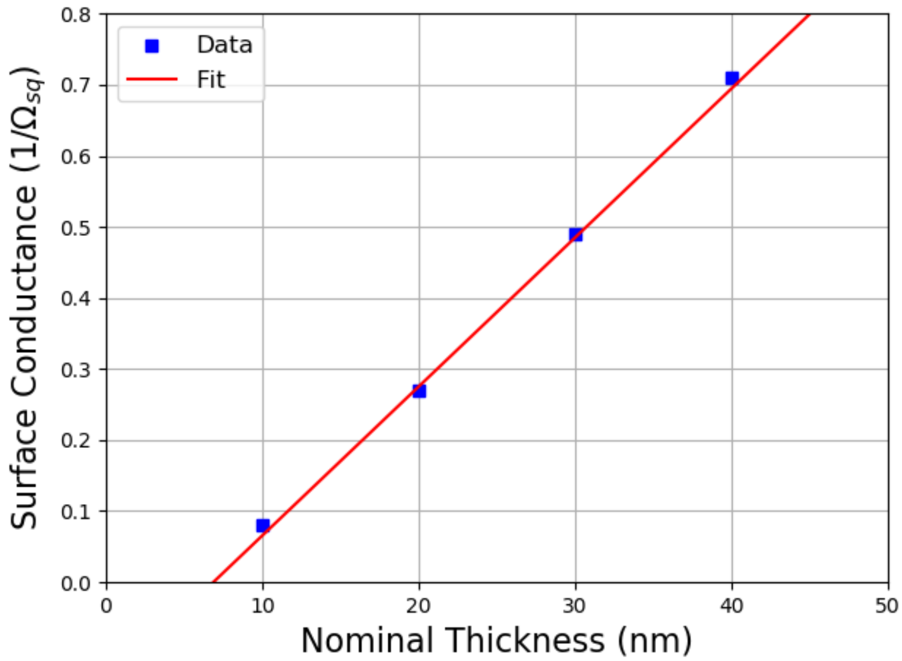


Fig. 48 - Surface conductance as a function of nominal thickness of the aluminum. The red line represents the model fit and the blue squares the experimental data.

Measurements done on aluminum coated filters showed an attenuation increasing with the frequency and the thickness of the coating (fig. 48). The measurements performed on the two filters with 30 nm and 40 nm of aluminum are very similar, showing that there is not a significant gain in attenuation for aluminum thickness larger than about 30 nm. The plot also shows the open reference attenuation (measurement performed without filters) and the closed configuration (a 3 mm thick aluminum disc placed in the filter holder). The response of the filter with no coating (red curve in figure 49) is almost identical to the open reference (black line), indicating that the substrate is transparent to the RF. The top profile of the gray area is obtained by adding the open reference attenuation to the required 30 dB attenuation, therefore a curve within the grey area satisfies the attenuation requirement.

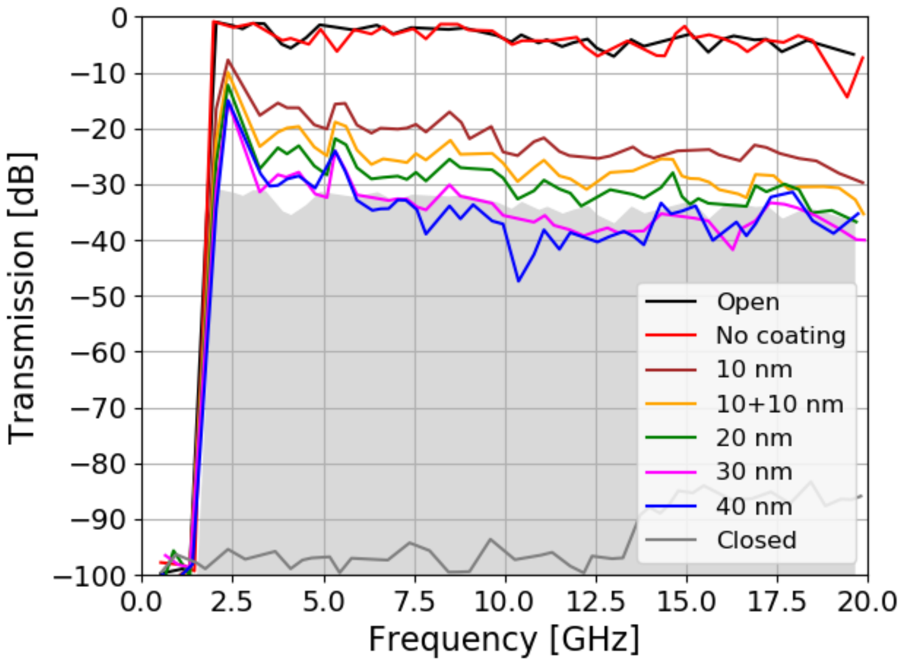


Fig. 49 - SE of thin Al films with different thickness. "Open" and "Closed" curves show measurements without filters and with a thick Al disk, as references. "No coating" refers to the plastic substrate alone. The gray area displays where the requirement is met.

The measurement performed on the mesh showed a higher attenuation at low frequencies (< 7 GHz) (red curve in figure 50). The attenuation measured at higher frequencies is mainly due to the reduction in diameter from 100 mm of the open configuration (black line in figure 50) to 56 mm diameter of the copper mesh (red line in figure 50) and likely not due to the mesh itself. Coupling the two kinds of filters together, there is a compensation of the different behaviors, improving the overall performance. The gray area in the plots shows where the requirement is satisfied, as in figure 49. SE of the copper mesh combined with different Al films, along with references (as in figure 49), in red the SE of the mesh alone and in gray the area where the requirement is met.

Effective SE is obtained by subtracting the open reference attenuation to that of the filter. Minimum attenuations obtained in 400 MHz bands, centered at the specified frequencies, are shown in table 28. The reports both attenuations of the aluminum filters alone and the combinations of those filters with the mesh.

