Development of the low power HEMPT EV0

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Abstract: Thales Germany GmbH developed a new thruster named EV0 that is optimized for the use on small satellites and constellations. The thruster can be throttled in a range from 700W down to 200W and be used in a range from 300V to 800V. At high power and low voltage, the thruster generates high thrust of more than 32mN. At higher voltage, the thruster reaches an ISP above 2100s, leading to high fuel savings. For lifetime prediction of the thruster an endurance test of 2000h has been performed. The thruster performance degenerated less than 1% in this test which is due to the exceptional low erosion rate of the thruster. From the test a lifetime of more than 10000h continuous operation can be predicted. The thruster is optimized for the use of Xenon as well as Krypton as propellant. Krypton is a much cheaper propellant that allows for a higher ISP. With Krypton the thruster produces more than 28mN of thrust with an ISP of above 1400s at high power and low voltage.

Nomenclature

T = thrust
$\dot{m}$ = mass flow
g = gravitational constant
U = voltage
I = current
P = power
FCU = Xenon propellant Flow Control Unit
HEMPT = High Efficiency Multistage Plasma Thruster
RPA = retarding potential analyzer
ISP = specific impulse
TTPR = thrust to power ratio

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I. Introduction

Several satellite constellations are in active development with the goal to deliver broadband data links anywhere on the globe. The constellations are comprised of many hundreds of satellites demanding for highly efficient and very cost-effective solutions. A crucial component of these satellites is the propulsion system that is used for orbit razing, station keeping and deorbiting.

For this purpose Thales Germany GmbH developed a thruster that is optimized for the use on small satellites, named EV0.

The EV0 has optimized magnetic field topology that increases the plasma confinement and further reduces energy losses to the discharge channel wall. This leads to an increased life time and increased performance.

The simplified module design increases reliability and reduces production cost and lead time. Total mass of the thruster module is below 1.5kg. The geometrical envelope is 180x190x90mm. The thruster is designed for high radiation tolerance, with additional shielding for the harness it can tolerate up to 40Grad. The EV0 uses the same qualified neutralizer HCN5000 as the HEMPT3050.[1,2,4] The thruster is optimized for the use of Xenon and Krypton. All measurements in this article are made on a breadboard model of the EV0 thruster.

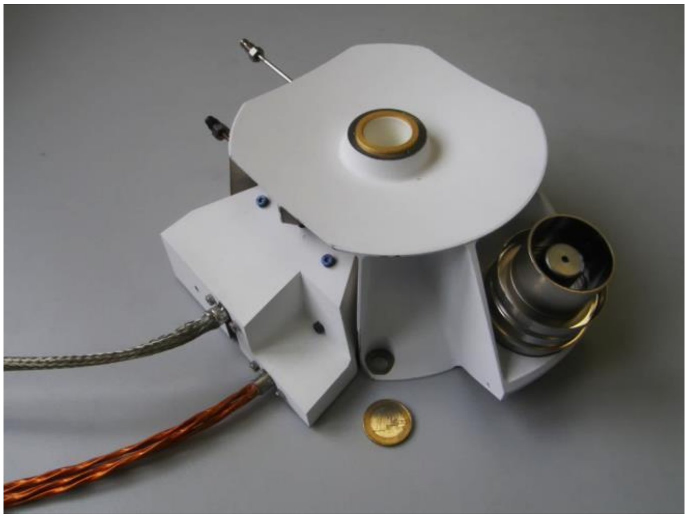

Figure I-1: Photo of the EV0 module.

II. Working principle

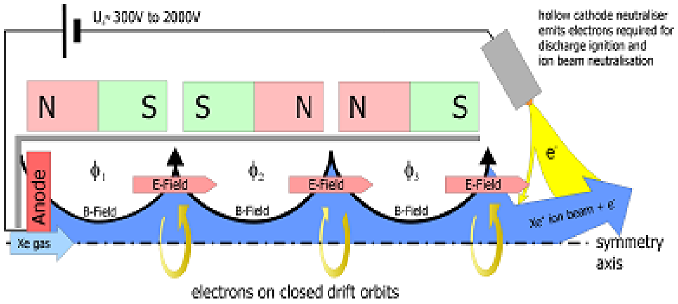

Figure II-1. Working principle of a HEMPT[1]

The discharge in a HEMPT is strongly confined in the magnetic field of the surrounding permanent magnets. The electrons in the discharge are magnetized and can only follow magnetic field lines, magnetic mirrors at the cusps reflect the electrons and so a high confinement time can be achieved. This leads to high ionization efficiency because of the high electron density at the center of the discharge.

