DEVELOPMENT OF A PROTON IRRADIATION SITE AT BONN UNIVERSITY

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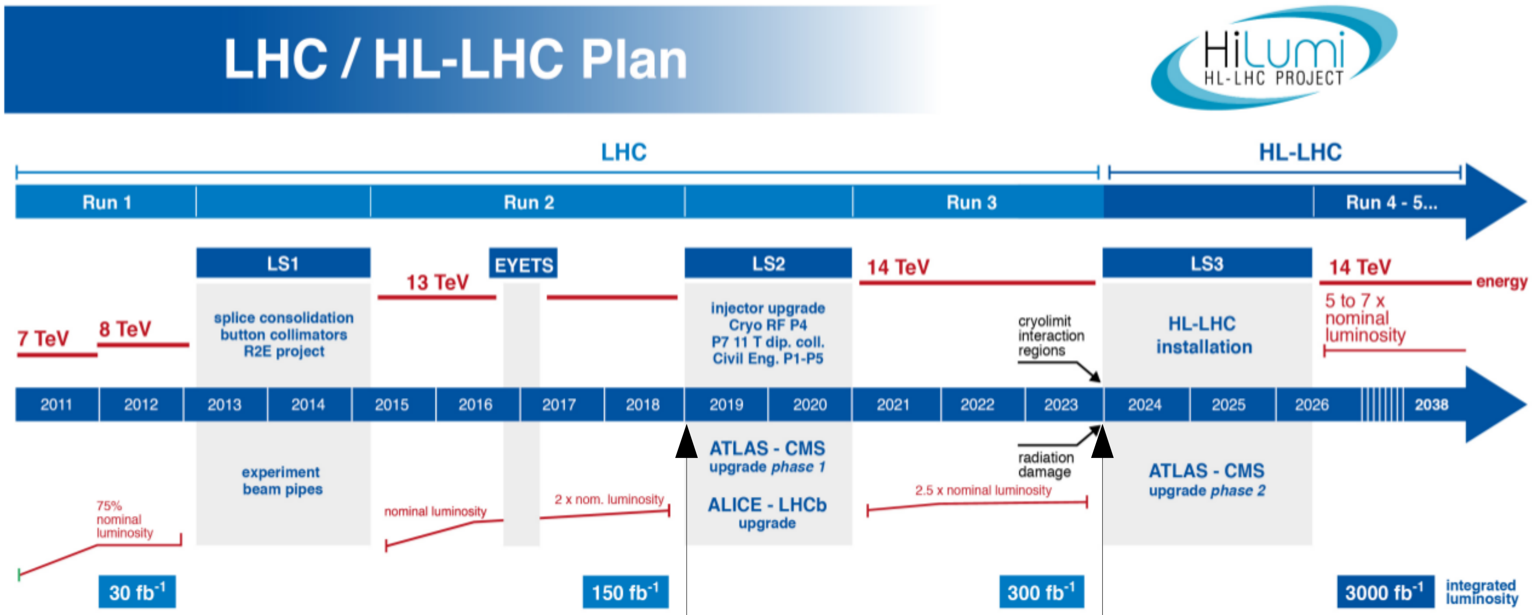
MOTIVATION
-HL-LHC-



We are here!

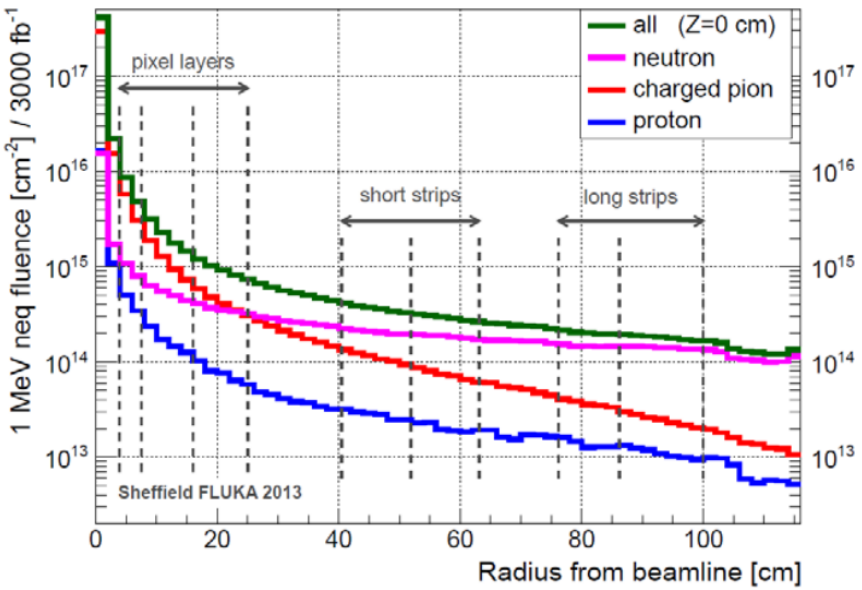
ATLAS ITk upgrade

http://hilumilhc.web.cern.ch/about/hl-lhc-project

MOTIVATION

-HL-LHC-

- 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)
  - - Sensitive volume (- Signal)
  - + Trapping (- Signal)
- Radiation damage studies needed to test prototypes ➞ **Irradiation facilities needed**



