# UPGRADED PROTON IRRADIATION SITE AT BONN UNIVERSITY

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# MOTIVATION

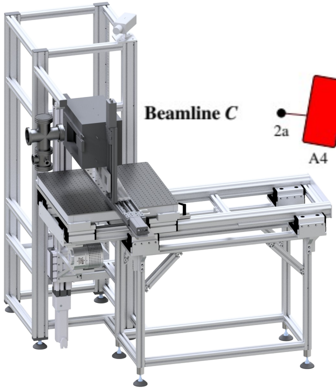
- Reduce systematic uncertainty on primary proton fluence
  - Proton irradiation fairly new in Bonn (development since 2018)
  - Fluence determination different from other sites (KIT, Birm.)
  - Low beam energies challenging

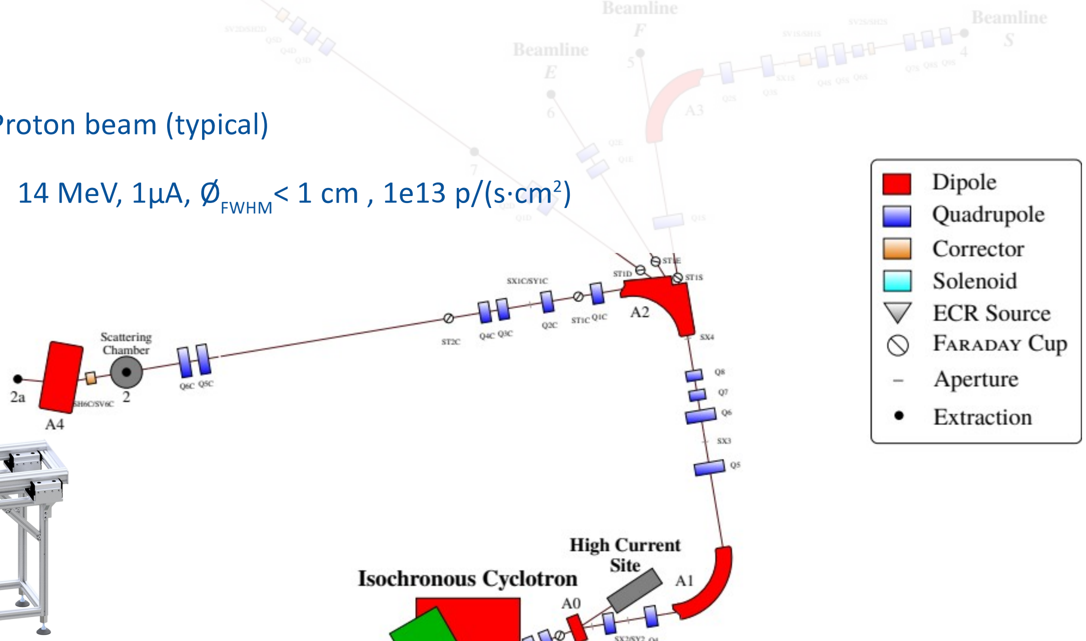
  → Need to characterize setup very well to enable precise determination of proton NIEL damage
- Develop generic, modular and flexible setup for ion irradiation
  - Allow flexible irradiation modes
  - Enable other facilities to easily use our setup (or parts of it)

# OVERVIEW

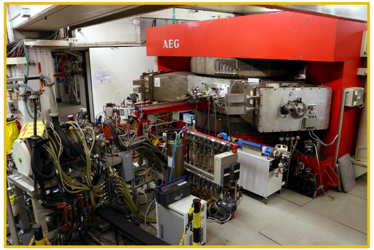
- Irradiation Site
- Beam Diagnostics
- Irradiation Procedure
- Proton NIEL
- Conclusion

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





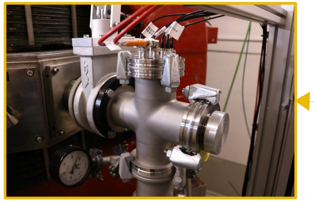

- ECR source & cyclotron
  - Protons to carbon
  - 7 – 14 MeV / nucleon



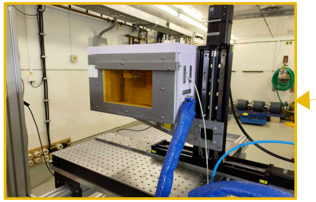
# IRRADIATION SITE

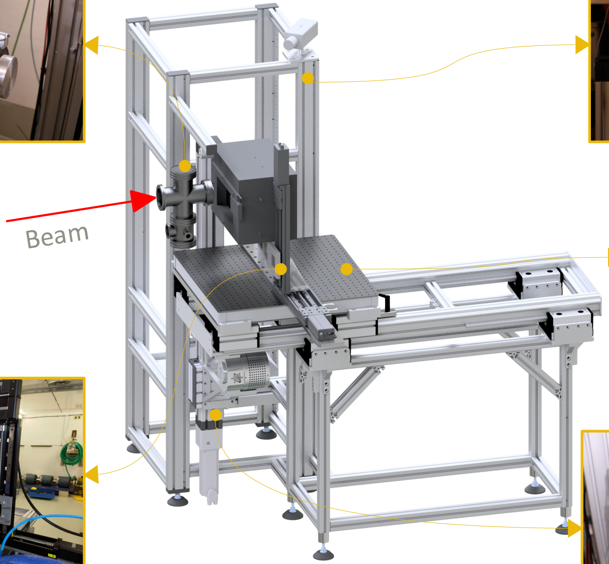
## --SETUP--

- Calibrated, online beam monitor
  - Current, position & loss
  - Housed in cross-piece, at extraction
  - Fluence measurement

