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A PROTON IRRADIATION SITE FOR SILICON DETECTORS AT BONN UNIVERSITY

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DPG Frühjahrstagung 2022, Heidelberg, T13: Semiconductor Detectors

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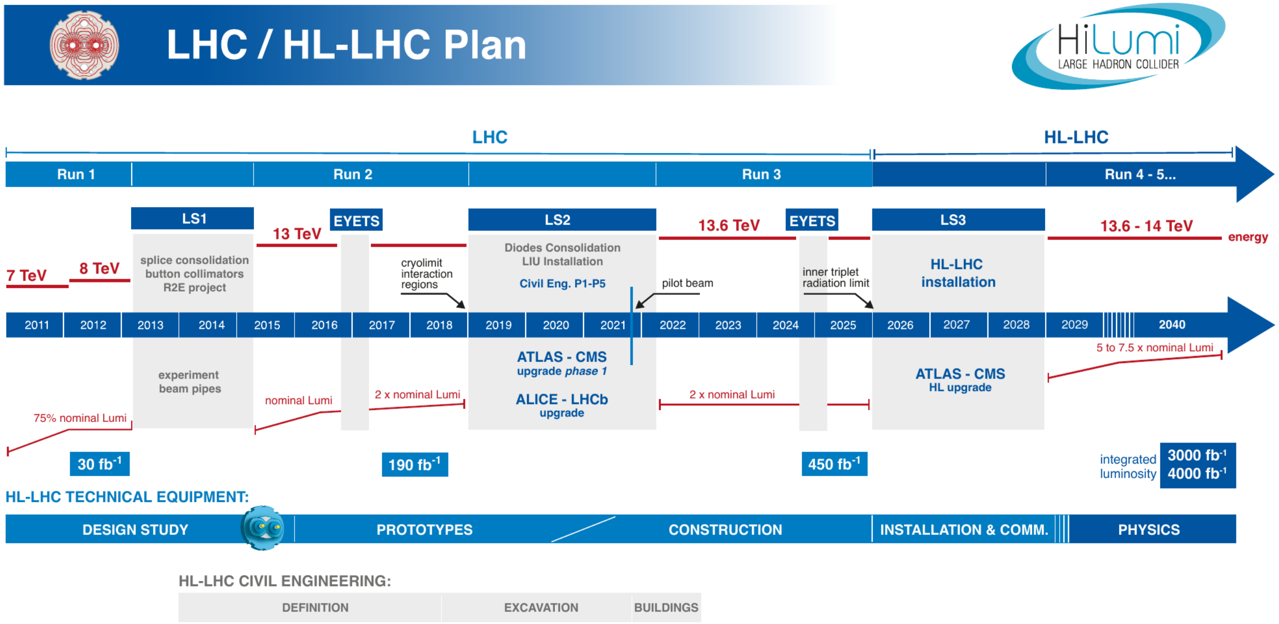
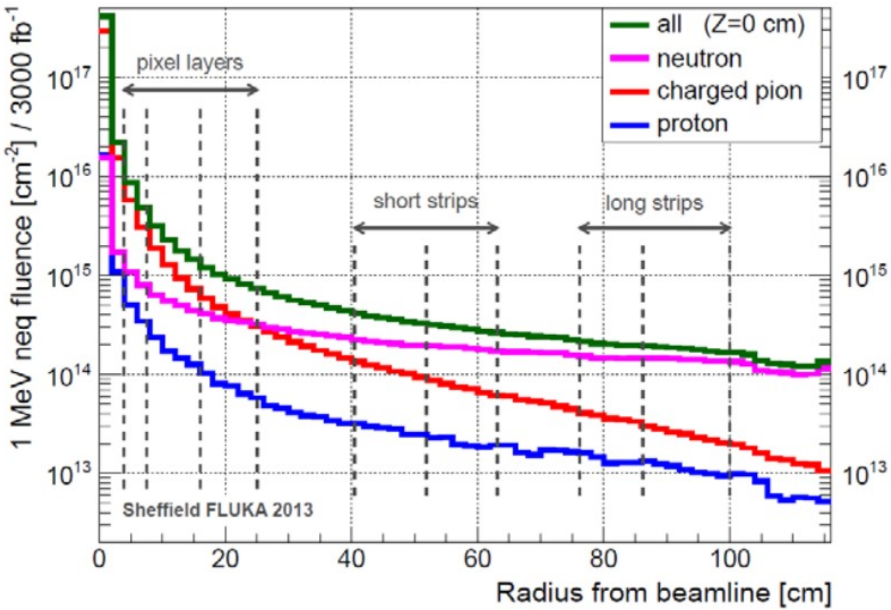
MOTIVATION



https://hilumilhc.web.cern.ch/article/ls3-schedule-change

MOTIVATION

- Estimated radiation levels for ITK after 3000 fb^{-1} scaled to 1-MeV neutron equivalent fluence n_{eq}:
  - Pixels @ 4 cm ≈ 1.5 x 10^{16} n_{eq}/cm^2
- Si-sensors suffer from **radiation damage**:
  - + Leakage current (+ Noise, + Power)
  - - Sensitive volume (- Signal)
  - + Trapping (- Signal)
- Radiation damage studies needed to probe requirements
  - NIEL scaling allows usage of accelerators
  - End-of-Life damage can be induced within O(hours)

