Design and Space Qualification of a VUV Telescope Mirror for Solar Orbiter SPICE

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MPS Solar Group Seminar
Overview

• Introduction:
  – The Solar Orbiter Mission
  – The SPICE Spectrograph
• SPICE Telescope Mirror design requirements
• Test programme of mirror samples
• Space qualification results
• Final design of the Mirror
Solar Orbiter Mission

Top-level science questions:
• What drives the solar wind and where does the coronal magnetic field originate from?
• How do solar transients drive heliospheric variability?
• How do solar eruptions produce energetic particle radiation that fills the heliosphere?
• How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Science payload
• In-Situ Instruments:
  • Energetic Particle Detector (EPD)
  • Magnetometer (MAG)
  • Radio and Plasma Wave analyser (RPW)
  • Solar Wind Analyser (SWA)

• Remote-Sensing Instruments:
  • EUV full-Sun and high-resolution Imager (EUI)
  • Coronagraph (METIS)
  • Polarimetric and Helioseismic Imager (PHI)
  • Heliospheric Imager (SoloHI)
  • X-ray spectromter/telescope (STIX)
  • EUV spectrographic Imager (SPICE)
EUV Emission of the Sun

Figure 8

Ultraviolet emission from plasma in the Sun's atmosphere, revealing the complex magnetic field structures around active regions. (SDO AIA 17.1 nm image.)

Streamers that might be plasmoids or might be pile-up from reconnection high in the corona. Finally, there might be a continuous outward leakage of plasma from high in the solar corona where the plasma pressure becomes comparable to the magnetic pressure in the weak field at the apex of closed loops.

(b) Source regions of the heliospheric magnetic field.

Our current knowledge of the surface magnetic field of the Sun and its extension into the solar atmosphere and interplanetary space is based on measurements of the photospheric line-of-sight (and recently, vector) magnetic field, coupled with spacecraft measurements of the field *in situ*. The vast majority of the magnetic flux from the Sun closes in the lower layers of the solar atmosphere, within the chromosphere and lower corona, in multiple small-scale bipolar regions with strong local fields, and it is only a small fraction which extends high enough in the solar atmosphere to be dragged out into the heliosphere by the solar wind. In addition, the intense magnetic fields in the lower atmosphere are highly variable and dynamic at scales extending down to instrument resolution limits in both time and space, continuously reconnecting and contributing to the intense activity, spicules and jets in the chromosphere and lower corona. The magnetic connection between the solar wind and the solar source therefore hinges on understanding what determines the amount of open flux from the Sun, how open field lines are distributed at the solar surface at any given time, and how these open field lines reconnect and change their connection across the solar surface in time, processes which are controlled by interchange reconnection (Wang, Lean, and Sheeley, 2000; Fisk and Schwadron, 2001).
Mission Orbit

Figure 1: Payload accommodation onboard Solar Orbiter. In this rendering, one side wall has been removed to expose the remote-sensing instruments mounted on the payload panel. The SPICE instrument (not visible) is mounted to the top panel from below. See Section 2.1 for a payload description and acronyms.

Figure 2: Solar Orbiter’s trajectory viewed from above the ecliptic (January 2017 launch). The gravity assist maneuvers (GAM) at Earth (E) and Venus (V) are indicated, along with the orbits of these two planets.

Closest Perihelion at 0.284 AU
Figure 3
Mission profile for a January 2017 launch, showing heliocentric distance (top) and latitude (bottom) of Solar Orbiter as a function of time. Also indicated are the times at which gravity assist maneuvers at Venus and Earth occur (blue).
Orbit inclination

Figure 3: Mission profile for a January 2017 launch, showing heliocentric distance (top) and latitude (bottom) of Solar Orbiter as a function of time. Also indicated are the times at which gravity assist maneuvers at Venus and Earth occur (blue).
Solar Orbiter Payload
SPICE – Extreme-Ultraviolet Spektrograph:
The SPICE instrument is a high-resolution imaging spectrograph to observe the solar corona both on the solar disk and off the solar limb. To optimize throughput, the instrument consists of only two optical elements:

- a single off-axis parabolic telescope mirror
- a toroidal variable line-spaced grating which re-images the spectrally dispersed radiation onto two array detectors.

Two spectral pass bands are recorded simultaneously with two intensified active pixel sensor (IAPS) detectors.

