DEVELOPMENT STATUS OF A PROTON IRRADIATION SITE AT BONN UNIVERSITY

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33rd RD50 Workshop CERN, 26.11.2018

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OUTLINE

- The isochronous cyclotron Bonn at HISKP
  - Specifications, setup site & common isotopes for proton irradiation
- Beam current monitoring:
  - Custom-made secondary electron monitors (SEMs) and readout (RO) electronics
  - Proof of concept
- GEANT4 energy distribution simulations
- Proton hardness factor estimations and planned measurements
- Foreseen irradiation parameters

THE HISKP ISOCHRONOUS CYCLOTRON

THE HISKP ISOCHRONOUS CYCLOTRON

-SPECIFICATIONS-

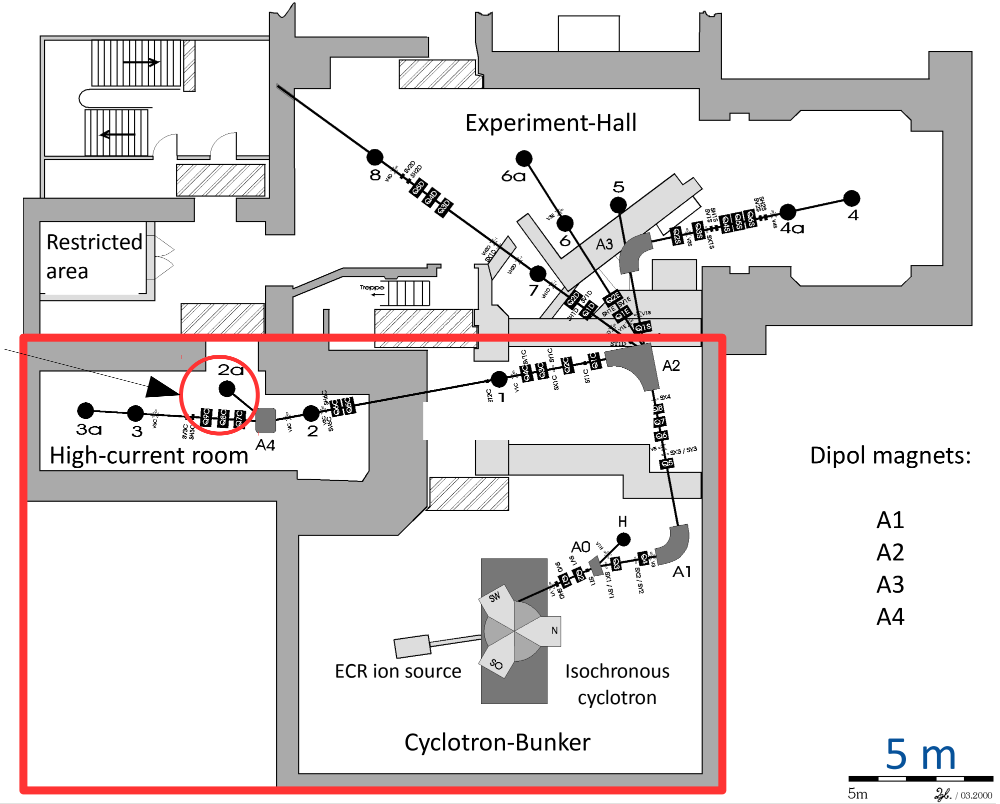
- ECR[1] ion source:
  - Protons, Deuterons, Alphas... up to ^{12}C
- E_{kin} from 7 MeV to 14 Mev per nucleon
- Proton beam:
  - Currents from few **nA** to 1 **µA**
  - Gaussian, 1 **mm** ≤ FWHM ≤ 2 **cm**
  - Flux(1 µA) ≈ $6 \times 10^{12}\ s^{-1}\ cm^{-2}$

[1]Electron-Cyclotron-Resonance

THE HISKP ISOCHRONOUS CYCLOTRON

-SETUP SITE-

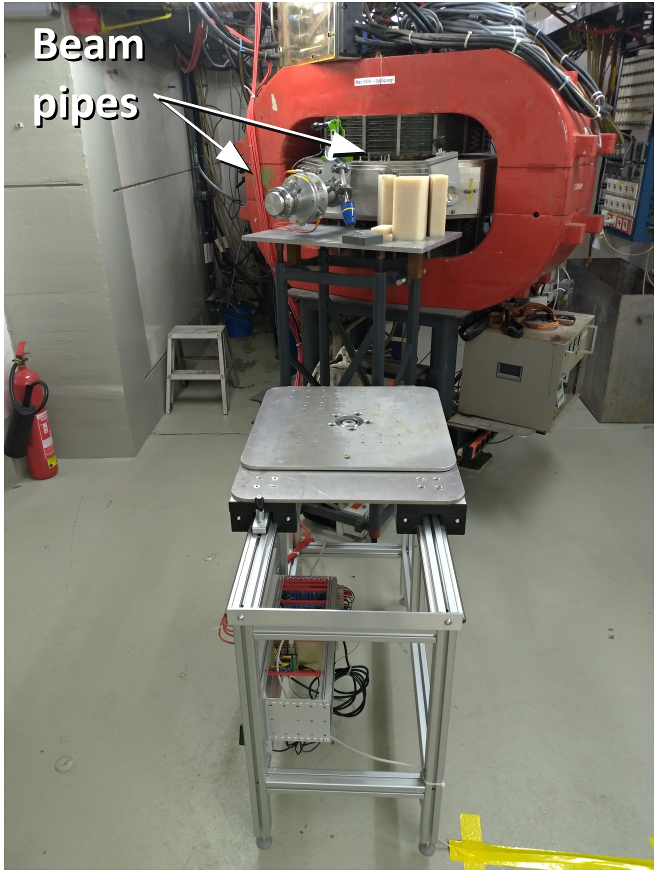
- Overview of cyclotron hall
  - Multilple beam lines and extractions
  - Irradiation site located at **high-current room** behind A4 magnet
  - Additional PC setup possible in cyclotron control room or at site, but:
    - Setup located at site during beam has to be released by radiation protection officer



THE HISKP ISOCHRONOUS CYCLOTRON

-SETUP SITE-

- Easily accessible setup, free space
- Two extraction lines under 15° and 39°
  - FWHM$_{Max}$(15°) ≈ 2 cm; **FWHM$_{Max}$(39°) ≈ 1 cm**



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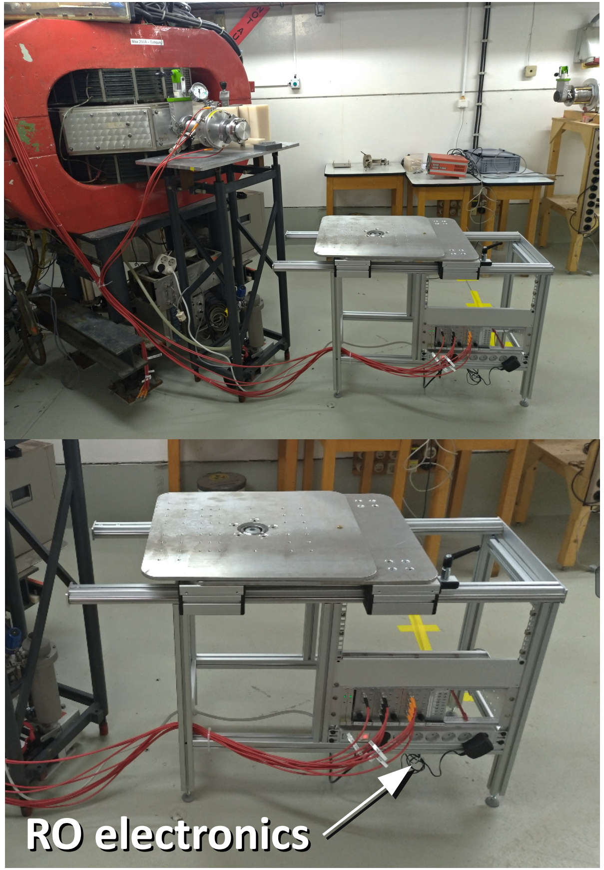
THE HISKP ISOCHRONOUS CYCLOTRON