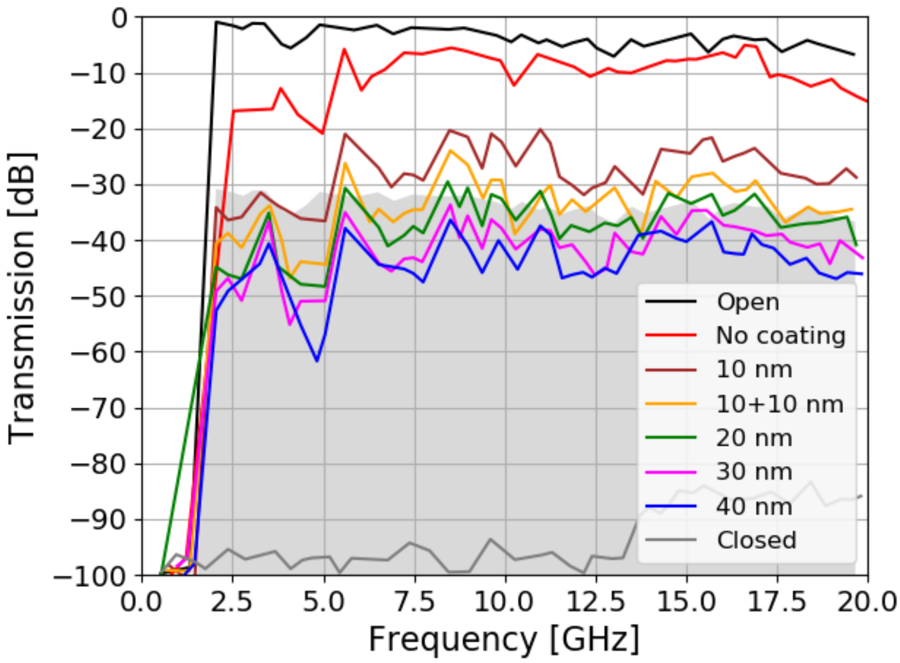


Fig. 50 - SE of the copper mesh combined with different Al films, along with references (as in figure 49). In red the SE of the mesh alone. In gray the area where the requirement is met.

Table 28: Attenuation values obtained for Al filters alone and for the combination of aluminum filter and mesh at different frequencies.

Attenuation (dB)								
Frequency (GHz)	**2.4**		**6**		**10**		**18**	
Al coating (nm)	**No mesh**	**mesh**	**No mesh**	**mesh**	**No mesh**	**mesh**	**No mesh**	**mesh**
0	0	15	0	11	0	4	0	6
10	6	35	17	31	21	19	21	25
10+10	8	37	22	37	23	26	26	30
20	11	45	25	41	25	29	26	33
30	14	45	30	43	32	34	30	36
40	13	48	31	45	34	37	27	39

In conclusion, the mesh exhibits a good attenuation below 7 GHz and the aluminum filters perform better at higher frequencies. The combination of the mesh coupled with the aluminum filters showed a compensation of the two opposite behaviors, providing a good attenuation in the whole frequency range of interest. In particular, coupling the mesh with a 30 nm thick aluminum filter, the measured RF attenuation is higher than 30 dB and thus compatible with requirements.

10. Vibro-Acoustic Tests

Vibro-acoustic tests are performed to validate predicted performances from dynamic load structural analysis, demonstrate mechanical robustness of manufactured representative filter samples, and optimize the filter, mesh, and frame design.

10.1 Vibration Tests

Assessments of filter interface load levels at launch have still to be finalized. Nevertheless, we report hereafter reference values, used in mechanical vibration and shock tests carried out so far in compliance to the requirements specified in the Statement of Work (Appendix 1 to ITT AO/1-8786 /16/NL/BJ). Table 29 reports the sine (0-peak amplitude level) and random vibration (Power Spectral Density) test reference spectra. Shock response spectrum having 400 g plateau between 1000 and 3000 Hz, with the ramp defined by 20 g at 100 Hz has been used for tests.

Table 29: Sine, random, and shock vibration qualification levels.

SINE (Sweep rate: 2 Oct/min)

Frequency	**Level**
(5-23) Hz	11.7 mm (0-peak)
(23 -100) Hz	25.0 g (0-peak)

RANDOM (16.9g RMS, Duration: 150 s)

f1 [Hz]	f2 [Hz]	PSD
20	100	+3.00 dB/oct
100	300	0.5 g^2/Hz
300	2000	-5.00 dB/oct

SHOCK (Q = 10)

Frequency (Hz)	SRS (g)
100	20
1000	400
3000	400

November 2017 Test Campaign

Sine, random, and shock vibration tests have been carried out using the shaker model UD T-1000 at the Max-Planck-Institut fuer extraterrestrische Physik on November 6-11, 2017. Both out of plane and in-plane tests have been carried out on different samples of Si_3N_4 membranes bare or coated with Al, unsupported or supported by Si mesh (see table 30).

Table 30: List of filter samples tested at MPE.

Sample #	Mesh Parameters		Film Thicknesses		Frame type
	Open Area (%)	Thickness (μm)	Si_3N_4 (nm)	Al (nm)	
1	80	3	40	20	TO8
2	88	15	145	20	TO8
3	93	3	40	20	TO8
4	98	3	40	20	TO8
5	80	15	40	20	TO8
6	88	15	40	20	TO8
7	93	15	40	20	TO8
8	98	15	40	20	TO8
9	100	0	40	20	TO8
10	93	15	145	20	TO8
11	98	15	145	20	TO8
12	100	0	145	20	TO8
M1	81	15	40	0	TF112
M2	88	15	40	0	TF112
M3	88	30	40	0	TF112
M4	93	30	40	0	TF112

Figure 51 shows a picture of all the tested samples mounted on the interface plate that is attached to the shaker plate. Together with HS-FOILS Si_3N_4 samples, we have tested also a single quadrant WFI LDA OBF (polyimide 150 nm + aluminum 30 nm supported by a Au plated SS mesh) manufactured by LUXEL, which arrived in Palermo partially damaged with the polyimide film broken in two cells. The goal of testing this sample was to verify that a damage localized inside a cell did not propagate during vibration tests. All vibration tests were performed with filters in atmospheric pressure.