It covers the extreme ultraviolet wavelength bands from 70.2 nm to 79.2 nm and from 97.0 nm to 105.0 nm (and 48.5 nm to 52.5 nm in 2nd order).
Heritage of SPICE design

• Originally proposed by Roger Thomas (GSFC) after an optical concept of an TVLS grating of Kita and Harada (J)
• SERTS, EUNIS, RAISE, rocket spectrographs
• HINODE / EIS
Already space proven (EUV Imaging Spectrograph on the Hinode mission), however, a challenge for Solar Orbiter is the management of the heat from the Sun.
Primary mirror design driving requirements

Principal Requirements:

1. high VUV reflectance over large spectral range
2. manage thermal heat load, high vis-IR transmission

- form: off-axis paraboloid
- surface: low scatter, 1” PSF
- substrate: fused silica
- coatings:
  - front: thin boron carbide
  - back: anti-reflective

=> heat will be transmitted towards space
Power distribution of solar irradiance

Mirror samples produced by FhG-IOF with various thicknesses of boron carbide ($B_4C$)

Measurements of Reflectance and Transmission, Absorption.

Simulation of solar power distribution

- Budget for a 10 nm $B_4C$ coating:
  - $T = 77\%$
  - $R = 13\%$
  - $A = 10\%$
Space qualification of mirror coatings

Environmental conditions of Solar Orbiter mission:

• Space radiation simulation: irradiation with 10 - 60 MeV protons

• Solar wind simulation: irradiation with 1 keV protons (mission equivalent dose)

• Solar UV simulation: irradiation with UV (20 solar constants)
# Qualification Test Plan

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Samples Coated</th>
<th>Samples Uncoated</th>
<th>Note</th>
</tr>
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<tbody>
<tr>
<td>AFM (1μm² +10μm²)</td>
<td>0</td>
<td>18</td>
<td>characterization surface roughness</td>
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<tr>
<td>Coating B₄C 10 nm</td>
<td>10</td>
<td>1</td>
<td>surface coating with B₄C for 10 nm</td>
</tr>
<tr>
<td>Coating for B₄C 16 nm</td>
<td>6</td>
<td>1</td>
<td>surface coating with B₄C for 16 nm</td>
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<tr>
<td>AFM (1μm² +10μm²)</td>
<td>13</td>
<td>2</td>
<td>surface roughness after coating</td>
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<tr>
<td>X-ray diffraction</td>
<td>16</td>
<td>0</td>
<td>coating thickness calculation</td>
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<tr>
<td>Spectral photometry (T/R)</td>
<td>16</td>
<td>1</td>
<td>visible reflectance/transmittance</td>
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<tr>
<td>VUV-Reflectance Test</td>
<td>16</td>
<td>1</td>
<td>VUV measurements at PTB-MLS</td>
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<tr>
<td>Irradiation protons</td>
<td>6</td>
<td>1</td>
<td>protons at 10 MeV - 60 MeV (PSI)</td>
</tr>
<tr>
<td>Irradiation protons</td>
<td>6</td>
<td>1</td>
<td>solar wind protons at 1 keV (FZD)</td>
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<td>AFM (1μm² +10μm²)</td>
<td>12</td>
<td>2</td>
<td>surface roughness after irradiations</td>
</tr>
<tr>
<td>X-ray diffraction</td>
<td>12</td>
<td>2</td>
<td>coating thickness verification</td>
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<tr>
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<td>12</td>
<td>2</td>
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<td>12</td>
<td>2</td>
<td>VUV measurements at PTB-MLS</td>
</tr>
</tbody>
</table>
EUV reflectance of samples

Summary of all reflectance measurements in the EUV range
Reflectance of B₄C coatings

16-nm coatings
10-nm coatings
no coating

EUV reflectance
vis-IR reflectance

@PTB
@ FhG-IOF
Irradiation tests: protons

- High energy $p^+$

<table>
<thead>
<tr>
<th>Position</th>
<th>Sample #</th>
<th>Proton Energy</th>
<th>Fluence [#/cm²]</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>$P1$</td>
<td>12894</td>
<td>10 MeV</td>
<td>$4 \times 10^{10}$</td>
<td>10 nm B₄C</td>
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<tr>
<td>$P2$</td>
<td>12891</td>
<td>10 MeV</td>
<td>$4 \times 10^{10}$</td>
<td>16 nm B₄C</td>
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<tr>
<td>$P3$</td>
<td>12930</td>
<td>20 MeV</td>
<td>$+8 \times 10^{10}$</td>
<td>10 nm B₄C</td>
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<tr>
<td>$P4$</td>
<td>12890</td>
<td>20 MeV</td>
<td>$+8 \times 10^{10}$</td>
<td>16 nm B₄C</td>
</tr>
<tr>
<td>$P5$</td>
<td>12637</td>
<td>60 MeV</td>
<td>$+2 \times 10^{10}$</td>
<td>10 nm B₄C</td>
</tr>
<tr>
<td>$P6$</td>
<td>12645</td>
<td>all</td>
<td>$+2 \times 10^{10}$</td>
<td>shielded</td>
</tr>
<tr>
<td>$P7$</td>
<td>12931</td>
<td>60 MeV</td>
<td>$+2 \times 10^{10}$</td>
<td>no coating</td>
</tr>
</tbody>
</table>

made at Paul-Scherrer-Institut (CH)

