UNIVERSITÄT BONN Physikalisches Institut HISKP SI LAB Silizium Labor Bonn FSP ATLAS Erforschung von Universum und Materie

A HIGH PRECISION IRRADIATION SITE FOR SILICON DETECTORS AT BONN UNIVERSITY

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DPG Frühjahrstagung 2023, Dresden, T96: TestBeam, RadHard for Si and Pixel

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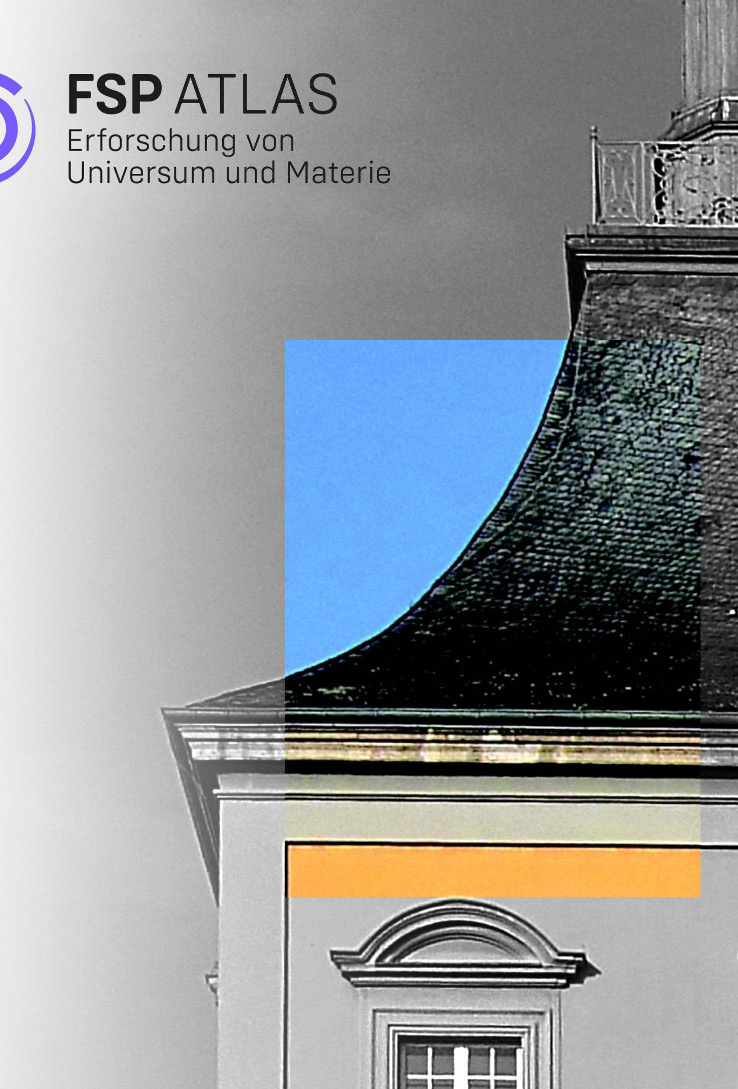


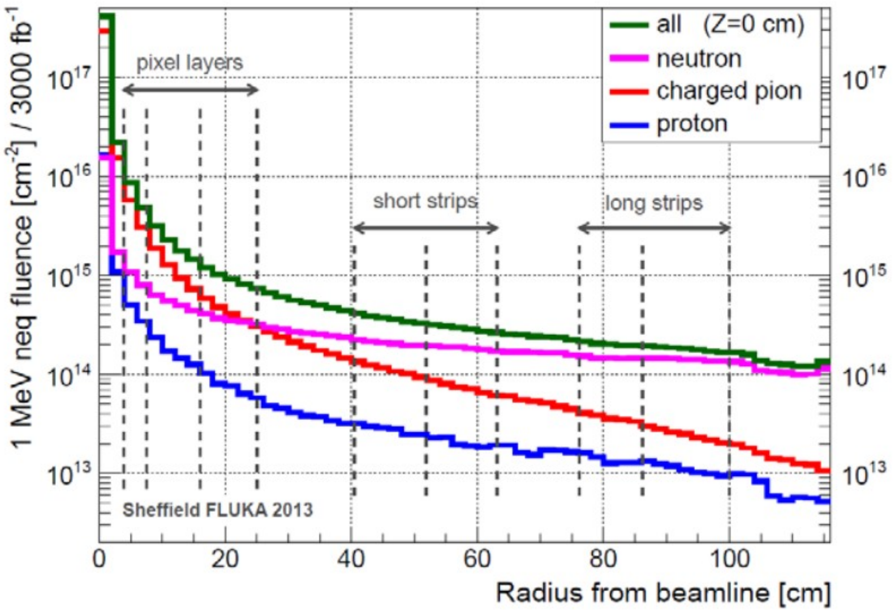
MOTIVATION

- Estimated radiation levels for ATLAS ITK after 3000 fb^{-1} scaled to 1-MeV neutron equivalent fluence n_{eq}:
  - Pixels @ 4 cm ≈ 2 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)