The discharge is ignited by applying DC voltage between the anode and the neutralizer. Because of the high electron confinement time only a small electron current from the neutralizer is necessary for the startup.

Since the discharge is conductive it is at anode potential and the potential drop at the exit region accelerates the ions. To neutralize the ion beam an electron current of the same magnitude is emitted by the cathode.

The advantage of this type of thruster is the long lifetime and performance stability because the erosion of the discharge channel is almost negligible. This makes the technology especially interesting for small thrusters, where the surface to volume ratio leads to higher erosion and energy losses. The EV0 has improved confinement and potential shape in the exit region, this allows improved performance.

III. Performance

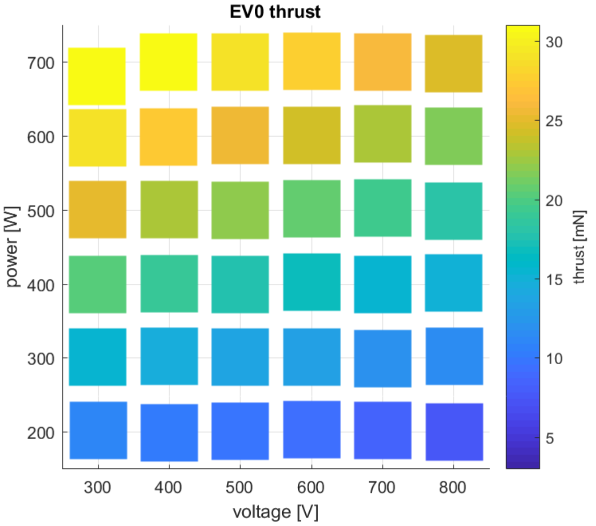

Figure III-1. EV0 thrust *Measured with thrust balance a background pressure < 1E-5mbar*

All tests were performed in the two test chambers of Thales Ulm. Chamber 1 is 4m long, has a diameter of 2.4m and is equipped with 8 cryopumps. The chamber has a measured pumping speed for Xenon of 50000 l/s.

Chamber 2 has a diameter of 1.4m, a length of 2.8m and is equipped with 3 cryopumps and N2 Baffles. The measured Xenon pumping speed is 25000 l/s. Both chambers have a base pressure < 1.0E-7 mbar and experiments are usually performed with a background pressure <1E-5 mbar.

Both chambers are equipped with thrust balances with an accuracy of 0.1mN. Functional principle is a counterforce on an inverted double pendulum. The chambers also have Retarding Potential Analyzers (RPA) for plume diagnostic.

The test procedures are completely automated so that 100 working points of a thruster can be measured in one day including 30 RPA scans. For an accurate thrust measurement the thruster is operated for at least 15 min on every working point and then switched off.

HEMPT thrusters usually have a wide working range and can be operated at different voltages and different power levels without any change on the hardware.[7] The switching time between different settings is thereby in the order of milliseconds for a voltage change. A change in gas flow is limited be the used flow control unit (FCU) and is typically finished after 1-4s. The working points can also be switched ion orbit if the PPU and FCU support the switching.

The EV0 thruster has a working range of 200W to 700W and 300V to 800V. The thruster can be operated almost at the same performance level with Krypton as well as with Xenon as will be shown below. For better comparability the performance diagrams in Figs.III.1-6 show the Xenon performance.