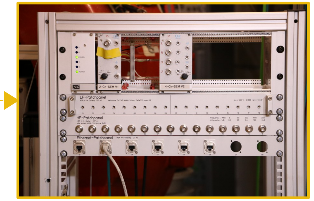


- Insulated DUT box on 2D motorstage
  - Houses DUT @ < -20 °C
  - 19x11 cm² max. DUT size
  - Interface for powering, R/O during irradiation
  - Homogeneous irradition by scanning box through beam



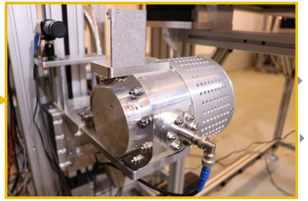



- 19“ rack w/ interfaces to setup and R/O board
  - Interface DUT, lab devices provide custom signals
  - RJ45, BNC, Lemo, …
  - Connection to DAQ Rpi



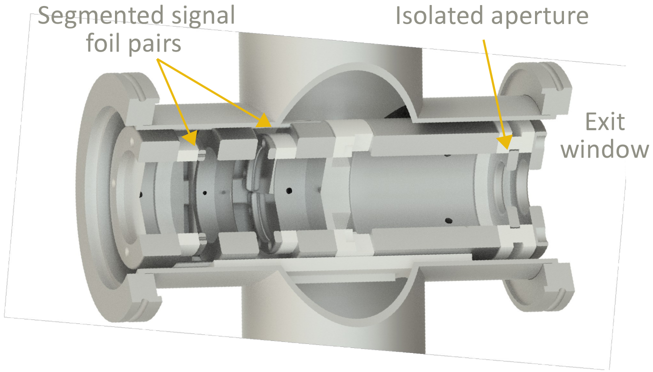
- Movable setup table with optical grid

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



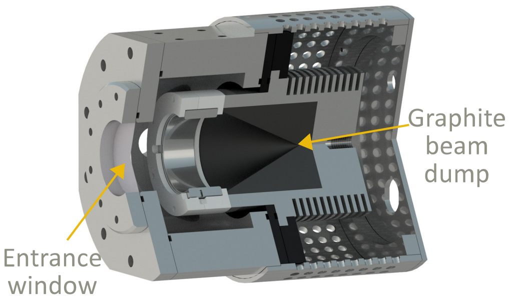
# CUSTOM BEAM DIAGNOSTICS

## --OVERVIEW--



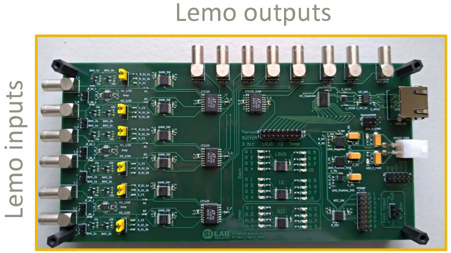

Beam monitor, v3

- 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 in front of extraction provides direct beam cut-off measurements




Faraday cup (FC), v2

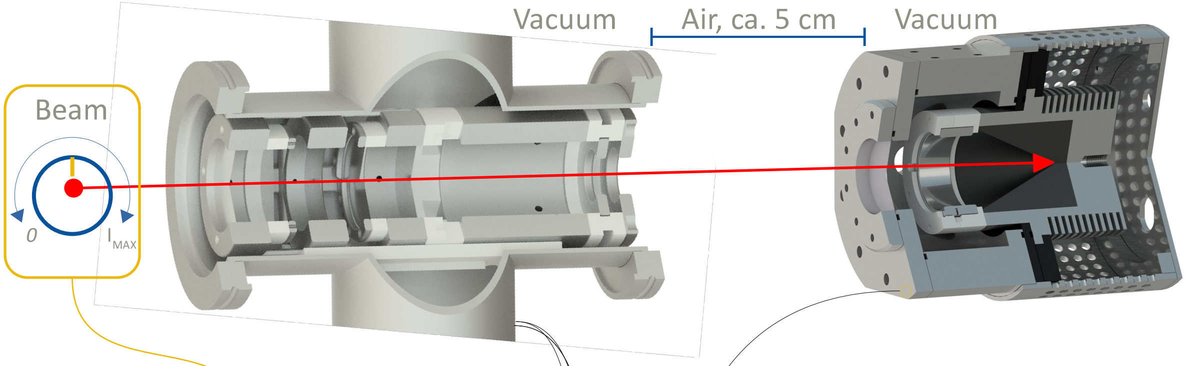
- Beam current $I_{beam}$ measurement by dumping into graphite cone
- Separate vacuum of < 1e-6 mbar
- Directly obtain current $I_{FC} = I_{beam}$ with low uncertainty
  - $\Delta I_{FC}/I_{FC} \leq 1\%$