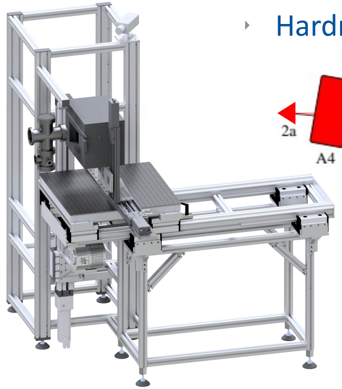


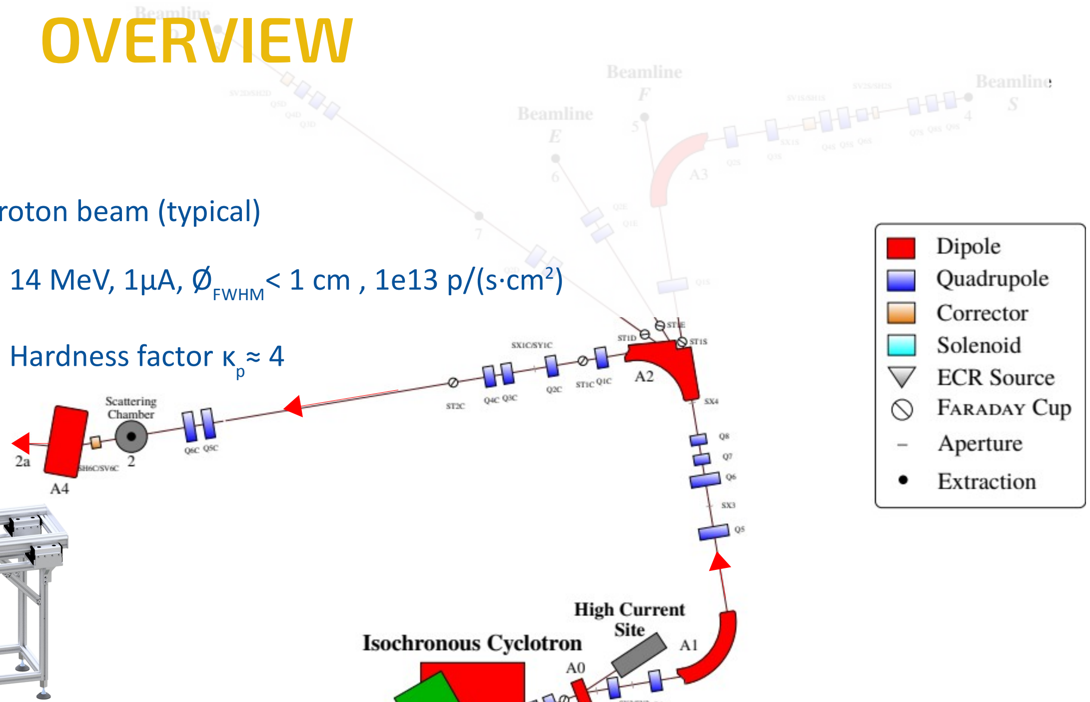
P. S. Miyagawa and I. Dawson, "Radiation background studies for the phase ii inner tracker upgrade," CERN, Tech. Rep. ATL-UPGRADE-PUB-2014-003, Sep. 2014.

OVERVIEW

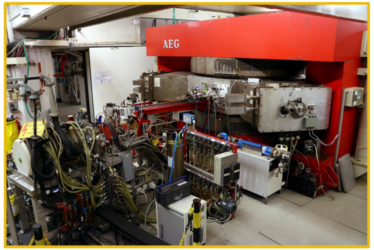
- Setup
- Diagnostics
- Irradiation Procedure
- Recent Campaigns
- Conclusion

- Proton beam (typical)
  - 14 MeV, 1μA, $Ø_{FWHM}$< 1 cm , 1e13 p/(s·cm²)
  - Hardness factor $\kappa_p \approx 4$



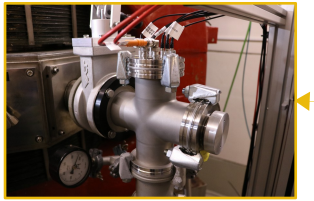


- ECR source & cyclotron
  - Protons to carbon
  - 7 – 14 MeV / nucleon

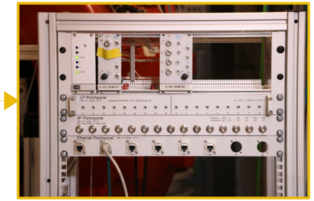


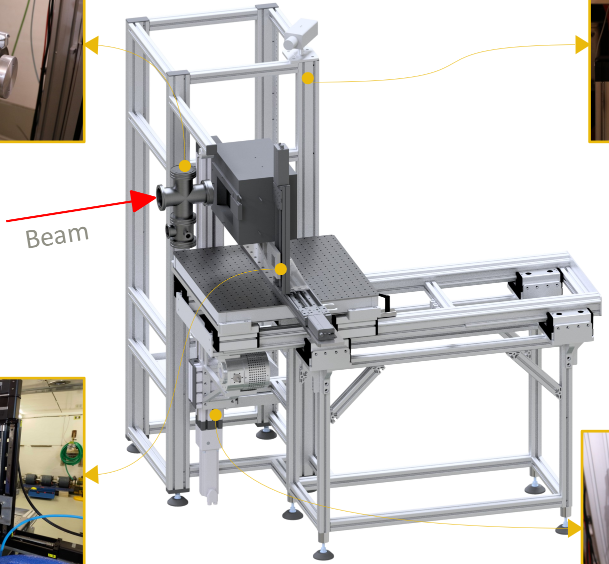
IRRADIATION SITE
--SETUP--

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

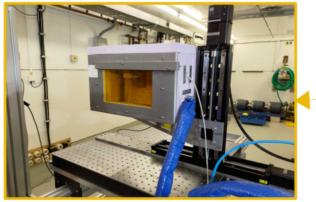


- 19“ rack w/ interfaces to setup and R/O
  - Interface DUT, lab devices provide custom signals
  - Connection to DAQ

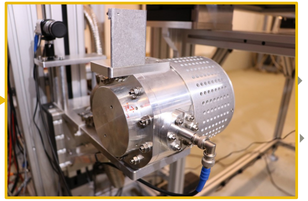




- Insulated DUT box on 2D motorstage
  - Houses DUT @ < -20 °C
  - 19x11 cm^2 max. DUT size
  - Interface for powering, R/O during irradiation

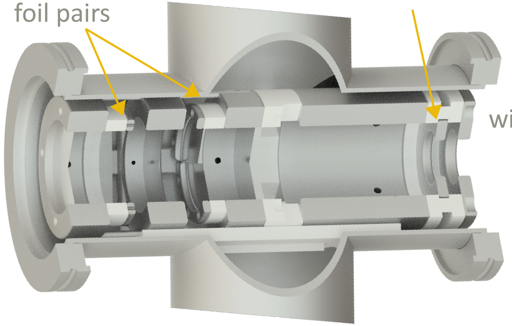


- Faraday cup (FC) with screen on motorstage
  - Destructive beam current measurem. at DUT position
  - Visual inspection of beam
  - Calibrating beam monitor



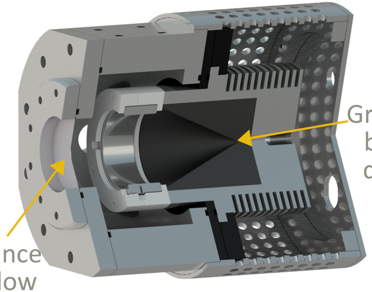
BEAM DIAGNOSTICS

--OVERVIEW--



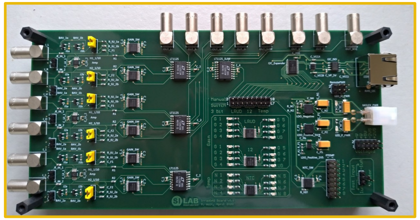
Beam monitor

- 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
  - $\Delta I_{FC}/I_{FC} \leq 1\%$