The thrust levels of 36 representative working points in the operational range are shown in Fig. III-1. The smooth gradient with power and voltage shows the good operation of the thruster in the operational range. 32mN for

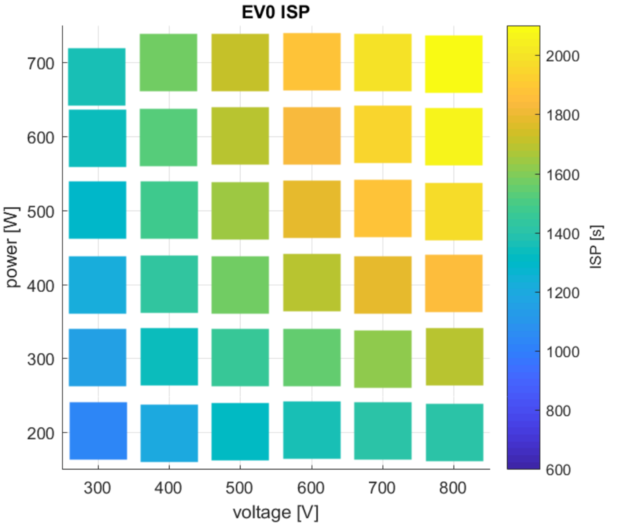

Figure III-2. EV0 Xenon Specific impulse (ISP)

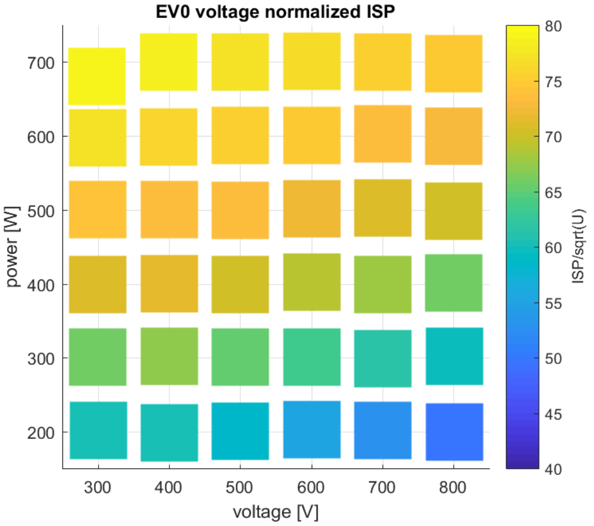

Figure III-3. Voltage normalized ISP

a thruster with only 20mm exit diameter is a very high thrust and power density compared to other technologies. For short duration the thruster can be operated also above 700W.

The measured specific impulse ($ISP = \frac{T}{\dot{m}g}$) is shown in Fig. III-2. The thruster reaches its maximum ISP of 2100s. Naturally the ISP increases with higher acceleration voltage. The increase of the ISP with power is a characteristic of the thruster and is caused by the increased ionization rate and fuel efficiency at higher power. To separate physical dependencies from the characteristic properties of the thruster it is useful to normalize the ISP by the voltage dependence. Fig. III-3 shows the *voltage normalized ISP*, which is $\frac{ISP}{\sqrt{U}}$. The figure shows that the ISP of the thruster is good at a wide voltage range and even best at low voltage. This means that an ISP of 1400s at 300V is actually better result than the 2100s at 800V. But the small gradient shows a good operation in the whole range without any signs of mode changes.