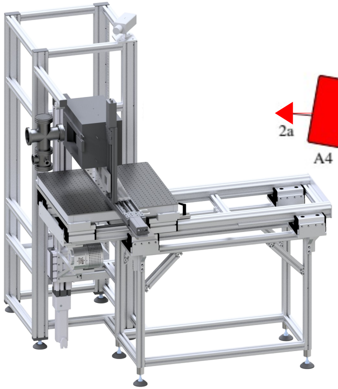


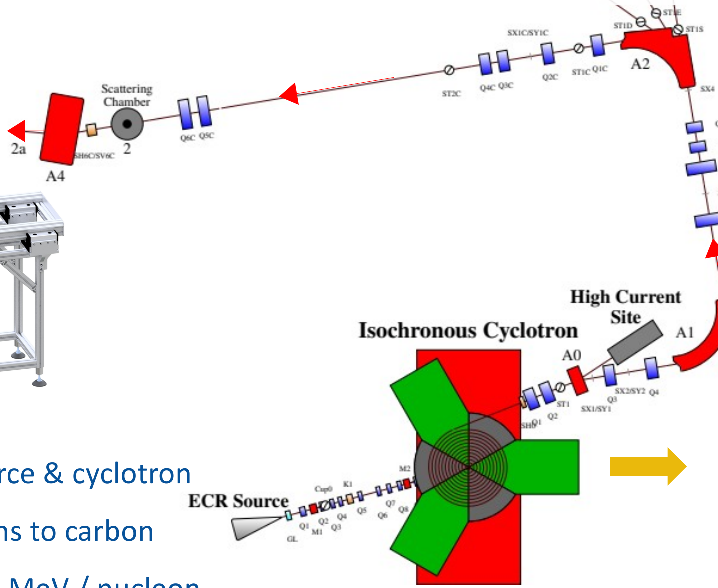
P. S. Miyagawa and I. Dawson, "Radiation background studies for the phase ii inner tracker upgrade," CERN, Tech. Rep. ATL-UPGRADE-PUB-2014-003, Sep. 2014.

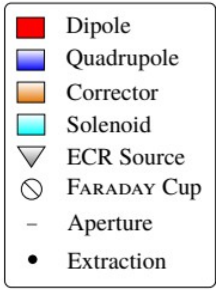
OVERVIEW

- Setup
- Diagnostics
- Irradiation
- Proton NIEL
- Conclusion

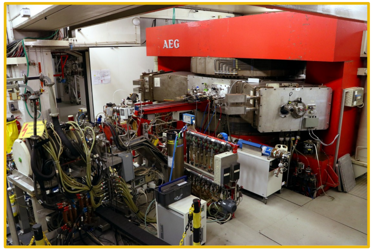
- Proton beam (typical)
  - 14 MeV, 1µA, $Ø_{FWHM}$< 1 cm , 1e13 p/(s·cm²)







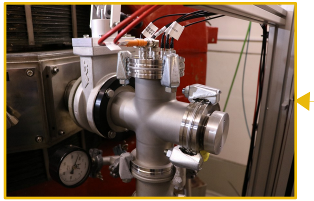
- ECR source & cyclotron
  - Protons to carbon
  - 7 – 14 MeV / nucleon



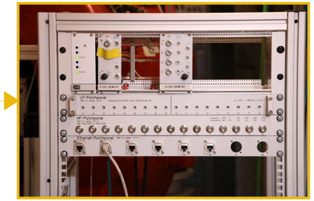
IRRADIATION SITE

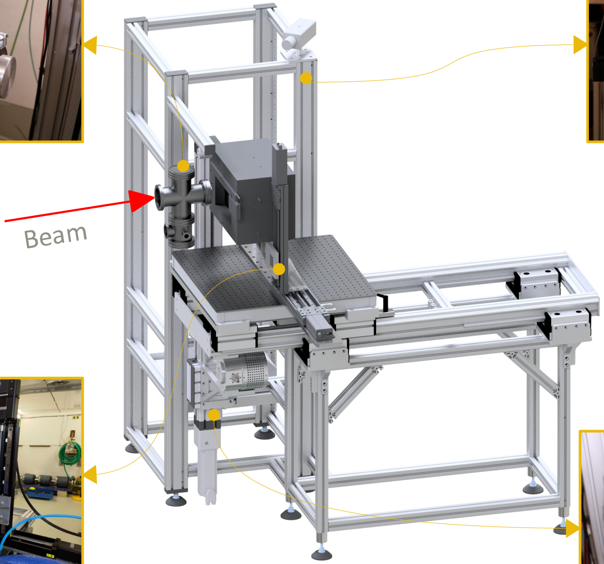
--SETUP--

- Calibrated, online beam monitor
  - Beam parameter meas. at extraction
  - Crucial for **fluence measurement**

