Grazing angle soft proton concentrating experiments with X-ray mirrors

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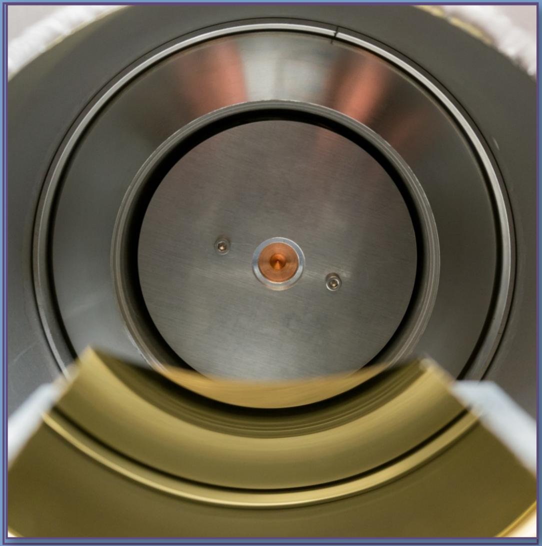
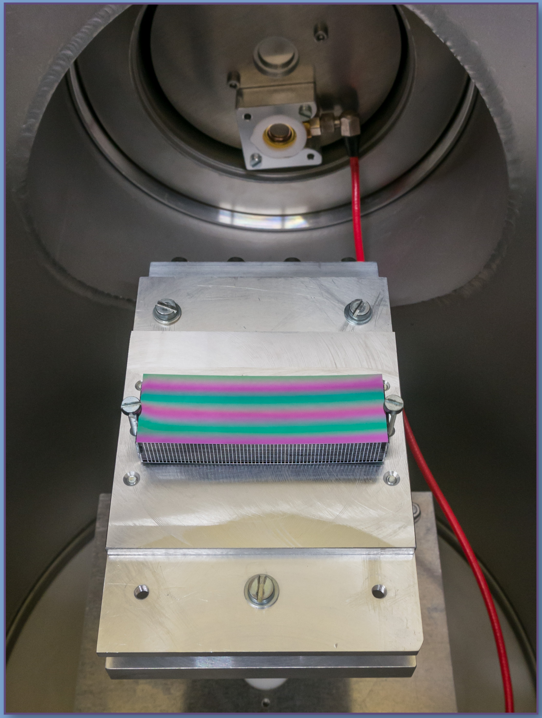




Accelerator facility

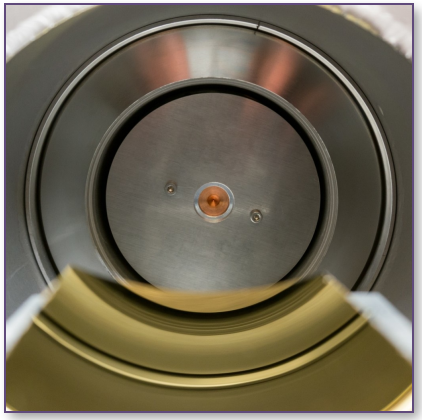
3MV single-ended Van de Graaff accelerator at the University of Tübingen, Germany

- Beam energy range: **100 keV - 2.5 MeV**
- Beam current: **200 nA - 40 μA**
- **6 beam lines** (selectable via switching magnet)
- **Several ion types** (p, H^+_2, d, D^+_2, $^4He^+$, $^{12}C^+$, $^{13}C^+$, $^{16}O^+$)

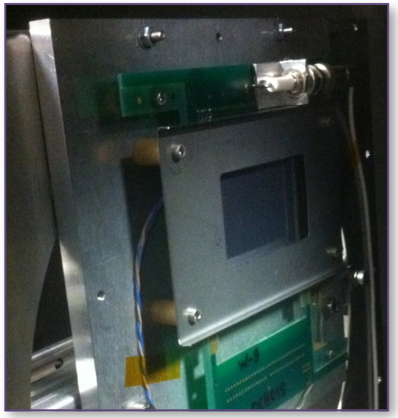
Soft proton focusing experiments with X-ray mirrors

Overview

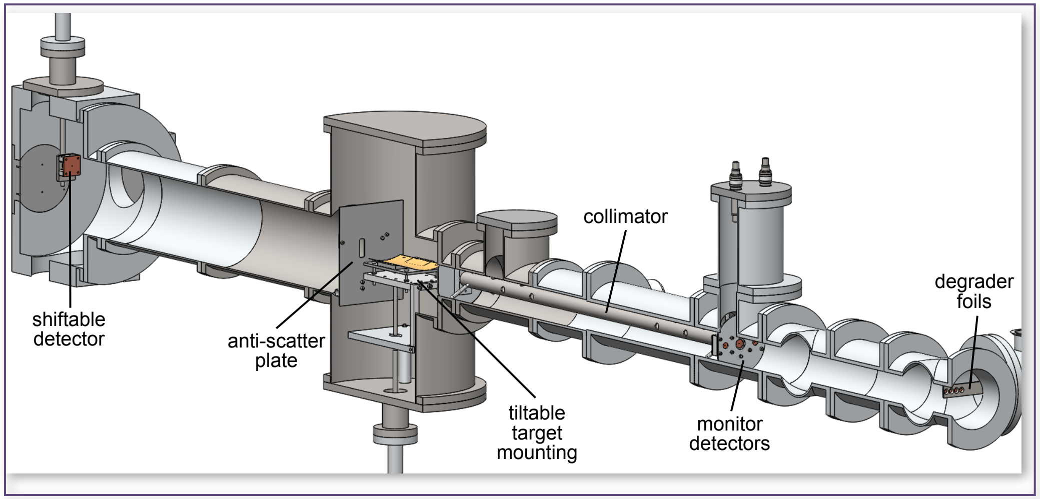
- Soft (E: 10 keV to 10 MeV) proton **effects on X-ray detectors**
- **Reflection** of soft protons on **X-ray mirrors**
    - Experimental setup at the accelerator facility
    - Measurement results
    - Modelling of the reflection in **Geant4**



eROSITA Mirror Segment



LOFT Detector Prototype in the Chamber

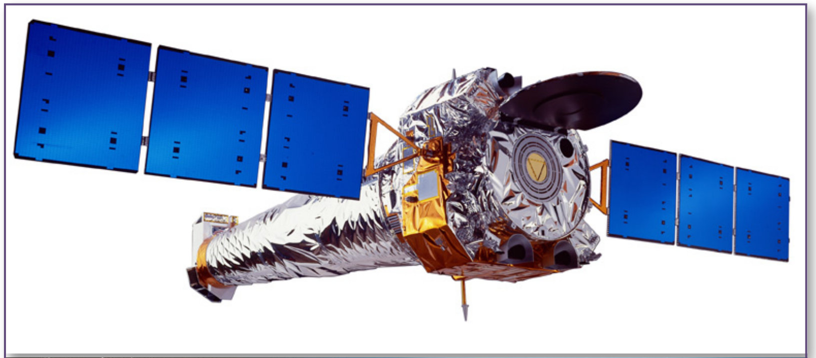


Schematics of the Reflection Setup

Motivation

Two categories of proton irradiation effects in astronomical observations:

- Degradation of the detector performance
- Contributions to background of observations
- Severity of effects depends on radiation environment and detector properties