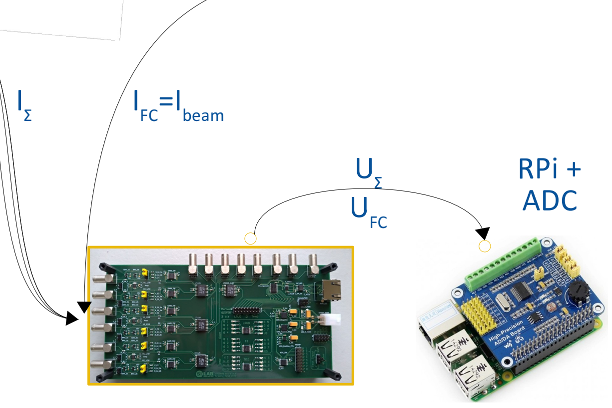


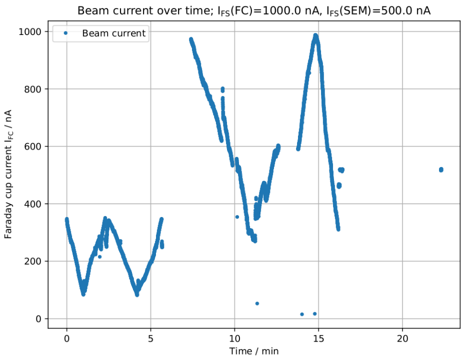

R/O board, v2

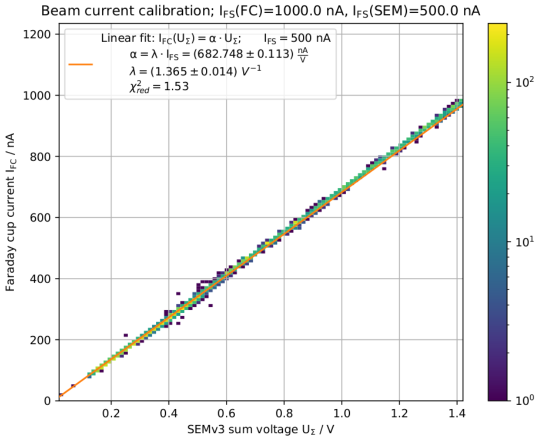
- Analog R/O of beam monitor & FC
- Mapping input current I:
  - $0 - I_{FS} \rightarrow 0 - 5V$
- Multiple, switchable scales $I_{FS}$ allow large range of input currents
- Provides fast feedback to stabilize beam, based on beam at extraction

# BEAM DIAGNOSTICS
## --CALIBRATION--



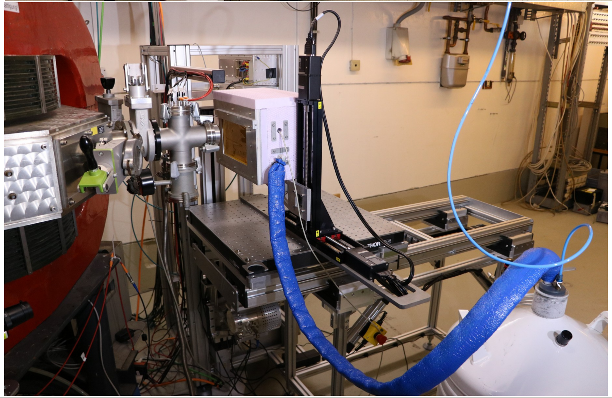

- Calibration $I_{Beam} = \alpha * U_{\Sigma}$ with $\alpha = \lambda * I_{FS}$
  - $$\mathbf{I_{beam}\,(I_{FS}, U_{\Sigma}) = \lambda \cdot I_{FS} \cdot U_{\Sigma}}$$
- Uncertainty consideration:
  - $$\frac{\Delta\lambda}{\lambda} = \frac{\Delta I_{FS}}{I_{FS}} = \frac{\Delta U_{\Sigma}}{U_{\Sigma}} = 1\% \Rightarrow \frac{\Delta I_{beam}}{I_{beam}} = \sqrt{3}\%$$
- Allows optimizing irradiation for high homogeneity with low uncertainty

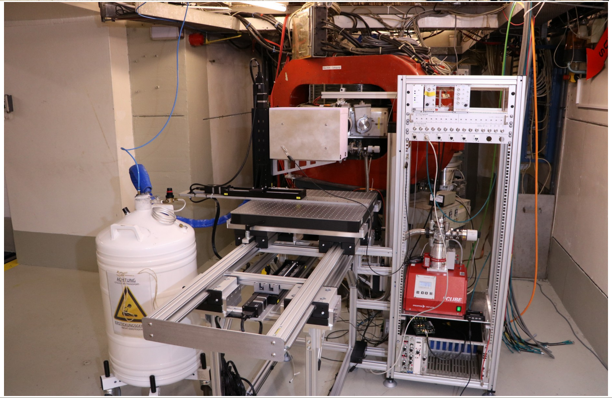
# IRRADIATION

## --OVERVIEW--

Control room: Irradiation procedure supervised from here. Irradiation parameters controlled and visualized by irrad_control software

Irrad. setup, front view (left): Setup in irradiation position. Liquid nitrogen dewar used to cool nitrogen gas. Back view (right)

