Proton Irradiation Site for High-Homogeneity Radiation Hardness Tests of Silicon Detectors at the Bonn Isochronous Cyclotron

Dennis Sauerland[1], R. Beck[1], J. Dingfelder[2],
P.-D. Eversheim[1], P. Wolf[2]

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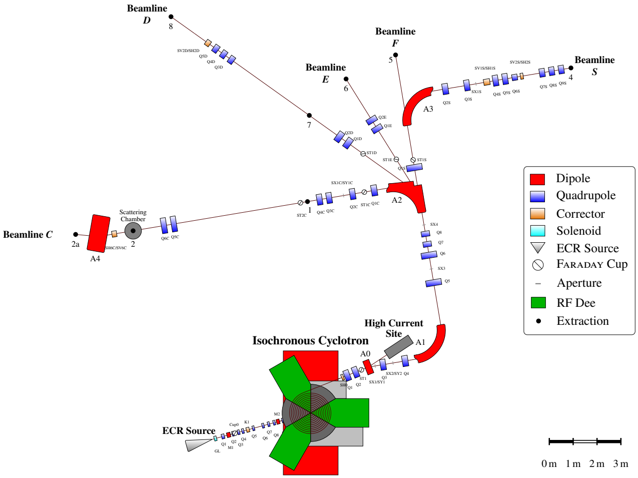
sauerland@hiskp.uni-bonn.de
[1]Helmholtz-Institut für Strahlen- und Kernphysik (HISKP), University of Bonn
[2]Silizium Labor Bonn (SiLab), Physikalisches Institut, University of Bonn

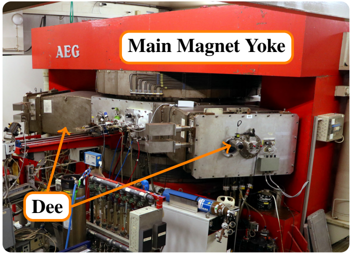
Cyclotron Facility in Bonn



D. Sauerland, Nov. 2021

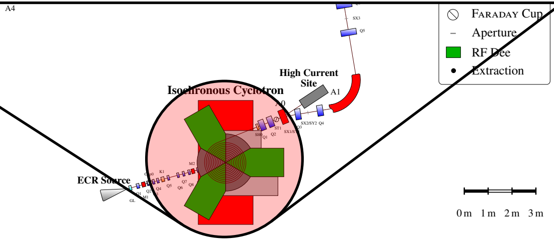
Cyclotron Facility in Bonn - Cyclotron

Isochronous Cyclotron:

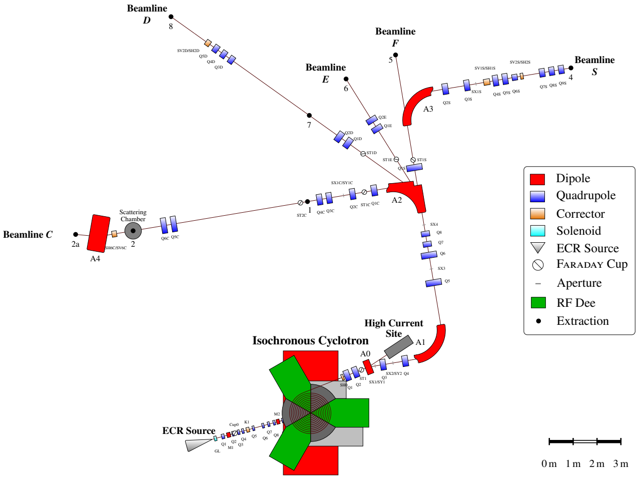


- Vertical injection into the cyclotron.
- Three-sector Hill-and-Valley magnetic guiding field (max. 0.7 T to 1.9 T).
- Particle acceleration by three RF Dees within $\approx$ 120 revolutions (20.1 MHz to 28.5 MHz, max. 40 kV).
- Extracted beam current $\lesssim$ 1 µA with $\Delta E/E \approx 4$ ‰.

Particle	p	d	α
E / MeV	7 to 14	14 to 28	28 to 56



Cyclotron Facility in Bonn



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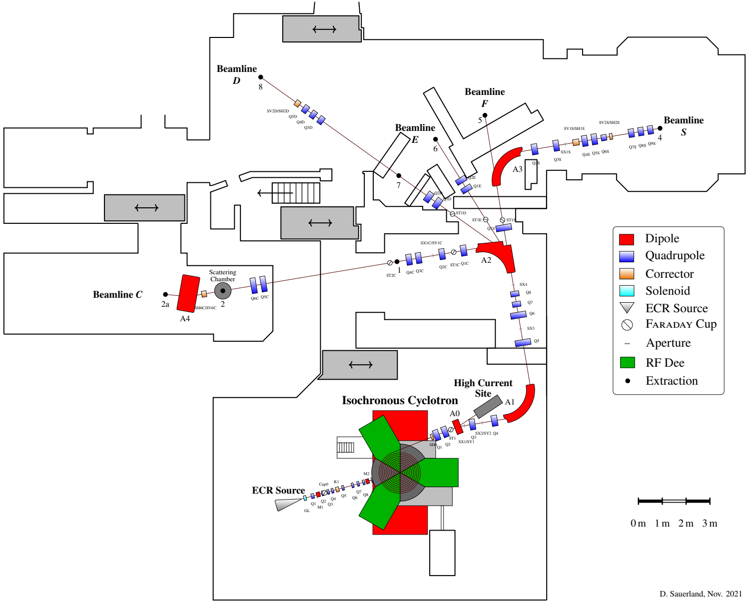
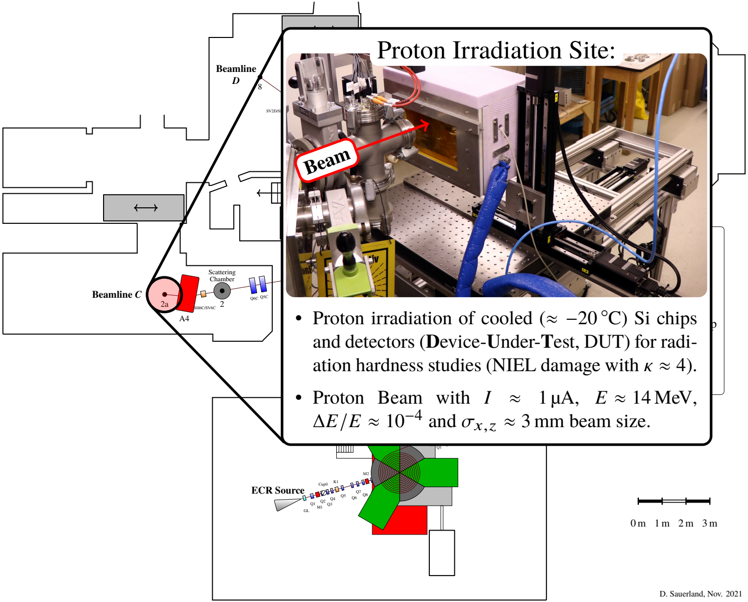
Cyclotron Facility in Bonn



