Appendix P

Solar Simulator Testing and Correlation of PHI Heat Rejecting Entrance Window (HREW) of Solar Orbiter

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Abstract

The ESA mission Solar Orbiter will provide a look at the Sun closer than ever before. Among other instruments is the Polarimetric and Helioseismic Imager (PHI) lead by the Max Planck Institute for Solar System Reseach (MPS). PHI instrument will observe the Sun through the Heat Rejecting Entrance Window (HREW) which is an optical filter that has to be placed at the entrance of the instrument acting as a filter rejecting all the radiation coming from the Sun with the exception of a very narrow spectral band around 613.3nm where it is provided a 80% transmission.

A Thermal Balance Test of HREW filter and mounting frame has been held in December 2011 using the Solar Simulator facility of CISAS University of Padova to validate the values of the thermal parameters adopted for the thermal modeling of the HREW window in operative conditions. This paper describes the solar simulator test campaign and the thermal modeling performed in order to compare numerical and experimental results. A thermal mathematical model of the test-bed with all the thermal and mechanical interfaces has been added to the filter model in order to compare the experimental data with the results of the numerical models. Thermal model correlation allow to validate the HREW filter thermal mathematical model providing more reliable prediction of thermal behavior of rejecting window during Solar Orbiter mission.

Solar Simulator Testing and Correlation of PHI Heat Rejecting Entrance Window (HREW) of Solar Orbiter

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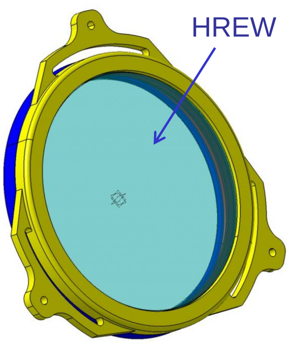
Introduction

The ESA mission Solar orbiter will investigate the Sun closer than ever before. Among other instruments is the **Polarimetric and Helioseismic Imager (PHI)** lead by the Max Planck Institute for Solar System Research (MPS) that will observe the Sun through the **Heat Rejection Entrance Window (HREW)** which is an optical filter that has to be placed at the entrance of the instrument.



A **Thermal Balance Test** of HREW filter and its mounting frame has been held in December 2011 using the **Solar Simulator** facility of CISAS "G.Colombo" University of Padova in order to validate the values of thermal parameters adopted for the thermal modeling of HREW filter

Thermal model **correlation** allow to validate the TMM of the HREW filter providing more reliable prediction of thermal behavior of rejecting window during Solar Orbiter mission

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Solar Simulator Testing and Correlation of HREW filter

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Overview

- Description of the HREW filter
- Test lay-out: Solar Simulator and TBT set-up
- TBT test campaign and results
- Modelling the HREW and TBT set-up
- HREW Thermal Model correlation
- Conclusions

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Description of HREW filter

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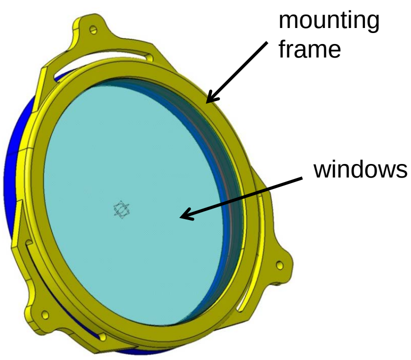
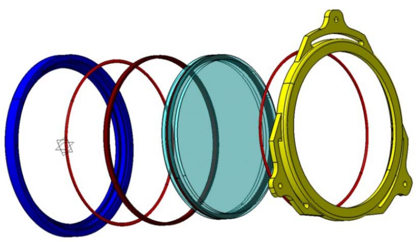
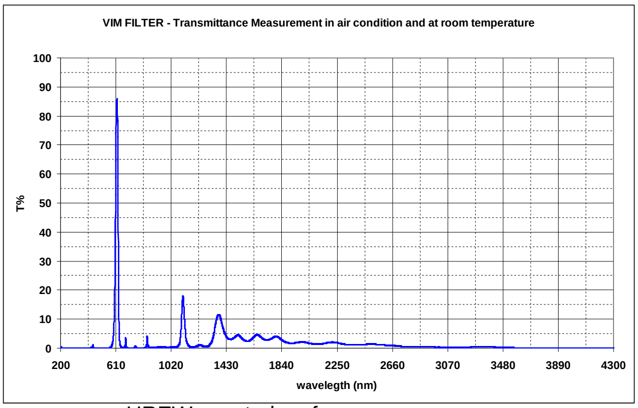




HREW filter exploded view

The Heat Rejection Entrance Window is on optical component that has to be placed at the entrance of PHI instrument acting as a filter rejecting the radiation in the range from 200nm to 5000nm with the exception of a very narrow band at 617,3nm where the transmission is more than the 80%.