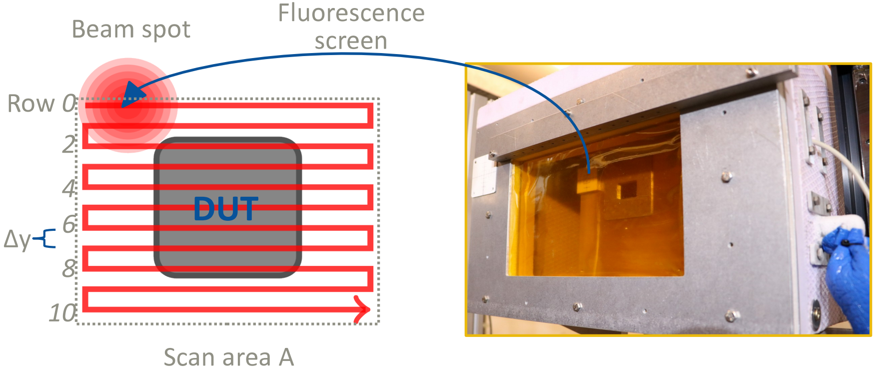




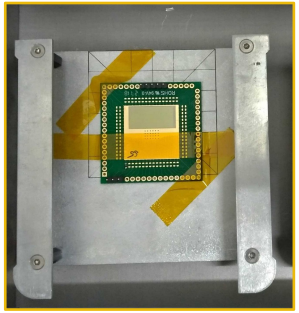
# IRRADIATION

## --PROCEDURE--

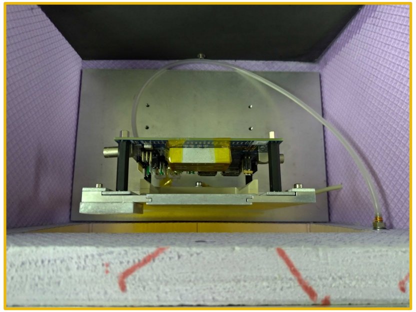
- DUTs mounted behind custom shielding @ < -20 °C, temp monitoring via NTCs in box
- Beam-based alignment using fluorescence screens, cameras and beam monitor
- Homogeneous irradiation by overscanning DUT area
- Row-wise scanning with row separation Δy and velocity v
- Proton fluence per completed scan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




Surfboard + sensor on carrier



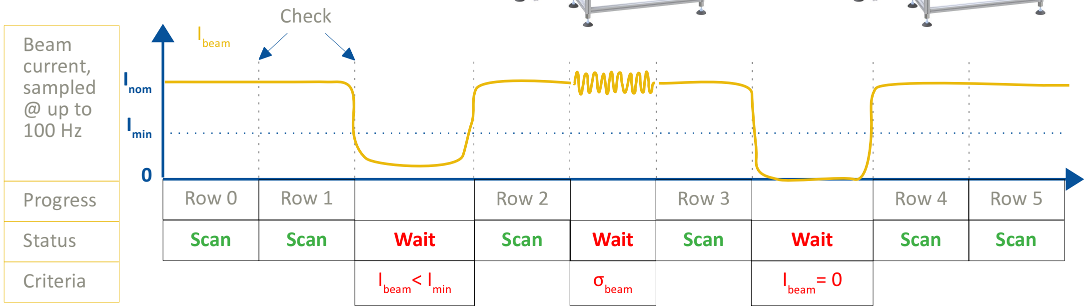
RD53A module on SCC behind shield (top view)



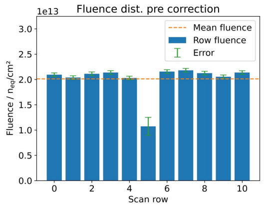
# IRRADIATION
## --IMPROVING UNCERTAINTY/HOMOGENEITY--

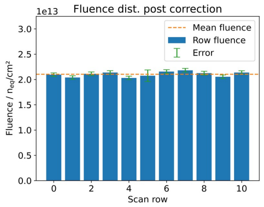
- Pre-irradiation:
  - On-the-fly calibration before / after irradiation to maximize calibration precision
- Irradiation:
  - **Beam-driven** scan procedure; scan checks criteria
  - Damage measured per row; uncertainties due to in-row beam variations are measured
  - Allows pausing irradiation for in-between analysis; IV-curves, threshold scan, power up, ...
  - Visualization of irrad. parameters in GUI control software
- 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



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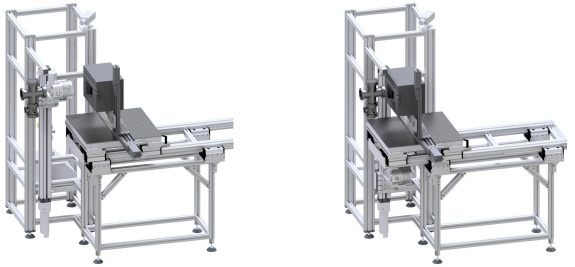

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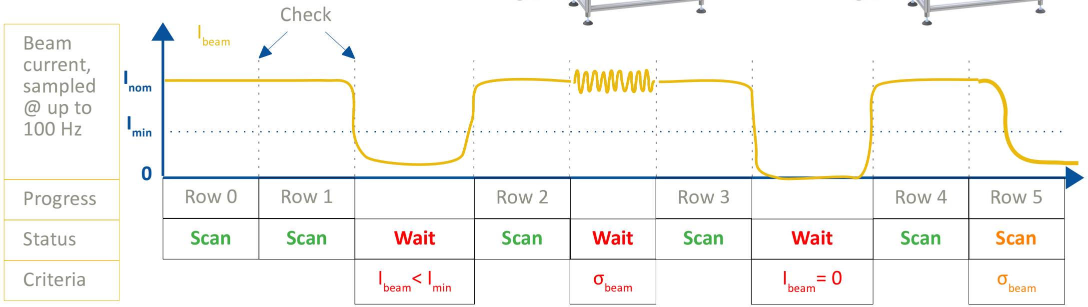


