Die VUV-Instrumente der Solar Orbiter Mission

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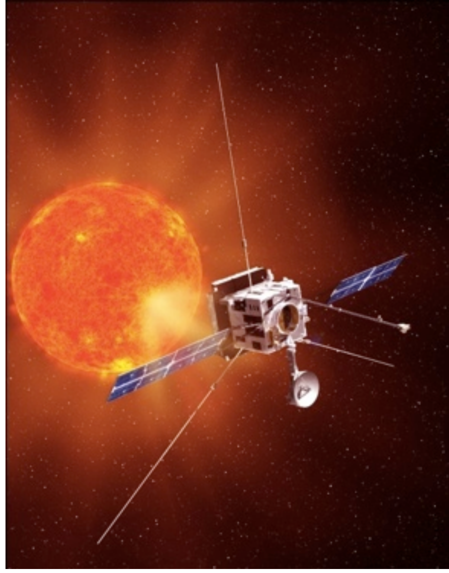
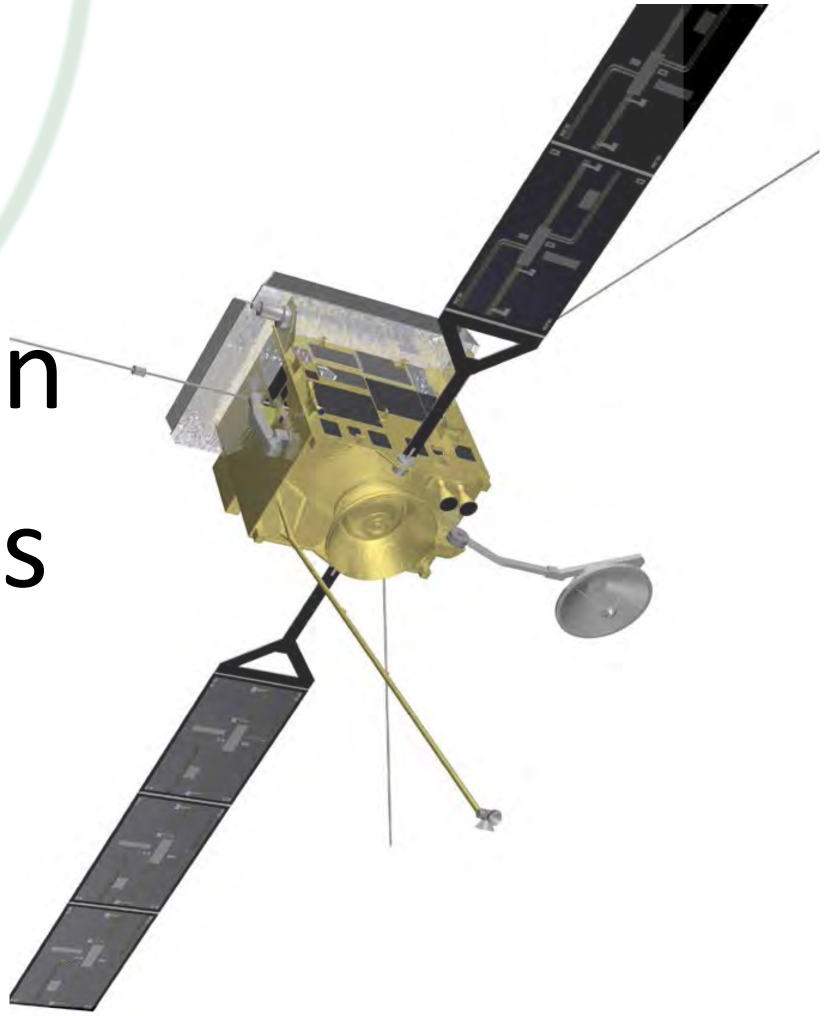
Justus-von-Liebig-Weg 3
Göttingen

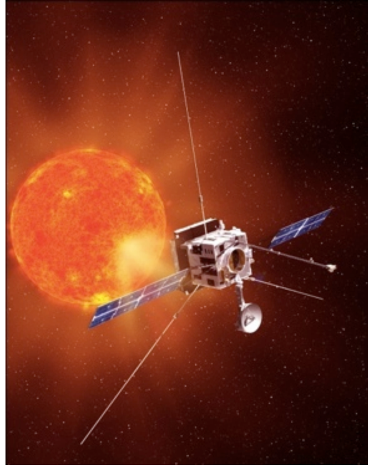


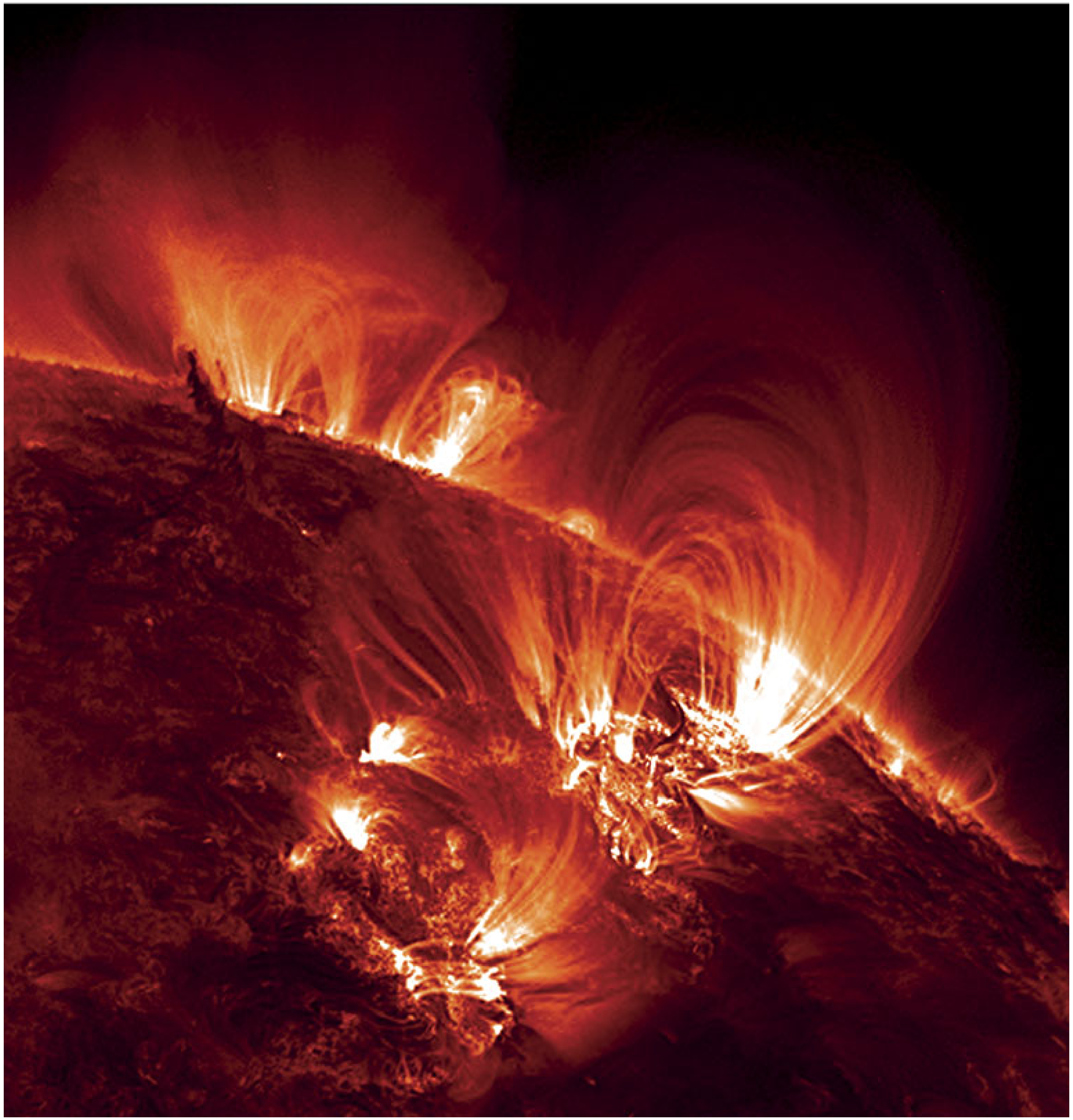
Überblick

- Einleitung: Die Solar Orbiter Mission
- Die Nutzlastinstrumente
- Der VUV Spektrograph “SPICE”
- SPICE Teleskopspiegel Design
- Test Programm der Spiegelproben
- Design und Fertigung des Spiegels



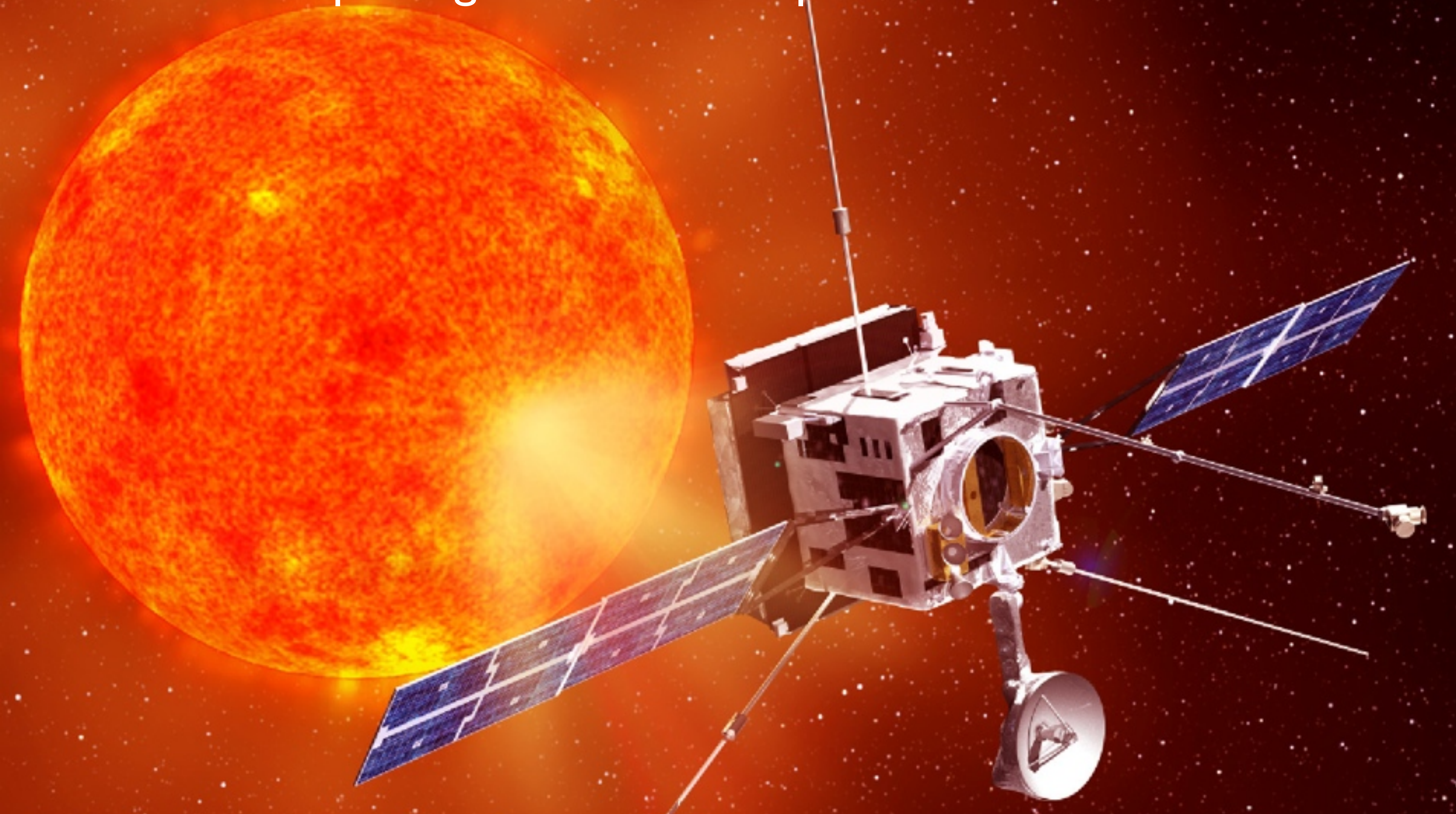
EUV-Emission der Sonne





Solar Orbiter

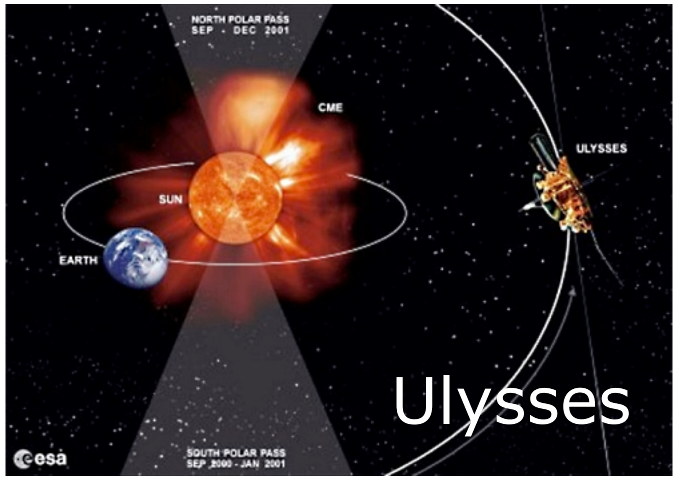
Exploring the Sun-Heliosphere Connection

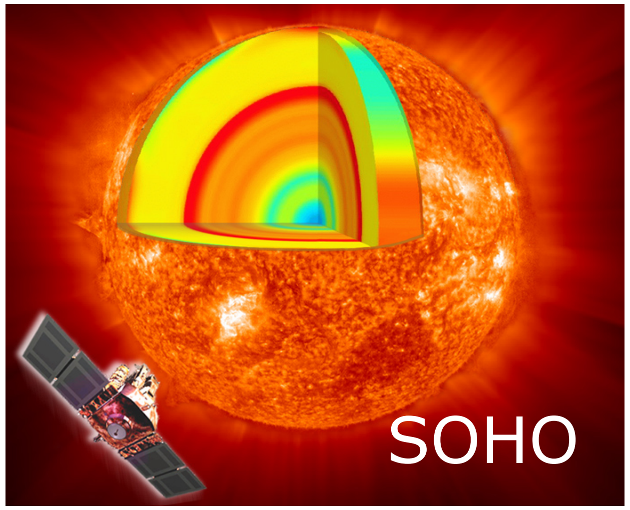


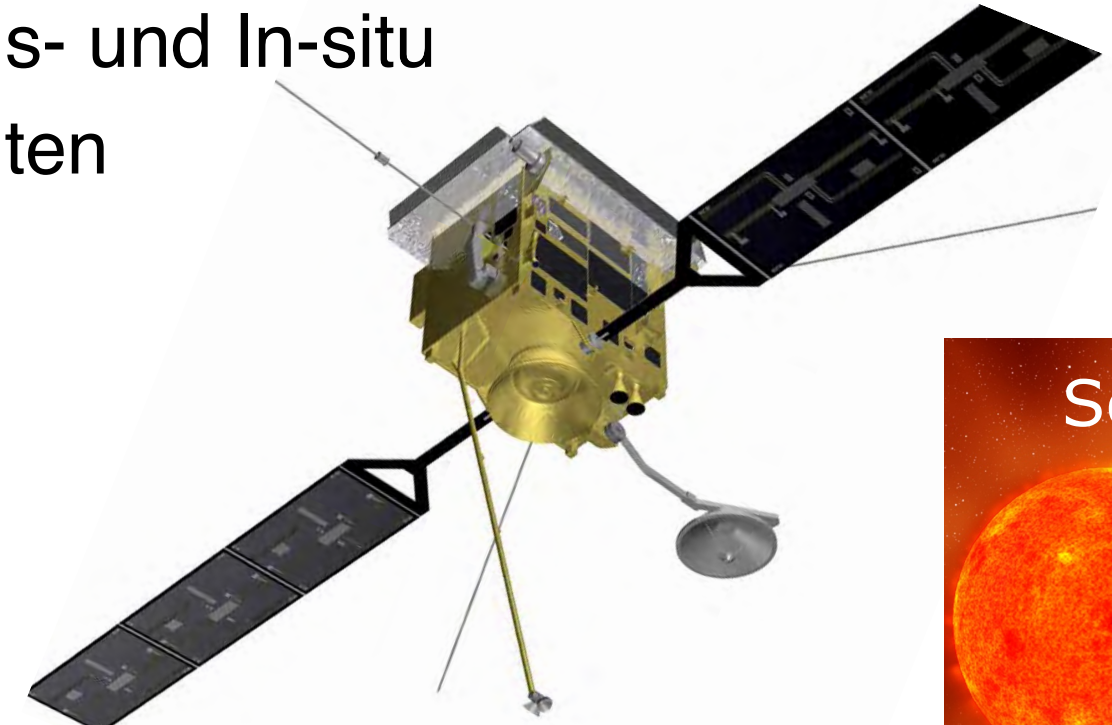
Solar Orbiter
Exploring the Sun-Heliosphere Connection

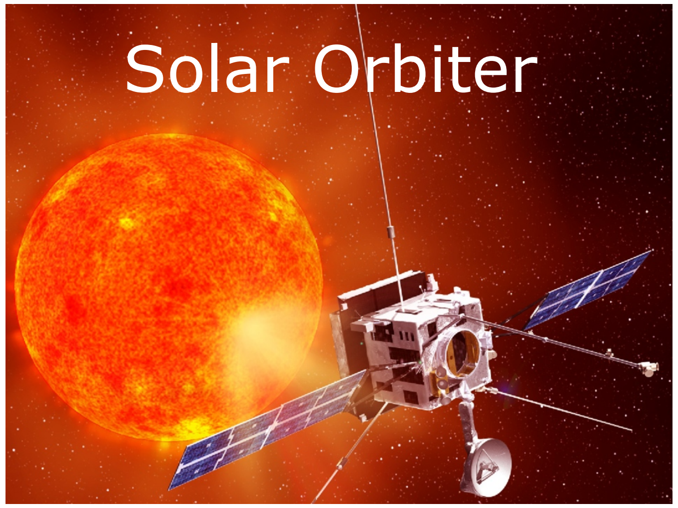
- Erste “Medium-Class Mission in ESA’s Cosmic Vision Programm 2015 - 2025 gemeinsam mit NASA

- Spezialisierte Nutzlast mit 10 Fernerkundungs- und In-situ Messinstrumenten

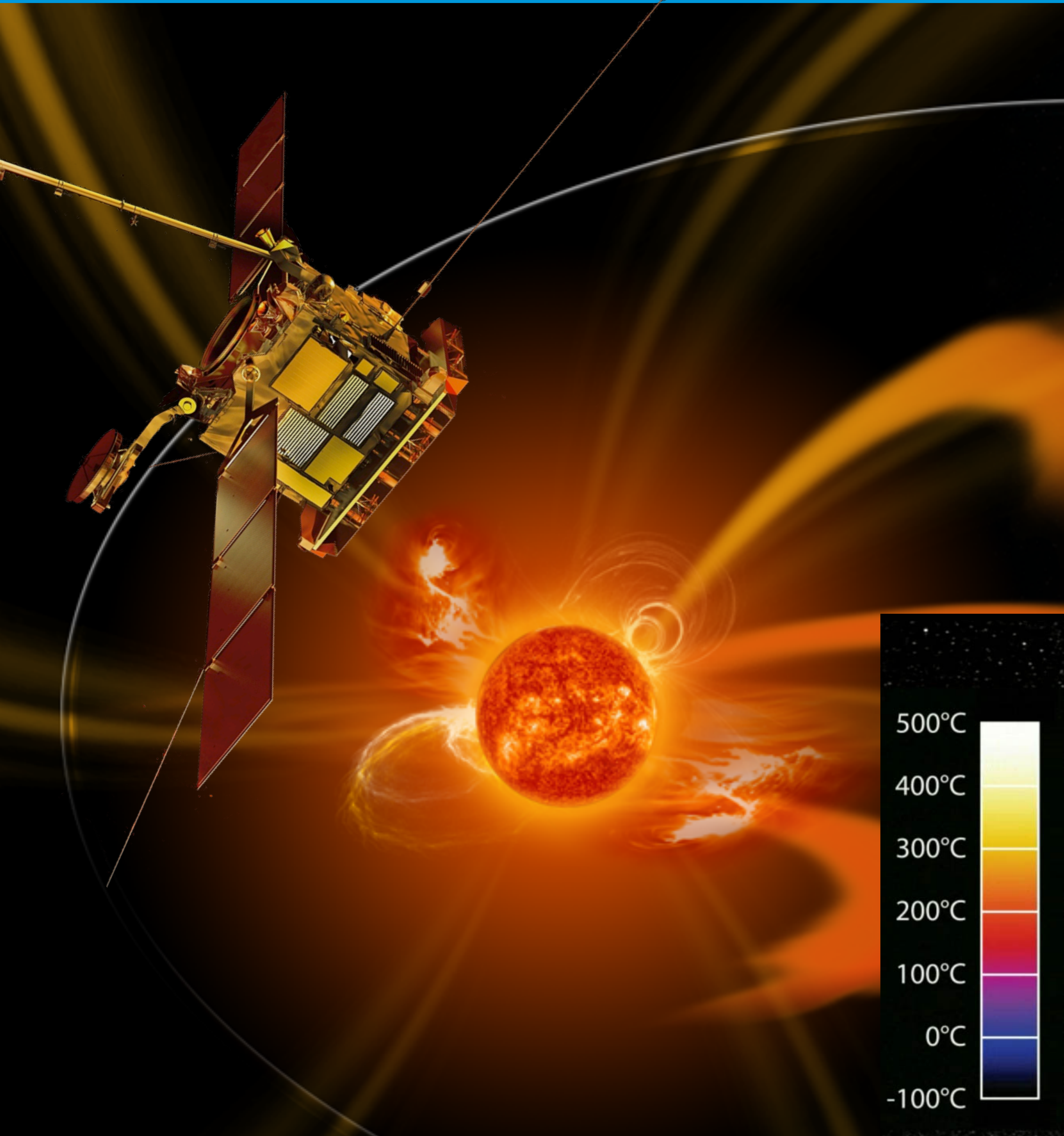






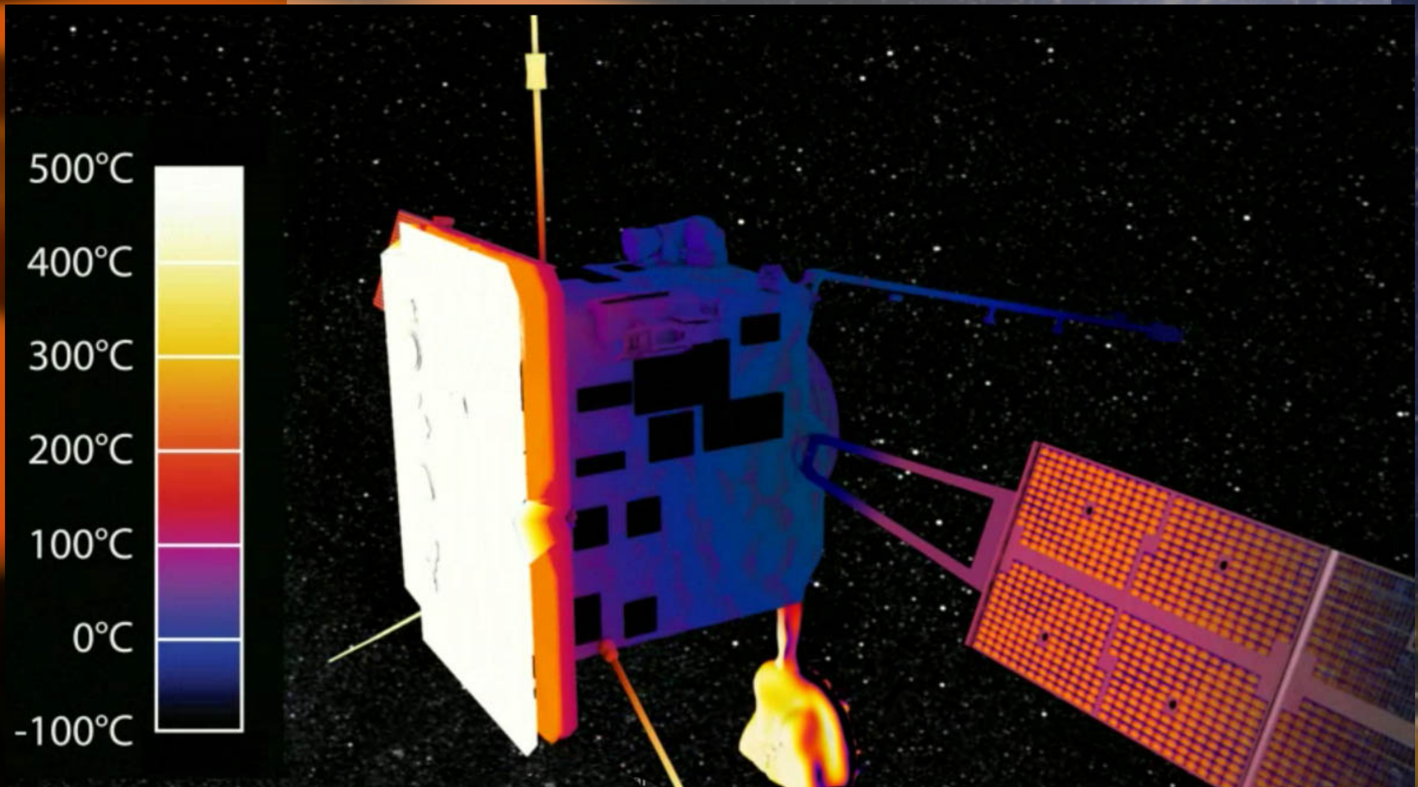


Solar Orbiter
Exploring the Sun-Heliosphere Connection

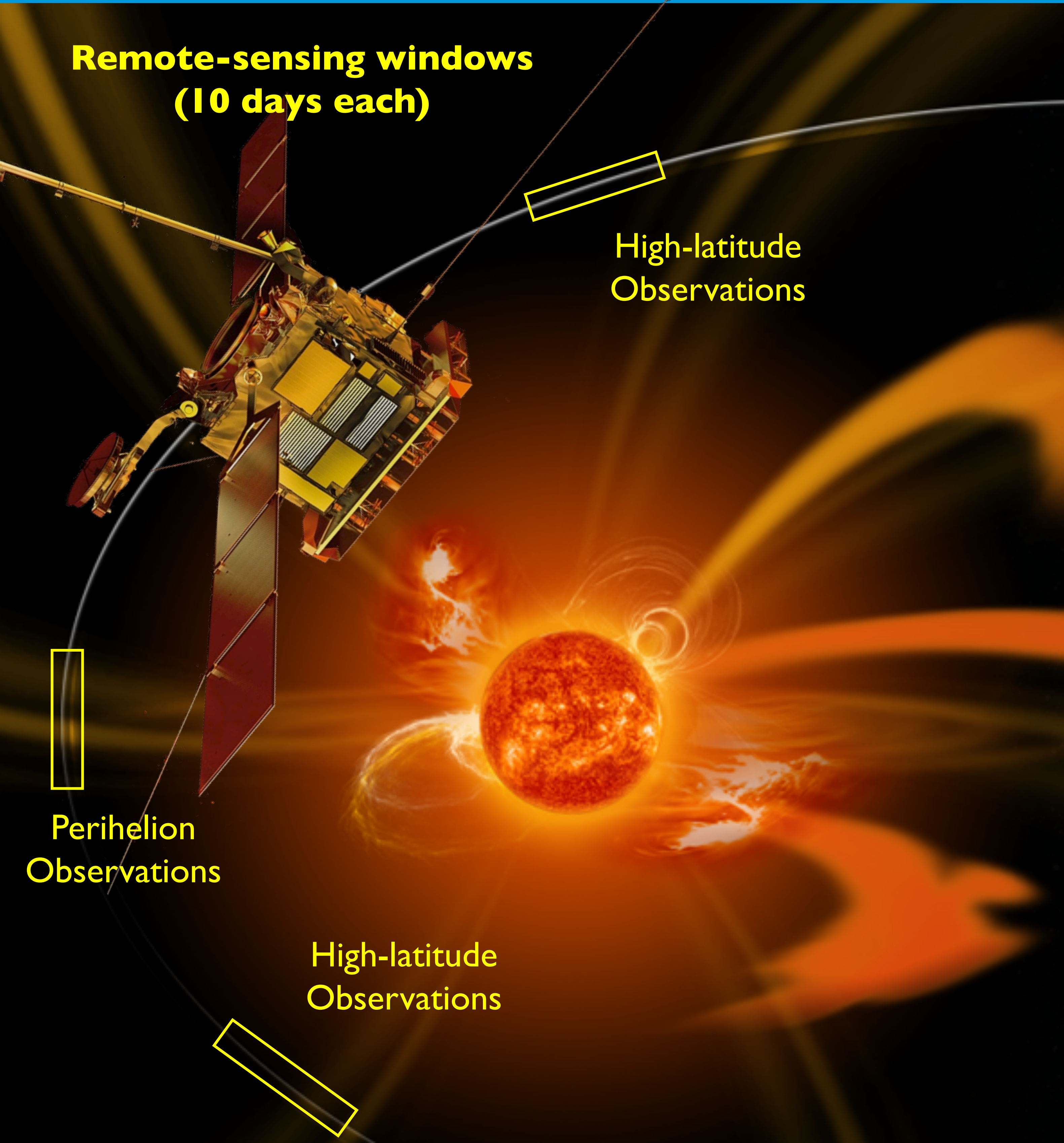


Die Raumfähre:

- Drei-Achsen-stabilisiert
- Gewicht: 1,8 t
- Sonnenzentriert mit Ausrichtungsmöglichkeit +- 2°
- Perihel: 0.28 AU
- Hitzeschild notwendig



Solar Orbiter
Exploring the Sun-Heliosphere Connection



Mission Summary

Launch Date: 2017

Cruise Phase: 3 years

Nominal Mission: 3.5 years

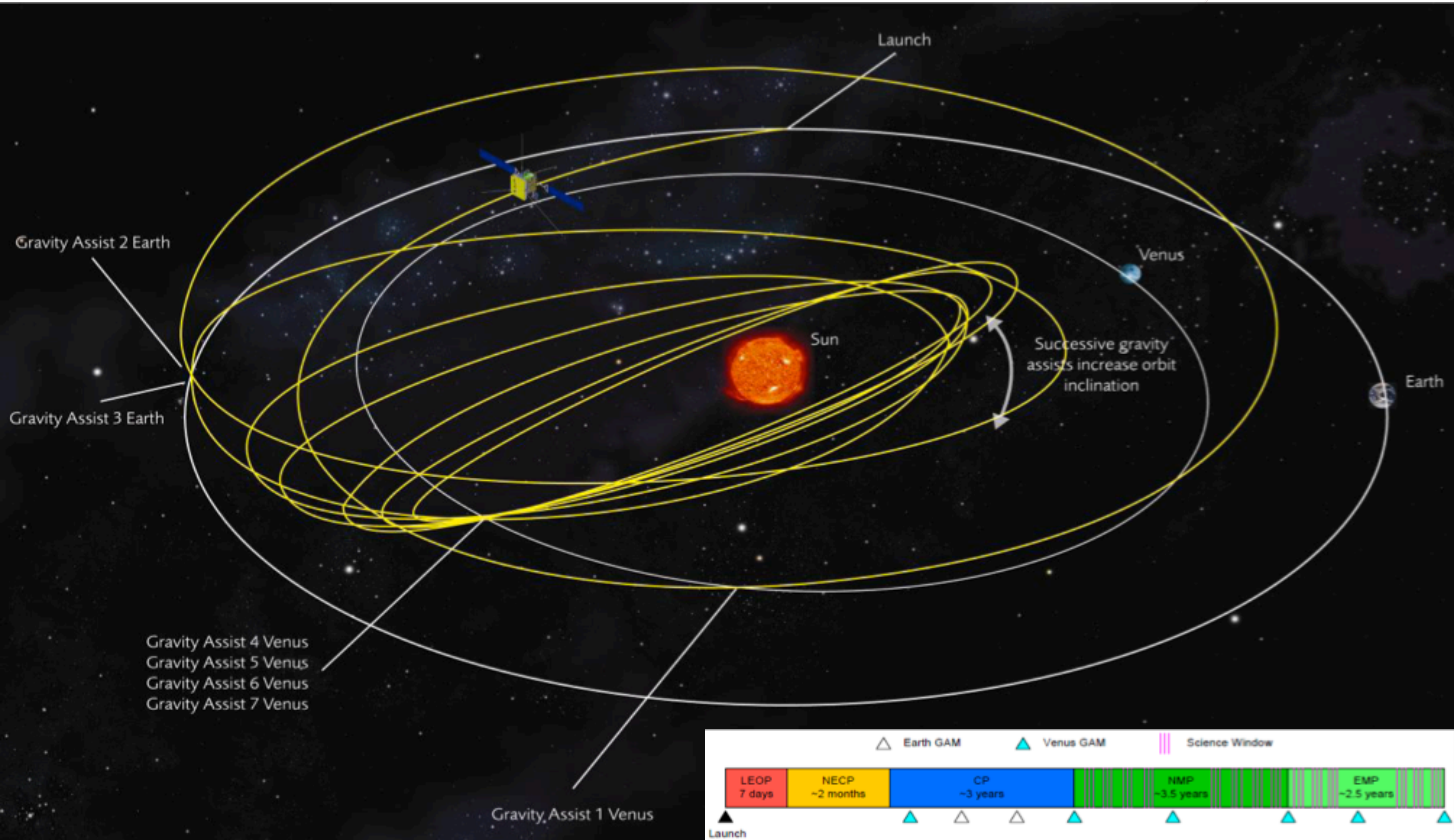
Extended Mission: 2.5 years

Orbit: 0.28–0.91 AU (P=150-168 days)