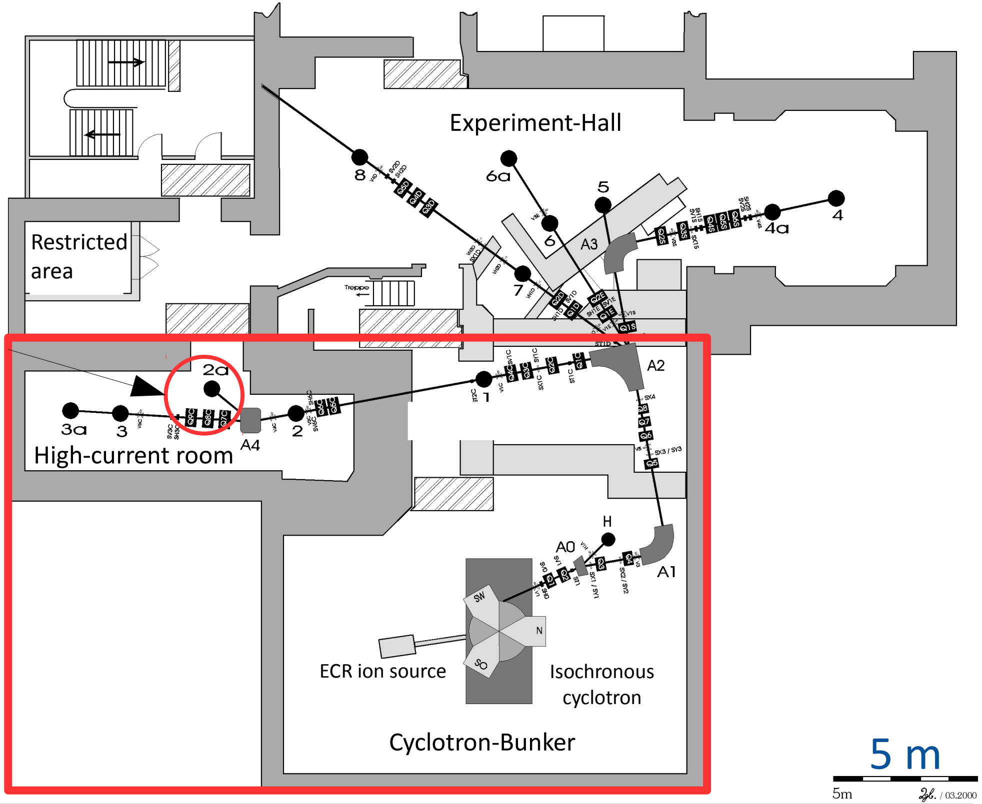
P. S. Miyagawa and I. Dawson, "Radiation background studies for the phase ii inner tracker upgrade," CERN, Tech. Rep. ATL-UPGRADE-PUB-2014-003, Sep. 2014.

THE BONN ISOCHRONOUS CYCLOTRON
-SPECIFICATIONS-

- Eelectron-Cyclotron-Resonance ion source:
  - Protons, Deuterons, Alphas... up to ^{12}C
- E_{kin} from 7 MeV to 14 Mev per nucleon
- Proton beam:
  - Currents from few **nA** to 1 **µA**
  - Gaussian, 1 **mm** ≤ FWHM ≤ 2 **cm**
  - Flux(1 µA) ≈ $6x10^{12}$ s^{-1} cm^{-2}

THE BONN ISOCHRONOUS CYCLOTRON
-SETUP SITE-

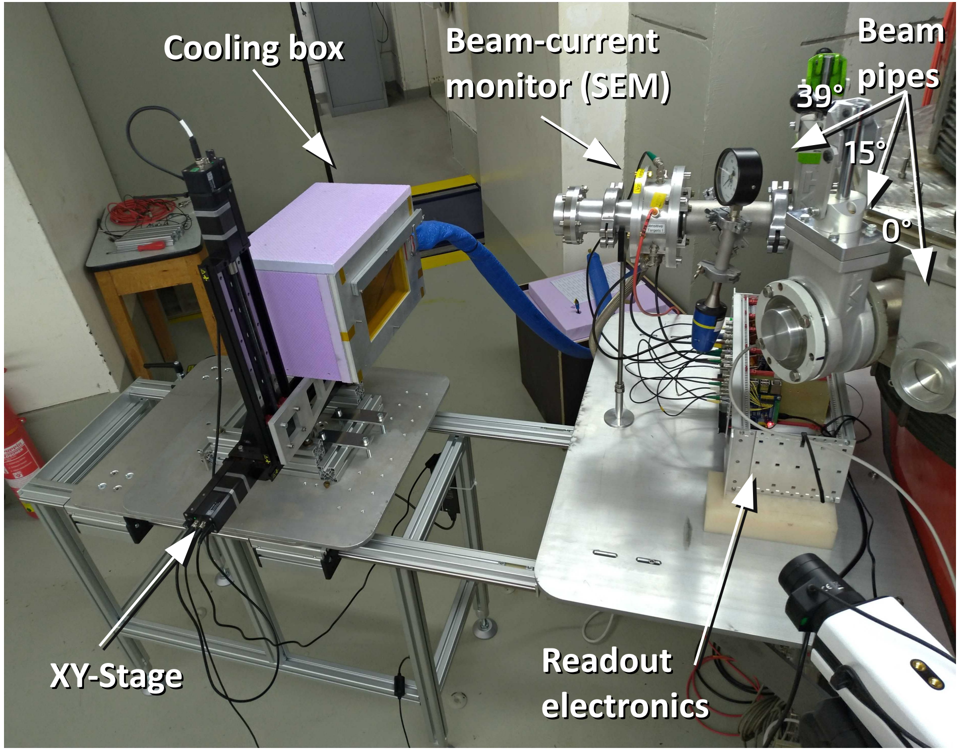
- Overview of cyclotron hall
  - Multilple beam lines and extractions
  - Irradiation site located at **high-current room** behind A4 magnet
  - Entire cyclotron hall is **control area** with regard to radiation protection