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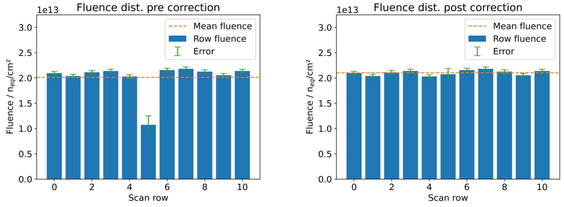

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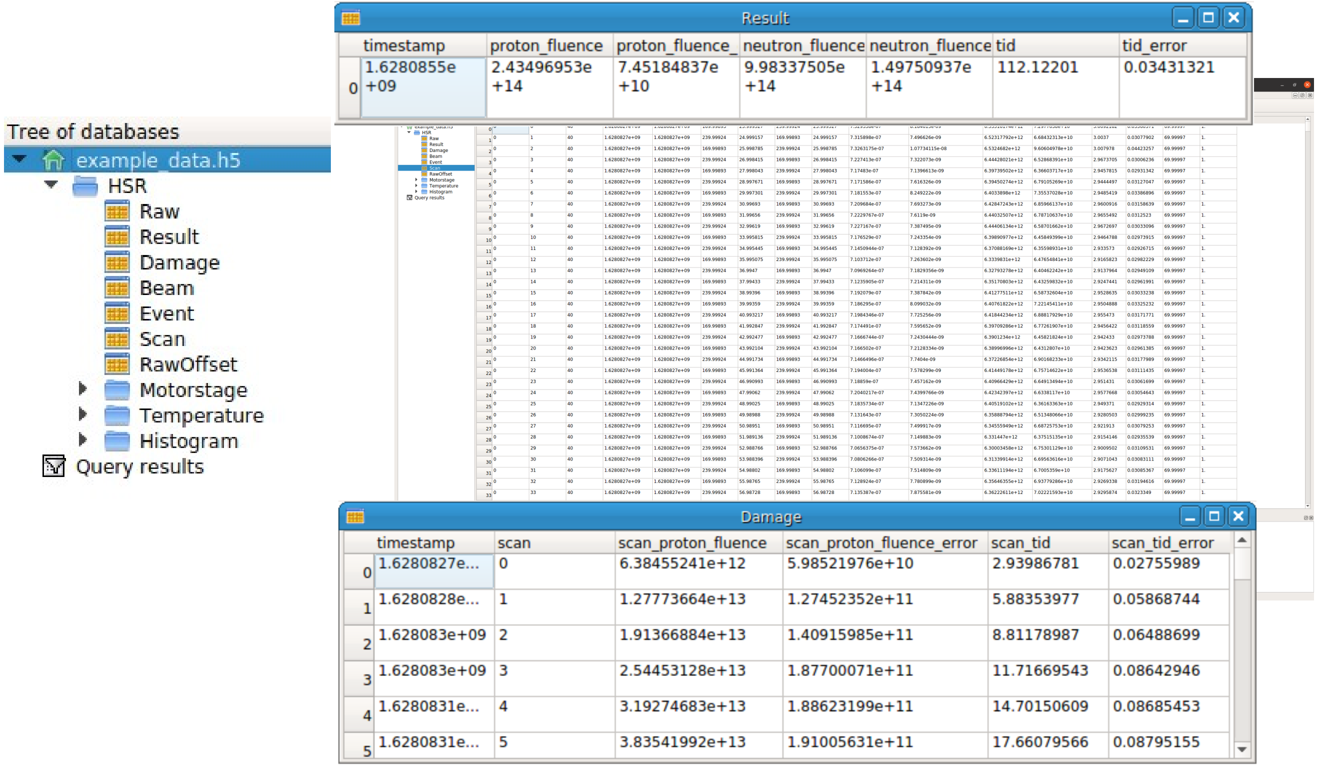
# IRRADIATION

## --OUTPUT DATA--

- Complete dataset of irradiation parameters available: raw, beam, temperature, scan, etc.
- Resulting proton / neutron fluences + TID as well as uncertainties
  - Allows to correct
- Automated generation of comprehensive collection of plots
- Transparency




**Result**

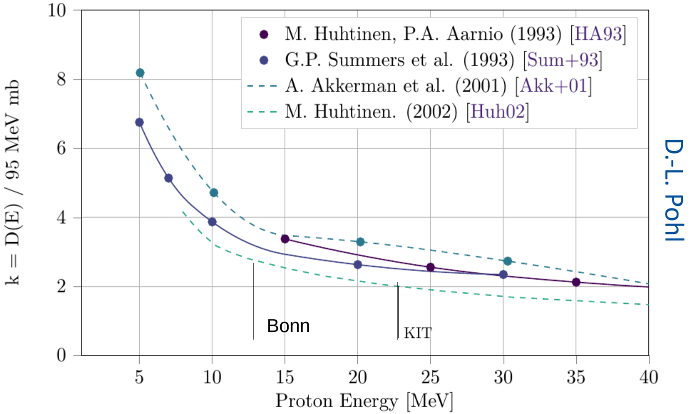
| | timestamp | proton_fluence | proton_fluence_ | neutron_fluence | neutron_fluence | tid | tid_error |
|---|---|---|---|---|---|---|---|
| 0 | 1.6280855e+09 | 2.43496953e+14 | 7.45184837e+10 | 9.98337505e+14 | 1.49750937e+14 | 112.12201 | 0.03431321 |