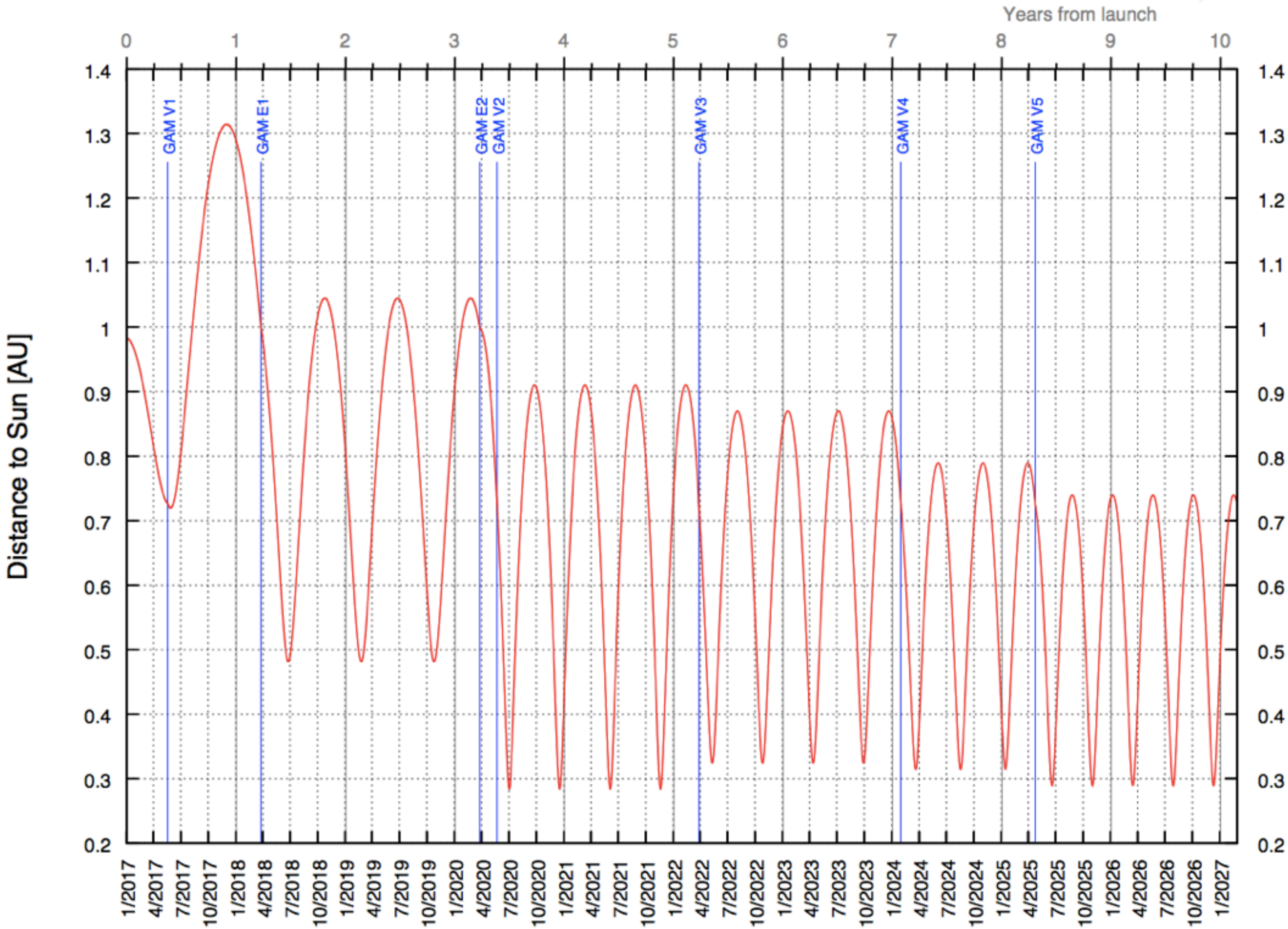
Out-of-Ecliptic View:
Multiple gravity assists with Venus to increase inclination out of the ecliptic to >24° (nominal mission),
>34° (extended mission)

Reduced relative rotation:
Observations of evolving structures on solar surface & in heliosphere for almost a complete solar rotation

Missionsprofil

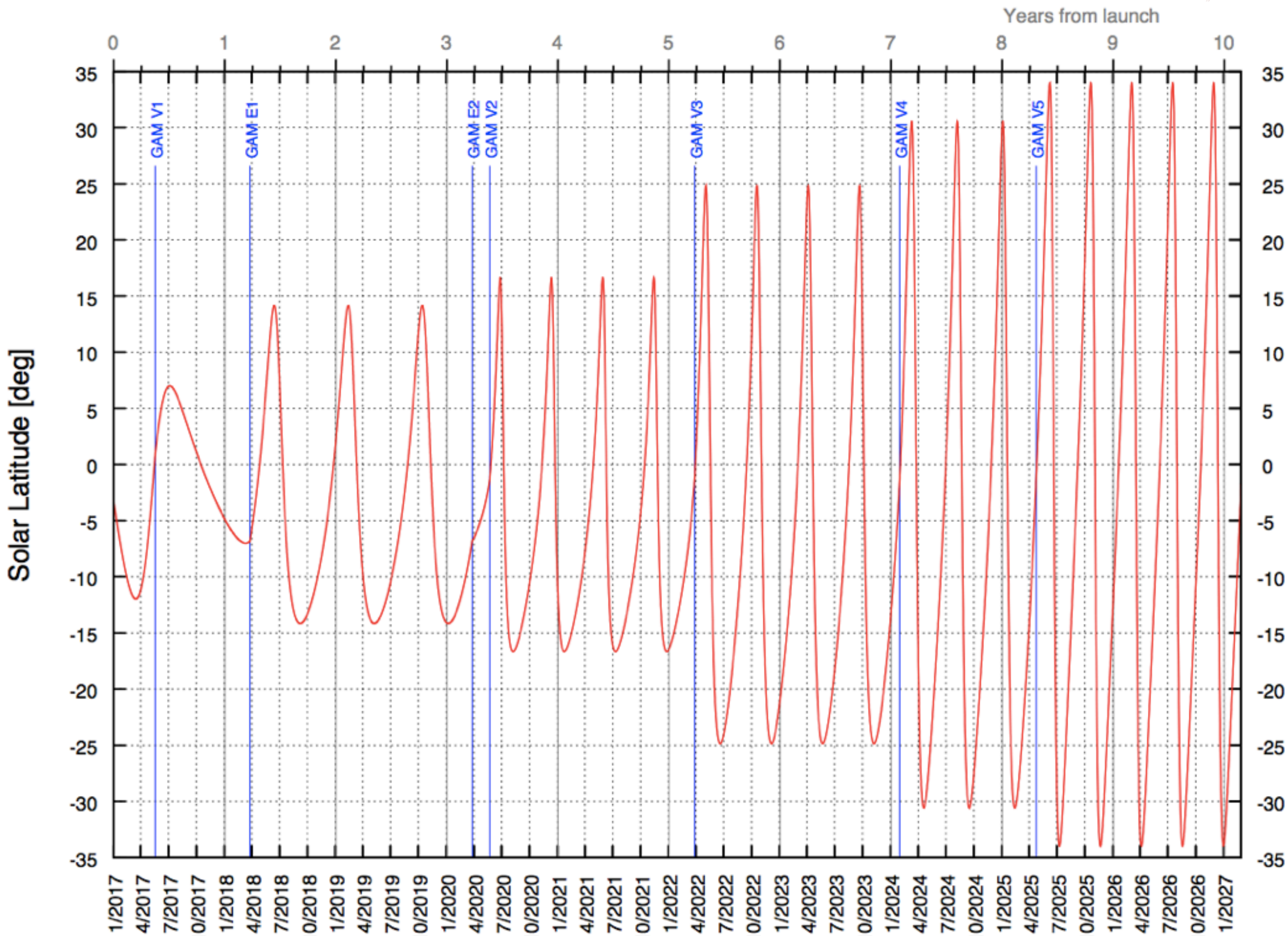


2017 Launch: Sun-Spacecraft Distance

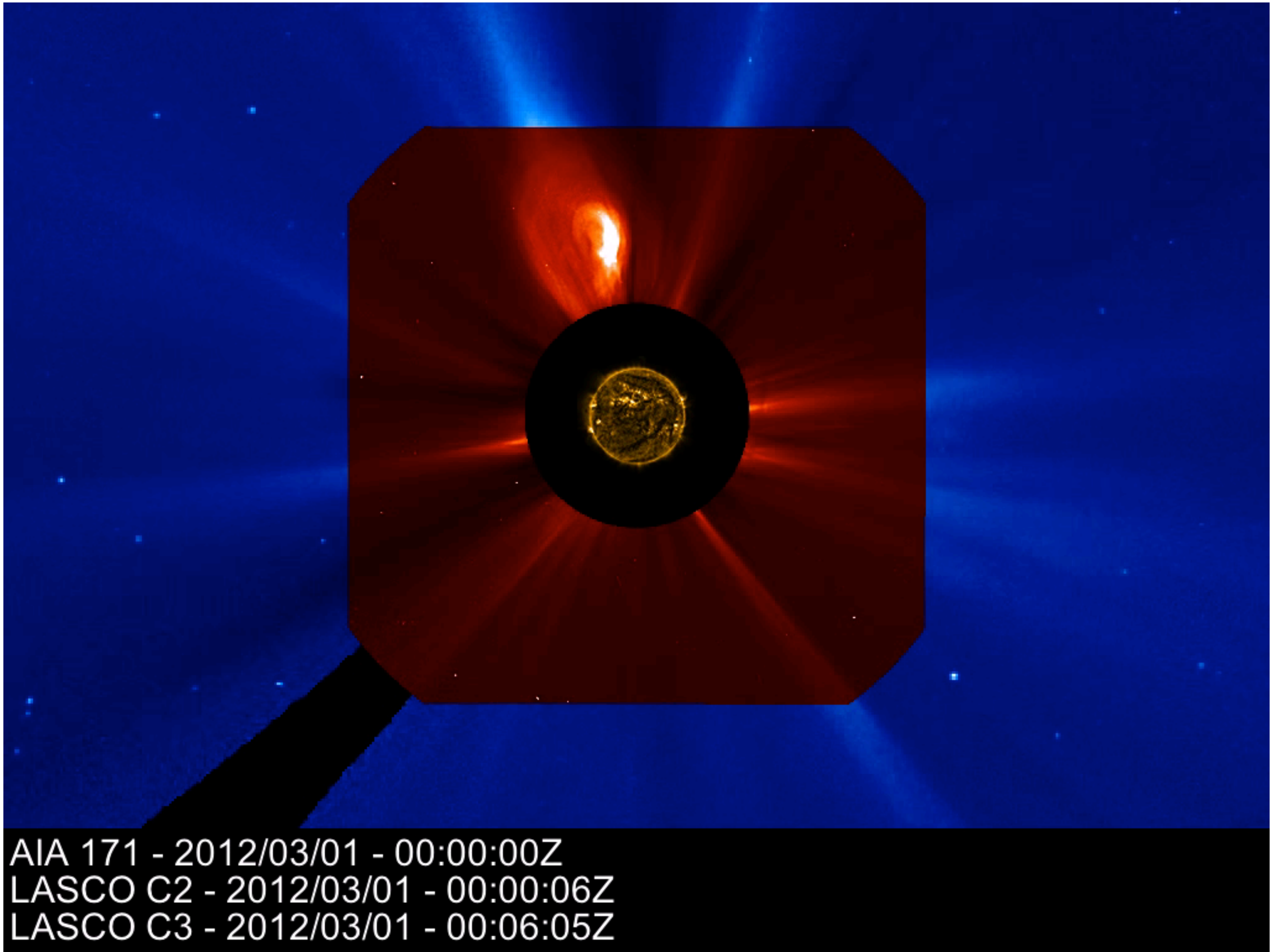


SOLAR ORBITER

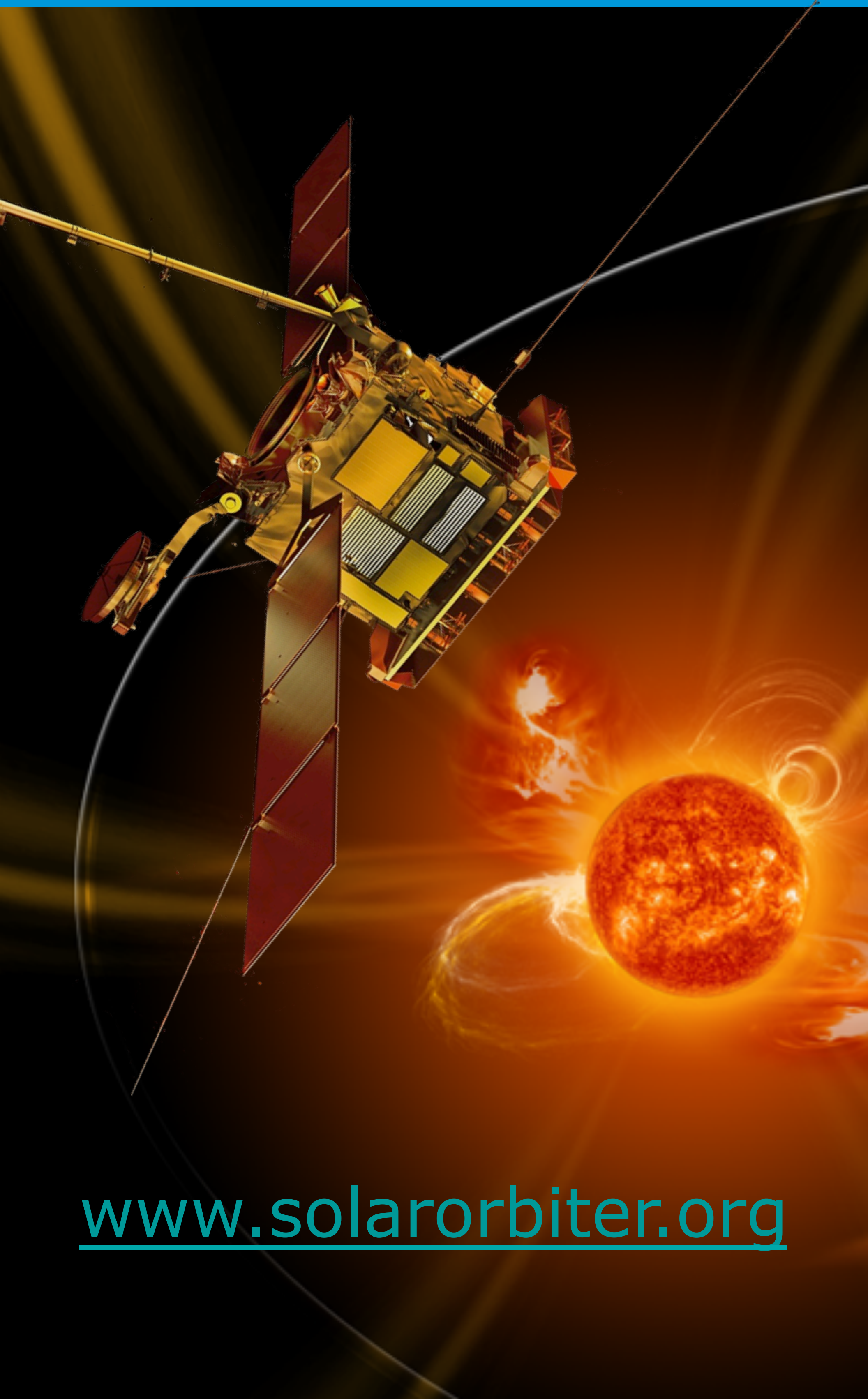
2017 Launch: Orbit Inclination



Sonnenkorona, Sonnenwind und magnetische Aktivität → Dynamik der Heliosphäre



Solar Orbiter
Exploring the Sun-Heliosphere Connection



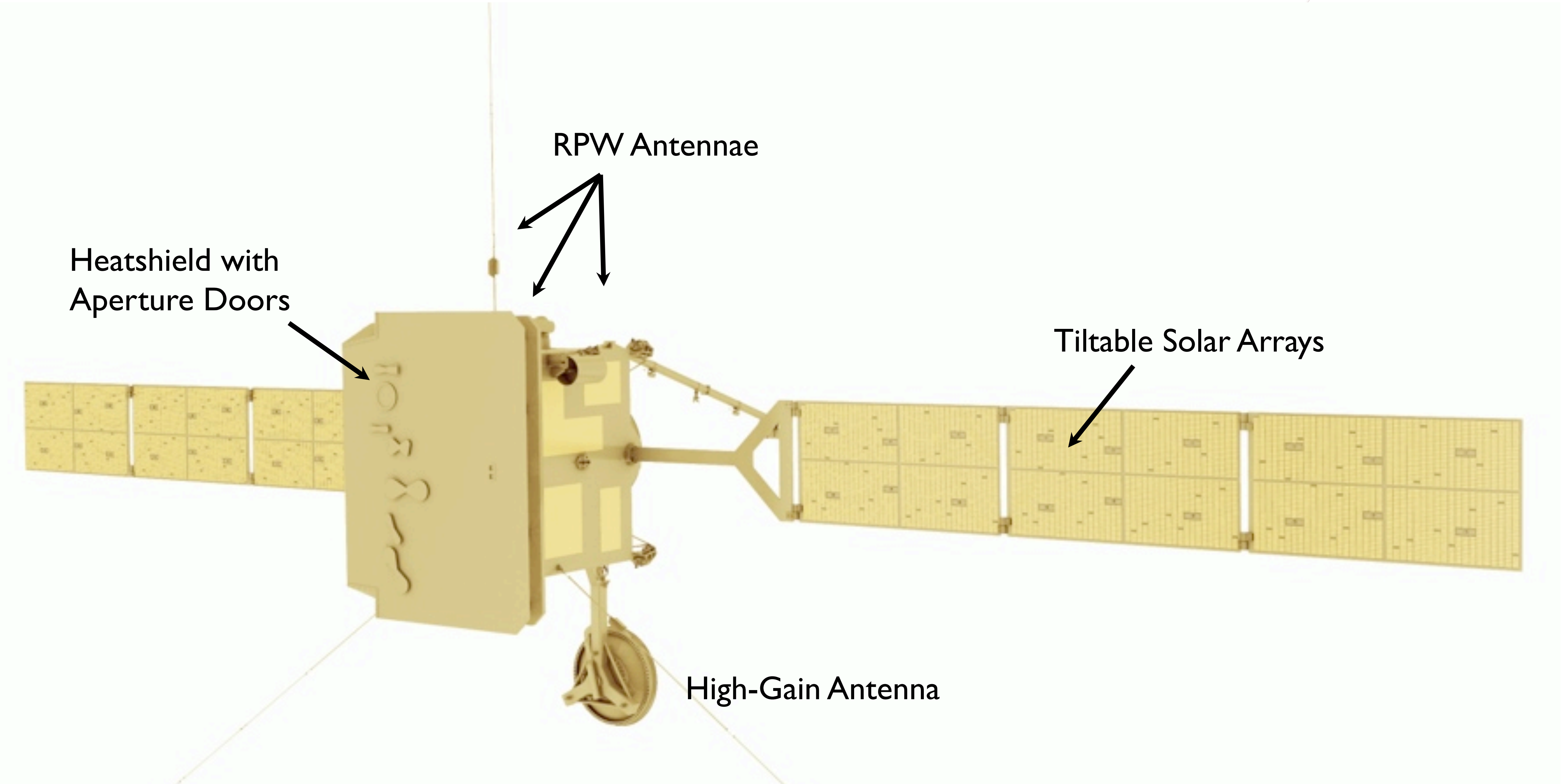
www.solarorbiter.org

Instrumente der Nutzlast

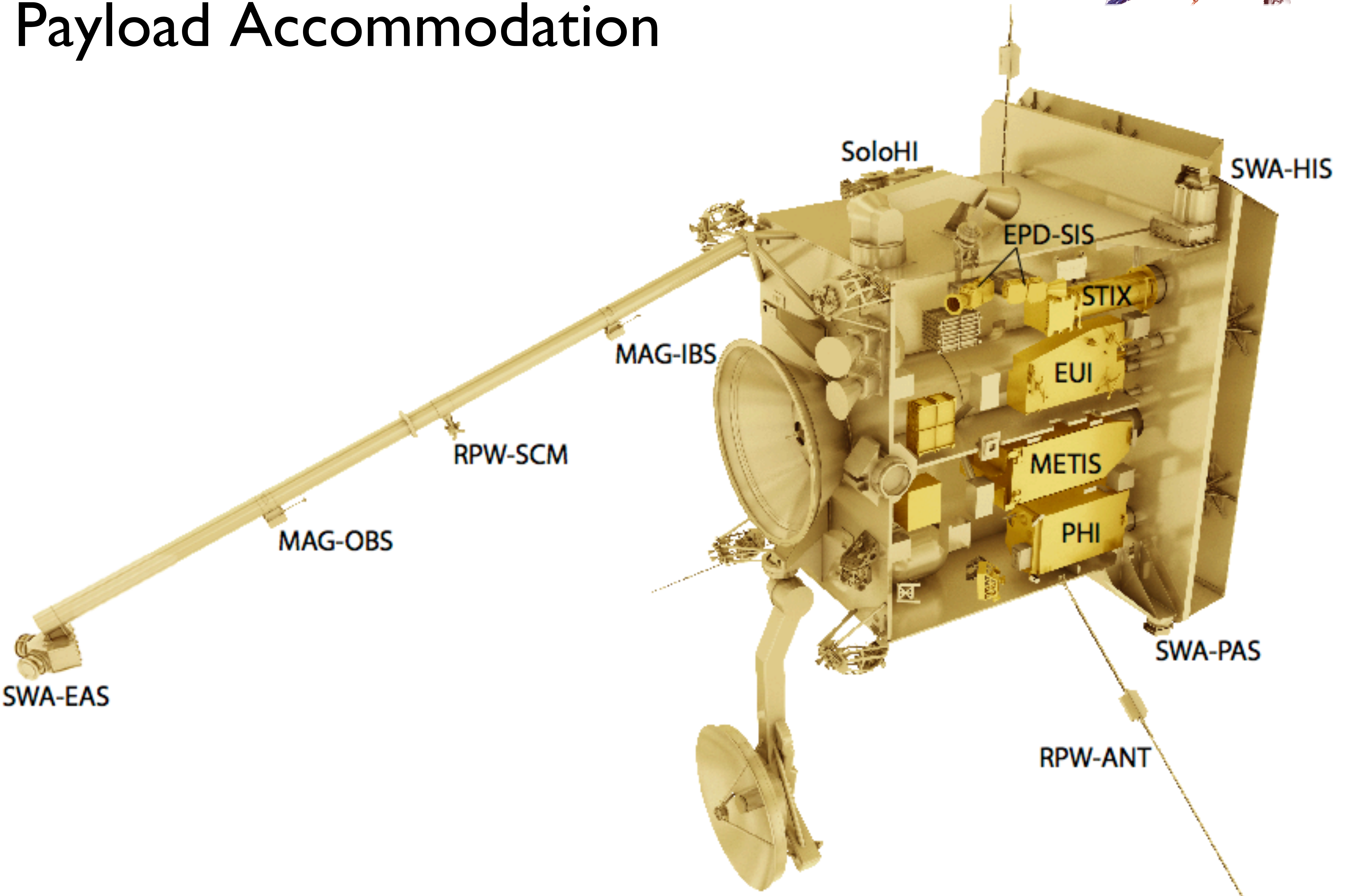
In-Situ Instruments			
EPD	Energetic Particle Detector	J. Rodríguez-Pacheco	Composition, timing and distribution functions of energetic particles
MAG	Magnetometer	T. Horbury	High-precision measurements of the heliospheric magnetic field
RPW	Radio & Plasma Waves	M. Maksimovic	Electromagnetic and electrostatic waves, magnetic and electric fields at high time resolution
SWA	Solar Wind Analyser	C. Owen	Sampling protons, electrons and heavy ions in the solar wind
Remote-Sensing Instruments			
EUI	Extreme Ultraviolet Imager	P. Rochus	High-resolution and full-disk EUV imaging of the on-disk corona
METIS	Multi-Element Telescope for Imaging and Spectroscopy	E. Antonucci	Imaging of the off-disk corona
PHI	Polarimetric & Helioseismic Imager	S. Solanki	High-resolution vector magnetic field, line-of-sight velocity in photosphere, visible imaging
SoloHI	Heliospheric Imager	R. Howard	Wide-field visible imaging of the solar off-disk corona
SPICE	Spectral Imaging ... Coronal Environ...		EUV spectroscopy of the solar disk and near-Sun corona
STIX	Spectrometer/Telescope for Imaging X-rays	S. Krucker	Imaging spectroscopy of solar X-ray emission

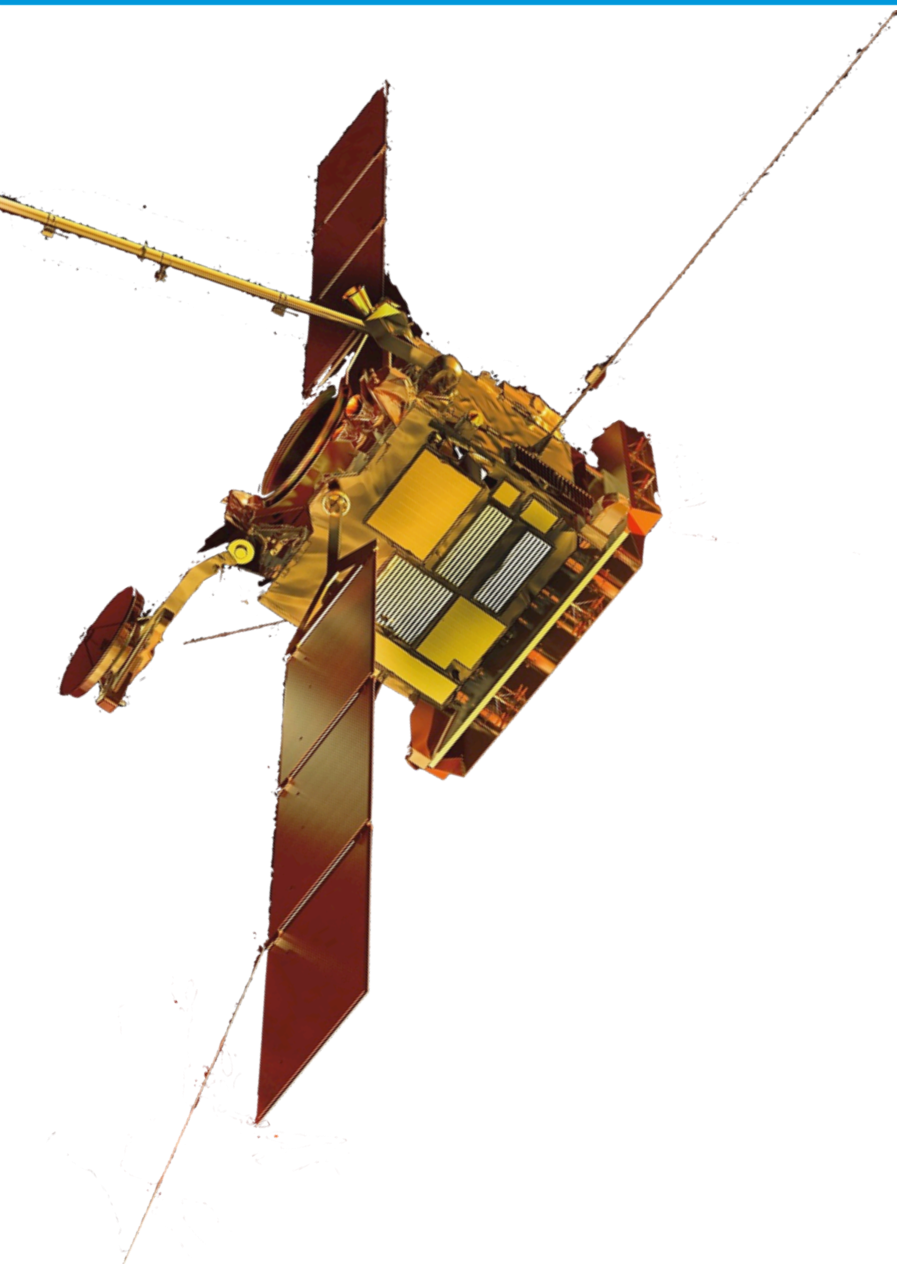
Instrument with high-res spectrographic capabilities

The Spacecraft



Payload Accommodation





Missions-Charakeristik

- In-situ Instrumente für Sonnenwind und energetische Teilchenstrom von der Sonne
- Fernerkundungsinstrumente zur Beobachtung der Sonnenscheibe und der Korona
- Gleichzeitige hochaufgelöste Beobachtungen der Sonne mit Ausrichtung der Raumfähre auf Zielgebiete
- Autonome Messinstrumente, die gemeinsam nach Zeitplan operieren

Nutzlastinstrumente

Remote-sensing-Instrumente

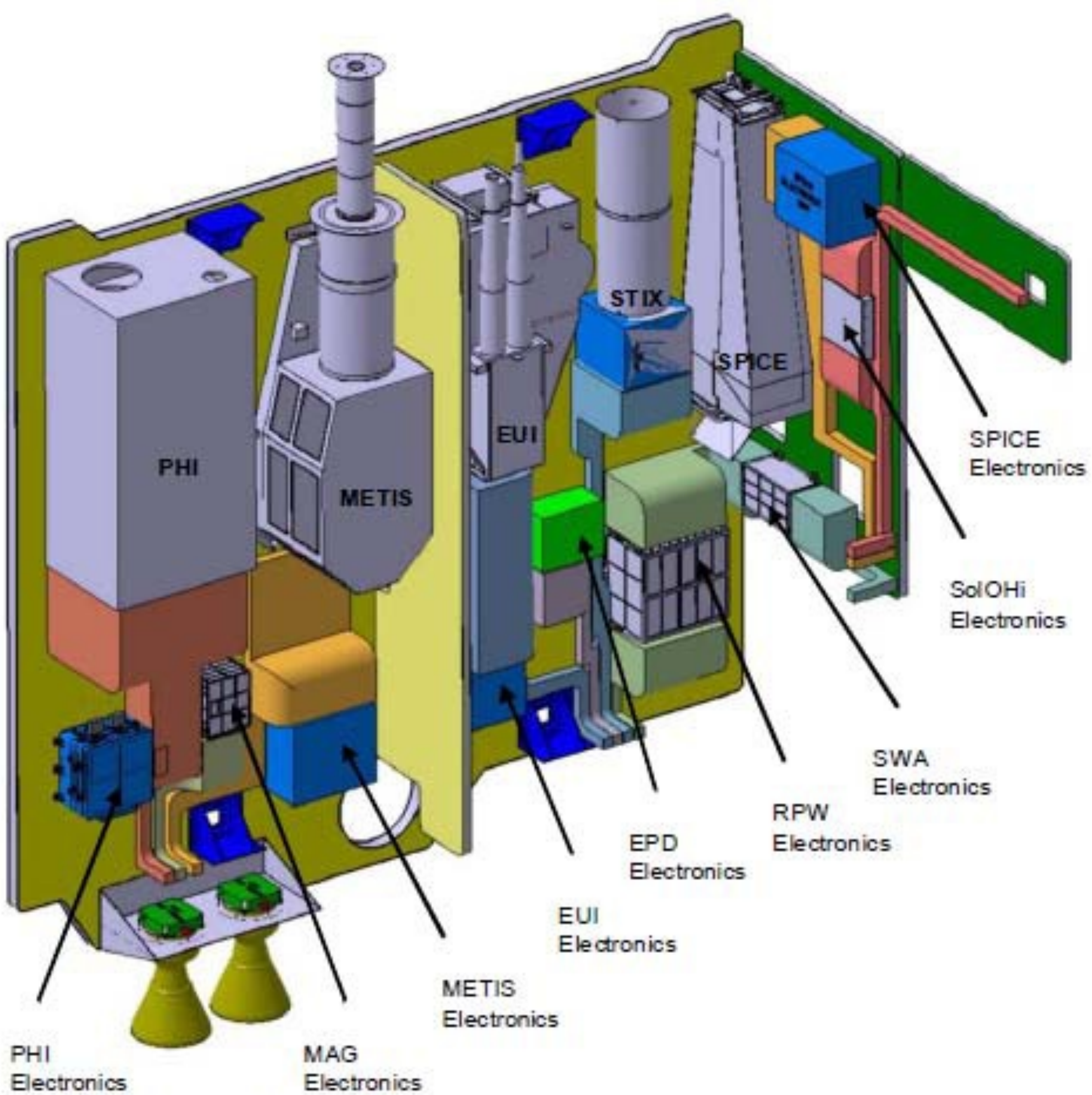


Figure 5-2 Internal Payload Accommodation on –Y Wall (including Harness Volume)