D. Sauerland, Nov. 2021

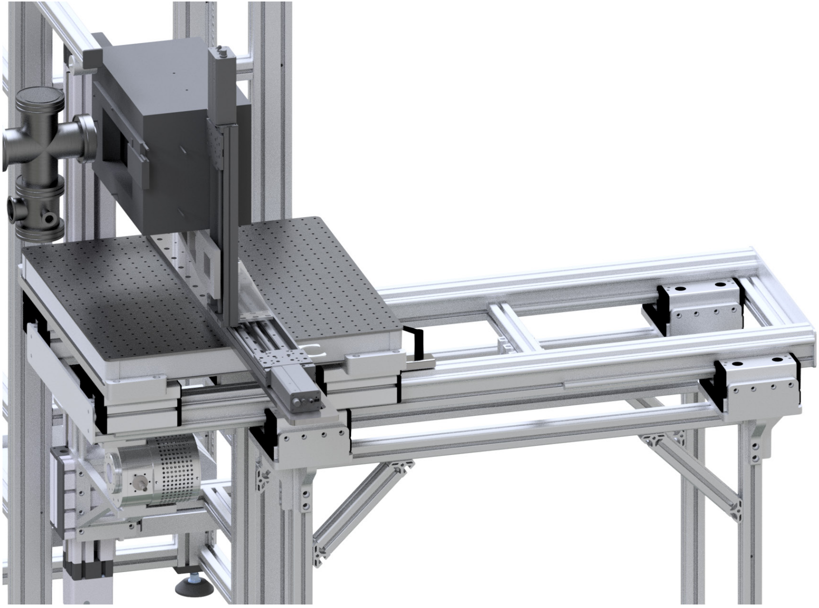
Cyclotron Facility in Bonn - Proton Beam Line



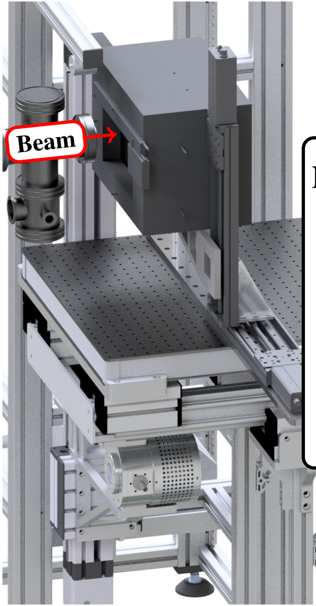
Proton Irradiation Site:

- Proton irradiation of cooled ($\approx -20\,^\circ$C) Si chips and detectors (**D**evice-**U**nder-**T**est, DUT) for radiation hardness studies (NIEL damage with $\kappa \approx 4$).
- Proton Beam with $I \approx 1\,\mu$A, $E \approx 14\,$MeV, $\Delta E/E \approx 10^{-4}$ and $\sigma_{x,z} \approx 3\,$mm beam size.

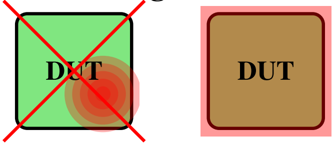
Irradiation Site



Irradiation Site

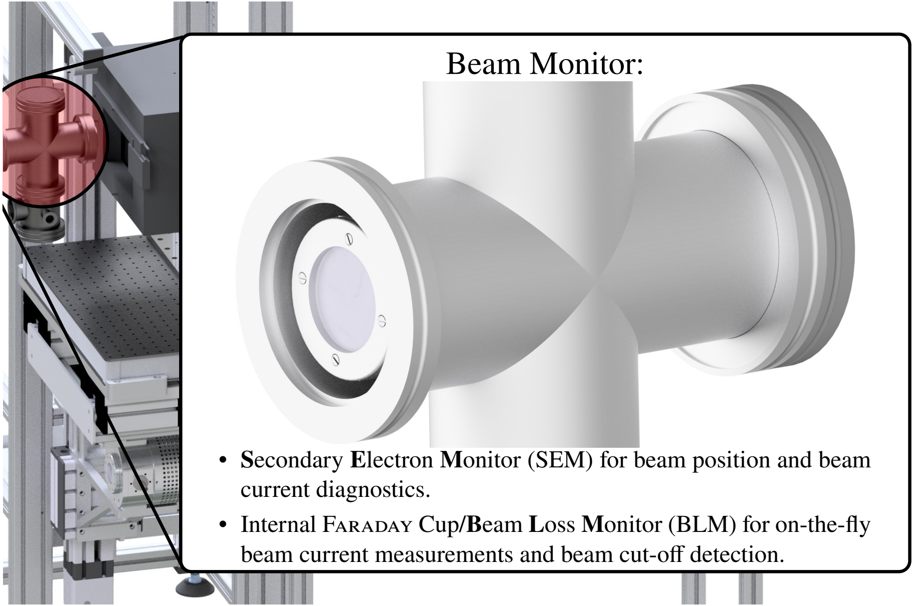


Necessities for **Homogeneous** Proton Fluence:



- Beam position diagnostic
- Online, non-destructive beam current measurement
- Beam-driven irradiation scheme

