PROTON HARDNESS FACTOR AT THE BONN IRRADIATION SITE

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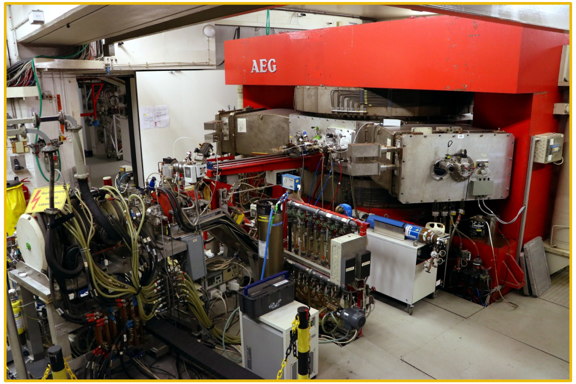
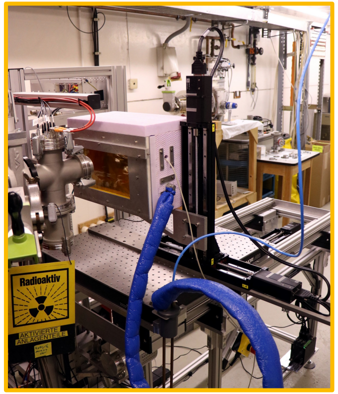
OUTLINE

- Irradiation setup & procedure
- Dosimetry
- Hardness factor
  - Expectations
  - Previous measurements and their flaws
  - Latest results
- Conclusion



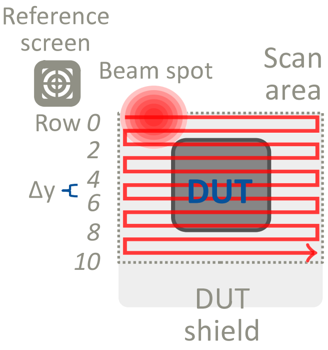
- Bonn Isochronous Cyclotron
  - ECR ion source yields light ions
  - Ion energies 7-14 MeV / nucleon

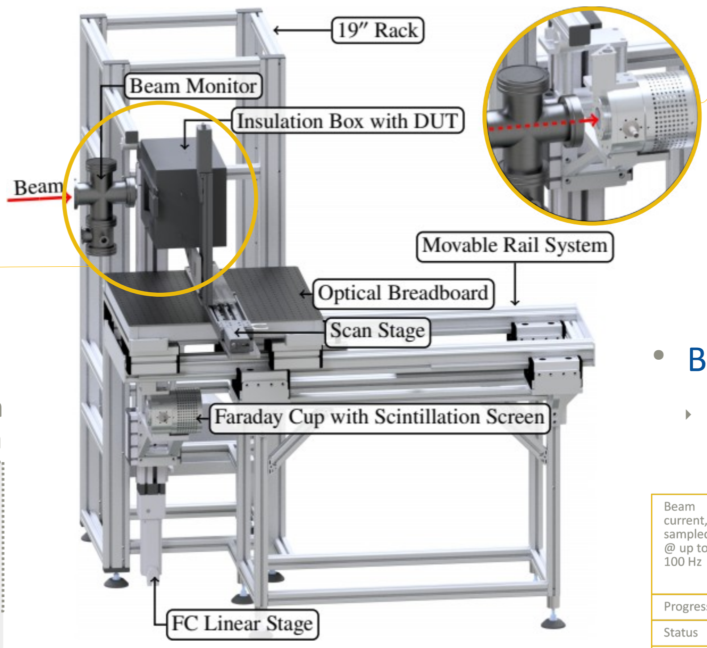


- Irradiation site
  - 14 MeV proton beam
  - 20 nA <= I_{beam} <= 1 µA
  - $Ø_{FWHM}$ few mm

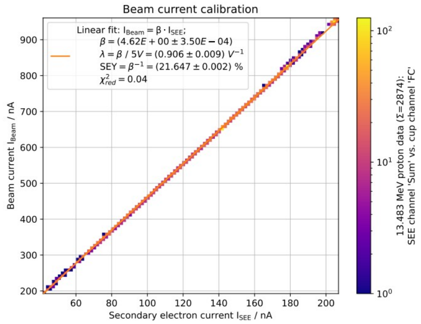
IRRADIATION SITE
--SETUP & PROCEDURE--

- Setup
  - Calibrated beam monitor
  - DUT box, mounted on XY-stage
  - Setup table on rail system
  - External Faraday Cup (FC)
- Procedure
  - Scan DUT in grid with equidistant rows
  - Online beam sampling
  - Temp < -20°C via N_2

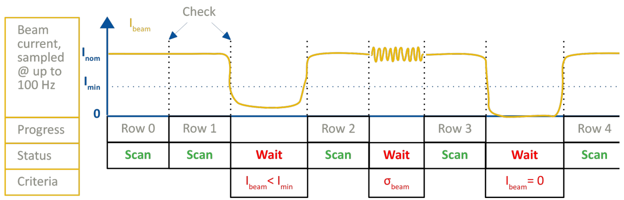




- Beam monitor calibration:
  - $I_{monitor} = \beta \cdot I_{beam}$



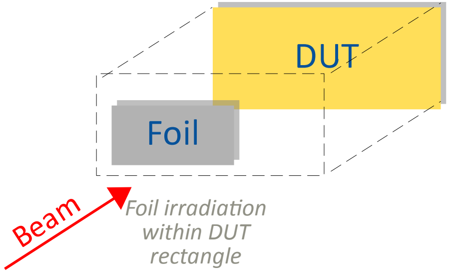
- Beam-driven scan routine:
  - Scan adapts to beam → uniformity



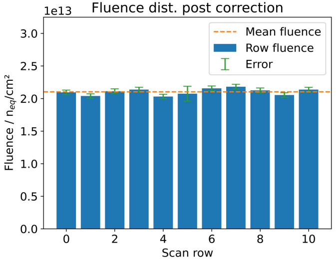
DOSIMETRY

--METHODS--

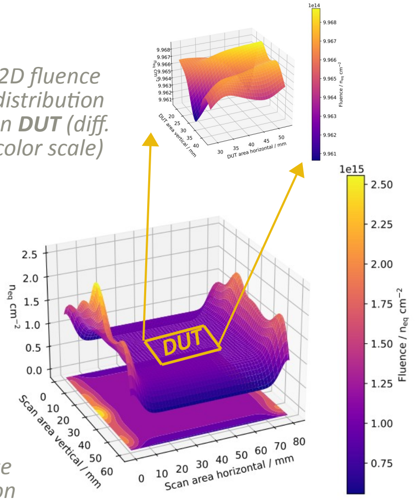
- Standard method: dosimetry via metallic **foil activation**:
  - Irradiation of metallic foil (e.g Ni/Ti) alongside DUT
  - Measure activation of specific isotope X via spectroscopy
    - Fluence as scalar via $\phi_p \left[p \xrightarrow{\Omega_p^X} X \right] \Rightarrow A^X,\ \Omega_p^X,\ \lambda^X,\ m_{mol}^X,\ m_{foil}$
    - No spatial information
- Bonn method(s): dosimetry via **beam current** sampling:
  - Fluence per row via approx. formula $\phi_p = \frac{I_{beam}}{q_e \cdot v \cdot \Delta y}$
    - Distribution per row (1 dim) via
    - Online analysis → Enables post-irrad corrections
  - Fluence from irradiation data analysis:
    - Fluence map over scan area and DUT (2 dim)