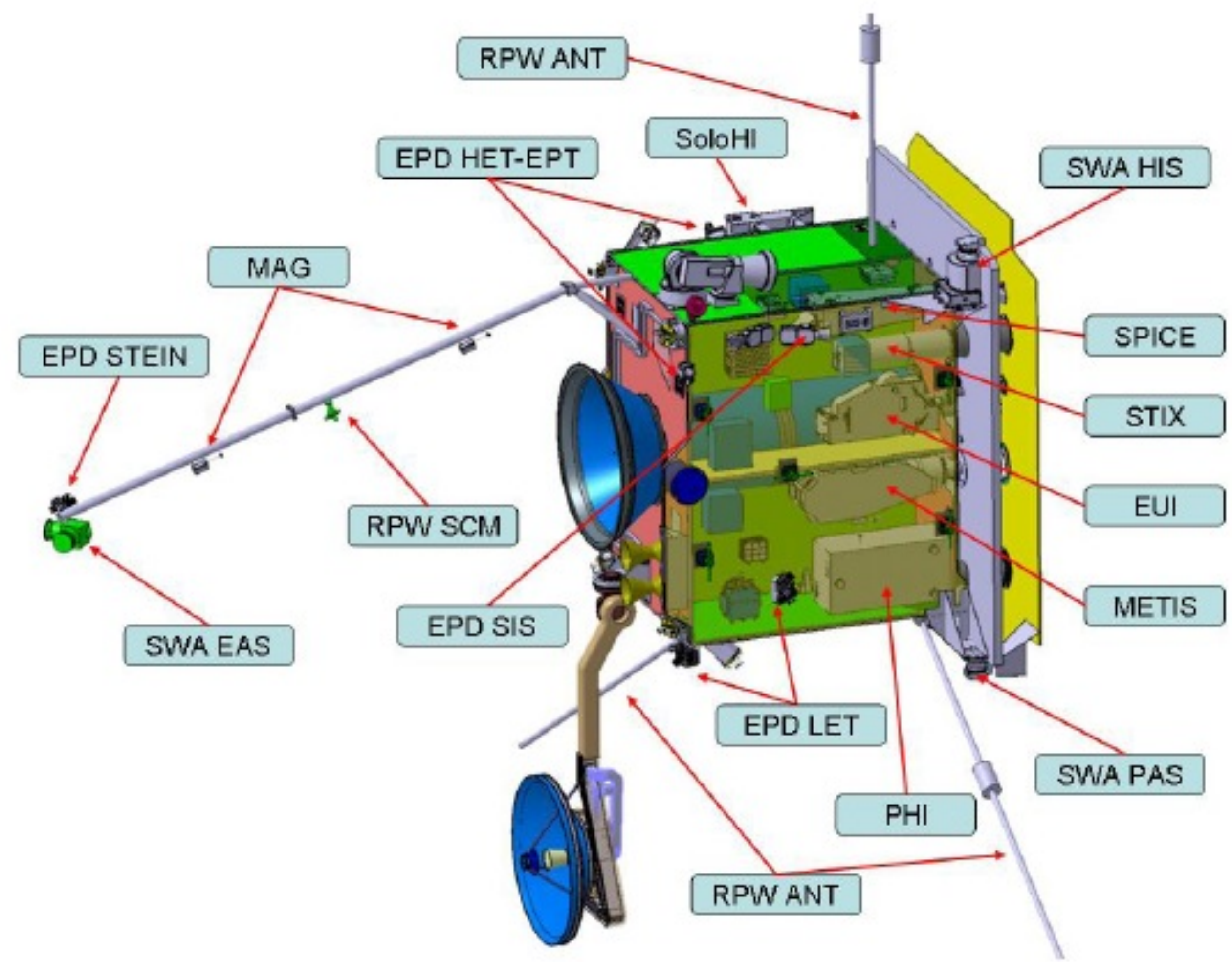
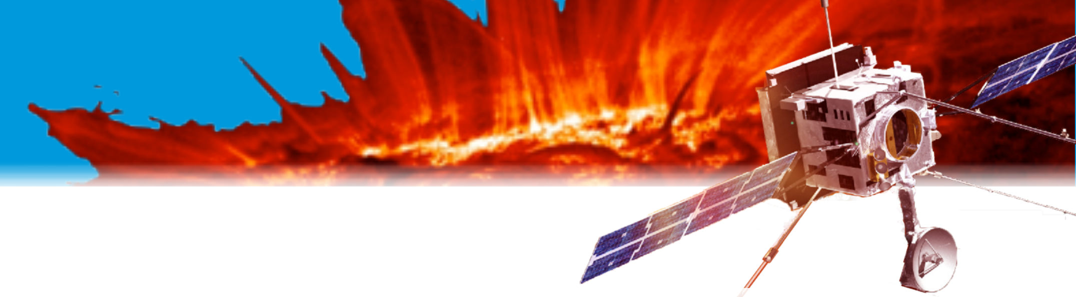


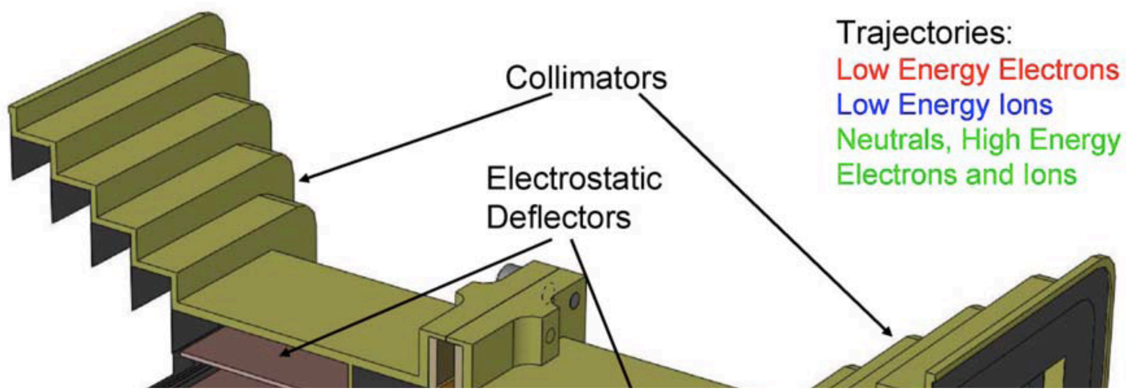
Figure 5-1 External Overview of Payload Accommodation

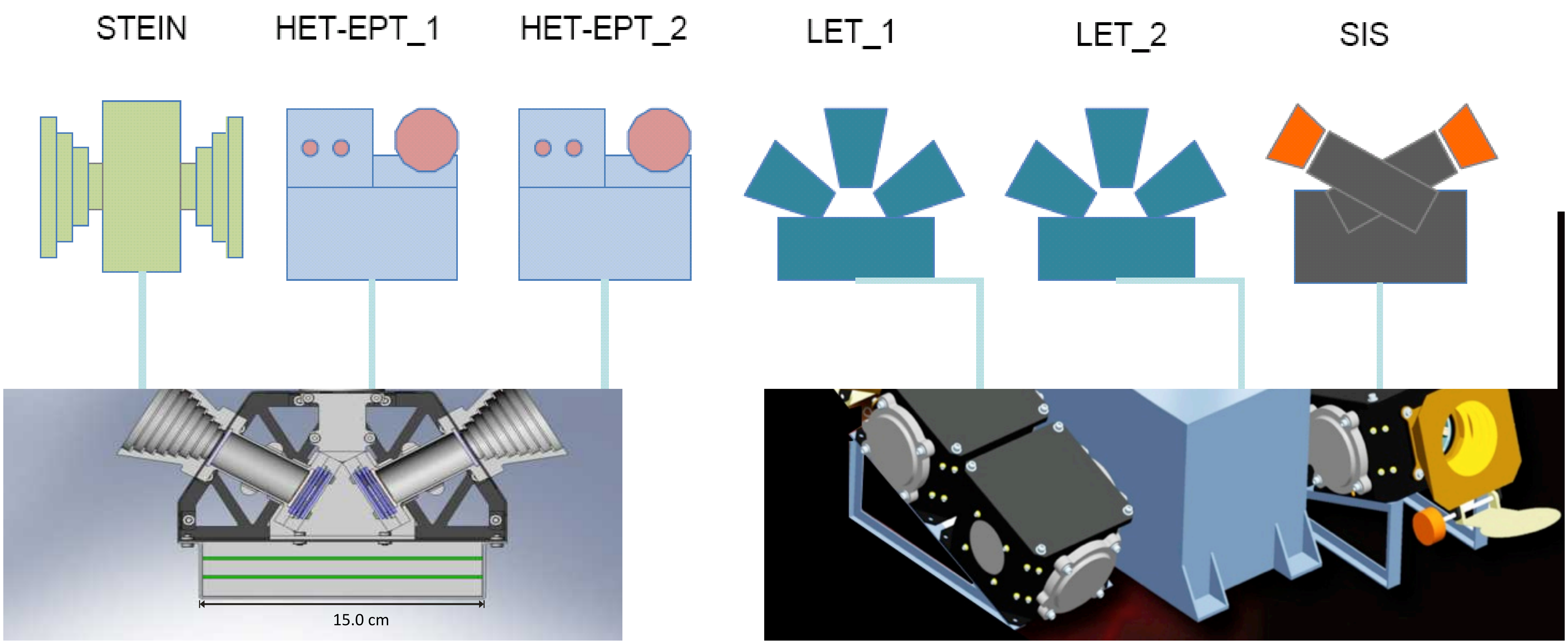
In-situ-Instrumente

In-situ instruments (I)

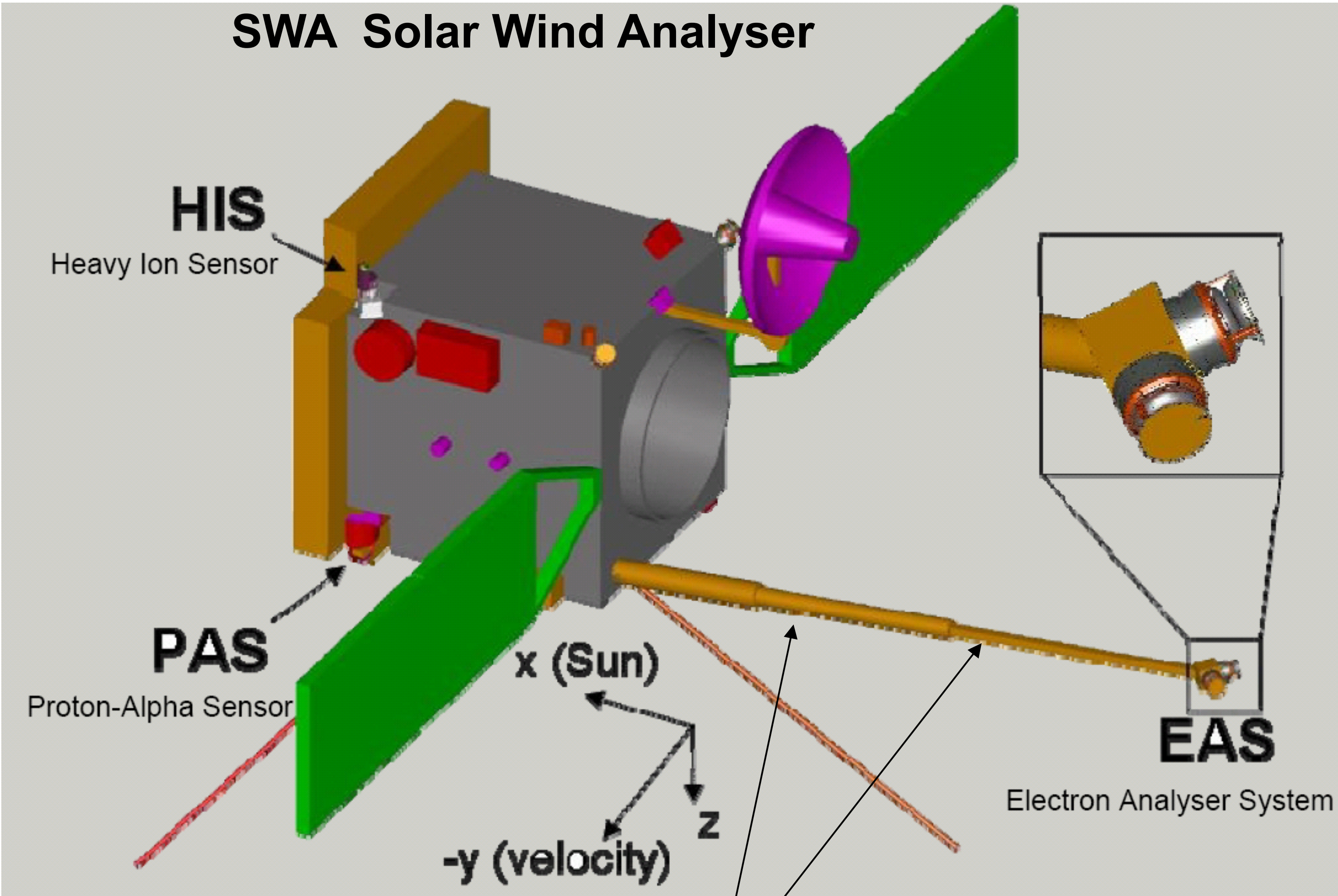


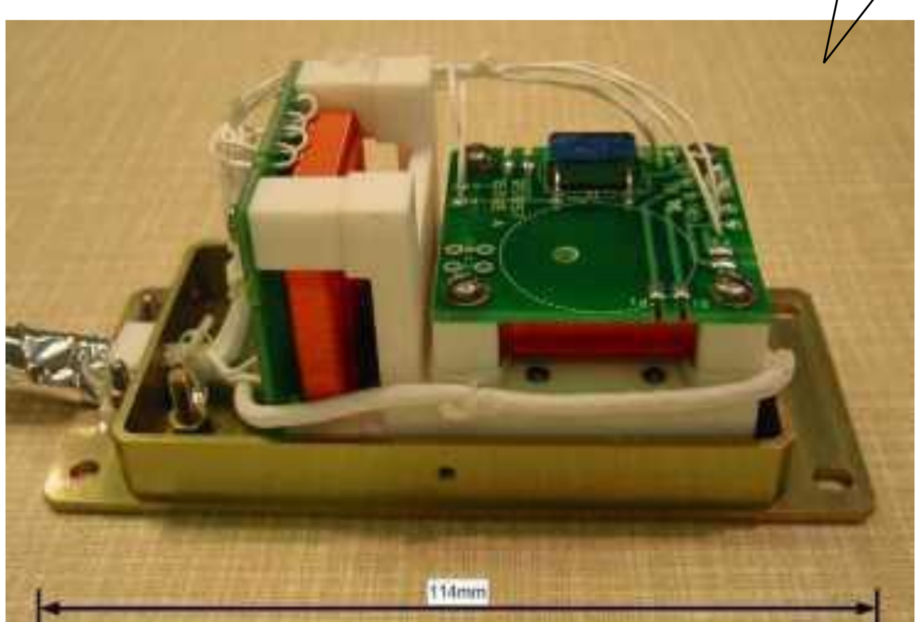
EPD Energetic Particle Detectors





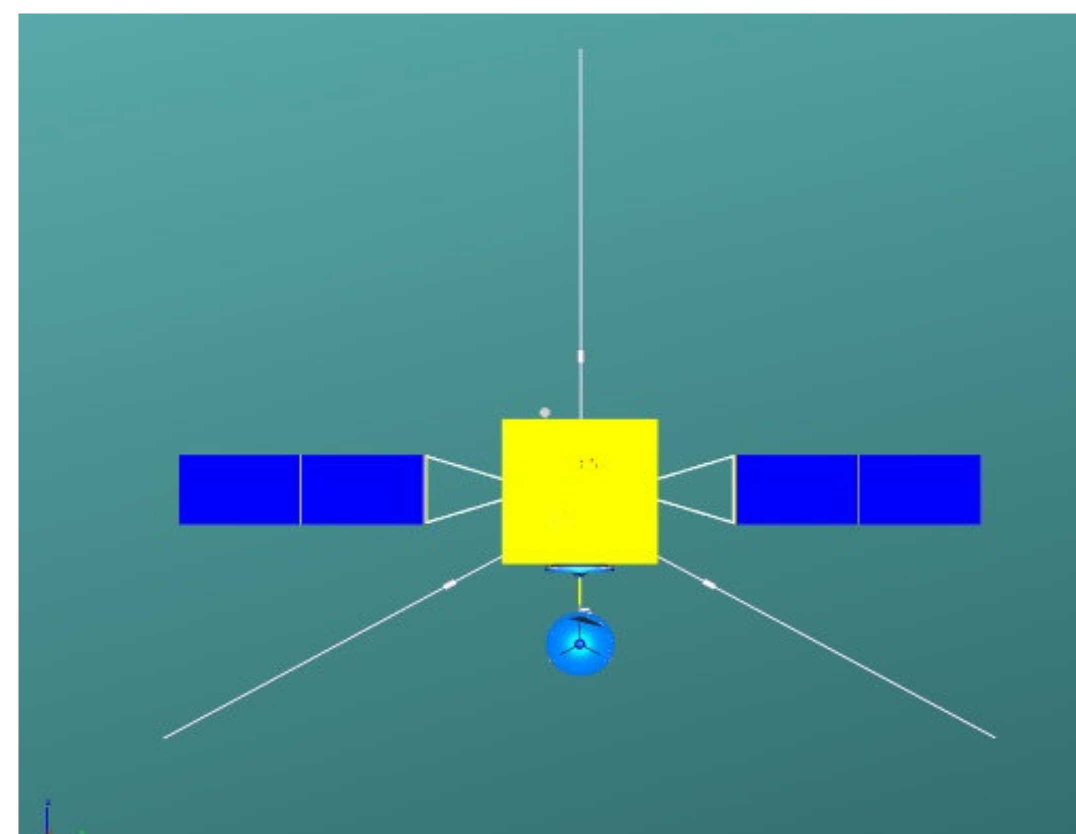
In-situ instruments: (II)





MAG
Magnetometer

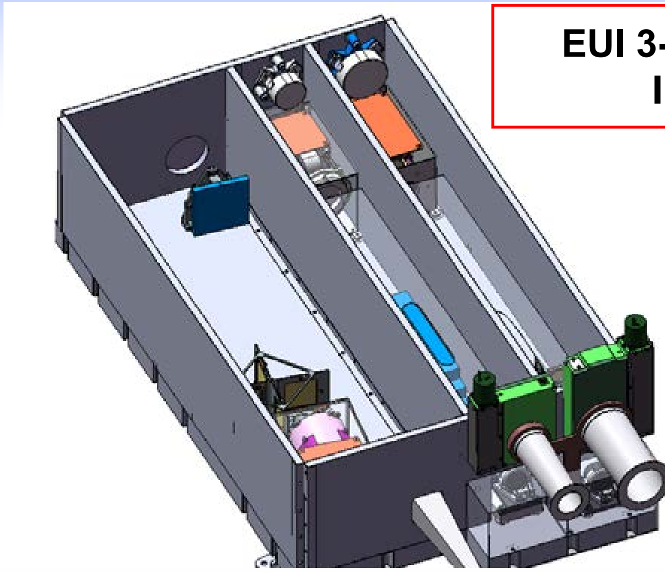
RPW Radio and Plasma Waves



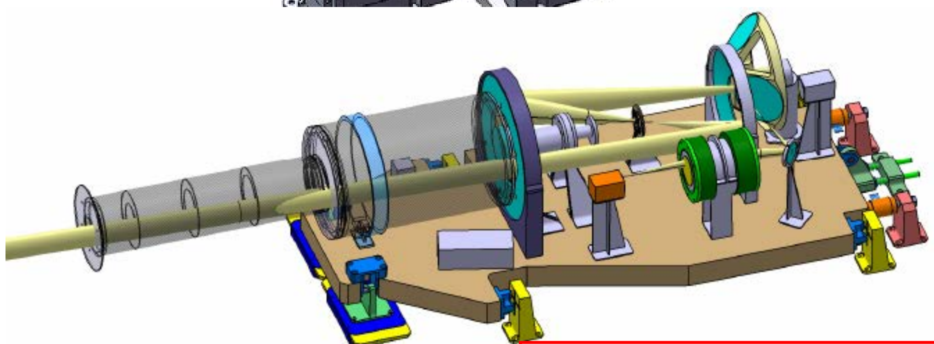
Remote Sensing Instruments

Suite of 6 Instruments

- **Imagers / polarimeter / coronograph** (EUI, SOLOHI, PHI, METIS)
  - Bandwidth: Visible, UV, EUV bands
- **Spectral Imagers / Spectrometers** (SPICE, STIX)
  - Bandwidth: EUV and x-ray

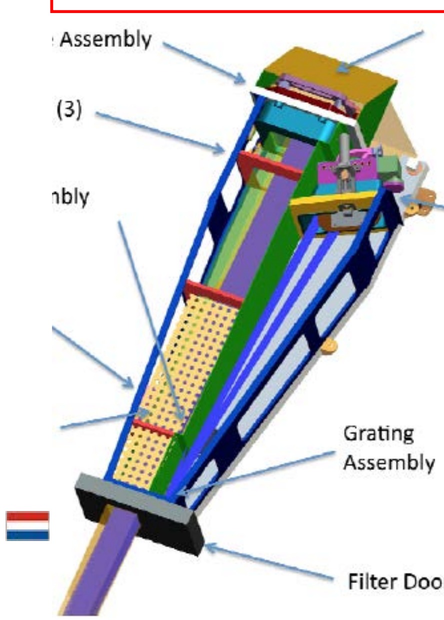


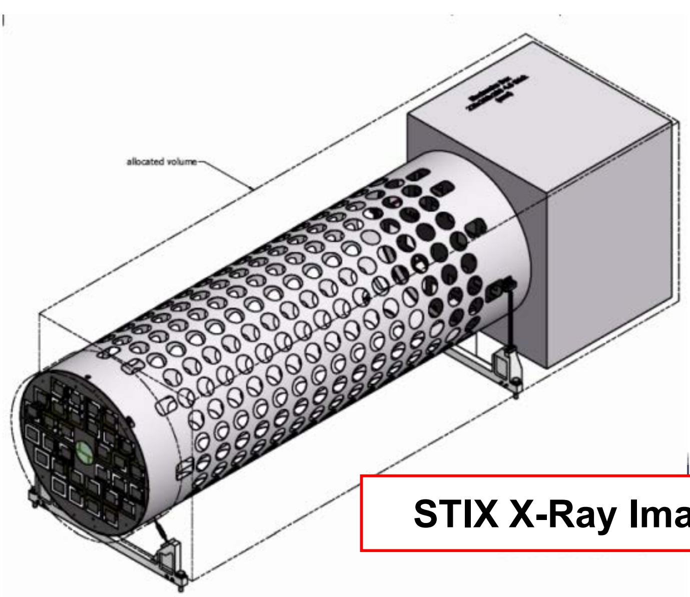
EUI 3-telescopes Imager



METIS 2-channels Coronograph

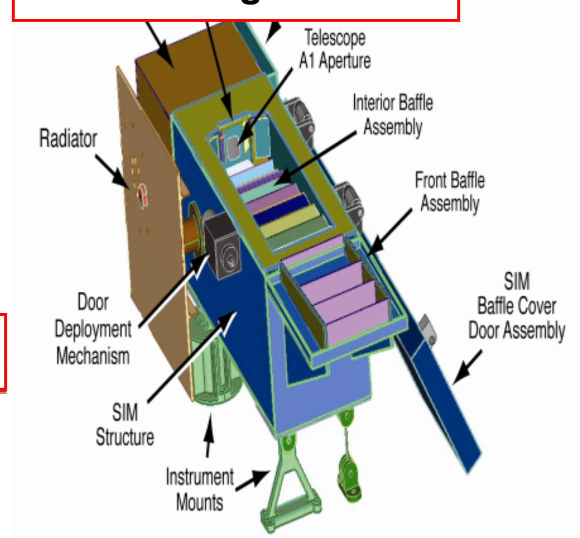
SPICE Spectral Imager



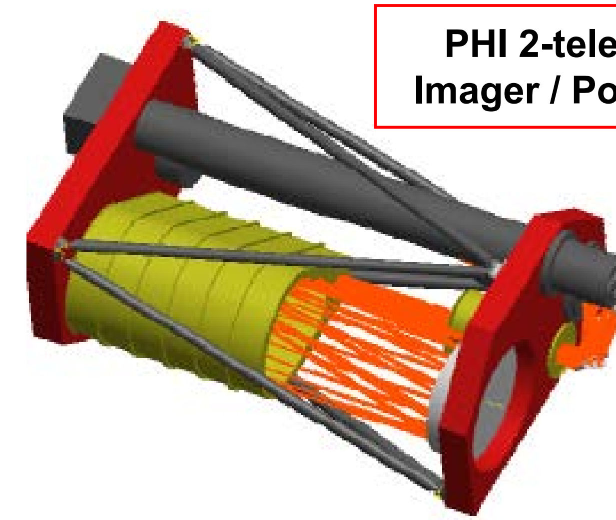


STIX X-Ray Imager

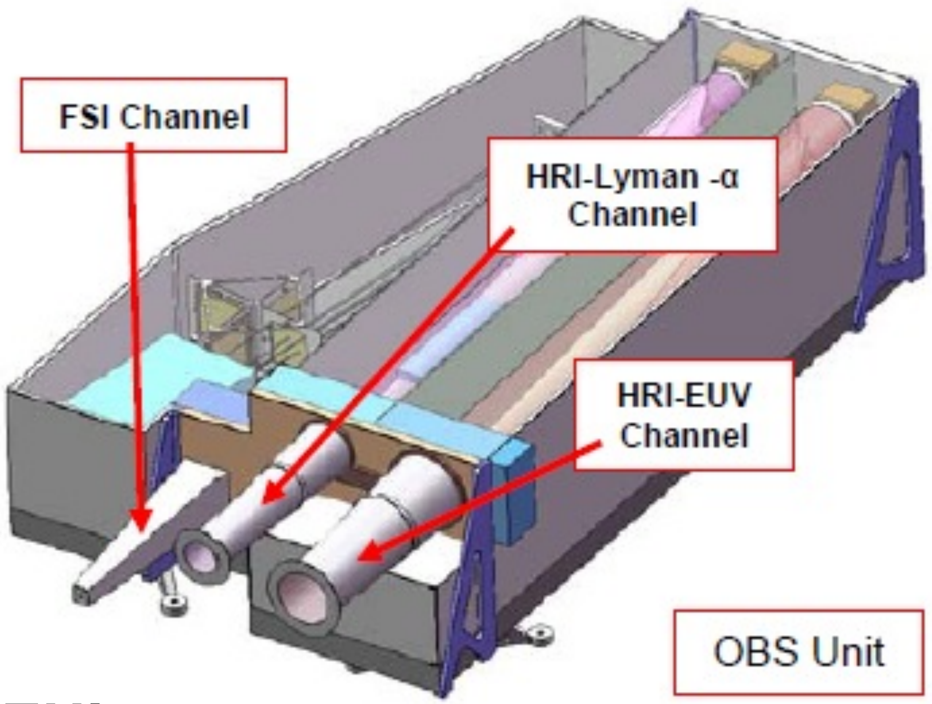
SOLOHi 1-telescope Imager



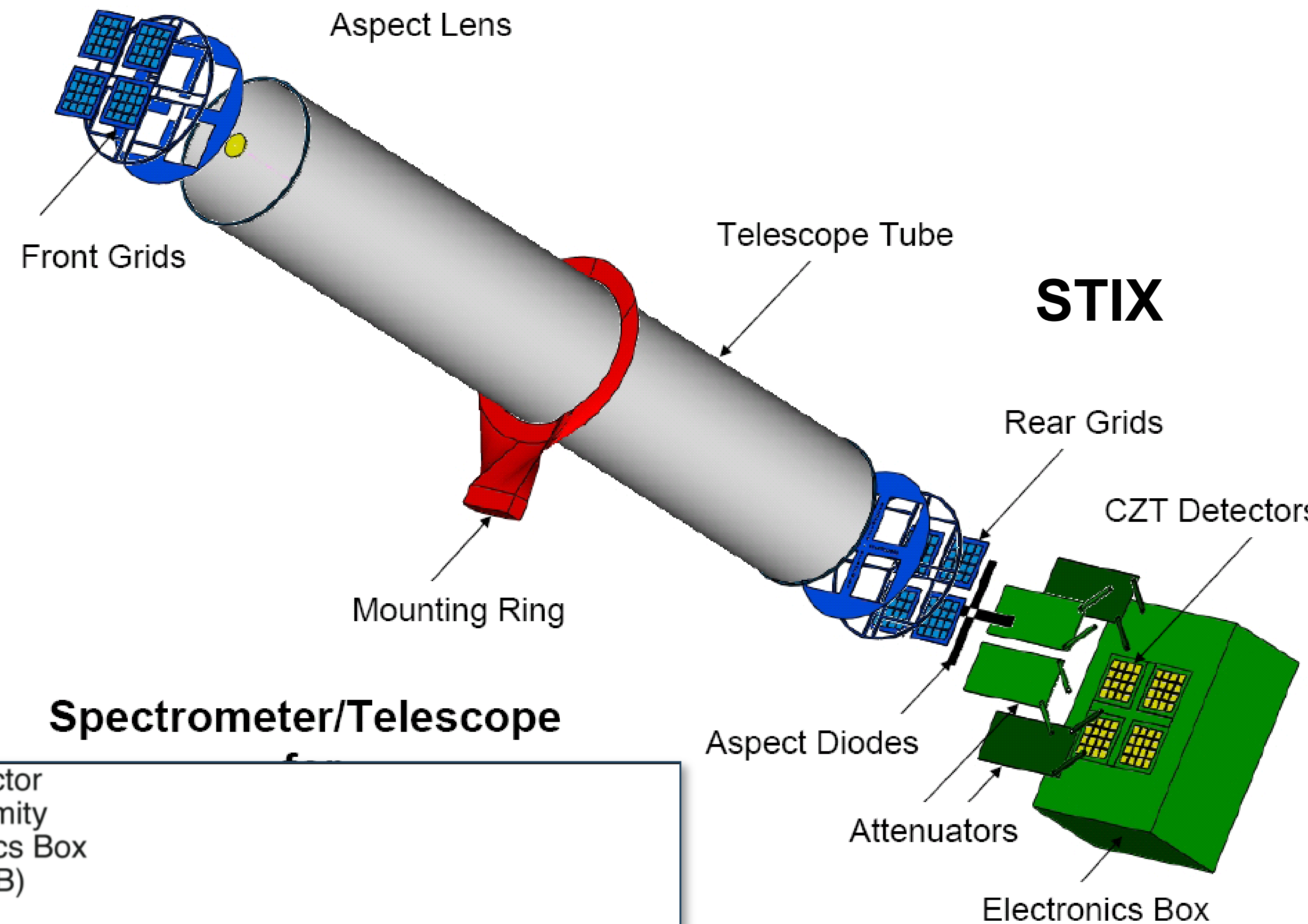
PHI 2-telescopes Imager / Polarimeter



Remote-sensing instruments (I)