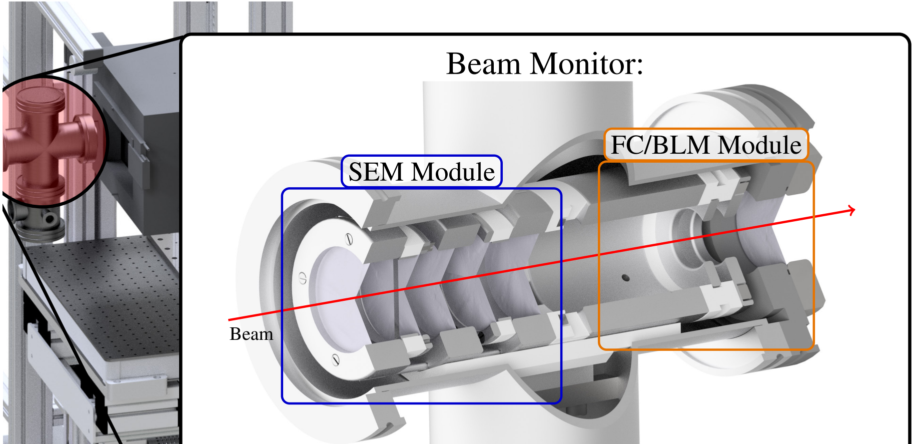
Irradiation Site - Beam Monitor



Beam Monitor:

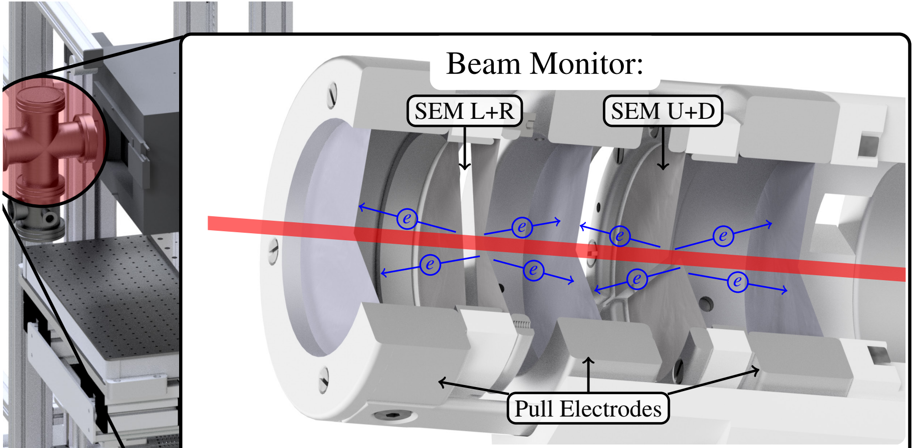
- **S**econdary **E**lectron **M**onitor (SEM) for beam position and beam current diagnostics.
- Internal FARADAY Cup/**B**eam **L**oss **M**onitor (BLM) for on-the-fly beam current measurements and beam cut-off detection.

Irradiation Site - Beam Monitor



- **Secondary Electron Monitor (SEM)** for beam position and beam current diagnostics.
- Internal Faraday Cup/**B**eam **L**oss **M**onitor (FC/BLM) for on-the-fly beam current measurements and beam cut-off detection.

Irradiation Site - Beam Monitor (SEM)



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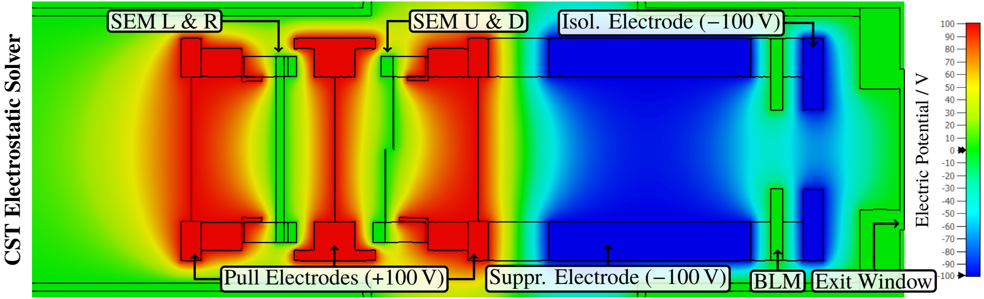
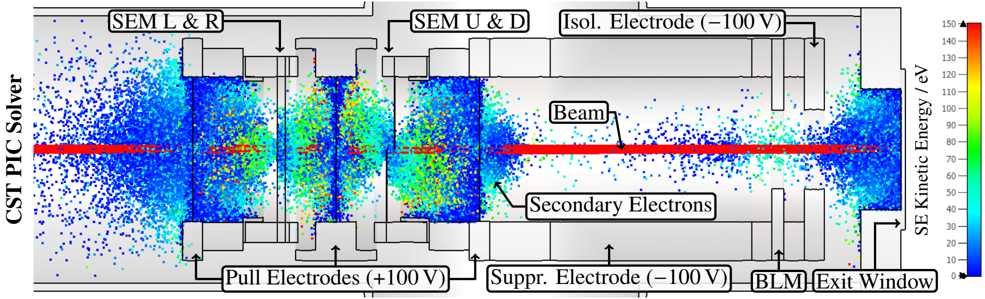
Irradiation Site - Beam Monitor (SEM)