Foil irradiation within DUT rectangle



Fluence distribution per row



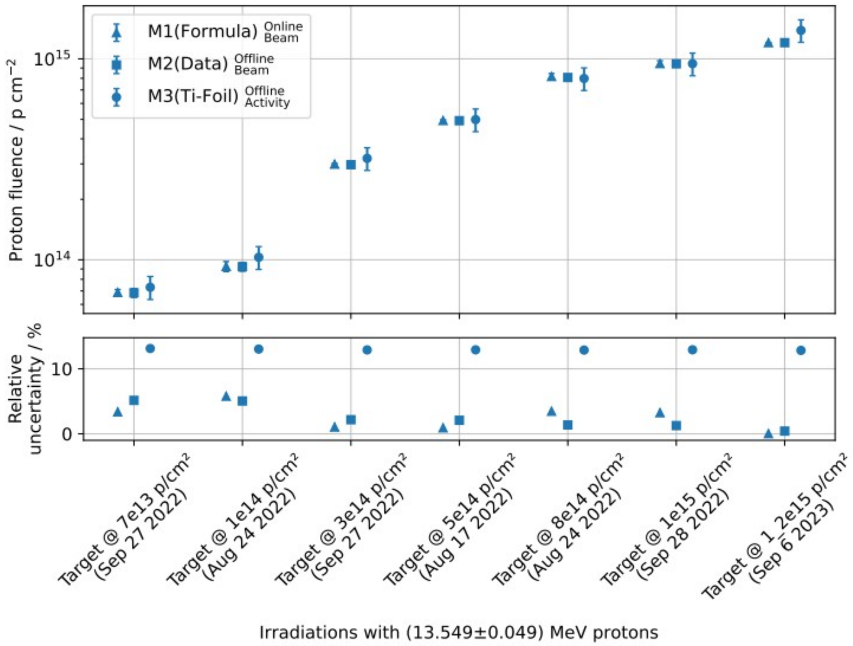
*2D fluence distribution on **DUT** (diff. color scale)*

*2D fluence distribution on **scan area***

DOSIMETRY

--COMPARISON--

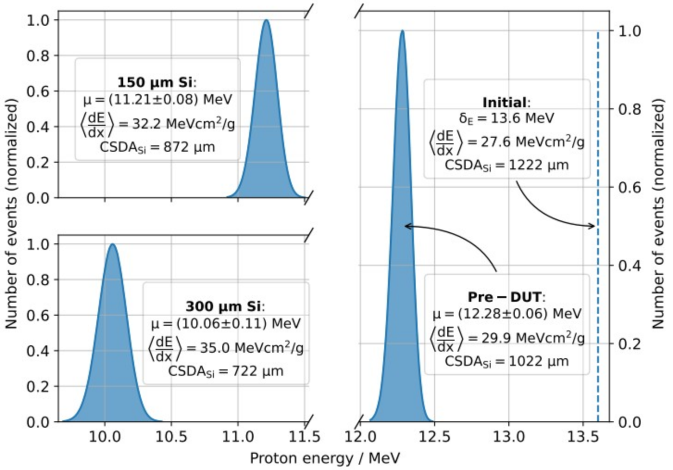
- Irradiation of 7 Ti-foils across 1 order of proton fluence magnitude over 1 year
- Irradiation parameters (e.g. mean beam current, scan speed, row separation) varied to ensure result is independent
- Compare dosimetry using all available methods
  - Results are in good agreement
  - Beam-based methods yield lower, relative uncertainty consistently
  - Beam-based method uncertainties include variation across spatial distribution
- Beam-based dosimetry verified to be in agreement with standard foil method

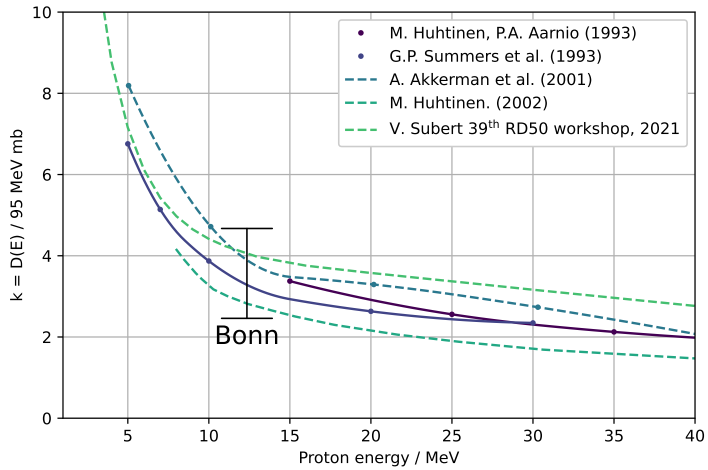


HARDNESS FACTOR

--EXPECTATIONS--

- The Bonn Isochronous Cyclotron provides upt to 14 MeV protons
  - For typical operation, accelerator yields 13.6 MeV protons
  - Energy degrades on transmission to setup → **12.3** Mev on DUT
  - Expectation: $\kappa(p_{12.3\ MeV}) \approx$ **3 – 4**





Adapted from D.-L. Pohl "3D-Silicon and Passive CMOS Sensors for Pixel Detectors in High Radiation Environments", PhD thesis, 2017