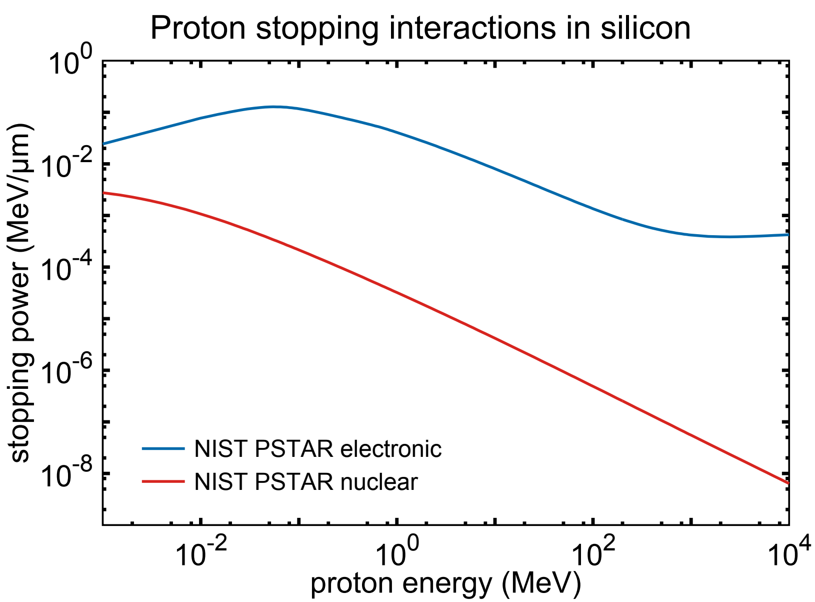


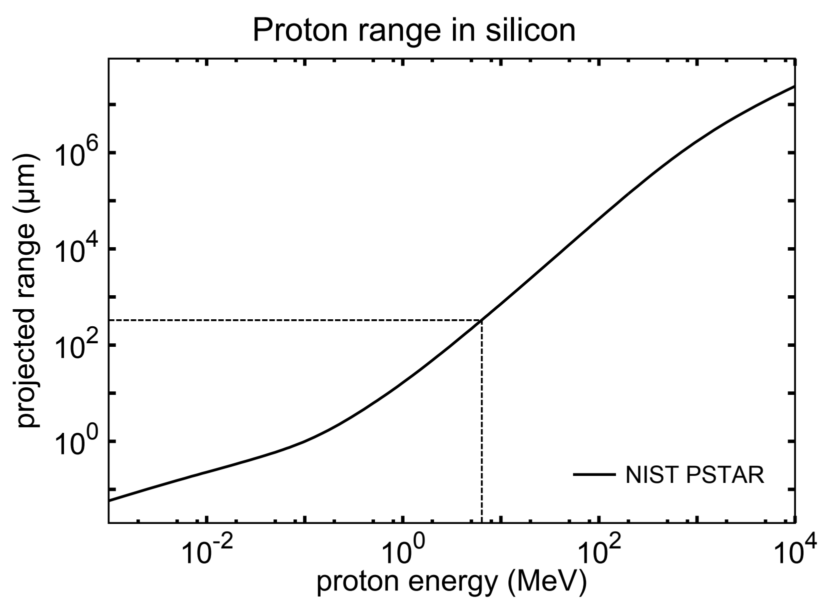
Soft protons are actually more harmful to X-ray observatories than higher energy protons.

Interactions of protons with detectors

Two types of interactions of charged particles with the detector material:

- Electron scattering => **ionization (TID)**
- Nuclear scattering => **lattice defects and vacancies (NIEL)**





Interactions of protons with detectors

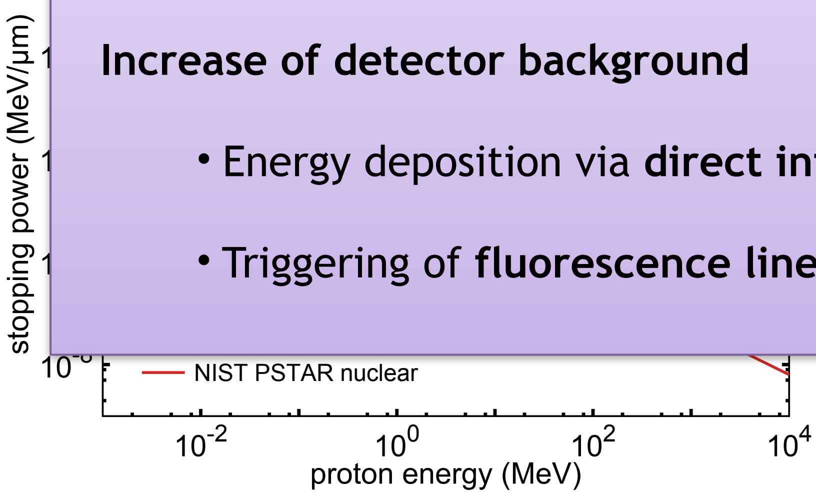
Two types of interactions of charged particles with the detector material:

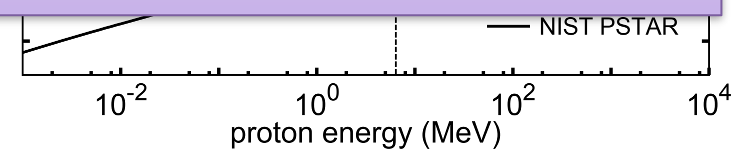
Degradation of the photon detection performance

- Charges trapped in insulator => reduced depletion region
- Creation of intermediate energy levels => increased **leakage current**
- Creation of **charge traps** => degrading the CTE