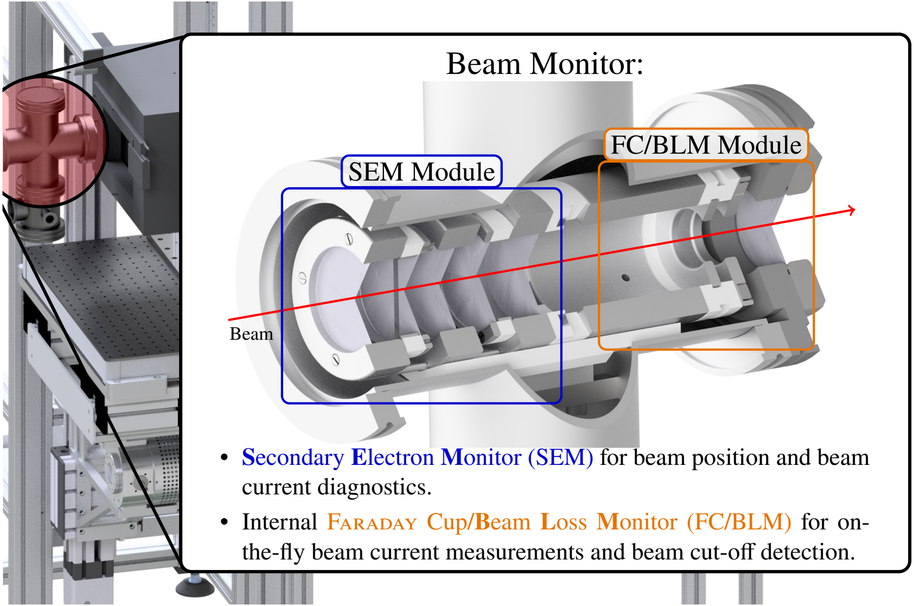
- Use carbon-coated Al foils (≈ 70 nm layer thickness) to anticipate foil-carbonization with time.

Irradiation Site - Beam Monitor (SEM)



- Use carbon-coated Al foils (≈ 70 nm layer thickness) to anticipate foil-carbonization with time.

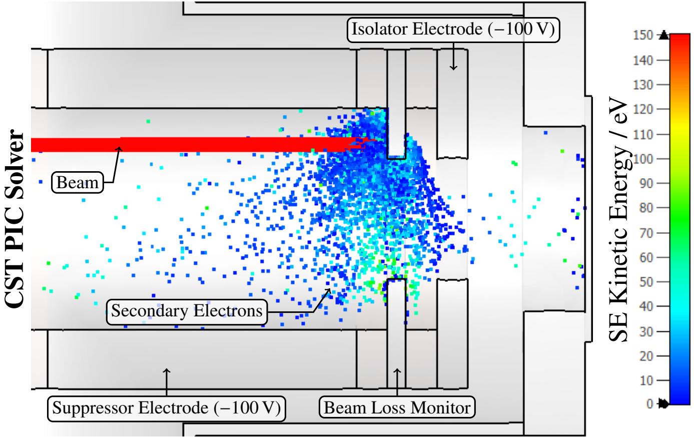
Irradiation Site - Beam Monitor (BLM)



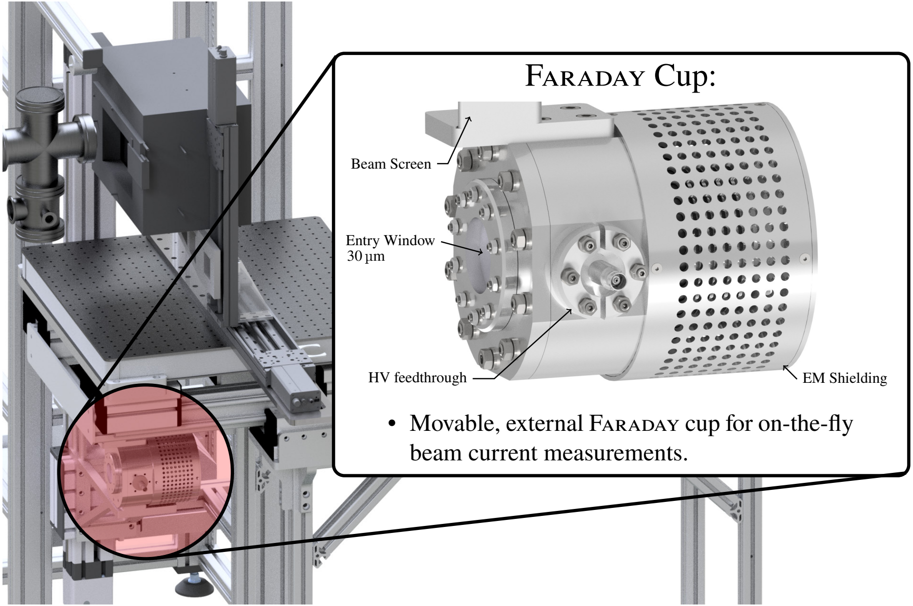
- Secondary Electron Monitor (SEM) for beam position and beam current diagnostics.
- Internal Faraday Cup/Beam Loss Monitor (FC/BLM) for on-the-fly beam current measurements and beam cut-off detection.

Irradiation Site - Beam Monitor (BLM)

- Charge collection efficiency of internal Faraday cup: > 99 %
- Isolator electrode prevents secondary electrons from exit window to reach BLM.