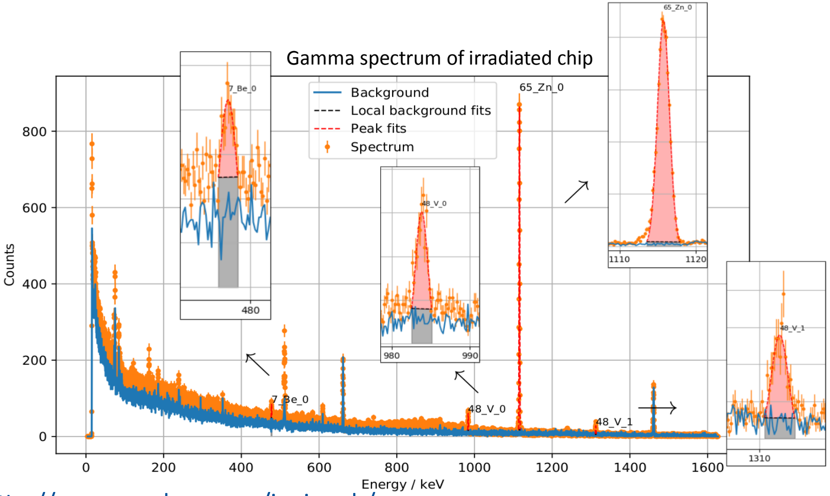
-SETUP SITE-

- Easily accessible setup, free space
- Two extraction lines under 15° and 39°
  - $\mathrm{FWHM}_{\mathrm{Max}}(15°) \approx 2$ cm; **$\mathbf{FWHM}_{\mathbf{Max}}(39°) \approx 1$ cm**
- Custom setup table:
  - supports load ≤ 200 kg
  - Rotating mounting plate, slides along beam axis allow positioning close to extraction
  - Integrated RO electronics stack



THE HISKP ISOCHRONOUS CYCLOTRON
-COMMON ISOTOPES-

- Uncontrolled irradiation of broken chip to probe activity:
  - 14 MeV protons, $\phi \approx 2e15\ p/cm^2$, **no** scanning or shielding
- Gamma-spectroscopy[2] identifies long-lived isotopes:
  - ^{65}Zn from ^{65}Cu ($\sigma \approx 600$ mb)[3] , $T_{1/2} \approx 244d$
  - ^{48}V from ^{48}Ti ($\sigma \approx 500$ mb)[3], $T_{1/2} \approx 16d$
  - ^{7}Be from ^{14}N ($\sigma \approx 10$ mb)[3], $T_{1/2} \approx 53d$
- Estimated time for release from radiation protection after irradiation date: **1-2 weeks**

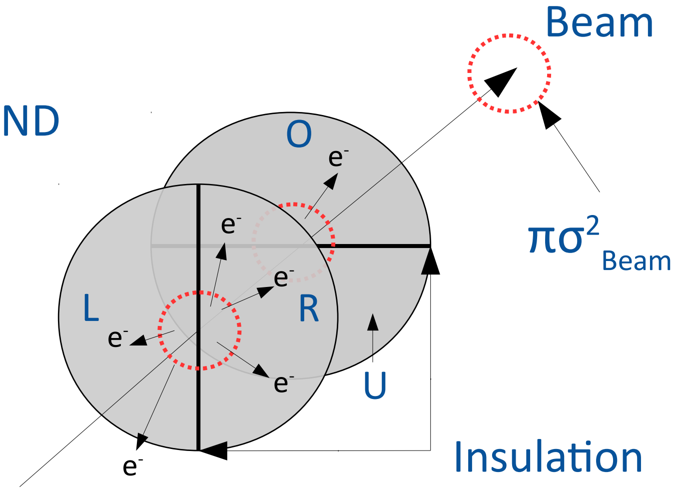


[2]Gamma-Spectroscopy performed approx. 1 month post irradiation [3]14 MeV protons from http://www.oecd-nea.org/janisweb/

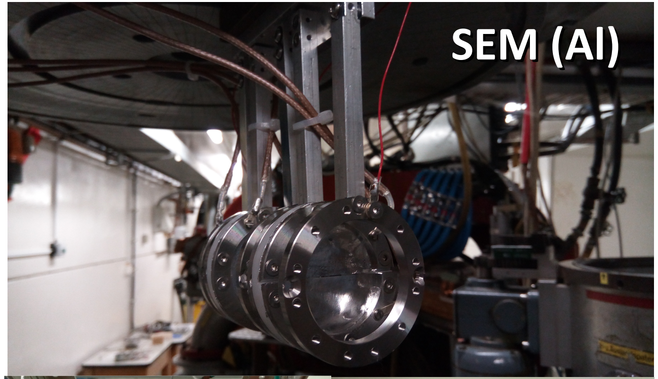
BEAM CURRENT MONITORING

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

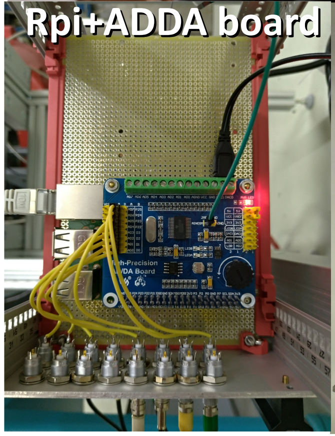
- Motivation: Use integrated beam current for **proton fluence calculation**
- SEM consists of two pairs of thin, segmented foils (Al, C), penetraded by beam:
  - ΔE to e^- => λ_{mean} sufficient for e^- at foil surfaces to transit to vaccum with E_{kin} ~ 10 eV
  - e^- captured by HV rings => foils positive w.r.t. GND
  - Secondary current $\mathbf{I_{SEM} = const \cdot I_{Beam}}$ from foils to GND
  - Each foil independent **RO channel:** L, R, O, U
  - Segmentation gives **position information**
- **Allows on-line beam-current & position monitoring**

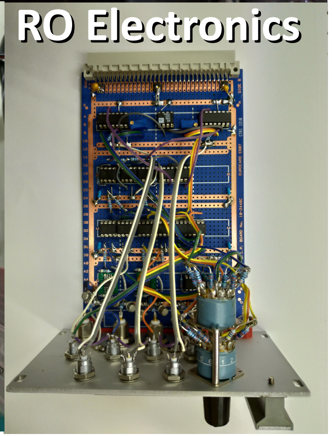


BEAM CURRENT MONITORING
-SEMs & READOUT ELECTRONICS-



- Secondary current range: **nA ≤ I_{SEM} ≤ μA**
  - Custom RO electronics developed and tested
  - Conversion & projection of I_{SEM} to **0 – 5 V**
  - Selectable resolutions from 3 nA to 1 μA
  - Approx. 1% uncertainty on I_{SEM} measurement
  - Readout via RPi & 8-Ch. ADDA board