**Damage**

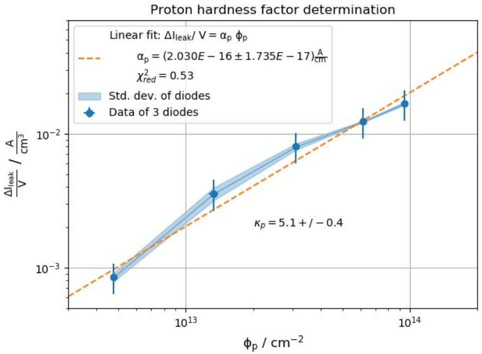
| | timestamp | scan | scan_proton_fluence | scan_proton_fluence_error | scan_tid | scan_tid_error |
|---|---|---|---|---|---|---|
| 0 | 1.6280827e... | 0 | 6.38455241e+12 | 5.98521976e+10 | 2.93986781 | 0.02755989 |
| 1 | 1.6280828e... | 1 | 1.27773664e+13 | 1.27452352e+11 | 5.88353977 | 0.05868744 |
| 2 | 1.628083e+09 | 2 | 1.91366884e+13 | 1.40915985e+11 | 8.81178987 | 0.06488699 |
| 3 | 1.628083e+09 | 3 | 2.54453128e+13 | 1.87700071e+11 | 11.71669543 | 0.08642946 |
| 4 | 1.6280831e... | 4 | 3.19274683e+13 | 1.88623199e+11 | 14.70150609 | 0.08685453 |
| 5 | 1.6280831e... | 5 | 3.83541992e+13 | 1.91005631e+11 | 17.66079566 | 0.08795155 |

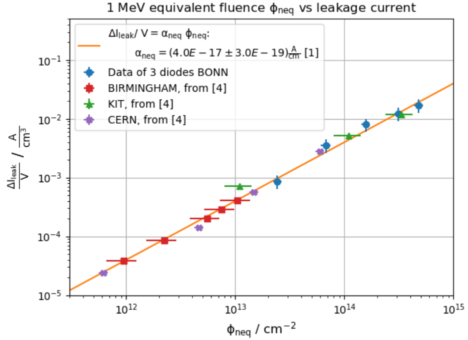
# RADIATION DAMAGE

## --RECAP--



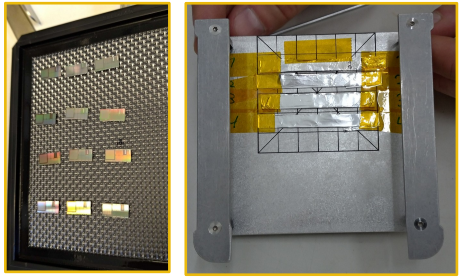

- *33rd RD50 workshop, CERN Nov 2018*
- No setup yet, work-in-progress
- Energy simulations for 14 Mev proton yield ≈ 12.5 MeV on DUT
- Data-driven simulations allow hardness factor estimation $\kappa_p \approx 3 - 4$



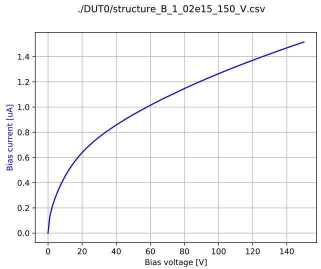




- *35th RD50 workshop, CERN Nov 2019*
- Basic setup working, still in development
- Irradiation of commercial (BPW34F) diodes yield $\kappa_p = 5.1 \pm 0.4$
- Expected linear behaviour, **very good** agreement with other facilities
- Higher than expected $\kappa_p$ → Non-negligible energy loss in diode packaging due to low E → Accounting for this in sim. Agrees with Akkerman et al.
- Use preliminary $\kappa_p = 4 \pm 1$ for thin DUTs according to sim.

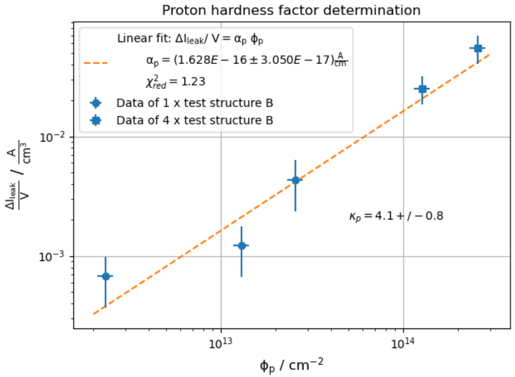
# RADIATION DAMAGE
## --LATEST MEASUREMENTS--



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 via CV-measurement poses problem
  - No setup at the time for reliable CV
- Workaround: use Edge-TCT measurements from I. Mandić† to make qualitative estimation full depletion voltage