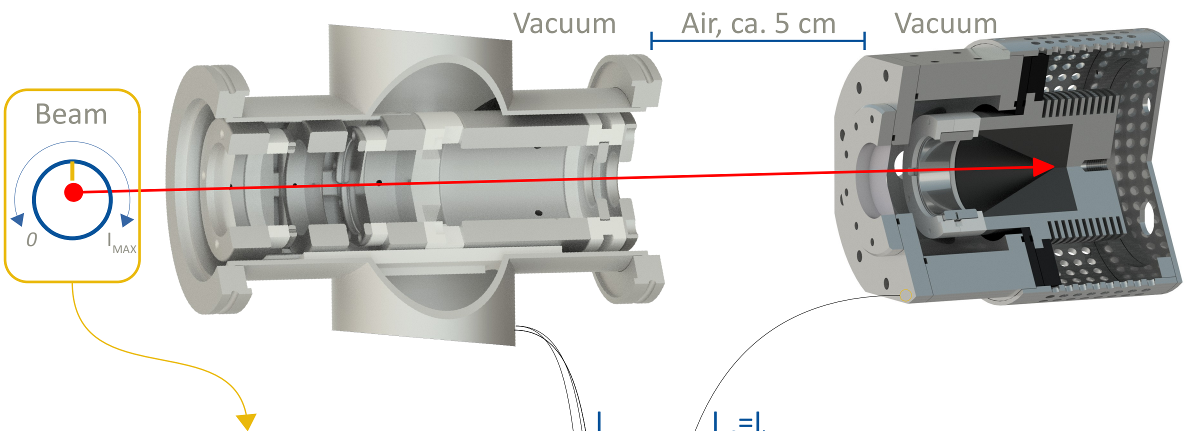


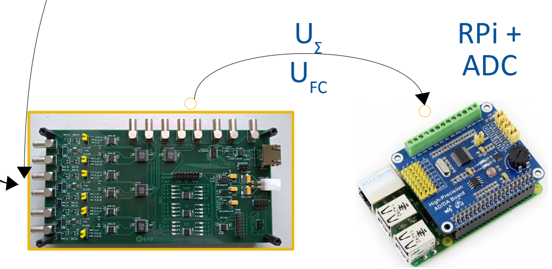
R/O board

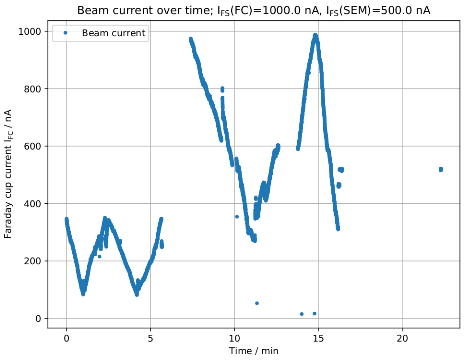
- Analog R/O of beam monitor & FC
- Linear mapping of input current I
  - $0 - I_{FS} \rightarrow 0 - 5V$
- Multiple, switchable scales I_{FS}
- Used to digitize signals

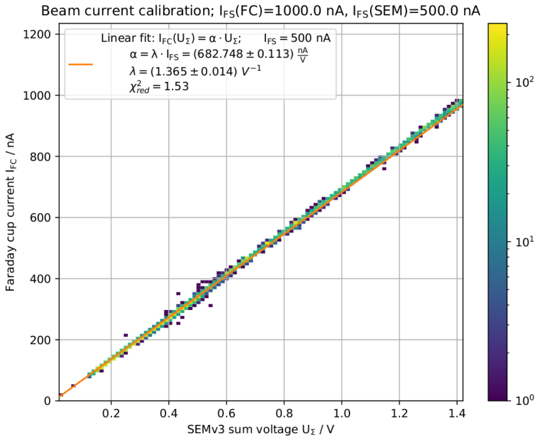
BEAM DIAGNOSTICS

--CALIBRATION--





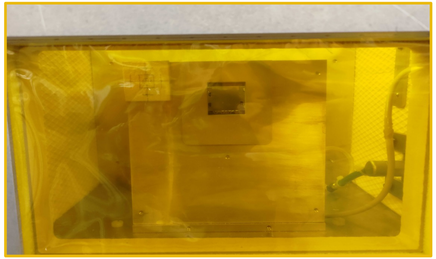




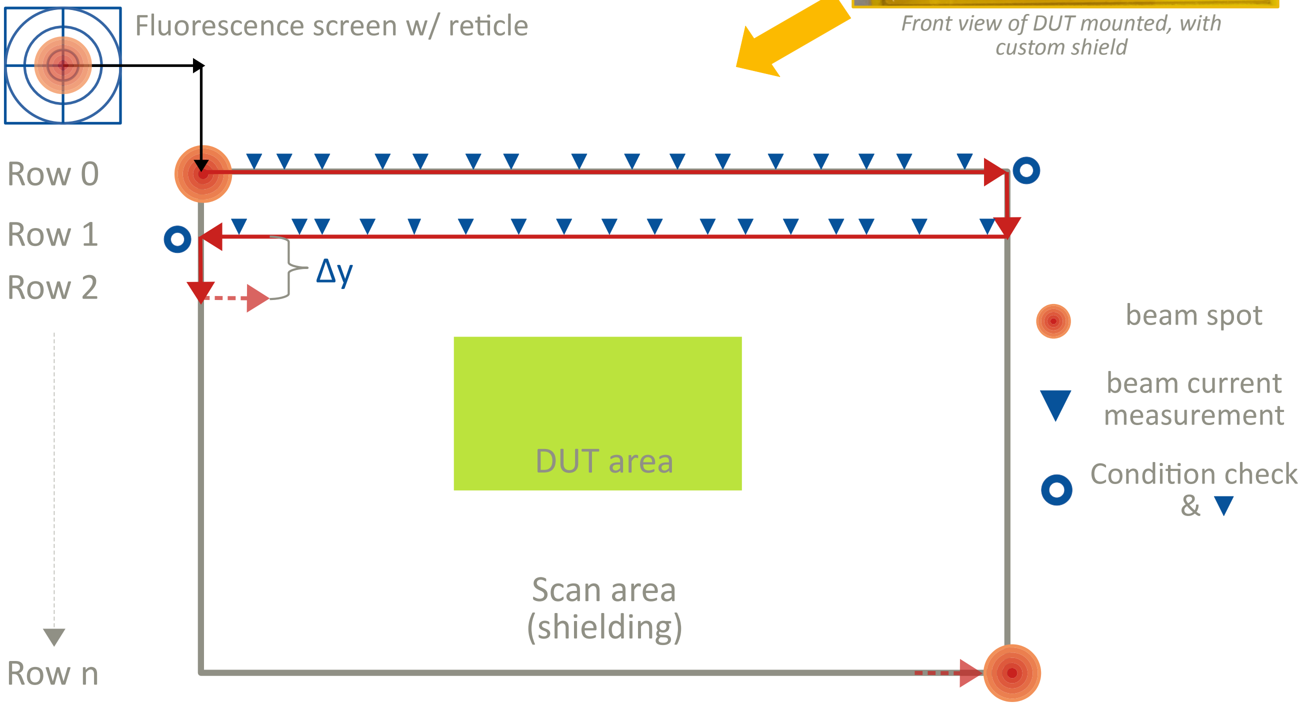
- Calibration $I_{Beam} = \alpha * U_{\Sigma}$ with $\alpha = \lambda * I_{FS}$
  - $$\mathbf{I_{beam}\left(I_{FS}, U_{\Sigma}\right) = \lambda \cdot I_{FS} \cdot U_{\Sigma}}$$
- Uncertainty consideration:
  - $$\frac{\Delta\lambda}{\lambda} = \frac{\Delta I_{FS}}{I_{FS}} = \frac{\Delta U_{\Sigma}}{U_{\Sigma}}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