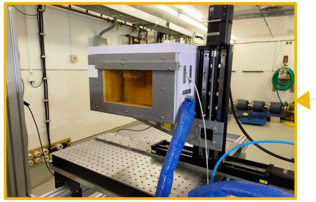


- 19“ rack w/ interfaces to setup and R/O
  - Interface DUT, lab devices provide custom signals
  - Connection to DAQ

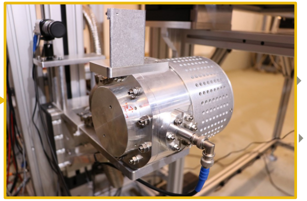




- Insulated DUT box on 2D motorstage
  - Houses DUT @ < -20 °C
  - 19x11 cm² max. DUT size
  - Interface for powering, R/O during irradiation

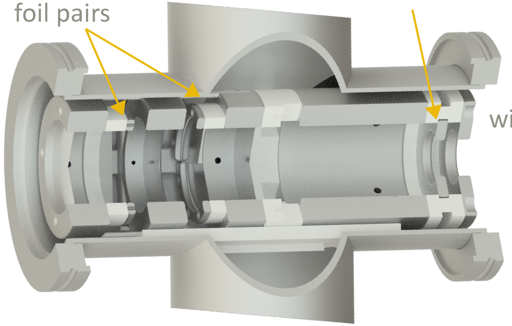


- Faraday cup (FC) with screen on motorstage
  - Destructive beam current measurem. at DUT position
  - Visual inspection of beam
  - Calibrating beam monitor



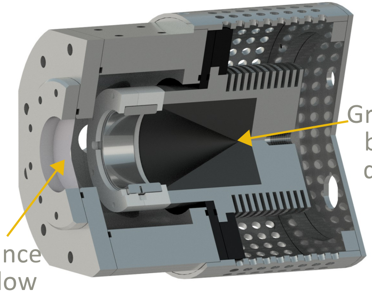
BEAM DIAGNOSTICS

--OVERVIEW--



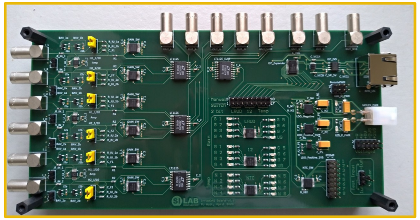
Beam monitor

- Based on secondary electron emission (SEE)
- Two pairs of 5 µm Al-foils, horizontally & vertically segmented
- Beam penetration causes signal $I_{foil} \sim I_{beam}$
  - 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
  - $\Delta I_{FC}/I_{FC} \leq 1\%$