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

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

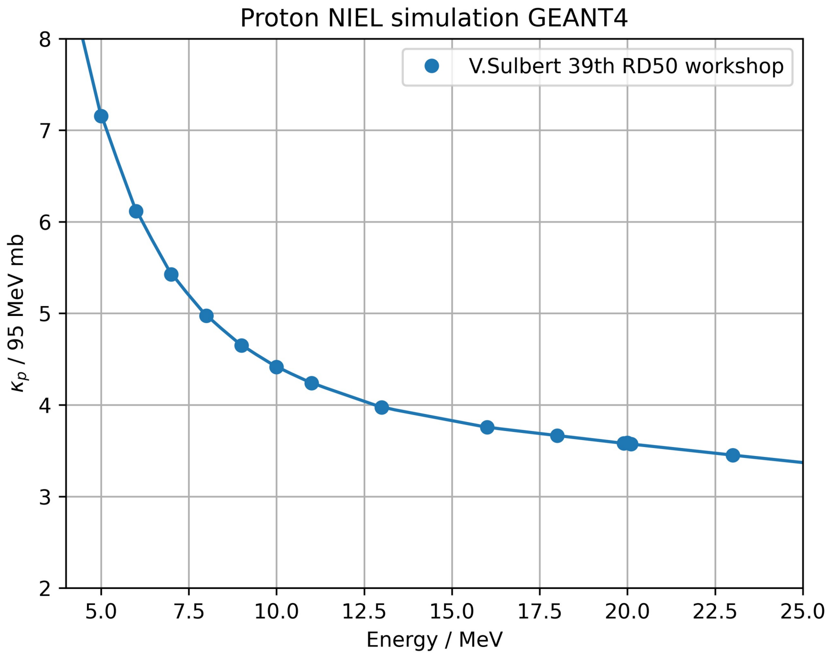
$$\alpha_{eq} = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A\,cm^{-1}}$$

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

- In agreement with expectations, indicates beam energy is sufficient for thin devices, but; large uncertainties still
- As of mid 2021: dedicated CV-measurement setup implemented in Bonn
- New irradiations to take place soon reduce uncertainty

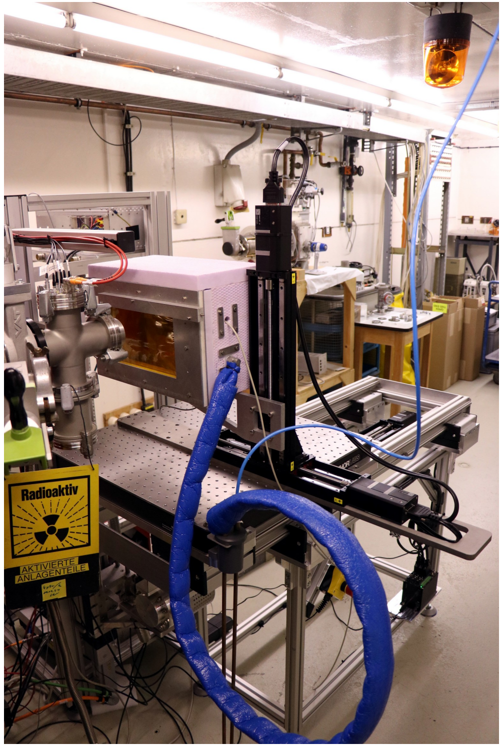
# RADIATION DAMAGE
## --LATEST SIMULATIONS--

- *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!



# CONCLUSION & OUTLOOK

- The proton irradiation site in Bonn has been upgraded to optimize fluence homogeneity and reduce uncertaity on the primary proton fluence
- Custom beam monitoring enables beam-driven irradiation procedure with $\frac{\Delta\phi_{\mathrm{p}}}{\phi_{\mathrm{p}}} \leq 2\%$
- The setup is modular and flexible: suitable to be ported to other ion beams to setup irradiation site or extend existing site with e.g. beam monitoring (please ask if interested)
- Latest irradiations of 200 µm thin LF structures and sim. support expectations of $\kappa_p \approx 4$ enabling irradiation of 1e16 $n_{eq}/cm^2$ within 2 h, but $\kappa_p$ main source of uncertainty ($\Delta\kappa_p/\kappa_p \approx 20\%$)
  - Thorough elec. characterization before/after irradiation of thin devices needed for precise meas.
- Outlook:
  - Hardness factor measurement using thin, well-characterized structures
  - 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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SI LAB Silizium Labor Bonn

# Thank you

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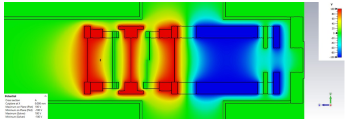
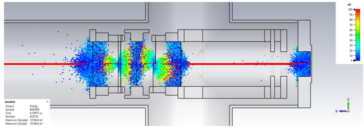
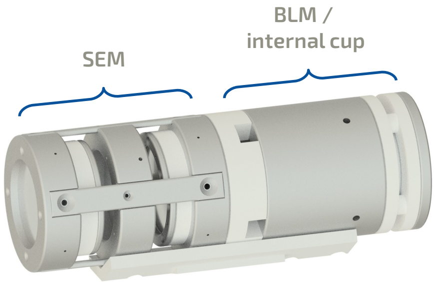
# BACKUP

