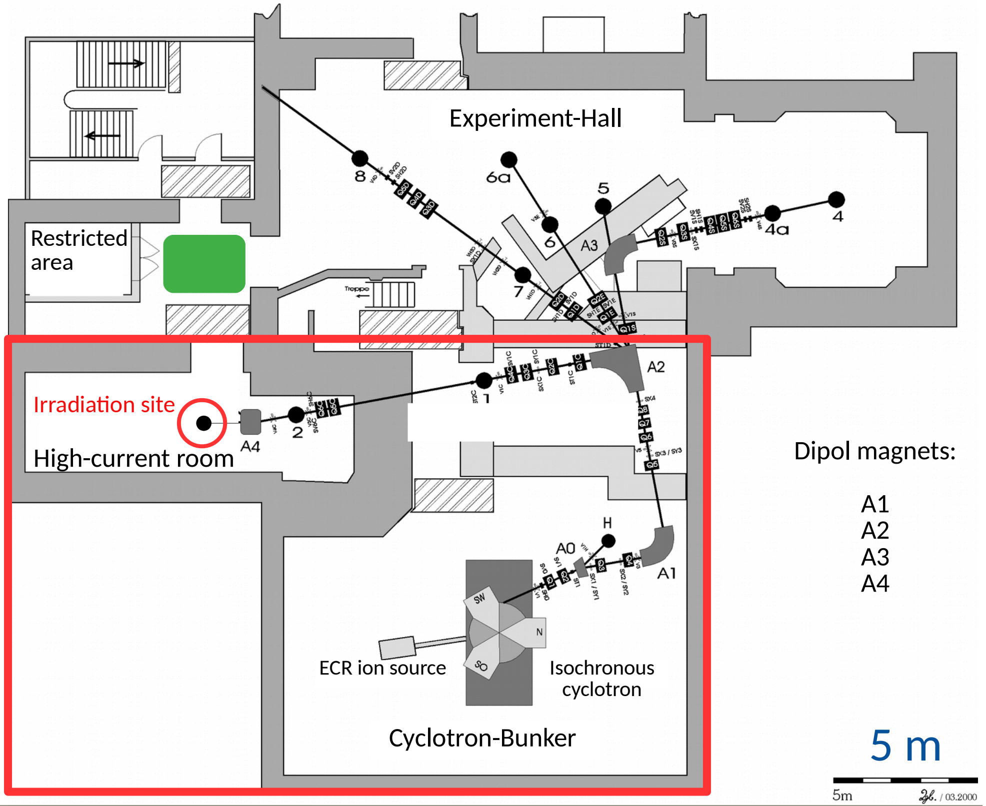
OUTLINE

- Irradiation site
- Beam monitoring
- Irradiation procedure
- Radiation damage
- Conclusion & outlook

The Bonn Isochronous Cyclotron at Helmholtz Institut für Strahlen- und Kernphysik

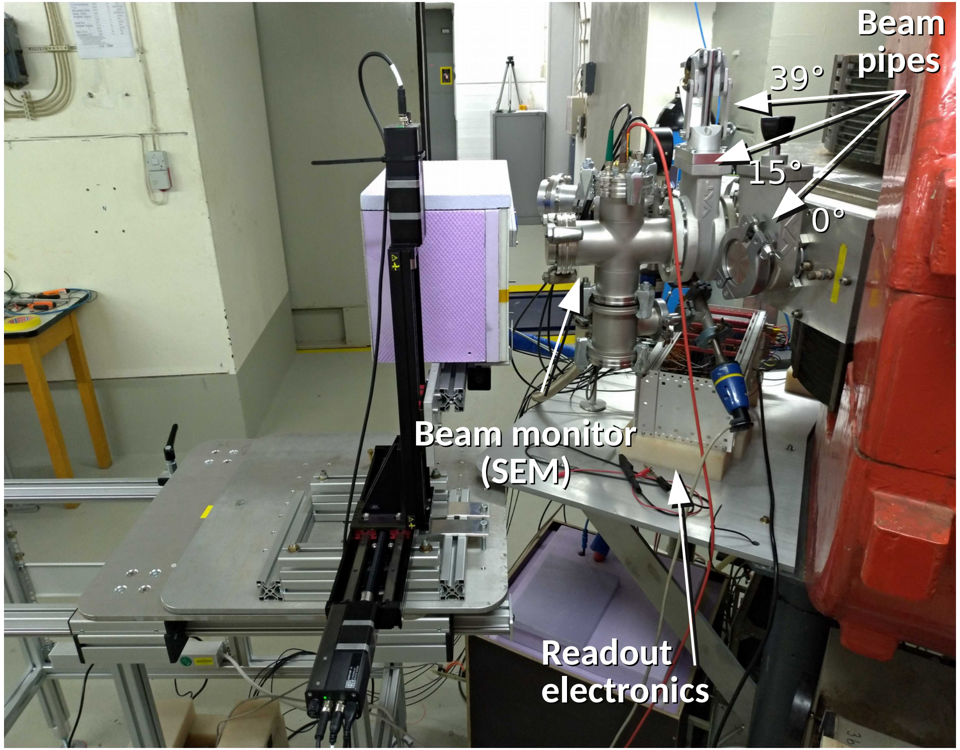
BONN ISOCHRONOUS CYCLOTRON

- Electron-Cyclotron-Resonance ion source: Protons, Deuterons, Alphas, …, ^{12}C
- Cyclotron: E_{kin} from 7 MeV to 14 MeV per nucleon
- Protons @ irradiation site:
  - Beam current: few **nA** to 1 **µA**
  - Beam profile: few **mm** ≤ $Ø_{FWHM}$ ≤ 2 **cm**
  - Flux(1 µA, $Ø_{FWHM}$= 1cm) ≈ 8e12 p/(s·cm²)
- (green box) := Access during irradiation (DAQ equipment)
- (red box) := No access (DAQ equipment with constraints)

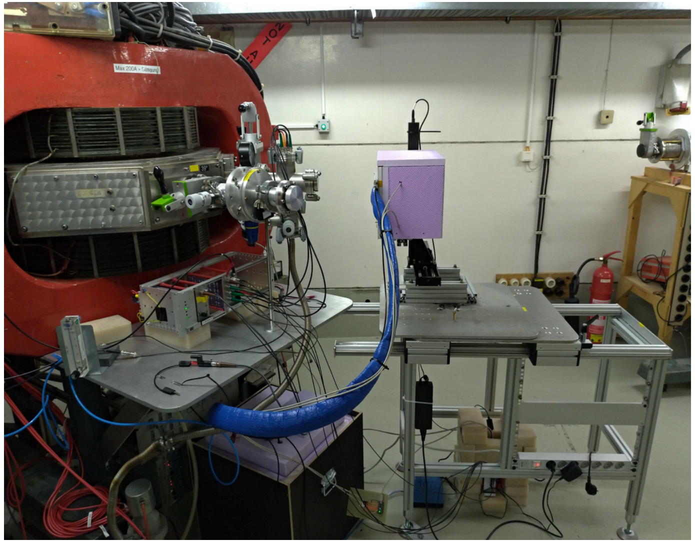


THE IRRADIATION SITE

- Three extraction lines under 0°, 15° and 39° w.r.t beamline for e.g. different particles
- Extraction to irradiation site under **15°**:
- $FWHM_{Max}(15°) \approx 2$ cm
- Beam diagnostics **at extraction** allow online beam monitoring
- Distance irradiation setup <-> extraction = < **5 cm** during irraditon



THE IRRADIATION SETUP

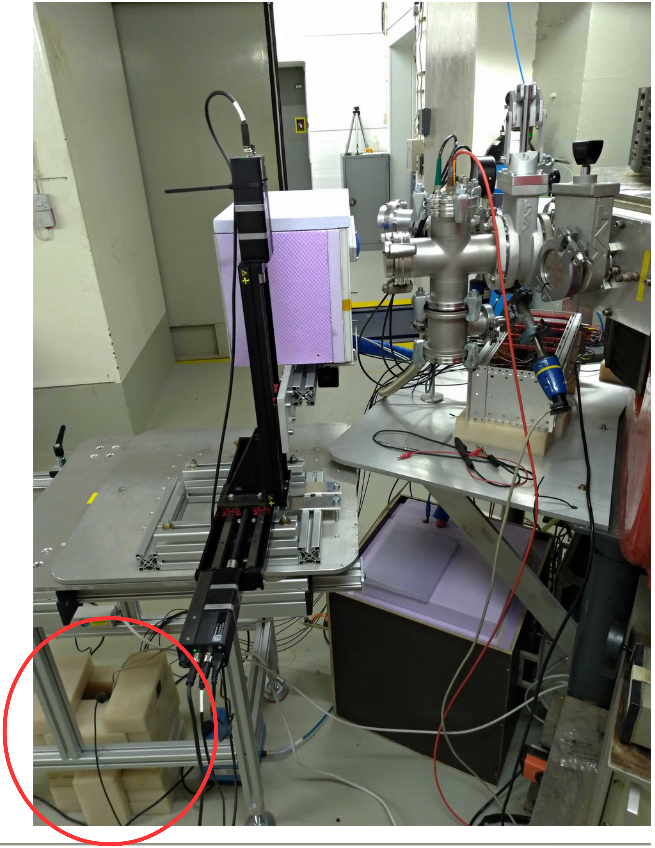


Setup control & DAQ: On-site RaspberryPi (Rpi) server controls **XY-stage, ADC board** and reads **NTCs** temperatures. All data is digitized & available in institute network:

=> Easily replaceable at low cost after potential TID death

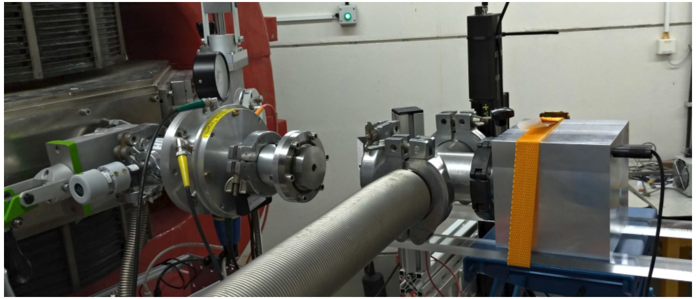
Cooling: irradiation in **cooling box**, N_2 gas cooling (in liquid N_2 reservoir) to prevent **annealing** effects. Temperature monitoring via NTCs at 2 positions.