https://www.zyklotron.hiskp.uni-bonn.de/zyklo/technik/technik.html

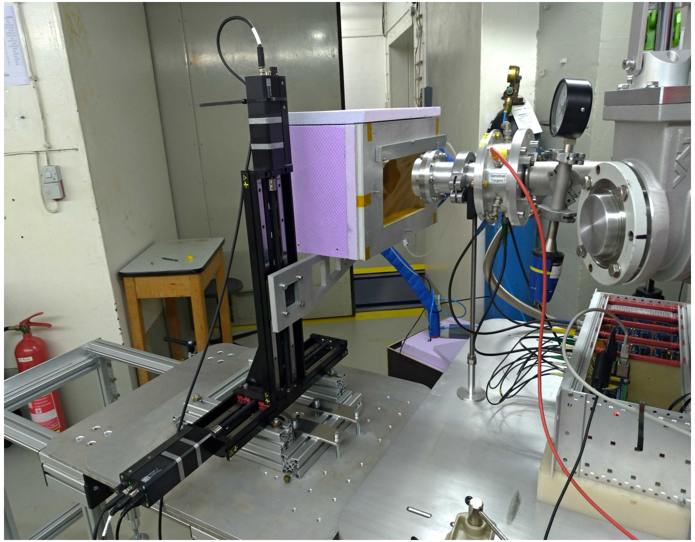
THE IRRADIATION SITE
-SETUP-

- Three extraction lines under 0°, 15° and 39° w.r.t beamline for e.g. different particles:
  - $FWHM_{Max}(15°) \approx 2$ cm
  - **$FWHM_{Max}(39°) \approx 1$ cm**
- Console table for RO electronics + support
- Aluminium profile setup table:
  - load ≤ 200 kg, flexible position
  - Rotating mounting plate, slides along beam axis
  - Mount for XY-Stage + cooling box



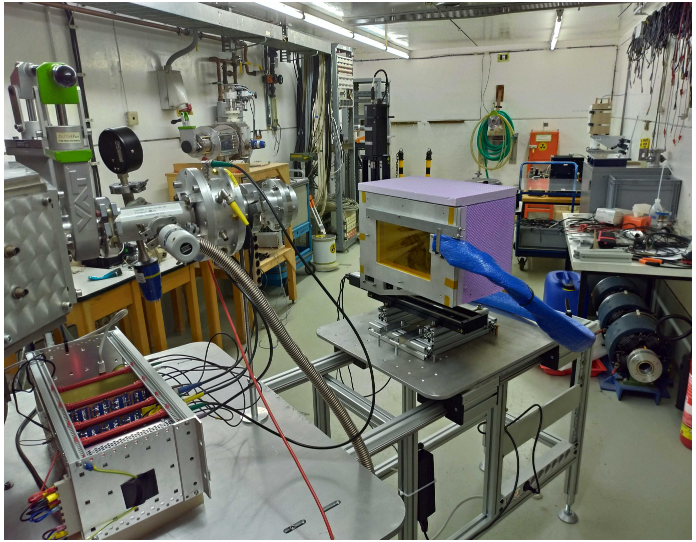
THE IRRADIATION SITE

-SETUP-



Setup in irradiation position. Cooling box to prevent self-heating and annealing effects.

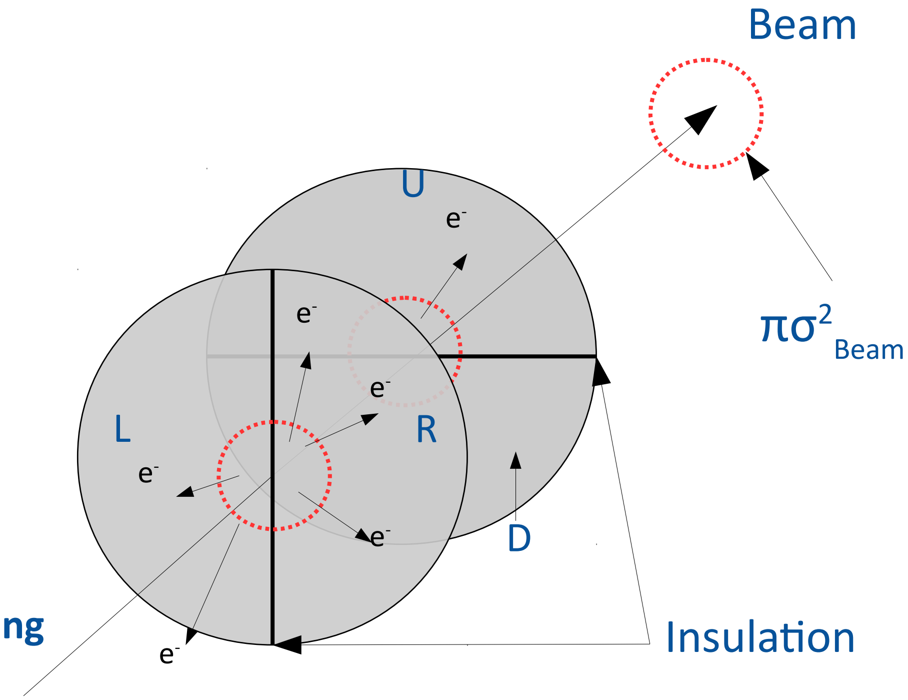
Liquid N_2-reservoir for gas cooling and respective gas cylinder