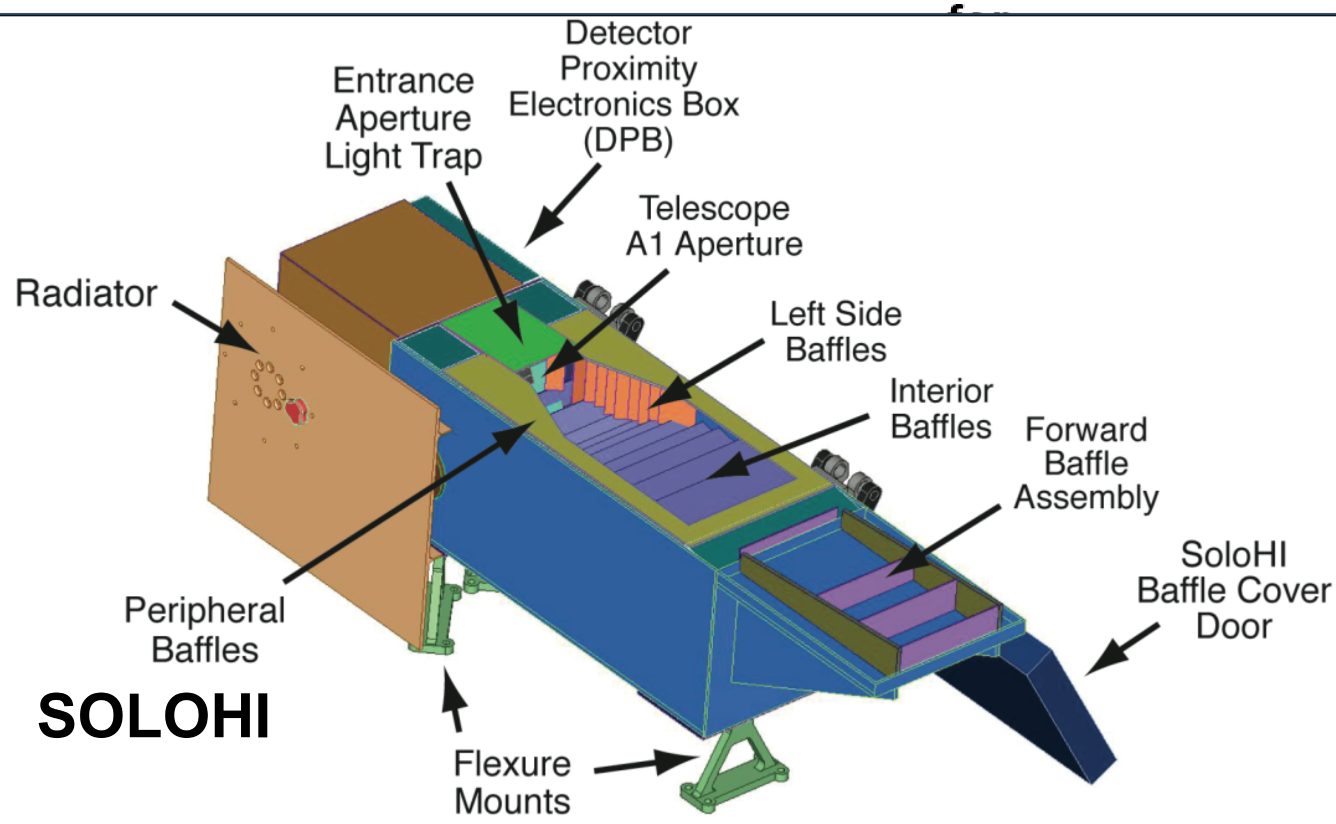


EUI



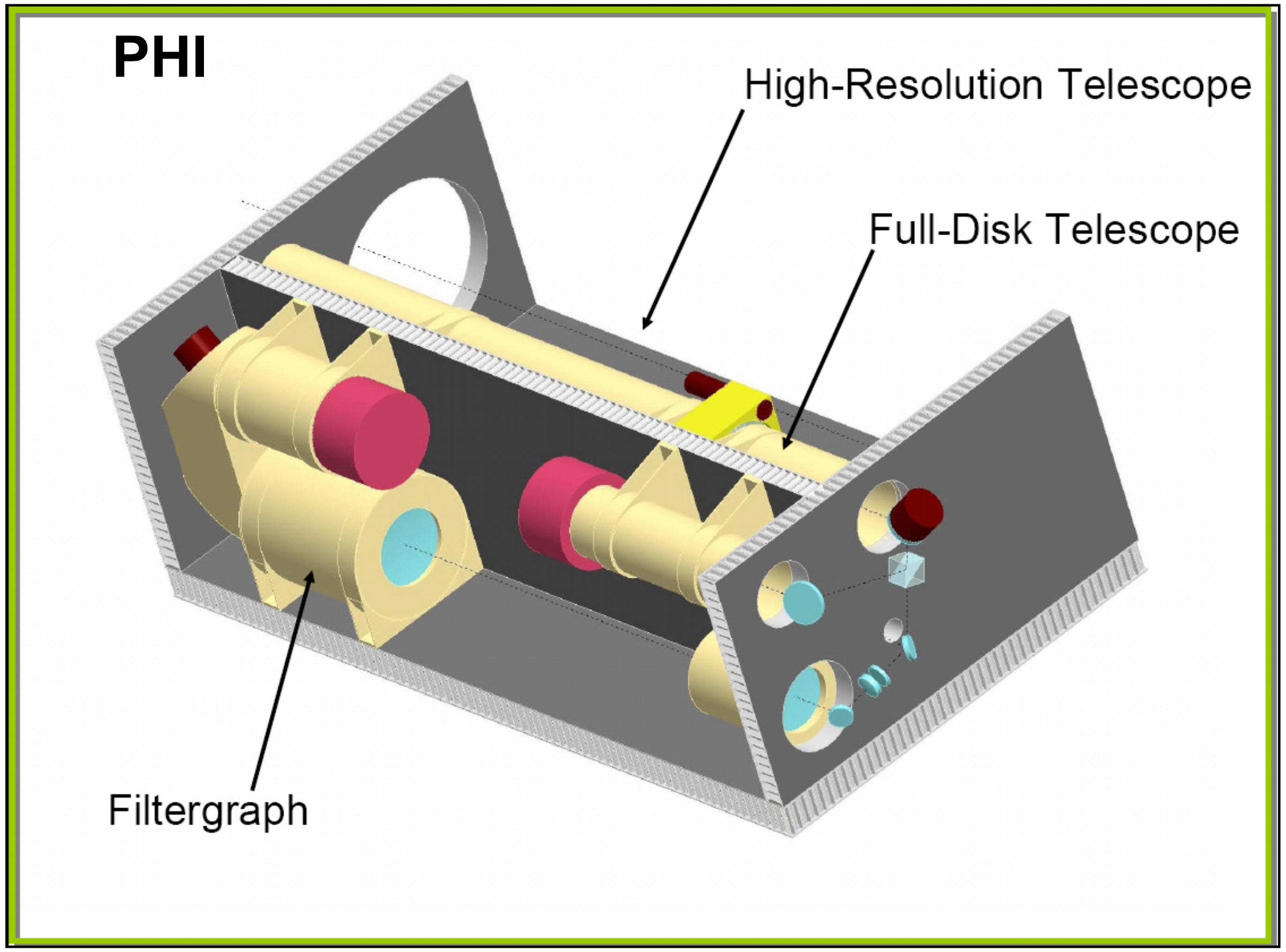
STIX

Spectrometer/Telescope

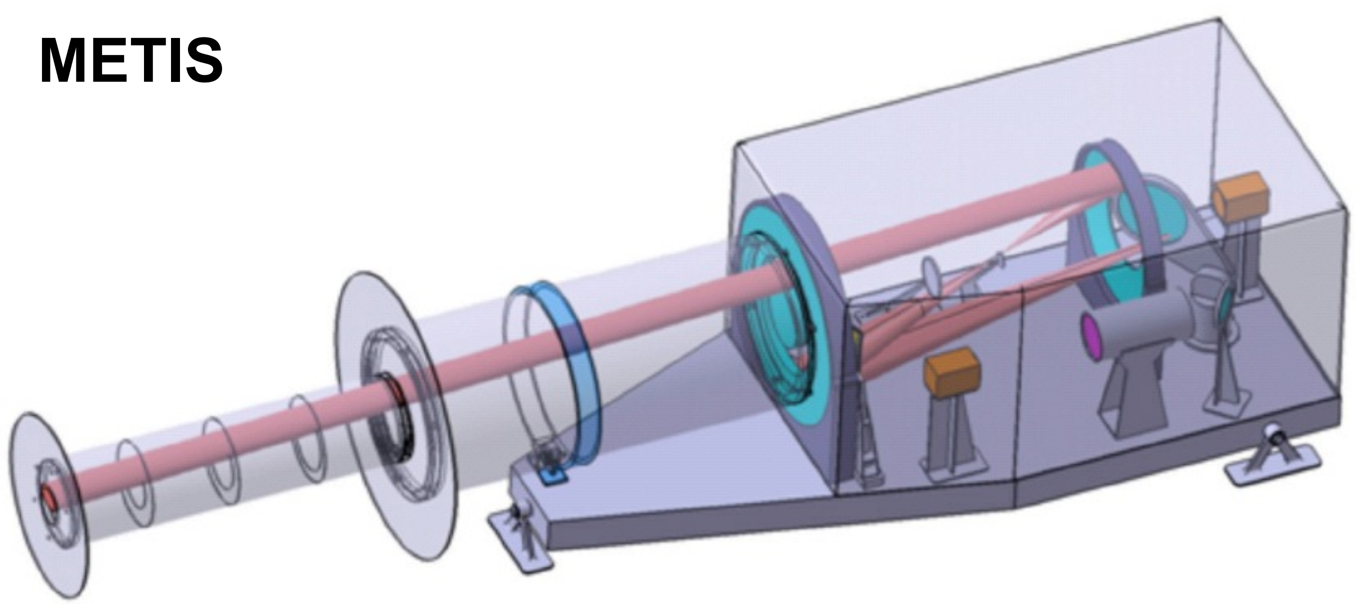


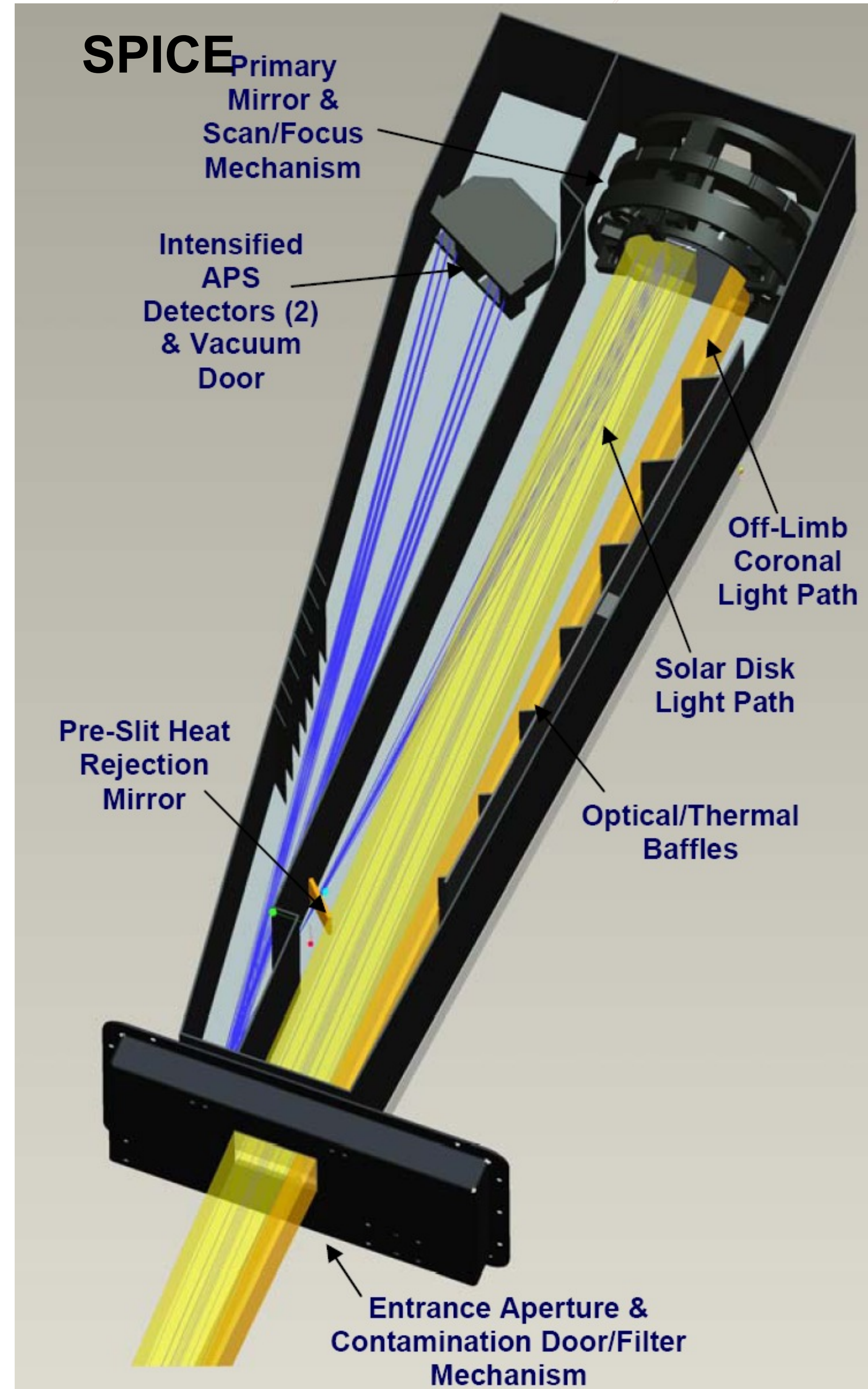
SOLOHI

Remote-sensing instruments (II)

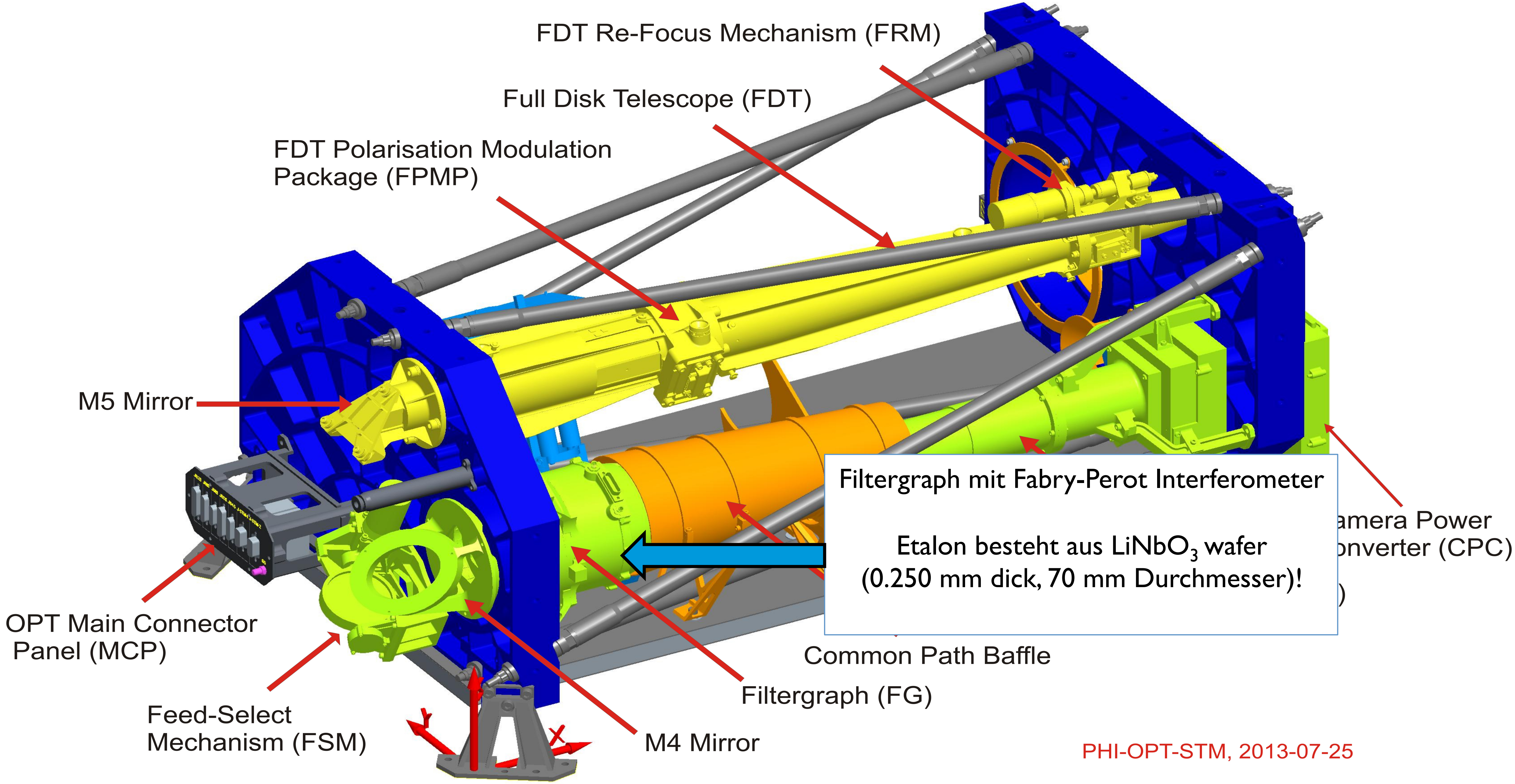


METIS

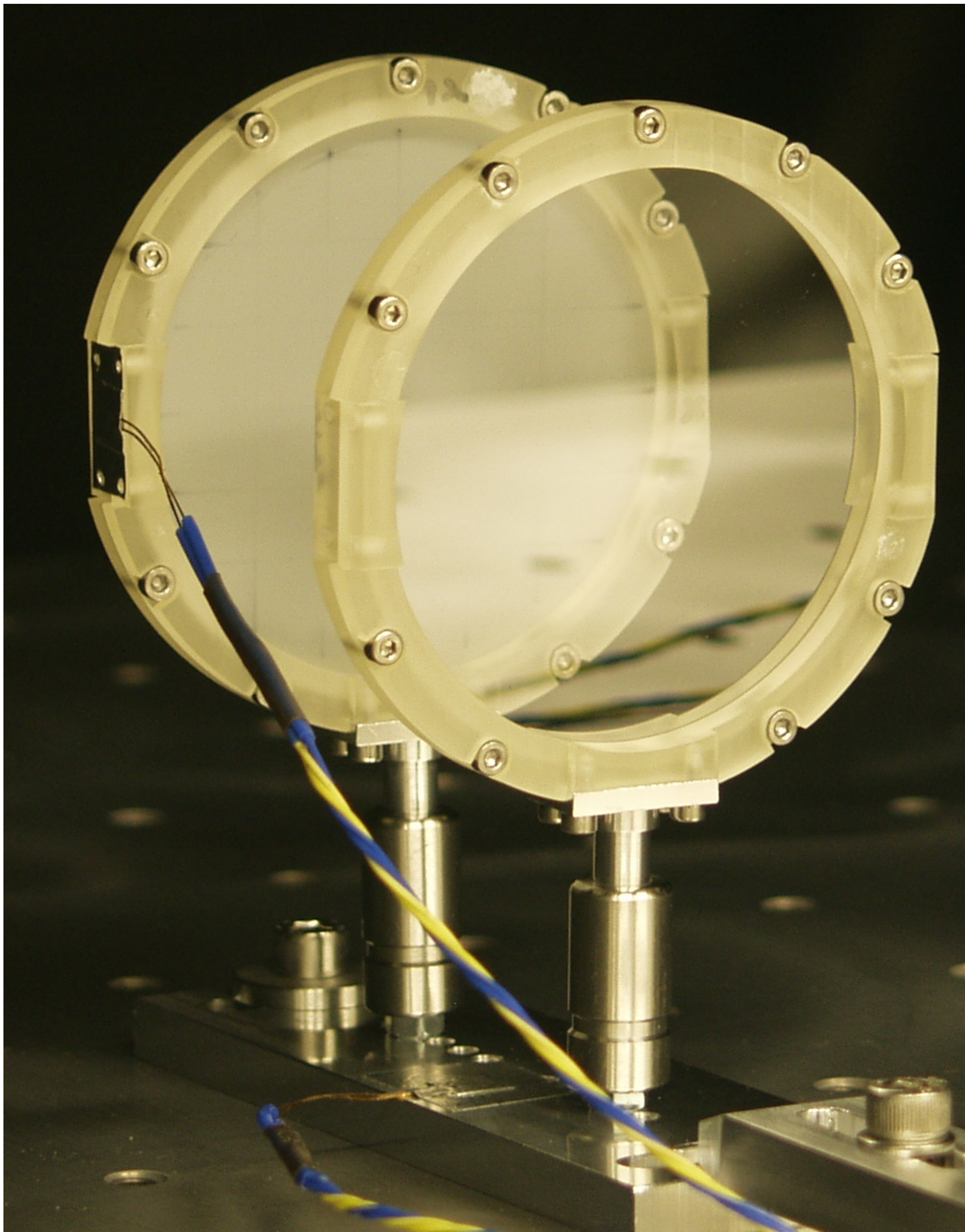




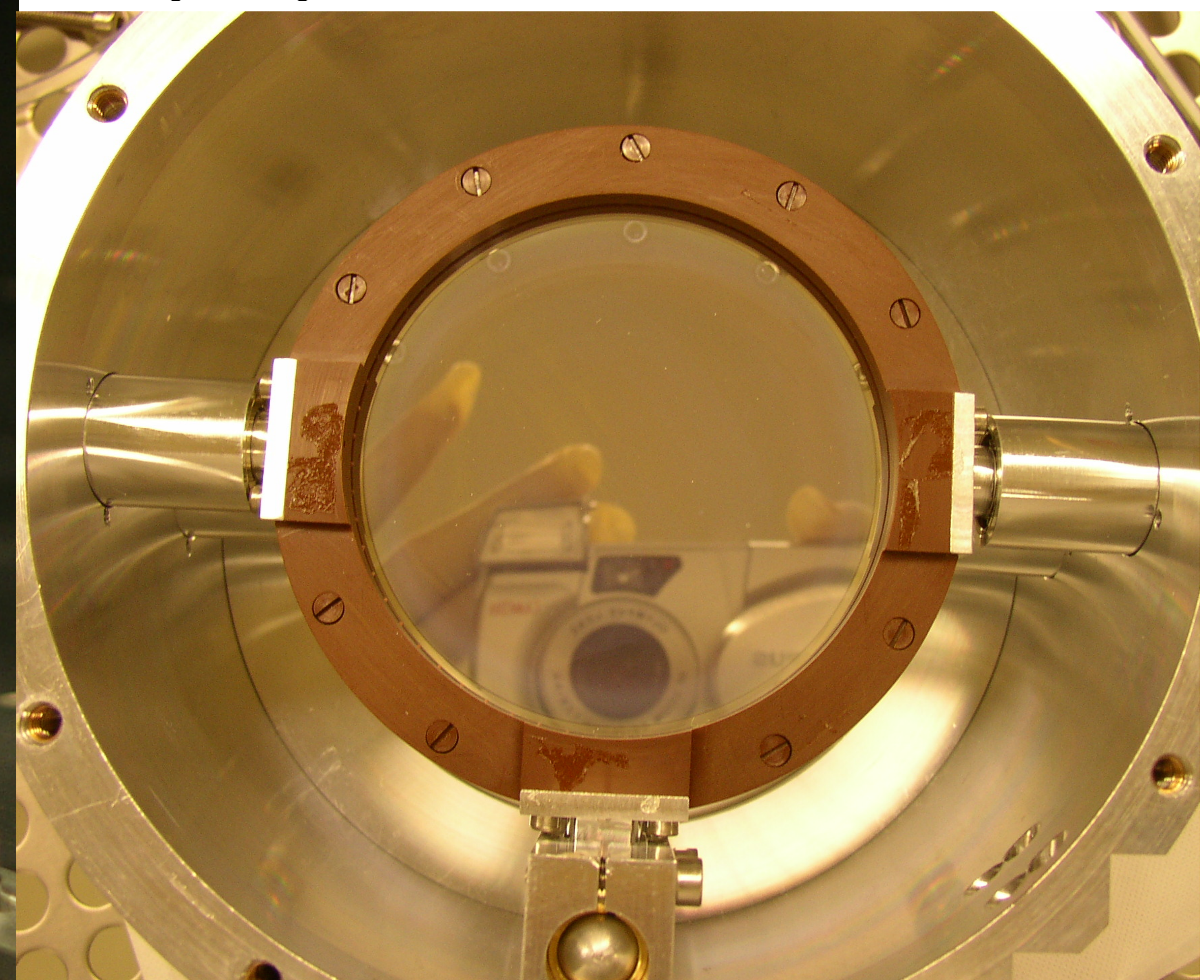
Polarimetric & Helioseismic Imager (PHI)



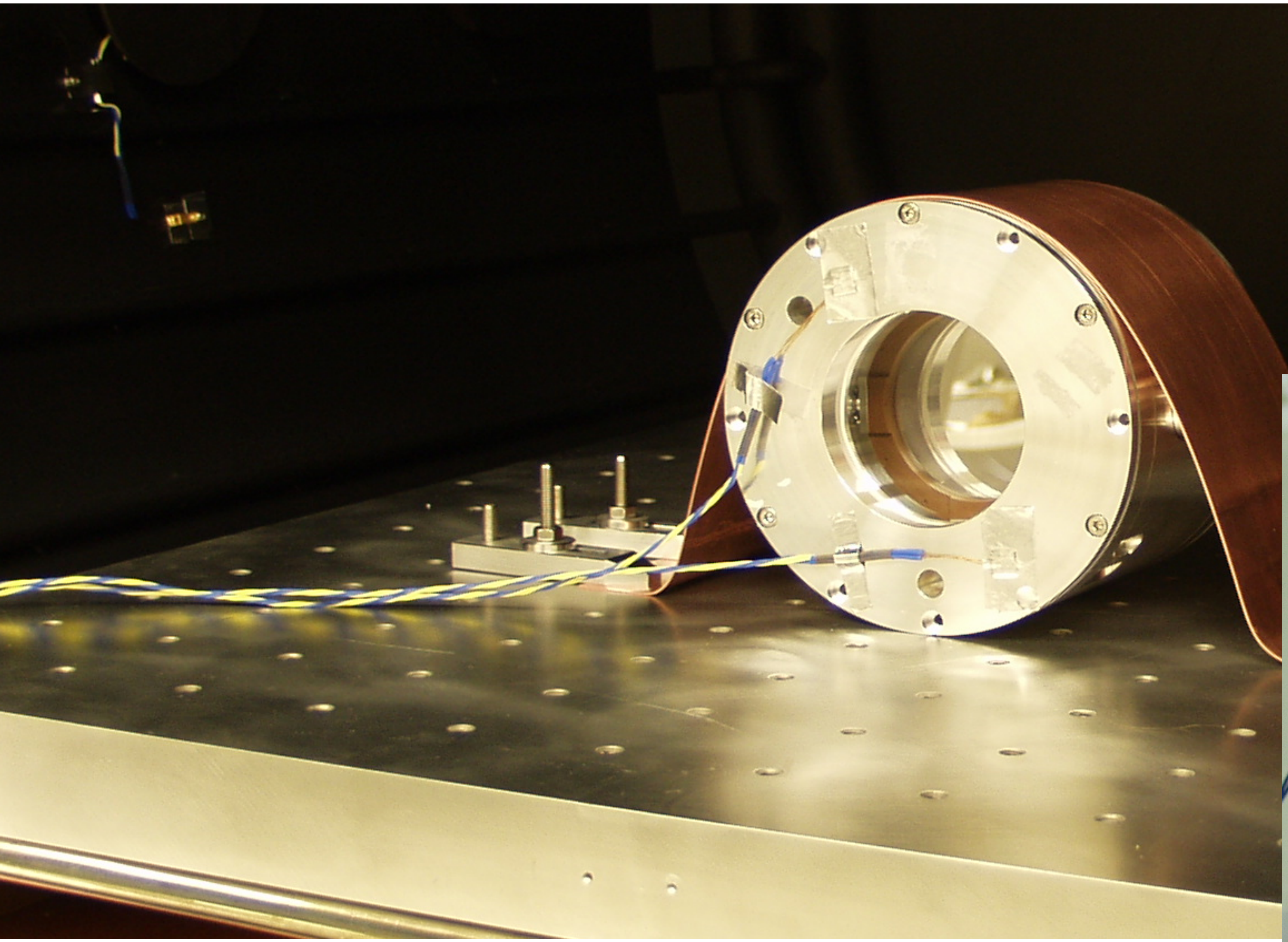
Einschub: Lithium-Niobat-Filter

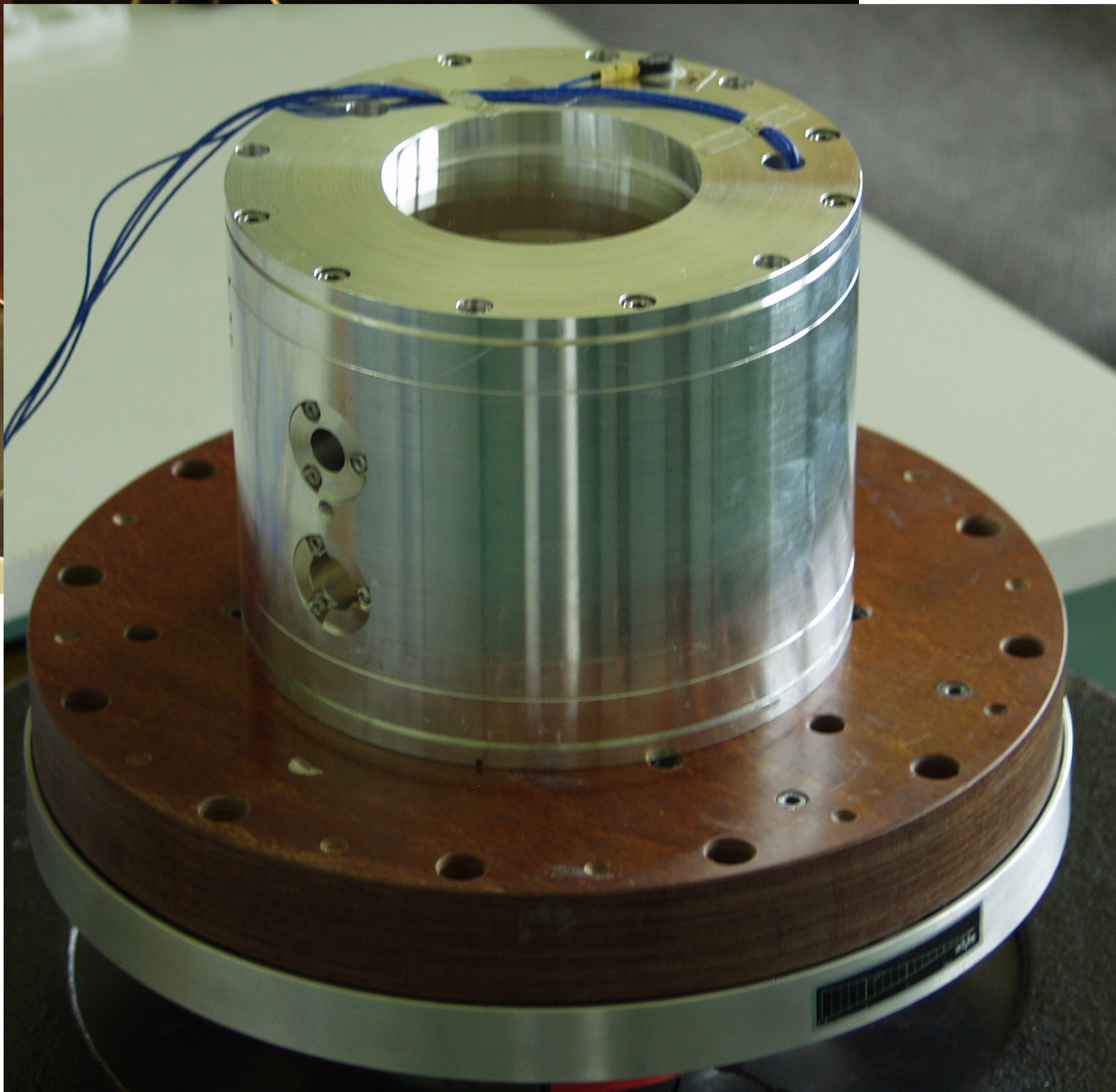


3” $LiNbO_3$ wafer („z-cut“): CSIRO
(Commonwealth Scientific and Industrial Research Organisation, Australi
Apertur: 70 mm Durchmesser
Dicke: 0.250 mm
Finesse: >20
Metallbeschichtet + kontaktiert
→ Voltage tuning !



Einschub: $LiNbO_3$ Etalon



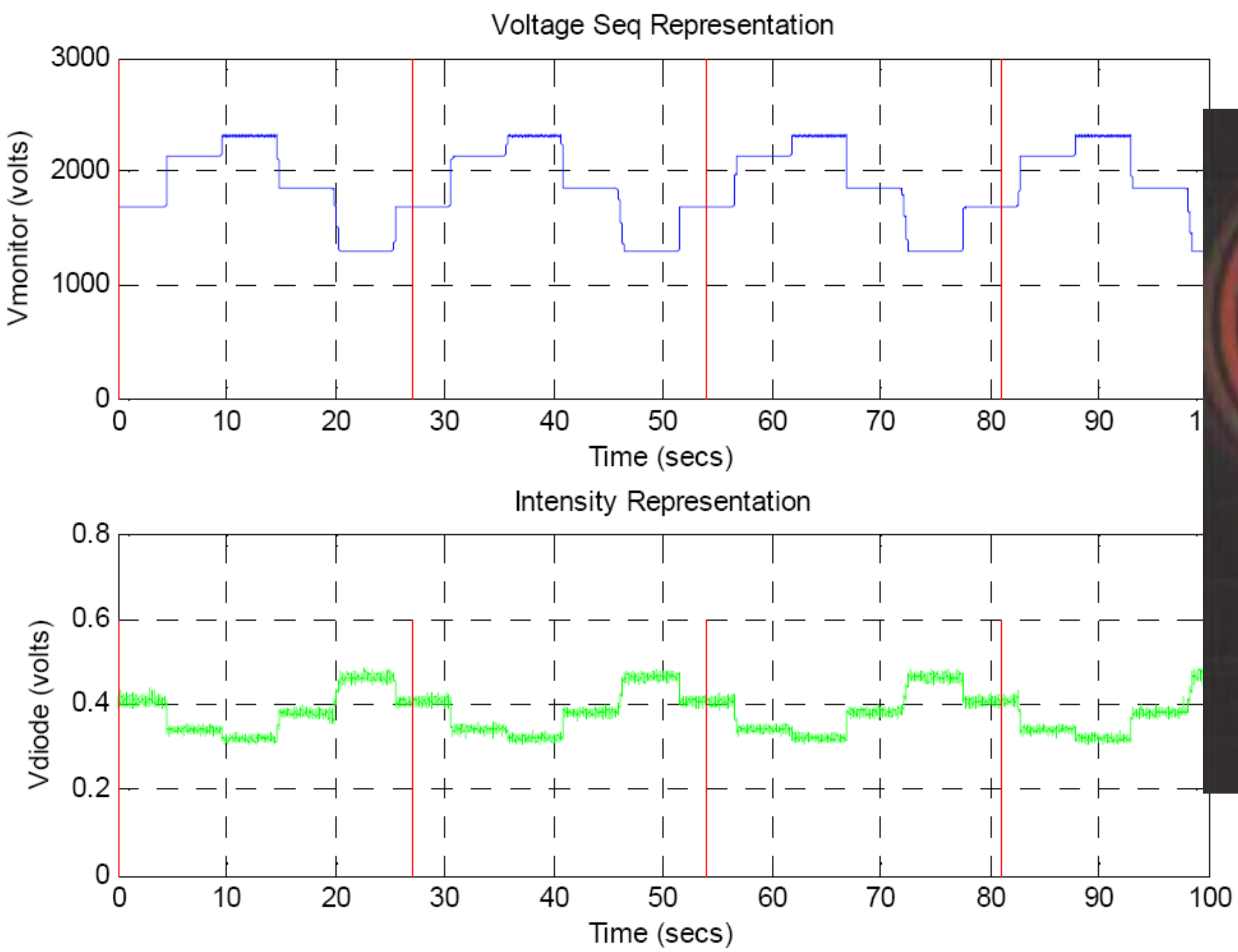


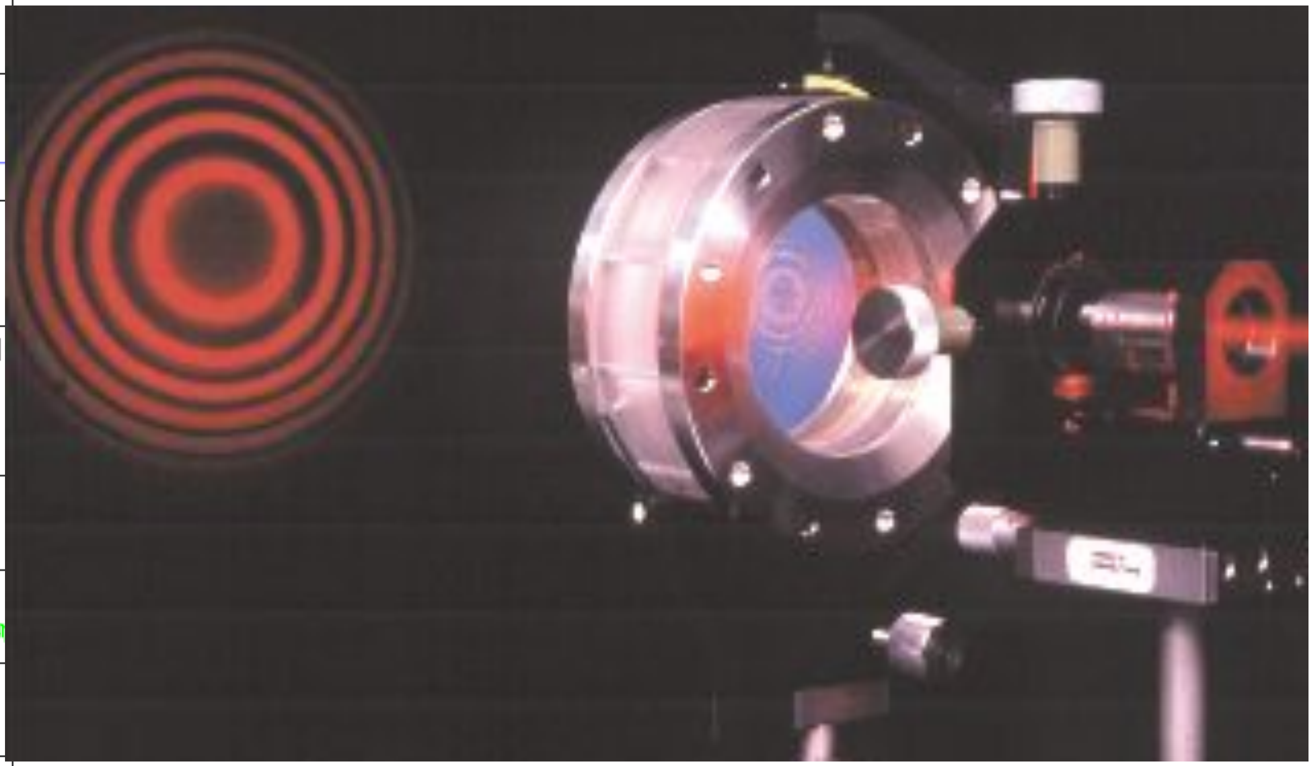
- Thermalzyklus-Test unter Vakuum
- Vibrationstest
- Voltage tuning Tests