HREW spectral performance

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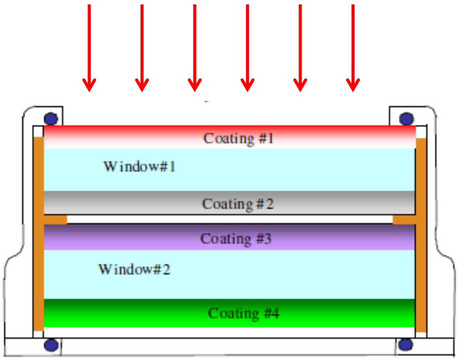
Description of HREW filter

The filter is composed by two quartz windows (diameter = 160 mm, thickness = 10mm) separated by a 3mm gap.

The optical performances are provided by 4 coatings on windows



The optical performances are provided by 4 coatings:

- **Coating #1**: UV Mirror to reflect the UV radiation down to 200 nm
- **Coating #2**: High-Pass Dichroic to define the cut on the band pass
- **Coating #3**: Low-Pass Dichroic to define the cut off on the band pass
- **Coating #4**: IR Shield to reflect the IR radiation up to 4300 nm

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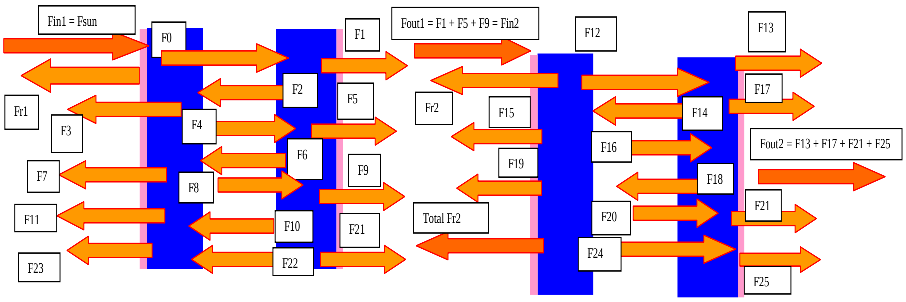
Thermal Model of HREW filter

How to model in ESATAN-TMS wavelength dependant optical surface ?



$$\alpha_i^{rel} = \frac{\sum_{\lambda=250nm}^{\lambda=2500nm} F_i(\lambda)\cdot A_i^{coating}(\lambda)}{\sum_{\lambda=250nm}^{\lambda=2500nm} F_i(\lambda)}; \quad \rho_i^{rel} = \frac{\sum_{\lambda=250nm}^{\lambda=2500nm} F_i(\lambda)\cdot R_i^{coating}(\lambda)}{\sum_{\lambda=250nm}^{\lambda=2500nm} F_i(\lambda)}; \quad \tau_i^{rel} = \frac{\sum_{\lambda=250nm}^{\lambda=2500nm} F_i(\lambda)\cdot T_i^{coating}(\lambda)}{\sum_{\lambda=250nm}^{\lambda=2500nm} F_i(\lambda)}$$

$A_i^{coating}(\lambda)$ absorbtivity

$R_i^{coating}(\lambda)$ reflectivity

$T_i^{coating}(\lambda)$ transmittance

$F_i(\lambda)$ Flux to the coating taking into account the multiple reflections (ASTM-E90 solar spectrum model)

For each single coating, the parameters in this case have been calculated considering the sum of all fluxes at each single wavelength, including fluxes coming from multiple reflections and averaging the thermo-optical properties to the Solar Spectrum (C.Damasio, ESA & Selex Galileo)

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TEST LAY-OUT: Solar Simulator and TBT set-up

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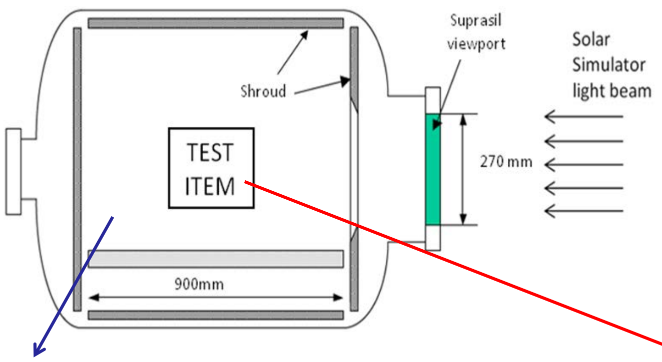
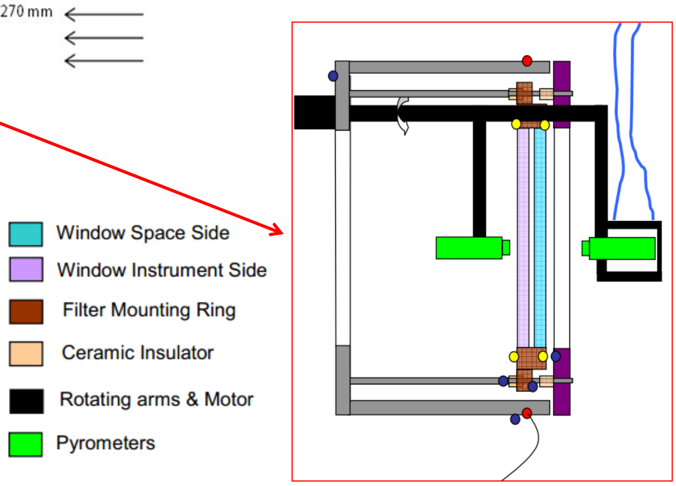