Overview of high-current room

BEAM CURRENT MONITORING
-SECONDARY-ELECTRON-MONITOR (SEM)-

- Motivation: **proton fluence ϕ_p**
- Two pairs of thin, segmented foils (C)
- Beam penetration releases e^-
- e^- captured by HV
- Secondary current $\mathbf{I_{SEM} = const \cdot I_{Beam}}$
- Each foil independent **RO channel:** L, R, U, D
- Segmentation gives **position information**
- **Allows online beam-current & -position monitoring**



BEAM CURRENT MONITORING
-CUSTOM READOUT ELECTRONICS-

- Input current is projected to **0 – 5** V:

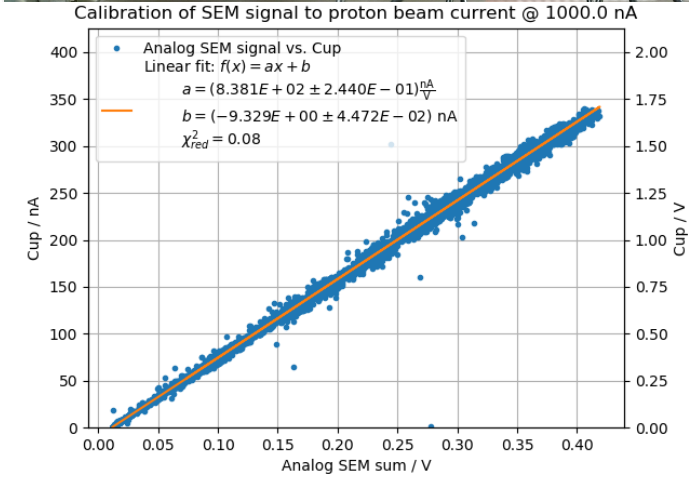
$$U_{OUT} = \frac{I_{IN}}{R_{FS}} \cdot 5\,V \quad \Leftrightarrow \quad I_{IN} = \frac{U_{OUT}}{5\,V} \cdot R_{FS}$$

with R_{FS} = **full-scale (5V) current resolution** of RO electronics: R_{FS} ϵ {3.3, 10, 33, 100, 330, 1000} nA

- Calibration of SEM current to beam current needed:
  - Correlate U_{Σ} of SEM to I_{beam} :

$$I_{Beam}(U_{\Sigma}) = \lambda_{\Sigma} \cdot R_{FS} \cdot U_{\Sigma}$$

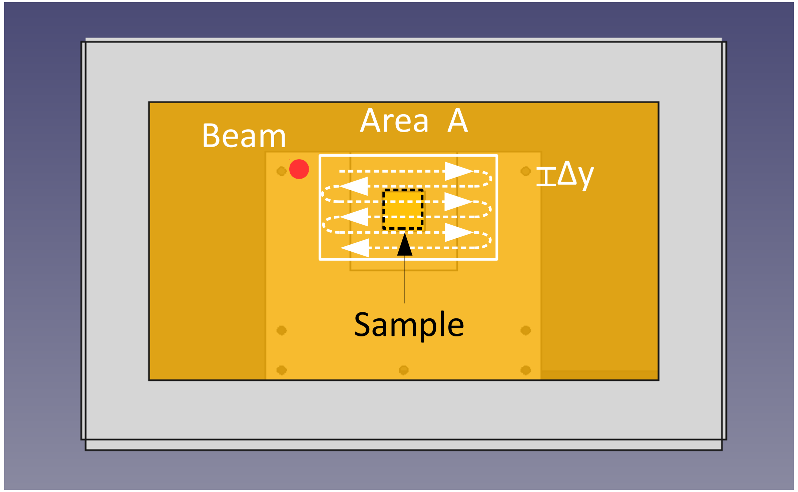
with $\lambda_{\Sigma} = (853.48 \pm 10.96) \times 10^{-3}\,\frac{1}{V}$



IRRADIATION PROCEDURE
-PROTON FLUENCE-

- Proton fluence $\phi_p = \frac{I_p \cdot t}{e \cdot A}$
- By scanning in equidistant rows with width **Δy** and constant speed $\mathbf{v_x}$, the fluence per complete scan over **A** can be rewritten:

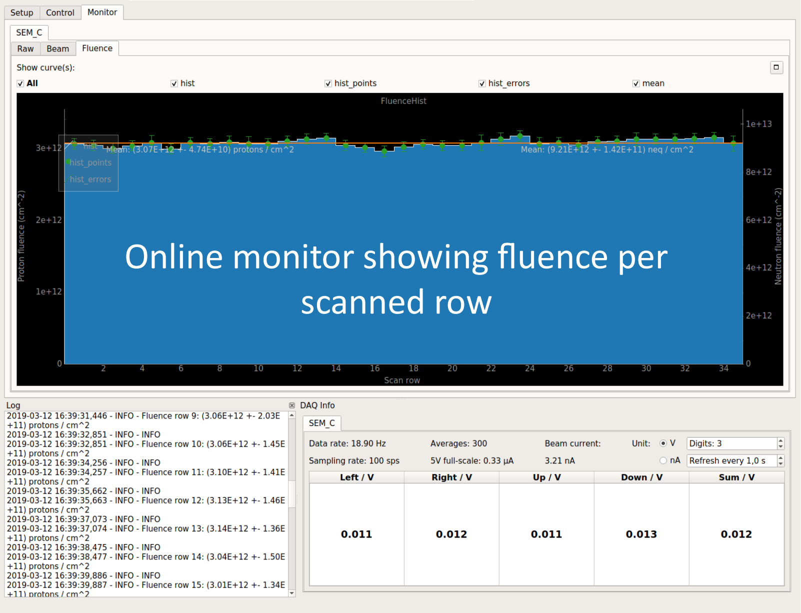
$$\phi_p = \frac{I_p}{e \cdot v_x \cdot \Delta y}$$