- Low energy $p^+$ (representing the solar wind at 1 keV)

<table>
<thead>
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<th>Sample ID</th>
<th>Fluence [#/cm²]</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>$P8$</td>
<td>12644</td>
<td>$1 \times 10^{10}$</td>
<td>10 nm B₄C</td>
</tr>
<tr>
<td>$P9$</td>
<td>12638</td>
<td>$5 \times 10^{10}$</td>
<td>10 nm B₄C</td>
</tr>
<tr>
<td>$P10$</td>
<td>11863</td>
<td>$10 \times 10^{10}$</td>
<td>10 nm B₄C</td>
</tr>
<tr>
<td>$P11$</td>
<td>12935</td>
<td>$30 \times 10^{10}$</td>
<td>16 nm B₄C</td>
</tr>
<tr>
<td>$P12$</td>
<td>12834</td>
<td>$60 \times 10^{10}$</td>
<td>16 nm B₄C</td>
</tr>
<tr>
<td>$P13$</td>
<td>12934</td>
<td>$60 \times 10^{10}$</td>
<td>no coating</td>
</tr>
<tr>
<td>$P14$</td>
<td>12893</td>
<td>shielded</td>
<td>~16nm B₄C</td>
</tr>
</tbody>
</table>

made at Ionenstrahlzentrum Dresden Rossendorf
Irradiation tests: VUV irradiation

High-intensity krypton lamp and hydrogen line source mounted to a reflectometer vacuum tank for the measurements at 121.6 nm and for the irradiation of samples with 123 nm wavelength.
Average reflectance and transmittance values of the samples irradiated by protons > 10 MeV

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>128</th>
<th>129</th>
<th>126</th>
<th>126</th>
<th>128</th>
<th>128</th>
<th>129</th>
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<tbody>
<tr>
<td></td>
<td>94</td>
<td>30</td>
<td>37</td>
<td>45</td>
<td>90</td>
<td>91</td>
<td>31</td>
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<tr>
<td>Fluence x10^{11} p/cm²</td>
<td>4,00</td>
<td>4,80</td>
<td>5,00</td>
<td>shied</td>
<td>4,80</td>
<td>4,00</td>
<td>5,00</td>
</tr>
<tr>
<td>R before</td>
<td>10,3</td>
<td>10,4</td>
<td>10,6</td>
<td>10,7</td>
<td>15,5</td>
<td>13,9</td>
<td>-</td>
</tr>
<tr>
<td>R after</td>
<td>10,2</td>
<td>10,3</td>
<td>10,4</td>
<td>10,6</td>
<td>14,3</td>
<td>13,7</td>
<td>6,4</td>
</tr>
<tr>
<td>T before</td>
<td>82,7</td>
<td>82,6</td>
<td>82,2</td>
<td>81,8</td>
<td>76,6</td>
<td>77,8</td>
<td>-</td>
</tr>
<tr>
<td>T after</td>
<td>83,1</td>
<td>83</td>
<td>82,5</td>
<td>82,1</td>
<td>76,8</td>
<td>77,9</td>
<td>91,8</td>
</tr>
<tr>
<td>R_{VUV} before</td>
<td>28,8</td>
<td>29,3</td>
<td>29,1</td>
<td>30,5</td>
<td>33,1</td>
<td>32,1</td>
<td>8,70</td>
</tr>
<tr>
<td>R_{VUV} after</td>
<td>28,0</td>
<td>28,0</td>
<td>29,2</td>
<td>29,9</td>
<td>32,1</td>
<td>31,3</td>
<td>9,50</td>
</tr>
</tbody>
</table>
VUV reflectance vs 1 keV proton fluence

Samples irradiated with increasing fluence =>

Reflectance [%]

proton fluence [10^16/cm²]
Average reflectance and transmittance values of the samples irradiated by protons at 1 keV
Micro-roughness plots before (upper panel) and after (lower panel) irradiations with solar wind protons at 1 keV. (AFM measurements by FhG-IOF)
Micro-roughness after 1 keV proton implantation
Summary of EUV reflectance measurements after irradiations
Comparison of reflectance before and after irradiation with $6 \times 10^{17}$ protons/cm$^2$ of 1 keV of the 15.5-nm coating
TEST CONCLUSIONS

- The stability of thin $\text{B}_4\text{C}$ coatings of 10 nm and 16 nm thicknesses under irradiation by high-energy and low energy (solar wind) protons has been investigated.