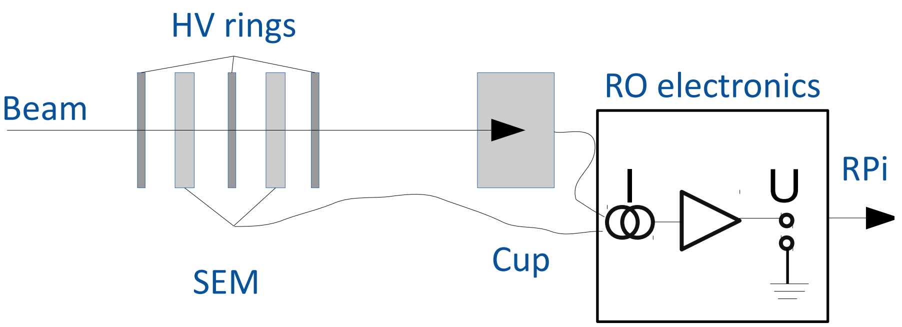


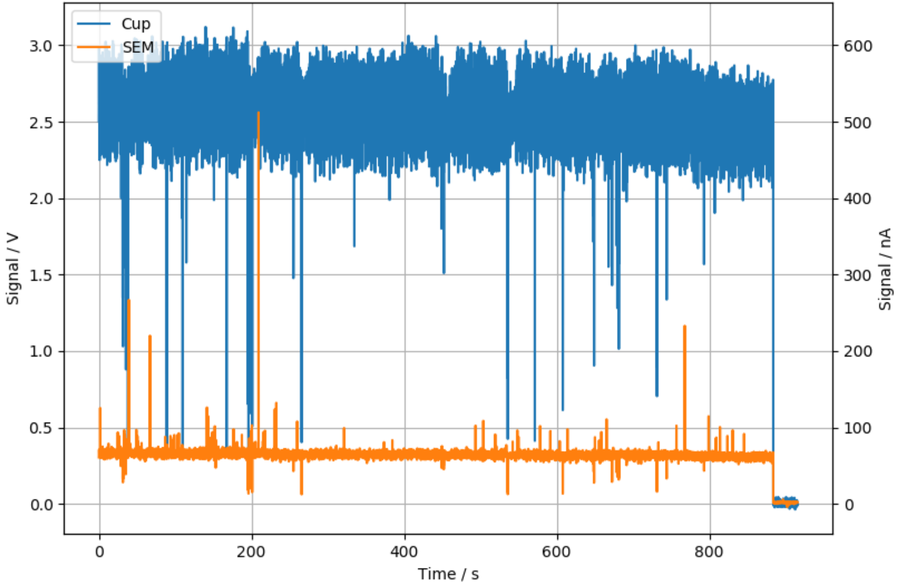
BEAM CURRENT MONITORING

-PROOF OF CONCEPT-

=> Calibration between beam- & SEM current needed!

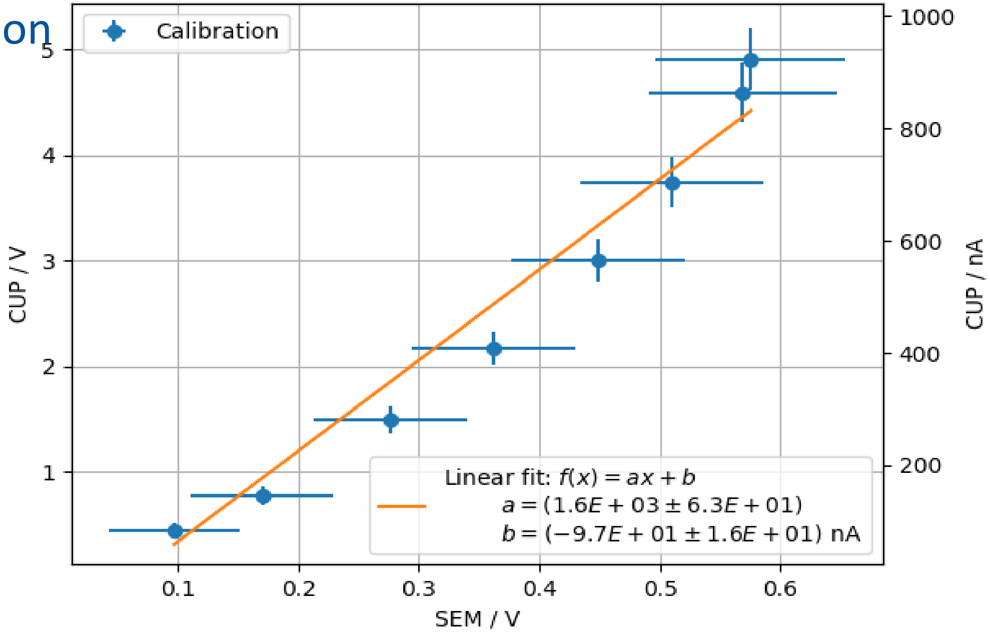
- Measure beam current destructively while measuring SEM current
- Find correlation parameters





BEAM CURRENT MONITORING
-PROOF OF CONCEPT-

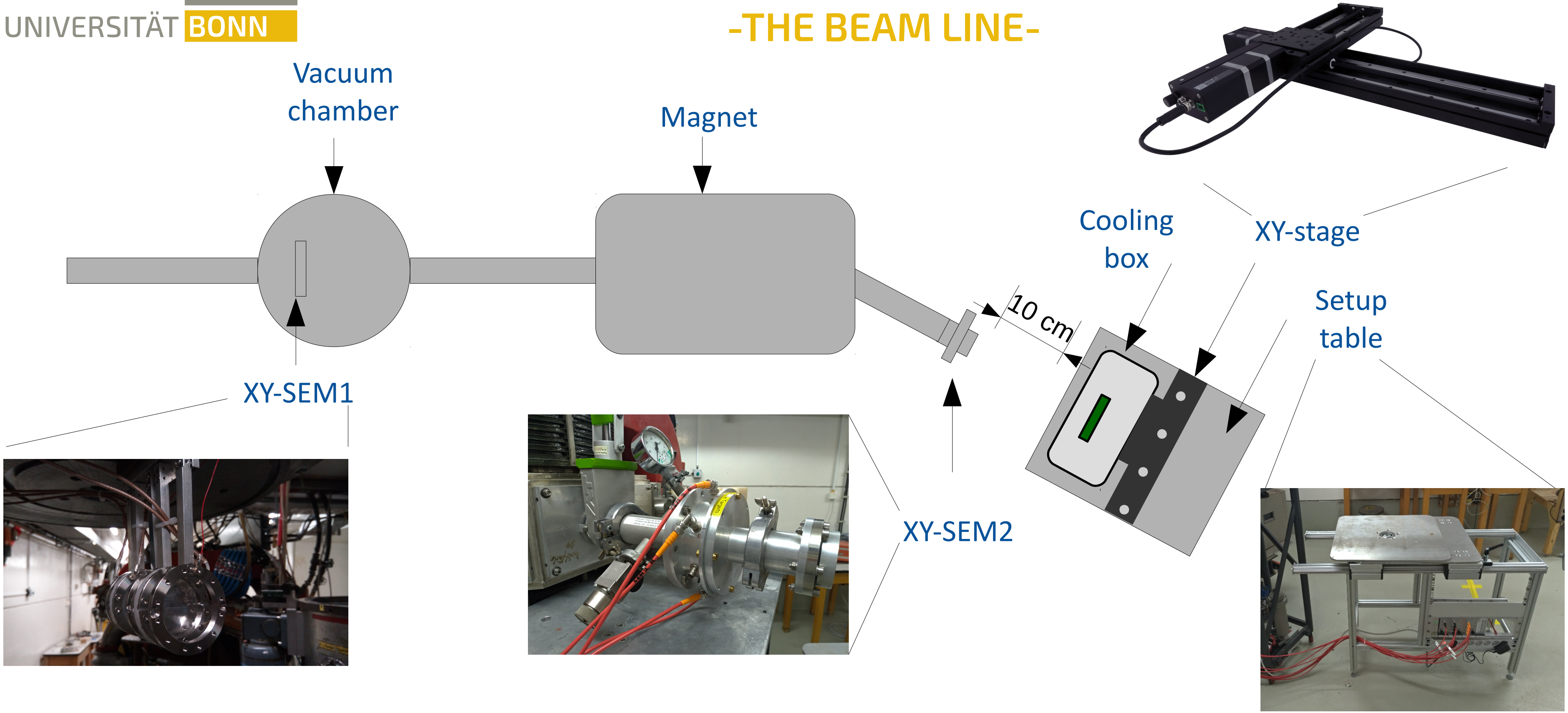
- First calibration could be done & correlation between I_{SEM} and I_{BEAM} could be verified!
- **Proof of concept** in worst-case-scenario:
  - Unstable, noisy beam due to violent shutdown of ECR-ion source
- Several calibrations needed to verify repeatability
- Errors are expected to be reduced significantly under normal conditions