Thermal Vacuum Chamber
A stainless steel vessel AISI 304 with a volume of about 1.2 m³ (available room inside cryostat 0.8 m³)
Vacuum sub-system, controlled via a dedicated PLC, able to pump down to 10^{-4} Pa
Shroud subsystem, cooled with liquid N_2 at cryogenic temperature (90K)



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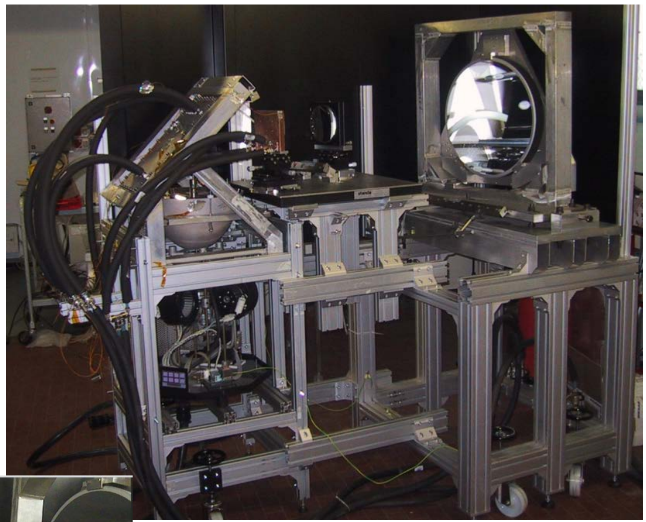
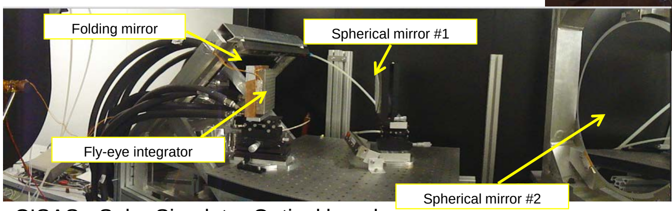
CISAS - Solar Simulator

Placed externally to the TVC, it produces a nearly–collimated (divergence < 30') steady beam with a homogeneous flux distribution (uniformity better than 10%) across an aperture of 300 mm diameter and allows to obtain an irradiance up to 6-7 SC.

The light beam is generated by a 10kW Xenon lamp placed in the focus of an ellipsoid mirror. The optical path is based on a series of multiple reflections onto thermally controlled mirrors to produce a collimated beam towards the TVC



CISAS - Solar Simulator lay-out



CISAS - Solar Simulator Optical bench

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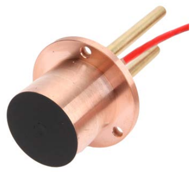
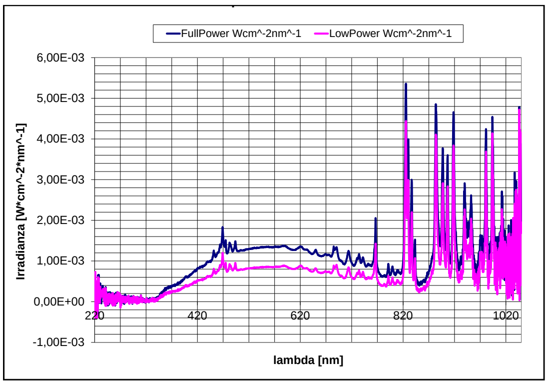
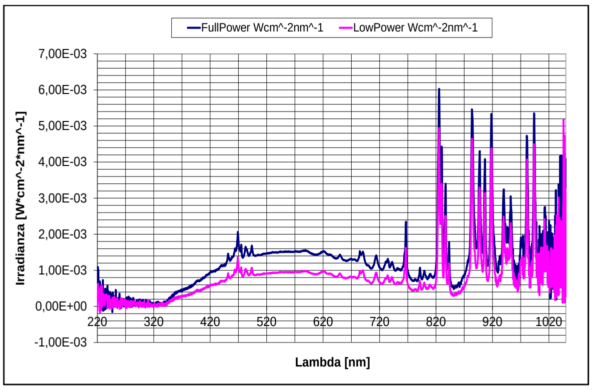
CISAS - Solar Simulator

Once aligned and correctly positioned with respect to the thermal vacuum chamber, the solar simulator has been characterized using a spectrometer (both outside and inside the thermal vacuum chamber) and a water cooled Gardon heat flux sensor
The maximum irradiance is of about 9-10 kW/m2





SS spectrum Inside Viewport : maximum and lowered power



SS spectrum Outside Viewport : maximum and lowered power

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HREW Thermal Balance Test set-up