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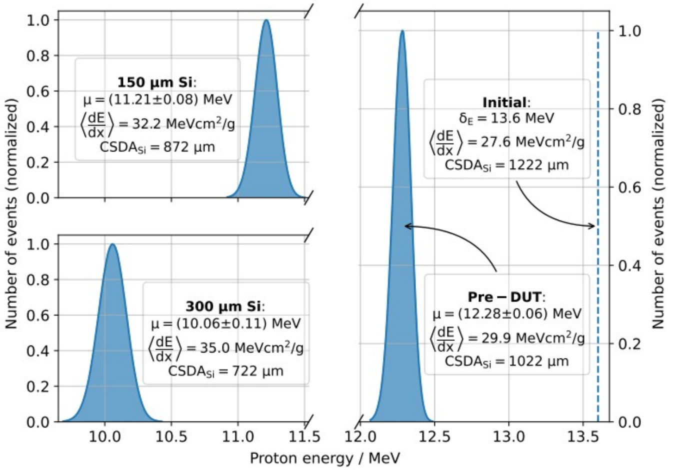
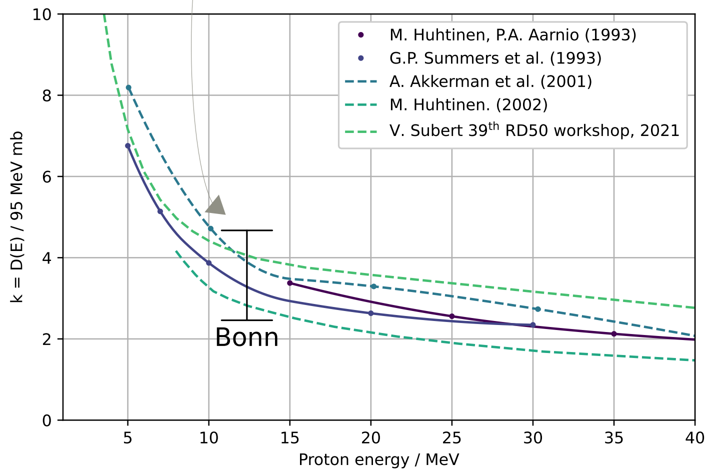
Limits DUT thickness; as thin as possible structures needed for precise measurement!

Hardness factor starts to strongly-depend on energy!





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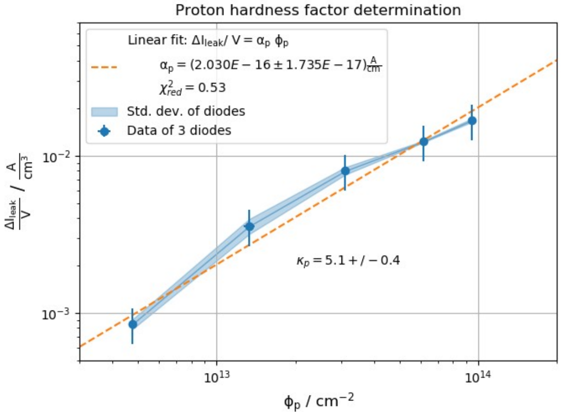
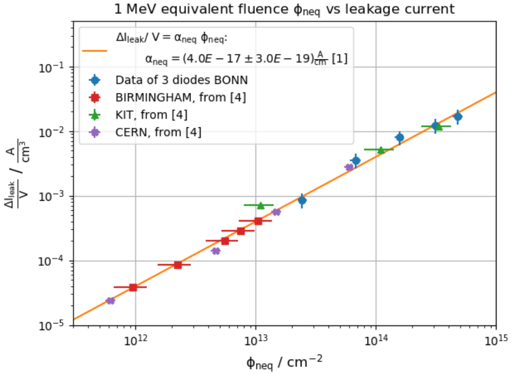
HARDNESS FACTOR
--MEASUREMENT 2019--

[1] F. Ravotti "BPW34 Commercial p-i-n Diodes for High-Level 1 MeV Neutron Equivalent Fluence Monitoring", 2008

[4] P. Allport et al., "Experimental Determination of Proton Hardness Factors at Several Irradiation Facilities", 2019

- First measurement of hardness factor using commercial diodes
  - BPW34F diodes, characterized for fluence monitoring in [1]:
    - → 300 µm Si-thickness, 500 µm packaging
  - Irradiation to 5 different fluences, 3 diodes per fluence
  - Good linear increase of leakage current with fluence
  - Hardness factor of κ = **5.1 ± 0.4** → larger than expected
    - → Material-budget of packaging artificially "pushes" damage
    - → No measurement of full-depletion voltage, assume 100 V
    - → Primary fluence determination still rudimentary
  - When putting in context with other results from [4], good agreement!



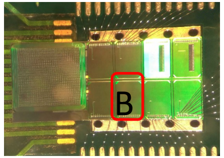


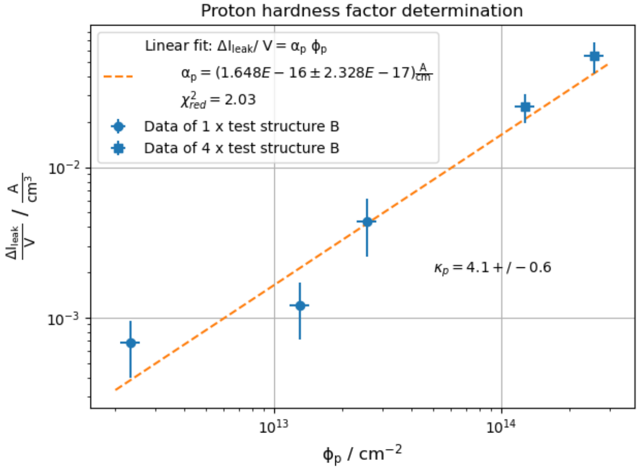
HARDNESS FACTOR

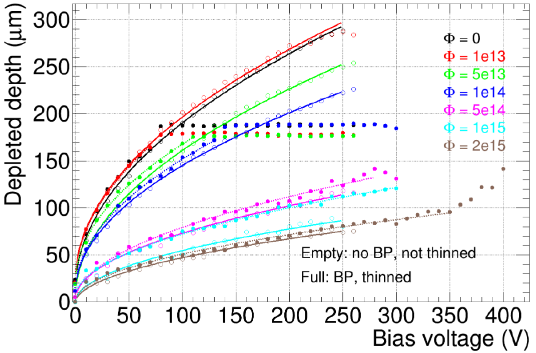
--MEASUREMENT 2020--

[2] I. Mandić, "Charge collection properties of irradiated depleted CMOS pixel test structures", 2018

- Measurement using 200 µm thin LFoundry test structures
  - 8 structures on chip, use „B" for analysis
  - Irradiation to 5 different fluences, 1 (4) structure per fluence
    - Choose fluences covered in [2] with assumption of $\kappa = 4$
  - Good linear increase of leakage current with fluence
  - Hardness factor of κ = **4.1 ± 0.6** → expected range
    - No measurement of full-depletion voltage, instead extract from [2]
    - Primary fluence determination still rudimentary
- Thin structures yield result witin expectations
  - Take κ = **4 ± 1** to account for uncertainties / assumptions