- For I_p = 1 µA, v_x = 100 mm/s and Δy = 1 mm, a proton fluence of $\boldsymbol{\phi_p \approx 6 \times 10^{12}}$ **p/cm²** is generated per scan
- Irradiation of 2 cm² device up to 5x10^{15} neq anticipated within 60 minutes

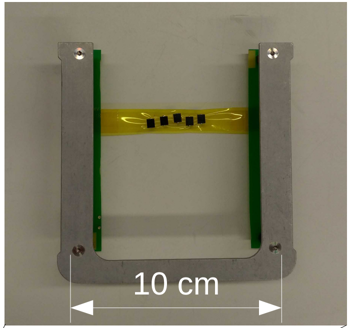
IRRADIATION PROCEDURE
-FIRST IRRADIATION-

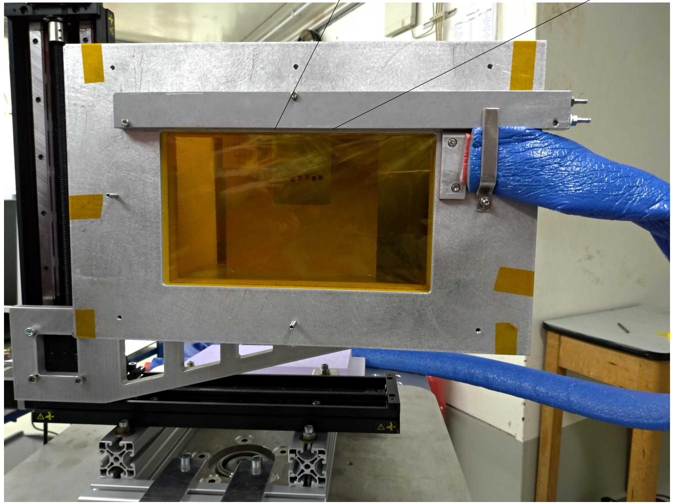
- Irradiation of 25 PiN-diodes (BPW34F) to 5 different fluences in order to measure hardness factor $\kappa = \alpha_{exp}/\alpha_{neq}$ via: $\Delta I = \alpha \cdot V \cdot \Phi_{neq}$



Online monitor showing fluence per scanned row

5 diodes on Kapton tape in device holder, mounted in box





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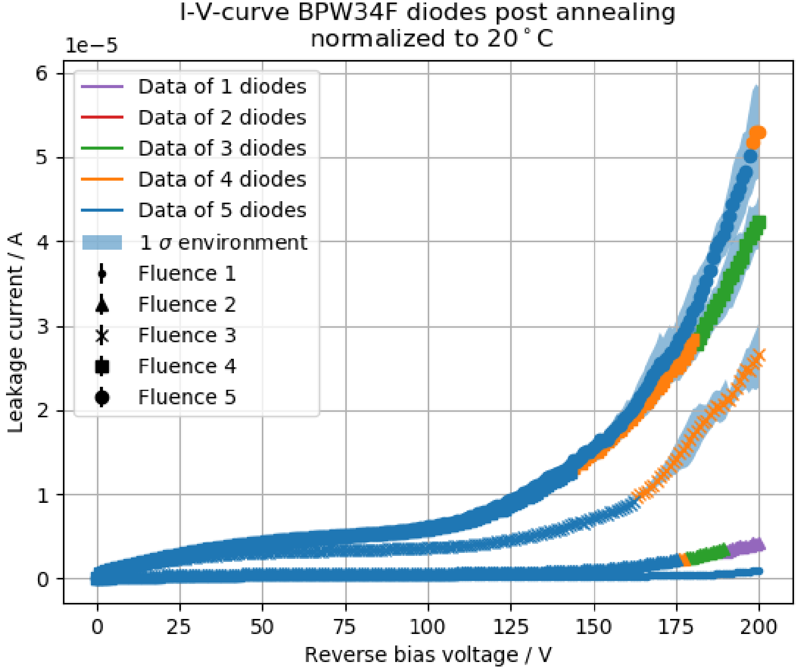
IRRADIATION RESULTS
-FIRST IRRADIATION-

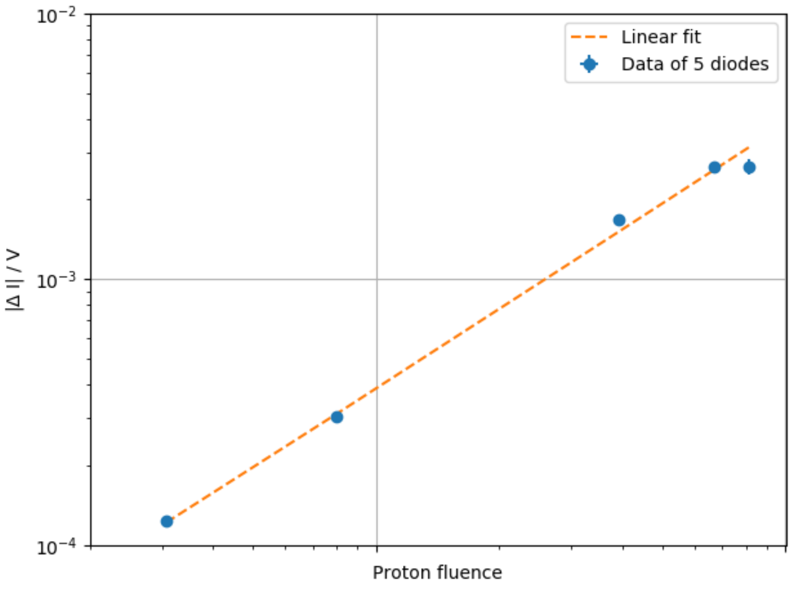


- I-V-curves of irradiated diodes:
  - Annealing for 80 min @ 60 °C, measured in climate chamber
  - Fluence increasing from 1 to 5
  - Leakage current increasing with fluence