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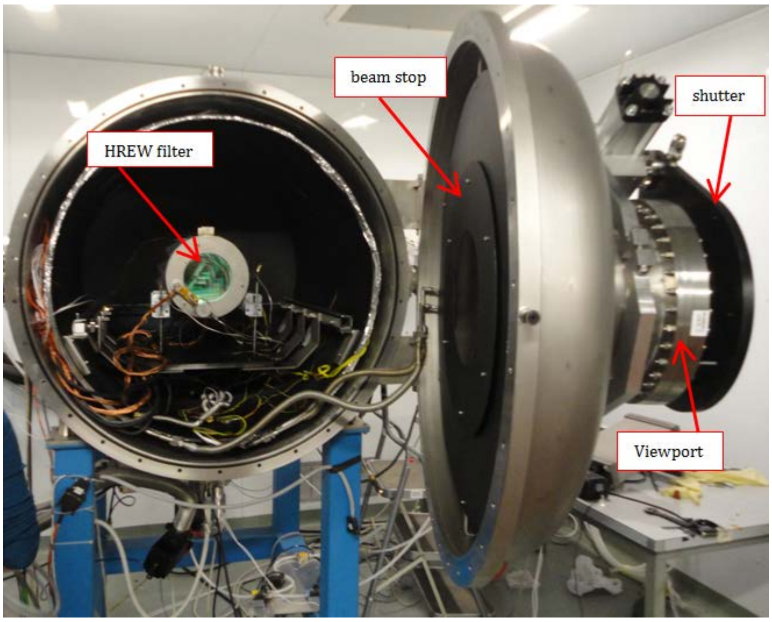

HREW filter inside TVC, diaphragm, viewport and external shutter

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HREW Thermal Balance Test set-up