- Irradiation by protons with energies between 10 and 60 MeV up to a mission-equivalent fluence of $5 \times 10^{11} \text{ cm}^{-2}$ has no negative effect on the performance of the mirror coatings. The surface micro-roughness and the VUV reflectance, as well as the thermo-optical properties are unaffected by the irradiations.

- The solar wind protons at a lower energy have an effect on the coatings because of the much higher fluence and because the stopping range is much shorter (it is on the same order as the coating thickness). At the energy of 1 keV it has a destructive effect on the coatings starting at a fluence of $1 \times 10^{16} \text{ cm}^{-2}$. At a fluence of $6 \times 10^{17} \text{ cm}^{-2}$ the 16-nm coating is evidently eroded such that the VUV reflectance is fully destroyed. At the same fluence, the irradiation leads also to a severe increase of the surface micro-roughness of the coated samples, as measured by AFM microscopy. Surprisingly, this increase of roughness has not been observed with the uncoated sample.

- The irradiation with high intensity Lyman Alpha radiation has no effect on the coating, except UV-induced contamination.
Detailed Instrument Design

- Heat dump (connected to HE interface)
- Mirror and Scan-Focus Mechanism (SFM)
- Slit Change Mechanism (SCM)
- Particle deflector
- SPICE Door Mechanism (SDM)
- Detector Assembly
Primary Mirror Design

- single parabola
- rectangular aperture area
- focal length of 622 mm
- mounted to a frame of the SFM
- substrate: square 103.0 mm
- 18 mm thickness at the centre.
- useful aperture is 95 mm x 95 mm
- square with rounded corners.
Detailed design

OFF-AXIS PARABOLOID GEOMETRY

- off-axis distance
- focal point
- effective focal length 622.0 mm
- parent parabola radius 1244.0 mm
- vertex
Detailed Design

- clear aperture thermal beam
- clear aperture optical beam
- optical axis

Dimensions:
- 103 mm
- 500 mm
- 150 mm
## Detailed specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Material</td>
<td>UV-grade fused-silica (Heraeus Suprasil 300)</td>
</tr>
<tr>
<td>Substrate Size</td>
<td>103 x 103 mm</td>
</tr>
<tr>
<td>Substrate Thickness</td>
<td>18 mm at centre</td>
</tr>
<tr>
<td>Figure of Front Surface</td>
<td>concave, off-axis parabolic</td>
</tr>
<tr>
<td>Off-axis Distance</td>
<td>55.0 mm</td>
</tr>
<tr>
<td>Base Radius</td>
<td>1244.0 mm</td>
</tr>
<tr>
<td>Figure Error</td>
<td>λ/20 RMS at 632.8 nm over clear aperture</td>
</tr>
<tr>
<td>Front-side Coating</td>
<td>single layer B$_4$C, 10 nm thickness, at central 50 x 50 mm</td>
</tr>
<tr>
<td>Clear Aperture of thermal beam</td>
<td>≥ 95.0 mm x 95.0 mm</td>
</tr>
<tr>
<td>Back-side Coating</td>
<td>Anti-reflective MgF$_2$ single layer</td>
</tr>
</tbody>
</table>
Primary Mirror Mount

- Silica glass mirror, -103x103mm square, -16.8mm min thickness
- Titanium mounting frame attached to SFM by 6x M3 fasteners
- Positioned with dowel pin on SFM
- Snubber restraint at top of mount
- Contamination control:
  - Viton seal from mirror rear perimeter to SOU wall
Mirror Fabrication

Collaboration of MPS with Fraunhofer Institut für Angewandte Optik und Feinmechanik (FhG-IOF) and optiX fab GmbH Jena

- Mirror substrate fabrication by subcontractor: Jenoptik in Jena
- Optical coatings and their characterization (XRD)
- Surface roughness measurements (AFM)
- Optical/thermal properties (R,T,A)
- Scatter model calculations

Physikalisch-Technische Bundesanstalt (PTB)

- Metrology Light Source (MLS)
- VUV and EUV metrology
Mirror Fabrication and Verification flow

Fabrication

Cutting & Figuring → Metrology, Figure, focal length
    | Polishing → Finish, roughness
    | Cleaning
    | AR coating → Verification of AR coating
    | B4C coating → Verification of B4C coating
    | Thickness verification by XRT
    | UV-Vis-IR Reflectance & Transmission
    | VUV Reflectance @ PTB

Delivery of Mirror and samples

Verification

Jenoptik

FhG IOF / optiX fab

PTB

MPS

First mirror to be delivered to RAL SPACE next week!