IRRADIATION
--SCANNING PROCEDURE--

- Align beam using fluorescence screen
- Construct scan area in relative coordinate system
- Irradiate DUT by scanning area in equidistantly spaced (**Δy**) rows with velocity **v**
- Beam current measured continuously with 10 -100 Hz at **all times**
- Beam condition checked at end of row, wait if needed
- DUTs mounted behind custom shielding @ < -20 °C, temp monitoring via NTCs in box

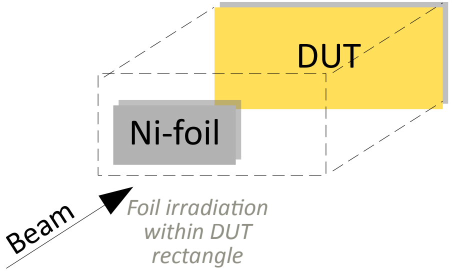


Front view of DUT mounted, with custom shield



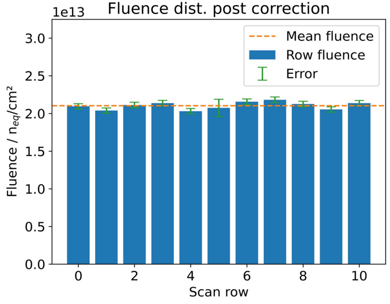
IRRADIATION
--DOSIMETRY--

- Dosimetry via **foil activation** (typically used):
  - Irradiation of (thin) metallic foil, e.g Ni/Ti (depending on energy), alongside DUT
  - Measure activation of isotope X; production cross section, foil weight, etc.
    - Fluence is **scalar** via $\phi_p \left[p \xrightarrow{\Omega_p^X} X \right] \Rightarrow A^X,\ \Omega_p^X,\ \lambda^X,\ m_{mol}^X,\ m_{foil}$
    - Offline analysis

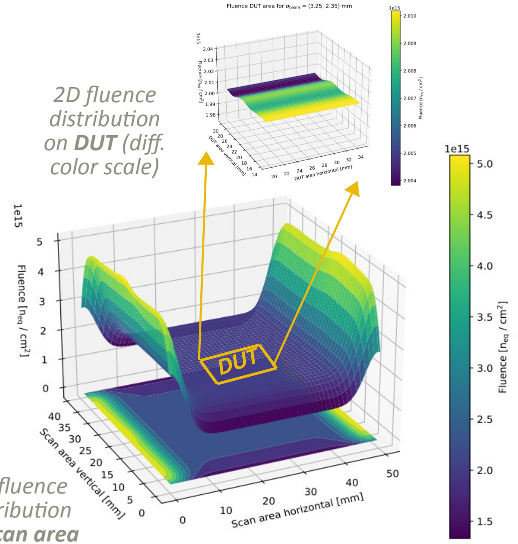


Foil irradiation within DUT rectangle

- Dosimetry via **beam current** (done in Bonn):
  - Fluence determination via: $\phi_p = \frac{I_{beam}}{q_e \cdot v \cdot \Delta y}$
    - Distribution per row (**1 dim**) via
    - Online analysis → feedback during/after irradiation
  - Fluence from irradiation data analysis:
    - Fluence map over scan area and DUT (**2 dim**)
    - Offline analysis



Fluence distribution per row



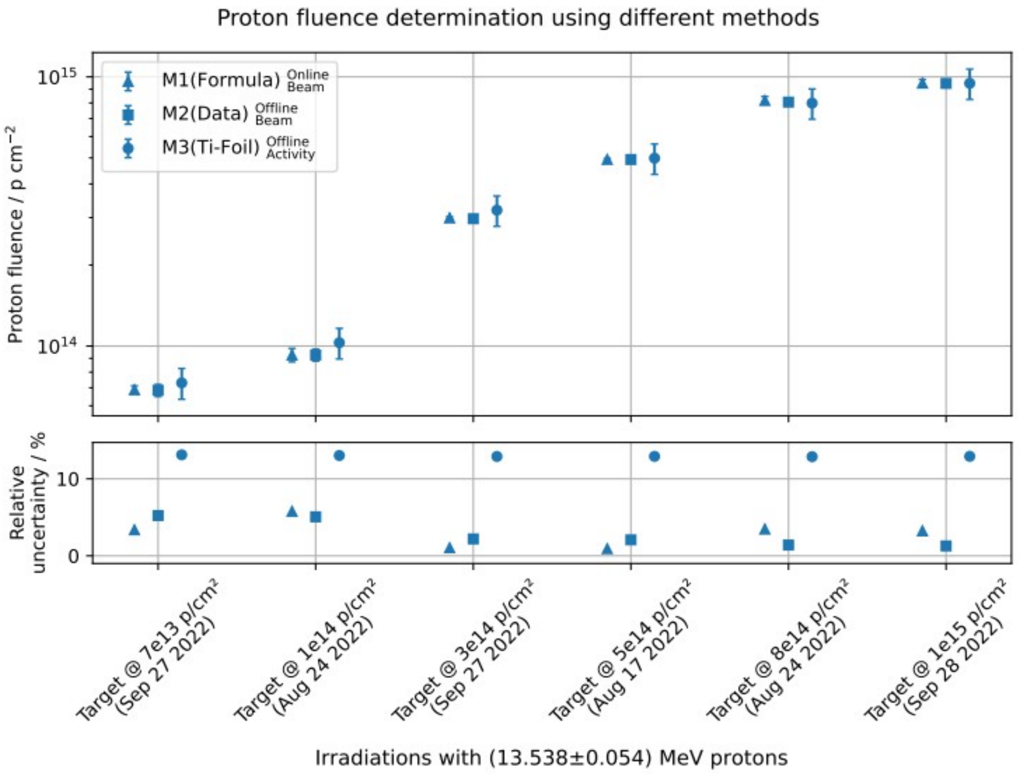
*2D fluence distribution on **DUT** (diff. color scale)*