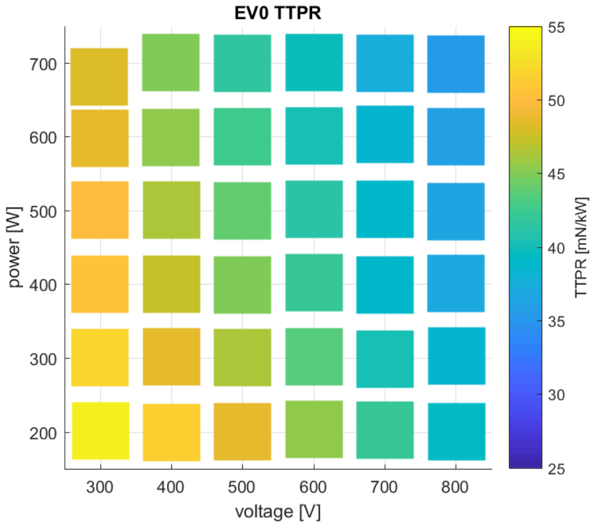

Figure III-4. EV0 Xenon Thrust to Power Ratio

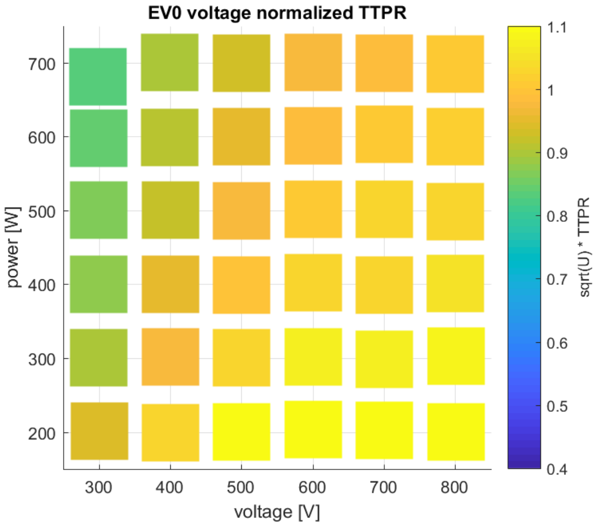

Figure III-5. Voltage normalized TTPR

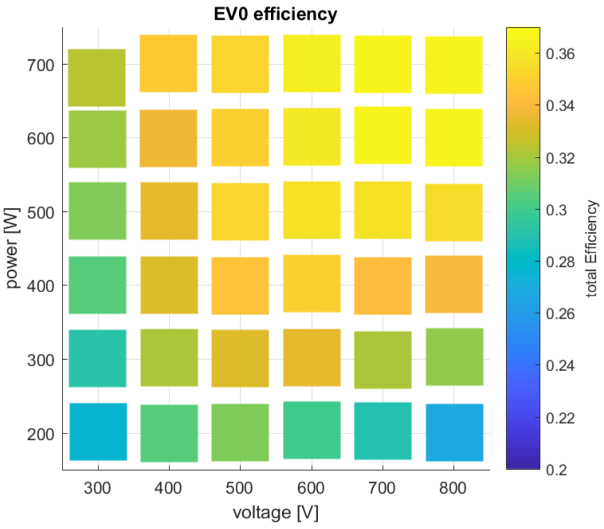

Figure III-6. EV0 Xenon total efficiency

The same kind of analysis can be done for the Thrust to Power Ratio ($TTPR = \frac{T}{P}$). Fig.III-4 shows the TTPR that naturally decreases with voltage. The dependence can be removed by multiplication by $\sqrt{U}$. This voltage normalized TTPR is shown in Fig.III-5. The thruster has the best TTPR at the lowest power because energy losses to the walls increase with higher discharge power. But the dependence on power is rather weak and the 48mN/kW at 300V 700W shows that the HEMPT operated at low voltage can have a comparable TTPR to a Hall-effect thruster of the same size.

The voltage normalized TTPR shows again the same inversion as the voltage normalized ISP. This means that a TTPR of 35mN/kW at 800V (almost independent on power) is a good value for those working points.

All these dependencies combined can be seen in Fig.III-6 that shows the total efficiency $\eta = \frac{T^2}{2\dot{m}P}$. It generally follows the trend of the ISP with the highest efficiency at 800V with more than 36% and still has more than 32% at 300V. The good performance of the thruster in a wide voltage range makes it an ideal candidate for dual mode operation. That means the orbit raising in a satellite mission can be done at low voltage, high thrust and high

TTPR to be in orbit as fast as possible. The station keeping and deorbiting can then be done at high voltage to save fuel and wet mass.

The wide power operation range allows either to use the same EP system for different sized satellites or to switch to a low power mode in orbit if the payload of the satellite is switched on. This makes the EV0 very versatile.

Another advantage of the EV0 is that it is compatible with any noble gas without any change on the hardware. In particular the performance with Krypton is very good. Fig.III-7 shows that the total efficiency with Krypton reaches almost the Xenon levels. This is attractive for satellite constellations since Krypton is ten times cheaper than Xenon. With Krypton the thruster produces almost 28mN of thrust with an ISP above 1400s at 700W and 300V.