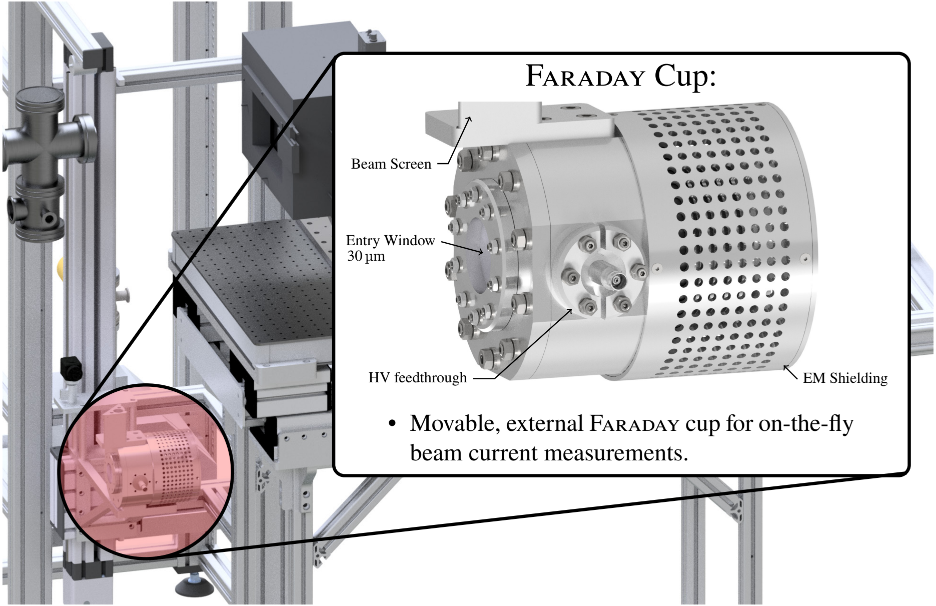


Irradiation Site - Faraday Cup

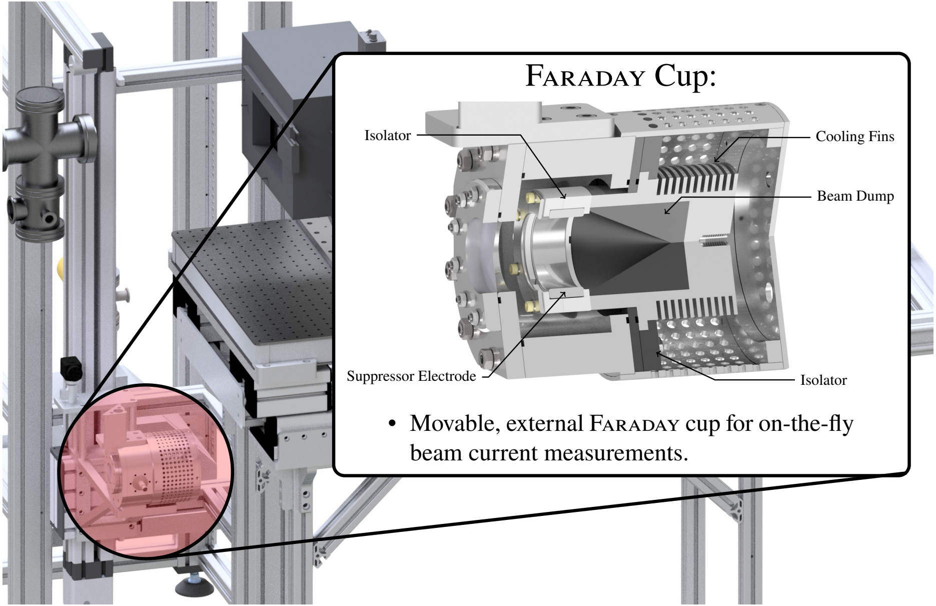


- Movable, external Faraday cup for on-the-fly beam current measurements.

Irradiation Site - Faraday Cup



Irradiation Site - Faraday Cup



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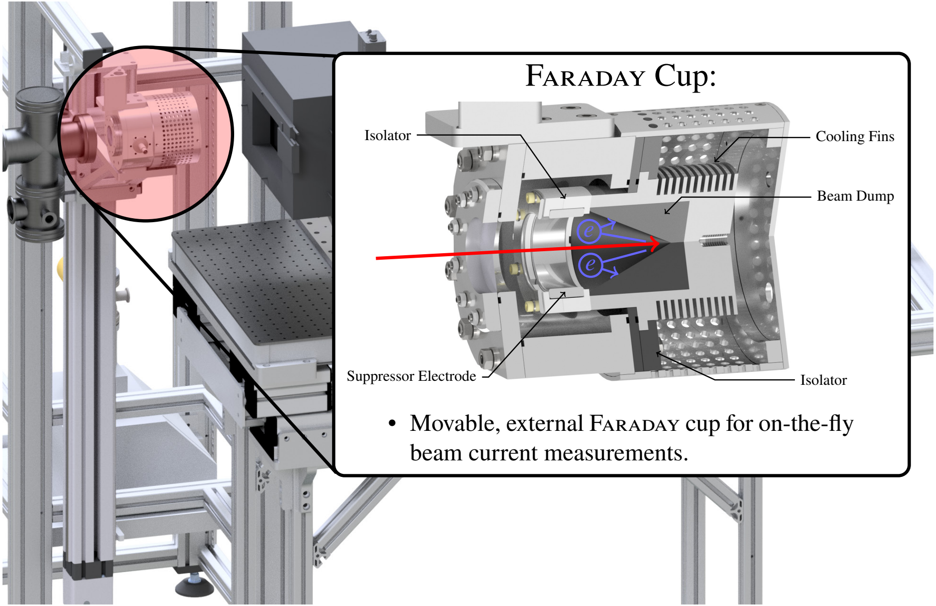
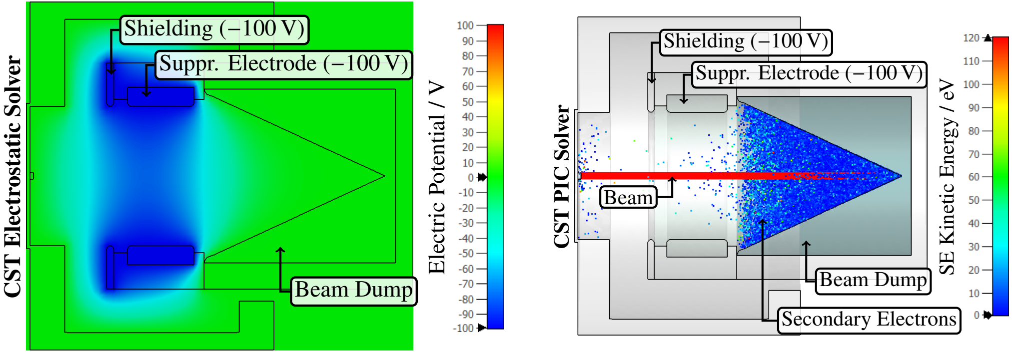
Irradiation Site - Faraday Cup