Before performing the qualification level tests according to table 29, lower level tests have been performed, both sine and random, namely levels S1/R1 and S2/R2 as shown in table 31.

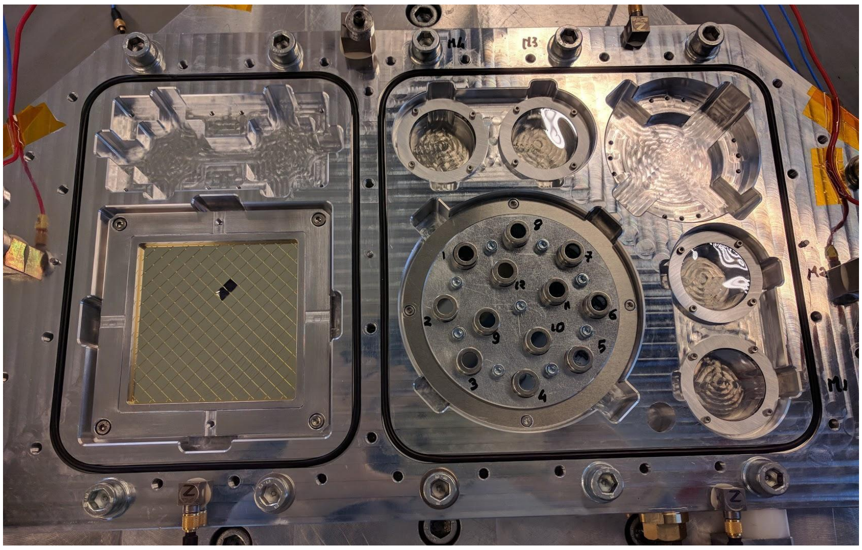


Fig. 51 - Picture of all tested HS-FOILS samples mounted on the interface plate together with a single quadrant WFI LDA OBF manufactured by LUXEL.

Table 31: Sine and random vibration lower test levels.

Sine load level S1 (Sweep rate: 4 Oct/min)

Frequency	Level
(5-20) Hz	3.88 mm (0-peak)
(20-100) Hz	6.25 g (0-peak)

Random Vibration level R1 (6.08g RMS, Duration: 30 s)

f1 [Hz]	f2 [Hz]	PSD
20	100	+3.00 dB/oct
100	300	0.0625 g^2/Hz
300	2000	-5.00 dB/oct

Sine load level S2 (Sweep rate: 4 Oct/min)

Frequency	Level
(5-20) Hz	7.0 mm (0-peak)
(20-100) Hz	12.5 g (0-peak)

Random Vibration level R2 (8.6g RMS, Duration: 30 s)

f1 [Hz]	f2 [Hz]	PSD
20	100	+3.00 dB/oct
100	300	0.125 g^2/Hz
300	2000	-5.00 dB/oct

No visible damage was found on the filters after the low level tests. The filters were than subject to the qualification level tests both sine and random. After the tests M1 is partially broken on the lower side along y, M2 is also partially broken but in a small region on the top side along y. Both M1 and M2 presents a few perforated mesh cells. M3 and M4 are undamaged. The WFI imaging filter is safe with no visible damage. All other filters are safe and with no visible damage.

A vibration test was then performed at higher level with respect to qualification level according to values reported in table 32.

Table 32: Sine and random vibration stress levels.

Sine load level S5 (Sweep rate: 2 Oct/min)

Frequency	**Level**
(5-26) Hz	11.0 mm (0-peak)
(26-100) Hz	30.0 g (0-peak)

Random Vibration level R5 (23.9g RMS, Duration: 150 s)

f1 [Hz]	f2 [Hz]	PSD
20	100	+3.00 dB/oct
100	300	0.998 g^2/Hz
300	2000	-5.00 dB/oct

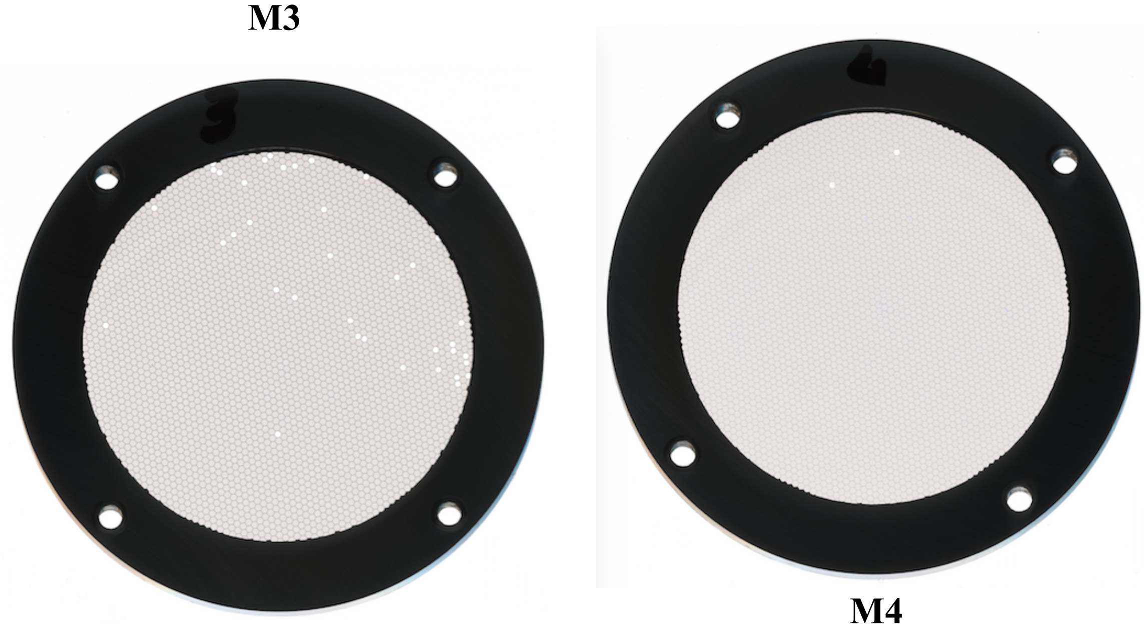
After the tests M1 is significantly broken on the lower side along Y and presents a few tens of perforated mesh cells. M2 is significantly broken on the upper side along Y and presents a few perforated mesh cells. M3 and M4 present few perforated mesh cells. The small filter samples mounted on T08 frames are all safe as well as the WFI filter. Figure 52 and 53 show the scanner image taken in transmission mode of HS-FOIL Si_3N_4 sample M1 and M3, M4 at the end of the S5/R5 level vibration tests, respectively.