GEANT4 ENERGY SIMULATIONS
&
PROTON HARDNESS FACTOR

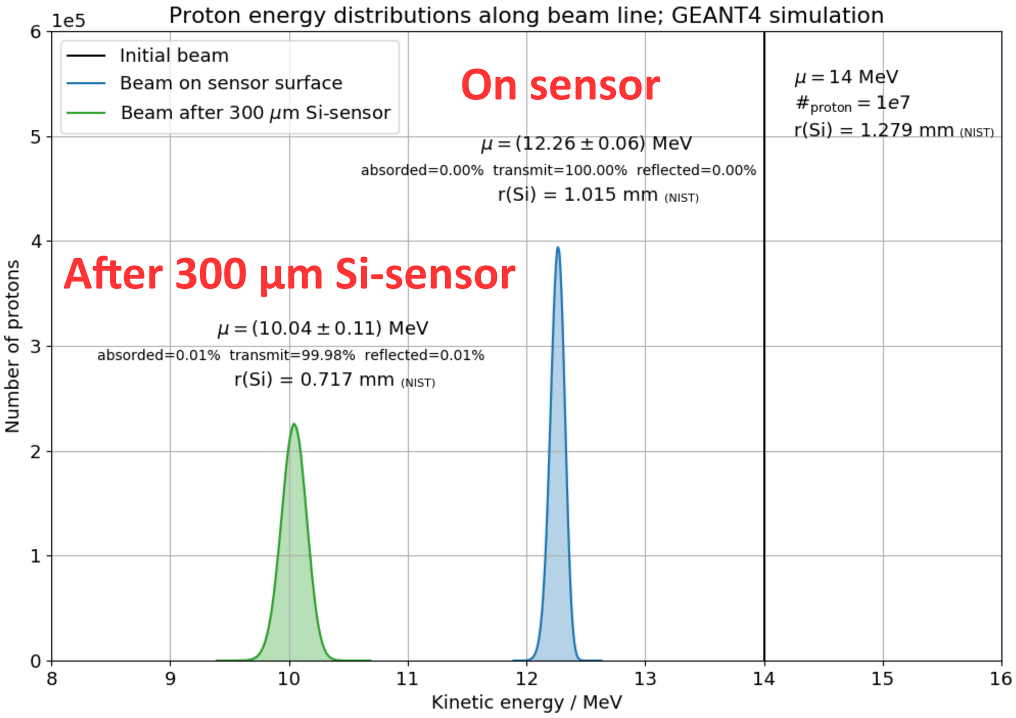
GEANT4 ENERGY SIMULATIONS

-THE BEAM LINE-



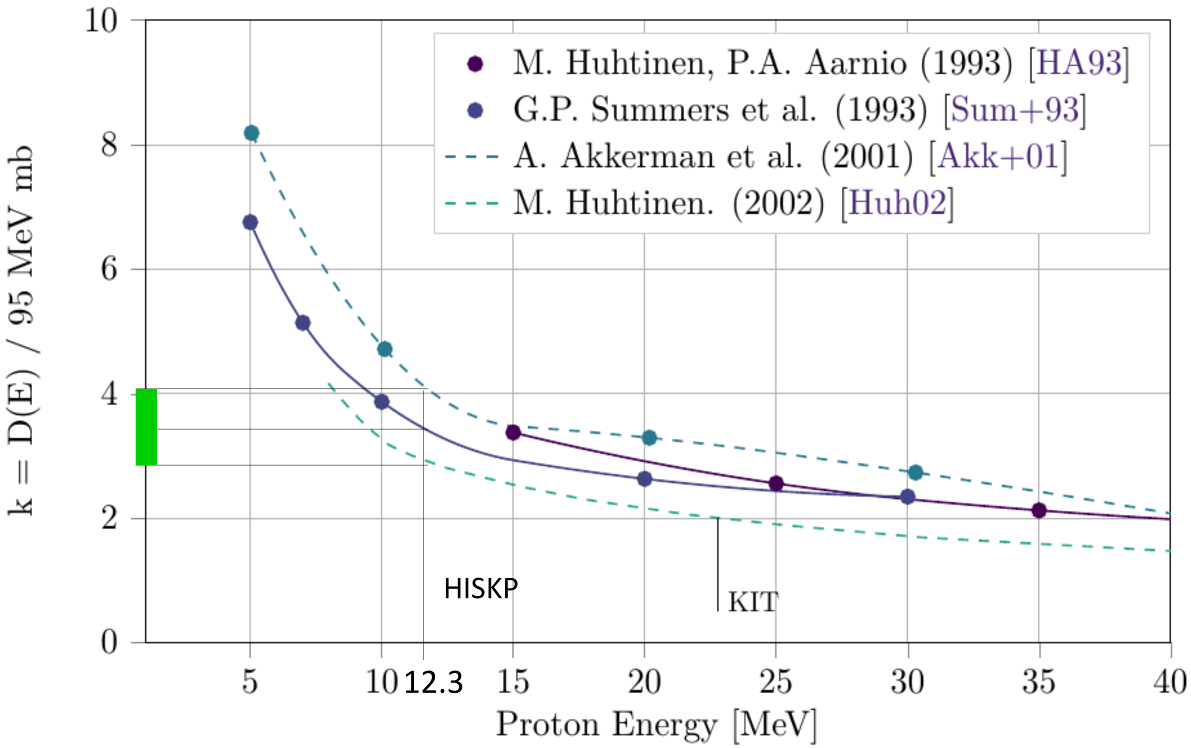
GEANT4 ENERGY SIMULATIONS
-PROTONS-

- 10^7 protons with 14 MeV along beam line
- Energy distributions **on** and **after** 300 µm Si-sensor
- Hardness factor
  - κ ≈ 3 - 4 (?)
  - (Slight) dependence of damage function on penetration depth (?)