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

IRRADIATION

--DOSIMETRY: METHOD COMPARISON--

- 6 x Ti-foils irradiated across 1 order of proton fluence magnitude
- Results are in good agreement
  - Beam-based methods yield lower, relative uncertainty consistently
    - Rel. Uncertainty M3 ≈ 15%, M1/2 ≈ 2%
  - Uncertainty for M1/2 methods includes variation across fluence distribution!
- Irradiations carried out using different parameters
- Beam-based dosimetry verified to be in agreement with typically-used foil method

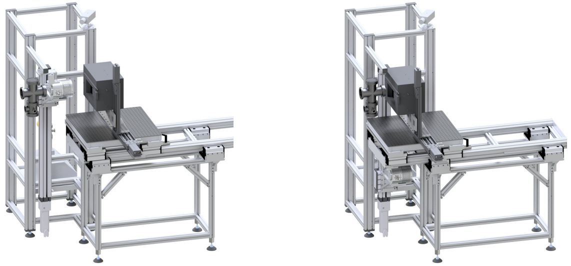


IRRADIATION

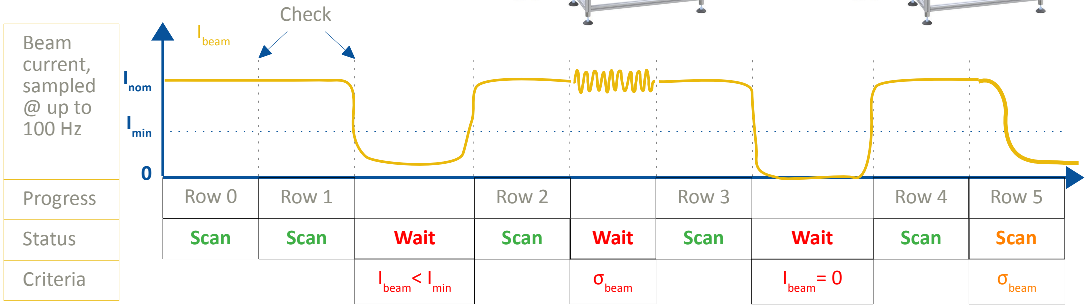
--IMPROVING UNCERTAINTY/HOMOGENEITY--

- Pre-irradiation:
  - On-the-fly calibration before / after irradiation to maximize calibration precision

Setup moving from calibration to irradiation position

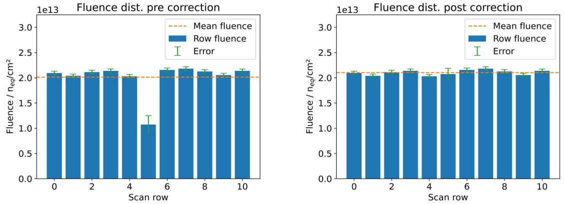


- Irradiation:
  - **Beam-driven** scan procedure; beam parameters checked for predefined requirements each row



- Post-irradiation:
  - Correction of fluence distribution by scanning individual rows → Especially useful for low-fluence scans

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

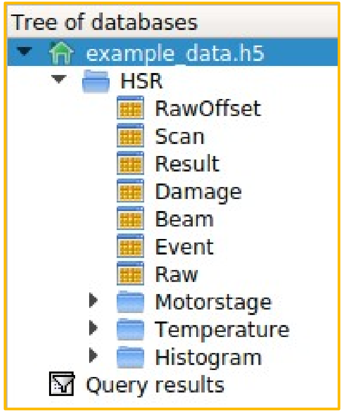


IRRADIATION

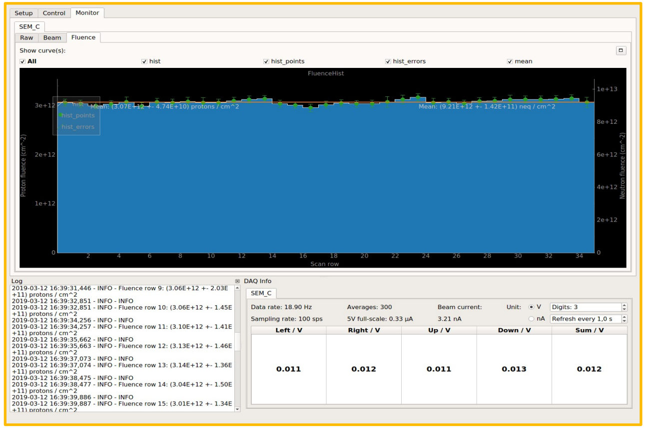
--DAQ, VISUALIZATION & CONTROL--

- Python-based, open-source software *irrad_control* feat. a GUI for online data visualization, analysis & hardware control
- Conducts beam-driven irradiation routine allowing manual interaction (e.g. pausing for in-between measurements) → flexible campaigns
- Generates extensive irradiation datasets:
  - Timestamped data of damage, beam, setup, etc., available to user
- Offers basic analysis functionalities to generate e.g. fluence / uncertainty distributions off datasets
- Generic design, suitable for porting to other sites
- GitHub:https://github.com/cyclotron-bonn/irrad_control