M1

Fig. 52 – Scanner image in transmission mode of the sample filter M1 at the end of the S5/R5 level vibration tests.

Considering that the HS-FOILS sample M1 and M2 have been severely damaged with reference and higher levels vibration tests, we decide not to test them under shock. On the other hand, samples M3 and M4 are still in good shape after the high level vibration tests and thus we let them pass also the shock test.

M3



M4

Fig. 53 – Scanner image in transmission mode of the sample filter M3 and M4 at the end of the S5/R5 level vibration tests.

April 2018 Test Campaign

Sine and random low level vibration tests have been performed on two Si_3N_4 filter samples using the shaker model UD T-1000 at the Max-Planck-Institut fuer extraterrestrische Physik on April 16-20, 2018 in order to evaluate the resonance frequencies and modes of the mesh-membrane filters. Out of plane vibration tests have been carried out on the two samples listed in table 33.

Table 33: Si_3N_4 filter samples under test

Sample code	Frame	Al (nm)	Si_3N_4 (nm)	Mesh
ReLax WP4 L1 W19 k1	TF112	2x15	40	15 µm Si mesh open area 92%
ReLax WP4 L1 W17 k4	TF112	2x15	40	30 µm Si mesh open area 92%

A laser scanner vibrometer Polytec PSV-500 has been used to detect the deflection shapes and resonance frequencies in frequency domain (Figure 54).

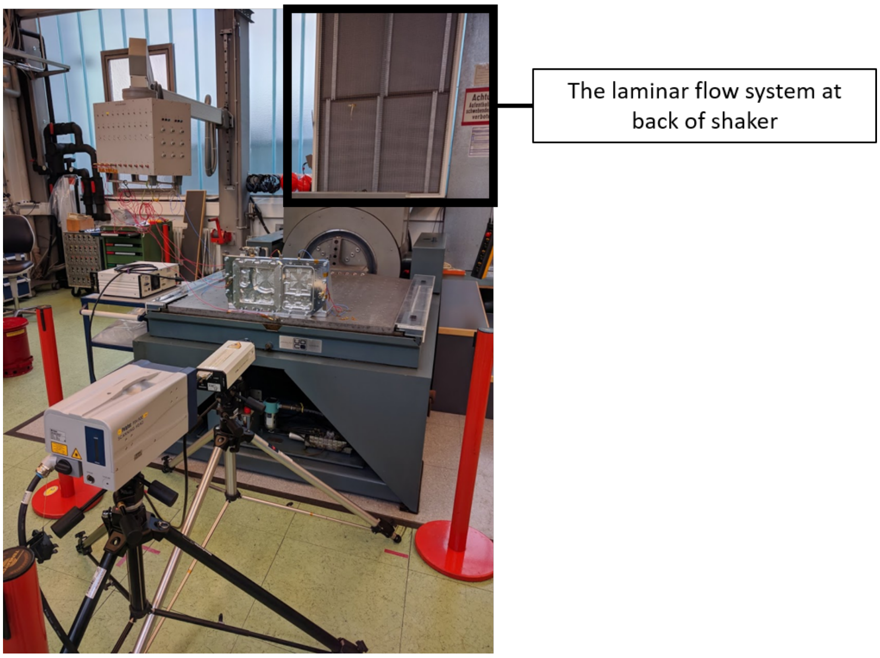


Fig. 54 – Laser scanner vibrometer Polytec PSV-500 of MPE.

The two tested filter samples have been mounted on the shaker slip table as shown in figure 55 and a sufficient number of accelerometers have been installed to control the applied loads at the interfaces.