HARDNESS FACTOR
-PROTONS-

- Large spread of literature values for proton hardness factors
- KIT κ=2
- HISKP κ≈ 3 **?**
- Proton hardness factor should be measured to reduce uncertainty on resulting ϕ_{eq}

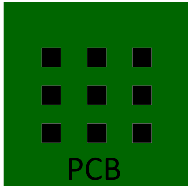


Plot from D.-L. Pohl

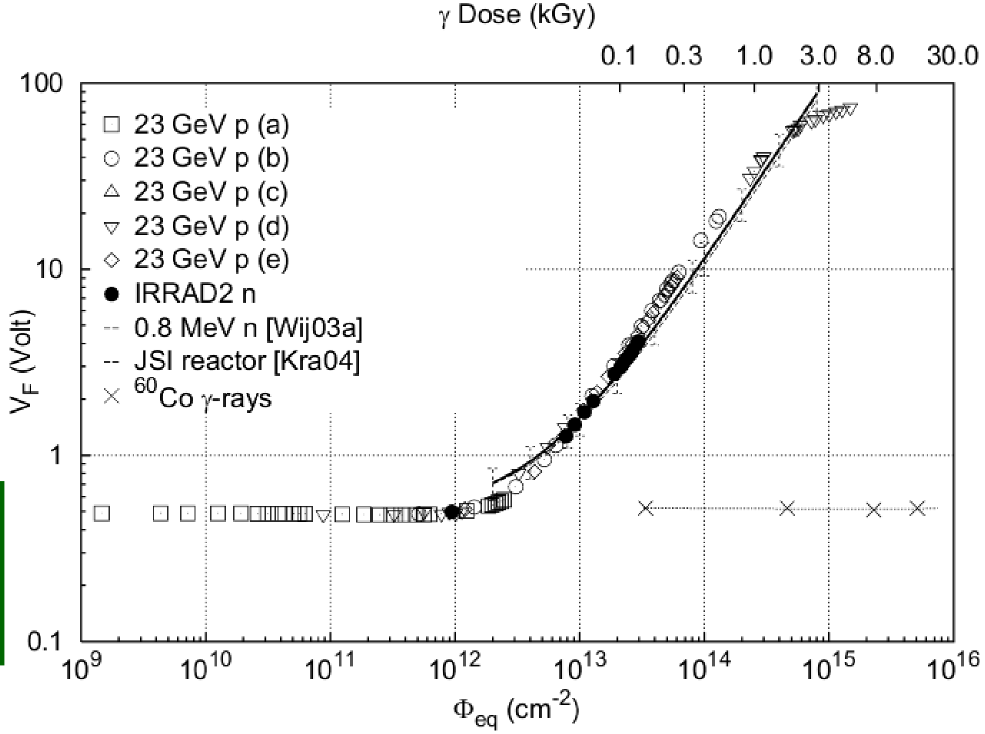
HARDNESS FACTOR
-MEASUREMENTS PLANS-

- Use commercial PiN-diode BPW34FS

- Forward voltage drop V_F shows linear dependance on ϕ_{eq} [4]
- Irradiate matrices of 3x3 diodes to different fluences



- Compare results to [4]
- Repeat for **deuterons ?**



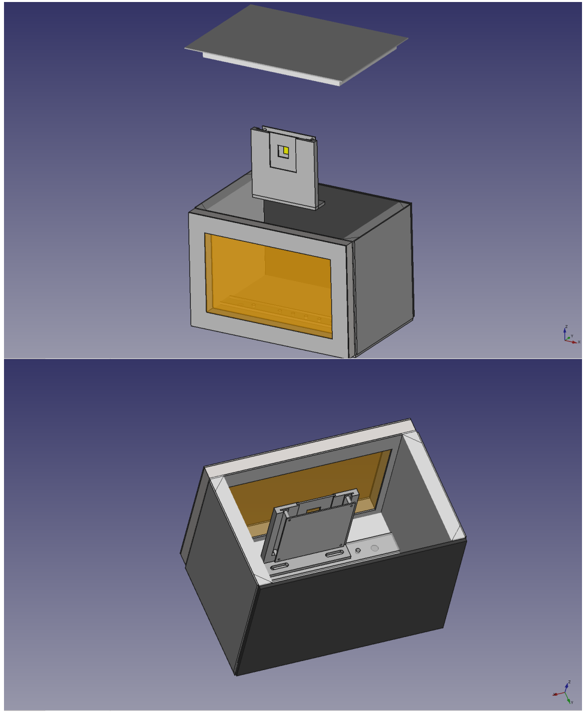
Plot from [4], p. 124

[4] F. Ravotti, Development and Characterization of Radiation Monitoring Sensors for the High Energy Physics Experiments of the CERN LHC Accelerator, Dissertation, Université Montpellier II, 2006 (PhD Thesis)

IRRADIATION PARAMETERS

IRRADIATION PARAMETERS
-FORESEEN PARAMETERS-

- Generally based on irradiation site & procedure at **KIT**
- Cooling with N_2-gas inside insulated box (to ≈ -40 °C)
- Shielding of carrier PCB with aluminum mask in box
- All dimensions for "standard" 10x10 cm² PCBs. Slightly larger devices might be possible as well as powering chips
- Box, mounted onto XY-stage, scanned through beam in grid
- Stopping & resuming of irradiation possible
- Access to the irradiation site during stops possible



IRRADIATION PARAMETERS
-FORESEEN PARAMETERS-

- Irradiations up to $10^{16}\ \frac{\text{n.e.q}}{\text{cm}^2}$ approx. possible within 60 min
- Equivalent fluence determination by integration of monitored proton current
- After irradiation sample stays in cooling box for several hours due to activation
- Storage in freezer at -20°C until release by radiation protection officer
- Release within 2 weeks estimated

SUMMARY & OUTLOOK

- The development status of a novel proton irradiation site has been presented
  - **14 MeV protons** with a hardness factor of **κ≈ 3** can be generated with beam currents of **up to ≈ 1 µA** at the HISKP cyclotron
  - **Beam-current** and **-position** monitoring as well as resulting **proton fluence determination** via **secondary electron monitors** and custom RO electronics
    - First calibrations verify principle
- Next steps:
  - Completing setup: Mount remaining hardware & implement irradiation procedure
  - First controlled (cooling, scanning, shielding) irradiation within next months
  - Irradiation of diodes in order to determine proton (& **deuteron**) hardness factors

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THANK YOU

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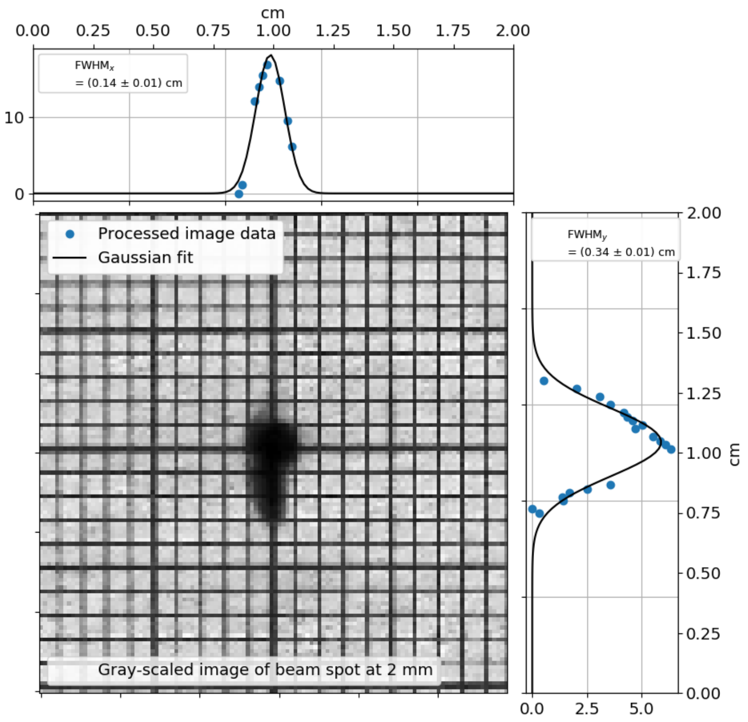
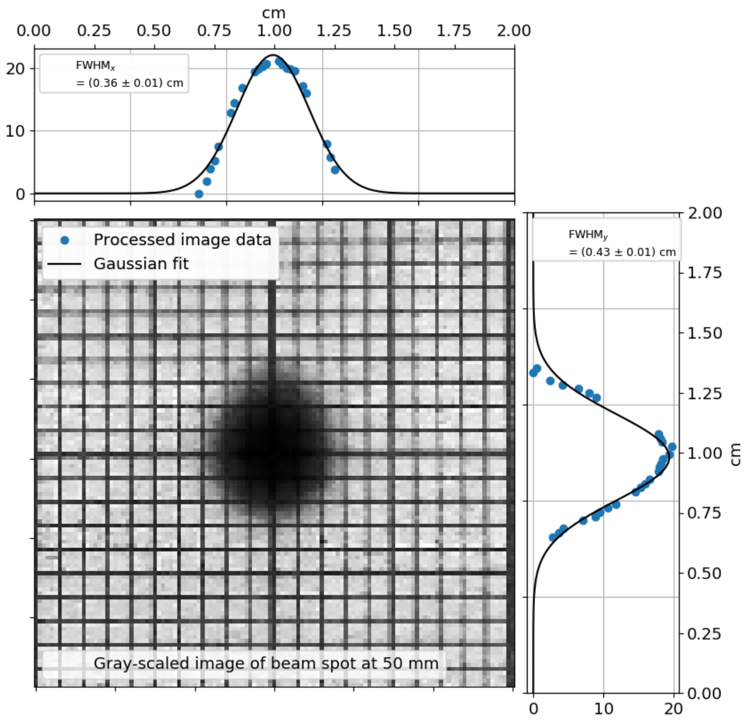
BACKUP