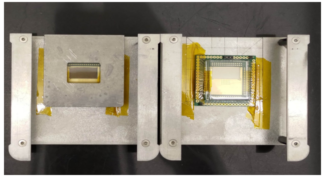


HARDNESS FACTOR
--MEASUREMENT 2023--

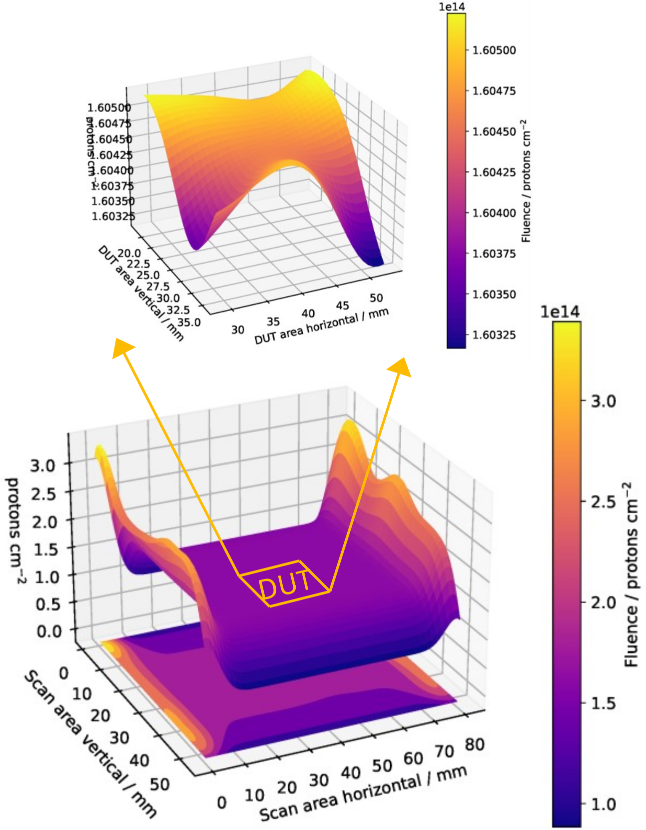
- Another attempt this year in September; what‘s different now?
  - Irradiation setup, procedure and analysis received **major upgrade** between 2021-2022
  - Redesign of irradiation-related diagnostics full-implementation of beam-driven irradiation routine
    - → Optimized for fluence **uniformity and accuracy**
  - Full-characterization of upgrade setup before new attempt at hardness factor measurement
    - → Reminder: we don‘t use „standard“ dosimetry → Need to know what we are doing!
  - Cross-check shows **reliable measurement** of proton fluence with low uncertainty
  - Thin devices as well as infrastructure to fully, electrically characterize available now as of late 2022
  - Ultimately, accelerator downtime of ~ **1 year** due to broken part prolongs new measurement…

HARDNESS FACTOR

--MEASUREMENT 2023--



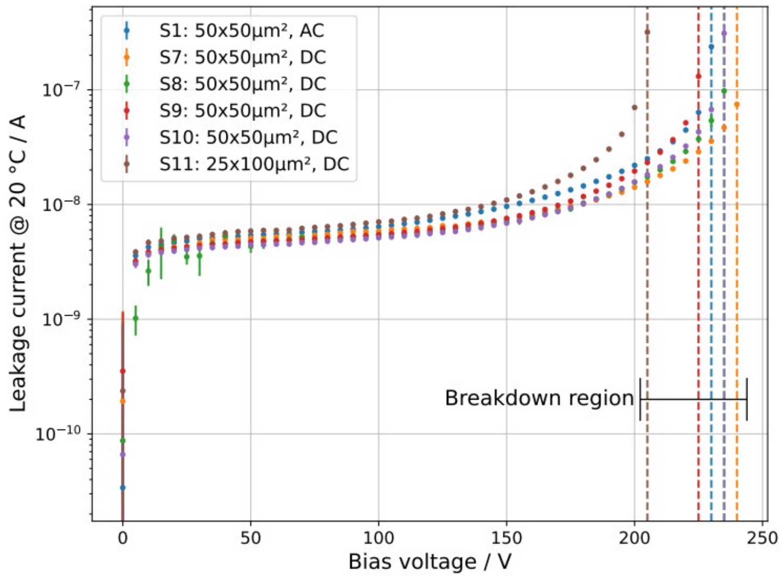
- Use thin, full-size pass. LFoundry sensors
  - 2 x 1 cm² active area, 150 µm thickness
  - Irradiation to 6 different fluences, 1 sensor per fluence
    - Sensors {S1, S7, S8, S9, S10, S11}
    - {5e12, 1e13, 2e13, 4e13, 8e13, 16e13} p / cm²
  - Proton energy : (13.52 ± 0.04) MeV → (12.19 ± 0.04) MeV on DUT
- Perform full electrical characterization pre- and post irradiation to minimize uncertainty
  - Measure leakage current post irrad in temperature-stable environment
  - Extract full-depletion voltage via CV measurement using LCR setup

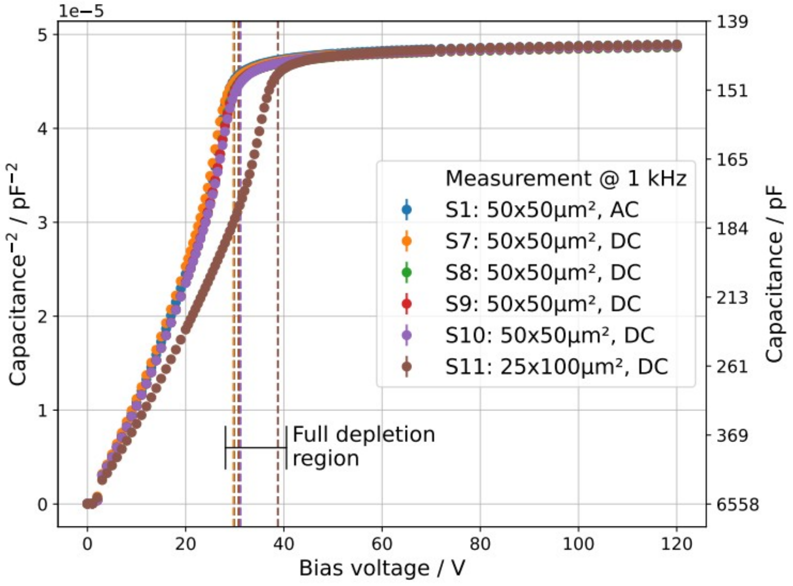


HARDNESS FACTOR

--MEASUREMENT 2023--

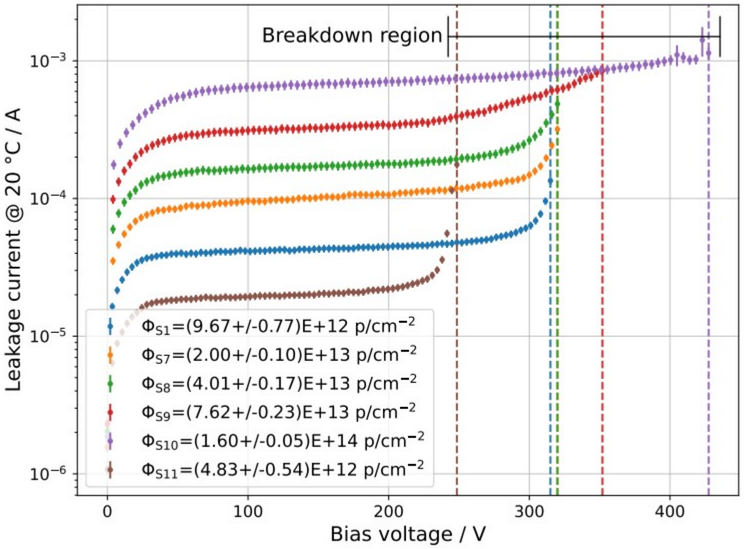
- Pre-irradiation electrical characterization:
  - IV and CV look as expected; slight deviation of CV from parallel plate model but characteristic shape present