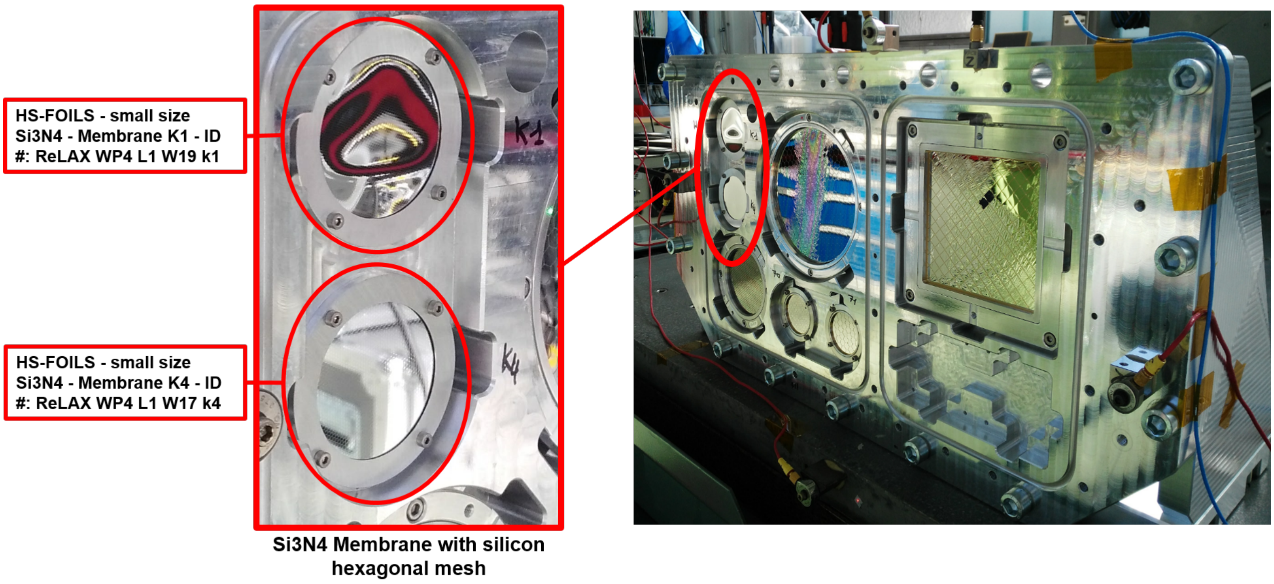


Fig. 55 –. The HS-FOILS samples mounted on the shaker interface.

The filters under tests have been subject to low level sine and random out of plane vibration tests. Tables 34 and 35 summarize the load level adopted for these tests.

Table 34: Low-level sine vibration loads

Axis	Freq. Range (Hz)	Excitation level (0 to peak, g)	Sweep Rate (Oct/min)
Z	5 to 2000	0.5	2

Table 35: Low-level random vibration loads

Axis	Freq. Range (Hz)	PSD	Sweep Rate (Hz)
Z	20 to 2000	0.0004 g^2/Hz	5

The test has been performed to measure the vibration of the membranes and frame of the filters with laser scanner vibrometer in three points as shown in figure 56.

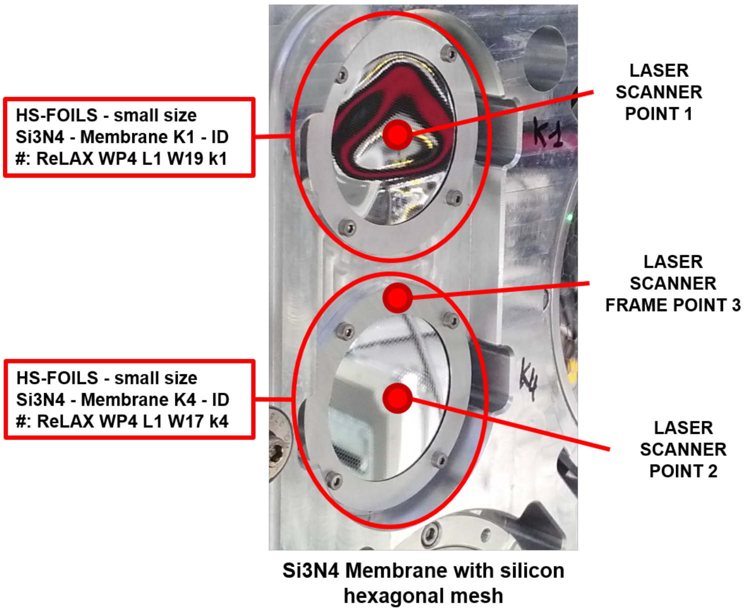


Fig. 56 – Measured points on the filter samples by the laser vibrometer.

Acceleration sensors were placed on the interface according to Figure 57.

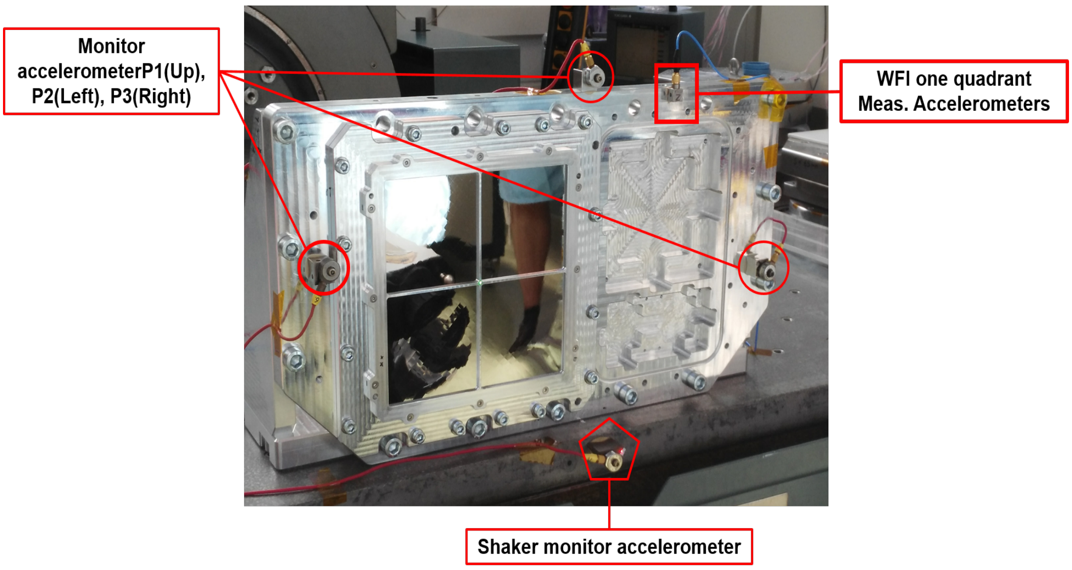


Fig. 57 – Accelerometer sensors positions on the interface plate.

Figure 58 shows the Laser scanner vibrometer measurements during the low-level random vibration performed on the HS-FOILS Si_3N_4 membrane k1. The blue line is the displacement of the center of the K1 mesh-membrane (point 1 in figure 56) and the red line is a point on the K4 frame filter (point 3 in figure 56).