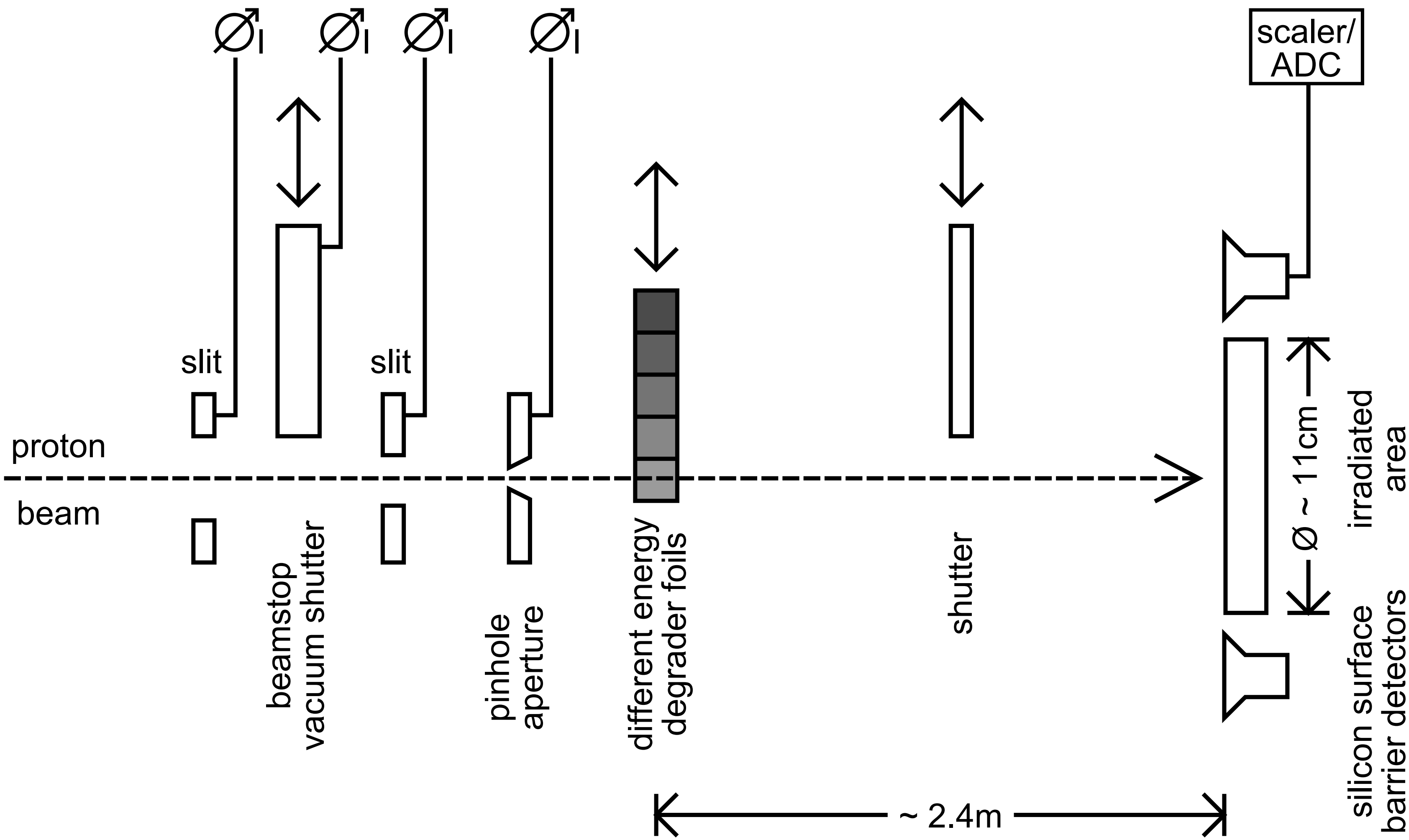
Increase of detector background

- Energy deposition via **direct interaction** in the detector
- Triggering of **fluorescence line emission** in the vicinity of the detector