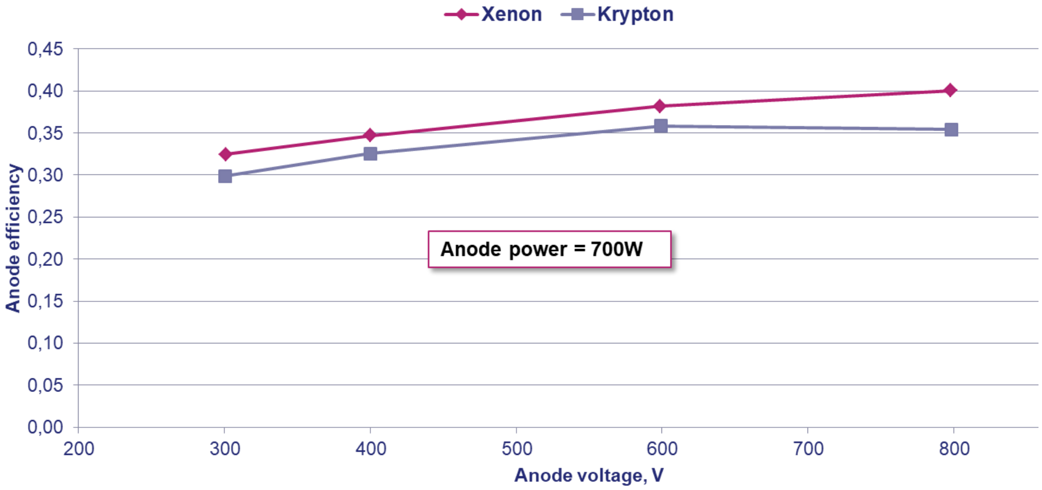

Figure III-7. Comparison Krypton, Xenon performance

IV. Life Time

HEMPT thrusters naturally have a very high lifetime because all surfaces are magnetically shielded from plasma contact.[3,5] The shielding is either done by surface parallel fields or by cusps that function as magnetic mirrors.

Another novelty of the EV0 that increases its life time is the neutralizer position. It has an increased distance from the thruster exit and is positioned upstream pointing away from the thruster. The position strongly reduces keeper erosion caused by the thruster plume, usually a lifetime limiting factor for the neutralizer. The neutralizer has in this position a very low coupling potential and therefore a high efficiency. Also the startup of the thruster benefits form this position which is very smooth and without huge current spikes. Auto oscillations common to HEMPT[6] stay at the desired low amplitude.

To assess the lifetime of the EV0 a 2000h continuous firing endurance test has been performed.

The most demanding working point regarding lifetime for a HEMPT regarding the lifetime is the one with the highest current, because the magnetic confinement has to balance the high densities. For this reason the test was conducted at the working point with the highest current which is 700W 300V. This is also the point with the highest thrust. The test was completed without any complications and the thruster accumulated 240kNs total impulse in this test.

The performance of the thruster did not change within the 2000h which can be seen in Fig.IV-1. This is a very good result especially for such a small thruster with high surface to volume ratio. The result confirms the good