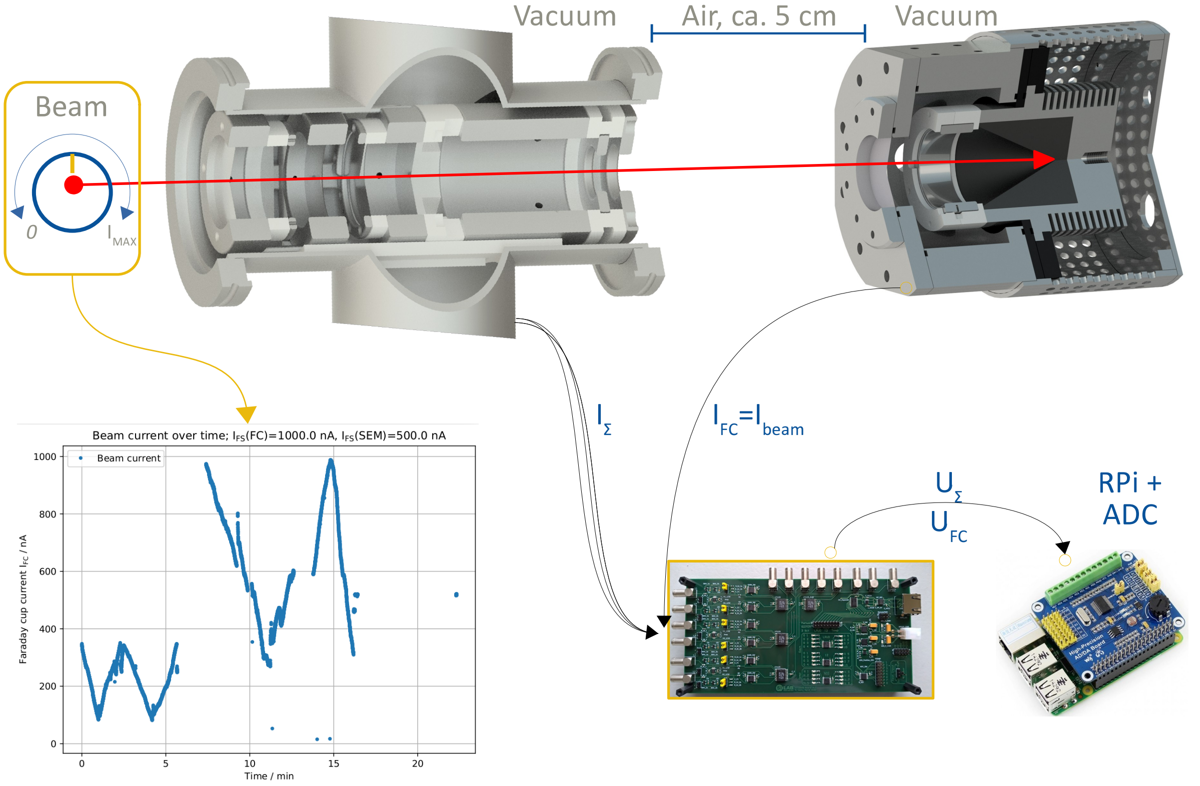


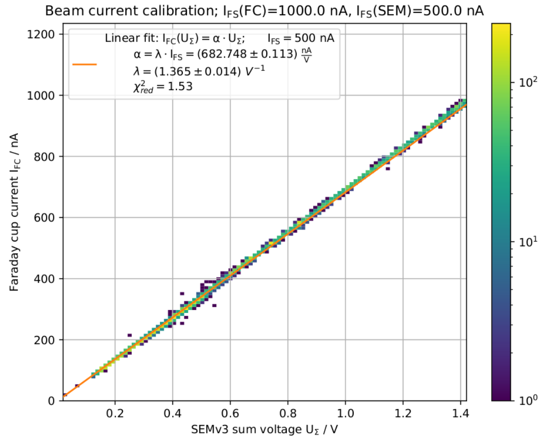
R/O board

- 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--

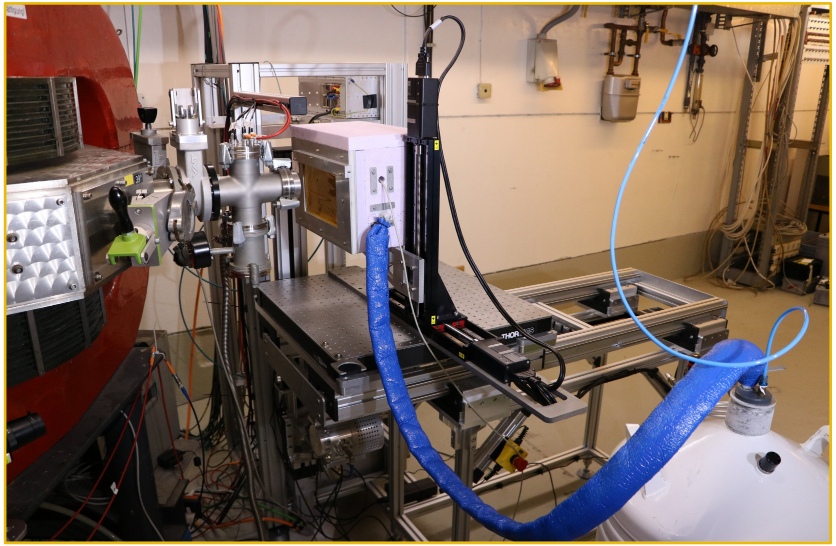




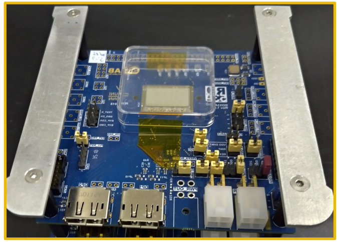
- Calibration $I_{Beam} = \alpha * U_\Sigma$ with $\alpha = \lambda * I_{FS}$
  - $$\mathbf{I_{beam}\,(I_{FS}, U_\Sigma) = \lambda \cdot I_{FS} \cdot U_\Sigma}$$
- Uncertainty consideration:
  - $$\frac{\Delta\lambda}{\lambda} = \frac{\Delta I_{FS}}{I_{FS}} = \frac{\Delta U_\Sigma}{U_\Sigma} = 1\% \Rightarrow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

IRRADIATION

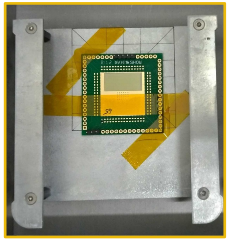
--SITE & TYPICAL DUTs--



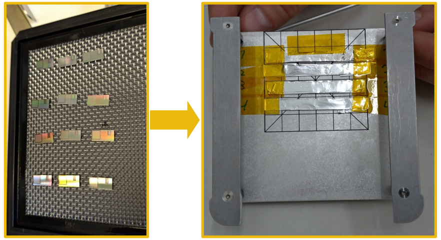
Setup in irradiation position. Liquid nitrogen dewar used to cool down nitrogen gas for cool, dry atmosphere inside box during iradiation



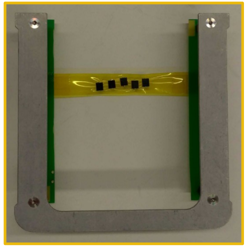
Assembly on SCC



Sensor on surfboad



Bare sensors, wrapped in Al-foil



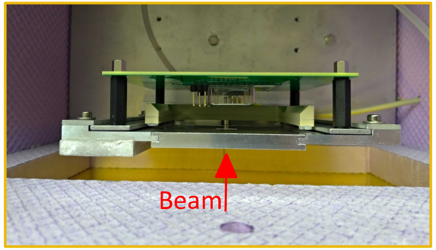
PiN-diodes on Kapton tape

Variety of different DUTs, all mounted on custom-made holder for installation inside box (behind shield if needed)