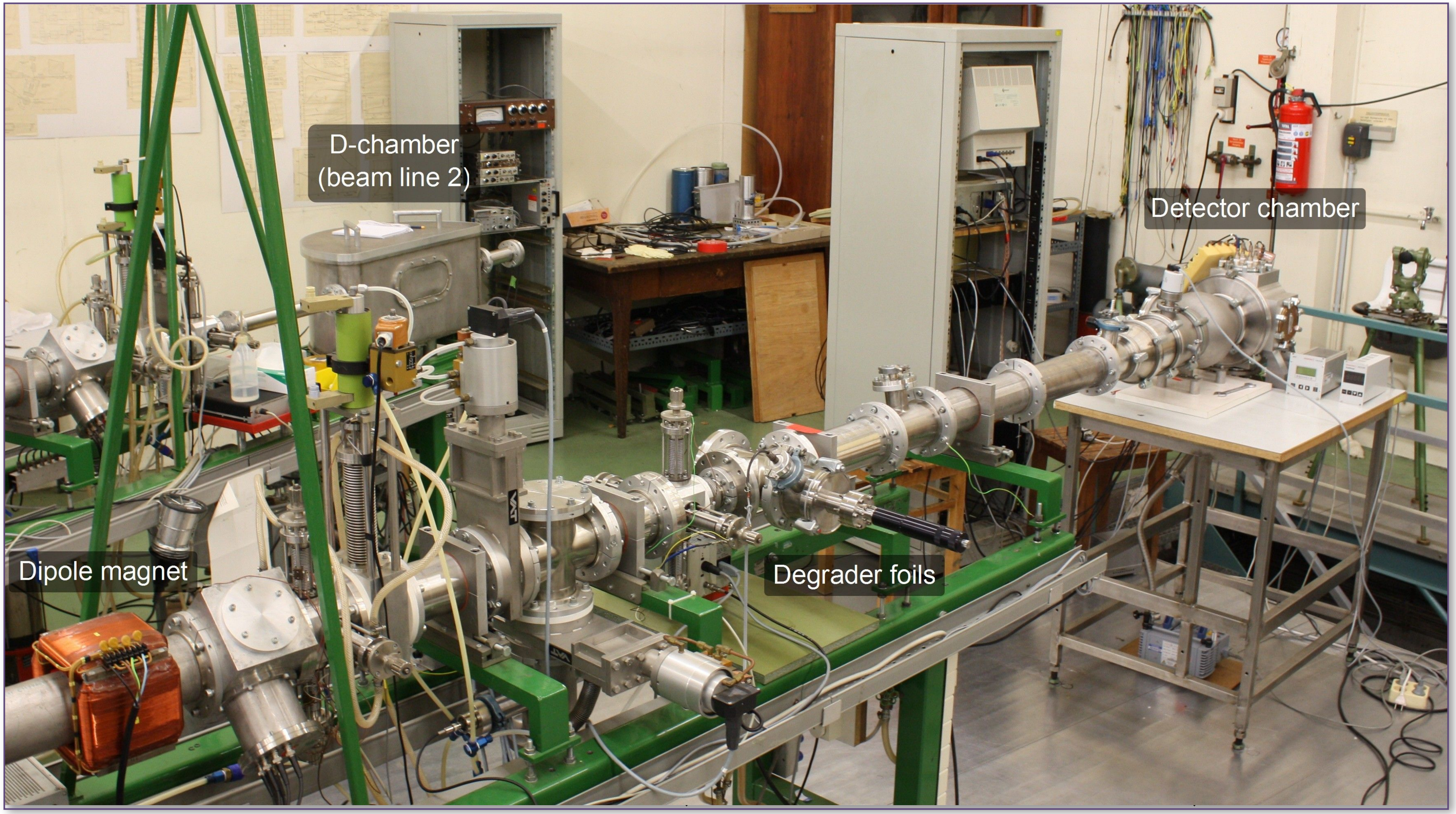




Detector irradiation setup

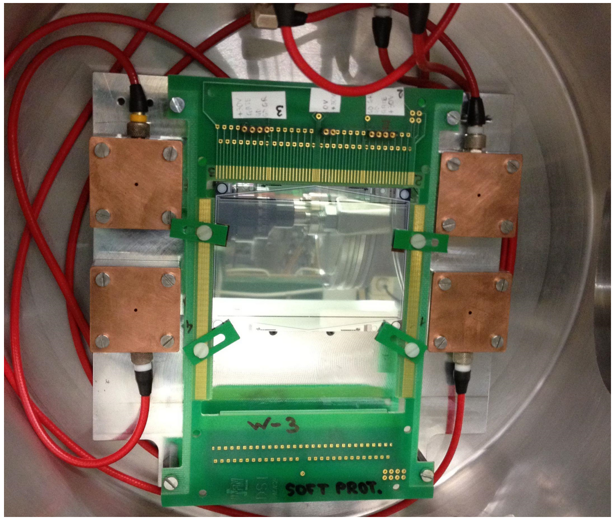


Detector irradiation setup

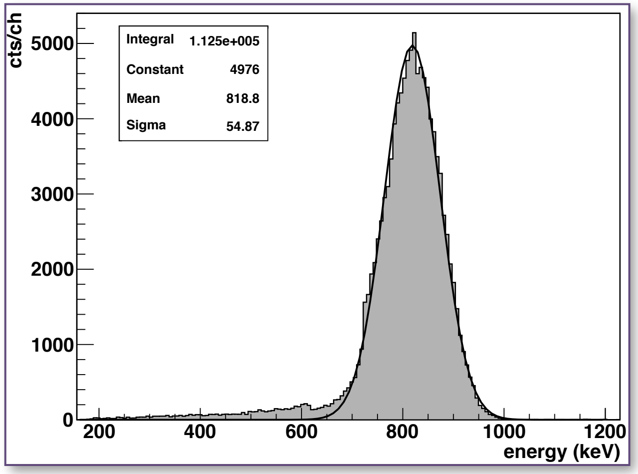


Detector irradiation

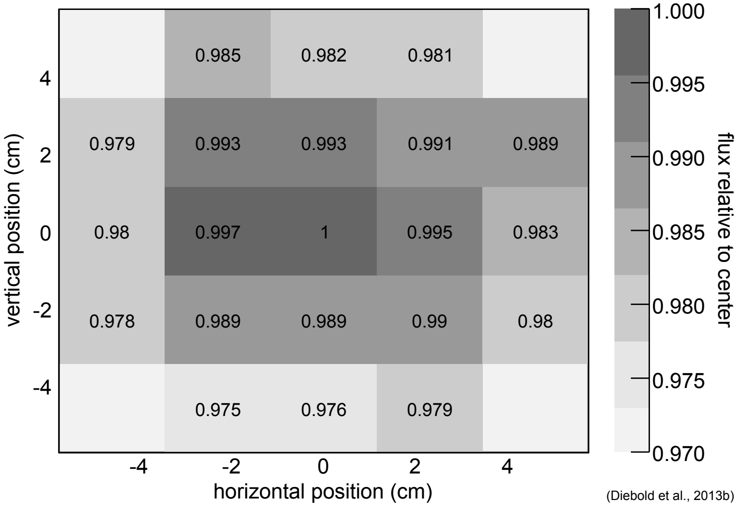
- Setup originally designed for **LOFT detectors**
- Allows **homogeneous flux distribution** over large detectors (11 cm diameter)
- Fluences of 0.5x, 1x, 5x and 10x mission lifetime were applied at different energies
- **leakage current** was measured at different temperatures and annealing was monitored in the following months



LOFT Detector Prototype



Input Spectrum Measured at the Detector Location



Homogeneity of the Irradiation

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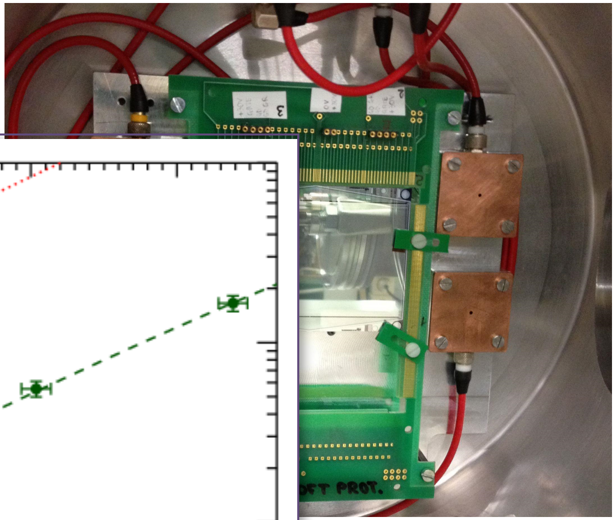
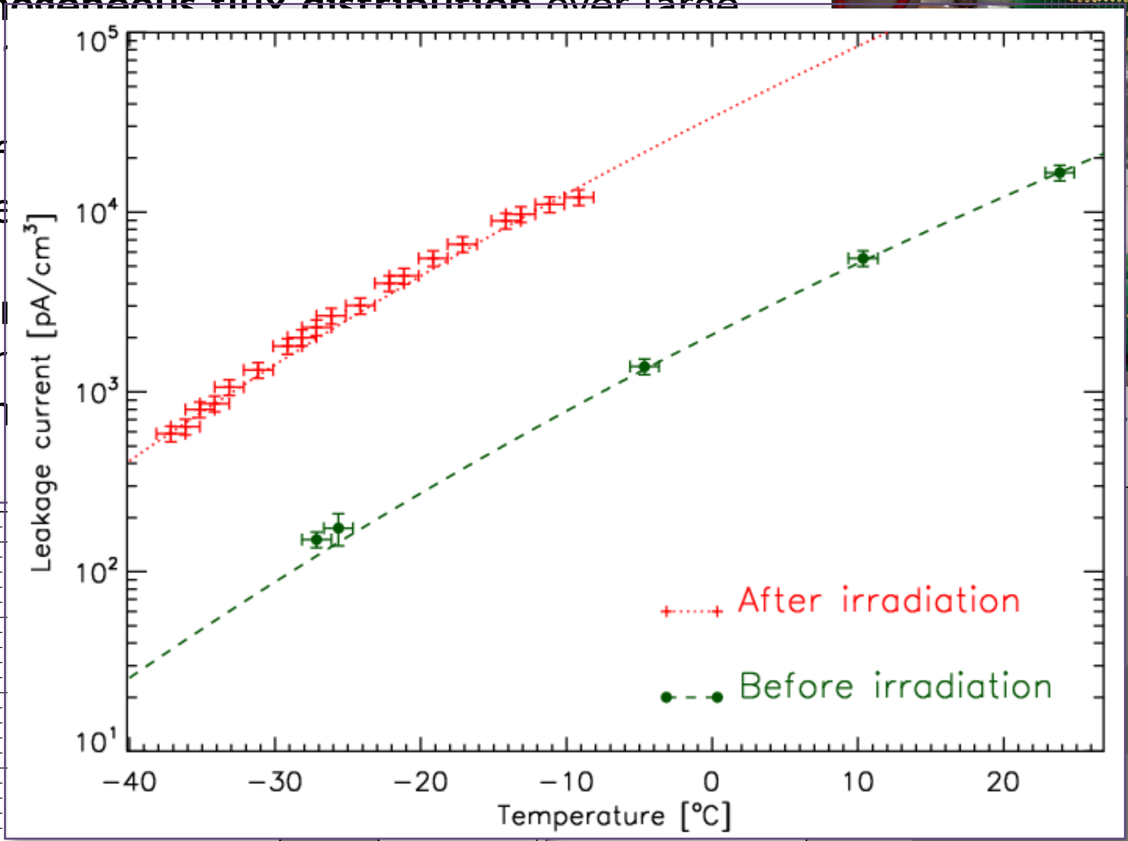
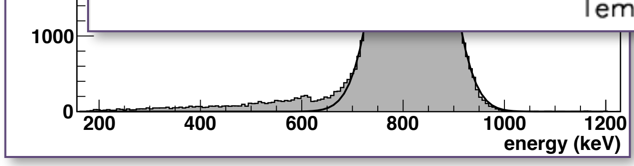