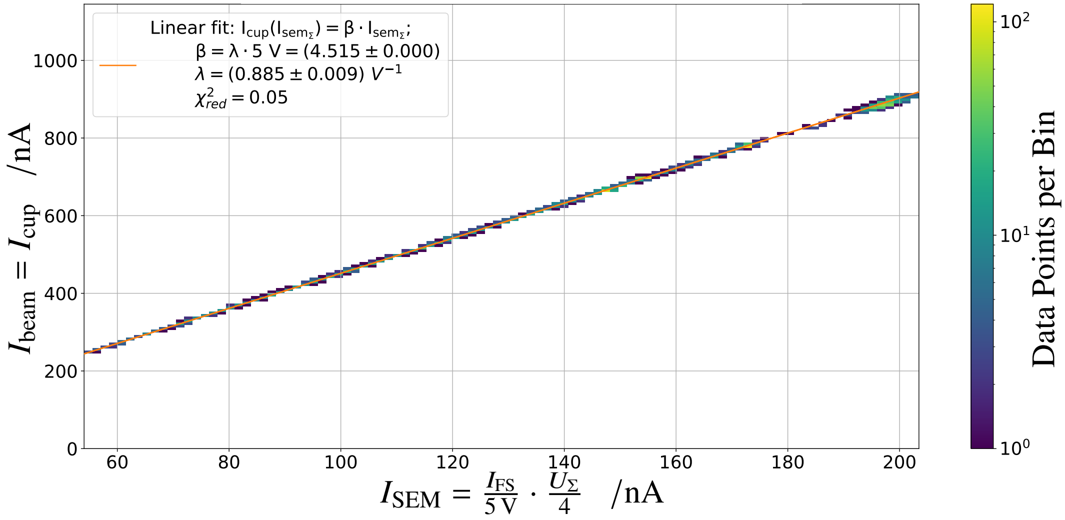
- Movable, external Faraday cup for on-the-fly beam current measurements.

Irradiation Site - Faraday Cup

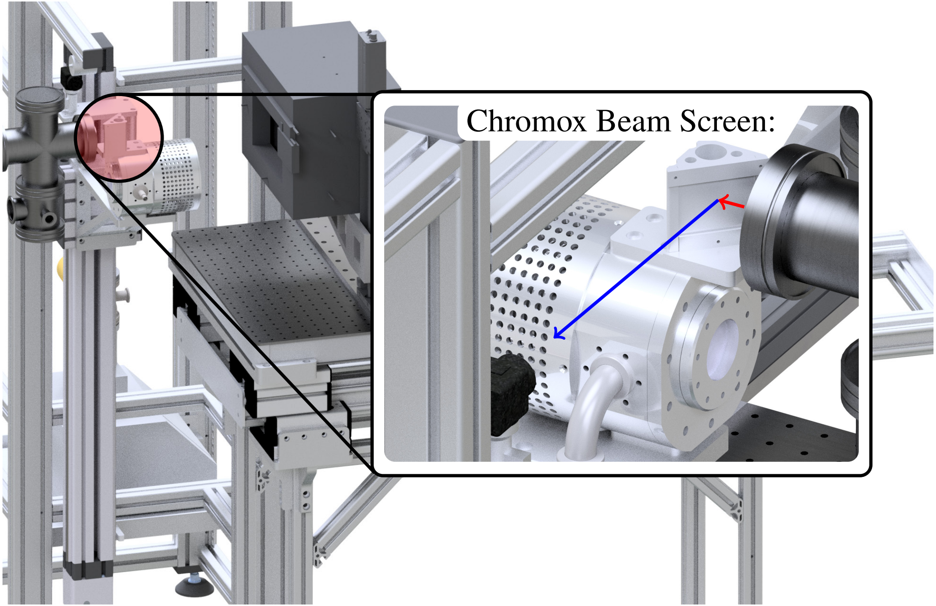


- Charge collection efficiency of Faraday cup: $> 99.99\,\%$, $\left(\frac{I_{\text{loss}}}{I} \approx 8 \cdot 10^{-5}\right)$

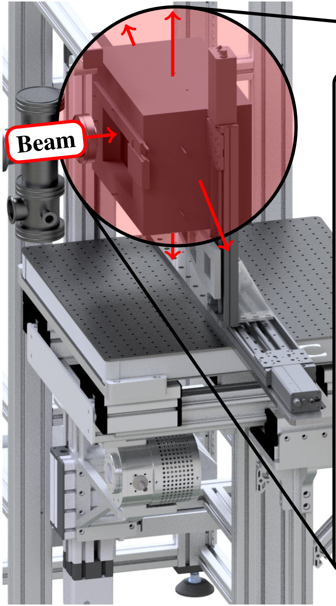
Irradiation Site - Beam Monitor Calibration



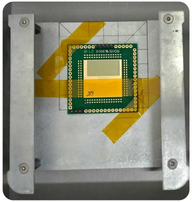
Irradiation Site - Chromox Screen

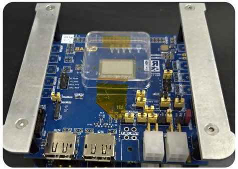


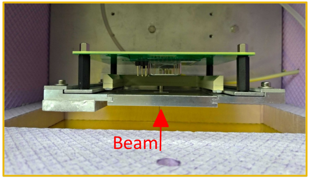
Irradiation Site - Irradiation Setup



Insulation Box with DUT:





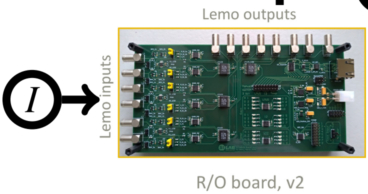


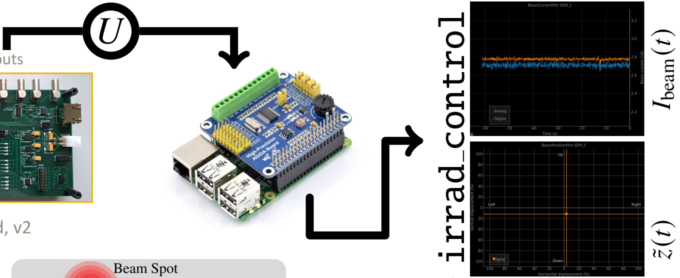
Top view of DUT mounted behind shield

- Transversely movable box with partly-shielded DUT

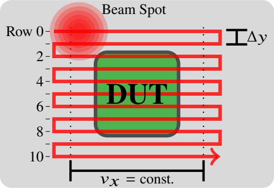
Irradiation Site - Irradiation Procedure