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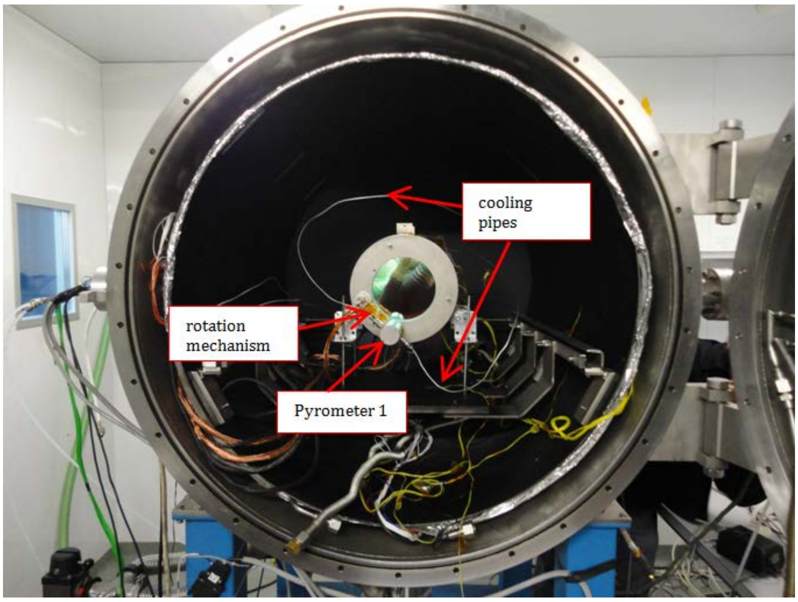
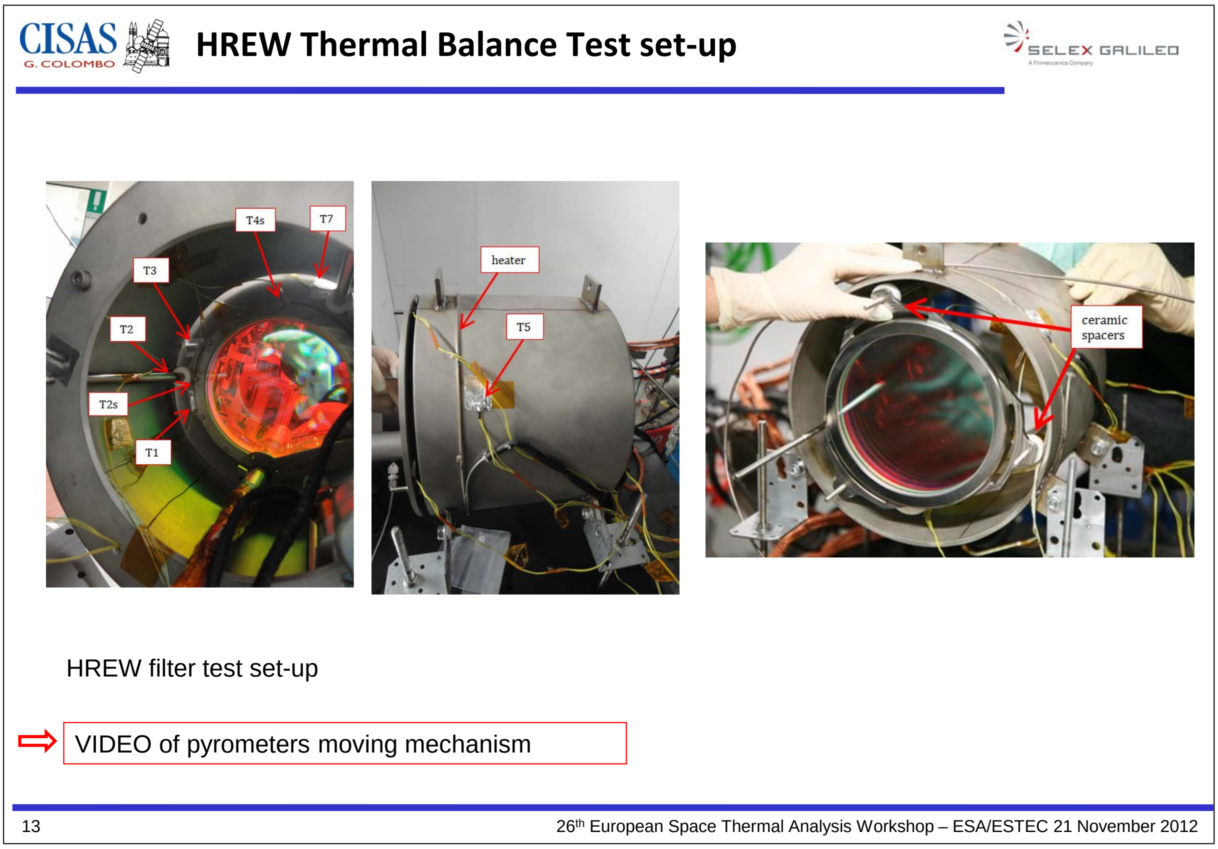
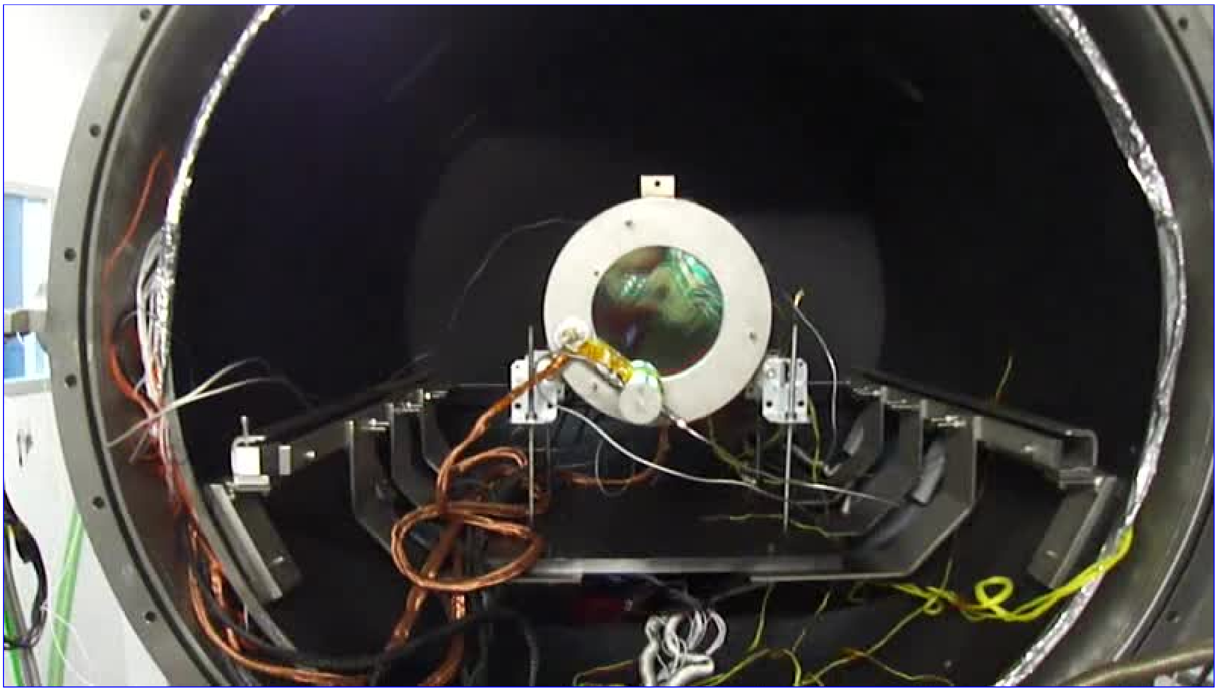


HREW filter inside TVC





If clicking on the picture above does not run the movie then try opening the file 'movies/Friso21Nov2012.html' manually.

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Solar Simulator Testing and Correlation of HREW filter

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TBT campaign and results

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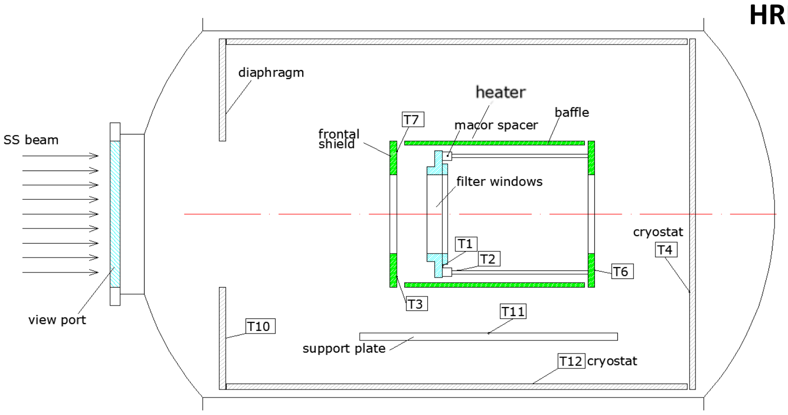