Einschub: $LiNbO_3$ Etalon

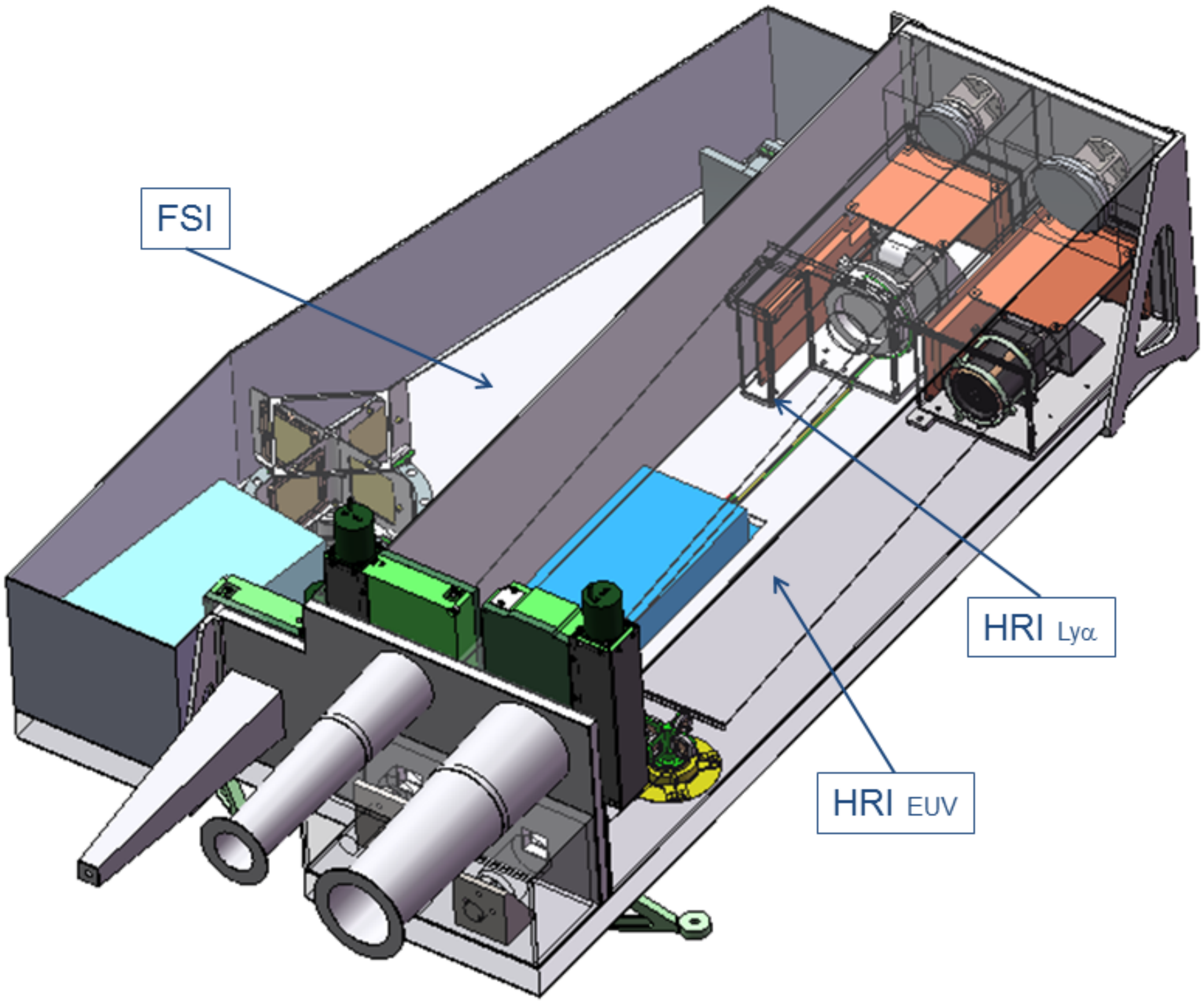
Voltage tuning test

Wechselspannung 3 kV/ s

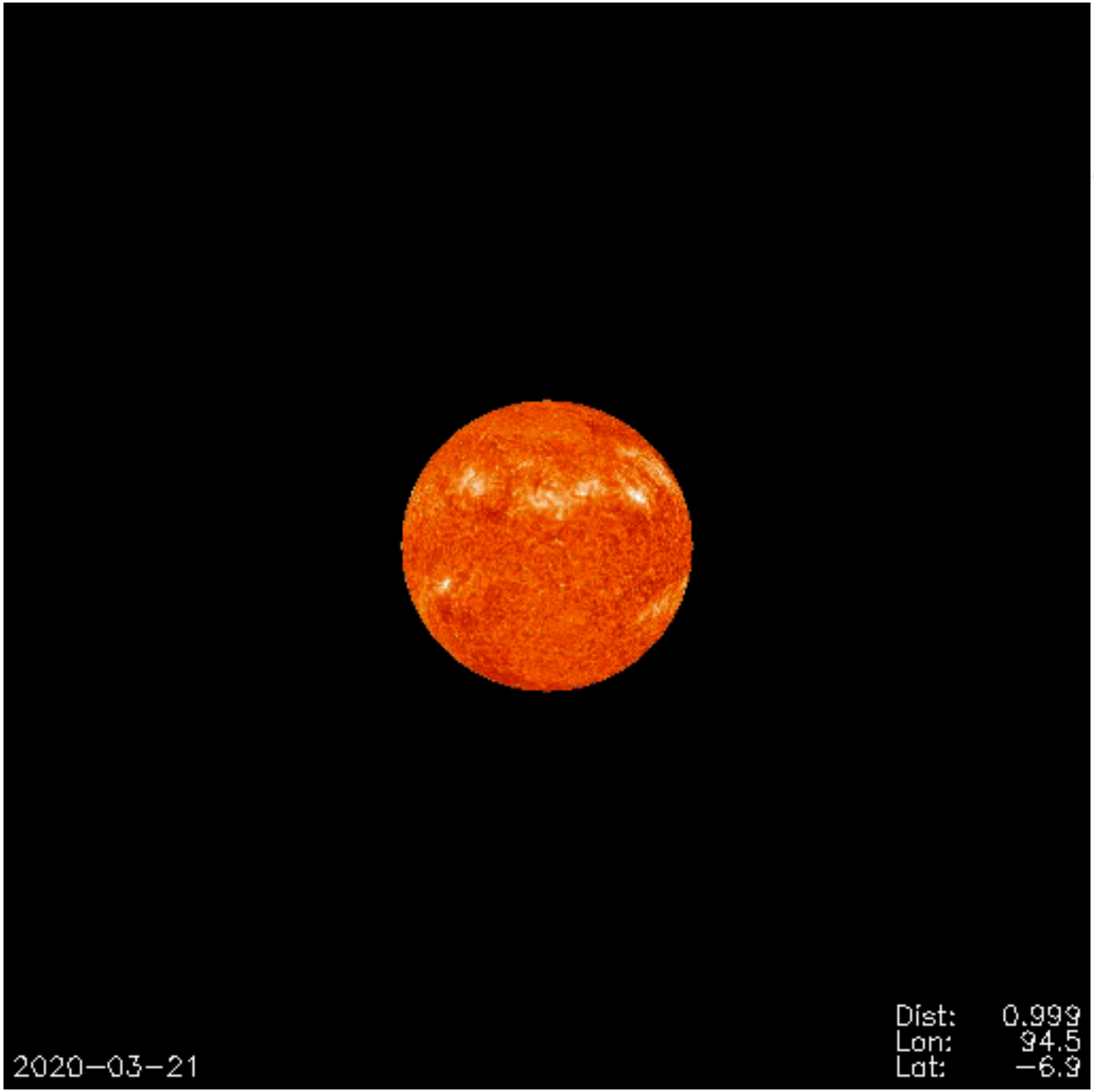




Extreme Ultraviolet Imager (EUI)



SOLAR ORBITER



Courtesy W.Thompson

Optische Anforderungen an die Instrumente

- Gemeinsame Bildfeldgröße von mind. 200”^{2}
- Auflösungsvermögen 1”
- Teleskope kleiner als 1 m
- Strahlungshartes Design
- Temperaturtoleranz

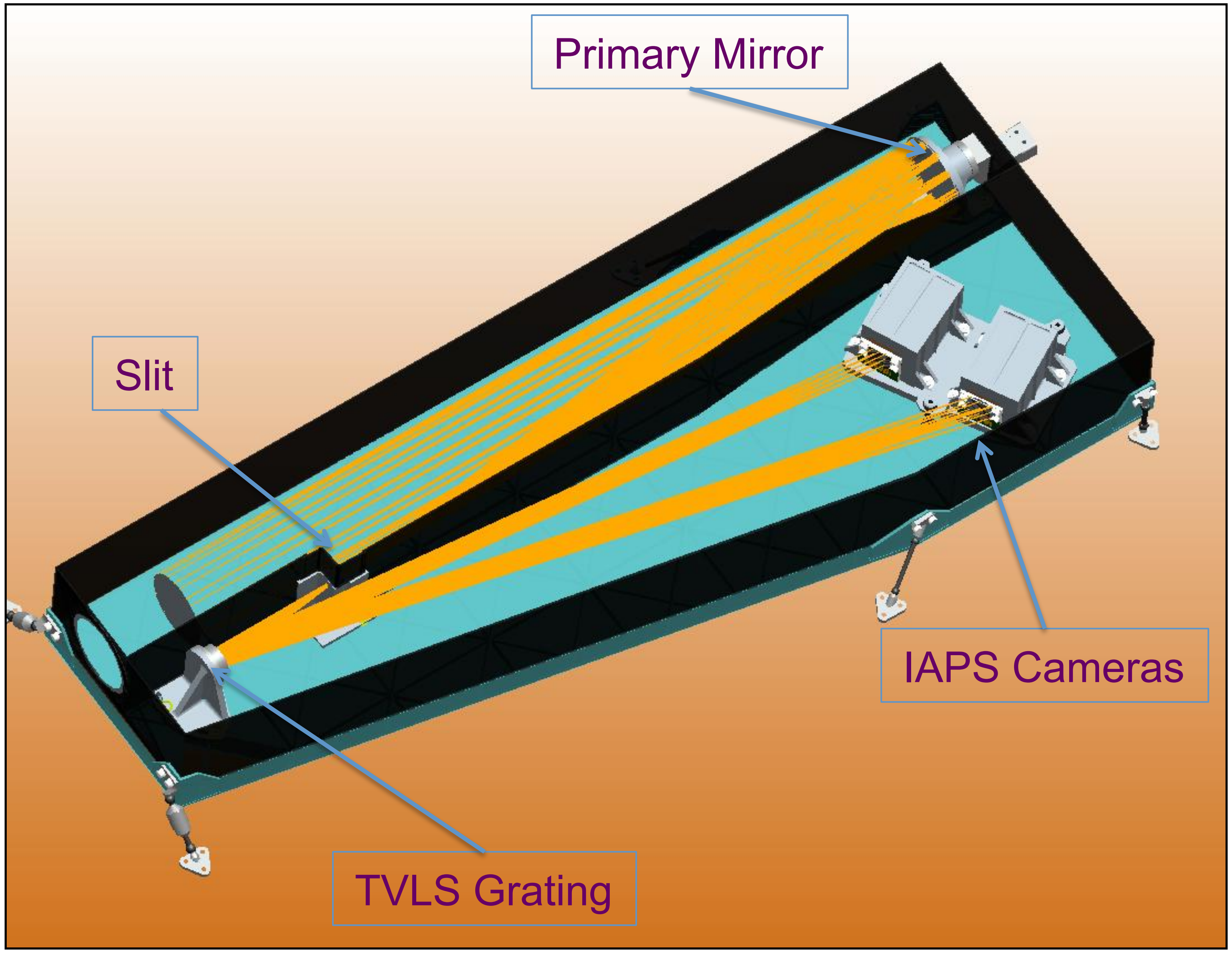
- Minimales Gewicht
- Autonomer Betrieb

Beispiel eines der Instrumente: SPICE

SPICE – Vakuum-Ultraviolett Spektrograph

für die Wellenlängenbereiche
70.2 nm bis 79.2 nm
und von
97.0 nm bis 105.0 nm

(48.5 nm bis 52.5 nm in 2. Ordnung).



Herkunft des SPICE Designs

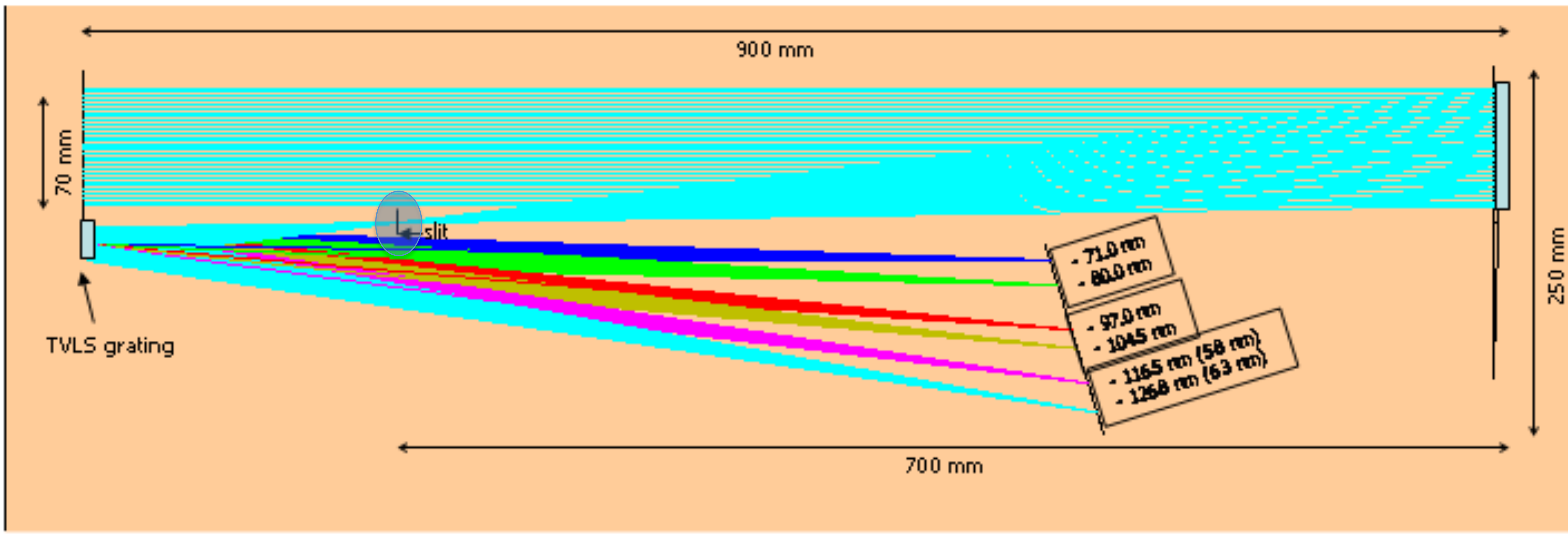
- Erstmals vorgeschlagen von Roger Thomas (NASA-GSFC) (2004)

- Optisches Konzept eines Toroidal Variable Line Space
Gitters von Kita and Harada (J) (1983)

- NASA-Raketennutzlast: EUNIS, RAISE (2006…)

- HINODE-Mission: Extreme Ultraviolet Imaging spectrograph EIS (2006)

SPICE Optische Design-Optimierung



Optisch ein Kompromiss aus vielen unterschiedlichen Anforderungen:

1. Große Apertur, Einzelspiegel,
2. großes Bildfeld & hohe Auflösung → kleiner Achsenabstand
3. Großer Bildbereich → großer Achsenabstand.
4. TVLS-Gitter in elliptischer Anordnung mit Vergrößerungsverhältnis
5. Temperaturstabilität ist die größte Herausforderung!

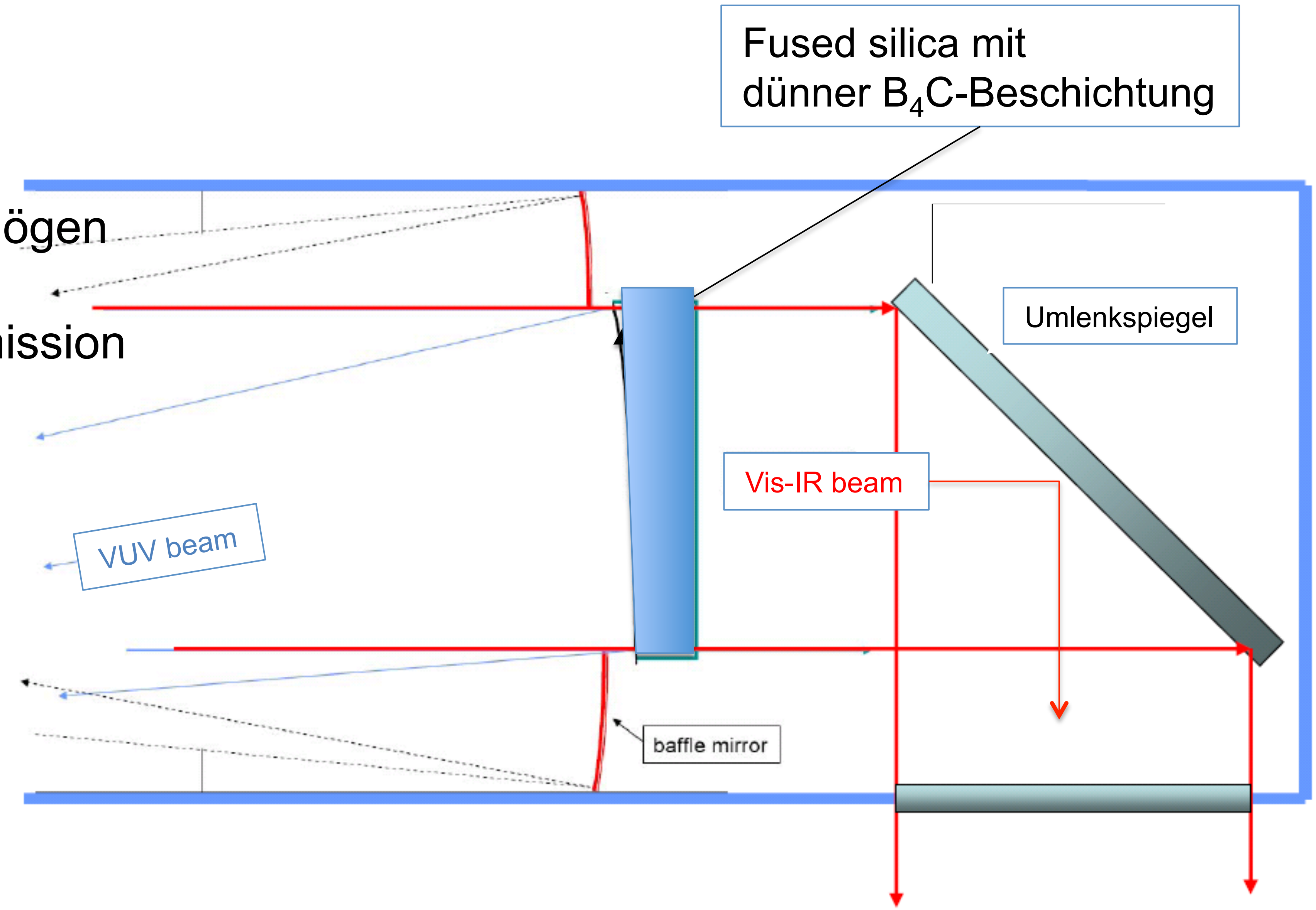
Teleskopspiegel Designanforderungen

Principal Requirements:

1. Hohes VUV Reflexionsvermögen über großen Spektralbereich
2. Hitzeverteilung: hohe Transmission von Vis-IR

➔

- Form: Off-axis Paraboloid
- Surface: low scatter, 1” PSF
- Substrat: fused silica
- Beschichtung:
  Front: dünne B_4C
  Rück: anti-reflex



==> Wärmestrahlung der Sonne wird durchgelassen!

Verteilung der Sonneneinstrahlung

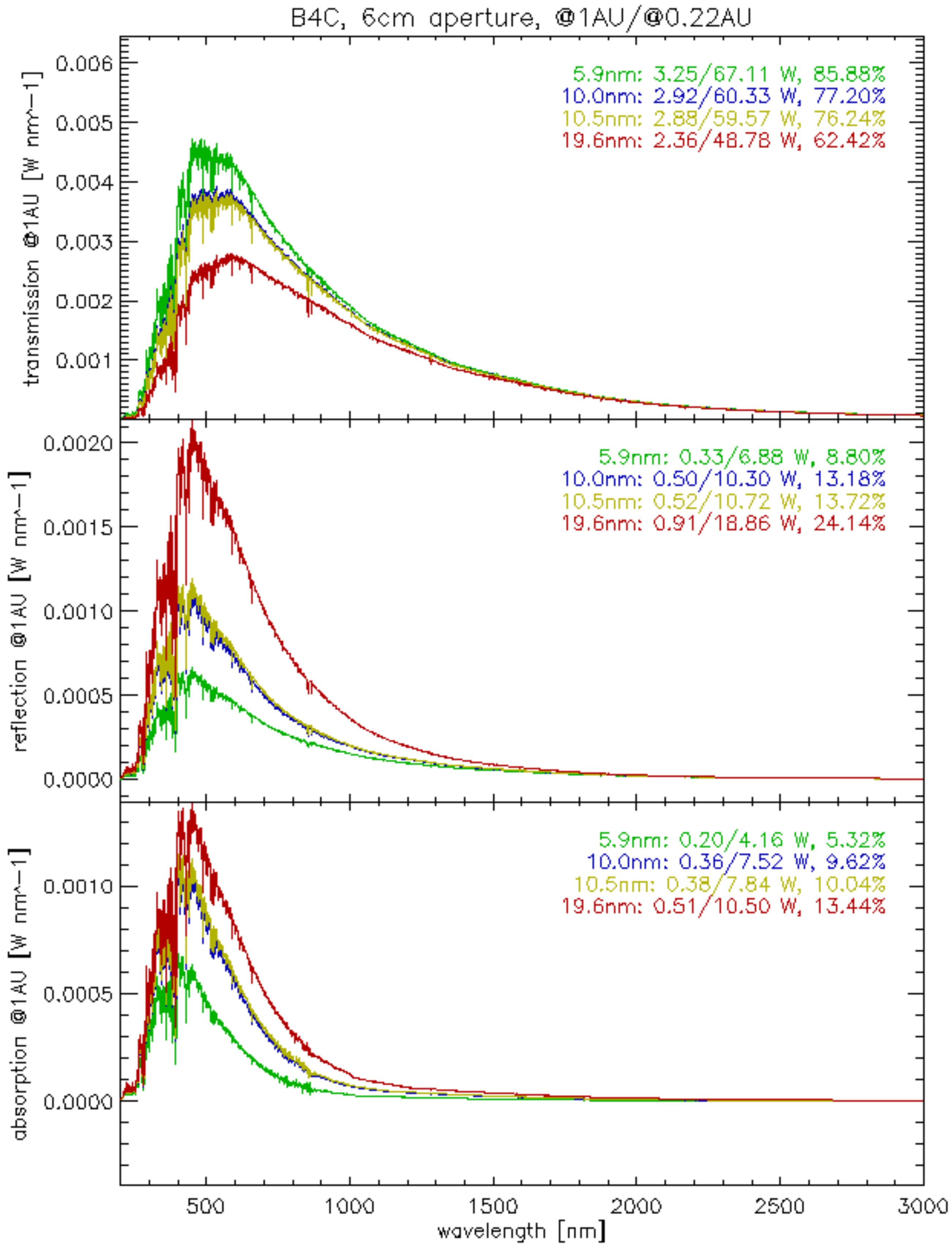
Spiegelproben von FhG-IOF mit verschiedenen Schichtdicken Borkarbid (B_4C).

Messung von Reflexion, Transmission und Absorption.

Simulation Strahlungsverteilung

➔ Energiebudget für eine 10 nm B_4C-Schicht:

T = 77 %
R = 13 %
A = 10 %



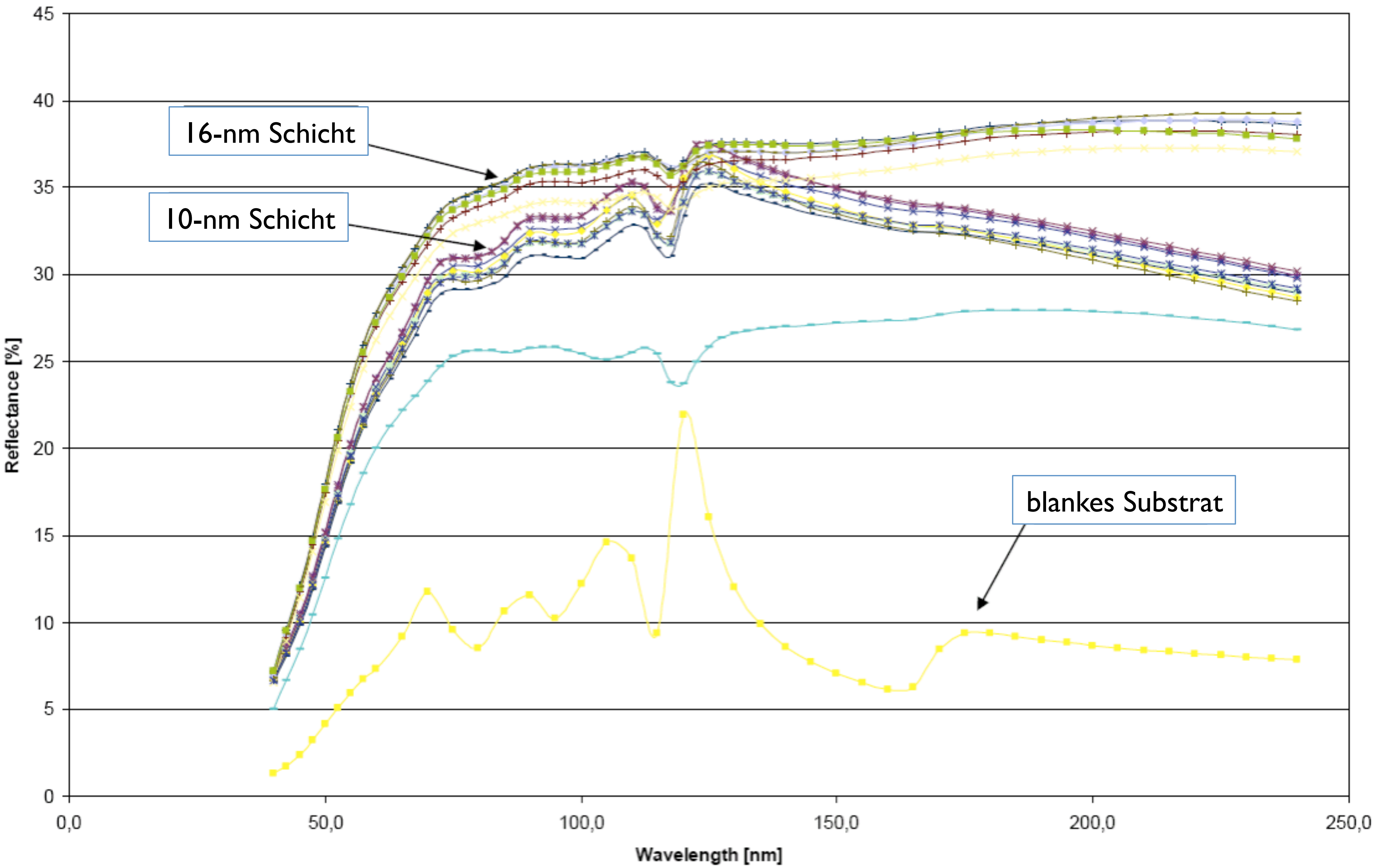
Weltraumqualifizierung

- Weltraumsimulation durch Bestrahlung mit 10 - 60 MeV Protonen
- Sonnenwindsimulation durch Bestrahlung mit 1 keV Protonen (Missionsäquivalente Dosis)
- Sonnen-UV-Simulation durch Bestrahlung mit hoch-intensiver UV-Quelle (möglichst mit 20-facher Solarkonstanten)

Qualifikationstestplan

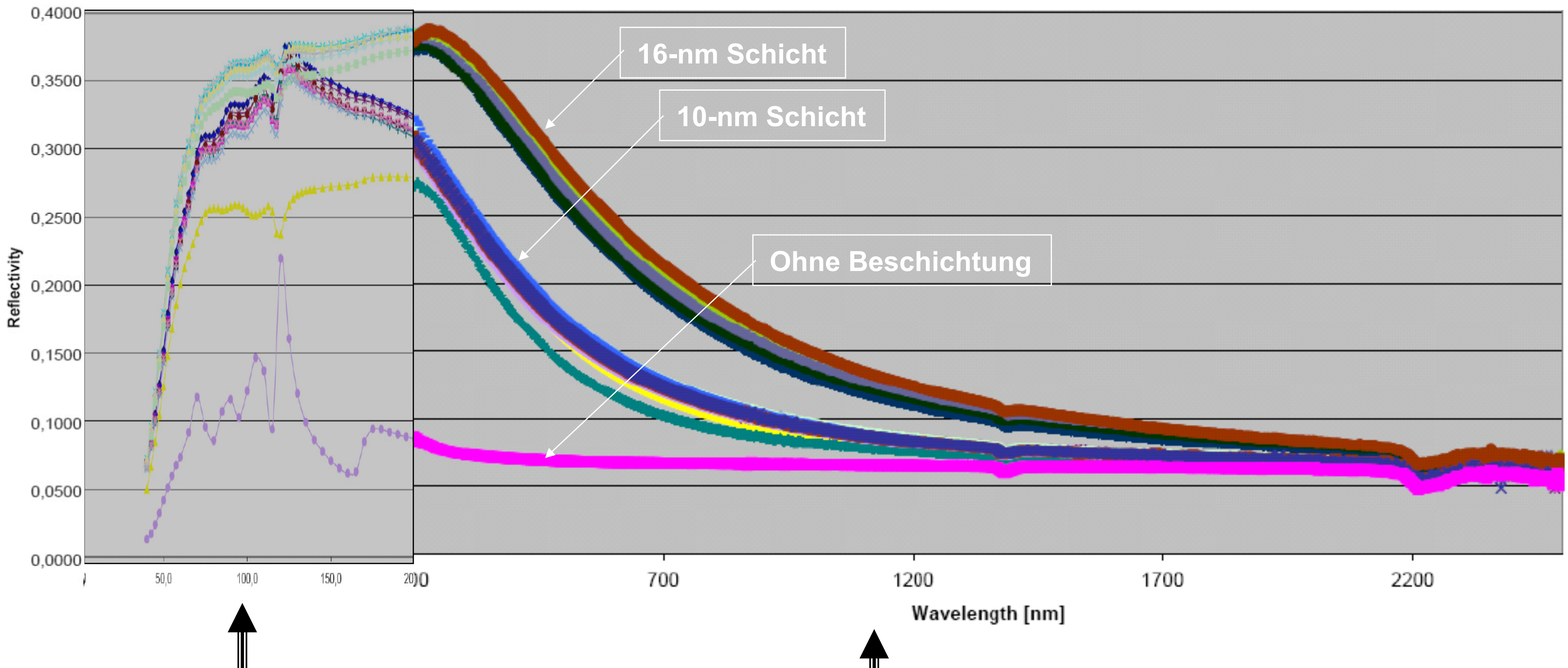
Measurement	Samples Coated	Samples Uncoated	Note
AFM (1µm² +10µm²)	0	18	charaterization surface rouhgness
Coating B_4C 10 nm	10	1	surface coating with B_4C for 10 nm
Coating for B_4C 16 nm	6	1	surface coating with B_4C for 16 nm
AFM (1µm² +10µm²)	13	2	surface roughness after coating
X-ray diffraction	16	0	coating thickness calculation
Spectral photometry (T/R)	16	1	visible reflectance/transmittance
VUV-Reflectance Test	16	1	VUV measurements at PTB-MLS
Irradiation protons	6	1	protons at 10 MeV - 60 MeV (PSI)
Irradiation protons	6	1	solar wind protons at 1 keV (FZD)
AFM (1µm² +10µm²)	12	2	surface roughness after irradiations
X-ray diffraction	12	2	coating thickness verification
Spectral photometry (T/R)	12	2	visible reflectance/transmittance
VUV-Reflectance Test	12	2	VUV measurements at PTB-MLS

EUV-Reflektivität



Reflektivitätskurven aller Proben

Reflektivität der B_4C-Schichten



EUV

@PTB

vis-IR

@ FhG-IOF

Bestrahlungstests mit Protonen

- High energy p^+

Position	*Sample #*	*proton energy*	*fluence [#/cm2]*	*Remarks*
P1	12894	10 MeV	4×10^{11}	10 nm B_4C
P2	12891	10 MeV	4×10^{11}	16 nm B_4C
P3	12930	20 MeV	$+8 \times 10^{10}$	10 nm B_4C
P4	12890	20 MeV	$+8 \times 10^{10}$	16 nm B_4C
P5	12637	60 MeV	$+2 \times 10^{10}$	10 nm B_4C
P6	12645	all	$+2 \times 10^{10}$	shielded
P7	12931	60 MeV	$+2 \times 10^{10}$	no coating