RPi + ADC board below setup table, shielded by bricks to minimize neutron flux



BEAM DIAGNOSTICS

- Two different ways to monitor the beam on-site
- **Destructively,** using external *Faraday cup*: allows direct beam current measurement at setup, calibration measurements
- **Non-destructively,** using **calibrated**, **S**econdary **E**lectron **M**onitor (SEM):
  - Two pairs of thin, (horizontally/vertically) segmented Al foils
  - Primary beam removes *secondray* e^- from foil surfaces
  - Removing these e^- with +HV: $\mathbf{I_{SEM} = const \cdot I_{beam}}$
- **=> Allows online beam current and position measurement ≈ 10 cm before irradiation setup**



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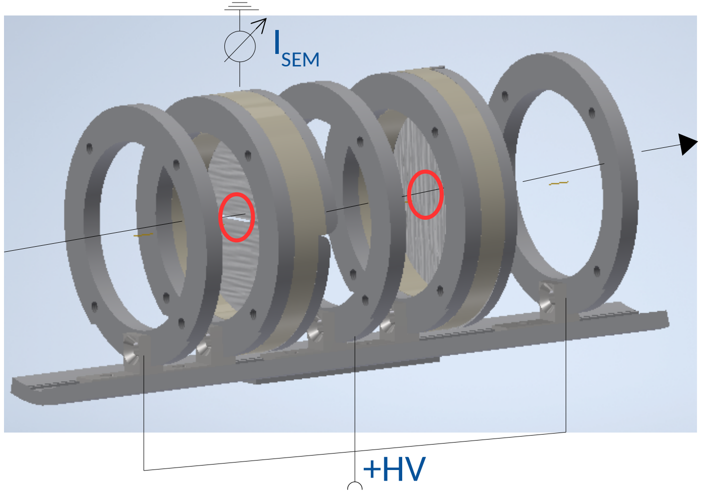

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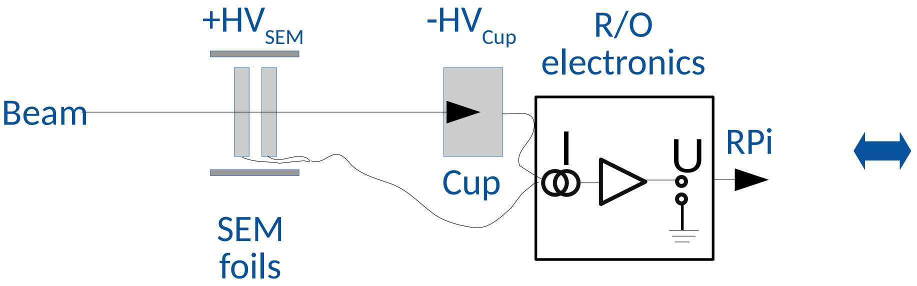
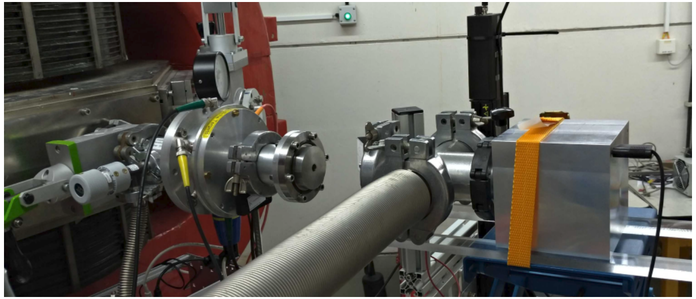
BEAM CURRENT CALIBRATION



Beam current calibration schematic setup



Beam current calibration actual setup

- Calibrate **sum currents** of SEM foils to absolute beam current measured in Faraday cup **at setup position:**
  - **Custom R/O electronics** converts all currents to voltages between 0 – 5 V for AD conversion
  - Different scales I_{FS} corresponding to 0 – 5 V selectable at R/O electronics for e.g. low or high currents
  - Calibration of I_p to U_Σ of SEM to get $\mathbf{I_p\left(U_\Sigma\right) = \lambda \cdot I_{FS} \cdot U_\Sigma}$

BEAM CURRENT CALIBRATION

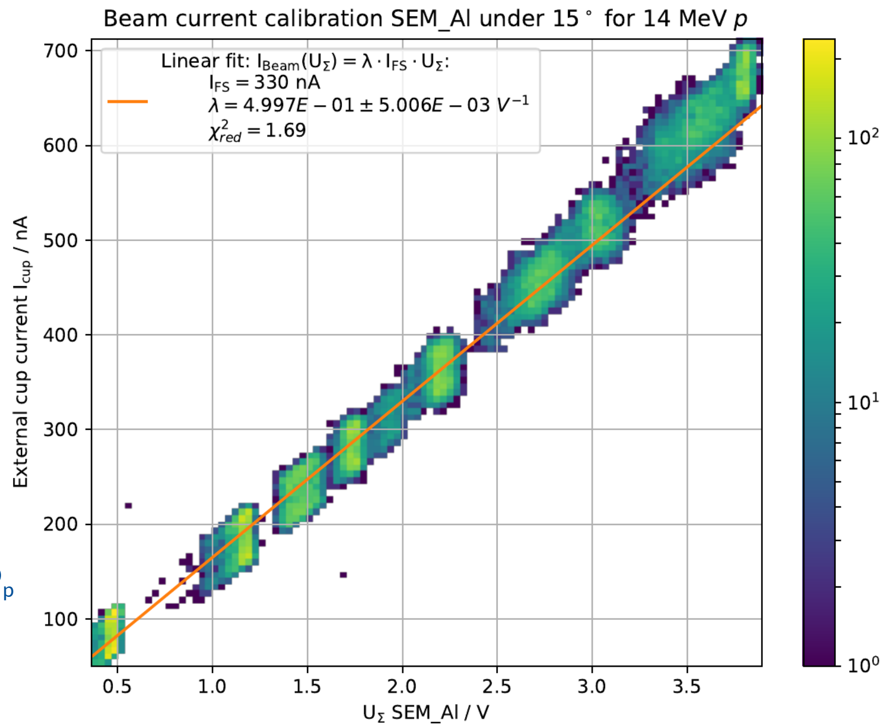
- Beam current calibration at setup position
- Uncertainty on proton current ΔI_p composed of

$$\Delta I_p = \sqrt{(\lambda \cdot I_{FS} \cdot \Delta U_\Sigma)^2 + (\lambda \cdot U_\Sigma \cdot \Delta I_{FS})^2 + (U_\Sigma \cdot I_{FS} \cdot \Delta\lambda)^2}$$

- Typically, the relative errors are

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta I_{FS}}{I_{FS}} = \frac{\Delta U_\Sigma}{U_\Sigma} = 1\% \Rightarrow \frac{\Delta I_p}{I_p} \approx 2\%$$

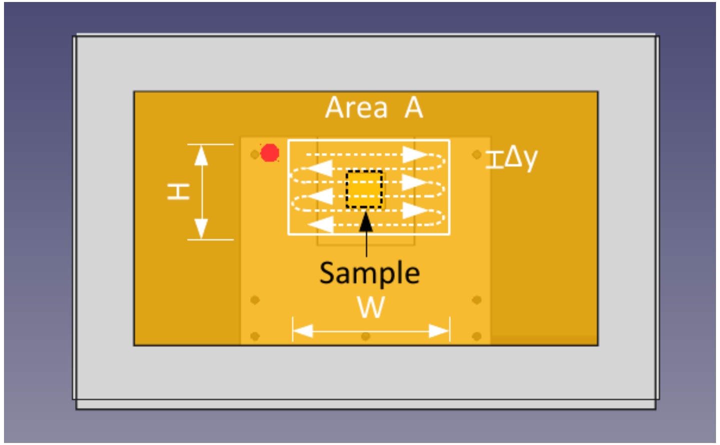
- Proton beam on device know with relative precision of approx. 2% => Reduce uncertainty on proton fluence φ_p



IRRADIATION PROCEDURE

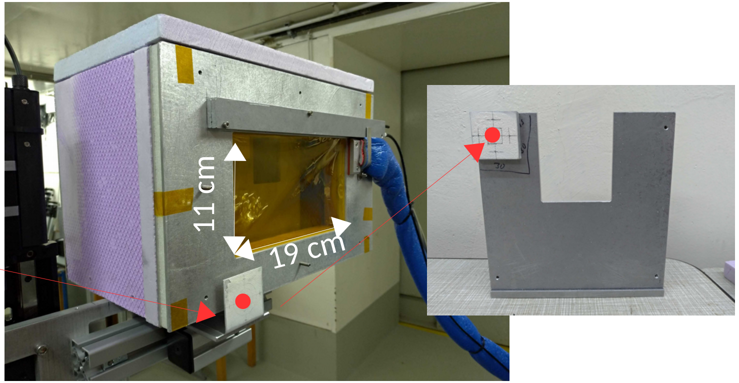
- Achieve **homogeneous** irradiation by **overscanning** DUT area: Typically @ -20 °C, Al shield, 10x10cm² PCB, SEM-DUT = 20 cm
- Proton fluence on device per full scan $\phi_p = \dfrac{I_p}{q_e \cdot v_x \cdot \Delta y}$
- Fluence uncertainty dominated by current measurement

$$\frac{\Delta\phi_p}{\phi_p} = \frac{\Delta I_p}{I_p} \approx \boxed{2\%}$$ vs. typically **20%**



- For I_p=1µA, v_x=80mm/s, Δy=1mm and 2x1xm² DUT:
  - φ_p≈8e12 p/cm² per full scan
  - **1e16 neq/cm²** in approx. 2 hours for 4cm² DUT (see next slides)

Fluorescence screens:
Relative position reference for scan on box and shield



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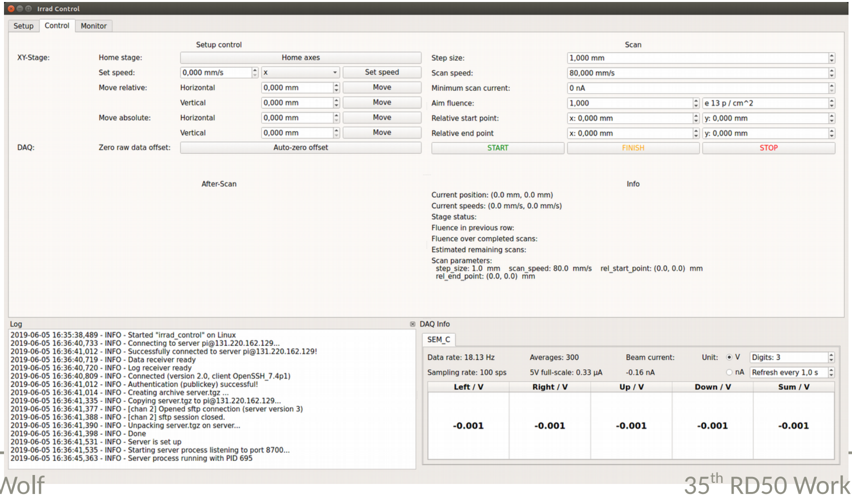
CONTROL SOFTWARE