Online data visualization on PC at control room



Example content of generated datasets

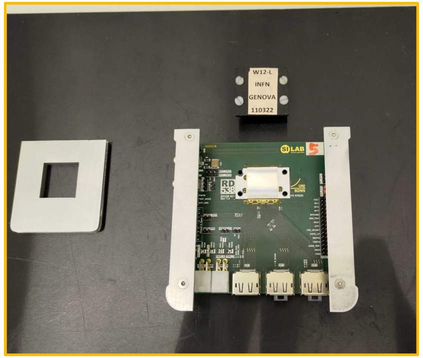


Online fluence per row monitor of irrad_control

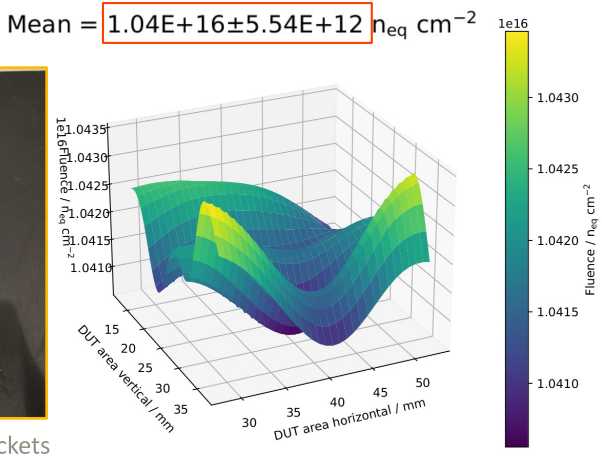
IRRADIATION
--RECENT CAMPAIGNS--

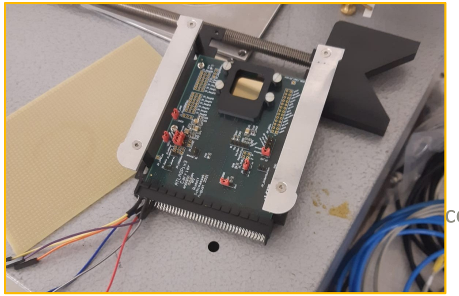
- Irradiation of 2 ItkPixV1 assemblies from CERN in May 2022
  - 2x2 cm^2, 1e16 neq / cm^2, **largest fluence per session so far**
  - Irradiations each completed within 1 day (6h, 9h)
  - Variation of fluence distr. over DUT < 1%

- Irradiation of ATLASPixV3.1 from Heidelberg in July 2022
  - 2x2 cm^2, ~ 2e14 neq / cm^2, **chip powered & IV scan during irradiation**
  - Very low fluence per scan, beam currents 20 - 50 nA
  - IV sweeps after completed scans & **during beam hitting chip**!



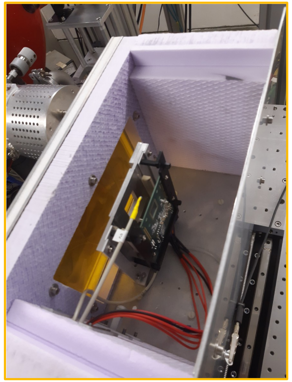
ITkPixV1 on SCC with mounting brackets





Left: ATLASPixV3.1 on SCC with mounting brackets

Right: ATLASPixV3.1 in cooling box behind shield, chip powered & HV



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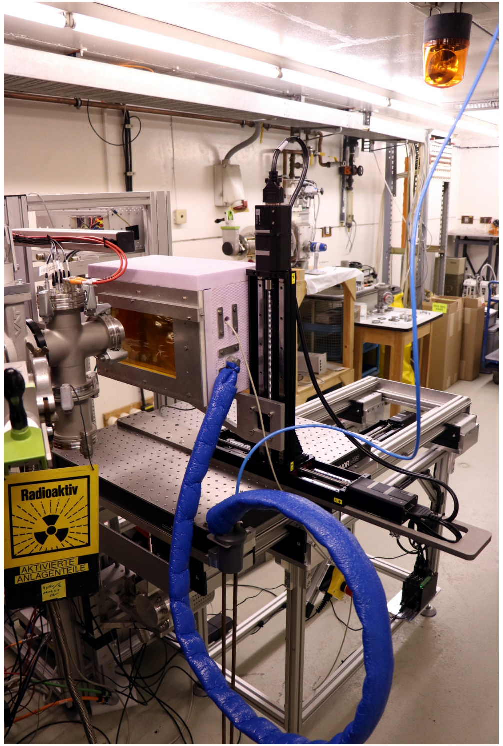
CONCLUSION & OUTLOOK



- The proton irradiation site in Bonn allows for optimized proton fluence homogeneity & uncertainty irradiations
- Custom beam monitoring & dosimetry enable beam-driven irradiation procedure with $\frac{\Delta\phi_p}{\phi_p} \leq 2\%$
- *irrad_control* software allows flexible campaigns and produces extensive datasets for analysis
- Proton ardness factor $\kappa_p \approx 4$ enabling irradiation of 1e16 n_{eq}/cm^2 within 2 h (shown for ITkPix)
- Outlook:
  - Currently Uni Bonn is working on giving **general** access to external groups
    - → Multiple external campaigns already conducted
  - Collaboration with other facilities (e.g. KIT, Birmingham) to realize generelazid procedures
  - Currently κ_p main source of uncertainty ($\Delta\kappa_p/\kappa_p \approx 20\%$) → Precise measurement to reduce overall uncertainty on equivalent fluence

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Thank you

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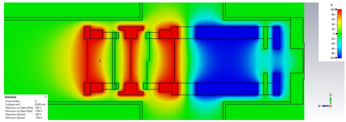
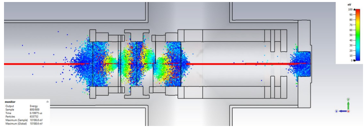
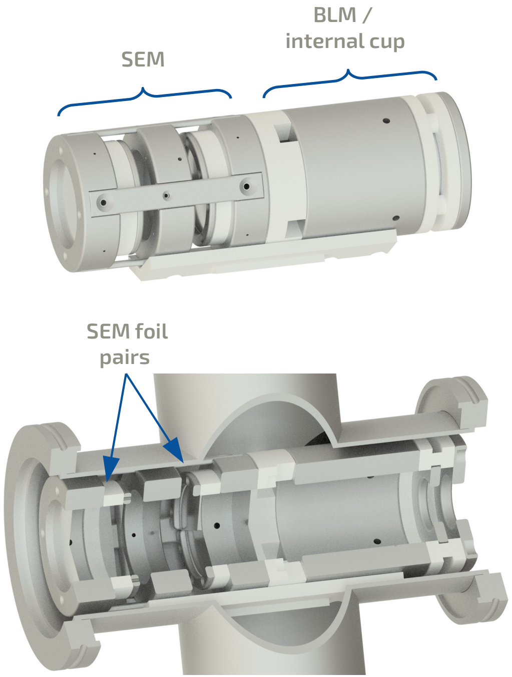
BACKUP

HARDWARE
-Beam Monitor-

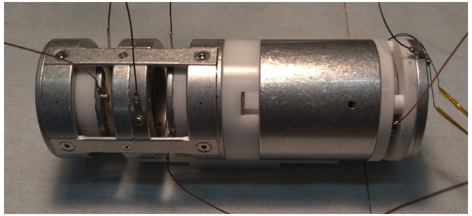
- Online beam parameter and cut-off monitoring
- Secondary electron monitor:
  - 2 C-coated, Al-foil pairs, 3 HV (+100V) foils
- Beam-loss monitor (BLM) / internal cup:
  - Isolated Al-apertue, HV (-100V) suppressor cylinder / aperture, monitoring NTC
- Fully CST-simulated design:
  - Electric field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