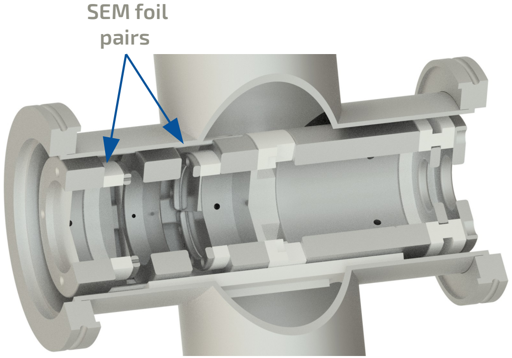
# HARDWARE
## -Beam Monitor-

- 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

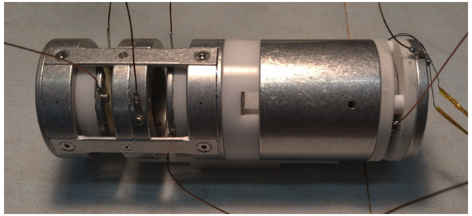


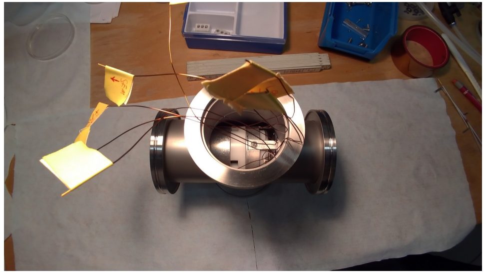





*CAD render of beam monitor by Dennis Sauerland, 2021*



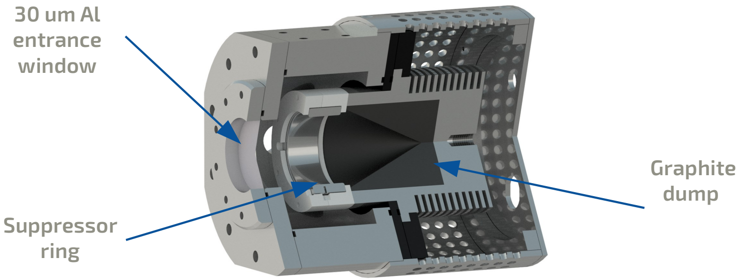


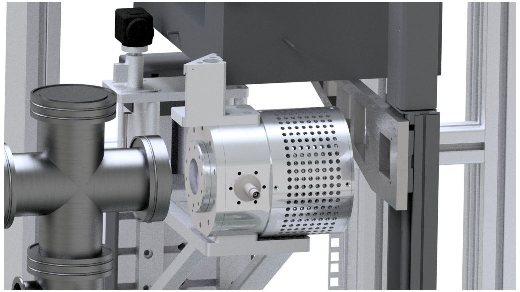
*Installation of beam monitor in cross-piece*

# HARDWARE

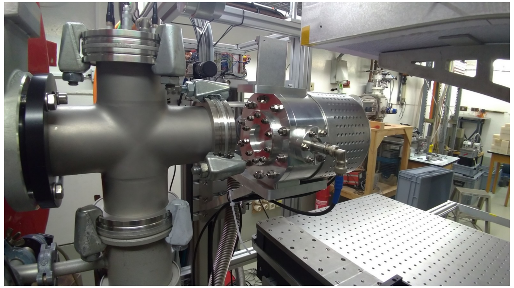
## -Faraday Cup with Camera / Screen-

- 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*

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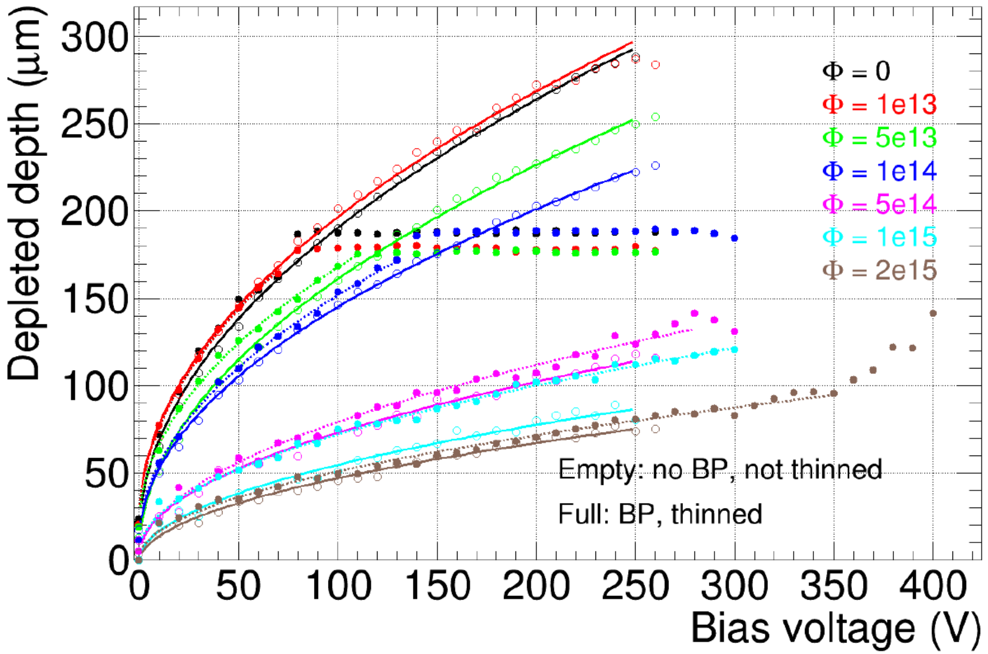
# RADIATION DAMAGE
## --PROTON HARDNESS FACTOR--




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