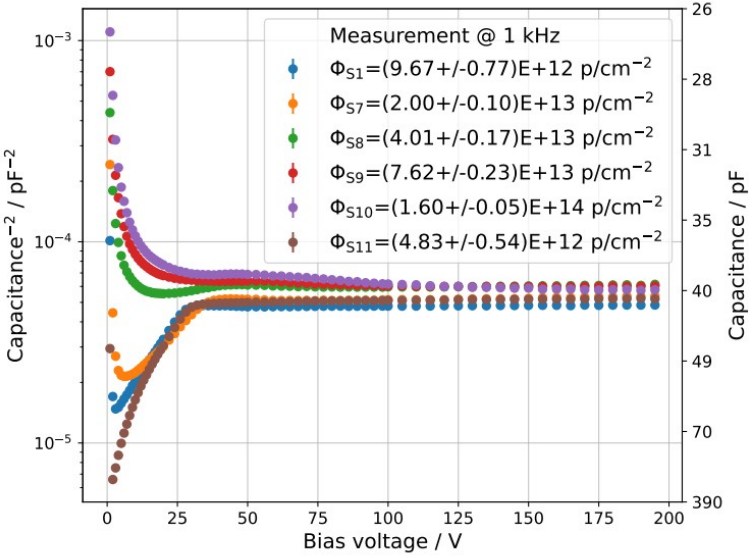




HARDNESS FACTOR
--MEASUREMENT 2023--

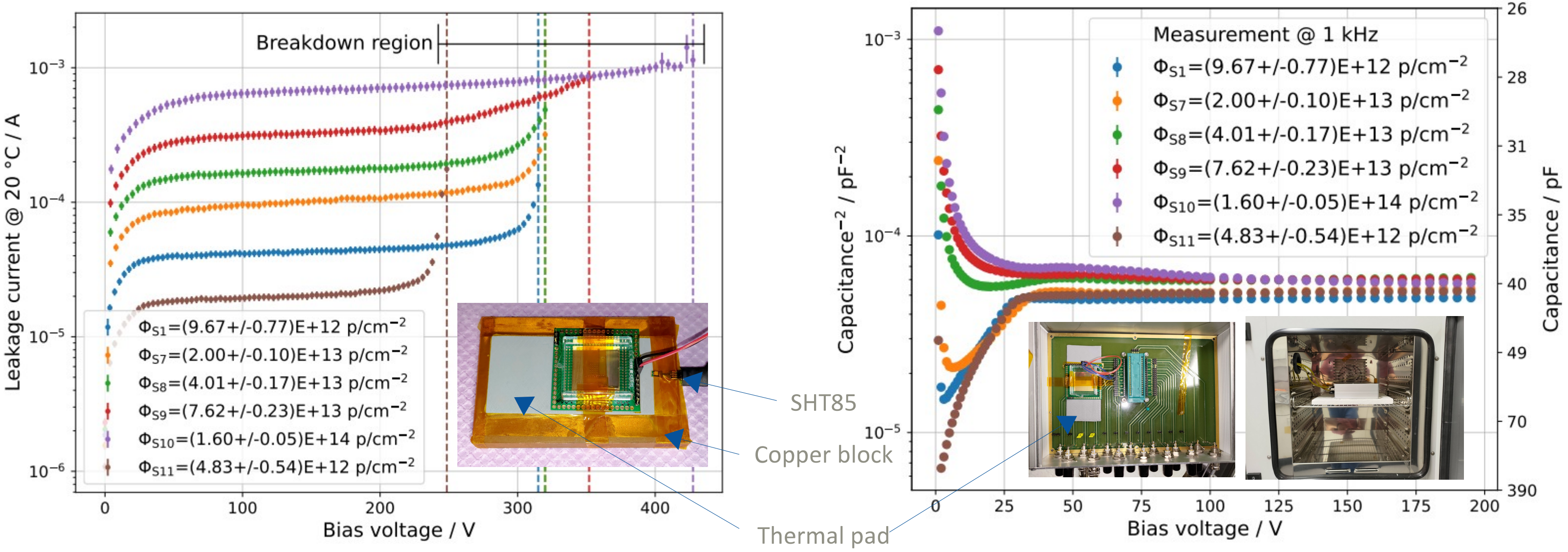
- Post-irradiation electrical characterization:
  - → IV as expected; leakage current increses with fluence, saturation after full depletion
  - → CV measured at RD50-recommended frequency of 1 kHz after irrad.; high fluence CV not characteristic