...ctor Prototype





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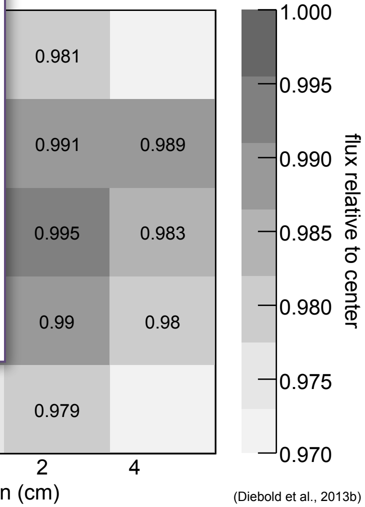
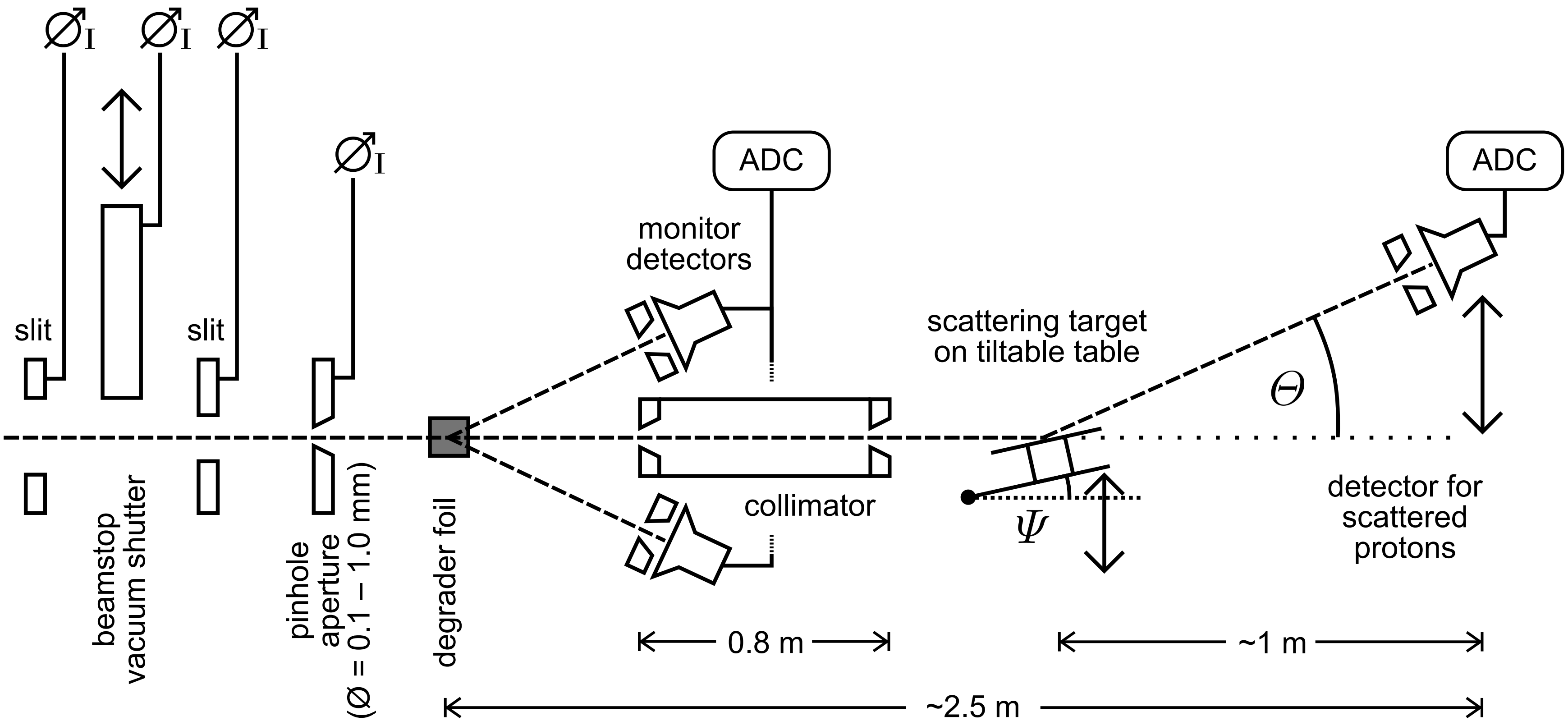


Homogeneity of the Irradiation

Soft proton focusing experiments with X-ray mirrors

Setup for reflection of soft protons on mirrors



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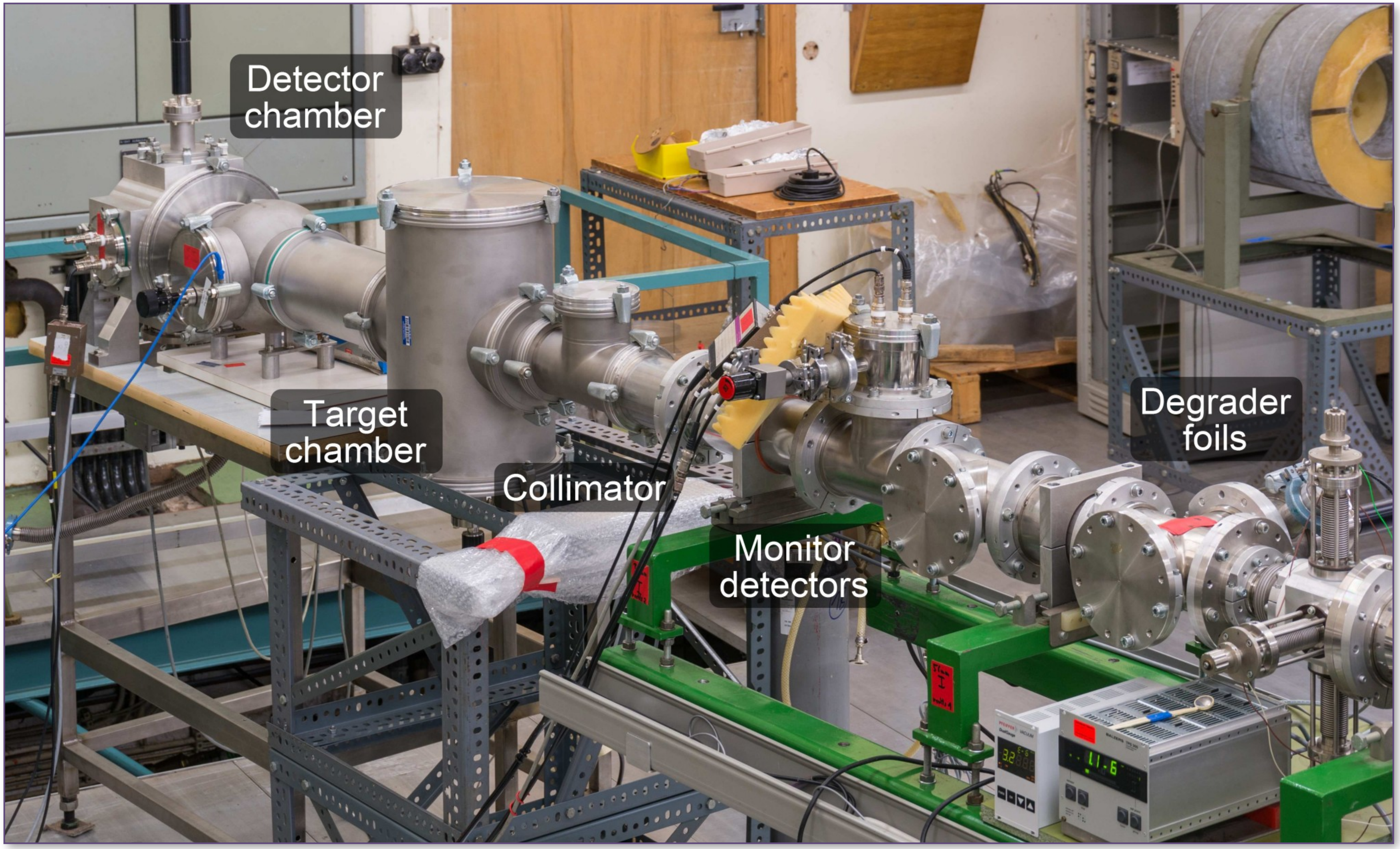
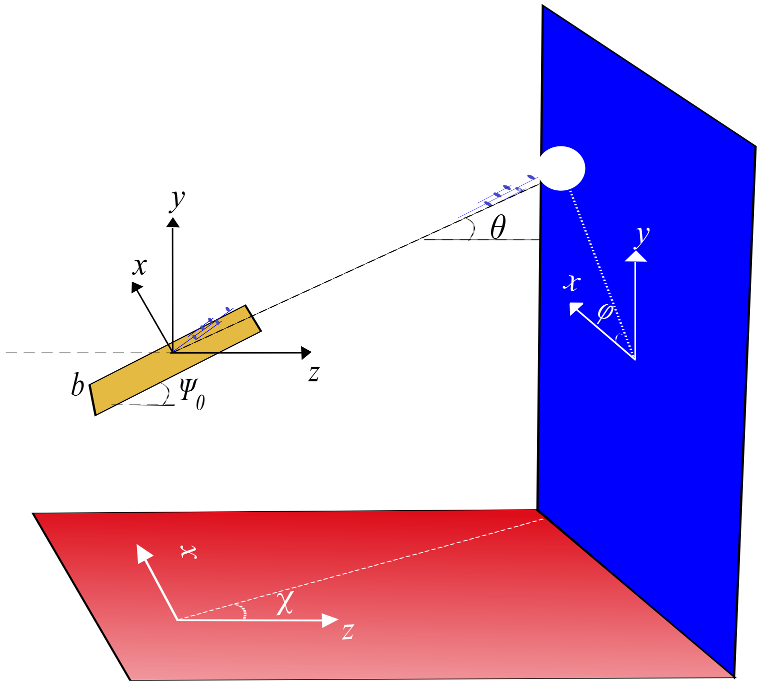
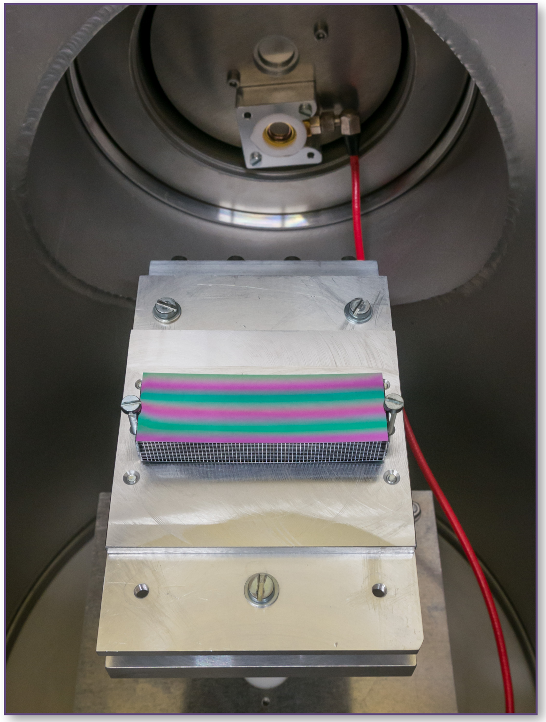