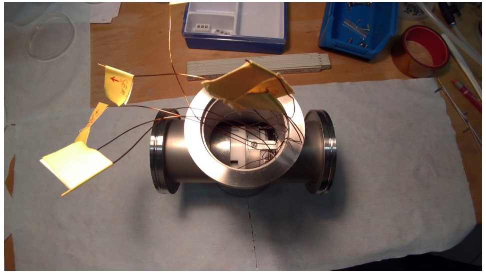






CAD render of beam monitor by Dennis Sauerland, 2021

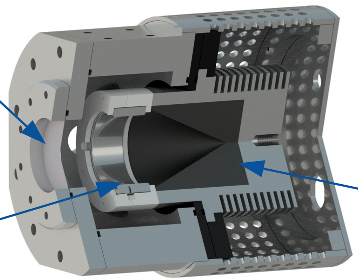


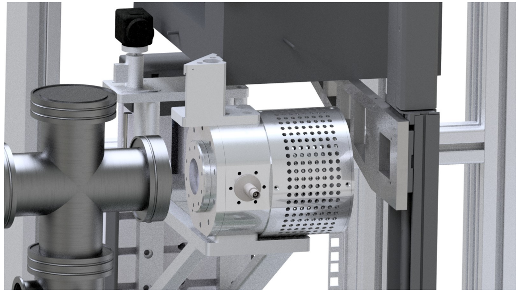


Installation of beam monitor in cross-piece

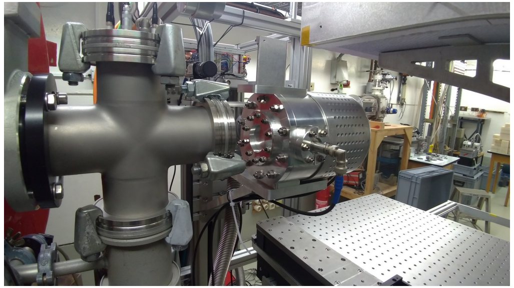
HARDWARE
-Faraday Cup with Camera / Screen-

- 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





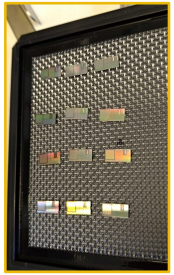
CAD render of Faraday CUp by Dennis Sauerland, 2021

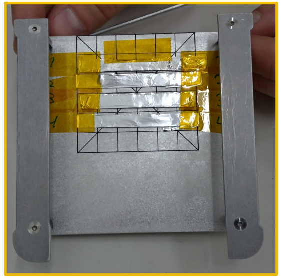


Beam monitor and FC aligned

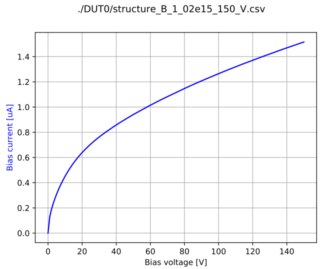
RADIATION DAMAGE

--LATEST MEASUREMENTS--

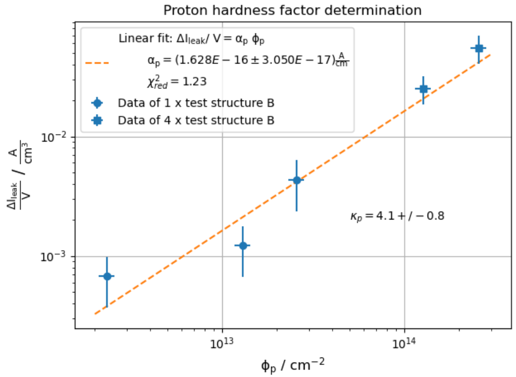




Test structures in gel pad and wrapped in 10 µm Al-foil on carrier for irradiation



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

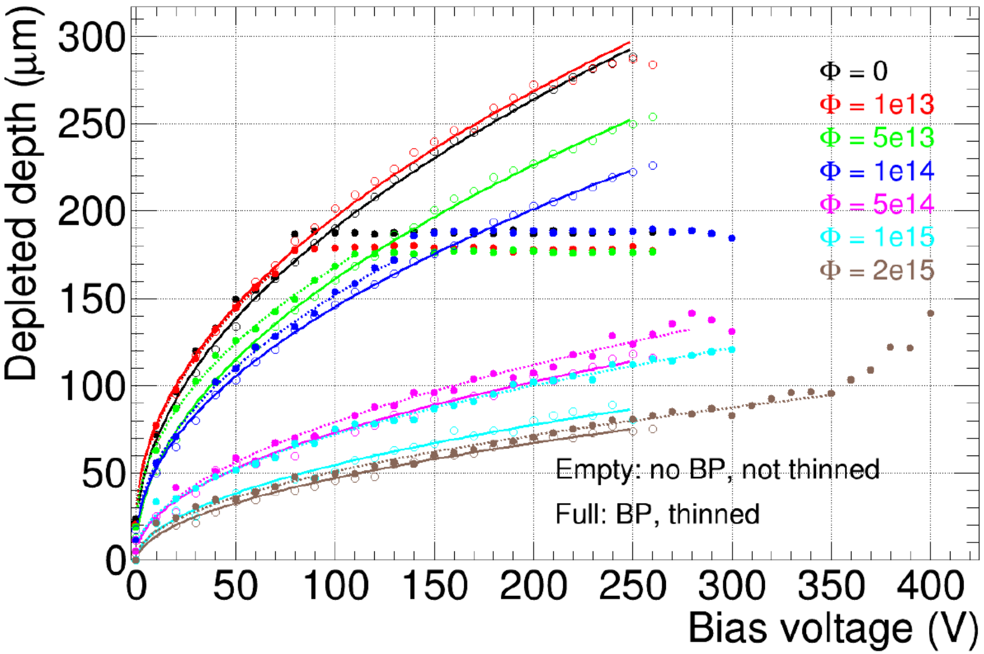
$$\alpha_{eq} = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A\,cm^{-1}}$$

  → $\kappa = \alpha_p / \alpha_{neq} = 4.1 \pm 0.8$
- 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