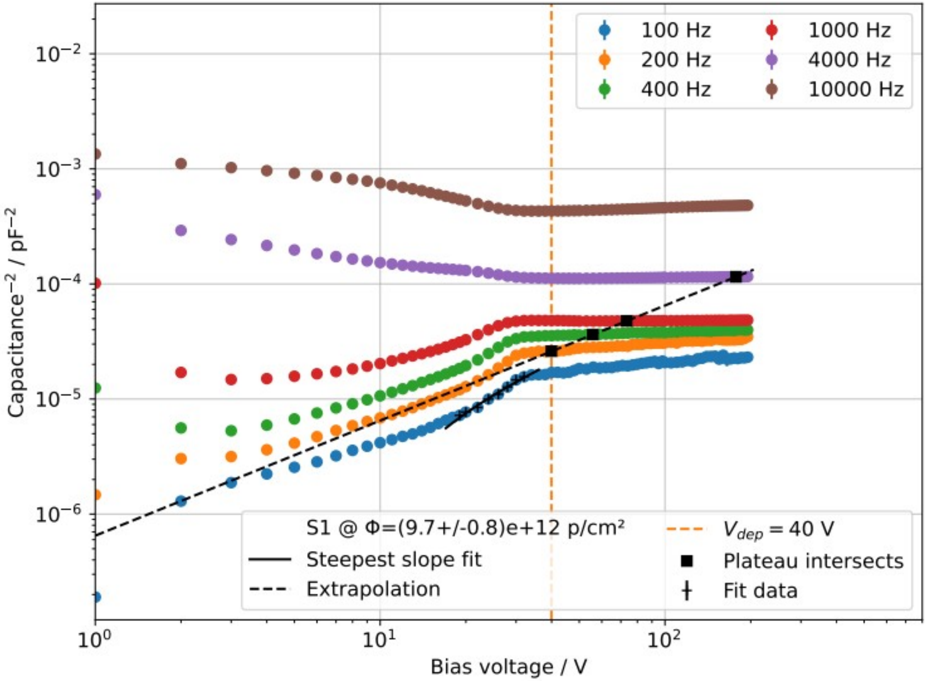
HARDNESS FACTOR
--MEASUREMENT 2023--

- Post-irradiation electrical characterization:
  - → IV as expected; leakage current increses with fluence, saturation after full depletion
  - → CV measured at frequency of 1 kHz after irradiation; high-fluence CV data not characteristic anymore



HARDNESS FACTOR
--MEASUREMENT 2023--

- Post-irradiation electrical characterization:
  - CV is expected to be highly-dependent on frequency
  - Typical aproach of 2-line-fit to extract full-depletion does not work reliably anymore
  - Alternative approach from RD50 contribution to extract “best possible result“[5]
    - → Measure multiple frequencies
    - → Find steepest slope
    - → Extrapolate through origin
    - → Intersection with plateau is best estimate
  - Measure for all sensors, measure at **V_{dep} + 50 V**

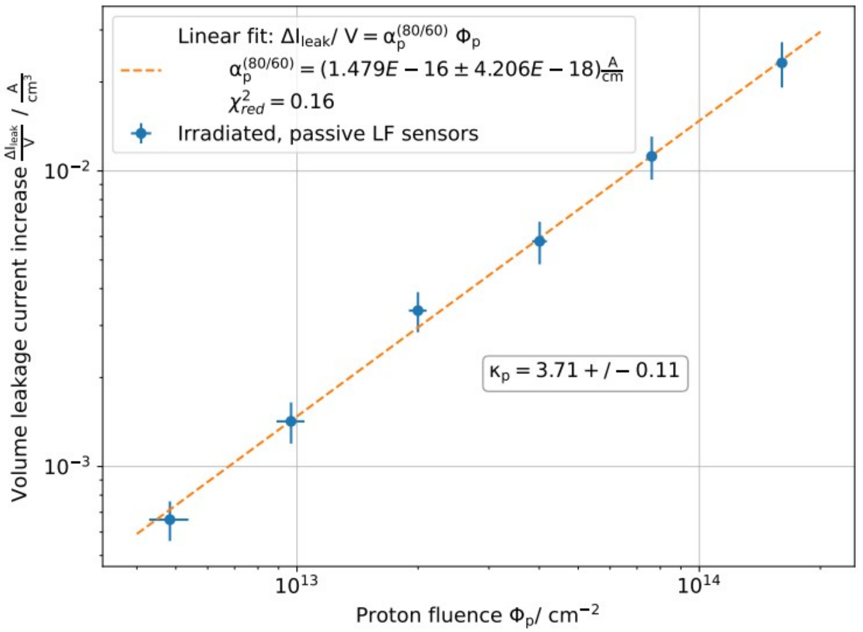


[5] S. Mägdefessel, “Understanding the frequency dependence of CV measurements of irradiated silicon sensors”, 41st RD workshop, Nov. 2022

HARDNESS FACTOR

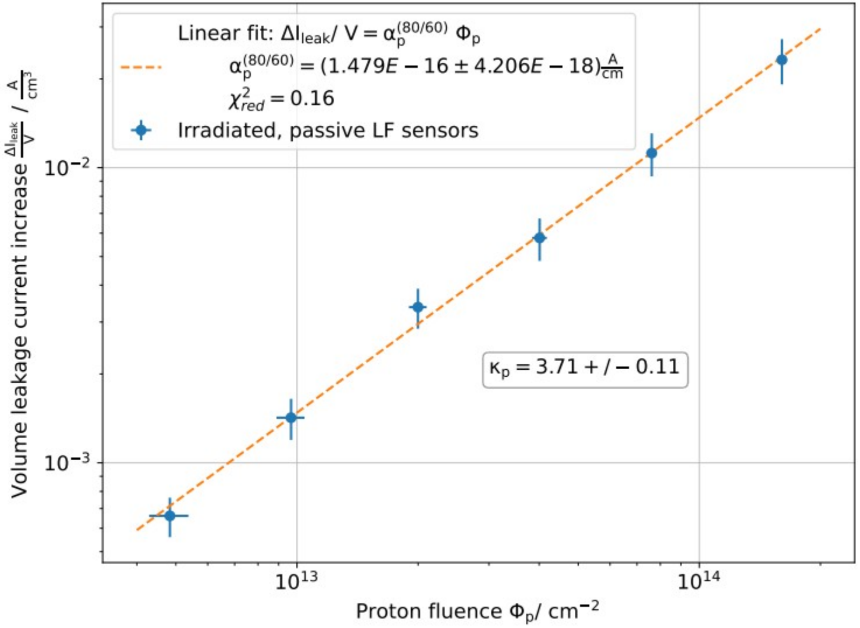
--MEASUREMENT 2023--

- Hardness factor determination:
  - Very good linear increase of leakage with fluence
  - Red. Chi² suggest data fits model better than assumed uncertainties
  - Hardness factor of κ_p = **3.71 ± 0.11**
  - In good agreement with previous value of 4 ± 1 and expectations
  - Low, relative uncertaity of approx. 3%
  - Irradiations with (12.19 ± 0.04) MeV protons
    - Approx. 1 MeV energy loss in 150 µm Si
    - Interp. Energy → k_p(11.7 MeV) = **3.71 ± 0.11**



HARDNESS FACTOR
--MEASUREMENT 2023--

- Implications:
  - Measurement performed using 150 µm Si
  - For thicker DUTs e.g. 300 µm expected increase from sims. of κ_p approx. 10% → measurement uncertainty of 3% significantly lower
  - Hardness becomes feature of DUT thickness
    - For „thin“ (<= 150 µm, no significant passivation in front of activate layer) DUTs hardness factor κ_p = **3.71 ± 0.11**
    - For „thick“ (<= 300 µm) DUTs assume 10% increase until measured → κ_p = **4.08 ± 0.41**
    - For DUTs > 300 µm significant depth-dependance of damage… difficult to estimate