- GUI-based control software for data visualization and setup control from **control room**
- Beam properties measured with **20 Hz - 200 Hz** during scanning => Allows reacting to changing beam conditions
  - Autonomous **stopping & resuming** of scan and **adapting** scan parameters if needed (e.g on beam-off)

    => Greatly **increases homogeneity** of fluence over scan area
- **Online** monitoring of **beam current- and position**, **proton fluence** per row & **temperature on-site**

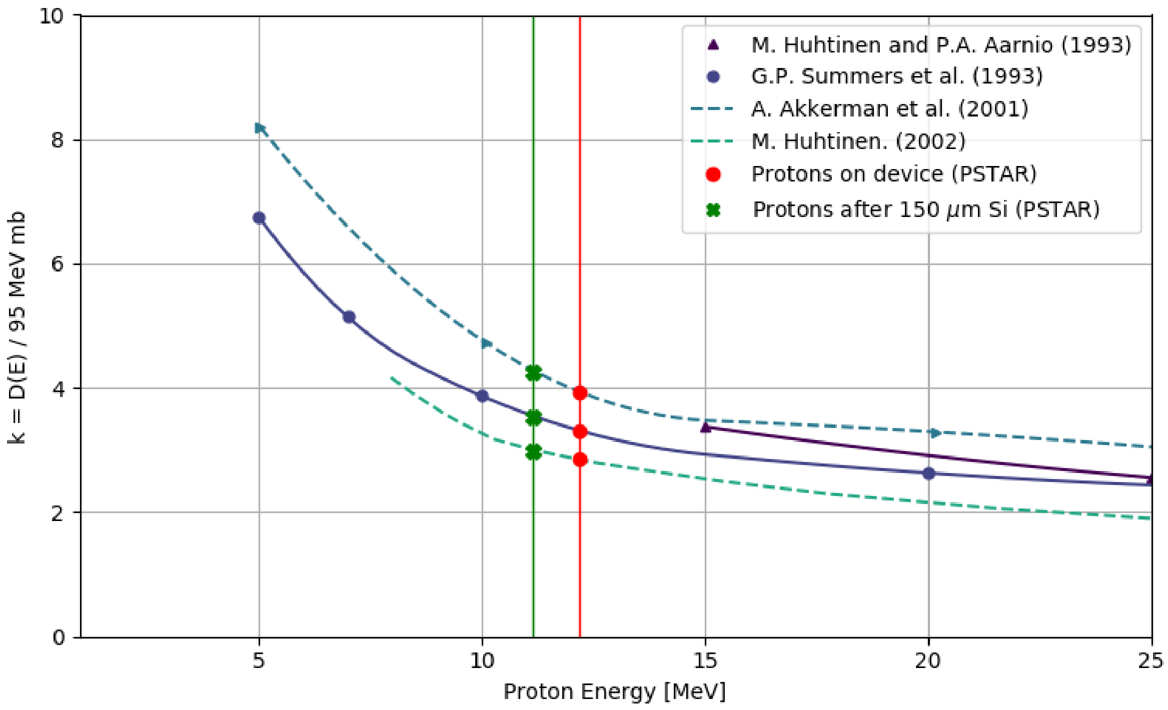


Interface for setting irradiation parameters and XY-stage control

Proton fluence histogram per row

RADIATION DAMAGE

- Calculation of proton energy on device allows to estimate *proton hardness factor* κ_p from simulations:
  - 12.2 MeV => κ_p = 2.8 – 3.9 depending on source
- After typical devices (for ATLAS, CMS) with 150 μm Si:
  - 11.2 MeV => κ_p = 3.0 – 4.3 depending on source
- Difference in κ_p at entrance / exit below 8 % for all sources => Expected hardness factor for **typical** devices: **κ_p = 2.8 – 4.3**



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PROTON HARDNESS FACTOR

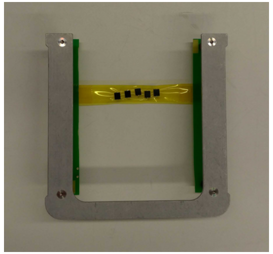
- „Standard procedure“ (see [3, 4]) to measure proton hardness factor κ_p:
  - Irradiation of BPW34F diodes to different ϕ_p
  - Measure **bulk leakage current increase** per fully-depleted volume

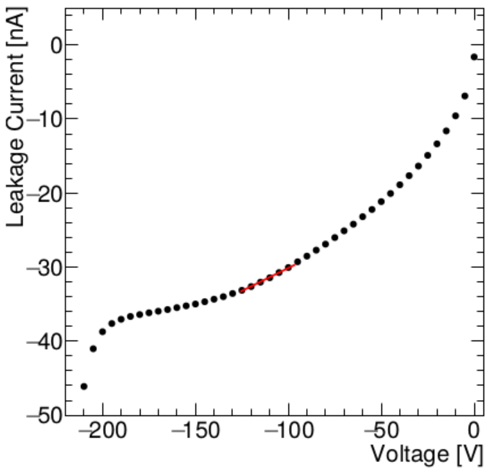
$$\frac{\Delta I_{leak}}{V} = \alpha_p \cdot \phi_p$$

  - After **annealing** for 80 min at 60 °C and **scaling** ΔI_{leak} to 20 °C [3]

$$\kappa_p = \frac{\alpha_p}{\alpha_{eq}}$$

with $\alpha_{eq} = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A\,cm^{-1}}$ [1]

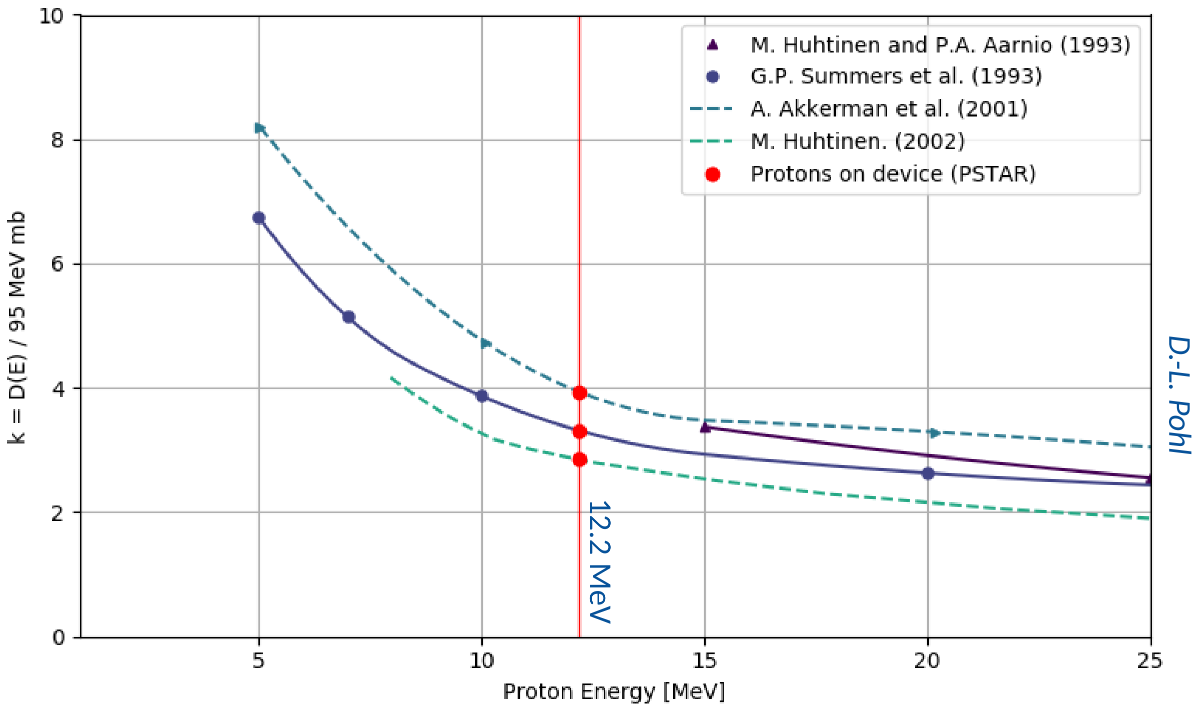




BPW34F characteristic from [4]

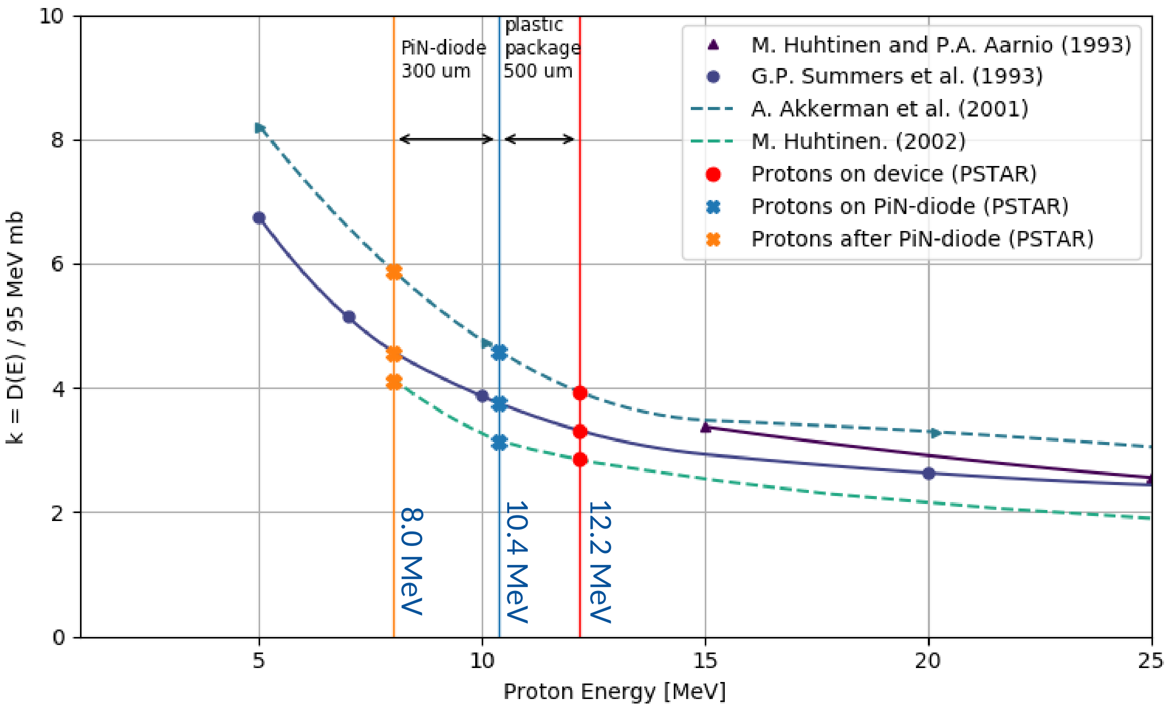
PROTON HARDNESS FACTOR

- Calculation of proton energy on device allows to estimate κ_p for particular BPW34F diodes:
  - "F" = Filter = 500 um plastic
  - 300 um Si