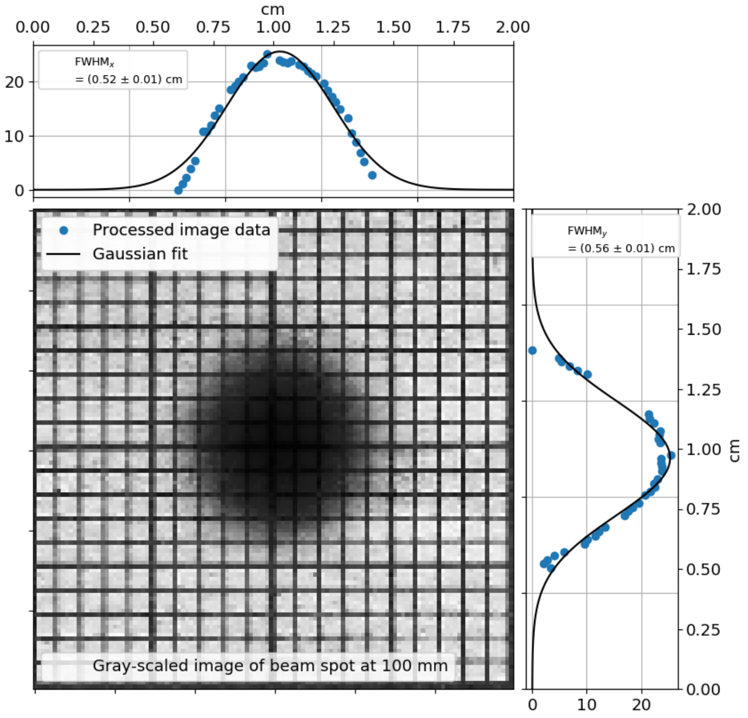
THE HISKP ISOCHRONOUS CYCLOTRON
-BEAM WIDTH EVOLUTION-