CONCLUSION

- Irradiation site in Bonn received major upgrades to the setup and related software within 2022
- Dosimetry verified to yield results in agreement with typically-used foil activation method
  - Beam-based methods show significantly **lower uncertainty**
  - Beam-based methods produce fluence distributions with **spatial resolution**
- Previous attempts of measuring hardness factor pointed towards the correct result
  - Full characterization of setup was needed to ensure we now „what we are doing“
- New results show hardness factor of κ = **3.71 ± 0.11** for „thin“ devices
  - In agreement with expectations and previous value of $\kappa = 4 \pm 1$
  - Due to low proton energies and high measurement precision → hardness factor function of DUT thickness
    - → DUT thickness <= 300 µm for precise 1 MeV n.e.q fluence statement

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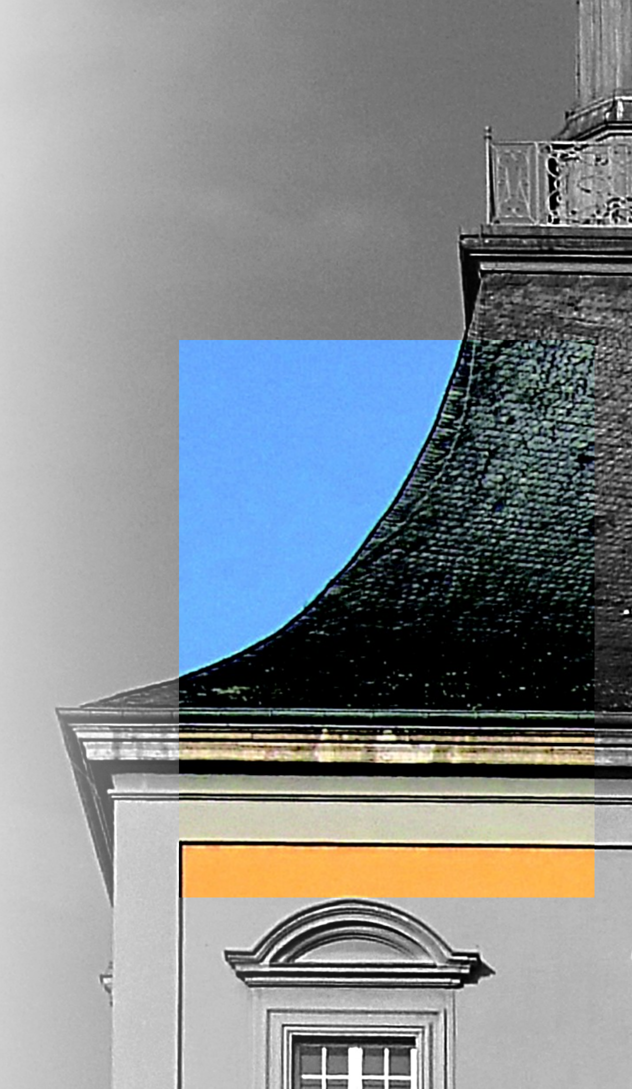
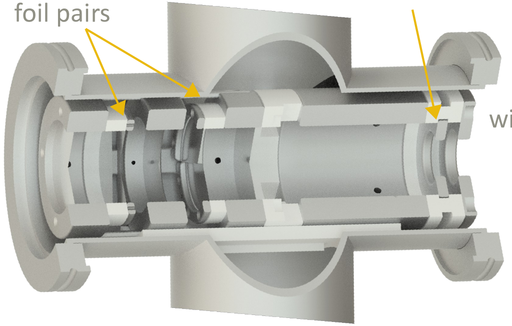
Thank you



BACKUP

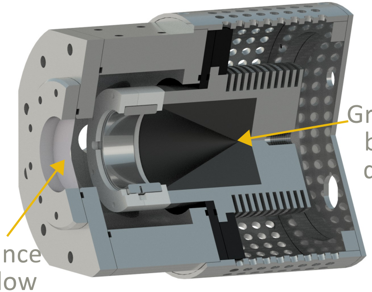
BEAM DIAGNOSTICS

--OVERVIEW--



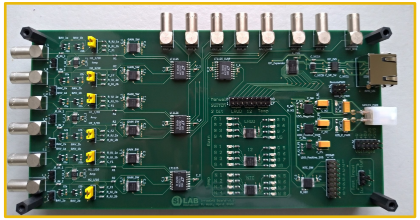
Beam monitor

- Based on secondary electron emission (SEE)
- Two pairs of 5 µm Al-foils, horizontally & vertically segmented
- Beam penetration causes signal Ifoil ~ Ibeam
  - Calibration allows online beam meas.
- Isolated aperture allows direct beam cut-off measurements



Faraday cup (FC)

- Beam current I_{beam} measurement by dumping into graphite cone
- Directly obtain current $I_{FC} = I_{beam}$ with low uncertainty
  - $\Delta I_{FC}/I_{FC} \leq 1\%$

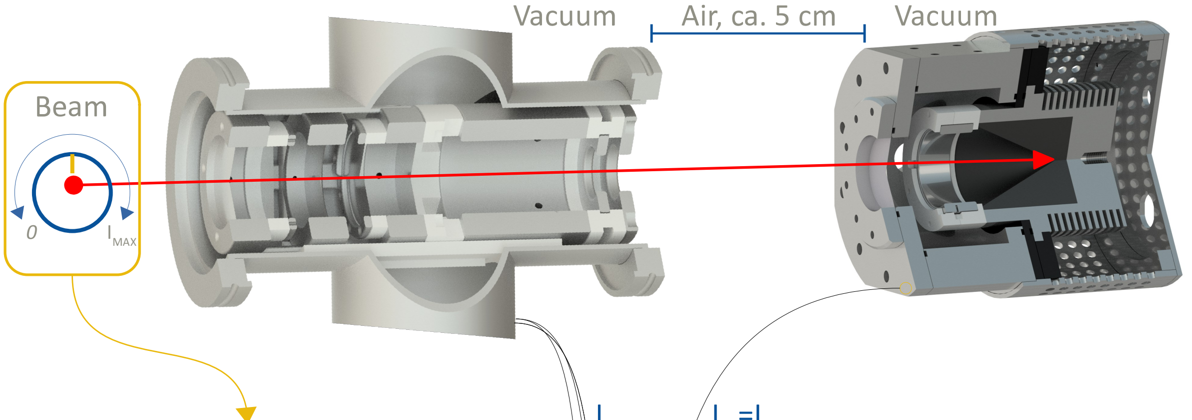


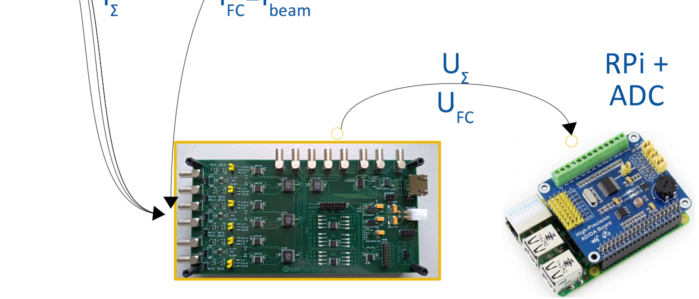
R/O board

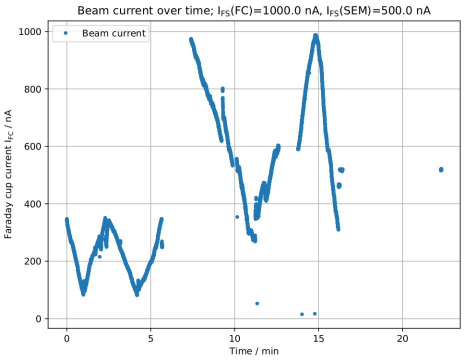
- Analog R/O of beam monitor & FC
- Linear mapping of input current I
  - $0 - I_{FS} \rightarrow 0 - 5V$
- Multiple, switchable scales I_{FS}
- Used to digitize signals