PROTON HARDNESS FACTOR

- Calculation of proton energy on device allows to estimate κ_p for particular BPW34F diodes:
  - “F“ = Filter = 500 um plastic
  - 300 um Si
- Energy loss in plastic packaging not negligible at these energies
- κ_p= 3.1 – 4.6 on entry, κ_p= 4.1 – 5.9 on exit of Si => Approx. 20% difference, non-negligible depth dependance of damage



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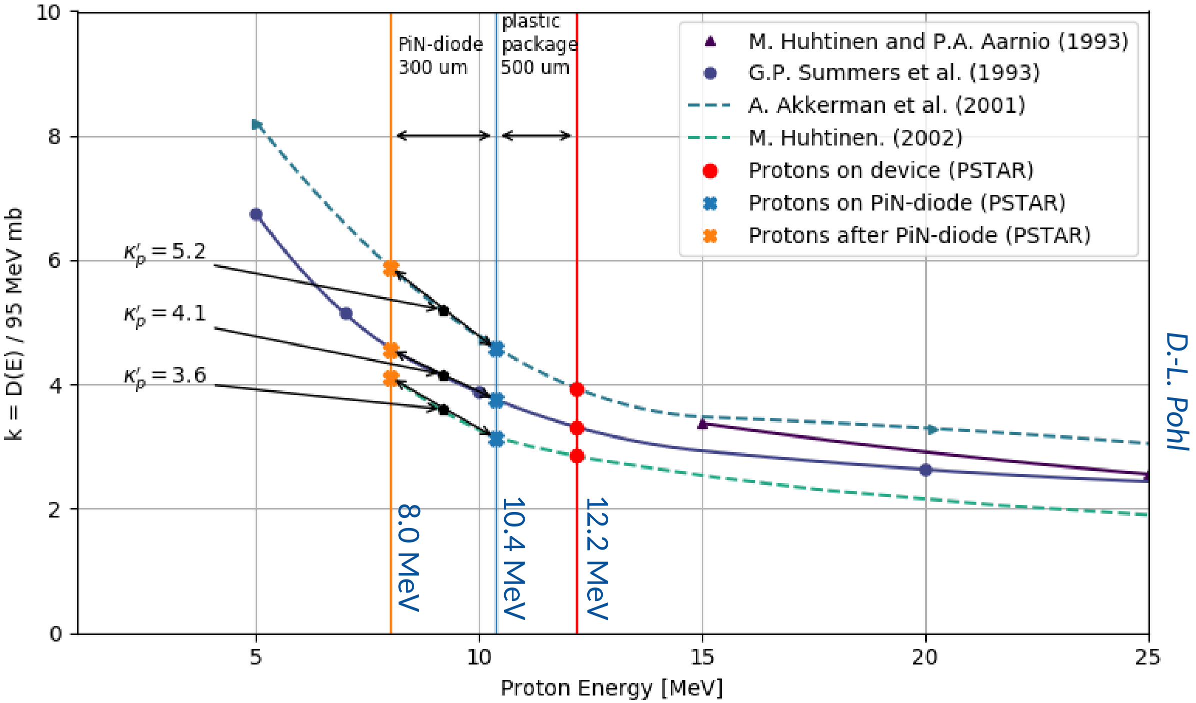
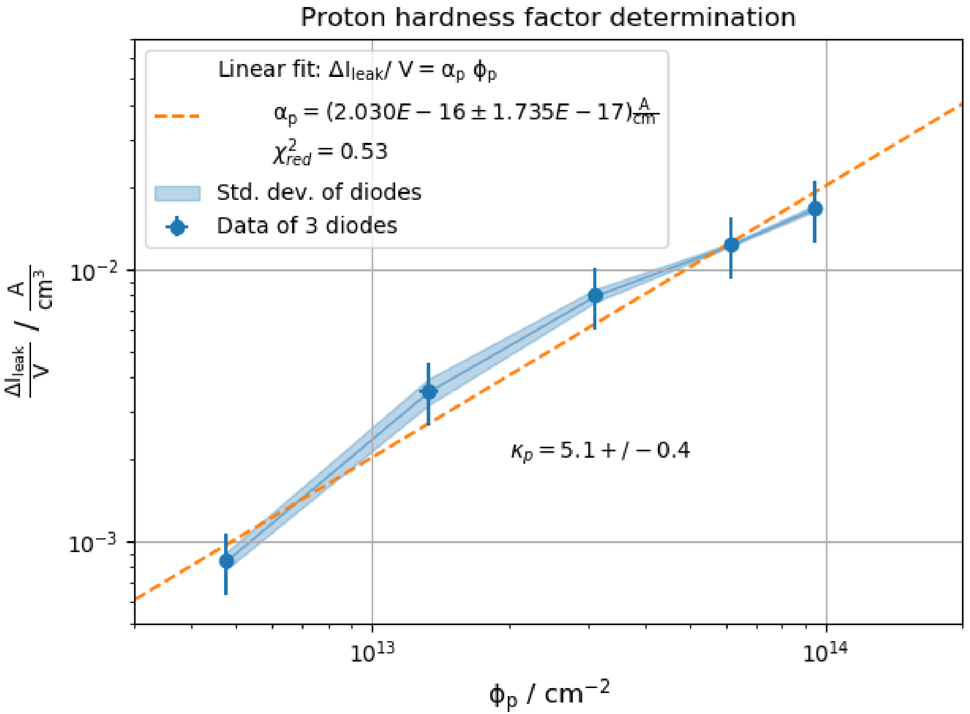
- Expect an *effective* κ'_p = 3.6-5.2; lin. interpolation as approximation



PROTON HARDNESS FACTOR

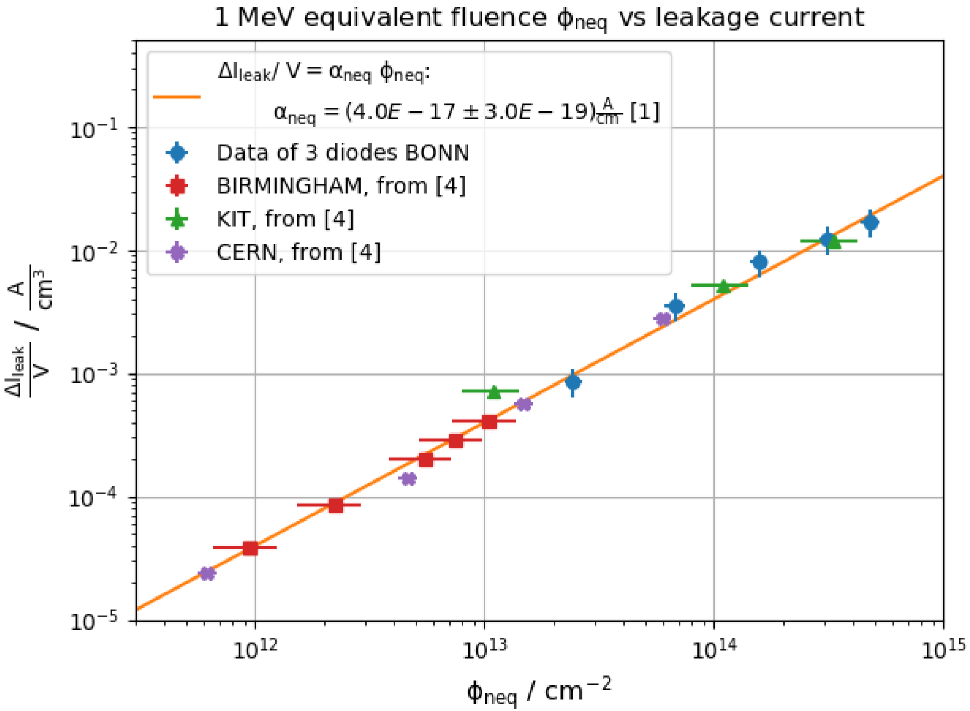
- Irradiation of BPW34F diode sets to **5** different fluences, **3** diodes per set
- I-V-curves measured @ -20 °C to avoid self-heating, evaluation at U_{dep} = (100 ± 10) V†
- Results:
  - Good linear relation, small variation within diode sets, y-errors dominate
  - Measured κ_p ≈ 5 for <u>BPW34F diode</u> agrees best with Akkerman et al
- Compare to results from [4] of various irradiation facilities



†*Mean value from results of [3, 4] with errors including both values*

PROTON HARDNESS FACTOR

- Comparison to **KIT**, **Birmingham** and **CERN** hardness factor measurements from [4] using BPW34F diodes:
  - **Very good** overall agreement
- Results show irradiation procedure is working
- **But…** using BPWF34F diode leads to increased κ_p due to high material budget
- Expected hardness factor of $\boldsymbol{\kappa_p \approx 4}$ (Akkerman et al.) for **typical** devices (< 300 µm Si) to be measured soon

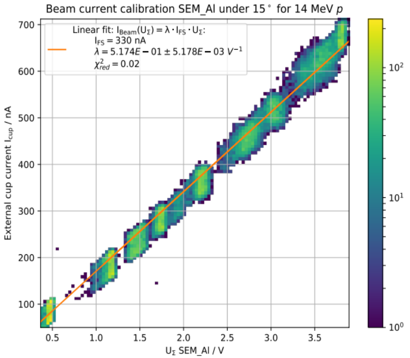


CONCLUSION

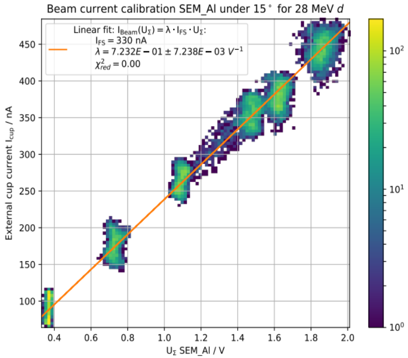
- A **new proton irradiation site** at Bonn University has been developed and is (physically) **ready** for use
- Custom beam diagnostics **reduce the uncertainty on the proton fluence** on-device to $\frac{\Delta\phi_p}{\phi_p} \leq 2\%$
- κ_p determined using BPW34F diodes in **agreement** with simulations and results from KIT, Birmingham & CERN [4]
- BPW34F diodes **not optimal for precise** measurement of κ_p at low energies due to plastic packaging
- Beam energy of 14 MeV is sufficient for **typical** silicon detectors (κ_p variation < 8/15% for 150/300 µm)
- Use **preliminary** hardness factor of **κ_p = 4 ± 1** w.r.t to Akkerman et al. [5]
  - **Soon** to be measured precisely using suitable diodes to reduce uncertainty
- Irradiation up to **1e16 neq/cm²** within **2 hour** anticipated for 4cm² DUT