HREW Test campaign: test levels

Four Steady State conditions have been reproduced :

- **A**: SS @ maximum power, heater off
- **B**: SS @ maximum power, heater on
- **C**: SS @ lowered power, heater off
- **D**: SS @ lowered power, heater on

The steady state condition has been considered achieved when the rate of change of the temperature sensors was ≤ 3°C/h

SS case	ref. #	SS Lamp	heater	Description
A	1	I = Imax	OFF	1st measure with pyrometers
	2			2nd measure with pyrometers
B	3	I = Imax	ON	1st measure with pyrometers
	4			2nd measure with pyrometers
C	5	I < Imax	OFF	1st measure with pyrometers
	6			2nd measure with pyrometers
D	7	I < Imax	ON	1st measure with pyrometers
	8			2nd measure with pyrometers

For each case (**A** to **D**):
- Solar simulator switched ON
- wait for thermal stability at set-up sensors
- shutter closed (SS beam blinded)
- pyrometer mechanism ON and temperature acquired on HREW (coating #1 and #4)
- shutter opened and wait for steady state condition. Repeat HREW measurement

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Some test results: HREW windows temperature

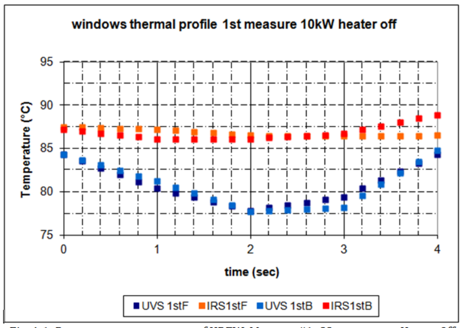

Fig. 4-1: Pyrometers measurement of HREW. Measure #1: SS max power, Heater Off

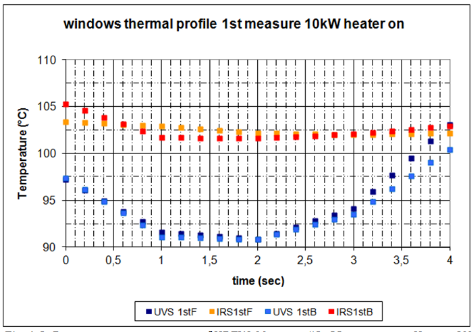

Fig. 4-3: Pyrometers measurement of HREW. Measure #3: SS max power, Heater ON

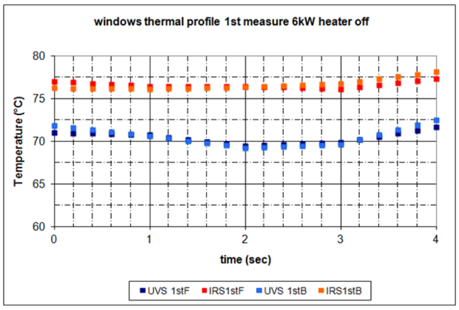

Fig. 4-5: Pyrometers measurement of HREW. Measure #5: SS low power, Heater OFF

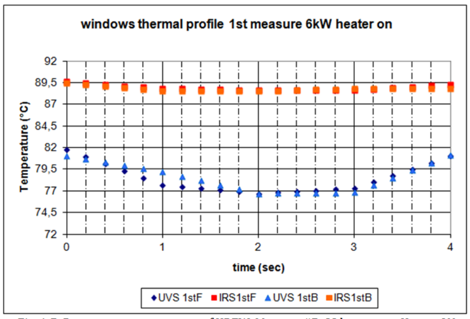

Fig. 4-7: Pyrometers measurement of HREW. Measure #7: SS low power, Heater ON

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Some test results: set-up temperature

Example: case A

Shutter closed.
HREW windows temperature acquired by pyrometers

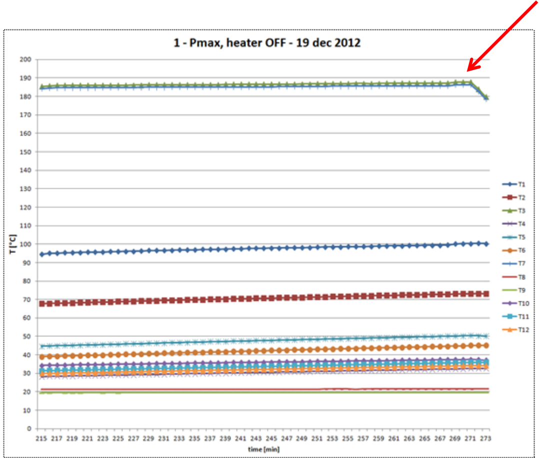

Figure 7: Lamp power = 10kW, I = Imax, heater OFF (tests of 19-dec-2011). 1st measure with pyrometers (#1)
The graph plots Pt100 temperatures 1 hour foregoing the pyrometer measurement