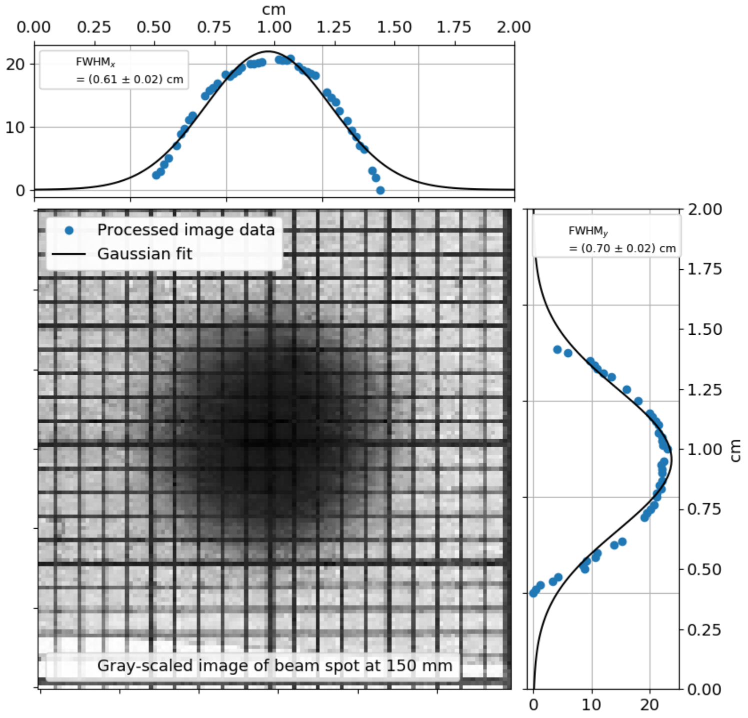




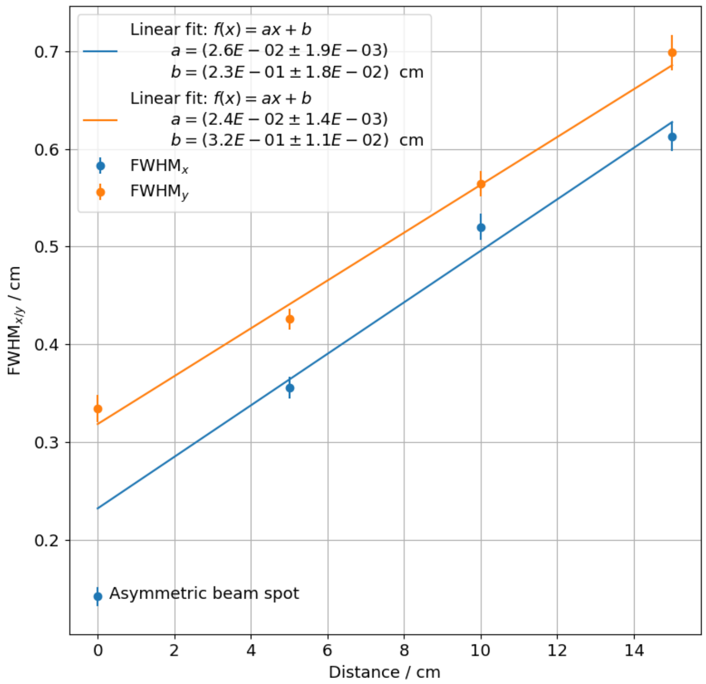
THE HISKP ISOCHRONOUS CYCLOTRON

-BEAM WIDTH EVOLUTION-





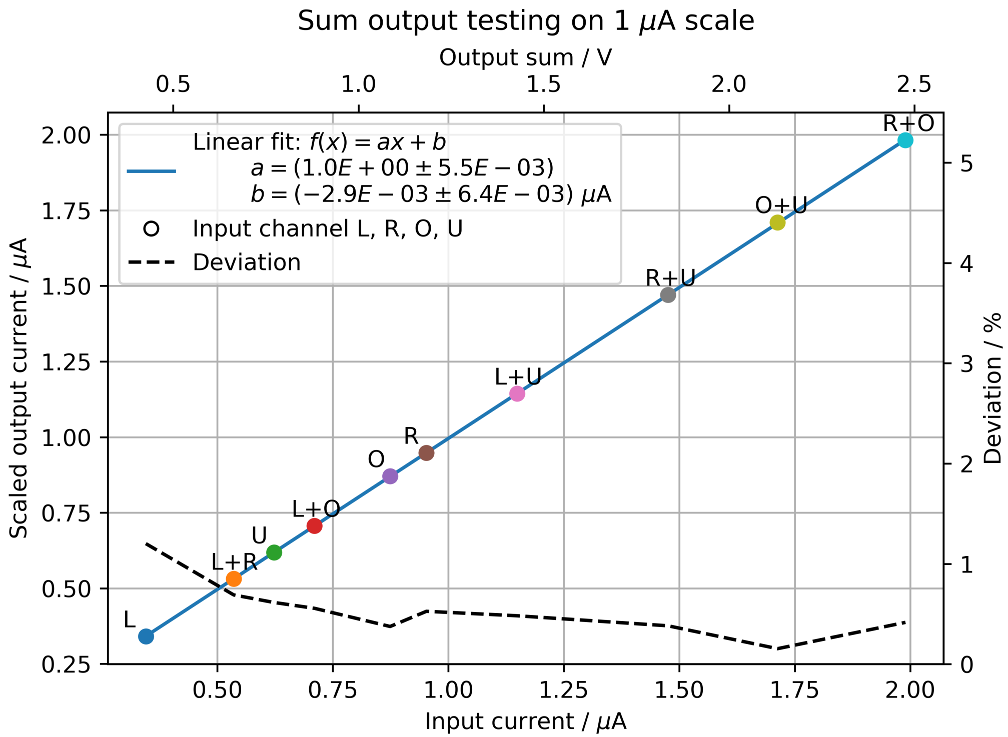
THE HISKP ISOCHRONOUS CYCLOTRON
-BEAM WIDTH EVOLUTION-



BEAM CURRENT MONITORING

-PRECISION-

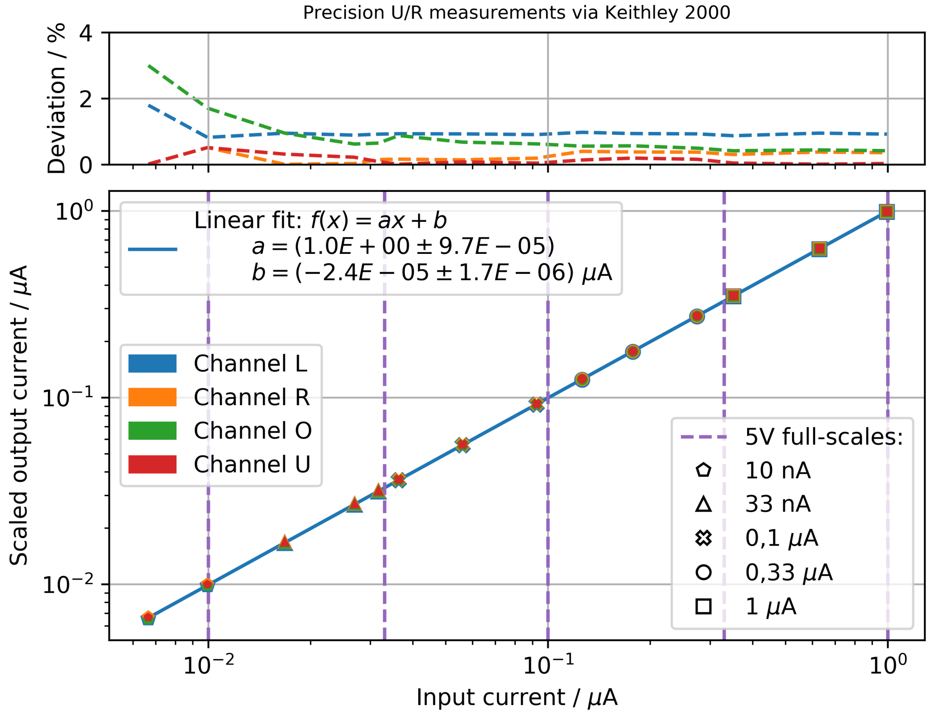
- Testing of electronics with sourced currents:
  - Source into different channels: L, R, O , U
- Deviation between sourced current and output ≈ **1 %**



BEAM CURRENT MONITORING
-PRECISION-

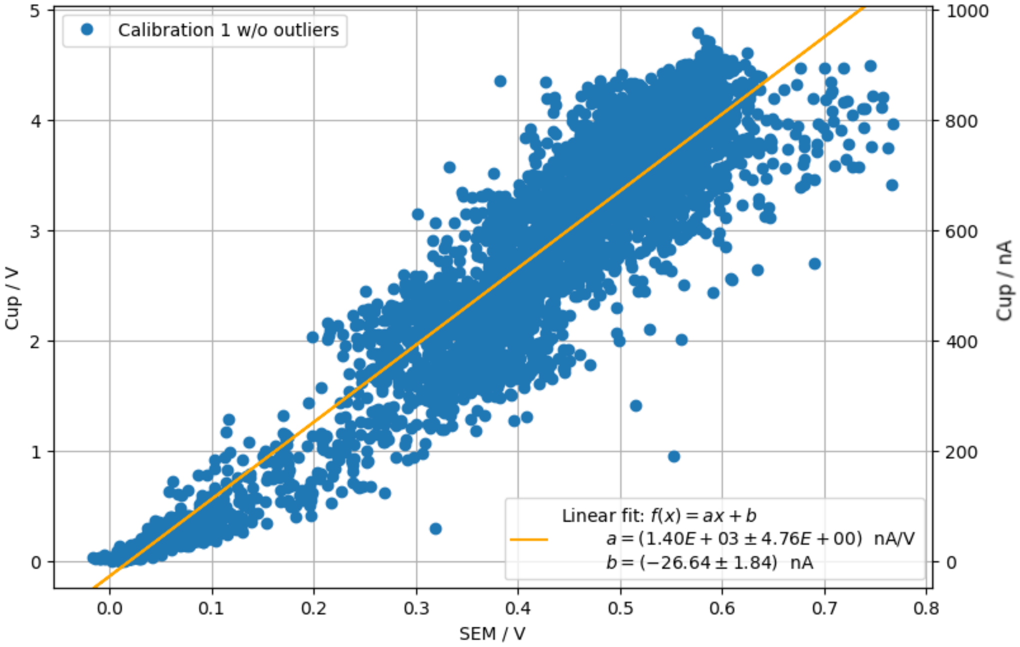
- Testing of electronics with sourced currents:
  - Source into different channels: L, R, O , U
- Deviation between sourced current and output ≈ **1 %**

Channel- and scale-wise output testing



BEAM CURRENT CALIBRATION

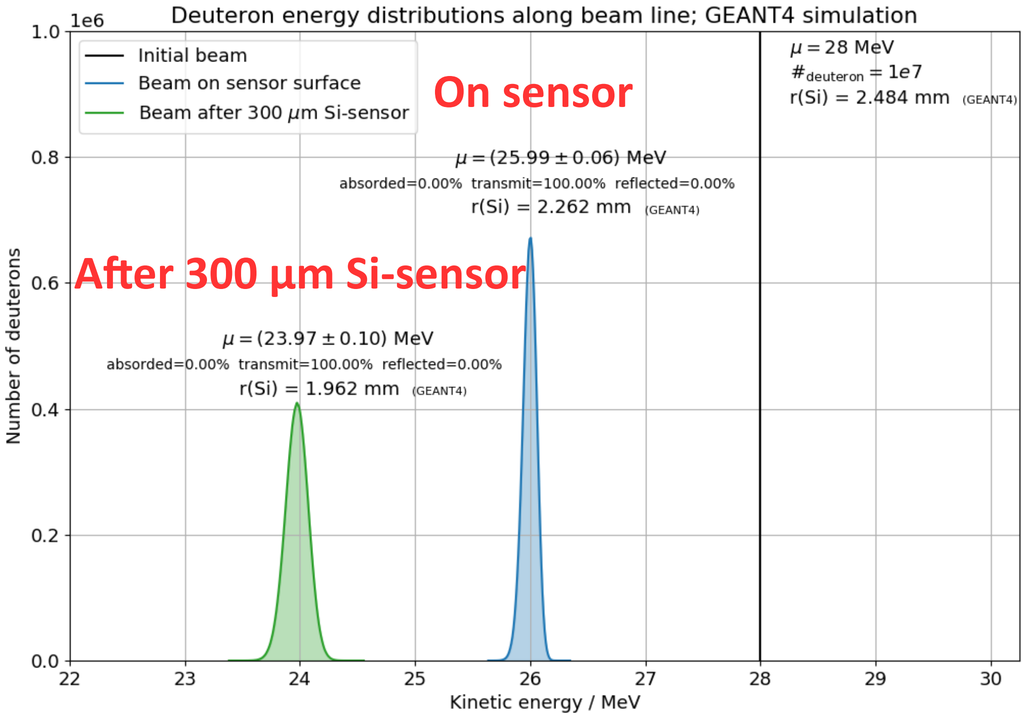
- Beam currents up to 1 µA validated
- Linear trend expected, but:
  - Large spread of distribution, noise
- Second measurement shows the same, but similar slopes of fit (~5% deviation)
- Reason: noisy, unstable beam due to violent system shutdown by PSA; significantly less noise in normal operation