OUTLOOK

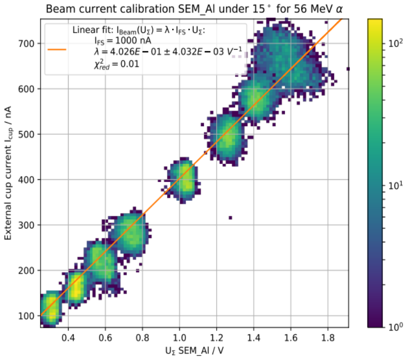
- Currently, 1 Bachelor, 1 Master, 1 PhD and 1 PostDoc are working on the characterization of the irradiation site
- Irradiation Si-diodes < 300 µm to determine hardness factor precisely
- Measurement of low-energy proton hardness factors
- As of now, the beam current for protons, deuterons and alphas is calibrated under 15° extraction:
  - Improve, calibration & measure hardness factor of these ions at their respective energy



Protons (14 MeV)



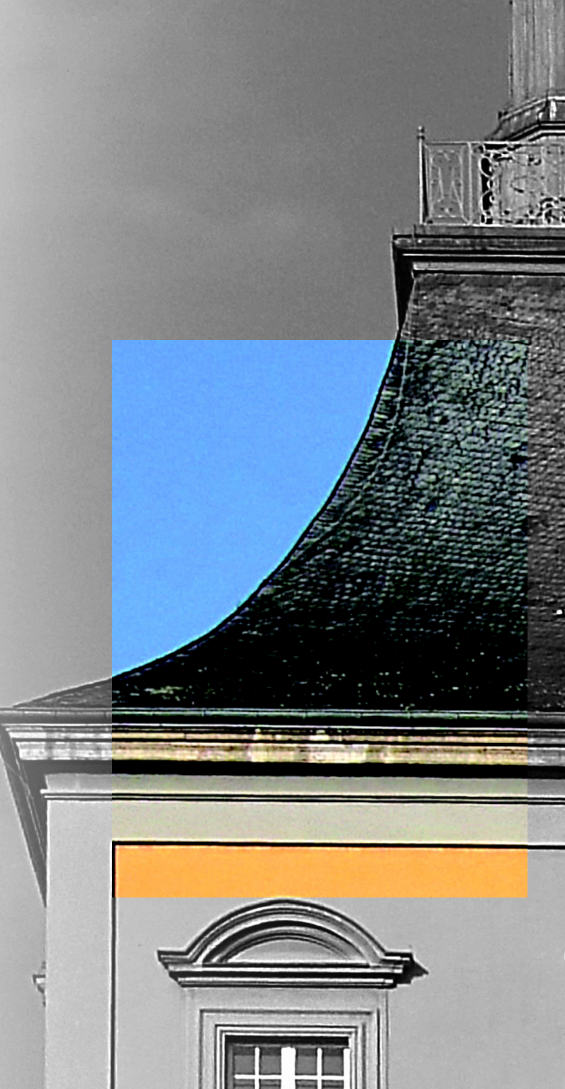
Deuterons (28 Mev)



Alphas (56 MeV)

THANK YOU

- [1] M.Moll, *Radiation damage in silicon particle detectors:Microscopic defects and macroscopic properties*, PhD thesis: Hamburg U., 1999
- [2] A. Chilingarov, *Temperature dependence of the current generated in Si bulk*, Journal of Instrumentation 8 (2013) P10003
- [3] F. Ravotti, *Development and Characterisation of Radiation Monitoring Sensors for the High Energy Physics Experiments of the CERN LHC Accelerator*, Presented on 17 Nov 2006
- [4] P. Allport et al., *Experimental Determination of Proton Hardness Factorsat Several Irradiation Facilities*, August 2019
- [5] A. Akkerman et al., *Updated NIEL calculations for estimating the damage induced by particles and γ-rays in Si and GaAs, 2001*



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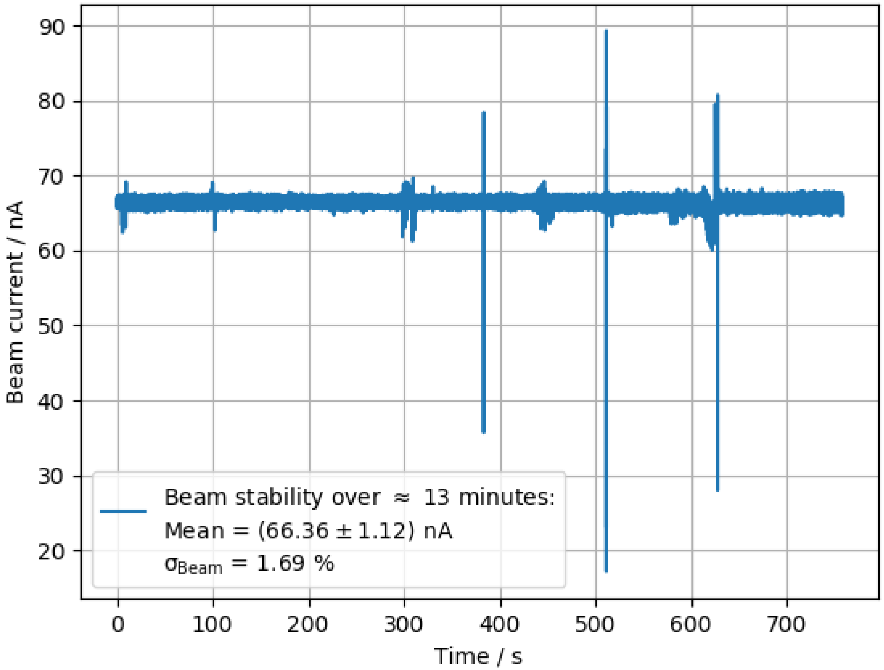
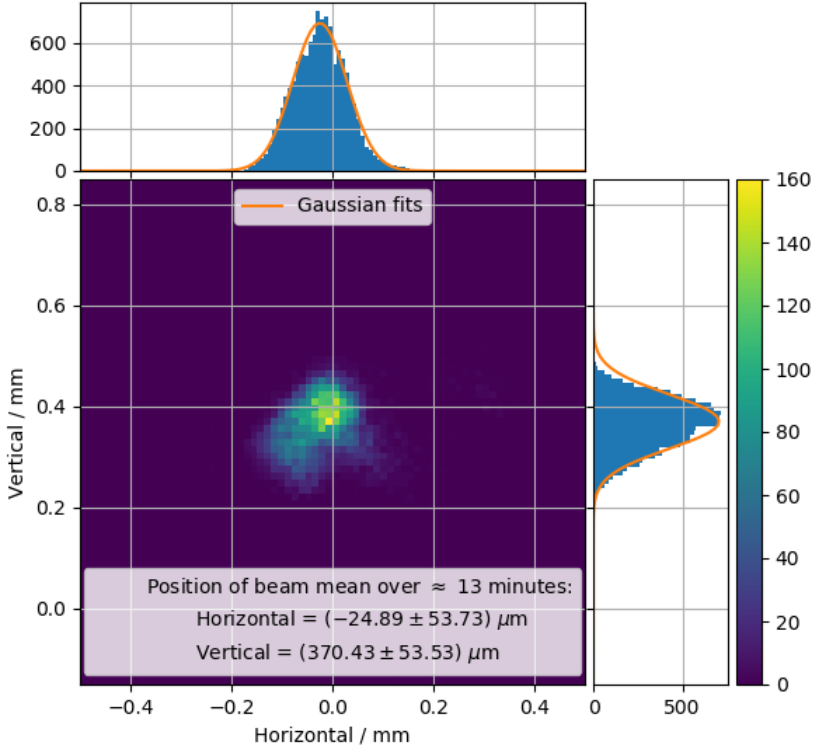
BACKUP

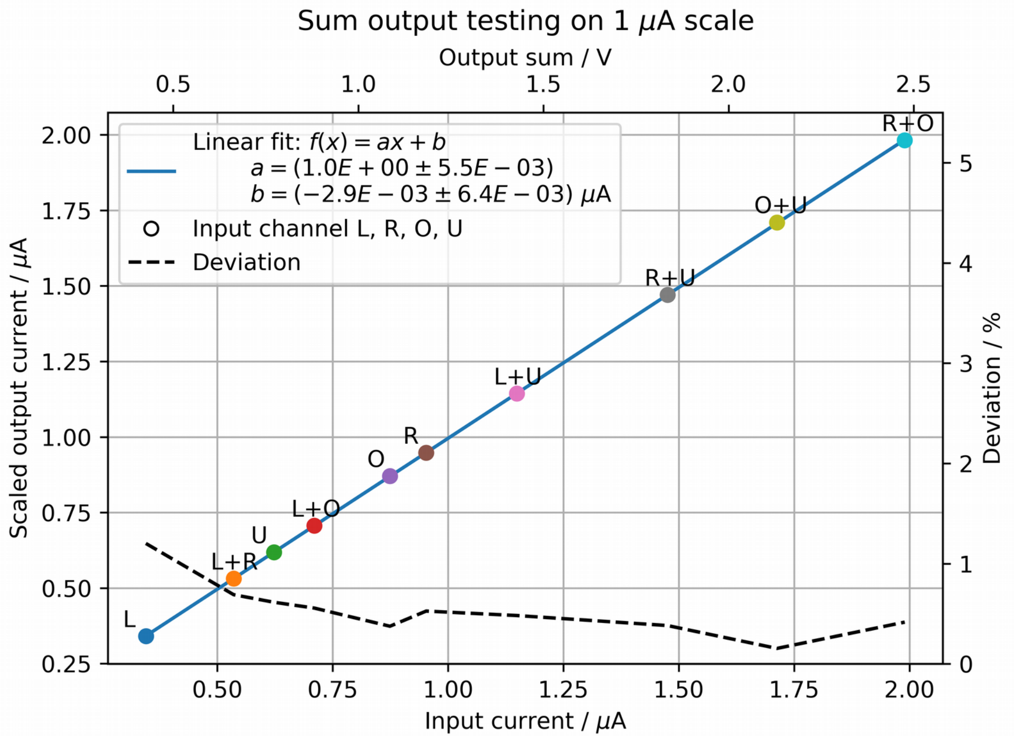
THE BONN ISOCHRONOUS CYCLOTRON





BEAM CURRENT MONITORING
-PRECISION-

- Testing of electronics with sourced currents:
  - Source into different channels: L, R, O , U
- Deviation between sourced current and output ≈ **1 %**