RADIATION DAMAGE

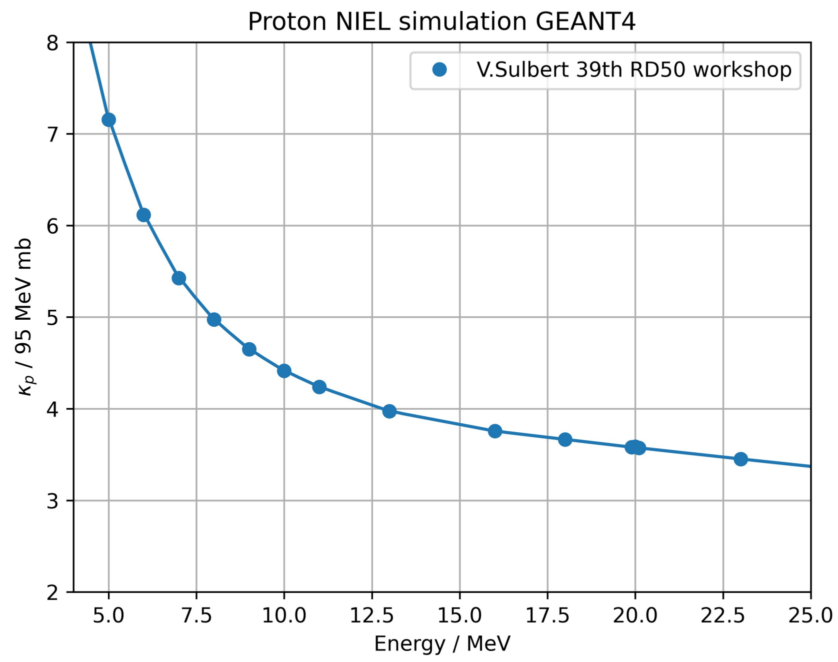
--PROTON HARDNESS FACTOR--



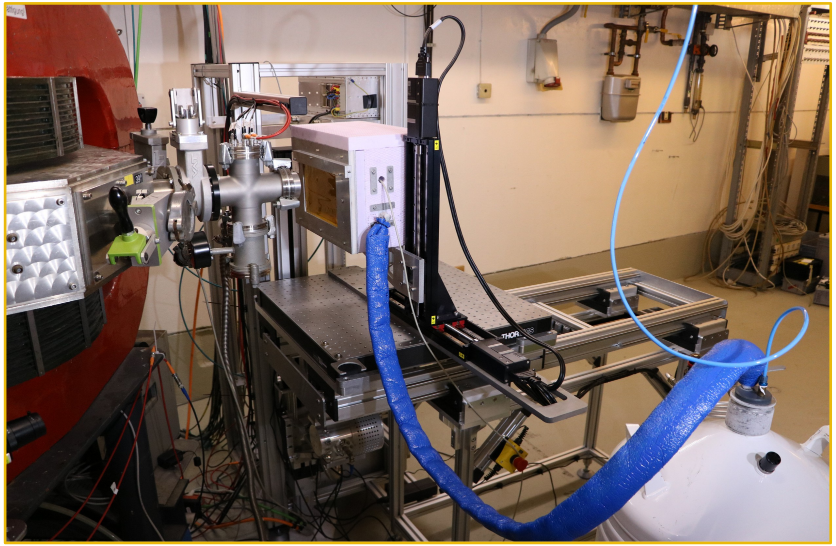
† Charge collection properties of irradiated depleted CMOS pixel test structures, I. Mandić

RADIATION DAMAGE
--LATEST SIMULATIONS--

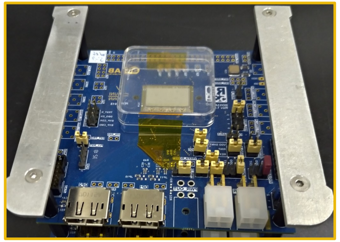
- *39th RD50 workshop, Valencia Nov 17 2021*
- V. Suberts talk: *Non-Ionizing Energy Loss: Geant4 simulations towards more advanced NIEL concept for radiation damage modelling and prediction*
- Agrees with what we expect and measure
  - 12.5 MeV protons → $\kappa_p = 4.04$
- Thanks to Vendula Subert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



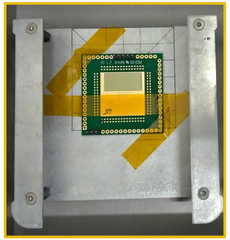
IRRADIATION
--SITE & TYPICAL DUTs--



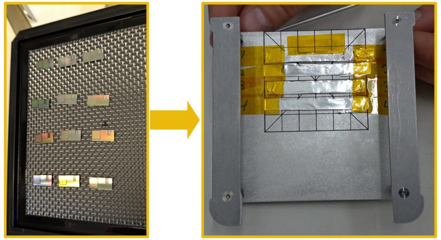
Setup in irradiation position. Liquid nitrogen dewar used to cool down nitrogen gas for cool, dry atmosphere inside box during iradiation



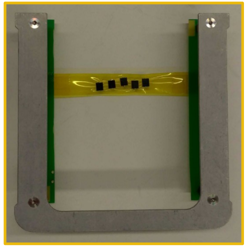
Assembly on SCC



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)

FLUENCE DETERMINATION
--(TITANIUM) FOIL METHOD--

- Use different irradiation parameters to show methods are independent:

$\text{Fluence}_{\text{aim}}$ / p/cm^2		7e13	1e14	3e14	5e14	8e14	1e15
$\text{Fluence}_{\text{meas}}$ / 10^{14} p/cm^2	M1(Formula)	0.70 ± 0.02	0.93 ± 0.05	2.98 ± 0.04	4.93 ± 0.06	8.18 ± 0.25	9.51 ± 0.38
	M2(Data)	0.69 ± 0.04	0.93 ± 0.05	2.97 ± 0.07	4.93 ± 0.10	8.06 ± 0.11	9.45 ± 0.12
	M3(Ti-Foil)	0.73 ± 0.10	1.03 ± 0.13	3.20 ± 0.41	4.99 ± 0.64	7.99 ± 1.03	9.46 ± 1.22
Scan speed v_x / mm s^{-1}		90	65	60	70	50	40
Row separation Δy / mm		1.25	0.75	1.50	1.00	0.50	0.25
Mean scan current I_{scan} / nA		368 ± 65	807 ± 164	661 ± 106	757 ± 123	759 ± 278	950 ± 202
Number of rows		24	40	20	30	60	120
Number of scans		34	9	65	73	43	16
Scan area A / mm^2		60.00×28.75	60.00×29.25	60.00×28.5	60.00×29.00	60.00×29.50	60.00×29.75
Calibration constant λ/ V^{-1}		0.897 ± 0.009	0.906 ± 0.009	0.897 ± 0.009	0.906 ± 0.009	0.906 ± 0.009	0.897 ± 0.009
Date		27/09/2022	24/08/2022	27/09/2022	17/08/2022	24/8/2022	28/09/2022