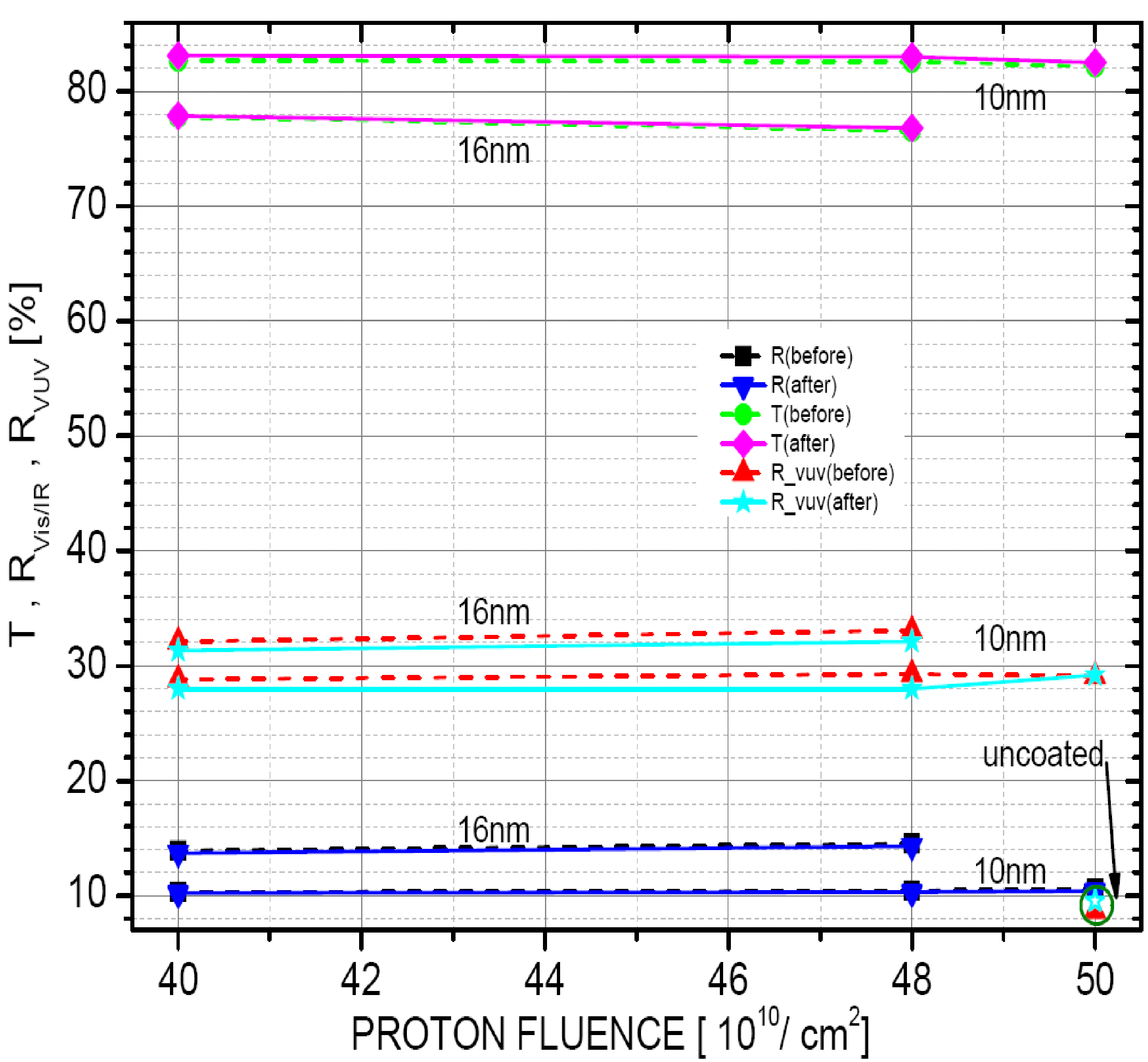
- Low energy p^+ (Sonnenwind-Äquivalent bei 1 keV)

C	*Sample ID*	*Fluence [#/cm^2]*	*Remarks*
P8	12644	1×10^{16}	10 nm B4C
P9	12638	5×10^{16}	10 nm B4C
P10	11863	10×10^{16}	10 nm B4C
P11	12935	30×10^{16}	16 nm B4C
P12	12834	60×10^{16}	16 nm B4C
P13	12934	60×10^{16}	no coating
P14	12893	shielded	~16nm B_4C

VUV-Bestrahlung im Vakuum

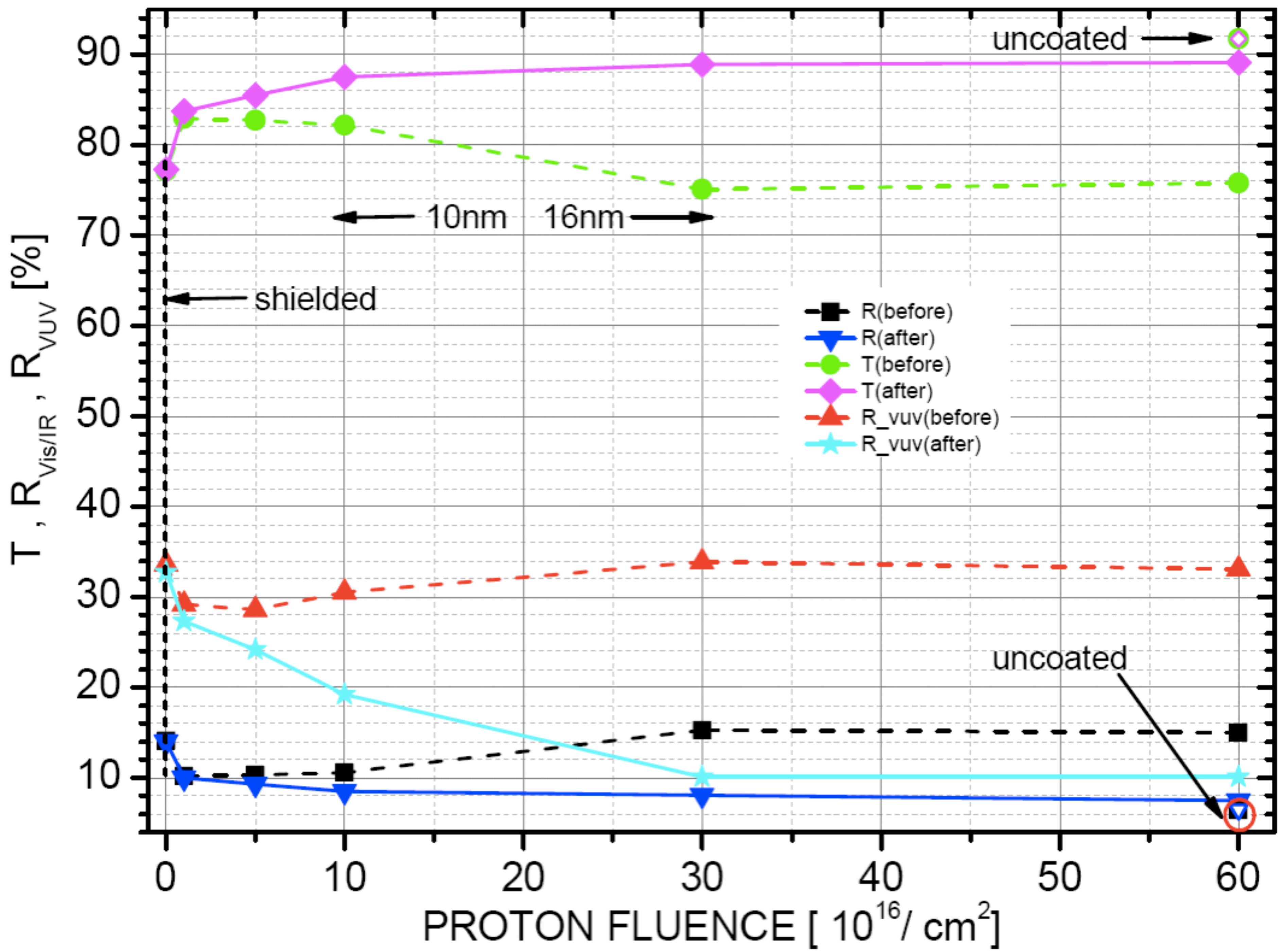
Hoch-intensive Krytonlampe für Bestrahlung bei 123 nm.
Wasserstoff-Lyman-Alpha-Quelle zur Messung bei 122 nm.

Reflektivität & Transmission nach Bestrahlung mit Protonen > 10 MeV

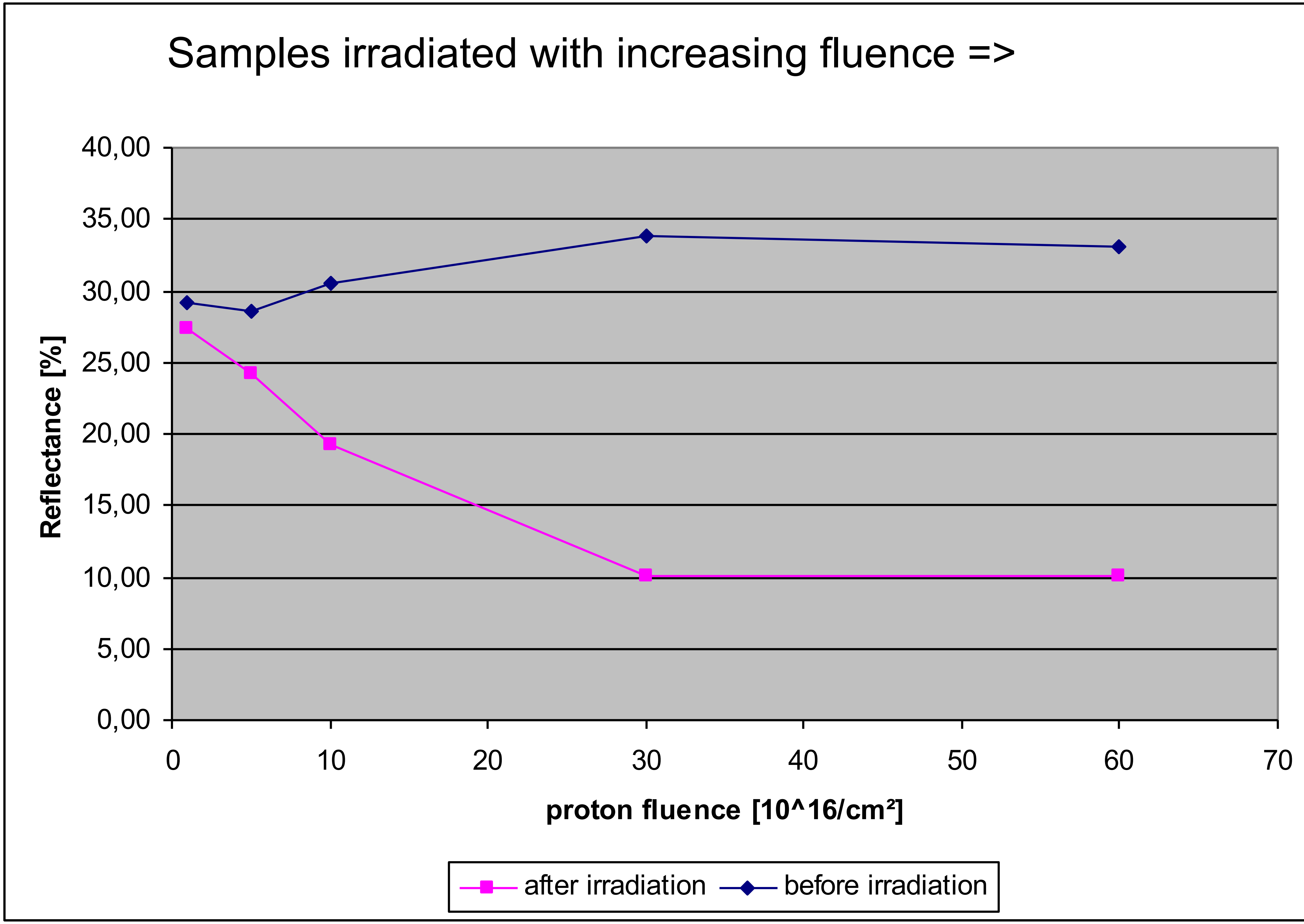


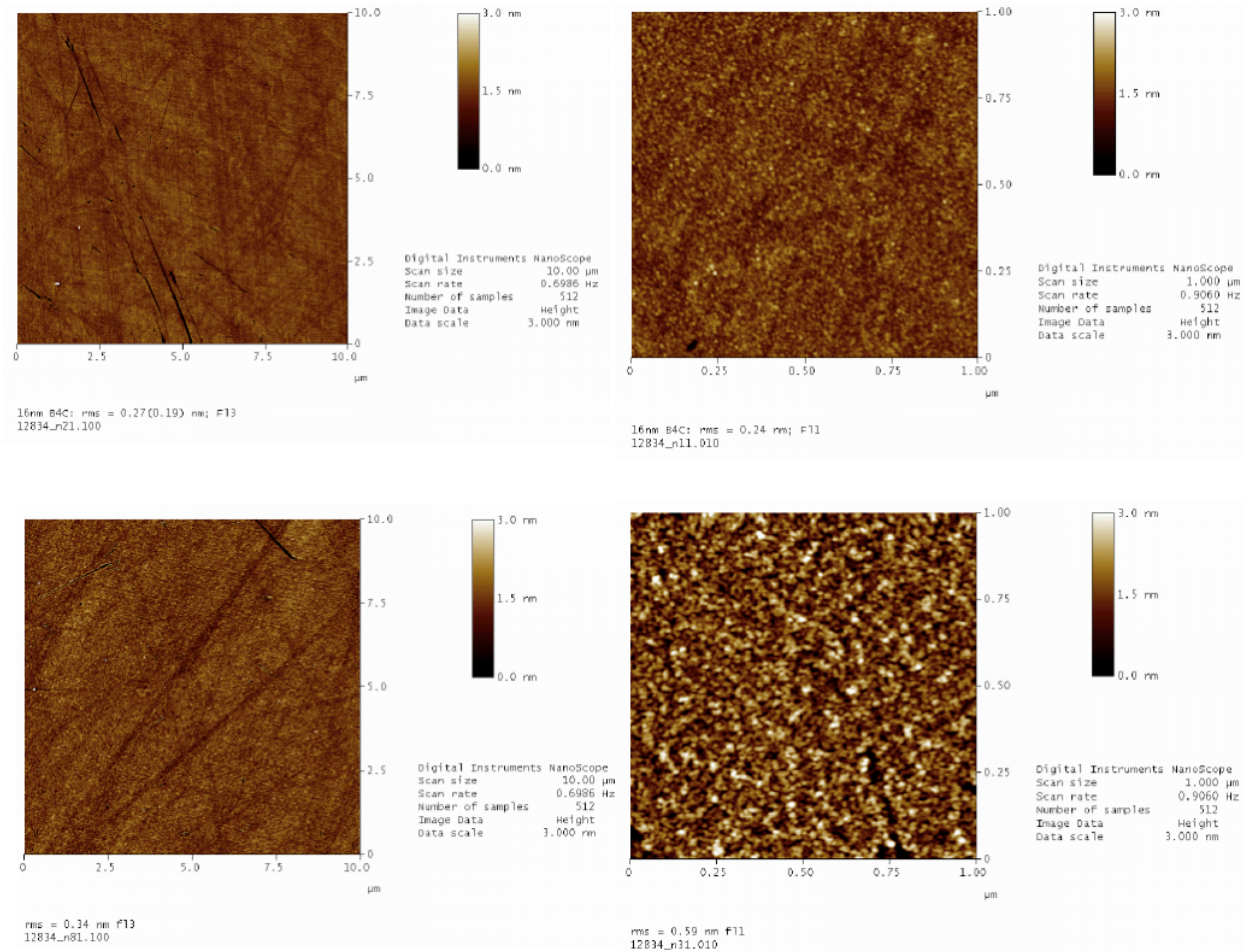
Sample ID	*128 94*	*129 30*	*126 37*	*126 45*	*128 90*	*128 91*	*129 31*
Fluence x10[11] p/cm²	4,00	4,80	5,00	shie lded	4,80	4,00	5,00
R_{before}	10,3	10,4	10,6	10,7	15,5	13,9	-
R_{after}	10,2	10,3	10,4	10,6	14,3	13,7	6,4
T_{before}	82,7	82,6	82,2	81,8	76,6	77,8	-
T_{after}	83,1	83	82,5	82,1	76,8	77,9	91,8
$R_{VUV\ before}$	28,8 0	29,3 0	29,1 0	30,5 0	33,1 0	32,1 0	8,70
$R_{VUV\ after}$	28,0 0	28,0 0	29,2 0	29,9 0	32,1 0	31,3 0	9,50

Reflektivität & Transmission nach Bestrahlung mit Protonen @ 1 keV



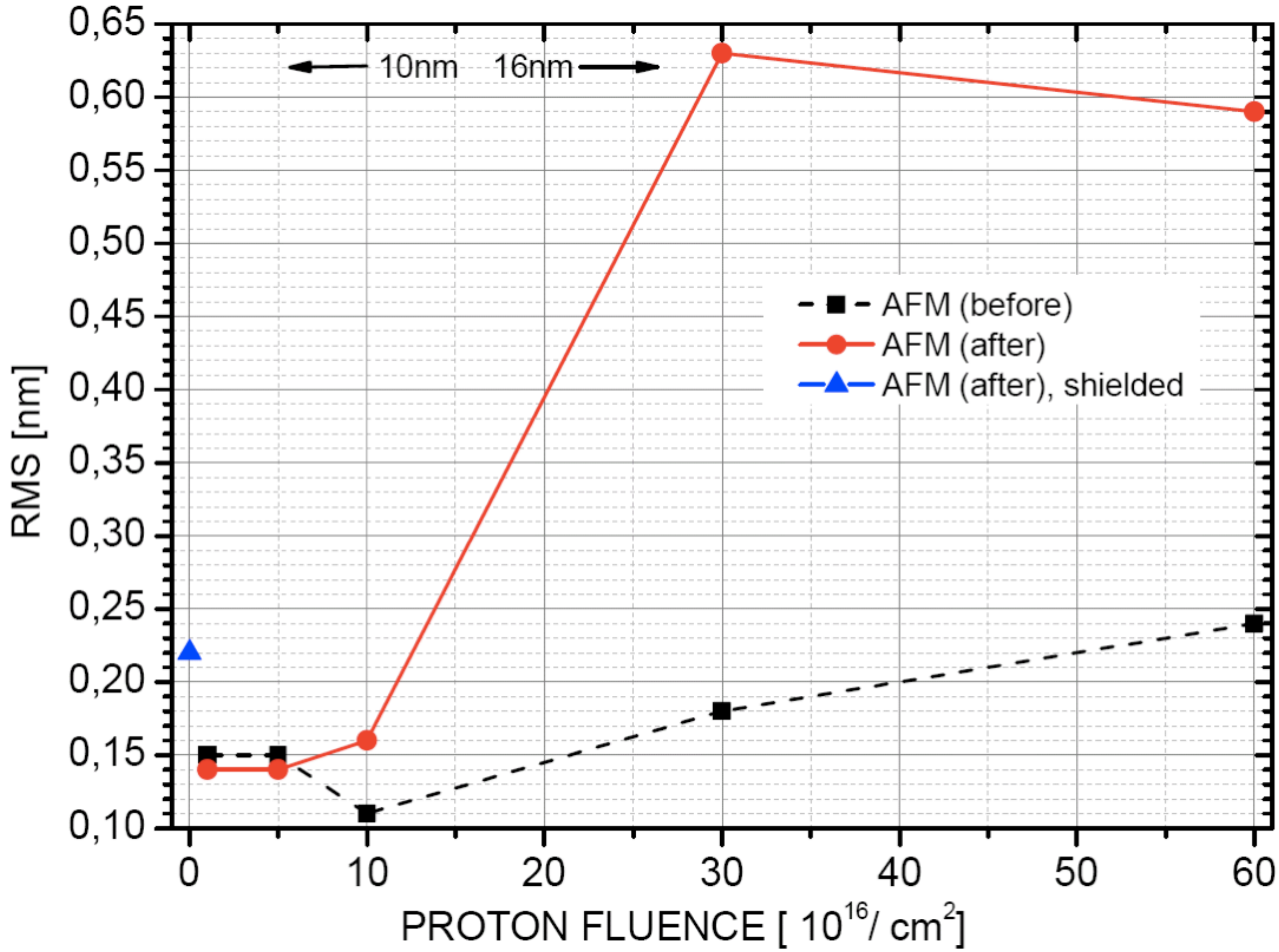
VUV-Reflektivität gegenüber Bestrahlungsfluss



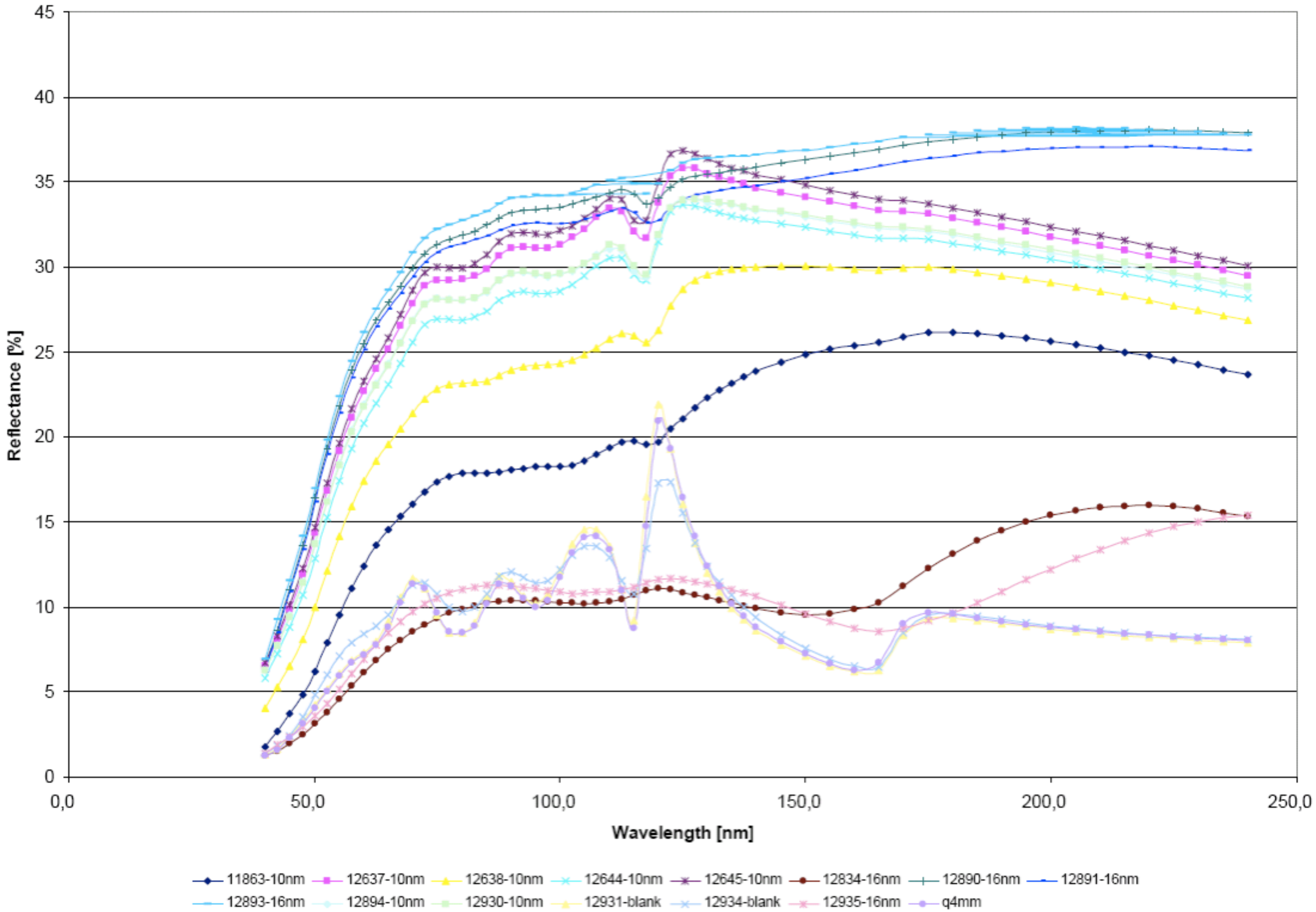


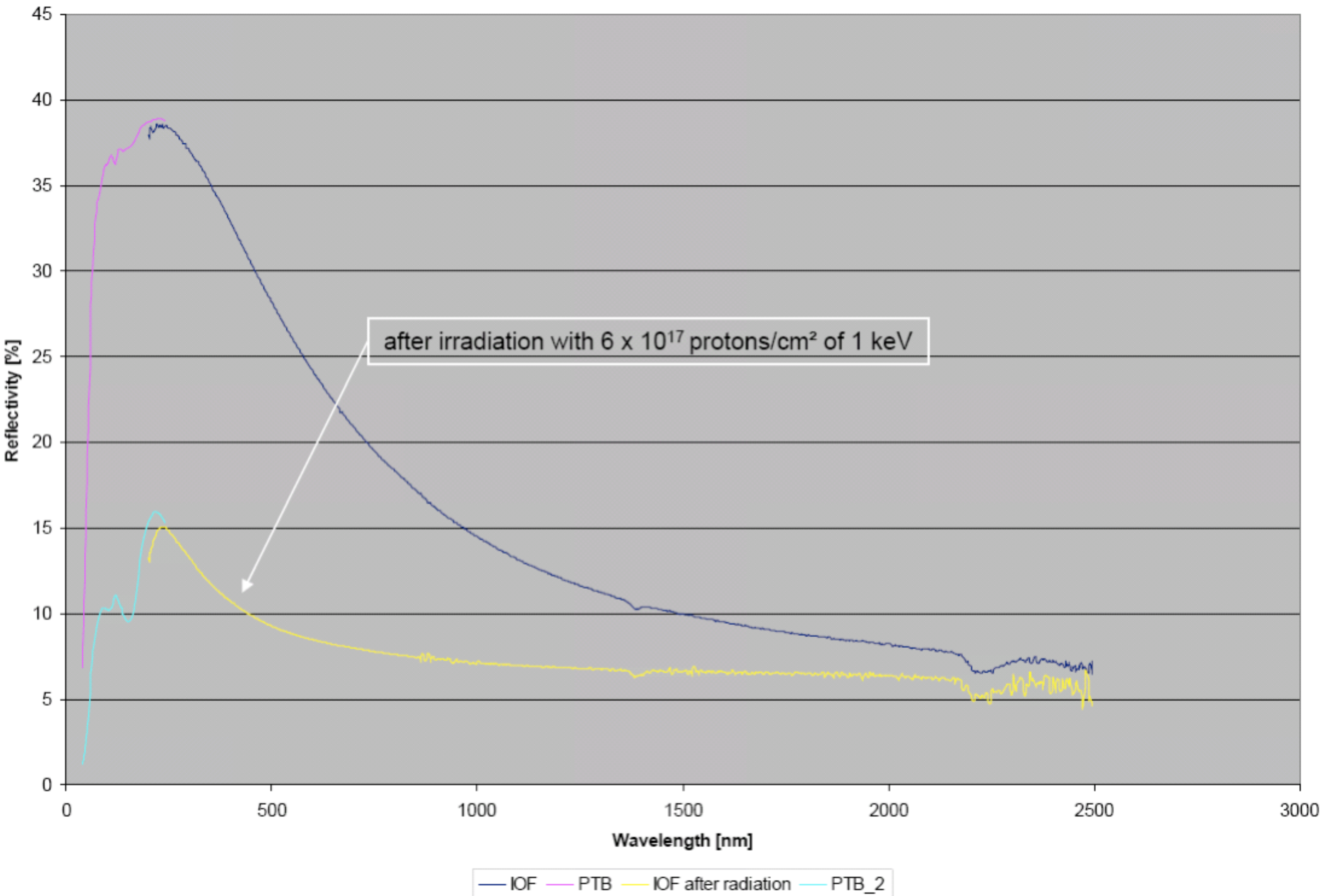
Mikro-Rauhigkeit vor (oben) und nach (unten)
Bestrahlung mit Sonnenwindprotonen bei 1 keV. (measured by FhG-IOF)

Mikro-Rauhigkeit nach 1 keV Protonenimplantation



EUV-Reflektivität nach Protonenimplantation





Vergleich der Reflektivität bevor und nach Bestrahlung mit $6x10^{17}$ p+/cm²

Testergebnisse

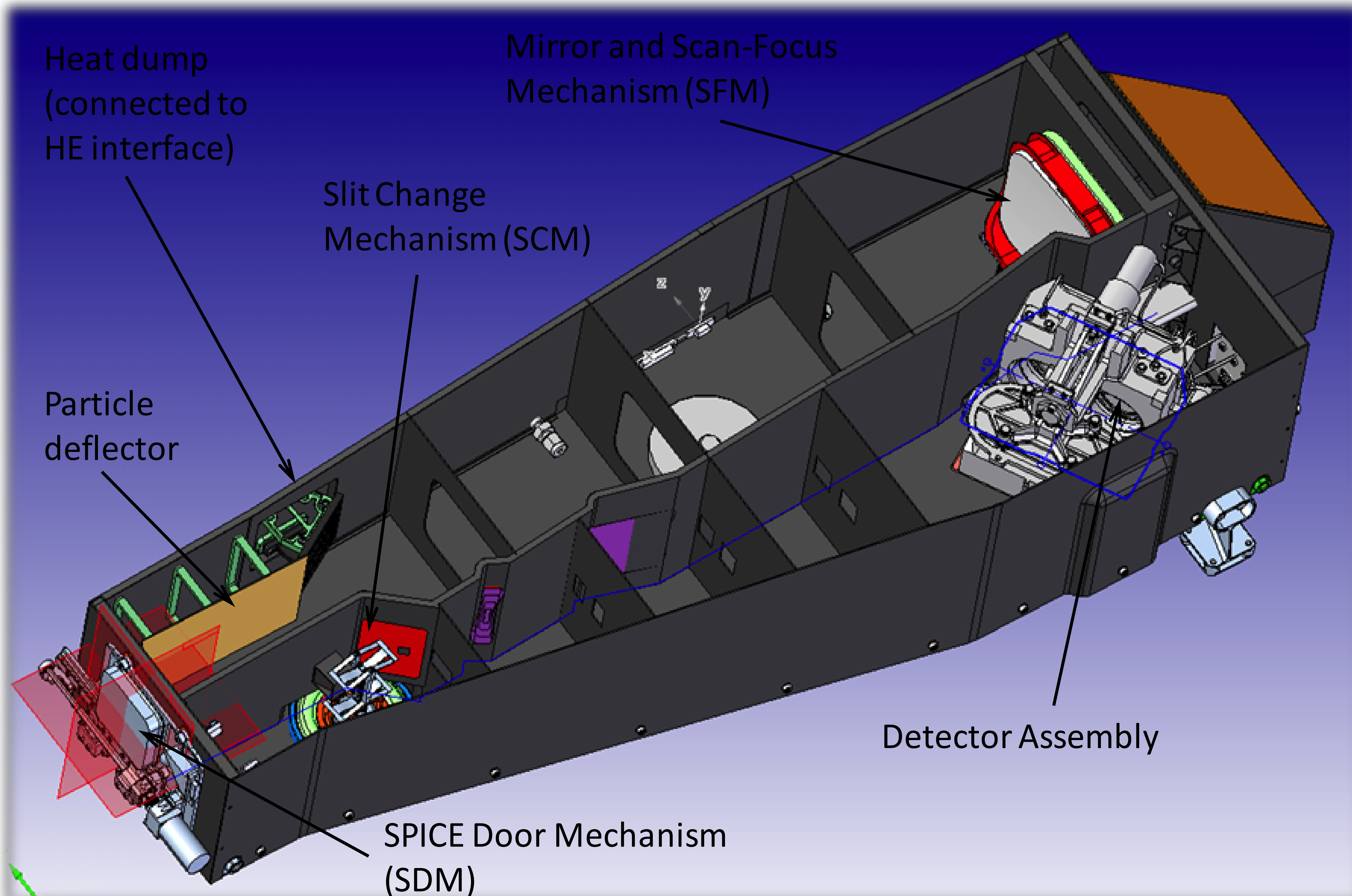
- Bestrahlung mit Protonen zwischen 10 MeV und 60 MeV bis zu einem Fluss von 5 x 10^{11} cm^{-2} hat keinen Einfluss auf die Spiegelbeschichtung (keinen Einfluss auf die VUV-Reflektivität, die thermo-optischen Eigenschaften und die Mikro-Rauhigkeit.)

- Bestrahlung mit Protonen des Sonnenwinds bei 1 keV bis zu einem Fluss von 1 x 10^{16} cm^{-2} hat einen zerstörenden Einfluss auf die Spiegelbeschichtung (auf die VUV-Reflektivität, die thermo-optischen Eigenschaften und die Mikro-Rauhigkeit.)

