Grazing angle soft proton concentrating experiments with X-ray mirrors

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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\(^+\), d, D\(^+\), \(^4\)He\(^+\), \(^{12}\)C\(^+\), \(^{13}\)C\(^+\), \(^{16}\)O\(^+\)
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**
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.
Two types of interactions of charged particles with the detector material:

- Electron scattering => ionization (TID)
- Nuclear scattering => lattice defects and vacancies (NIEL)
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
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Detector irradiation setup

- Proton beam
- Beamstop vacuum shutter
- Pinhole aperture
- Different energy degrader foils
- Shutter
- Silicon surface barrier detectors

~ 2.4m

Scaler/ADC

\( \varnothing \sim 11 \text{cm} \)

Irradiated area

Diebold et al., 2013b
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Detector irradiation setup

Soft Proton Irradiation Setup

Implementation at the Accelerator Facility

(Diebold et al., 2013b)
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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

**Input Spectrum Measured at the Detector Location**

**Homogeneity of the Irradiation**

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Detected irradiation

- Setup originally designed for LOFT detectors
- Allows homogeneous flux distribution over large detectors
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![Image of detector prototype]

**Input Spectrum Measured at the Detector Location**

**Homogeneity of the Irradiation**

**Figure 3**: Ratio between the measured and expected increment of leakage current as a function of time after the end of the irradiation.

**Figure 4**: Variation of the leakage current as a function of temperature before (green curve) and after (red curve) the irradiation.
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Setup for reflection of soft protons on mirrors

- Incident Flux Determination via Monitor Detectors
- Detector for scattered protons
- Scattering target on tiltable table
- Collimator
- Monitor detectors
- ADC
- Pinhole aperture (Ø = 0.1 – 1.0 mm)
- Degrader foil
- Beamstop, vacuum shutter
- Slit

Measurements:
- ~2.5 m
- ~0.8 m
- ~1 m
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Setup for reflection of soft protons on mirrors
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
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Reflection of soft protons on mirrors

- Calculating the scattering efficiency:

\[ \eta(\Psi, \Theta) = \frac{N_{\text{det}}(\Psi, \Theta)}{N_{\text{inc}}} \cdot \frac{1}{\Omega(\Theta)} \]

- Most probable energy loss:

\[ \Delta E(\Psi, \Theta) = \mu_{\text{Gauss,inc}} - \mu_{\text{Gauss,det}}(\Psi, \Theta) \]

- Parameters selected for efficiency and energy loss measurements:

<table>
<thead>
<tr>
<th>Proton energies (keV)</th>
<th>Incidence angle (\Psi) (deg)</th>
<th>Scattering angle (\Theta) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250, 500, 1000</td>
<td>0.3 – 1.2</td>
<td>0.5 – 4.1</td>
</tr>
</tbody>
</table>
Energy loss during scattering (gold coated nickel)

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

![Graph showing angular distribution after scattering](image)
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 $\sigma = \infty$ (no deceleration of particles, independence of target material)

- Differential backscattering coefficient:

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

\[\begin{array}{c}
\end{array}\]
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.
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.

• Remizovich model simulated with G4GrazingAngleScattering (green) (\( E = 977\text{keV}, \Psi = 1.03^\circ \))
• Remizovich Function (red)

• Rosenau model simulated with G4GrazingAngleScattering (green) (\( E = 977\text{keV}, \Psi = 1.03^\circ \))
• Remizovich Function (red)
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.