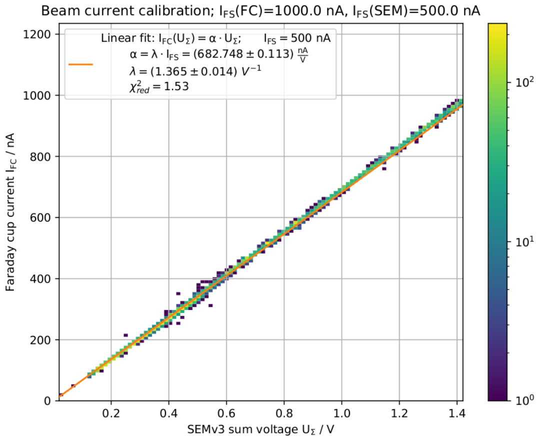
BEAM DIAGNOSTICS

--CALIBRATION--







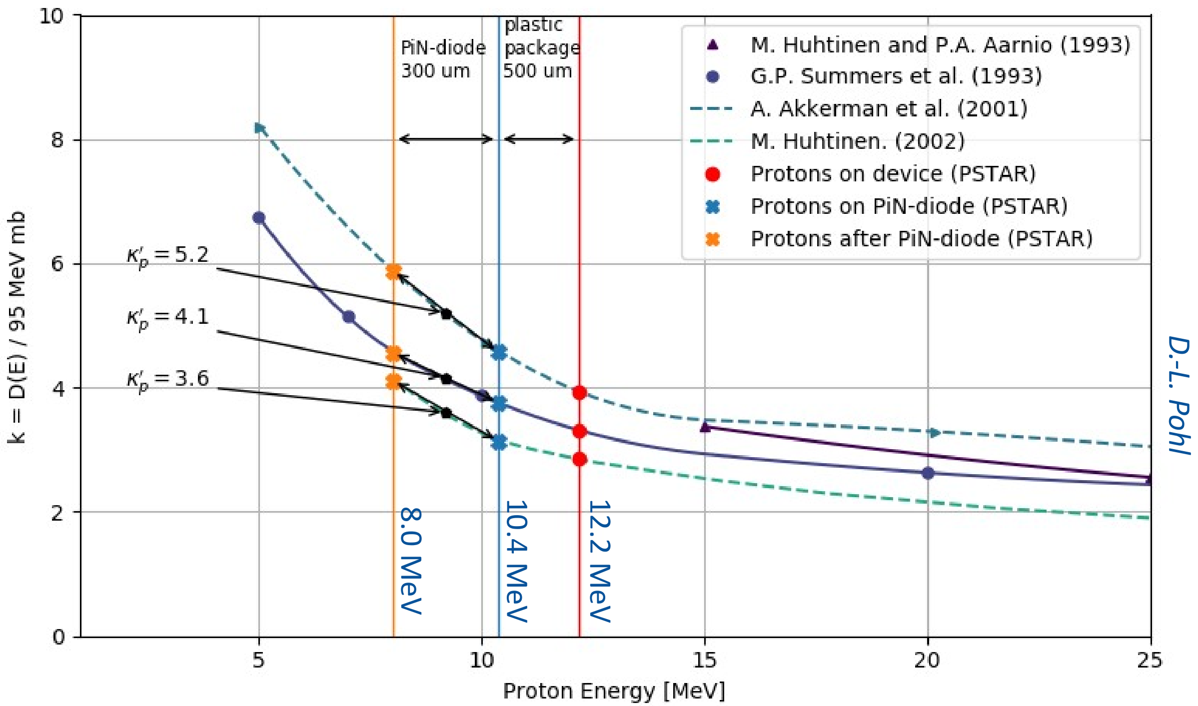


- Calibration $I_{Beam} = \alpha * U_\Sigma$ with $\alpha = \lambda * I_{FS}$
  - $\mathbf{I_{beam}\,(I_{FS}, U_\Sigma) = \lambda \cdot I_{FS} \cdot U_\Sigma}$
- Uncertainty consideration:
  - $\frac{\Delta\lambda}{\lambda} = \frac{\Delta I_{FS}}{I_{FS}} = \frac{\Delta U_\Sigma}{U_\Sigma} = 1\% \Rightarrow \frac{\Delta I_{beam}}{I_{beam}} = \sqrt{3}\%$
- Allows online beam current measurement during irradiation

HARDNESS FACTOR

--MEASUREMENT 2019--

- Calculation of proton energy on device allows to estimate κp for particular BPW34F diodes:
- “F“ = Filter = 500 um plastic
- 300 um Si
- Energy loss in plastic packaging not negligible at these energies
- κp= 3.1 – 4.6 on entry, κp= 4.1 – 5.9 on exit of Si => Approx. 20% difference, non-negligible depth dependance of damage
- Expect an effective κ'p = 3.6-5.2;
  - lin. interpolation as approximation



HARDNESS FACTOR
--MEASUREMENT 2023--

- Post-irradiation electrical characterization:
  - Resulting full-depletion voltages after irradiation:
    - → {S11: (33±3) V, S1: (39±4) V, S7: (74±7) V, S8: (71±7) V, S9*: (94±10) V, S10: (94±10) V}
  - Evaluate IV curves at **full-depletion + 50 V** to ensure full depletion
- A word on the uncertainties considered in final analysis:
  - Temperature during IV curve measurements: ± 1 °C
  - Max. depletion volume on sensors: %10
  - Effective energy for temperature scaling E_{eff}=(1.21±0.014)eV
  - Depletion voltage error from above
  - Error on 1 MeV neutron reference current related damage rate 1%

*Method yielded 180±20 for S9 which seems off; therefore use result of S10

HARDNESS FACTOR
--MEASUREMENT 2023--

- Simulation of ion energies on DUT for given initial energy