Scattering targets and detectors

Several scattering targets are used in the measurements:

- flat aluminum (250 nm) mirror on glass substrate
- eROSITA mirror shell (Nickel with Gold coating)
- ATHENA silicon pore optics prototypes





Silicon Surface Barrier Detectors to scan the "focal plane"

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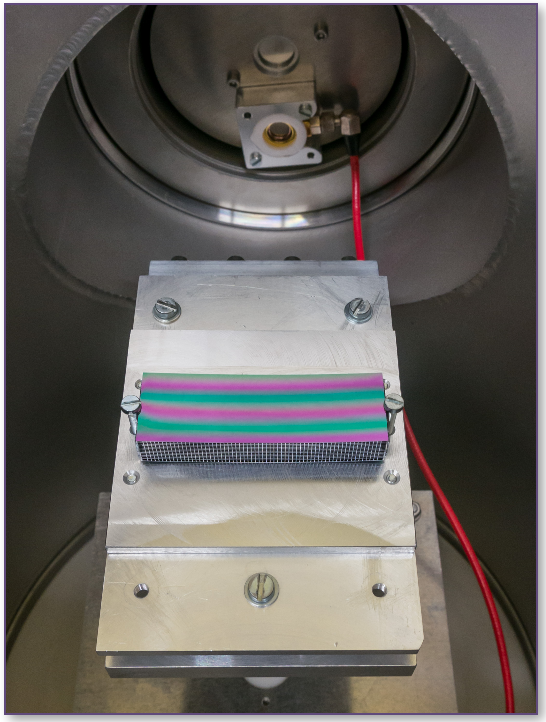
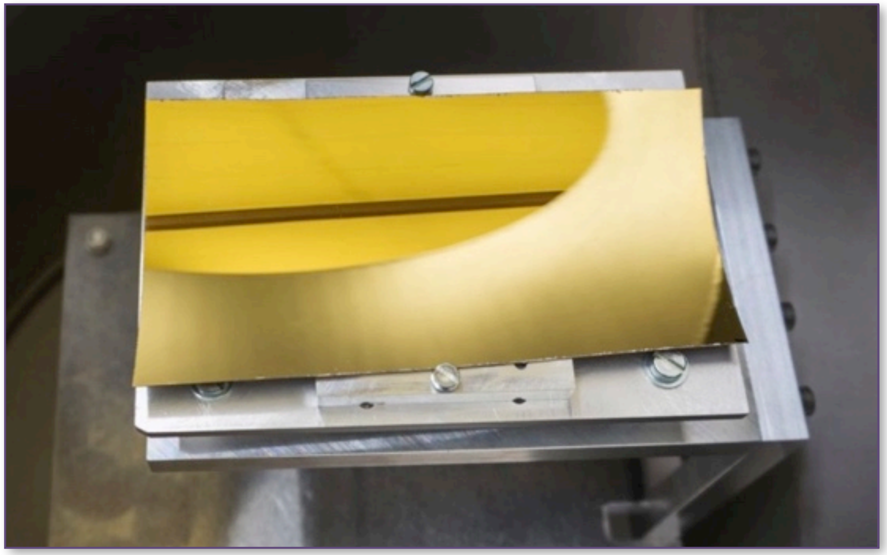




Silicon Surface Barrier Detectors to scan the "focal plane"

Reflection of soft protons on mirrors

- Calculating the scattering efficiency:

$$\eta(\Psi,\Theta) = \frac{N_{\mathrm{det}}(\Psi,\Theta)}{N_{\mathrm{inc}}} \cdot \frac{1}{\Omega(\Theta)}$$

- Incidence angle Ψ
- Scattering angle Θ
- Number of detected protons N_{det}
- Number of incident protons N_{inc}
- Solid angle of detector Ω

- Most probable energy loss:

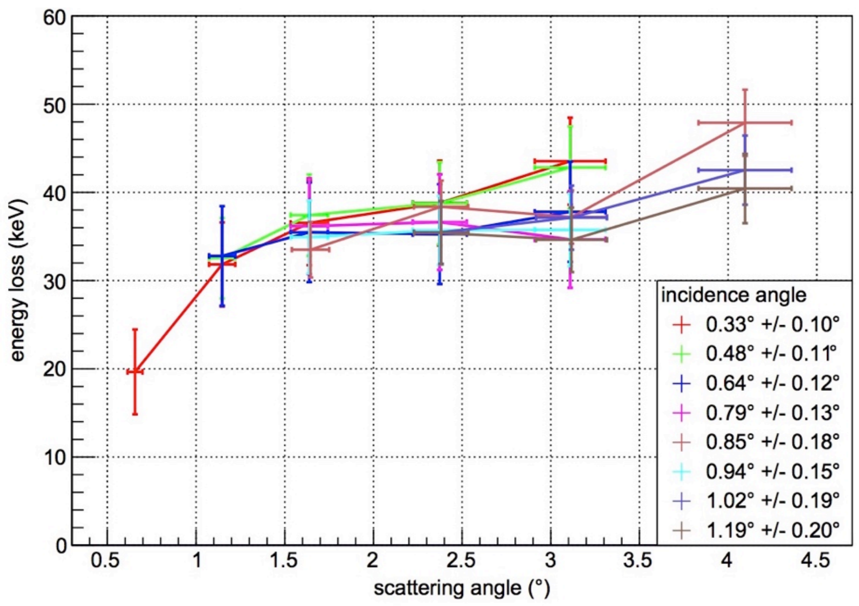
$$\Delta E(\Psi,\Theta) = \mu_{Gauss,inc} - \mu_{Gauss,\mathrm{det}}(\Psi,\Theta)$$