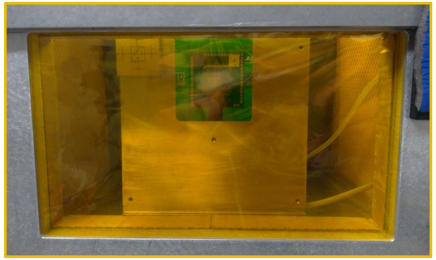
IRRADIATION

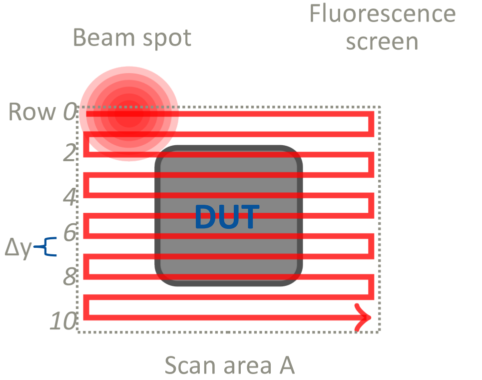
--PROCEDURE--

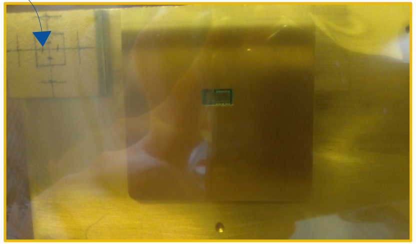
- DUTs mounted behind custom shielding @ < -20 °C, temp monitoring via NTCs in box
- Beam-based alignment using fluorescence screens, cameras and beam monitor
- Homogeneous irradiation by overscanning DUT area
- Row-wise scanning with row separation Δy and velocity v
- Proton fluence per completed scan (**v = const.** on DUT area) → $\phi_p = \frac{I_{beam}}{q_e \cdot v \cdot \Delta y}$
- Uncertainty dominated by I_{beam} → $\frac{\Delta \phi_p}{\phi_p} = \frac{\Delta I_{beam}}{I_{beam}} = \sqrt{3}\%$
- Typcial values: I_{beam} = 1µA, v = 70 mm/s, Δy = 1 mm
  - ϕ_p ≈ 1e13 p/cm^2 per scan → 1e16 n_{eq}/cm² in ~ 2h



Top view of DUT mounted behind shield


Front view of DUT mounted, w/o custom shield



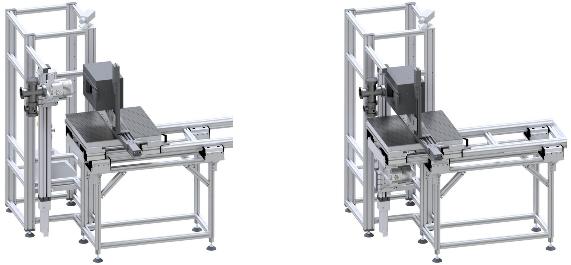

Front view of DUT mounted, with custom shield. Only DUT cross section sees beam

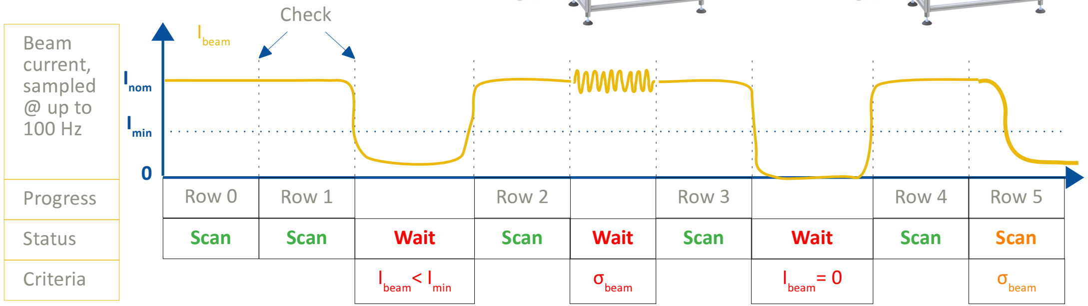
IRRADIATION

--IMPROVING UNCERTAINTY/HOMOGENEITY--

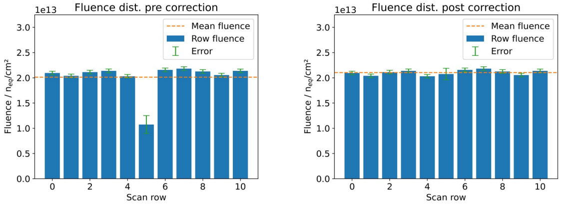
- Pre-irradiation:
  - On-the-fly calibration before / after irradiation to maximize calibration precision
- Irradiation:
  - **Beam-driven** scan procedure; beam parameters checked for predefined requirements each row
  - Allows pausing irradiation for in-between ana-lysis; IV-curves, threshold scan, power up, ...
  - Storage of all irradiation-related data for on and offline analysis
- Post-irradiation:
  - Correction of fluence distribution by scanning individual rows → Especially useful for low-fluence scans