=> Evaluation of leakage current at full-depletion voltage V_{dep} = 91 V*

**Talk by C. Simpson-Allsop at 33rd RD50 workshop @ CERN*

IRRADIATION RESULTS
-FIRST IRRADIATION-



- Linear relation between fluence and leakage current as expected from $\Delta \mathrm{I} = \alpha \cdot \mathrm{V} \cdot \Phi_{\mathrm{neq}}$
- ...but unknown, systematic loss of beam:
  - prevents for quantitative determination of hardness factor
  - possibly due to beam optics (focussing)

=> Apart from systematic effect, irradiation procedure works

SUMMARY & OUTLOOK

- A new proton irradiation site has been developed at Bonn University
  - Devices are scanned through static beam, **homogeneous** irradiation
  - On-line beam current measurement allows to determine fluence per scan & row:
    - Beam current measured non-destructively via calibrated SEM
  - Devices are **cooled** during irradiation to minimize annealing + self-heating effects
  - First irradiation of PiN-diodes show that the procedure works as expected:
    - I-V-curves look as expected, linear behavior of leakage current with increasing fluence
    - ..but, systematic loss of beam current needs to be investigated
- New irradaition of diodes with improved beam optics within this week in order to determine correct proton hardness factor

THANK YOU

UNIVERSITÄT BONN Physikalisches Institut HISKP SI LAB Silizium Labor Bonn

BACKUP

BEAM CURRENT MONITORING

-CUSTOM READOUT ELECTRONICS-

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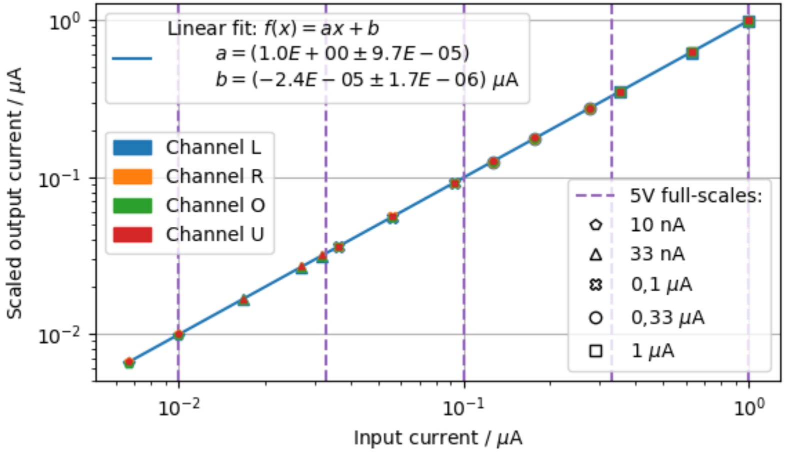
- Input current is projected to **0 – 5** V:

$$U_{OUT} = \frac{I_{IN}}{R_{FS}} \cdot 5\,\mathrm{V} \quad \Leftrightarrow \quad I_{IN} = \frac{U_{OUT}}{5\,\mathrm{V}} \cdot R_{FS}$$

  with R_{FS} = 5V full-scale current resolution of RO electronics: $R_{FS} \in \{3.3, 10, 33, 100, 330, 1000\}$ nA

- The RO electronics have 4 input channels:
  - One for each SEM foil: I_L, I_R, I_U, I_D
- … and 7 output voltages:
  - Raw input: U_L, U_R, U_U, U_D
  - Analog sum U_Σ, $U_{H/V\text{-}Shift} = U_{L/U} - U_{R/D} \;/\; U_\Sigma$

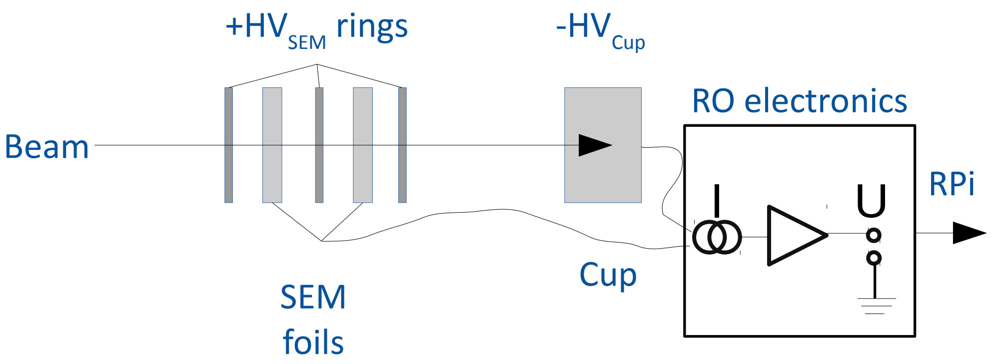


BEAM CURRENT CALIBRATION

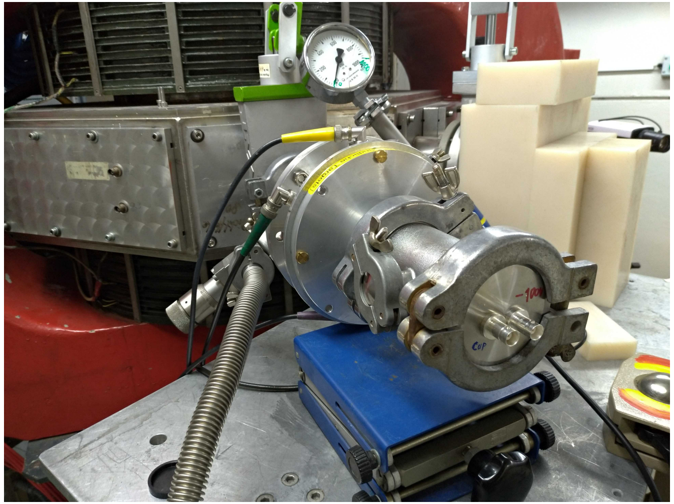
-MEASUREMENTS-

=> Calibration between SEM & beam current needed: $\mathbf{I_{SEM} = const \cdot I_{Beam}}$