- Parameters selected for efficiency and energy loss measurements:

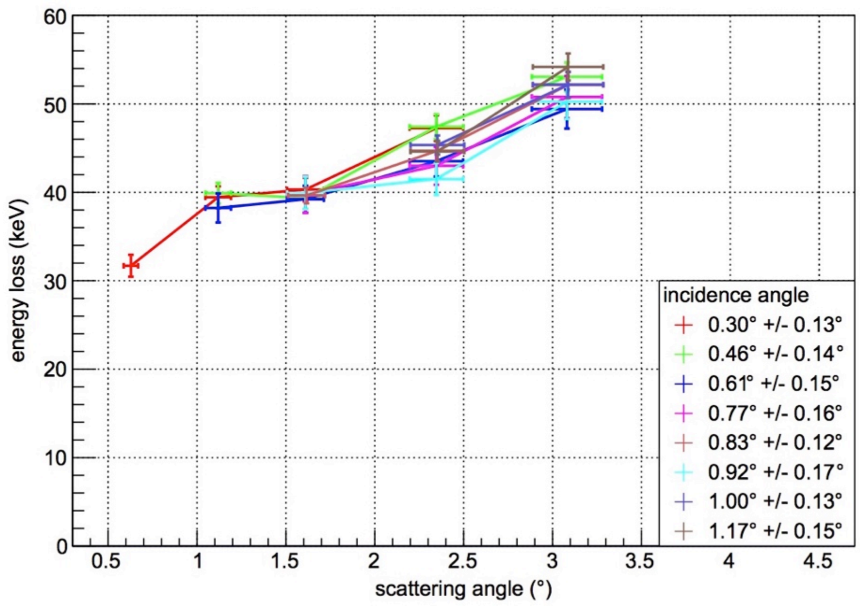
Proton energies (keV)	Incidence angle Ψ (deg)	Scattering angle Θ (deg)
250, 500, 1000	0.3 – 1.2	0.5 – 4.1

Soft proton focusing experiments with X-ray mirrors

Energy loss during scattering (gold coated nickel)



a) Energy loss for 500 keV



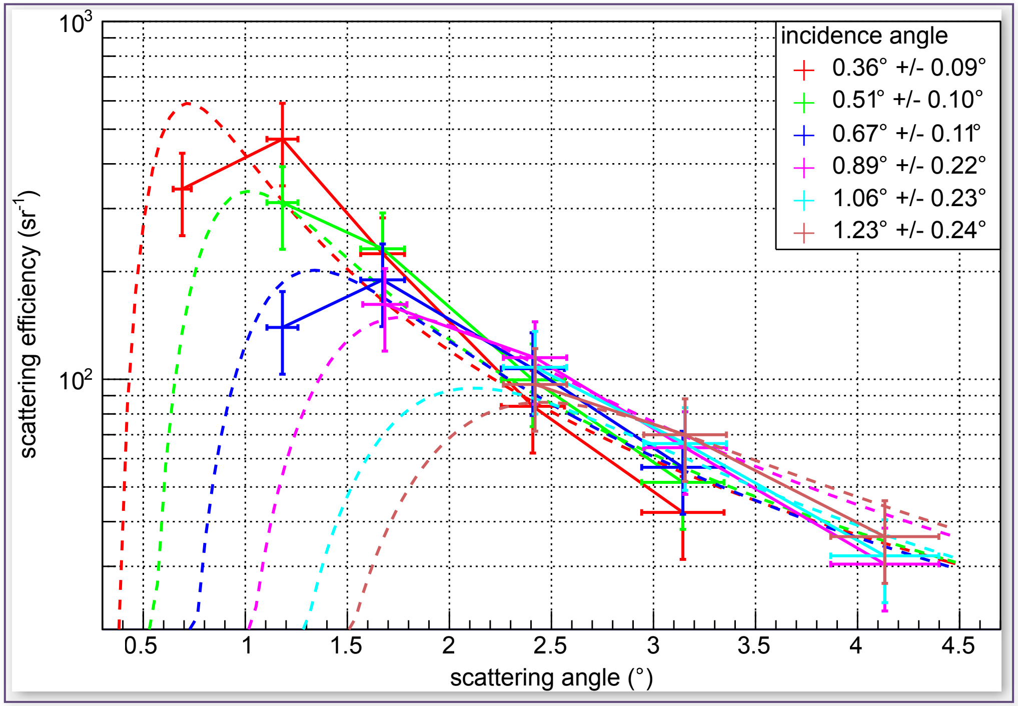
b) Energy loss for 1000 keV

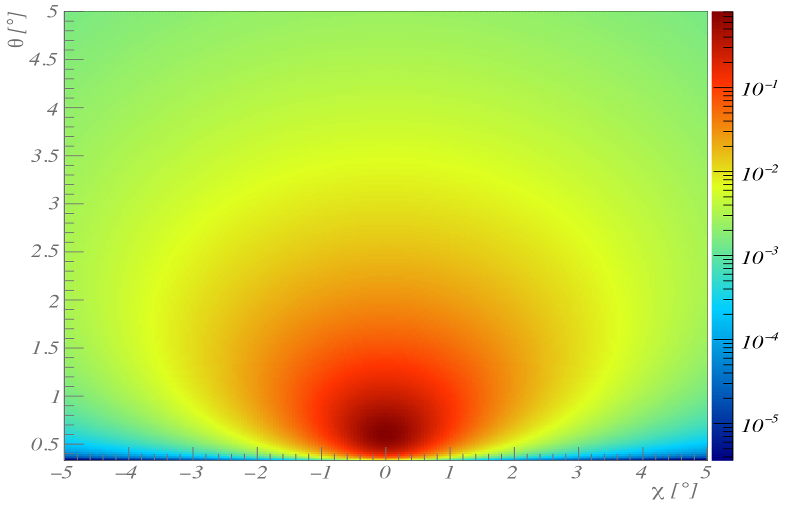
Energy loss depends slightly on the incidence energy, increases to larger scattering angles and is only minimally dependent on the incidence angle.

Angular distribution after scattering (gold coated nickel)

Measurement of the scattering efficiency:

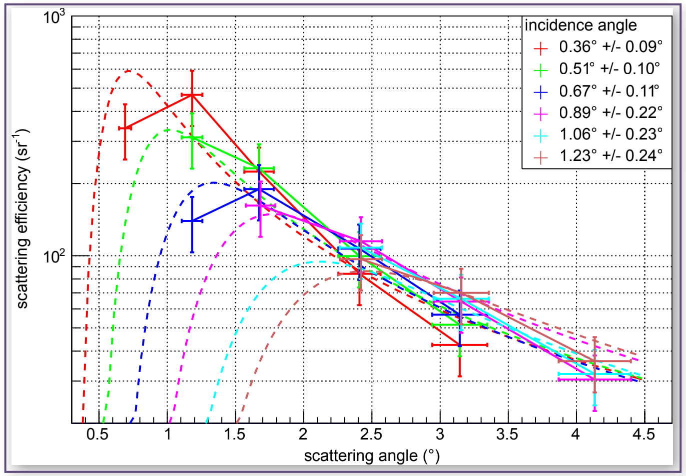
- **scan** the target area with an array of movable SSB detectors
- **record** the scattering efficiency for different incidence angles and energies
- **fit** with theoretical models to estimate the overall scattering efficiency