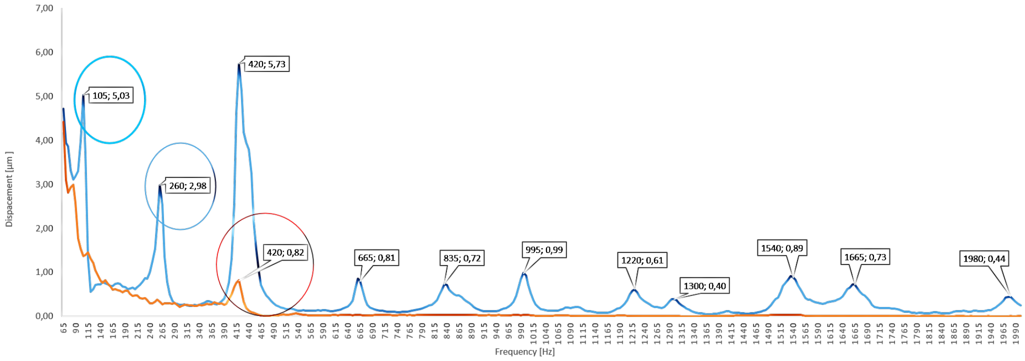


Fig. 58 - Displacement in frequency domain of the filter mesh-membrane K1 (Point 1)

The first and second resonance frequencies are 105 Hz and 206 Hz as confirmed by the velocity/frequency plot in figure 59. The peak at 420Hz is a resonance frequency of the I/F.

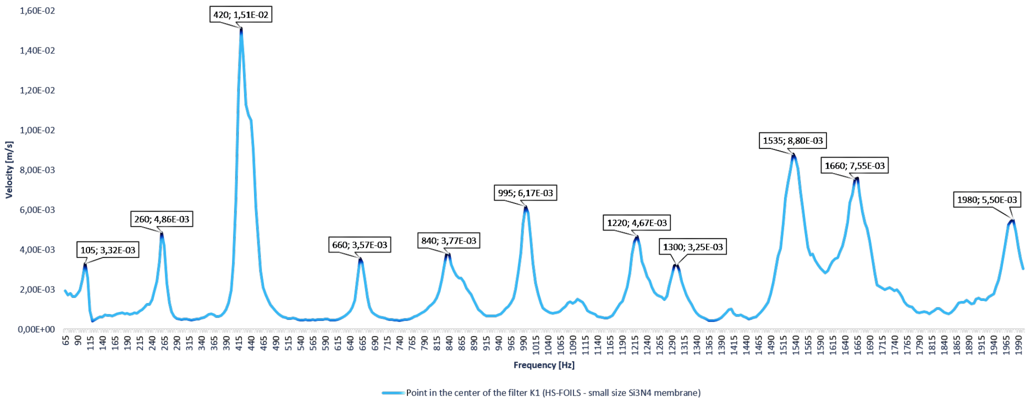


Fig. 59 Velocity in frequency domain of the filter mesh-membrane K1

Figure 60 shows the Laser scanner vibrometer measurements during the low-level random vibration performed on the HS-FOILS Si_3N_4 membrane k4.

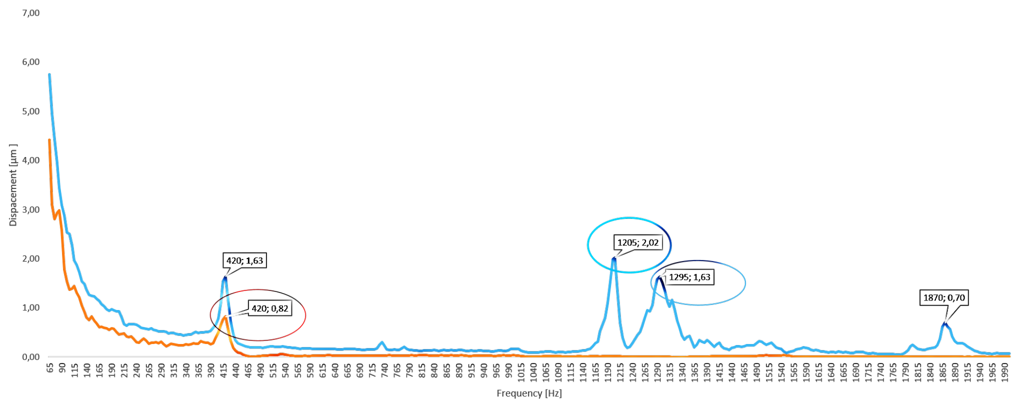


Fig. 60 – Displacement in frequency domain of the filter mesh-membrane K4

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The blue line is a displacement of the center of the mesh-membrane (point 2 in figure 56) and the red line is a point on the K4 frame filter (point 3 in figure 56). The first and second resonance frequencies are 1205 Hz and 1295 Hz as confirmed by figure 61 (velocity/frequency). The peak at 420Hz is a resonance frequency of the I/F.