Setup moving from calibration to irradiation position





One scan irradiation: Beam failure scanning row 5, corrected after scan



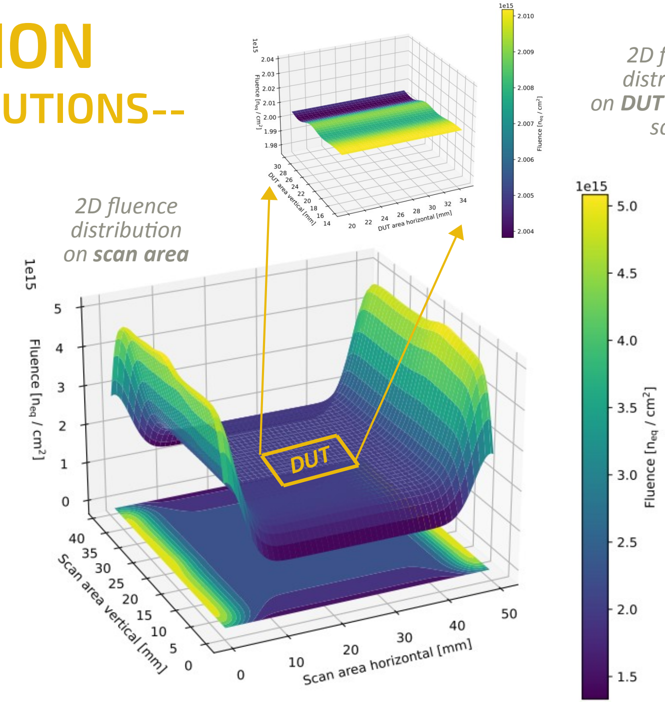
IRRADIATION

--FLUENCE DISTRIBUTIONS--

Online fluence monitor of control software

2D fluence distribution on scan area

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

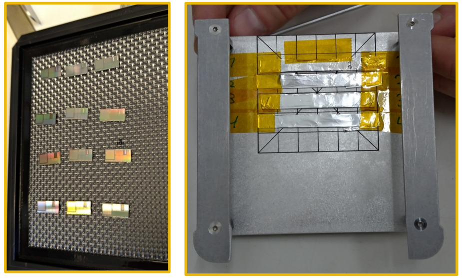


- Online, 1D fluence monitoring of control software
  - Fluence contribution of each row to overall fluence
  - Generated by $\phi_\mathrm{P} = \frac{\mathrm{I_{beam}}}{\mathrm{q_e} \cdot \mathrm{v} \cdot \Delta \mathrm{y}}$ for each row, turning points not considered

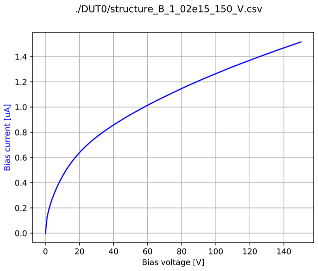
- Offline generated, 2D fluence distribution from raw irrad. data
  - Reconstruction of fluence distribution over entire scan area, considering turning points → extract 2D fluence dist. on DUT
  - On- and offline fluence yield same result → nice cross-check

RADIATION DAMAGE

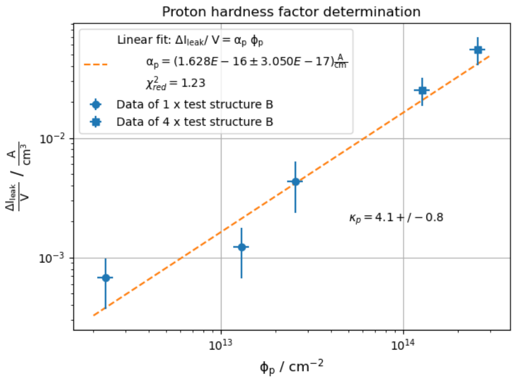
--LATEST MEASUREMENTS--



Test structures in gel pad and wrapped in 10 µm Al-foil on carrier for irradiation



IV-curve for TS B after 1e15 n_{eq}/cm^2



- Jun-Aug 2020: irradiation of 200 µm LFoundry test structures (TS)
  - {1 x 1e13, 1 x 5e13, 1 x 1e14, 4 x 5e14, 4 x 1e15} n_{eq}/cm^2
- Std. annealing for 80 min @ 60 °C, IV meas. in fridge
- Full depletion voltage for leakage measurement taken from †