- Measure beam current $\mathbf{I_{Beam}}$ versus $\mathbf{U_{\Sigma}}$ of the SEM and fit straight line
- Slope of fit gives proportionality constant for corresponding R_{FS}
- Check signal saturation depending on HV_{SEM} and HV_{Cup}



Setup on 22.01.19



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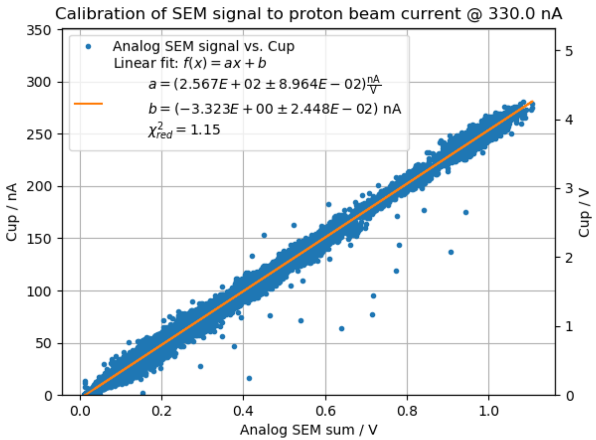
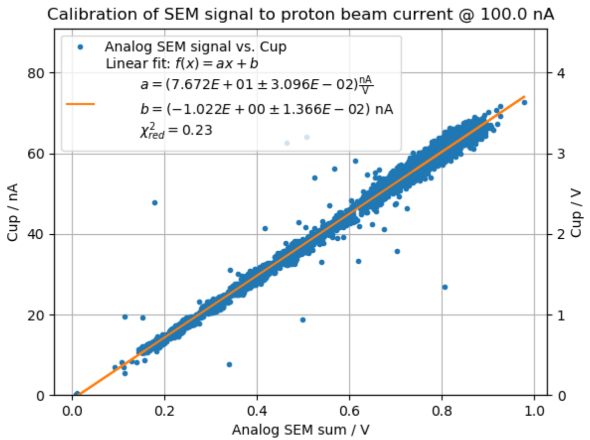
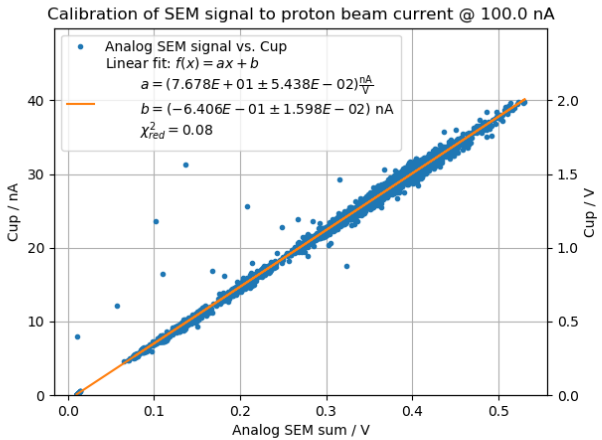
BEAM CURRENT CALIBRATION
-MEASUREMENTS HV_{SEM} @ 70V-



22.01.19, R_{FS} = 330 nA



22.01.19, R_{FS} = 100 nA



23.01.19, R_{FS} = 100 nA

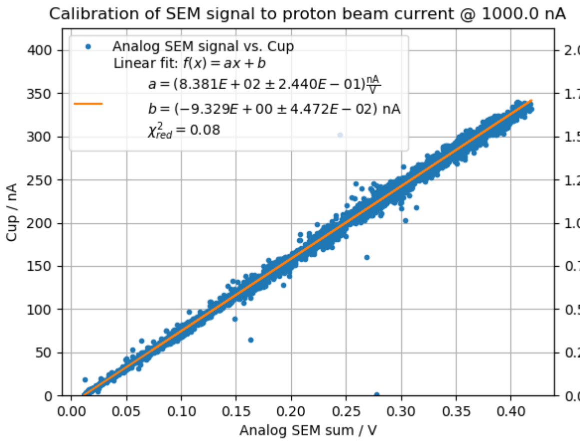
$$\lambda_1 = (777.94 \pm 0.27) \cdot 10^{-3} \frac{1}{\text{V}}, \quad \lambda_2 = (767.19 \pm 0.31) \cdot 10^{-3} \frac{1}{\text{V}}, \quad \lambda_3 = (767.78 \pm 0.54) \cdot 10^{-3} \frac{1}{\text{V}}$$