# 1	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Tmean	**99.6**	**72.7**	**187.1**	**32.2**	**50.0**	**44.6**	**185.6**	**21.5**	**19.6**	**37.2**	**35.5**	**33.8**
Tmin	99.0	72.3	184.0	31.8	49.4	44.0	182.7	21.5	19.5	37.0	35.0	33.4
Tmax	100.4	73.2	187.9	32.6	50.4	45.1	186.3	21.5	19.6	37.5	35.9	34.1

Table 2: Pt100 temperature (see Fig.5 , Fig. 6) computed on the set of data 10min foregoing the pyrometer measure

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Modelling the HREW and TBT set-up

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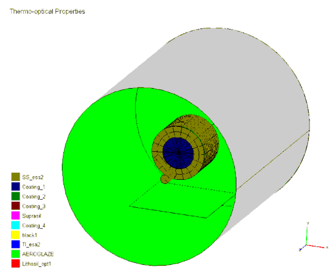
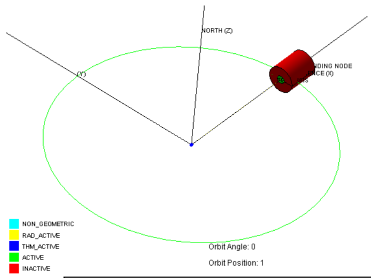
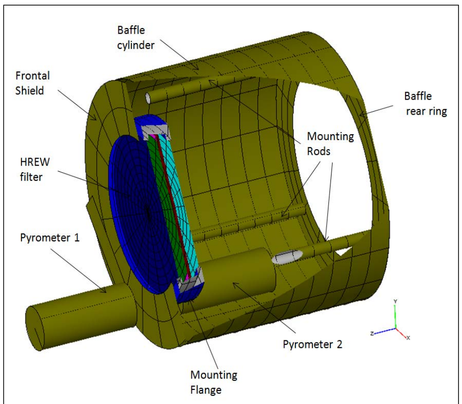
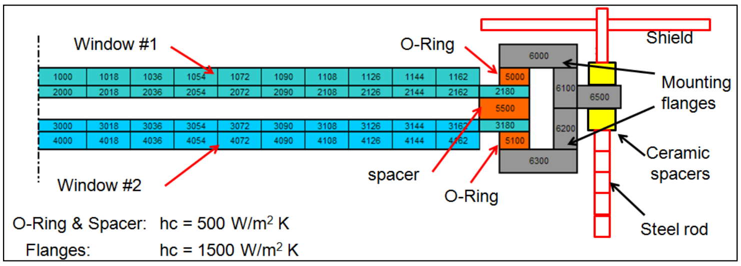




Sun centered orbit of the HREW testing in order to reproduce the light beam irradiance of the solar simulator facility

radiative case	q SS [W/m²]
Q5000	5000
Q10000	10000





The alpha and thermo-optical properties in the UV range have been re-calculated taking into account the SS lamp spectrum

Item	a_i^{rel}	t_i^{rel}	r_i^{rel}	ToT Rel
W1 -1	0,57%	81,95%	17,48%	100%
W1 -2	0,07%	73,88%	26,04%	100%
W2 -1	0,01%	43,83%	56,16%	100%
W2 -2	3,85%	10,32%	85,83%	100%

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Modelling the HREW and TBT set-up

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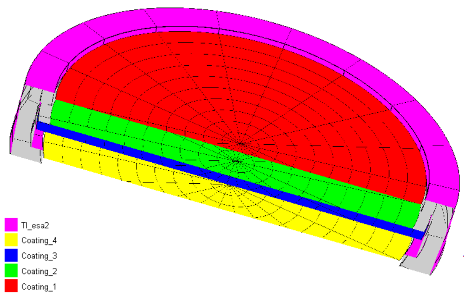
Thermo-optical properties of HREW test model

Name	Thermal Finish	ε_h	ρ_h^d	τ_h	α_s	ρ_s^d	τ_s	ρ_h^s	ρ_s^s
Window 1-1	UV shield (Coating_1)	0.86	0.000 (*)	0.0	0.0057	0.0	0.1748	0.140 (*)	0.8195
Window 1-2	High pass (Coating_2)	0.82	0.000 (*)	0.0	0.0007	0.0	0.2605	0.180 (*)	0.7388
Window 2-3	Low pass (Coating_3)	0.82	0.000 (*)	0.0	0.0001	0.0	0.5616	0.180 (*)	0.4383
Window 2-4	IR shield (Coating_4)	0.06	0.000 (*)	0.0	0.0385	0.0	0.8583	0.940 (*)	0.1032
Window 1-2 (edge)	Suprasil	0.90	0.0	0.0	0.05	0.0	0.5	0.1	0.45
Window 2-3 (edge)	Suprasil	0.90	0.0	0.0	0.05	0.0	0.5	0.1	0.45
Mounting flange Space side	Titanium (TI_esa2)	0.20	0.80	0.0	0.53	0.47	0.0	0.0	0.0
Mounting flange Instr. side	Titanium (TI_esa2)	0.20	0.80	0.0	0.53	0.47	0.0	0.0	0.0
Baffle cylinder	Stainless Steel (SS_esa2)	0.27	0.73	0.0	0.48	0.52	0.0	0.0	0.0