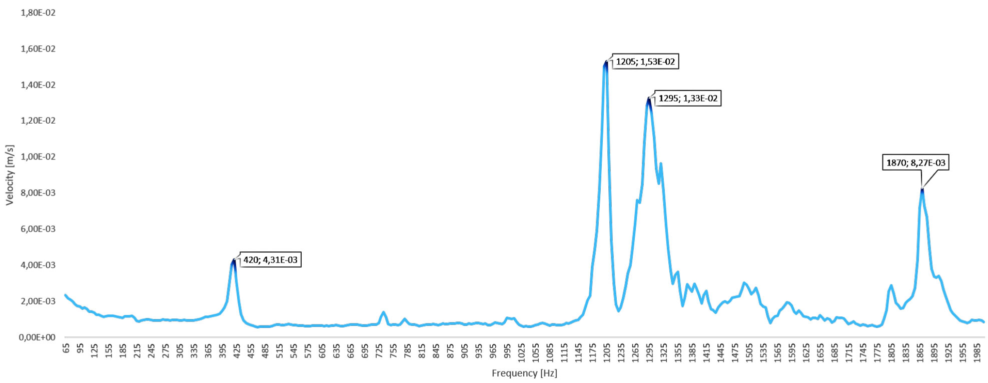

Fig. 61 – velocity in frequency domain of the filter mesh-membrane K4

December 2019 Test Campaign

Sine, random, and shock vibration tests have been carried out using the shaker model UD T-1000 at the Max-Planck-Institut fuer extraterrestrische Physik on December 9-13, 2019. In this campaign, two types of experimental tests have been performed: "Thin Membrane Contamination (TMC)" performed to evaluate the damage on an aluminium-coated thin film due to the presence of small metallic particles on the surface; "Thin membrane vibration (TMV)" performed to verify the mechanical resistance of polyimide/polyimide mesh and carbon nanotube membranes, to vibration stresses applying the Arian 5 qualification level. The following samples have been tested in this campaign:

Polyimide/aluminum small size samples

Al coated Polyimide film (LUXFilm®) mounted on TF110 and TF130 Al frames provided by Luxel Corp (table 36).

Table 36: Polyimide filter samples under test

Sample code	Frame	Al (nm)	Polyimide (nm)	Mesh
TF110-2460	TF110	30	150	No
TF110-2464	TF110	30	45	No

Si_3N_4/aluminum small size samples

Al coated Si3N4 foils mounted on TF111 Al frames provided by Ametek Finland Oy (table 37).

Table 37: Si_3N_4 filter samples under test

Sample code	Frame	Al (nm)	Si_3N_4 (nm)	Mesh
LAOF-S1-C1B5-W2-F3	TF111	2x15	40	Si honeycomb Thickness 50 µm, OA 97%
LAOF-S1-C1B5-W2-F4	TF111	2x15	40	Si honeycomb Thickness 50 µm, OA 97%

CNT/aluminum small size samples

Al coated CNT films mounted on TF111 Al frame provided by Ametek Finland Oy (table 38).

Table 38: CNT Filter sample under test

Sample code	Frame	Al (nm)	CNT (nm)	Mesh
LAOF-CNT2-C1B2-F03	TF111	17+17	120~150	No
LAOF-CNT2-C1B2-F01	TF111	11+11	120~150	No

Polyimide/aluminum supported by polyimide meshes large size samples

Double side Al coated thin nanometric polyimide film attached to a thin micrometric polyimide mesh, mounted on partially representative WFI one quadrant LDA OBF frame, provided by OXFORD Instruments Finland (table 39).

Table 39: Polyimide film/polyimide mesh filter samples under test

Sample code	Frame	Al (nm)	Polyimide (nm)	Mesh
W3a#03	WFI 1 quadrant 82 mm x 82 mm	30÷40	140	Polyimide honeycomb thickness: 17.4 µm ÷18.4 µm bar width: 20 µm, OA 95%
W3b#12	WFI 1 quadrant 82 mm x 82 mm	15÷20	140	Polyimide square pattern thickness: 17.4 µm ÷18.4 µm bar width: 20 µm, OA 95%

CNT/aluminum large size samples

Double side Al coated CNT films mounted on partially representative WFI LDA OBF one quadrant frame, provided by Ametek Finland Oy (table 40).

Table 40: CNT partial representative WFI one quadrant LDA OBF

Sample code	Frame	Al (nm)	CNT (nm)	Mesh
LAOF-CNT1-C1B1-F07	P/N WFI-UP-ASD-332110-000-02-001	11+11	120~150	No

CNT/aluminum large size samples

Double side Al coated carbon nanotube film mounted on a circular frame partially representative of X-IFU THF design, provided by Ametek Finland Oy (table 41).

Table 41: CNT partial representative X-IFU TF

Sample code	Frame	Al (nm)	CNT (nm)	Mesh
LAOF-CNT3-C1B2-F01 (2)	DWG No. ATHENA-01-03_D56	14+14	120~150	No

Polyimide/aluminum supported by polyimide meshes small size samples

Al coated Polyimide film mounted on TF111 Al frames supported by a polyimide mesh provided by OXFORD Instruments Finland (table 42).

Table 42: Polyimide film/polyimide mesh filter samples

Sample code	Frame	Al (nm)	Polyimide (nm)	Mesh
OIT-TF111-84	TF111	15+15	55	Polyimide honeycomb pitch = 0.97 mm, thickness = 18 μm, wire width = 15 μm,OA 97%

TMC Tests

Small size filter samples have been artificially contaminated with a few tens of SS microspheres, manufactured by Cospheric (CA, USA) and then vibrated to evaluate possible damages due to the high speed of the particles impacting on the film during vibrations. TMC vibrations have been performed with a monochromatic sine at 25 Hz and three different amplitude 0-peak, namely: MS1 = 8 g, MS2 = 16 g, and MS3 = 25 g. Table 43 and table 44 show the main characteristics of the available SS micro-spheres, while fig. 62 is a picture taken with an optical microscope of a bunch of SS microspheres of the largest size available.

Table 43: Nominal characteristics of Cospheric microspheres

Particles in size range	Sphericity	Density
> 90%	> 90%	7.7 – 7.9 g/cm3

Table 44: Available dimensions of Cospheric microspheres

Diameters [μm]	Mass [μg]
27 - 31	0.06-0.09
39 - 47	0.2 – 0.3
57 - 67	0.6 – 0.9
95 - 105	3 – 4
130 - 155	7 - 12
190 - 220	22 - 33

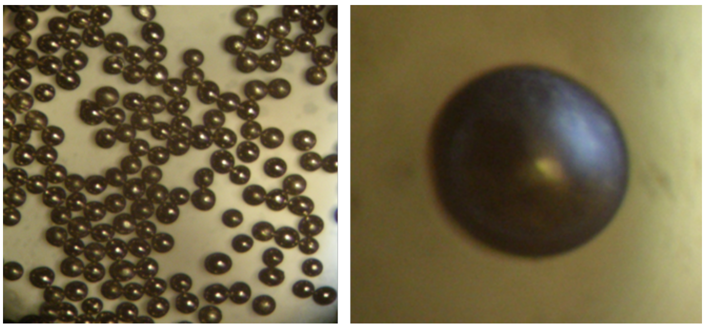

Figure 62 – Microscope images of a few Cospheric microspheres.