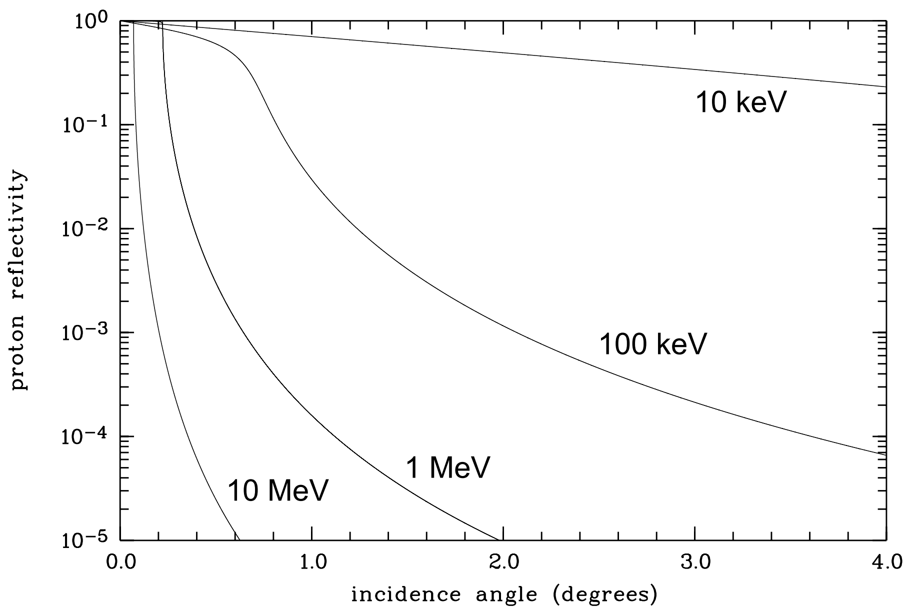
Firsov Scattering (1967)

- Protons interact with electron plasma above mirror surface
- Scattering efficiency increases towards low incidence angles
- Maximum at exit angle = incoming angle
- no or negligible energy loss
- does not consider azimuthal distribution, only scattering plane
- nothing is being said about the absolute scattering efficiency



Aschenbach Description (2007)

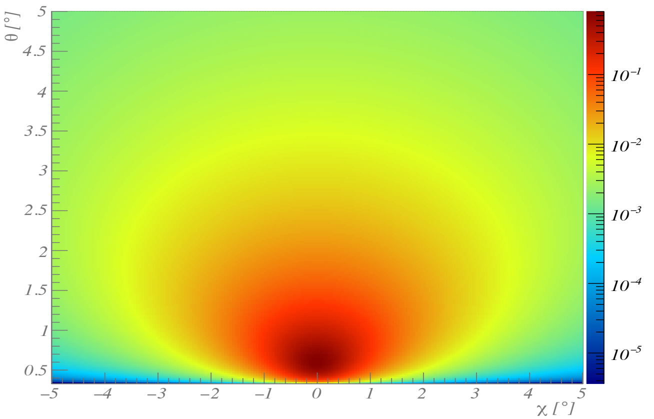
- Describes protons by means of the de Broglie wave formalism
- Reflection occurs equivalent to X-ray photons (“Proton Telescope”)
- Reflection efficiency depends on incidence angle and energy
- angular distribution follows PSF for X-rays
- no energy loss



Remizovich Reflection (1980)

- Solves transport equation for a particle flux propagating to a certain depth inside a dense target material
- Depending on the depth of interaction, the scattered particles emerge in a certain direction having lost a part of their energy
- Several parameters depend on the target **material properties**
- Firsov Scattering follows from this when integrating over azimuthal distribution and setting σ = infinity (no deceleration of particles, independence of target material)
- Differential backscattering coefficient:

$$W(\Theta,X,u)=\frac{\sqrt{3}}{2\pi^2}\frac{E_0}{\varepsilon(u)}\frac{\Theta}{R_0}\frac{e^{-\frac{\Theta^2-\Theta+1}{\sigma s(u)}}\,e^{-\frac{X^2}{4\sigma s(u)}}}{\sqrt{\sigma^3 s^5(u)}}\,\mathrm{Erf}\left(\sqrt{\frac{3\Theta}{\sigma s(u)}}\right)$$



Geant4 implementation (gold coated nickel)

Our experimental data reproduces the Remizovich Reflection over a large range of angles and energies. However, we observe an excess in reflection efficiency towards the maximum, situated at the incidence angle.

- For the upcoming Geant4 class G4GrazingAngleScattering, we implemented the Firsov and Remizovich description as well as a "Rosenau"-model that simulates a distribution reproducing our experimental data.

- This allows to simulate the measured behaviour of e.g. an actual eROSITA mirror behaviour rather than a theoretical model

- Geant4 is a Monte Carlo Toolkit that allows (among many other things) to track particles of an in-orbit radiation environment through a satellite geometry and see which primaries and secondaries end up depositing energy in the detector.

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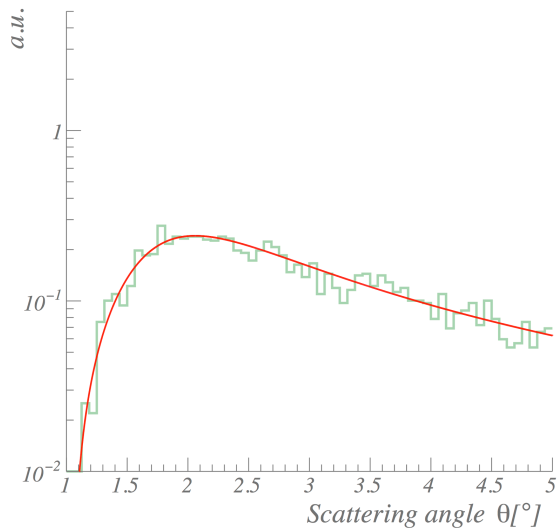

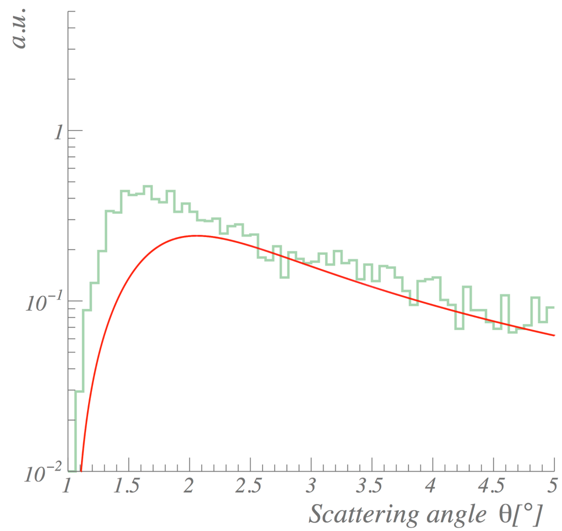

- Remizovich model simulated with G4GrazingAngleScattering (green) (E = 977keV, Ψ = 1.03°)
- Remizovich Function (red)

- Rosenau model simulated with G4GrazingAngleScattering (green) (E = 977keV, Ψ = 1.03°)
- Remizovich Function (red)

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Soft proton focusing experiments with X-ray mirrors

Summary

- We operate a setup at the accelerator in Tübingen to measure the effects of soft proton interactions on X-ray detectors.
- In addition, the setup can be used to investigate in detail the reflection of soft protons on X-ray mirrors
- We observe an excess in reflection efficiency towards the maximum, situated close to the incidence angle.
- Energy loss can be clearly observed. It depends slightly on the incidence energy, increases to larger scattering angles and is only minimally dependent on the incidence angle
- A model of our measured data has been implemented in a new G4GrazingAngleScattering class together with analytical descriptions of Remizovich and Firsov to enable the usage of recent experimental data for end-to-end simulations of X-ray telescopes in orbit.
- We are open to perform measurements for other detectors and mirrors in case anybody is interested.