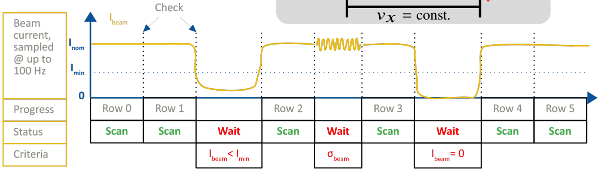
- **Digitization:**

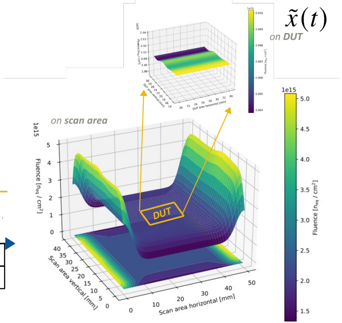




- **Beam-driven irradiation:**

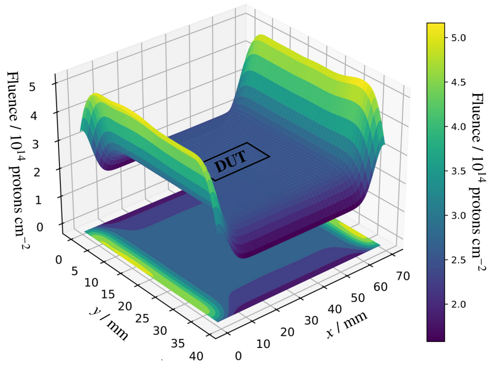




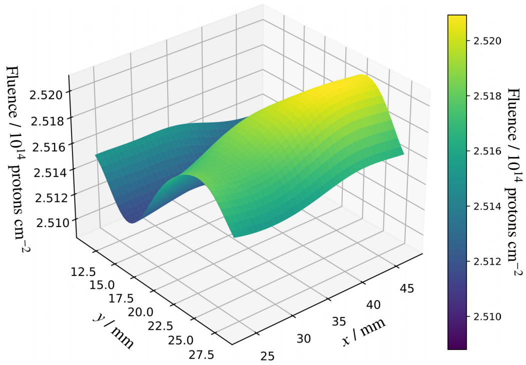


Irradiation Results and Error Estimation

Scan Area:



DUT:



Example: Irradiation of LFoundry Monopix2 with aim fluence of $2.5 \cdot 10^{14}$ protons cm^{-2}

Irradiation Results and Error Estimation

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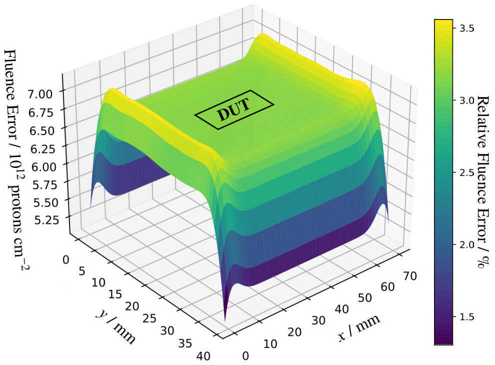
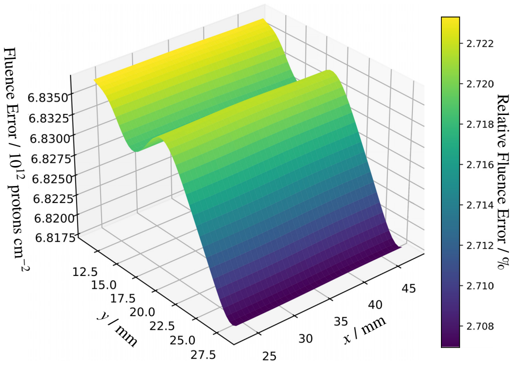


DUT:



Example: Irradiation of LFoundry Monopix2 with aim fluence of $2.5 \cdot 10^{14}$ protons cm^{-2}

Result: $(2.52 \pm 0.07) \cdot 10^{14}$ protons cm^{-2}

Summary & Outlook

Summary

- Modern irradiation site
  - Beam monitor for continous measurement of beam current, -position and beam cut-off
  - FARADAY cup with low SE losses for beam monitor calibration
  - Autonomous beam-driven irradiation technique based on real-time beam parameters
- Successful irradiation of DUTs with this setup since 2021:
  - ATLAS ITk PixV1.1
  - LF-Monopix2
  - TJ-Monopix2 chip (Belle-II candidate)
  - ATLASPix3 (LHCb candidate)
  - ...

  mostly through *internal* collaboration members.

Outlook

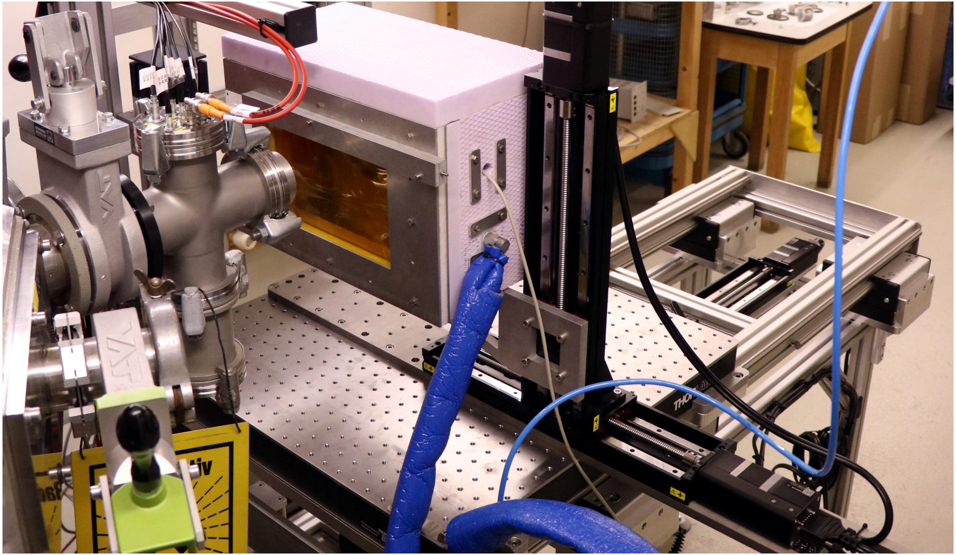
- Continuous improvement of `irrad_control` (features, usability, ...)
- Comparison of our irradiation technique with well-known foil activation method
- Open up the irradiation facility to *external* research groups.