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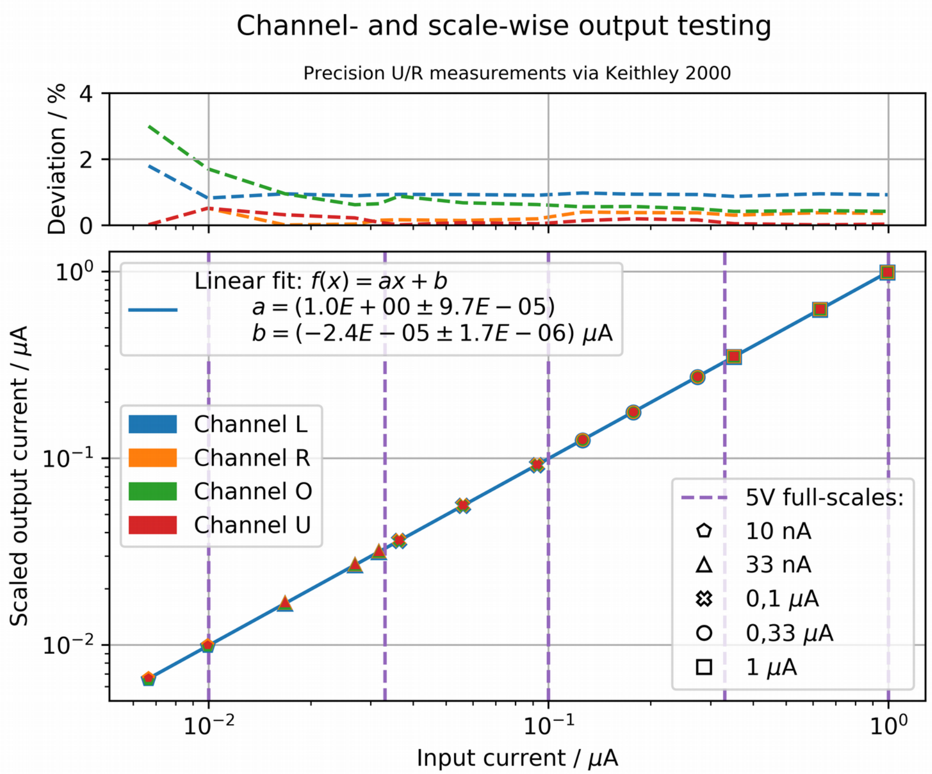

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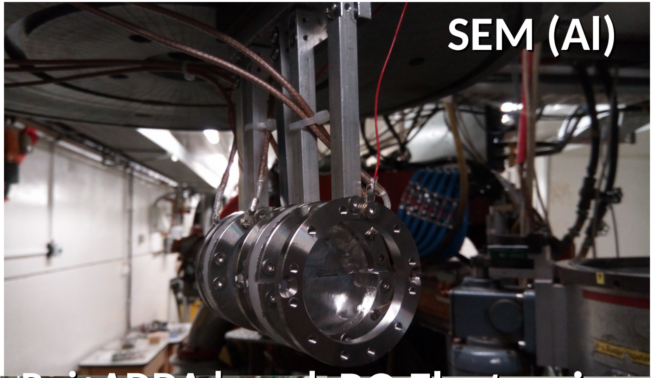
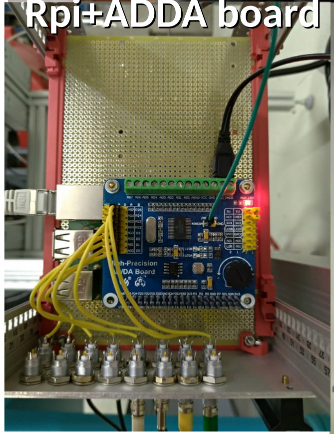
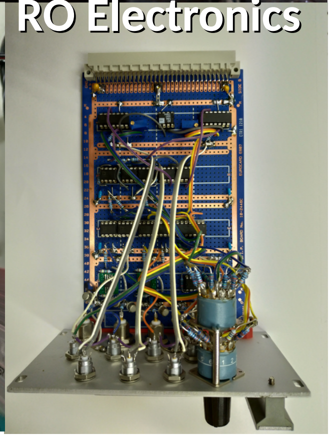
BEAM CURRENT MONITORING
-SEMs & READOUT ELECTRONICS-

- Secondary current range: **nA ≤ I_{SEM} ≤ µA**
  - Custom RO electronics developed and tested
  - Conversion & projection of I_{SEM} to **0 – 5 V**
  - Selectable resolutions from 3 nA to 1 µA
  - Approx. 1% uncertainty on I_{SEM} measurement
  - Readout via RPi & 8-Ch. ADDA board







BEAM CURRENT CALIBRATION

- Calibration R_{FS} = 1000 nA:

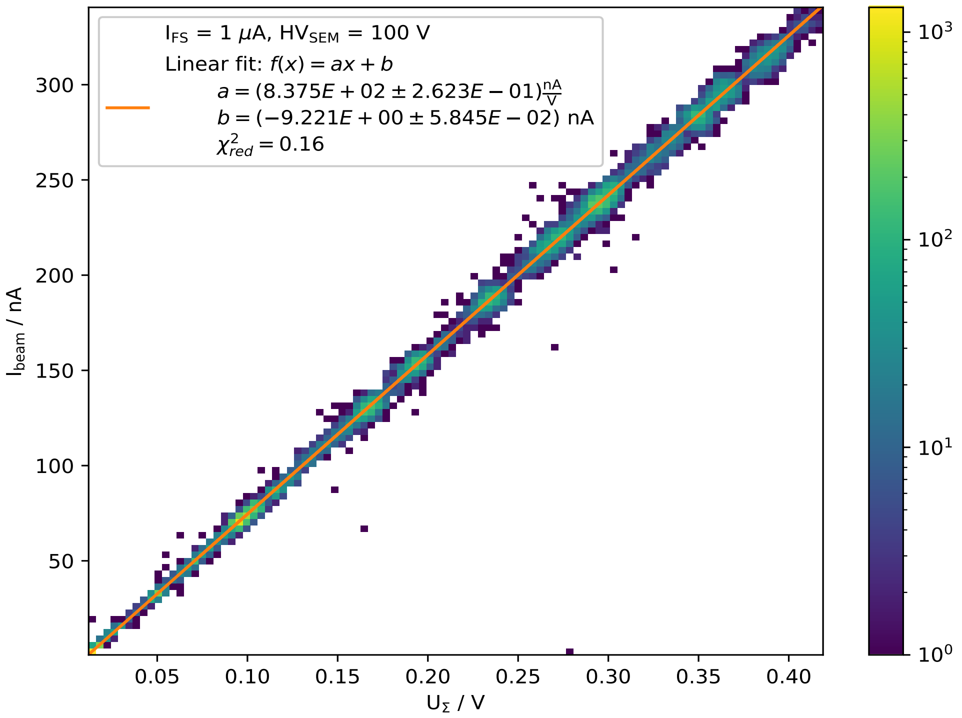
$$\lambda = (838.12 \pm 0.24) \times 10^{-3} \frac{1}{\mathrm{V}}$$

- Realiability needs to verified
- Measurement repeated several times for different R_{FS}:

  => $\lambda_{std} / \lambda_{mean}$ <= 1.5%

- Calibration model $I_{Beam} \propto U_{\Sigma}$:
  - Linear fit shows offset b != 0

  => Offset due to 1% precision of R_{FS}



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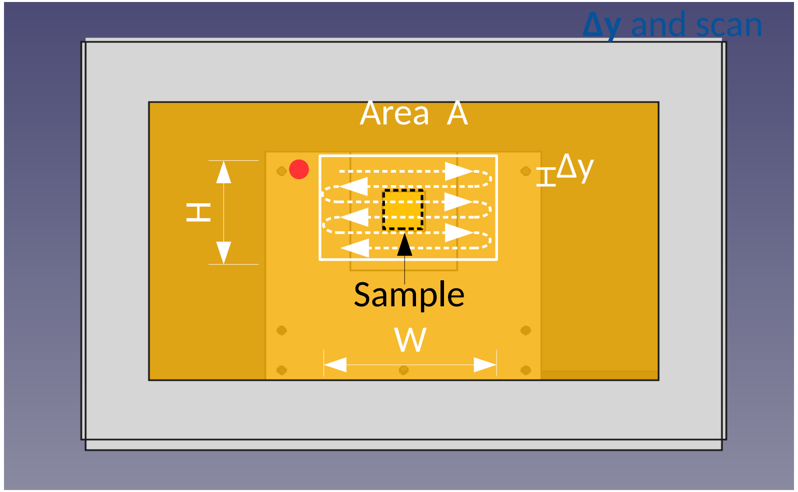
IRRADIATION PROCEDURE
-PROTON FLUENCE-

- Proton fluence: $\phi_p = \frac{I_p \cdot t}{q_e \cdot A}$ I_p = proton current, t = time, q_e = elem. charge, A = area
- **Homogeneous** irradiation of A desired:
  - Row-wise scanning of area **A** with step size speed $\mathbf{v_x}$ allows to rewrite **t**:



$$t = n \cdot \frac{W}{v_x} = \frac{H}{\Delta y} \cdot \frac{W}{v_x} = \frac{A}{\Delta y \cdot v_x}$$