Three separate tests have been performed using at each time microspheres of the same size (within the tolerance of the manufacturer), starting from the smallest ones in table 44 (27-31 μm diameters) up to the third size in the same table (57~67 μm diameters).

Table 45 summarizes the TMC vibration tests performed on each filter sample.

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Table 45: Resume of the TMC test with the time each filter was subjected to the MS load and contamination [in seconds]

Vibration level (vacuum)	Time each filter was subjected to the MS load and contamination (seconds)						
	TTF110-2460	TTF110-2464	LAOF-CNT2-C1B2-F01	LAOF-S1-C1B5-W2-F3	LAOF-S1-C1B5-W2-F4	LAOF-CNT2-C1B2-F03	OIT–TF111-84
MS1	10	10	10	10	\	\	\
MS2	10	10	10	10	\	\	\
MS3	10	10	10	10	\	\	\
MS1 with particle 27-31 um	30	30	30	Broken during manipulation before shaking	10 (1 broken cell) + 10	\	\
MS2 with particle 27-31 um	20	20	20	\	10 (3 broken cells)	\	\
MS3 with particle 27-31 um	10	10	10	\	\	\	\
MS1 with particle 39-47 um	30	30	30	\	\	\	\
MS2 with particle 39-47 um	20	20	20	\	\	\	\
MS3 with particle 39-47 um	10	10	10	\	\	\	\
MS1 with particle 57-67 um	30	30	Broken during contamination before shaking	\	\	30	30
MS2 with particle 57-67 um	20	20	\	\	\	20	20
MS3 with particle 57-67 um	10	10	\	\	\	10	10
MS1 with particle 95-105 um	30	30	\	\	\	30	30
MS2 with particle 95-105 um	20	20	\	\	\	20	20
MS3 with particle 95-105 um	10	10	\	\	\	10	10
Total time on MS1	130	130	70	10	10	60	60
Total time on MS2	90	90	50	10	10	40	40
Total time on MS3	50	50	30	10	\	20	20

The Polyimide/al filter samples TTF110-2460 and TTF110-2464 manufactured by LUXEL corp. have been vibrated with contamination particles of four different sizes and survived without any damage (see figure 63).

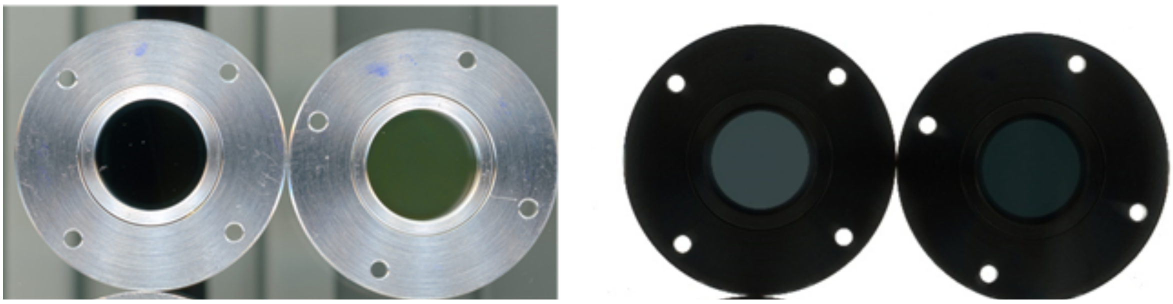

Fig. 63 - Reflection (on the right) and transmission (on the left) scan of the TTF110-2460 and TTF110-2464 filter at the end of the TMC test.

The Si_3N_4/aluminum sample LAOF-S1-C1B5-W2-F3 manufactured by AMETEK was broken during the manipulation activity before the shaking with the particles. In particular, one cell broke during the opening of its case, probably due to differential pressure (see figure 64).

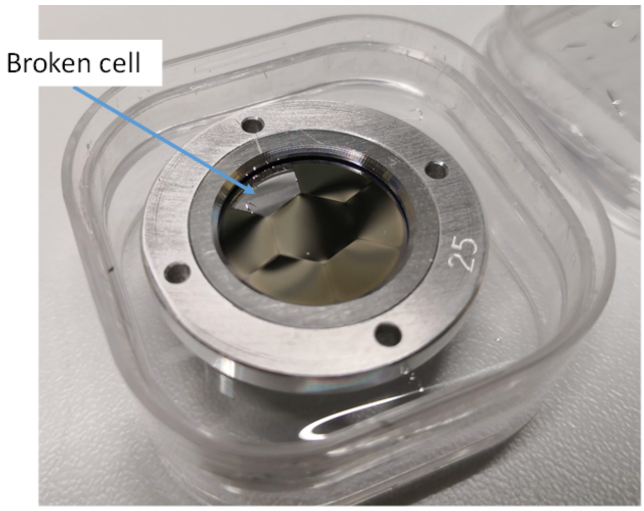

Fig. 64 - LAOF-S1-C1B5-W2-F3 with broken cell.

The twin filter called LAOF-S1-C1B5-W2-F4 replaced the broken LAOF-S1-C1B5-W2-F3 for the continuation of the TMC test. After the first MS1 level with the particle size 27-31 um the filter LAOF-S1-C1B5-W2-F4 presented one pinhole due to the particle perforation (see Figure 65).