Thank you
for
your attention!

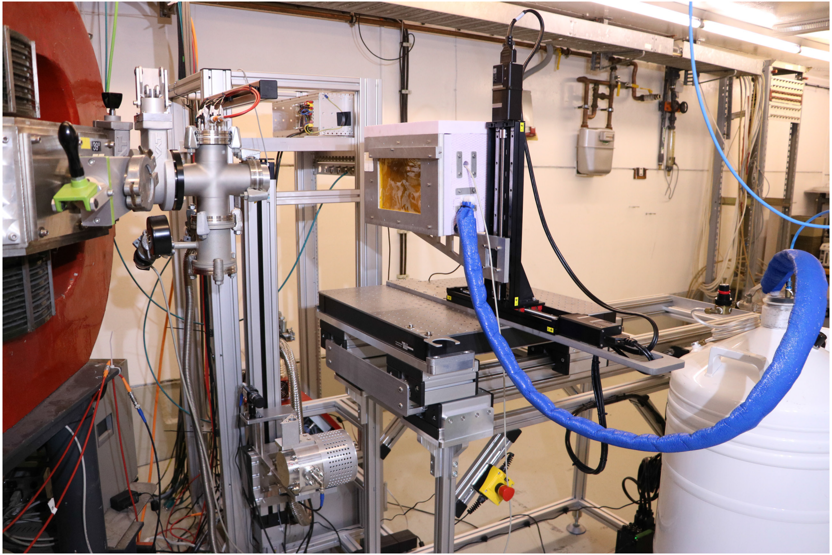
irrad_control software: https://github.com/cyclotron-bonn/irrad_control

sauerland@hiskp.uni-bonn.de

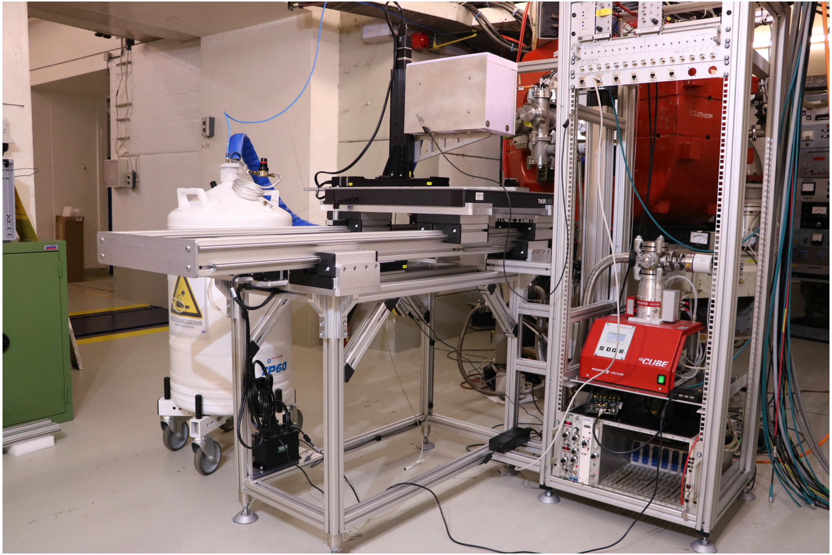
Appendix: Pictures



Appendix: Pictures



Appendix: Pictures



Appendix: Cyclotron Parameter

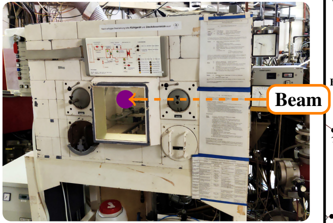
providable ions	p, d, α, …, $^{16}O^{6+}$
energy ($h = 3$, $Q/A \geq \frac{1}{2}$)	7 to 14 MeV/A
beam current (ext.)	$\lesssim 1\,\mu A$
injection / extraction radius	38 mm / 910 mm
number of revolutions	approx. 120
hill sectors	$3 \times 40°$, 0° spiral angle
hill / valley field strength	1.9 / 0.7 T (max.)
flutter	0.62
dees	$3 \times 40°$, 40 kV (max.)
cyclotron harmonic h	3, 9
rf frequency ν_{rf}	20.1 to 28.5 MHz
hor. / vert. emittance	16 / 22 mm mrad
relative energy width	4×10^{-3}

Appendix: Irradiation Site Parameter

used ion	proton (typ.)
beam energy	$7\,\mathrm{MeV}$ bis $14\,\mathrm{MeV}$
beam current	$20\,\mathrm{nA}$ to $1\,\mu\mathrm{A}$
beam width	$\approx 6\,\mathrm{mm}$ FWHM
DUT area	$19 \times 11\,\mathrm{cm}^2$ (max.)
DUT thickness at $14\,\mathrm{MeV}$	$300\,\mu\mathrm{m}$
DUT temperature	$-40\,°\mathrm{C}$ (min.), $-20\,°\mathrm{C}$ (typ.)
NIEL per scan	$5 \cdot 10^{11} \mathrm{n_{eq}cm^{-2}}$ (min.) to $10^{14} \mathrm{n_{eq}cm^{-2}}$ (max.)
NIEL/TID	$10^{11} \mathrm{n_{eq}cm^{-2}}$ per MGy
Hardness factor κ	$4.1(6)$

Appendix: High Current Site

High Current Site:



- Use the extracted beam with $\leq 10\,\mu\mathrm{A}$ to induce radioactivity into material.
- Examples:

Isotope	Reaction	$t_{1/2}$
^{11}C	$^{14}N\ (p, \alpha)\ ^{11}C$	20 min
^{74}As	$^{74}Ge\ (p, n)\ ^{74}As$	17.8 d