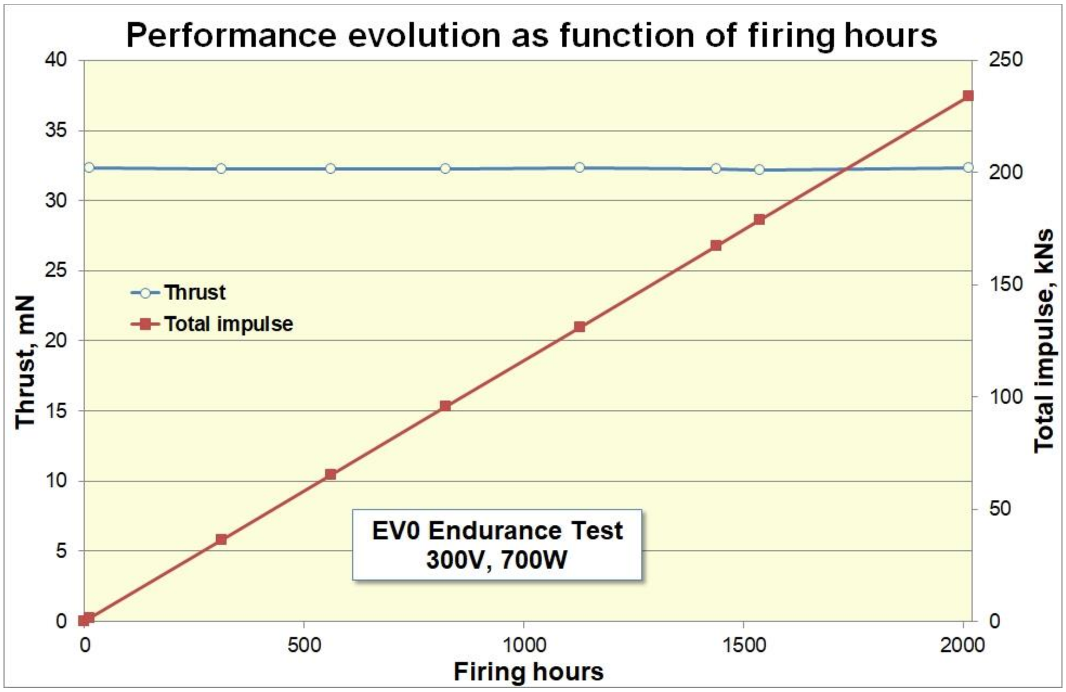

Figure IV-1. Thrust level and accumulated total impulse of the 2000h endurance test of EV0

magnetic confinement and surface shielding of the EV0 and the HEMPT technology. From the test a total lifetime prediction of at least 10000h and 1.2MNs can be made.

V. Plume diagnostic

Due to the working principle of HEMPT thruster the ions do not leave the thruster parallel but in a hollow cone or cone shaped comparable to hall thrusters. A wider cone means higher momentum losses, these losses can be quantified with the beam efficiency which is the cosine of the ion momentum relative to the thruster axis divided by the total momentum (e.g. if all ions leave the thruster parallel to the thruster axis the beam efficiency is 100%).

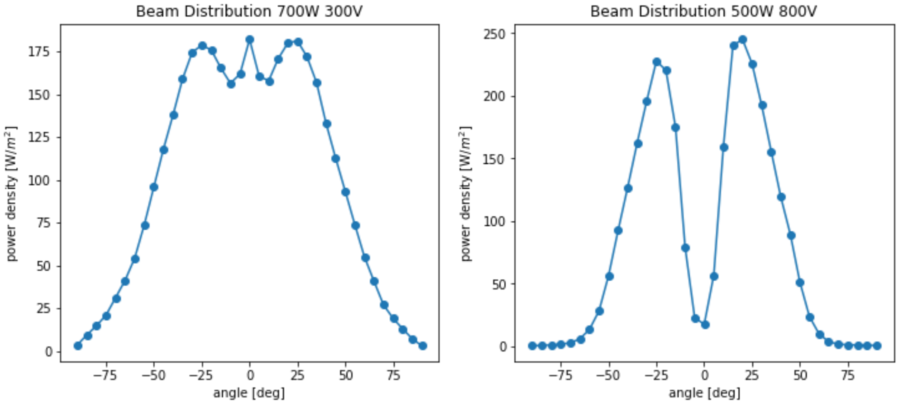

Figure V-1 Beam power distribution measured with RPA. (left) At 700W 300V, maximum power density at 0.0deg Beam efficiency 71% and (right) at 500W 800V, maximum power density at 22.3deg beam efficiency 81%.

To measure the plume divergence the Thales test chambers are equipped with retarding potential analyzers (RPA). With RPAs it is not only possible to measure the ion current distribution but also the energy distribution of the ions. This is necessary because not all ions leave the thruster at the same energy but with a distribution centered on the anode potential minus the coupling voltage to the neutralizer. By integrating the energy distribution we can obtain the power density of the ions at the RPA position.

The RPAs can be moved in the chamber in a circular path around the thruster to scan the whole plume distribution. Fig. V-1 shows the measured beam power distribution of the EV0 at two working points, one at low voltage (left) and one at high voltage (right). With higher voltage the beam of the EV0 is narrower and the beam efficiency reaches 81%. At low voltage the profile changes from a hollow cone to a filled cone with the maximum power density at the centerline. Half cone angle for 90% of the beam power is 51deg for high voltage and 71deg for the low voltage. Additionally there is a weak dependence of the beam efficiency on power. The efficiency increases slightly (1~4 percentage points) with lower power.