GEANT4 ENERGY SIMULATIONS

-DEUTERONS-

- 10^7 deuterons with 28 MeV along HISKP beam line
- Energy distributions **on** and **after** 300 µm Si-sensor
- Hardness factor
  - κ = **?**



RADIATION PROTECTION / RELEASE

- “StrlSchV“ §29 contains parameter tables for unrestricted releases, but:
  - They only apply to samples between 3 kg to 3 t
- For our case:

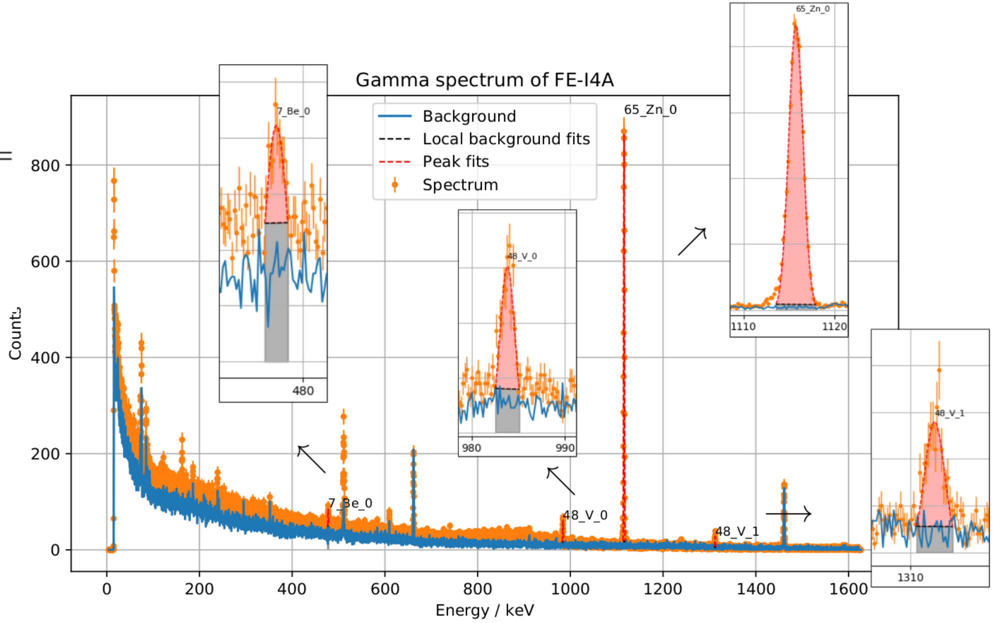
> The additional **effective dose** imposed to an **individual person** must be below the order of **10 µSv/year** in a **realistic** scenario

- Parameters of a realistic scenario:
  - Year = 2000 h (work year)
  - Distance to sample = 50 cm (working dist.)

RADIATION PROTECTION / RELEASE

- Spectroscopy results of irradiated FE-I4 SCC:

Isotope	Activity / Bq		
	initial[4] (4th July 2018)	measured (16th August 2018)	now (14th October 2018)
^{7}Be	105.99 ± 34.77	60.54 ± 19.86	**29.98 ± 9.84**
^{48}V	106.17 ± 30.34	16.42 ± 4.71	**1.58 ± 0.45**
^{65}Zn	1092.45 ± 52.17	966.63 ± 46.16	**829.10 ± 39.59**



=> $D_{eff}(^{65}Zn)$ = 0.64 µSv/year[2]

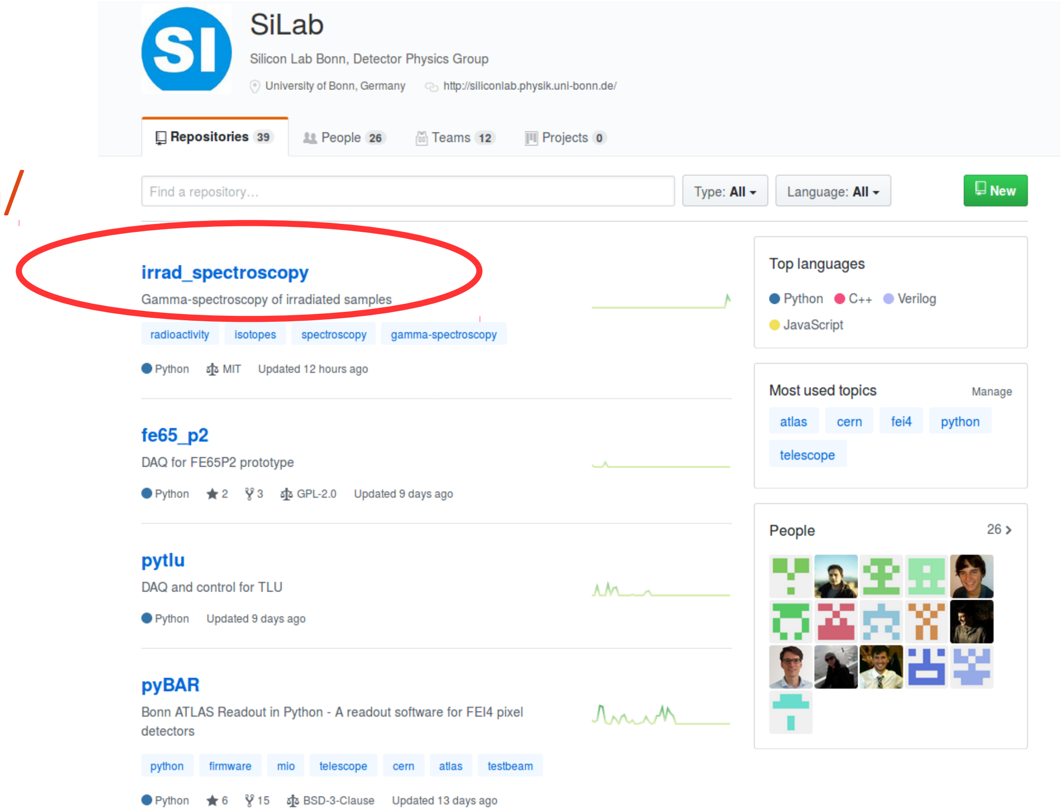
=> We should get the sample back!

[2]Over-estimation with constant activity over time

GAMMA SPECTROSCOPY

- Available on GitHub:

  https://github.com/SiLab-Bonn/irrad_spectroscopy
- Extensive examples
- Unittest



=> Feel free to contribute