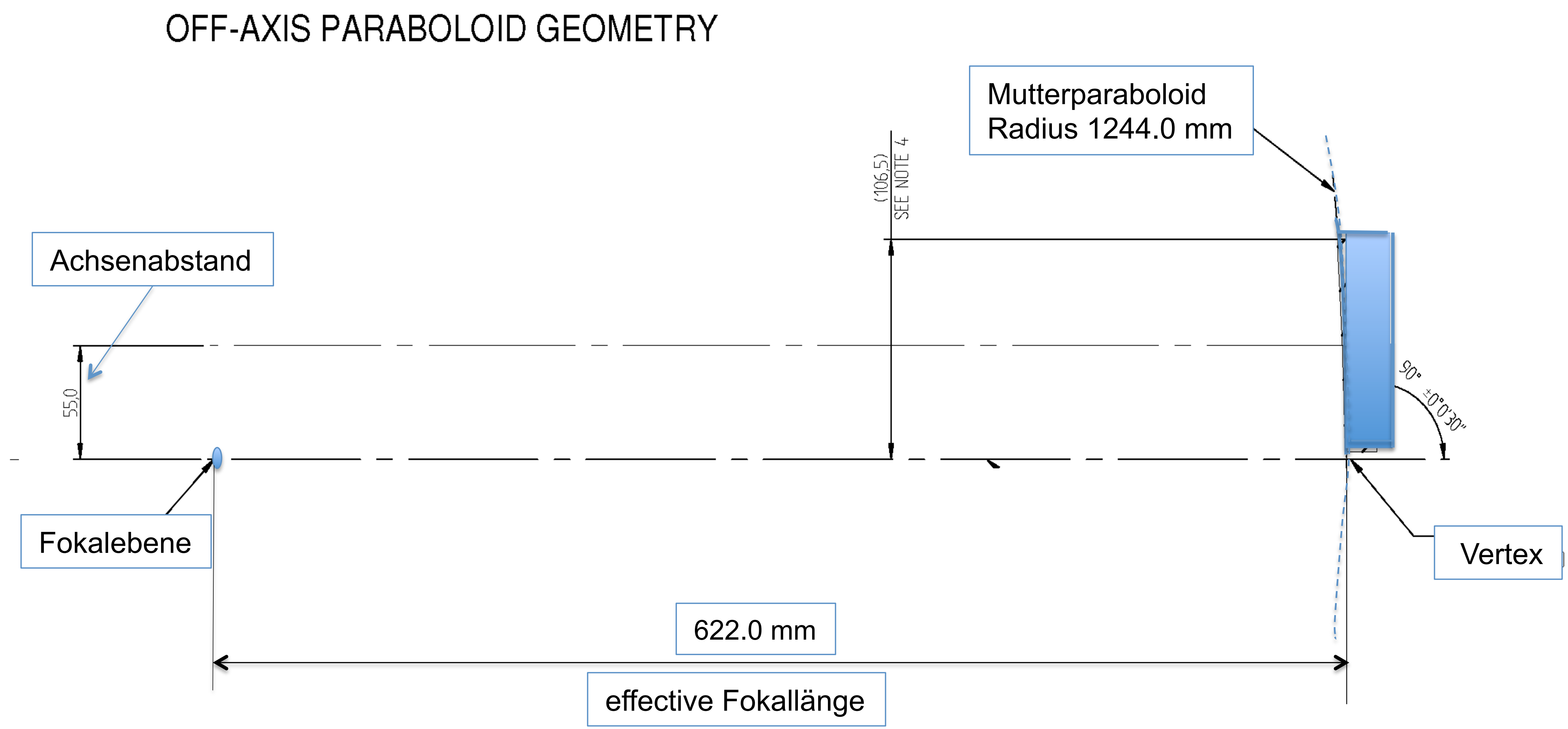
- Überraschenderweise wurden keine Effekte auf dem unbeschichteten Substrat gefunden.

- Die Bestrahlung mit der hochintensiven Lampe bei 123. nm hat keinen Effekt auf die Beschichtung.

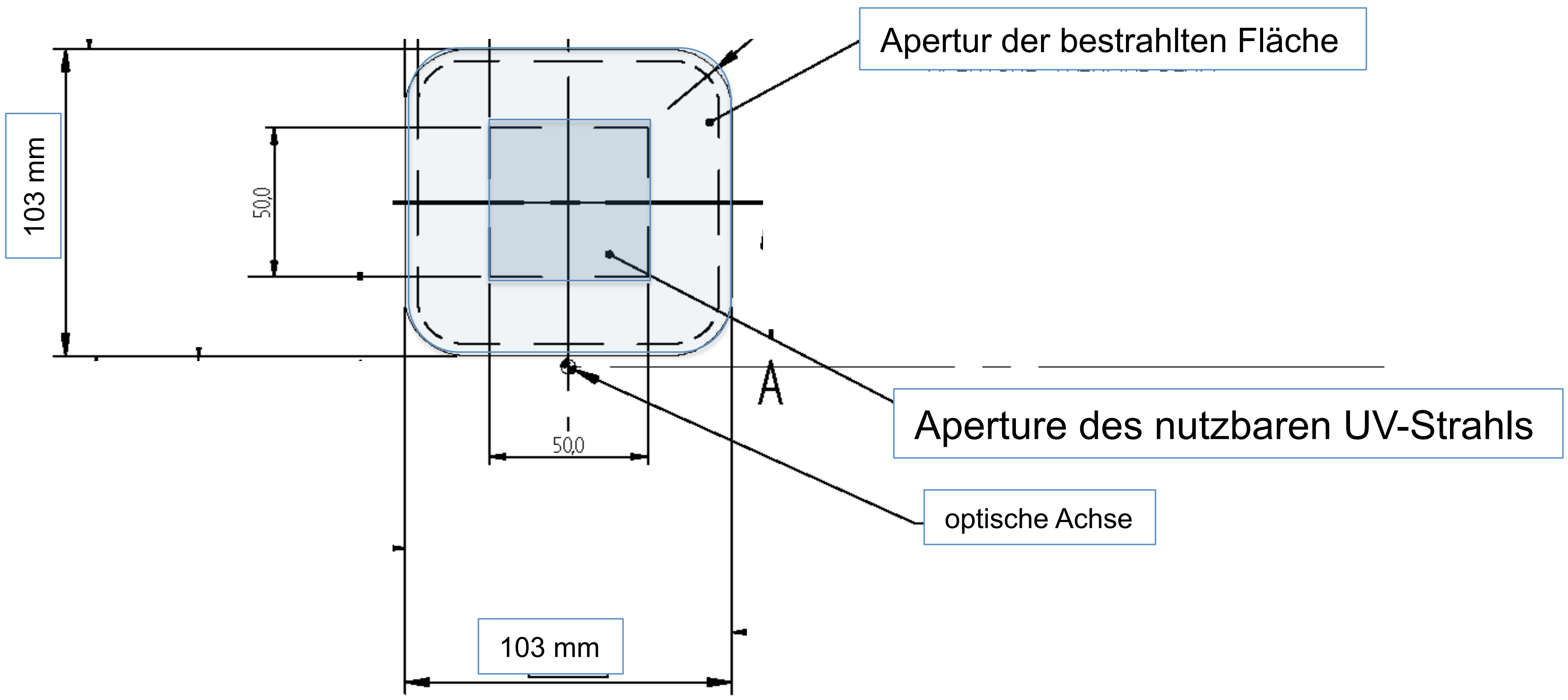
SPICE Instrumentdesign



Design des Teleskopspiegels



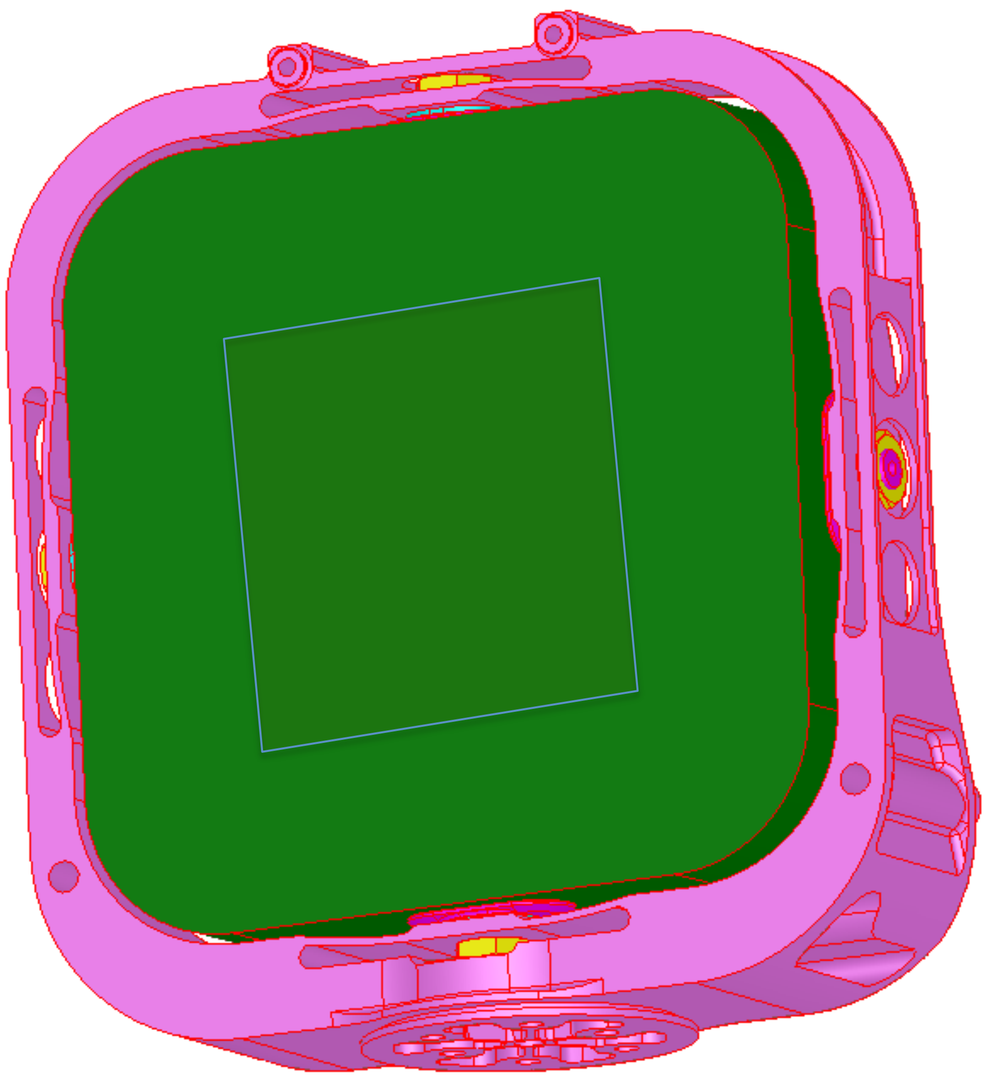
Geometrische Größen



Spezifikationen des Spiegels

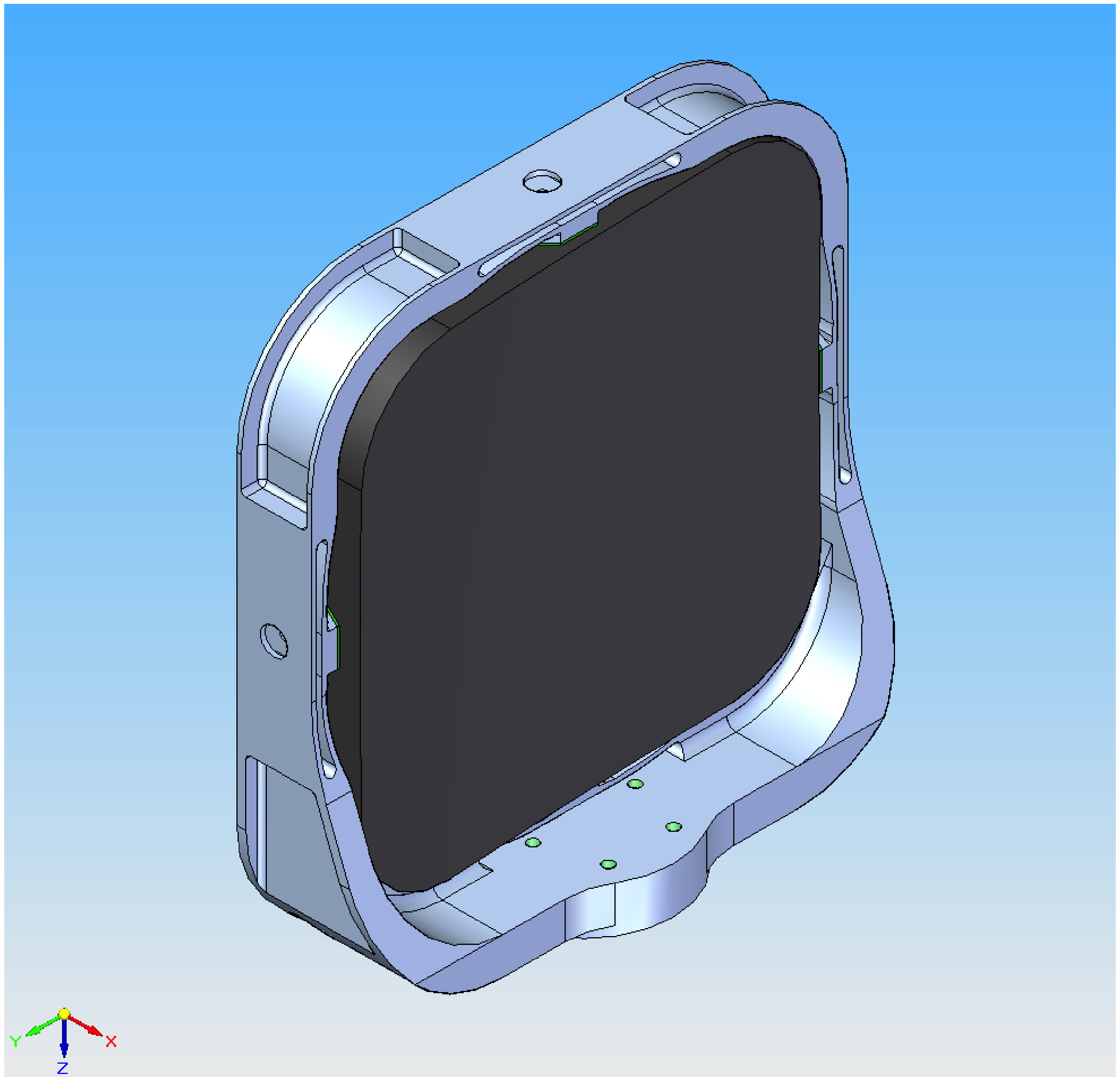
Substrate Material	**UV-grade fused-silica (Heraeus Suprasil 300)**
Substrate Size	103 x 103 mm
Substrate Thickness	18 mm at centre
Figure of Front Surface	concave, off-axis parabolic
Off-axis Distance	55.0 mm
Base Radius	1244.0 mm
Figure Error	λ/20 RMS at 632.8 nm over clear aperture
Front-side Coating	single layer B_4C, 10 nm thickness, at central 50 x 50 mm
Clear Aperture of thermal beam	≥ 95.0 mm x 95.0 mm
Back-side Coating	Anti-reflective MgF_2 single layer

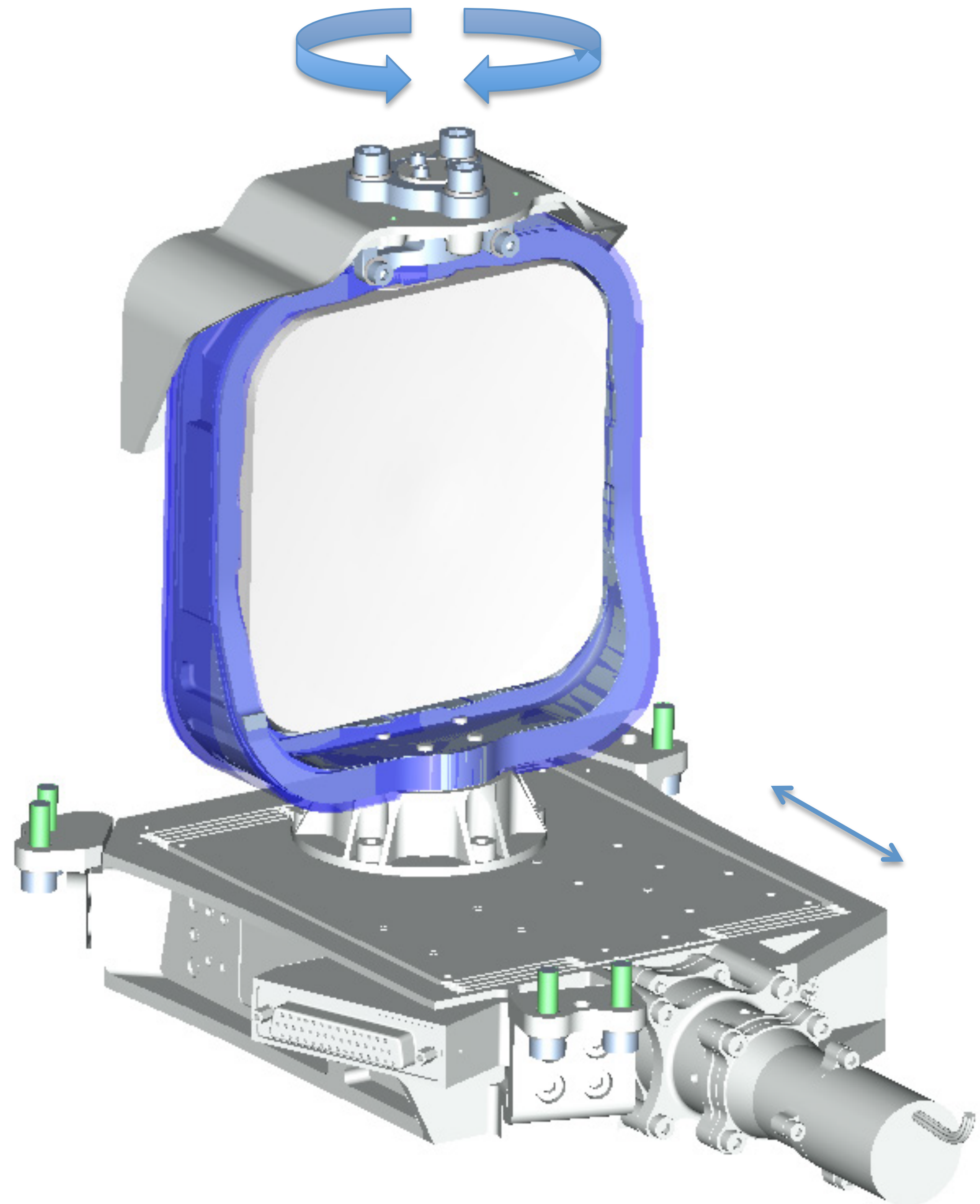
Spiegelaufhängung



- 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.

Aufhängung und Unterbringung





Fertigung des Spiegels

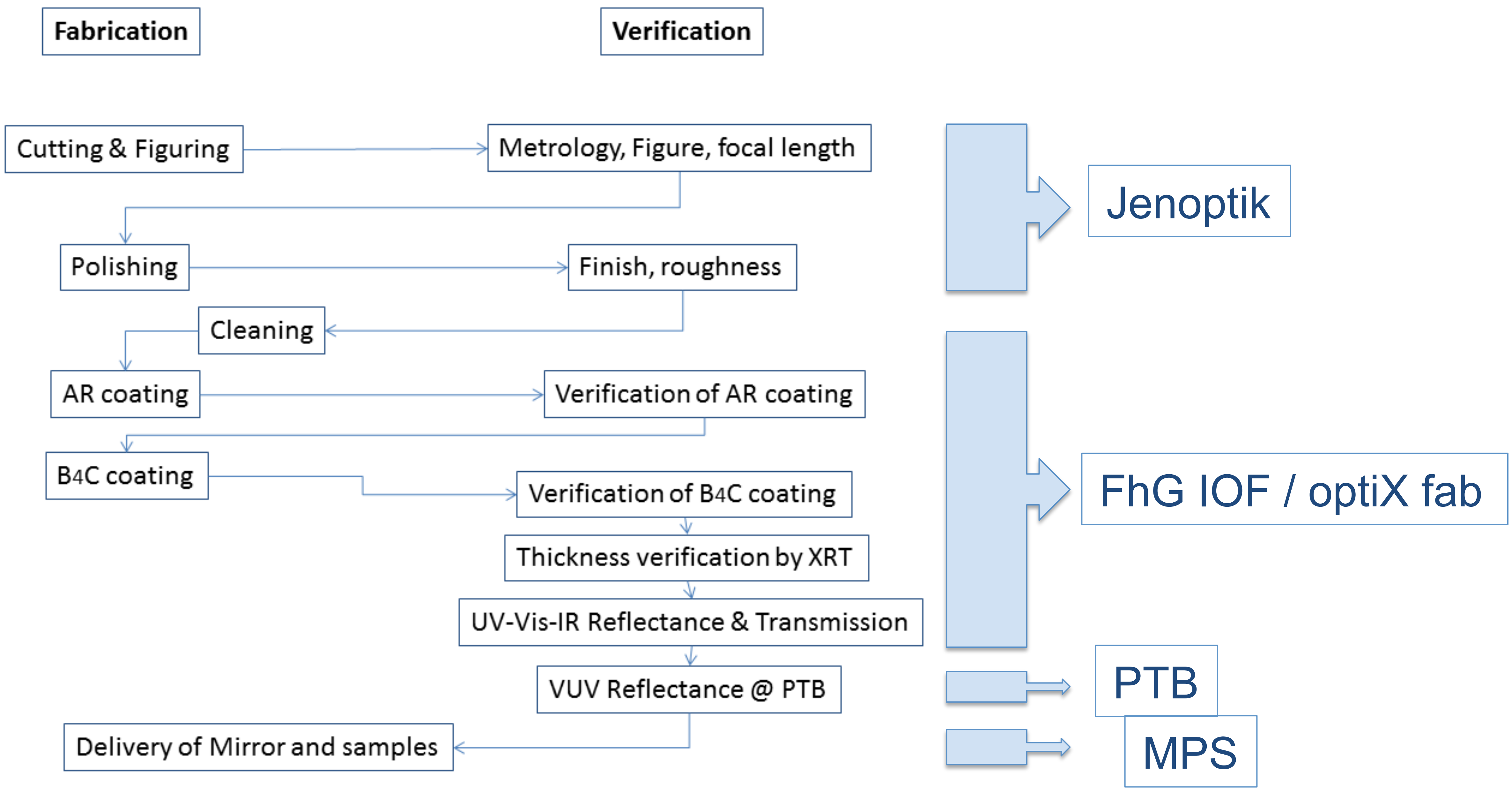
Zusammenarbeit zwischen MPS und Fraunhofer Institut für Angewandte Optik und Feinmechanik (FhG-IOF) und optiX fab GmbH

- Substratfertigung und Vermessung durch Jenoptik
- Optische Beschichtungen und Charackerisierung (XRD) optiXfab/FhG-IOF
- Rauhigkeitsmessungen (AFM) optiXfab/FhG-IOF
- Thermo-optische Eigenschaften (R,T,A) optiXfab/FhG-IOF
- Streulichtberechnungen optiXfab/FhG-IOF

Physikalisch-Technische Bundesanstalt (PTB)

- Metrology Light Source (MLS)
- VUV and EUV metrology

Spiegelfertigung und Verifikation

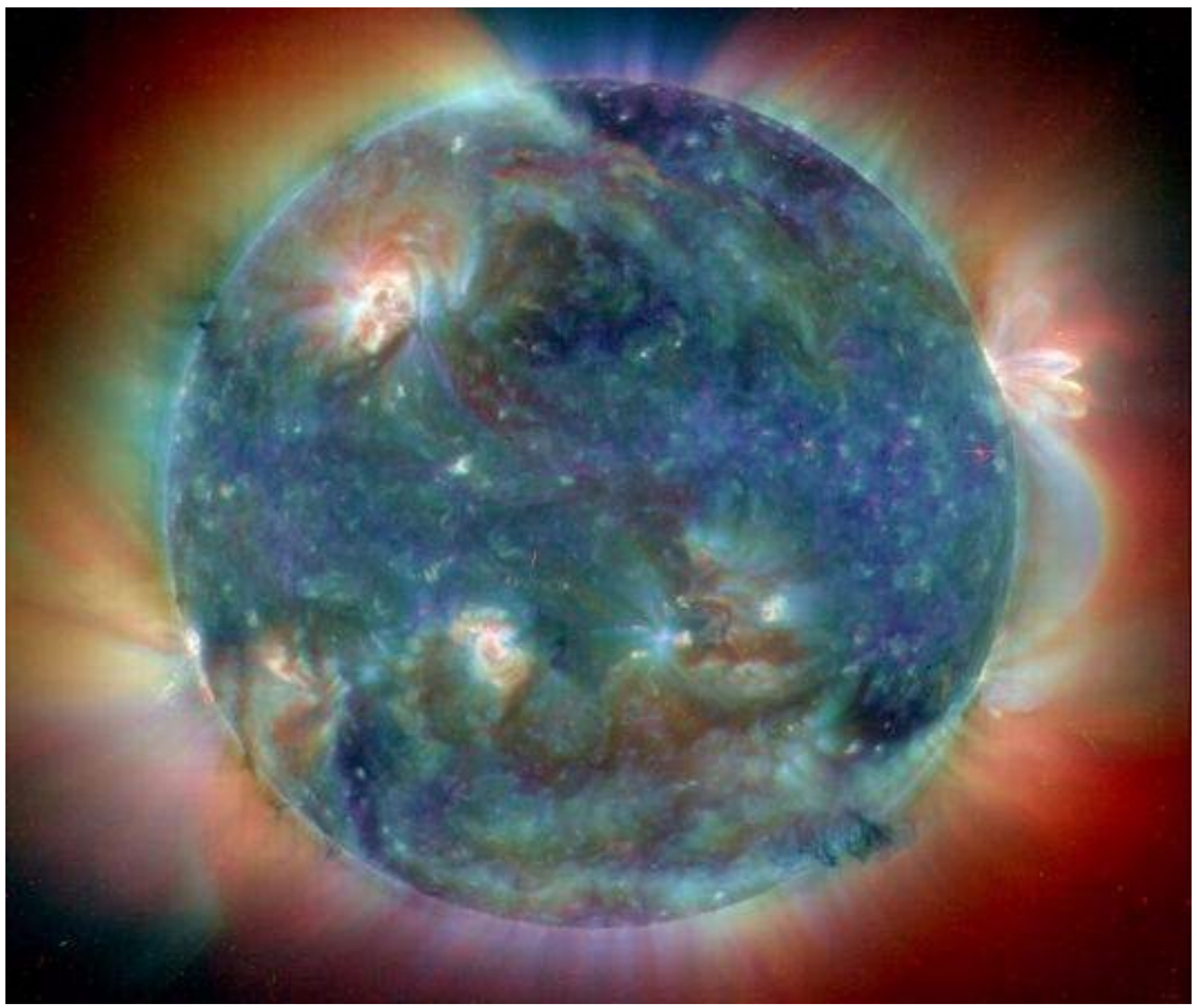


RAL Space
MPS
PTB
optiX fab.

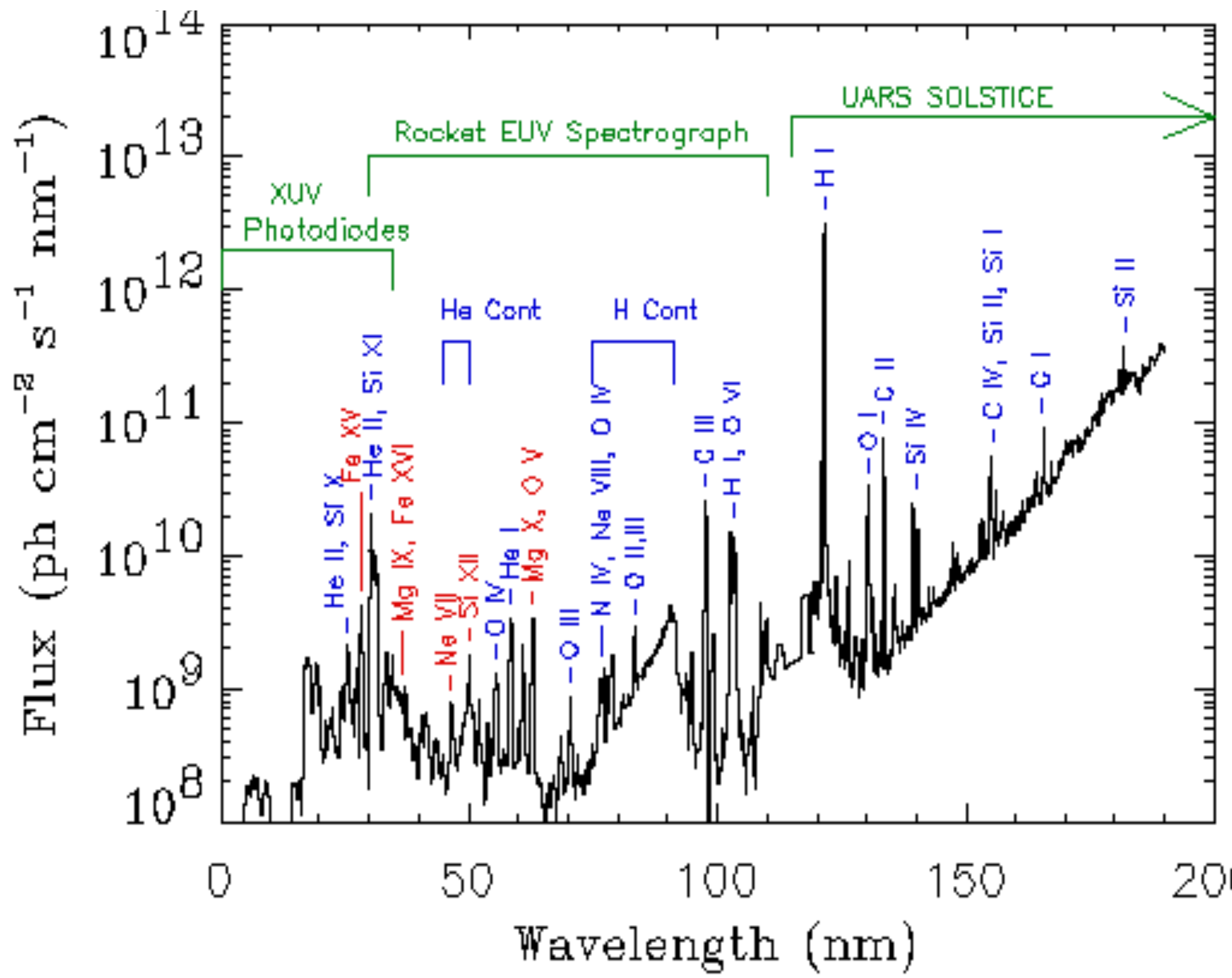
Zugabe:

VUV-Kameraentwicklung für Sonnenbeobachtung vom Weltraum

VUV-Detektoren für Sonnenobservation vom Weltraum



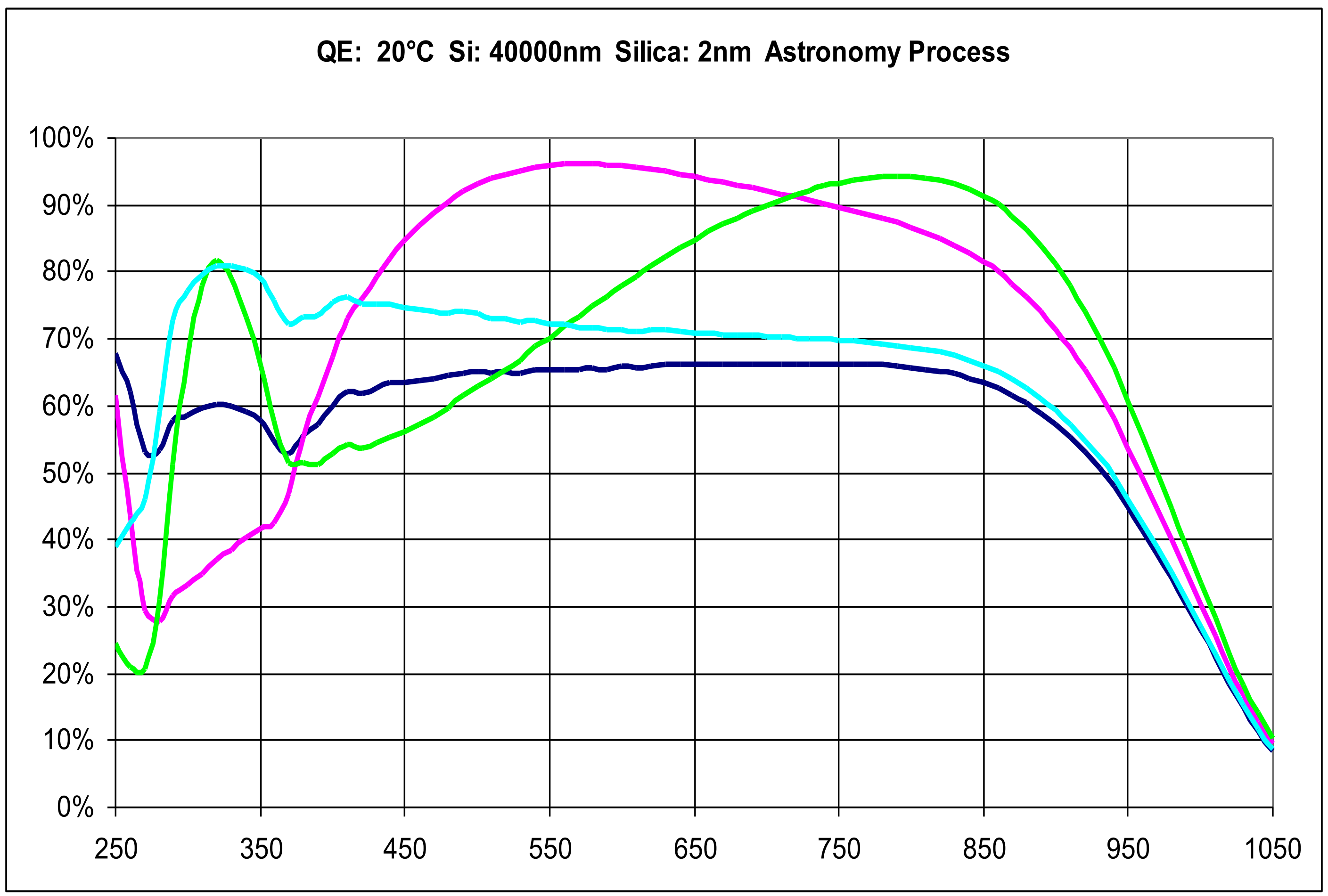
TRACE-image of the Sun in the EUV



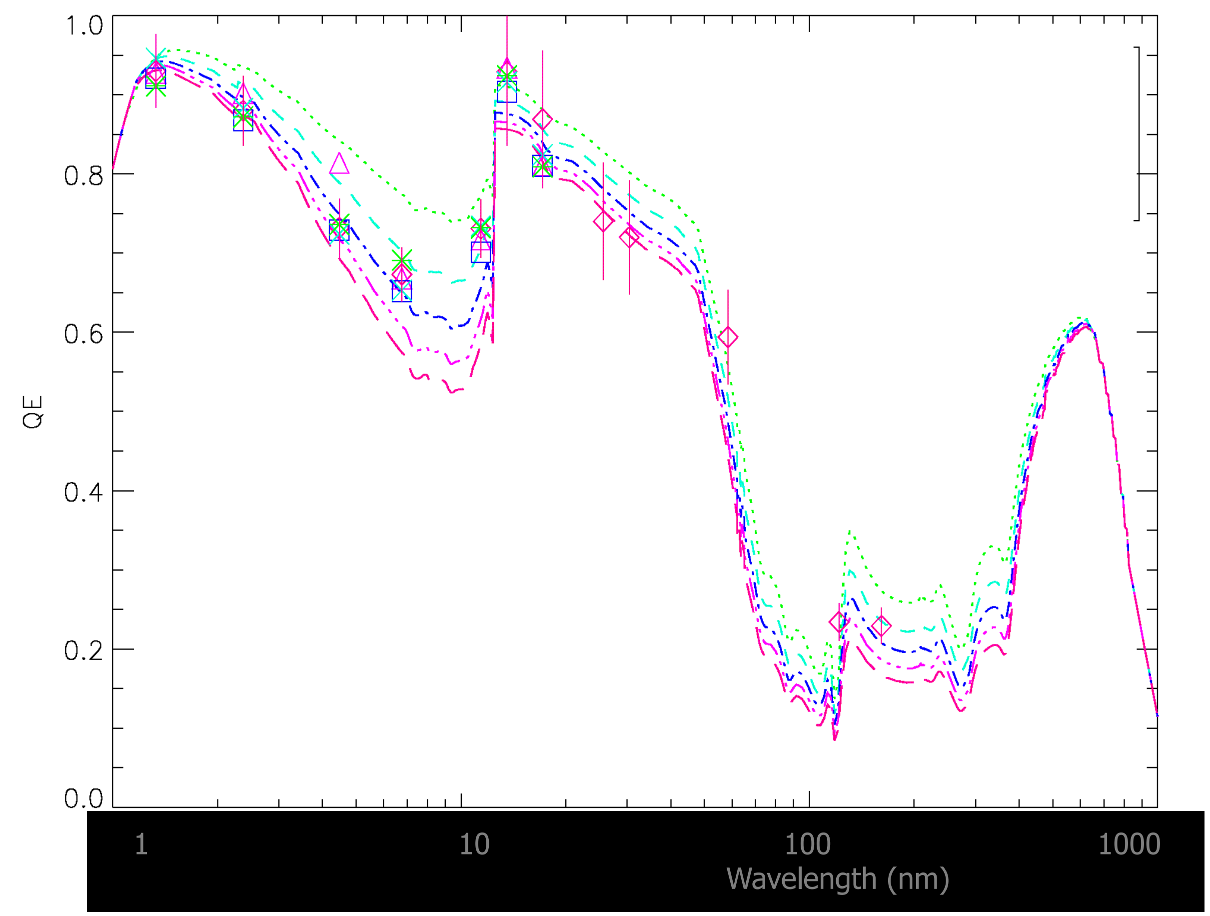
Emissionsspektrum der Sonne im VUV

Backside thinning of CCDs and APSs

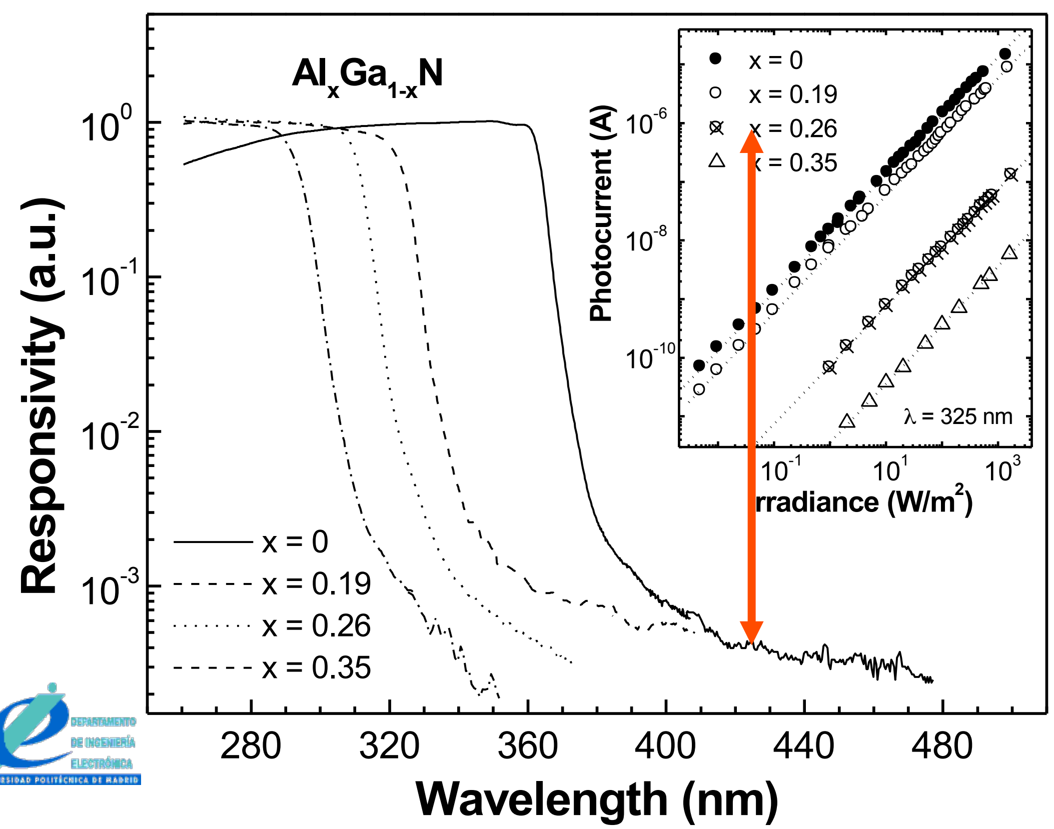
UV to NIR



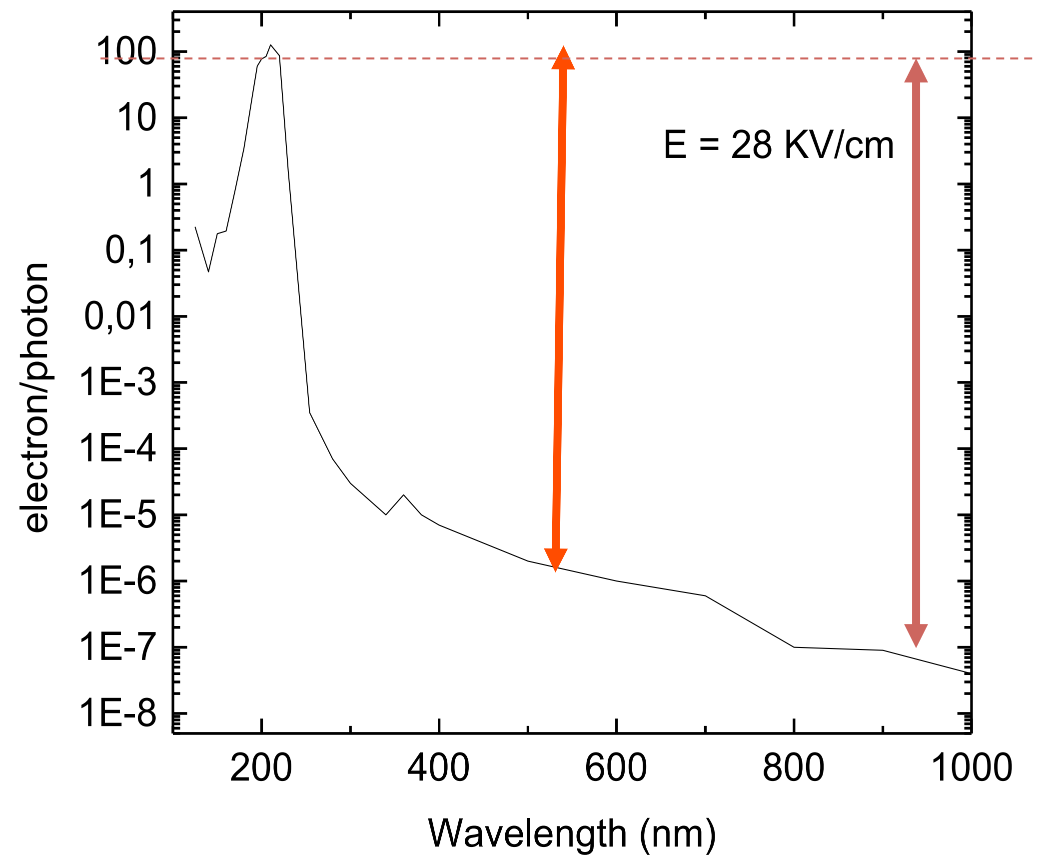
VUV to soft X-ray



Sensoren aus Material mit großer Bandlücke (wide band gap semiconductor sensors)



Pau *et al.* 2003. **Nitride**

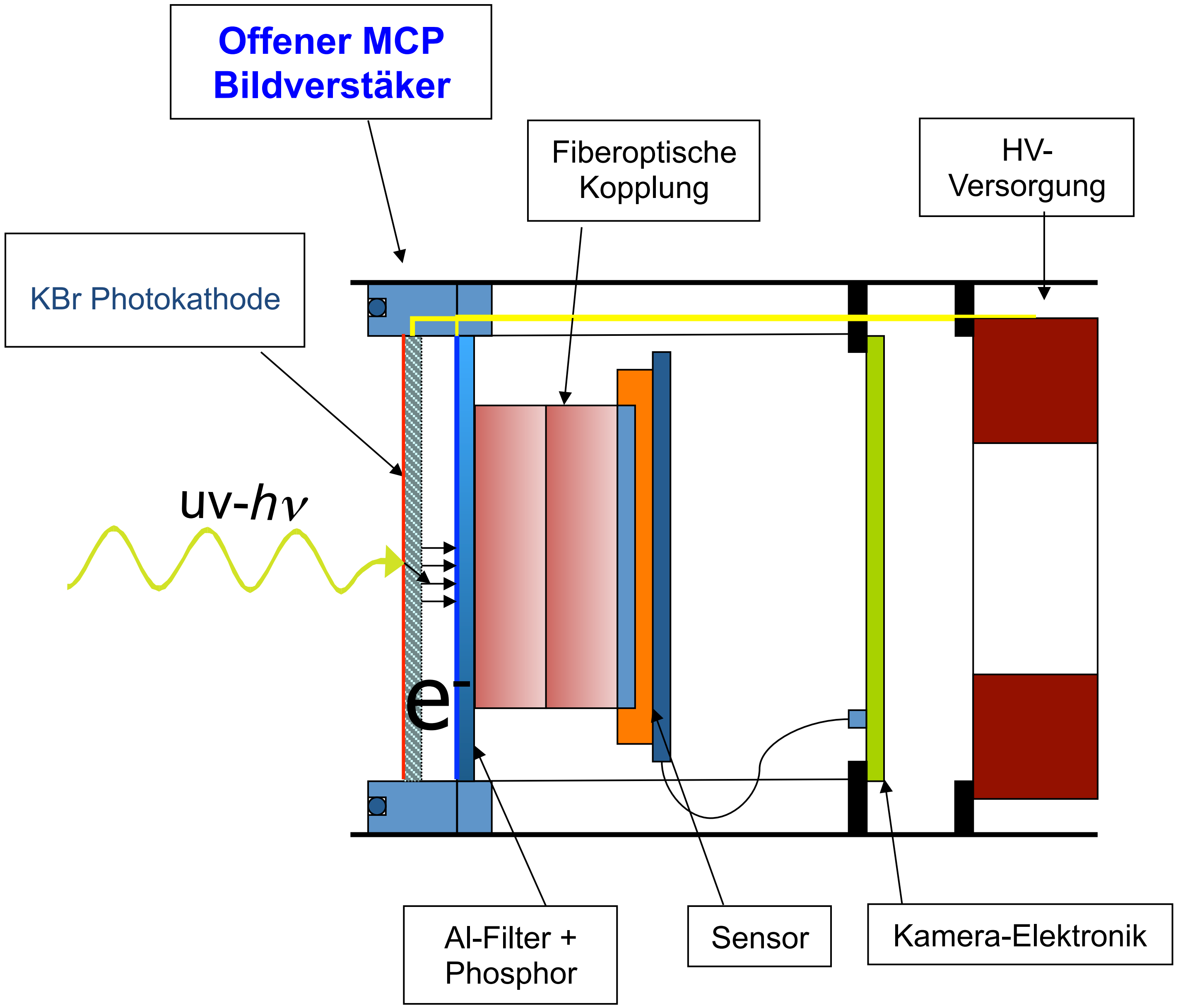


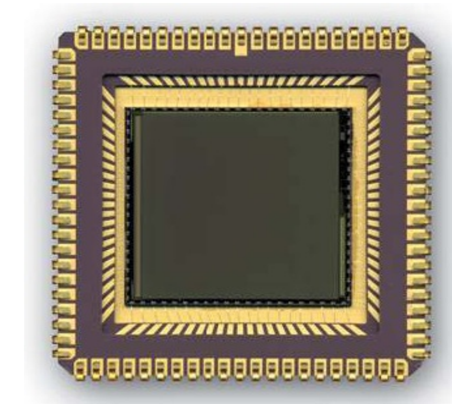
Diamond Pace *et al.* 2000.

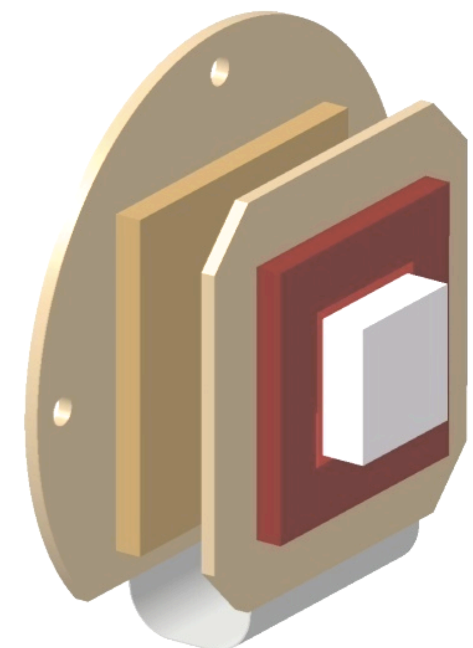
- ✓ blind im Sichtbaren
- ✓ geringer Dunkelstrom
- ✓ keine Kühlung erforderlich

Sichtbar-blinde Kamera mit Bildverstäker

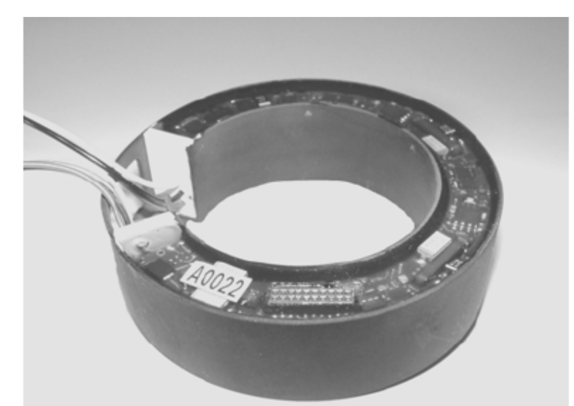
= MCP-Bildverstärker gekoppelt mit Bildsensor







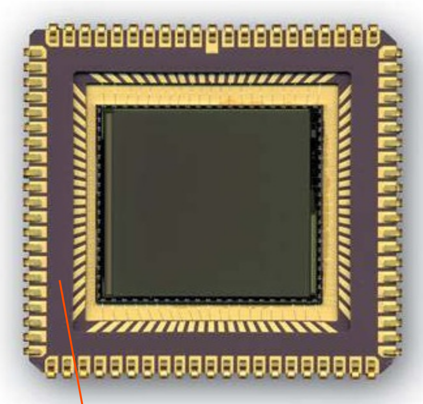
APS sensor array on PCB

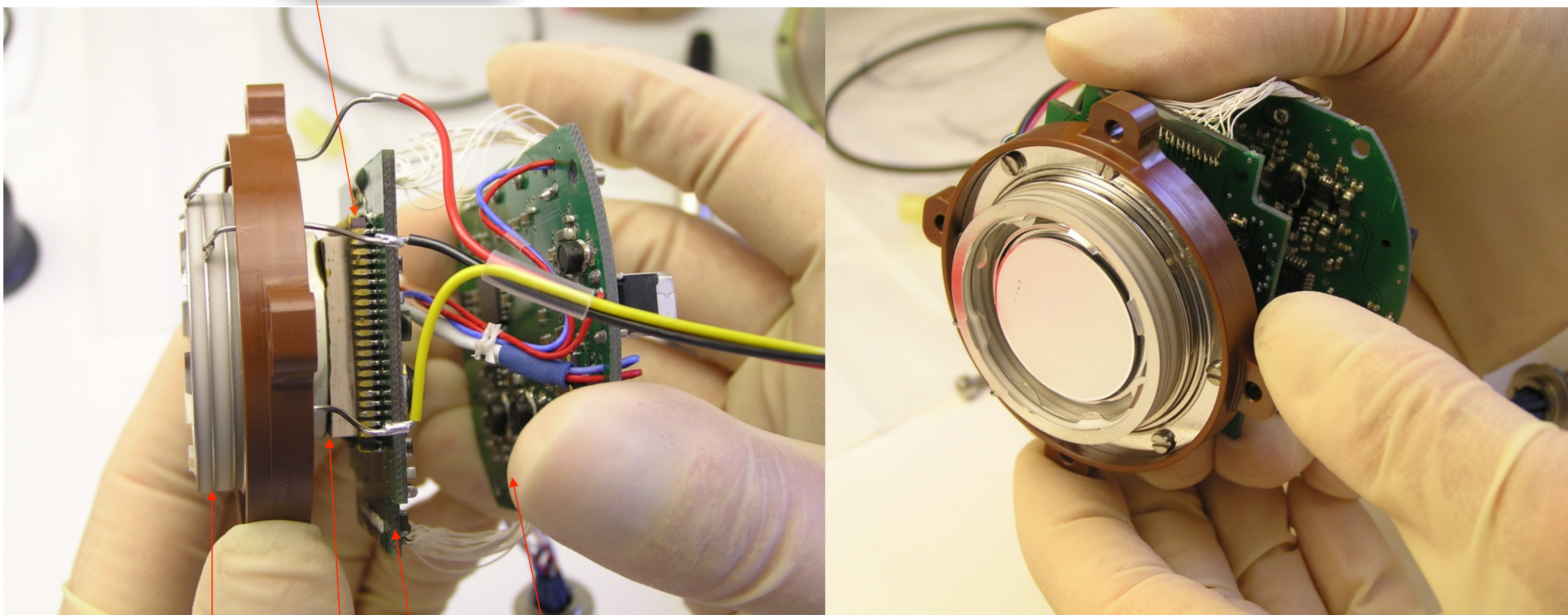


HV power supply

Offene Bildverstärker-Kamera

STAR 1000
visible CMOS-APS sensor





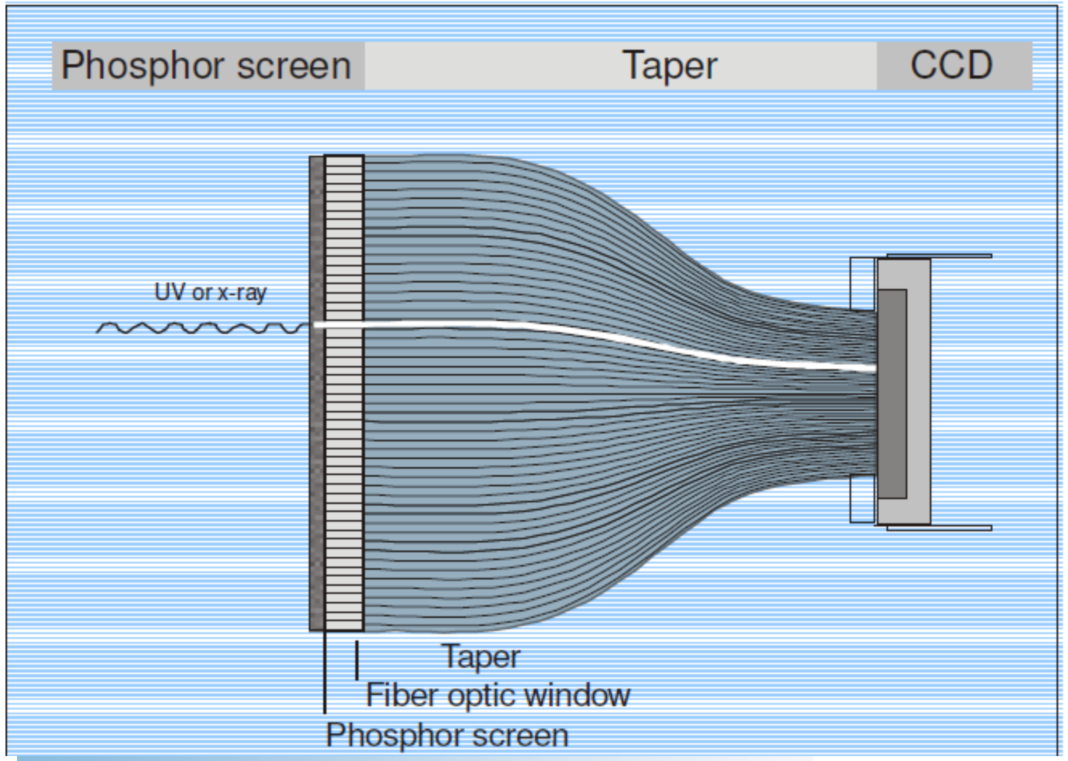
MCP stack

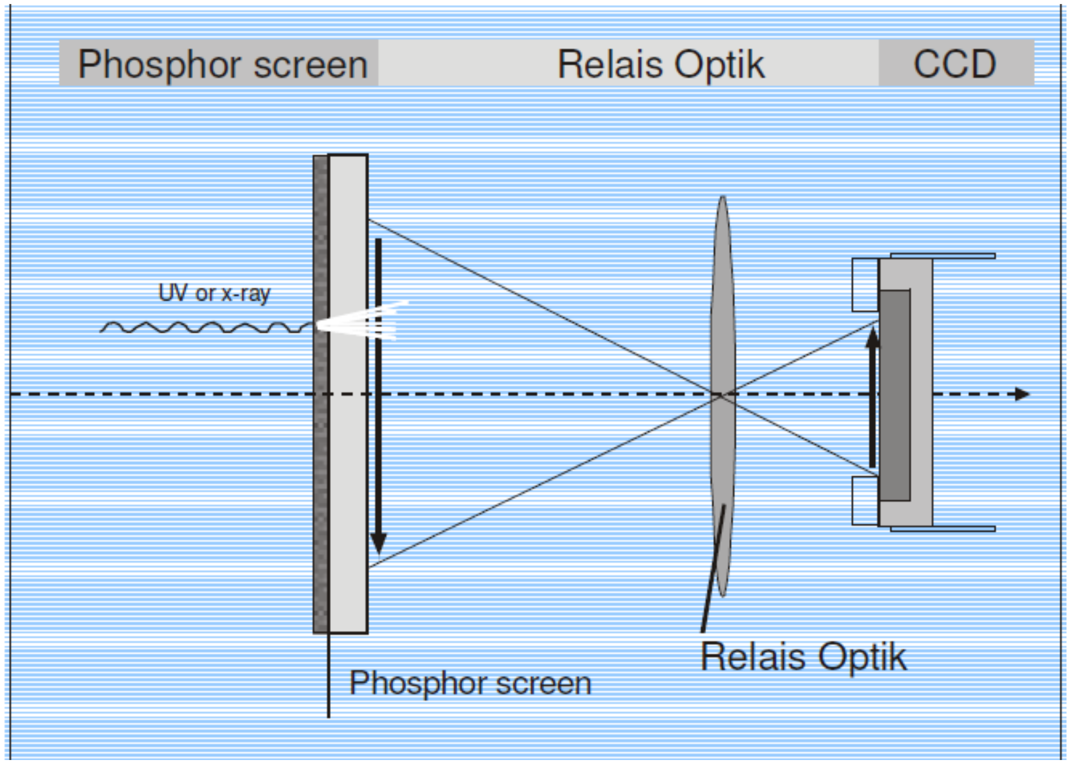
fiber optic blocks

APS sensor board

FEE board

Optische Kopplung



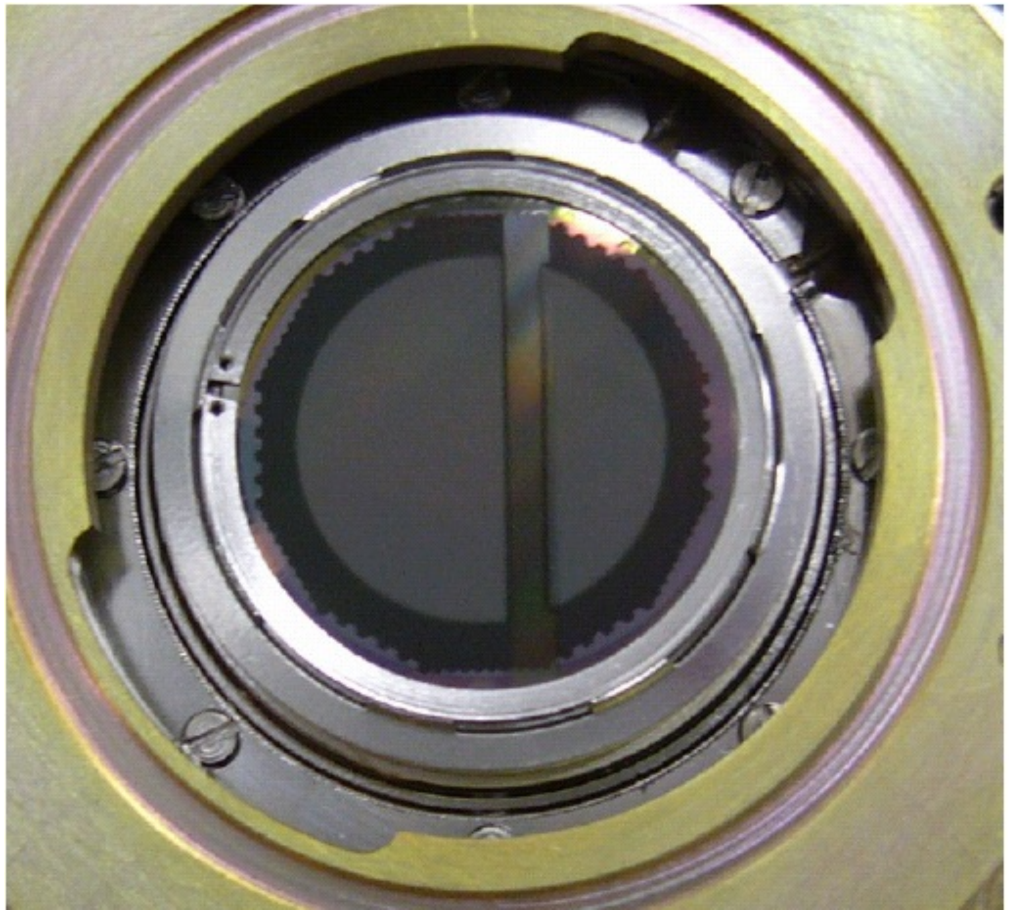


Bildverstärker kann an den Sensor angepasst werden

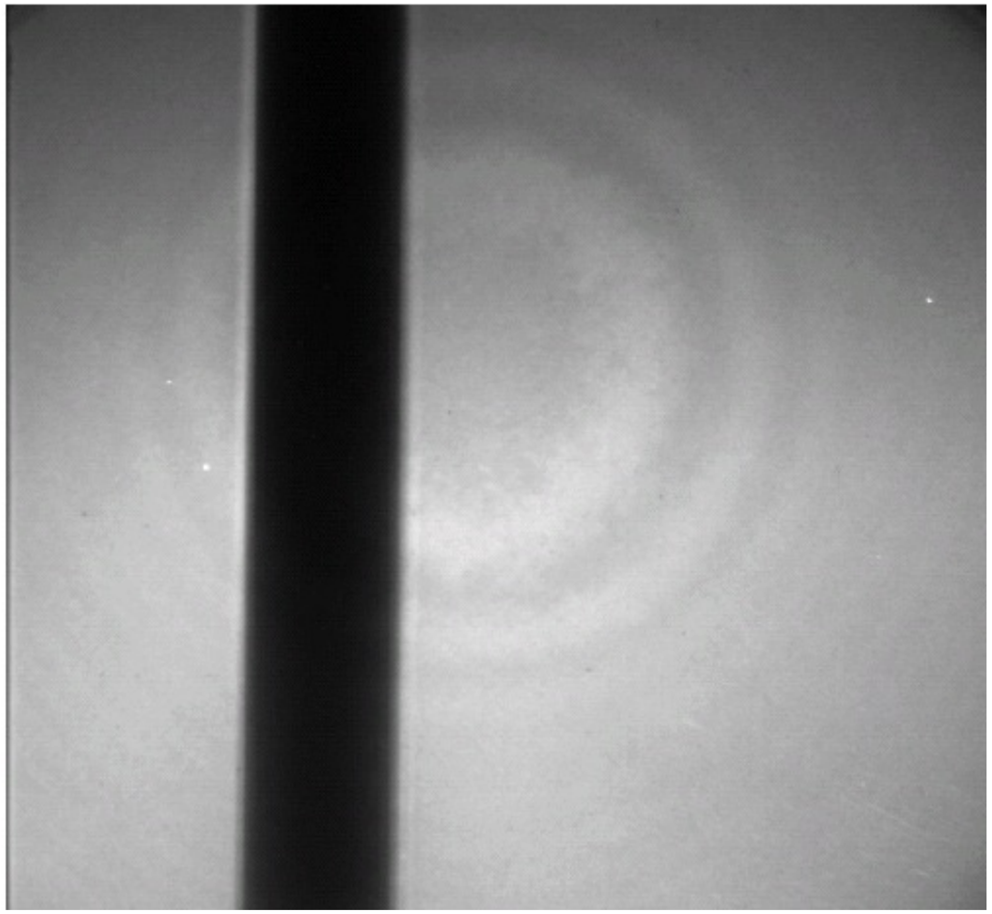
→ Bildfeldgröße ist wählbar unabhängig von der Sensorgröße!
→ Dynamikbereich kann angepasst werden (durch HV)
→ Photokathodenmaterial wählbar (sichtbar blind)

Selektive Photokathodenbeschichtung

Photokathode auf MCP-Vorderseite



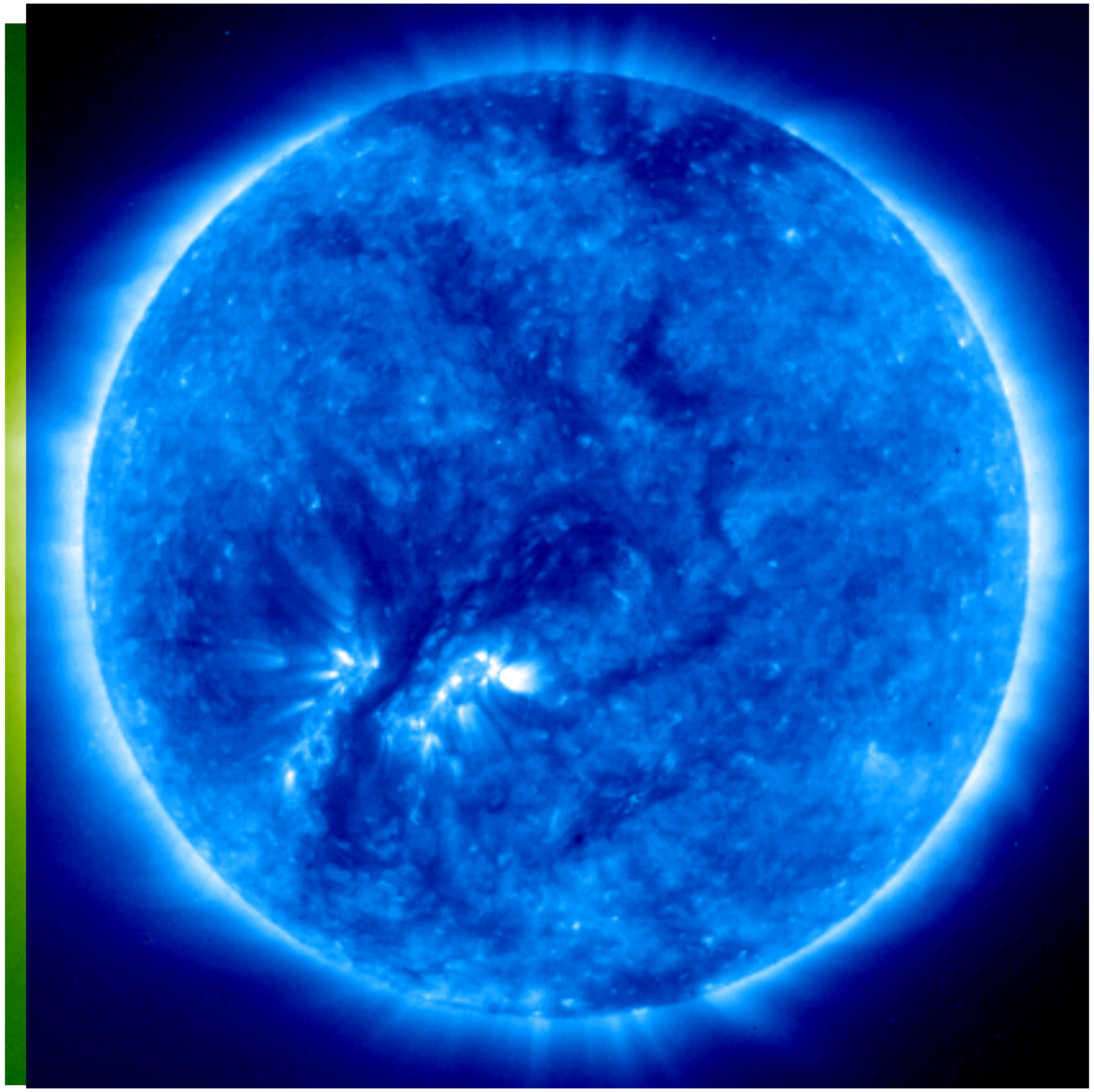
Testbild bei 121.6 nm



Beschichtung durch Verdampfen unter Vakuum

Die Sonne am 24. September 1996

Fe IX/X 17.2 nm
(SOHO/EIT)



H I Lyman-ε
(SOHO/SUMER)