- Fit of $\Delta I_{leak} / V_{dep} = \alpha_p \cdot \phi_p$

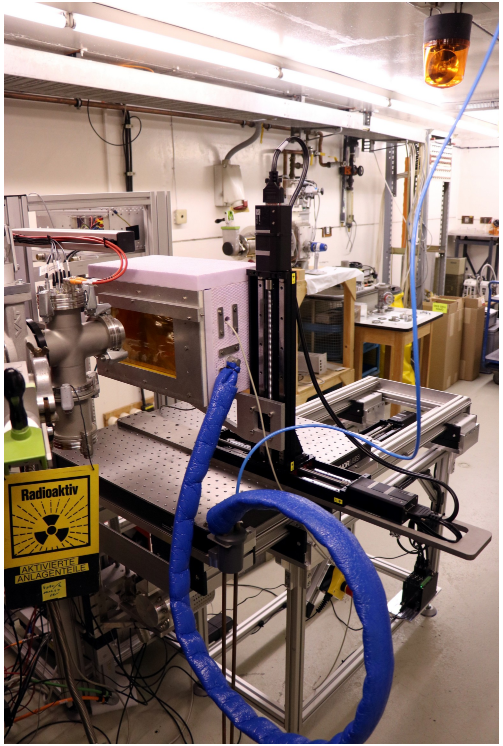
$$\alpha_{eq} = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A\,cm^{-1}}$$

  → $\kappa = \alpha_p / \alpha_{neq} = 4.1 \pm 0.8$
- In agreement with expectations but large uncertainty
- As of mid 2021: dedicated CV-measurement setup implemented in Bonn
- New irradiations to take place soon reduce uncertainty

† Charge collection properties of irradiated depleted CMOS pixel test structures, I. Mandić

CONCLUSION & OUTLOOK

- The proton irradiation site in Bonn allows for optimized proton fluence homogeneity & uncertainty irradiations
- Custom beam monitoring enables beam-driven irradiation procedure with $\frac{\Delta\phi_\mathrm{p}}{\phi_\mathrm{p}} \leq 2\%$
- Irradiation datasets allow for extensive analysis e.g fluence distributions
- Latest irradiations of 200 µm thin LF structures yield $\kappa_p \approx 4$ enabling irradiation of 1e16 n_{eq}/cm^2 within 2 h, but κ_p main source of uncertainty ($\Delta\kappa_p/\kappa_p \approx 20\%$)
- Outlook:
  - Thorough elec. characterization before/after irradiation of thin devices for precise hardness factor meas.
  - Currently Uni Bonn is working on giving access to external groups
  - New developments aiming for providing neutron beam for irradiation based on current setup



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Thank you

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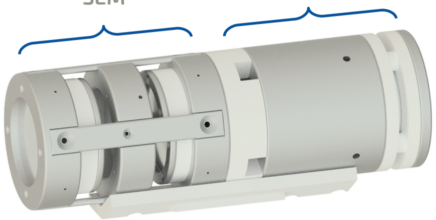
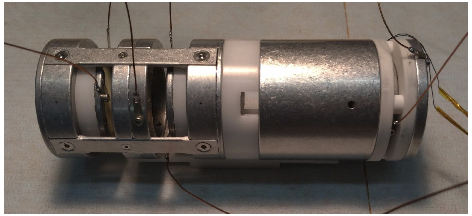
BACKUP

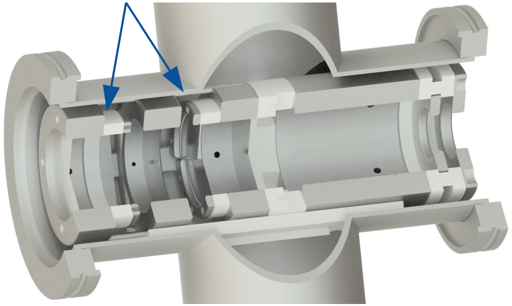
HARDWARE

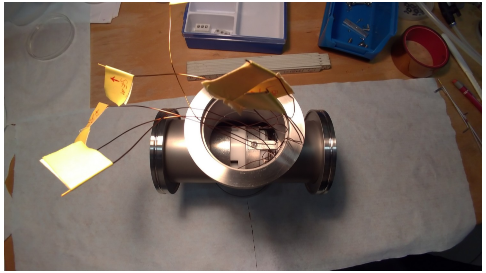
-Beam Monitor-

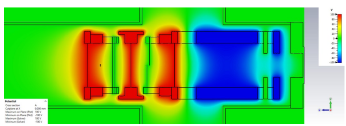
- Online beam parameter and cut-off monitoring
- Secondary electron monitor:
  - 2 C-coated, Al-foil pairs, 3 HV (+100V) foils
- Beam-loss monitor (BLM) / internal cup:
  - Isolated Al-apertue, HV (-100V) suppressor cylinder / aperture, monitoring NTC
- Fully CST-simulated design:
  - Electric field distribution
  - Secondary electron emission and capture
  - SE capture > 99% @ +- 100V