(*) All specular reflectivity in the IR range as baseline

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HREW thermal model correlation

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HREW thermal model correlation

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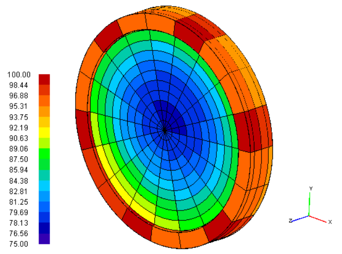
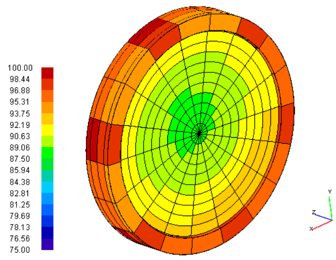
Boundary conditions/nodes used in thermal model correlation

Boundary Nodes	Name	Temp sensor	Analysis / Test case: MAX Power, heater OFF A (1,2) SB_Q10000	MAX Power, heater ON B (3,4) SBH_Q10000	Low Power, heater OFF C (5,6) LSB_Q5000	Low Power, heater ON D (7,8) LSBH_Q5000
B6500, B6600, B6700	Mounting Flange Blades	T1	100	116	88	101
B8126-B8143	Baffle HEATER	T5	52	93	51	91
B8300-B8353	Baffle rear ring	T6	47	72	48	69
B8409, B8509, B8609	Mounting Rods (IF nodes)	T2	75	97	68	88
B9000-B9035	Frontal Shield	(T3+T7)/2	187	193	157	161
B100100	Internal TVC Criostat cylinder	T12	36	52	38	49
B100200	Internal TVC Criostat end	T4	34	51	38	48
B100300	Internal TVC Criostat stop	T10	38	49	38	45
B200100	Internal TVC Base Plate	T11	38	56	42	54
B999999	Environment	T8, T9	20	20	20	20

Table 4-2: Boundary conditions used in TBT analysis



win 1-1 (UV shield) & mounting flange +Z
A: SS max power, Heater Off



win 2-4 (IR shield) & mounting flange -Z
A: SS max power, Heater Off

HREW windows as diffusive nodes and compared with temperatures acquired by pyrometers

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HREW thermal model correlation

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A comparison between the temperature range of HREW window obtained durign test campaign and the results of thermal model are summarized in Table

A	**model** [°C] SB_Q10000		**test** [°C] A - measure #1		**ΔT** [°C] # 1		**test** [°C] A - measure #2		**ΔT** [°C] # 2	
	periphery (*)	*center (**)*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*
UV shield (ext.)	87	78	84	78	3	<1	86	80	1	-2
IR shield (ext.)	92	89	87	86	5	3	91	90	1	-1
B	**model** [°C] SBH_Q10000		**test** [°C] B - measure #3		**ΔT** [°C] # 3		**test** [°C] B - measure #4		**ΔT** [°C] # 4	
	periphery (*)	*center (**)*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*
UV shield (ext.)	100	90	99	91	1	-1	98	91	2	-1
IR shield (ext.)	106	102	105	102	1	<1	-	-	-	-
C	**model** [°C] LSB_Q5000		**test** [°C] C - measure #5		**ΔT** [°C] # 5		**test** [°C] C - measure #6		**ΔT** [°C] # 6	
	periphery (*)	*center (**)*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*
UV shield (ext.)	75	68	72	69	3	-1	76	70	-1	-2
IR shield (ext.)	79	76	77	76	2	<1	80	79	-2	-3
D	**model** [°C] LSBH_Q5000		**test** [°C] D - measure #7		**ΔT** [°C] # 7		**test** [°C] D - measure #8		**ΔT** [°C] # 8	
	periphery (*)	*center (**)*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*	*periphery*	*center*
UV shield (ext.)	85	77	82	77	3	<1	82	77	3	<1
IR shield (ext.)	91	87	91	90	<1	-3	91	90	<1	-3

ΔT between experimental and numerical results is ≤ 3°C

Temperature range: periphery-center of the window:
(*) mean value of periphery rings nodes of the window
(**) mean value of center nodes of the window

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Solar Simulator Testing and Correlation of HREW filter

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Conclusions

- HREW filter has been tested using a Solar Simulator facility giving an experimental insight of the filter thermal behavior
- Thermal Model of the filter has been correlated to experimental results and the assumptions made on thermal propertied has been validated
- The updated HREW model provided more reliable prediction of thermal behaviour of rejecting windows during Solar Orbiter mission
- Wavelength dependant properties implementation on ESATAN-TMS would be a great advantage for modelling this kind of devices

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THANK YOU

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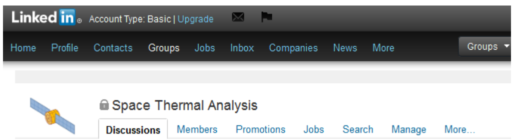

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