$$\boldsymbol{\lambda = (770.97 \pm 4.93) \times 10^{-3} \frac{1}{\text{V}}}$$

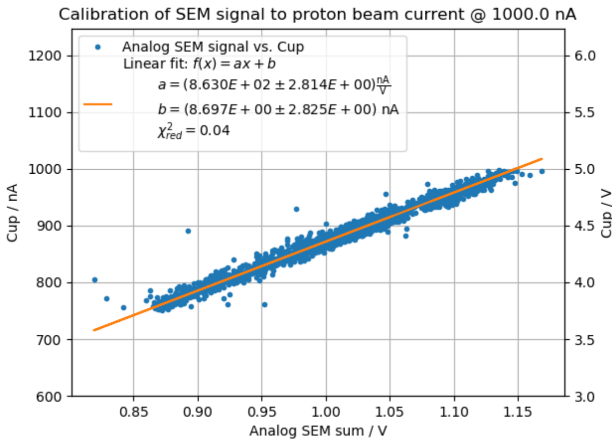
=> Δλ/λ ≈ 0.64 %

BEAM CURRENT CALIBRATION

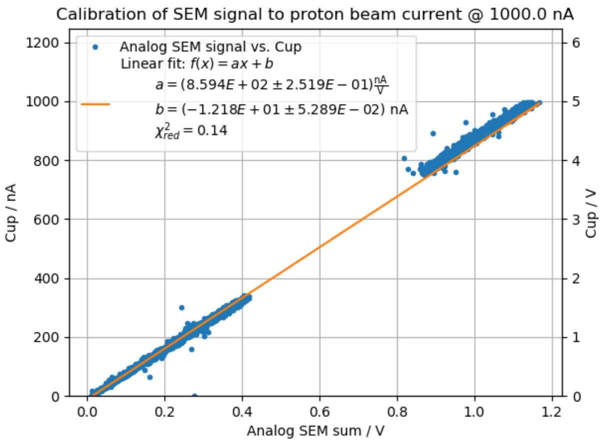
-MEASUREMENTS HV_{SEM} @ 100V-



05.02.19, R_{FS} = 1000 nA



12.02.19, R_{FS} = 1000 nA, w/ cuts



Combined

$$\lambda_1 = (838.12 \pm 0.24) \cdot 10^{-3} \frac{1}{\mathrm{V}}, \quad \lambda_2 = (862.98 \pm 2.81) \cdot 10^{-3} \frac{1}{\mathrm{V}}, \quad \lambda_3 = (859.35 \pm 0.25) \cdot 10^{-3} \frac{1}{\mathrm{V}}$$

$$\lambda = (\mathbf{853.48 \pm 10.96}) \times \mathbf{10^{-3} \frac{1}{V}}$$

=> Δλ/λ ≈ 1.3 %

FLUENCE UNCERTAINTY
-ESTIMATION-

- Proton fluence generally given by:

$$F_p = \frac{I_p \cdot t}{q_e \cdot A}$$

I_p = proton current, t = time
q_e = elem. charge, A = area

- When scanning the area **A=W*H** in **n** vertical steps of size **Δy** with horizontal scan speed $\mathbf{v_x}$,it follows for **t**:

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

- This allows to rewrite F_p:

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

=> **Uncertainty on fluence mainly given by error on $\mathbf{I_p}$ measurement!** (Δy & v_x precise in um range)

FLUENCE UNCERTAINTY
-ESTIMATION-

- For the beam current measurement uncertainty it follows:
  - $\Delta\lambda / \lambda \approx 0.6\,\% - 1.3\,\%$ => Estimate worst case: **3 %**
  - $\Delta R_{FS} / R_{FS} \approx$ **1%**
  - $\Delta U_{\Sigma} / U_{\Sigma} \approx$ **1%**
- Plug-in Gaussian EP: $$\Delta I_{\mathrm{Beam}}^2 = (\Delta\lambda \cdot R_{\mathrm{FS}} \cdot U_{\Sigma})^2 + (\lambda \cdot \Delta R_{\mathrm{FS}} \cdot U_{\Sigma})^2 + (\lambda \cdot R_{\mathrm{FS}} \cdot \Delta U_{\Sigma})^2$$ $$= \left(3\,\%\ I_{\mathrm{Beam}}\right)^2 + \left(1\,\%\ I_{\mathrm{Beam}}\right)^2 + \left(1\,\%\ I_{\mathrm{Beam}}\right)^2$$ $$\Rightarrow \Delta I_{\mathrm{Beam}} \approx 3.3\,\%\ I_{\mathrm{Beam}}$$
- Due to neglecting y-intersect in calibration, **we finally need to add the error of the respective R_{FS}**:

$$\boxed{\Delta I_{\mathrm{Beam}} = 3.3\,\%\ I_{\mathrm{Beam}} + 1\,\%\ R_{\mathrm{FS}}}$$

FLUENCE UNCERTAINTY
-ESTIMATION-

- The error on I_{Beam} contains constant part => Dominates for low beam currents measured in high R_{FS}:
  - I_{beam} = 10 nA, measured in R_{FS}= 1000 nA => ΔI_{beam} = 0.03 * 10 nA + 0.01 * 1000 nA = **10.3 nA**
- => Generally one should chose R_{FS} such that $U_{\Sigma} \gtrapprox 1$ V for which follows: $\mathbf{\Delta I_{Beam} / I_{Beam} < 5\ \%}$
- Taking this into account, the proton fluence can be measured knowing the beam current as

$$\mathrm{F_p} = \frac{\mathrm{I_{Beam}}}{\mathrm{q_e} \cdot \Delta \mathrm{y} \cdot \mathrm{v_x}} \quad \text{with} \quad \Delta \mathrm{F_p} = \frac{\Delta \mathrm{I_{Beam}}}{\mathrm{q_e} \cdot \Delta \mathrm{y} \cdot \mathrm{v_x}}$$

with the same relative uncertainty of $\mathbf{\Delta F_p / F_p < 5\%}$