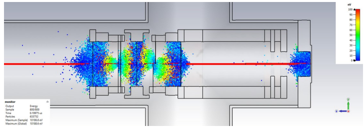










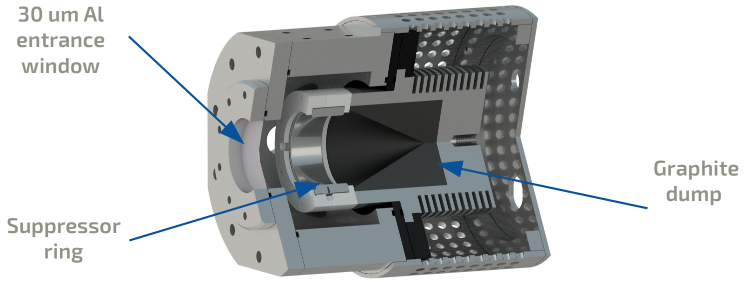


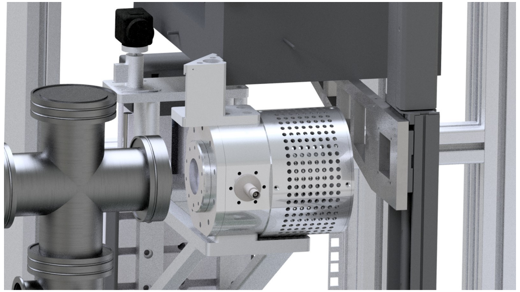
CAD render of beam monitor by Dennis Sauerland, 2021

Installation of beam monitor in cross-piece

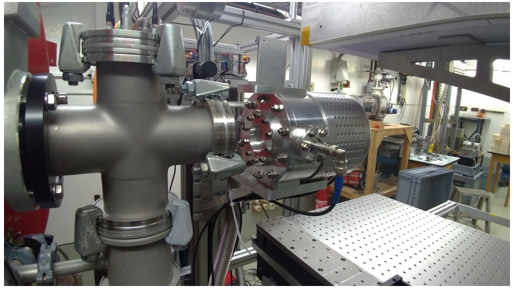
HARDWARE
-Faraday Cup with Camera / Screen-

- Absolute beam current measurement after extraction, on-the-fly calibration / adjustment
- Mounted on 700 mm vertical motorstage
- Camera / screen for beam adjustment and profile measurement
- 30 mm entrance window, < 1e-6 mbar, monitoring NTC, suppressor ring (-100V)
- Fully CST-simulated design:
  - Electric field distribution
  - Secondary electron emission and capture
  - SE capture > 99% @ -100V



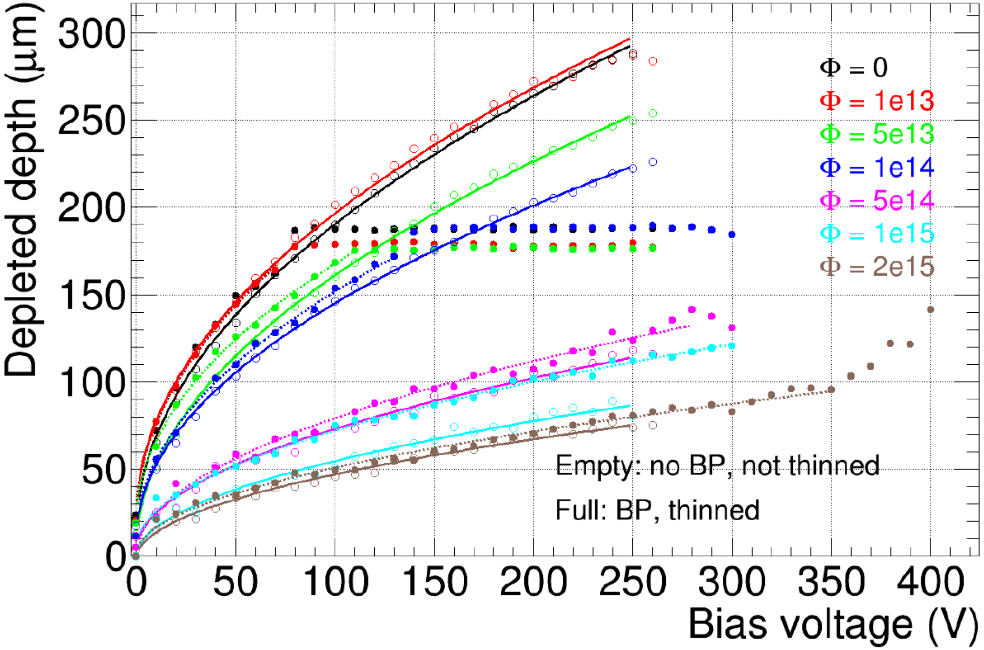


CAD render of Faraday CUp by Dennis Sauerland, 2021



Beam monitor and FC aligned

RADIATION DAMAGE
--PROTON HARDNESS FACTOR--



† Charge collection properties of irradiated depleted CMOS pixel test structures, I. Mandić

RADIATION DAMAGE
--LATEST SIMULATIONS--

- *39th RD50 workshop, Valencia Nov 17 2021*
- V. Suberts talk: *Non-Ionizing Energy Loss: Geant4 simulations towards more advanced NIEL concept for radiation damage modelling and prediction*
- Agrees with what we expect and measure
  - 12.5 MeV protons → $\kappa_p = 4.04$
- Thanks to Vendula Subert who provided me with her simulation data on short notice!