- Proton fluence per unit area **A** now given as:

$$\boldsymbol{\phi_p = \frac{I_p}{q_e \cdot v_x \cdot \Delta y}}$$

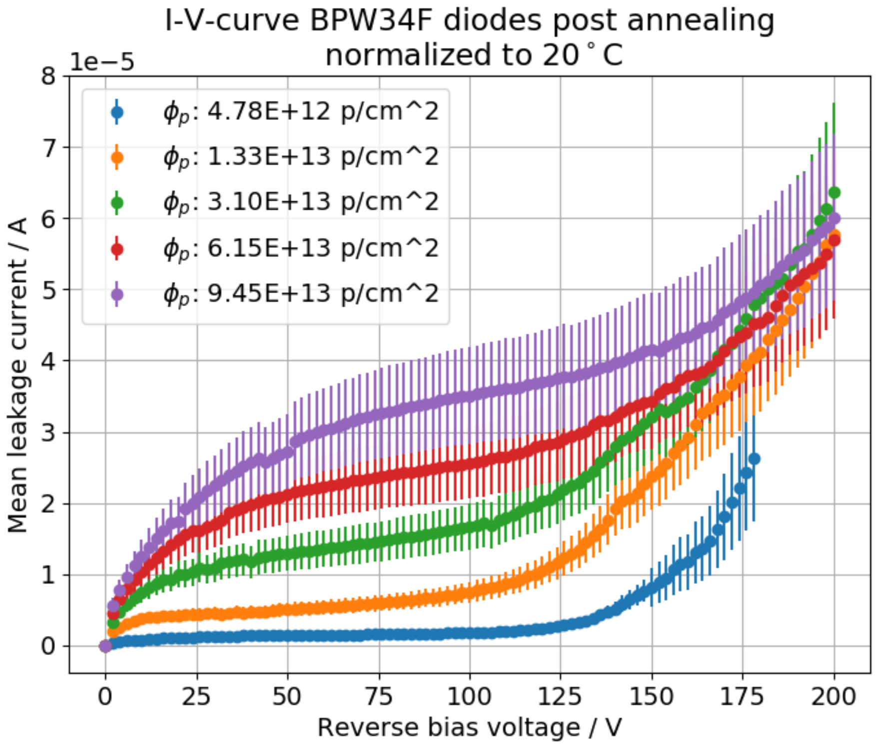
TEMPERATURE SCALING

- Annealing for 80 min @ 60 °C
- Measured in climate chamber using Keithley 2450 SourceMeter
- Leakage scaled to 20 °C by

$$I_{leak} \propto T^2 \cdot \exp\left(-\frac{E_{eff}}{2 \cdot T \cdot k_B}\right)$$

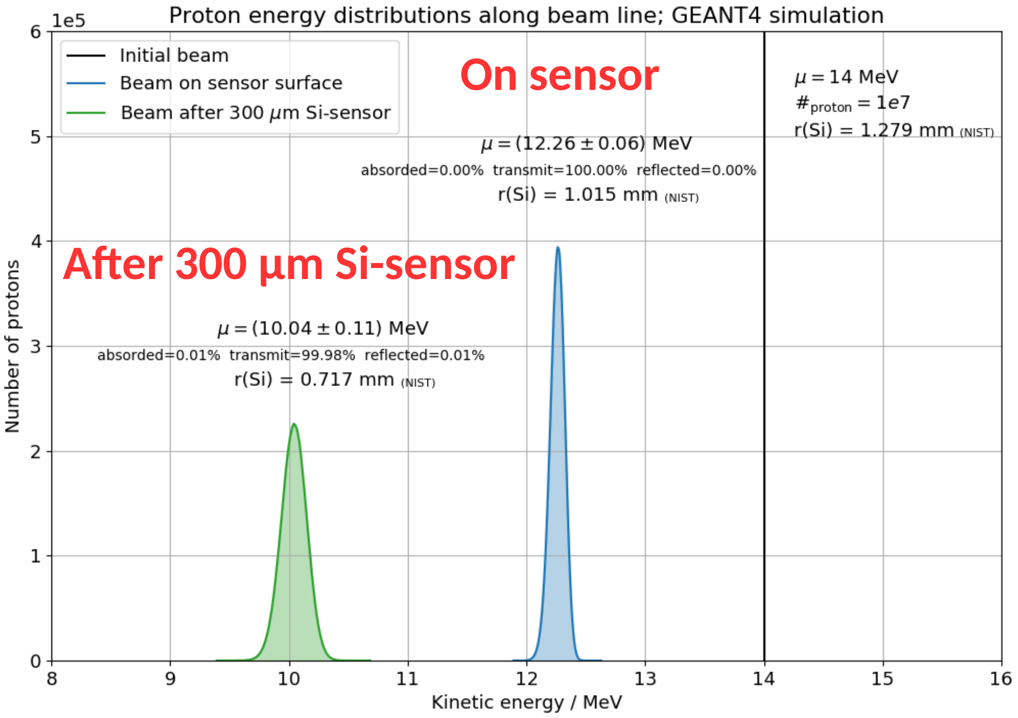
with E_{eff} = (1.214 ± 0.014) eV [2]

- Evaluation of leakage current at full-depletion voltage U_{dep} = (100 ± 10) V [3, 4]



GEANT4 ENERGY SIMULATIONS
-PROTONS 39° EXTRACTION-

- 10^7 protons with 14 MeV along beam line
- Energy distributions **on** and **after** 300 µm Si-sensor
- Hardness factor
  - κ ≈ 3 - 4 (?)
  - (Slight) dependence of damage function on penetration depth (?)



EFFECTIVE HARDNESS FACTOR

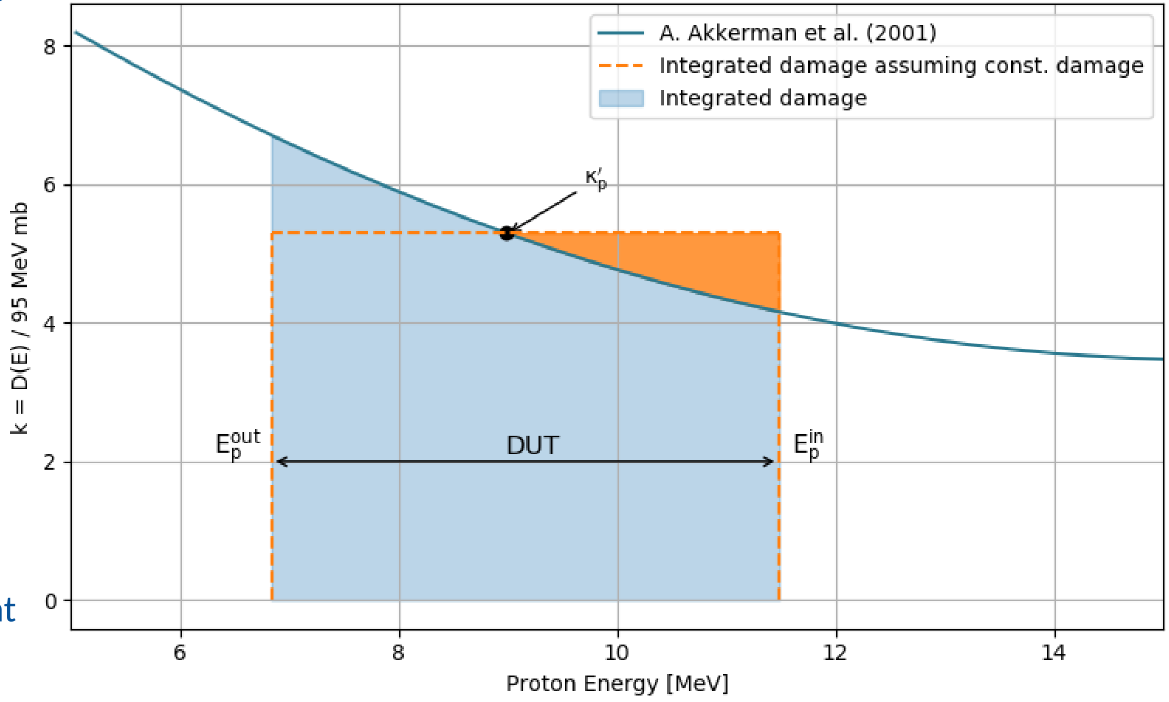
- **Thick** devices see *effective* hardness factor κ'_p at low energies

$$\frac{\Delta I_{leak}}{V} = \kappa_p \cdot \alpha_{eq} \cdot \phi_p$$

$$\frac{\Delta I_{leak}}{V} = \alpha_{eq} \cdot \phi_p \int_{E_p^{in}}^{E_p^{out}} \kappa_p (E_p)\, dE_p$$

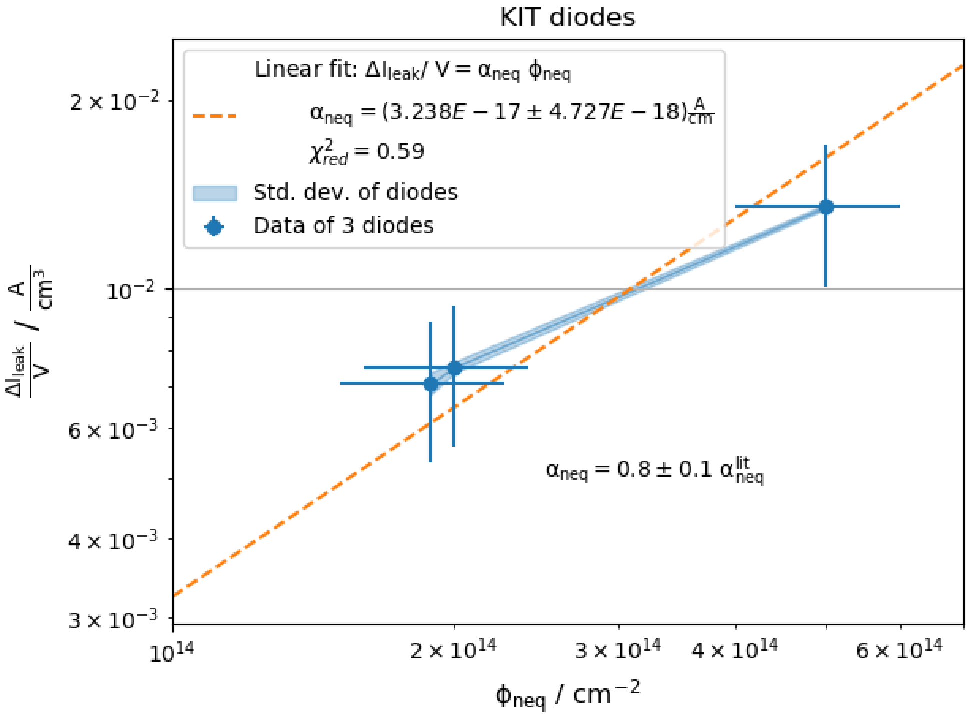
$$= \alpha_{eq} \cdot \phi_p \cdot \kappa'_p$$

- κ'_p corresponds to same integrated, **but constant** damage => That's what one measures via ΔI_{leak}



PROTON HARDNESS FACTOR

- Irradiation of BPW34F diode sets to **5** different fluences, **3** diodes per set
- I-V-curves measured @ -20 °C to avoid self-heating, evaluation at U_{dep} = (100 ± 10) V†
- Results:
  - Good linear relation
  - Small variation within diodes of same fluence
  - Expected hardness factor of $\kappa_p \approx 5$ for particular BPW34F didode
  - Compare to KIT…