VI. Environmental testing

As part of the qualification of the EV0 a vibration and shock test has been performed. After the tests an inspection and a performance test in the vacuum chamber confirmed the good condition of the thruster.

A. Shock test

The test was performed in the Airbus facilities in Friedrichshafen.

The shock test facility simulates the mechanical shocks which may occur during transport, launch and deployment event. The shock pulse is generated by a falling mass on a ringing plate. The maximal applied load was 2000g.

TableVI-1. Shocktest applied loads

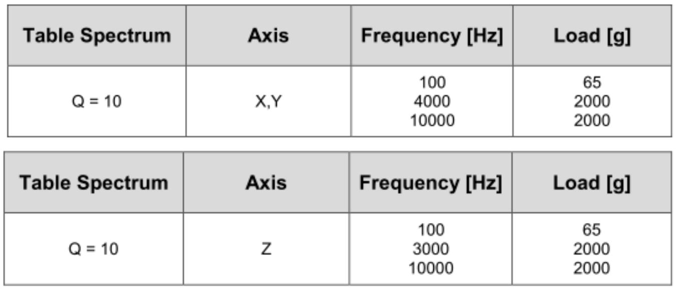

Table Spectrum	Axis	Frequency [Hz]	Load [g]
Q = 10	X,Y	100 4000 10000	65 2000 2000

Table Spectrum	Axis	Frequency [Hz]	Load [g]
Q = 10	Z	100 3000 10000	65 2000 2000

B. Vibration test

The vibration test was performed in the facilities of Thales in Ulm. Test loads are shown in the table and figure.

Table VI-2. Random Vibration Loads

Perpendicular to Mounting Plate Z-axis		Parallel to Mounting Plate X/Y-axis	
Range (Hz)	Power Spectral Density	Range (Hz)	Power Spectral Density
20 – 70	+ 9 dB/oct	20 – 150	+ 9 dB/oct
70 – 140	1 g²/Hz	150 – 500	0.7 g²/Hz
140 – 200	+5.85 dB/oct	500 – 2000	- 9 dB/oct
200 – 350	2 g²/Hz		
350 - 2000	- 9 dB/oct		
Global: 28.6 g_{rms}		Global: 20.9 g_{rms}	

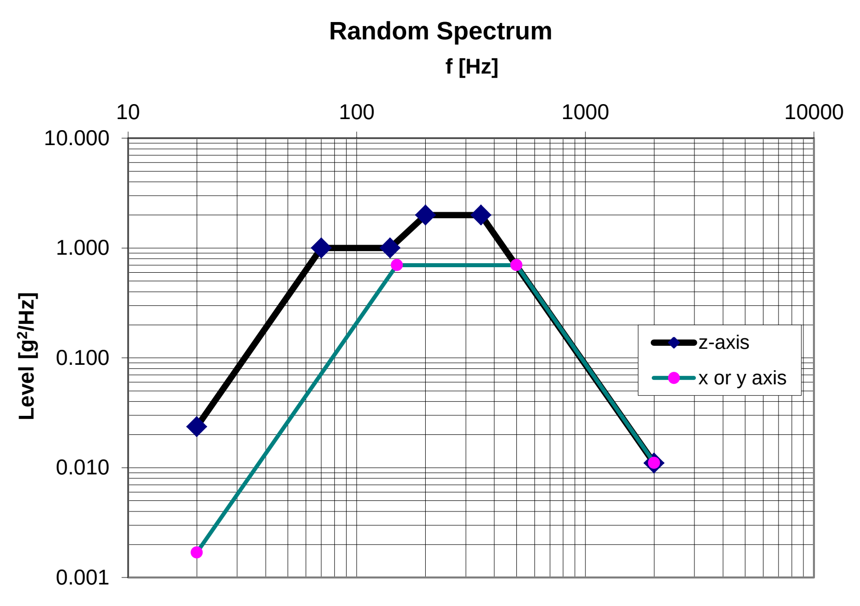

Figure VI-1. Random Vibration Loads

The design was found to be rigid and very stiff. This is in particular evident from high Q factor of NTR resonance and from the fact, that the first resonance frequency of the radiator is in excess of 700Hz. Accordingly it can be anticipated, that even higher random load can be accepted.

VII. Acknowledgments

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