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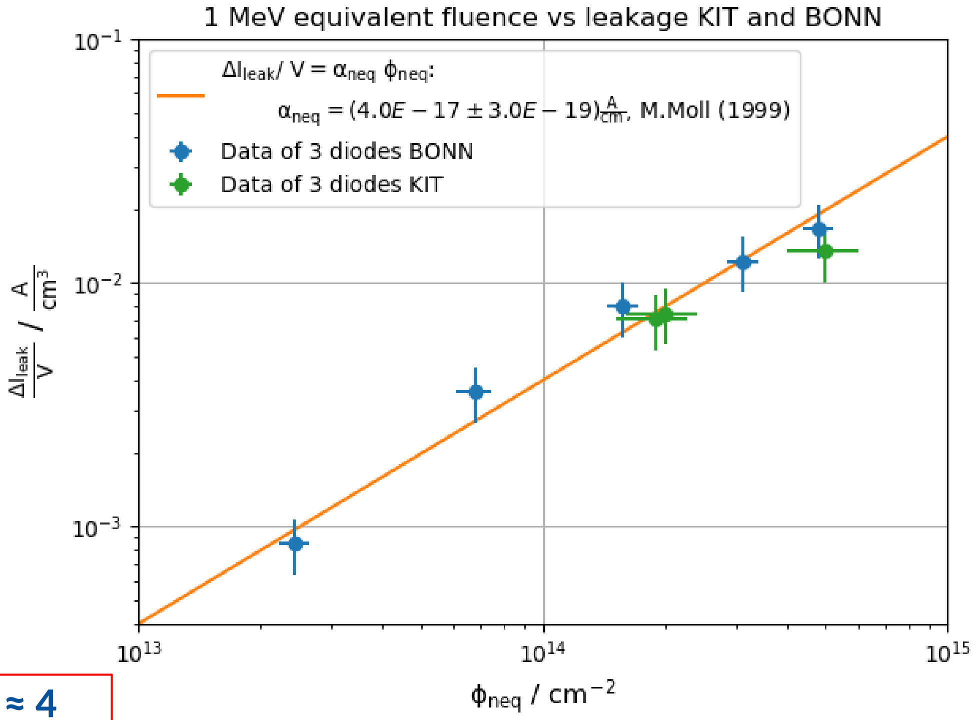
PROTON HARDNESS FACTOR

- Irradiation of BPW34F diode sets to **5** different fluences, **3** diodes per set
- I-V-curves measured @ -20 °C to avoid self-heating, evaluation at U_{dep} = (100 ± 10) V†
- Results:
  - Good linear relation, small variation within diode sets, y-errors dominate
  - Measured $\kappa_p \approx 5$ for BPW34F diode agrees best with Akkerman et al
  - Compare to KIT… in agreement!



But!.. not the expected hardness factor of $\kappa_p \approx 4$ (Akkermanet al.) for **typical** devices (< 300 µm Si)

† *Mean value from results of [3, 4] with errors including both values*

I-V-CURVES BPW34F [4]

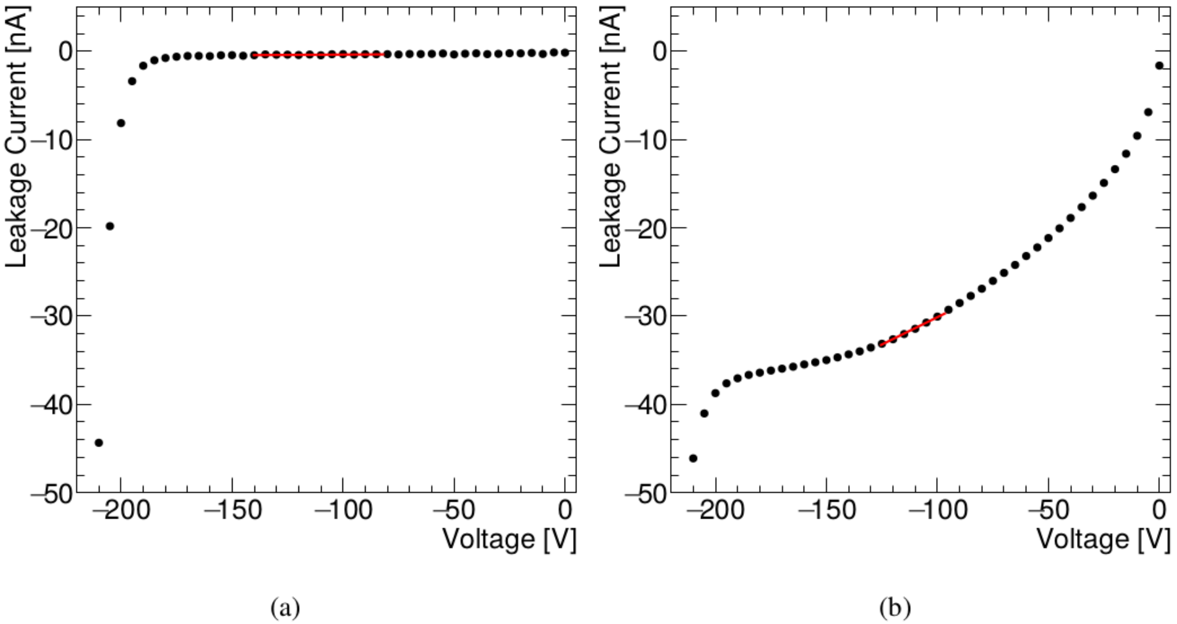
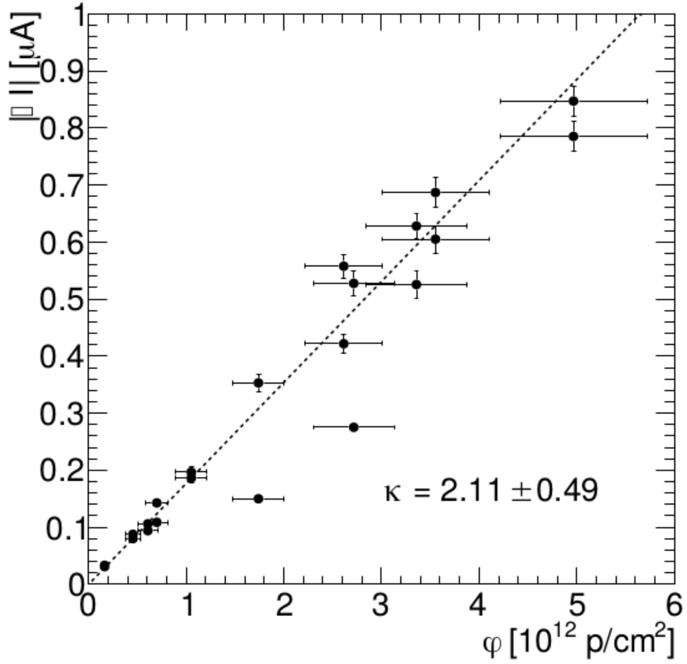
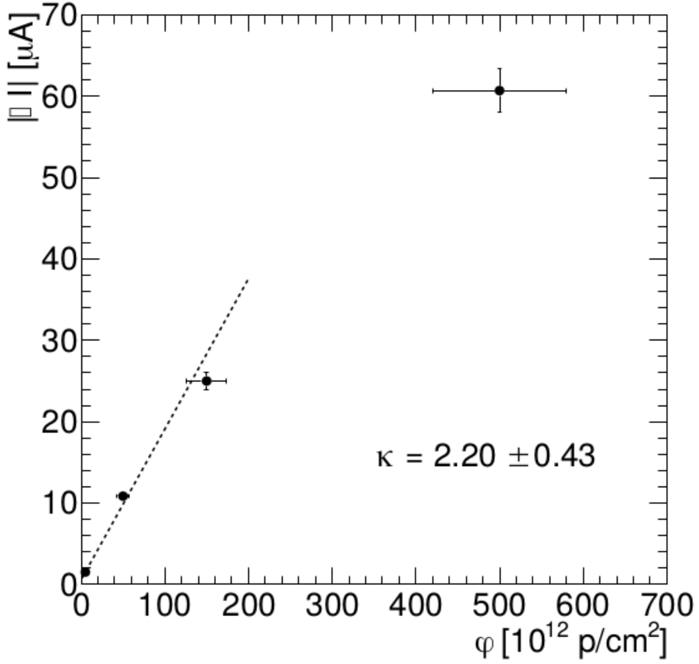


Figure 9. I–V curves fit with a first order polynomial. (a) Unirradiated diode; (b) Following irradiation at $(1.56 \pm 0.34) \times 10^{11}\,\mathrm{pcm}^{-2}$ and thermal annealing.

PROTON HARDNESS FACTORS [4]

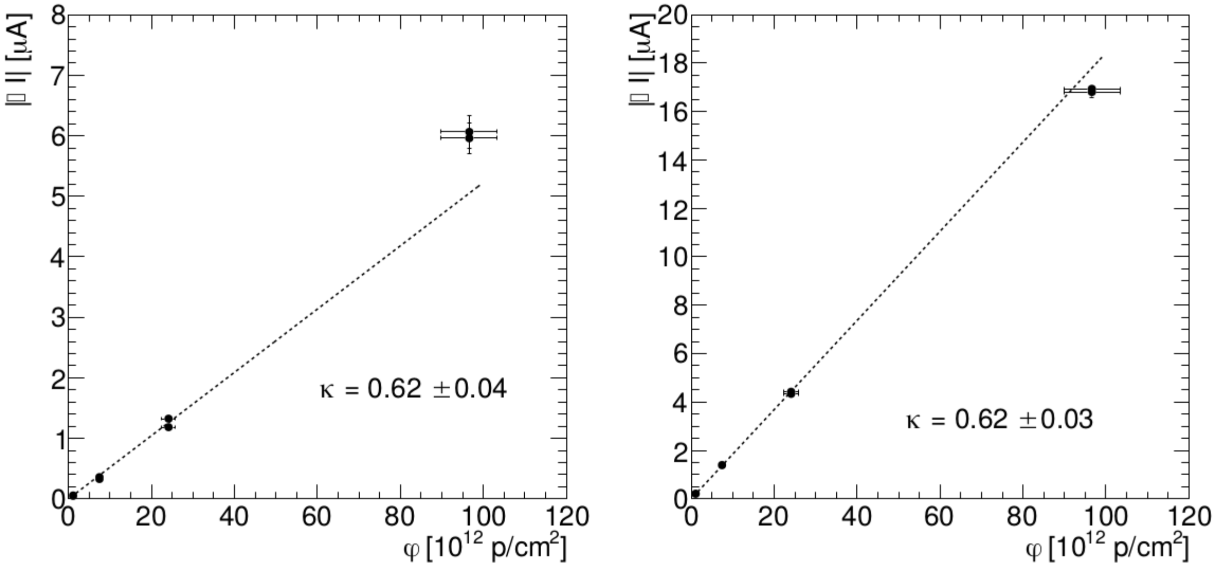


(a)



(b)

PROTON HARDNESS FACTORS [4]



(c) (d)

Figure 10. 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.