Test Facility for EMC-Characterization of Electric Thrusters in Operation using an evacuated Reverberation Chamber resp. an Anechoic Chamber with Vacuum Vessel and Honey Comb

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Abstract: The use of ion engines has increased significantly in recent years. Satellite manufacturers are now relying fully on this technology, which has led to enormous cost savings. In addition, a number of new engine concepts are entering the market. Like any electronic device, an ion engine must meet electromagnetic compatibility (EMC) requirements. There are two established concepts for EMC that will be discussed in this paper, the reverberation test chamber for susceptibility measurements and the anechoic chamber. An overview will be given about constructional details such as the combination of a vacuum chamber with a honey comb as rf-shielding for full compliance measurements. The measures for effectiveness of RF shielding is contrary to evacuation requirements. Verification by calculation and 3D-simulation are given.

Nomenclature

$\bar{c}$	=	mean particle velocity	α	=	damping coefficient
A	=	flow cross-section	a[dB]	=	attenuation in dB
P	=	probability of passage	RC	=	Reverberation Chamber
c	=	speed of light	ρ	=	specific resistance
λ	=	wavelength	ω	=	angular frequency
f	=	frequency	μ	=	permeability
a	=	honey comb diameter	δ	=	skin penetration depth

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I.Reverberation Chamber

Ion engines are typically operated in metallic vacuum systems. Therefore, measurements of the emitted electromagnetic radiation of the engines are not possible and require considerable effort. Nevertheless, the operation in a metallic chamber can be exploited for EMC investigations if the concept of the reverberation chamber (RC) is applied. From a physical point of view, an RC is a closed metallic cavity in which standing electromagnetic waves can form. The characteristic of the standing waves is determined by the frequency of the radiation and by the geometric boundary conditions of the cavity. RCs are compliant with the MIL-STD-461 standard typically used for space technology. The frequency range between 400 MHz and 40 GHz is covered in accordance with the standard, whereby the lower cut-off frequency depends on the geometry of the chamber. As an additional condition, the standard defines a mode number N of at least 100 for a given frequency f as the permissible lower limit in order to achieve meaningful results. RCs are only used for irradiation measurements in accordance with standards. An antenna within the cavity emits electromagnetic radiation with a defined intensity and frequency. The functionality of the device under test is examined depending on the irradiated power.

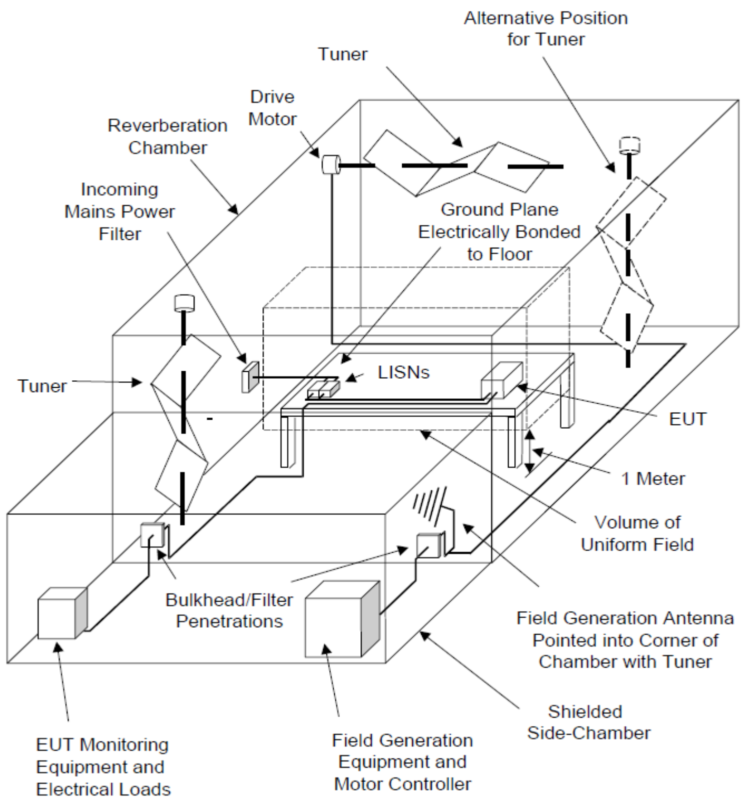

Fig.1. MIL_STD461: RS103. Reverberation chamber overview [1]

In cooperation with the University of Applied Sciences (THM), the ion thruster group of the University of Giessen plans to convert an existing vacuum chamber into an RC. This is done at the BigMac test facility, which has been extended by about two meters for this purpose. It has now a diameter of 160 cm and a length of 300 cm. Initial simulations have shown a lower cut-off frequency of 143 MHz for the TM_{010} mode resp. 234 MHz for the TE_{011} mode. Since integer multiples of this frequency lead to resonances within the chamber, only a discrete frequency spectrum for measuring can be covered. Furthermore, the standing waves - respectively the excited modes - lead to minima and maxima of the field strength in the course of the chamber volume. In order to achieve the widest possible and uniform field distribution, an RC therefore contains mode stirrers.

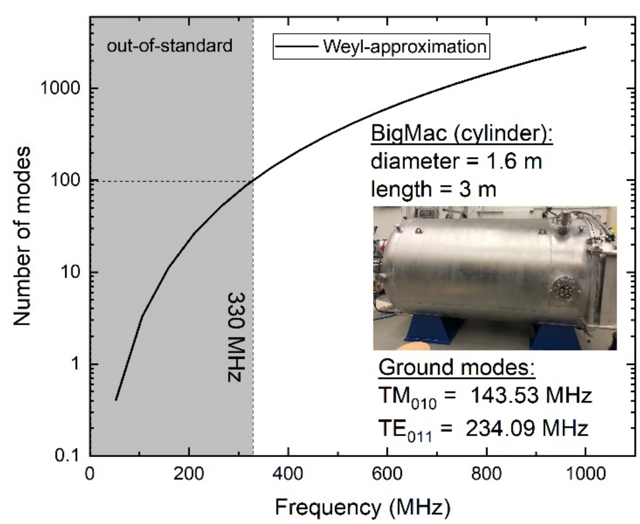

Fig.2. Determination of the lowest usable frequency

A mode stirrer is a mechanical component, which is typically mounted rotatably in the RC. It consists of electrically conductive material and is often asymmetrically shaped. In an RC, several mode stirrers can be used, which are usually placed away from the DUT for immunity measurements. Initial investigations have shown that only low RF power is required to achieve the required E-field strength of 20V/m. Using a planar antenna, 15V/m could be achieved with only 1W RF power at 235 MHz.

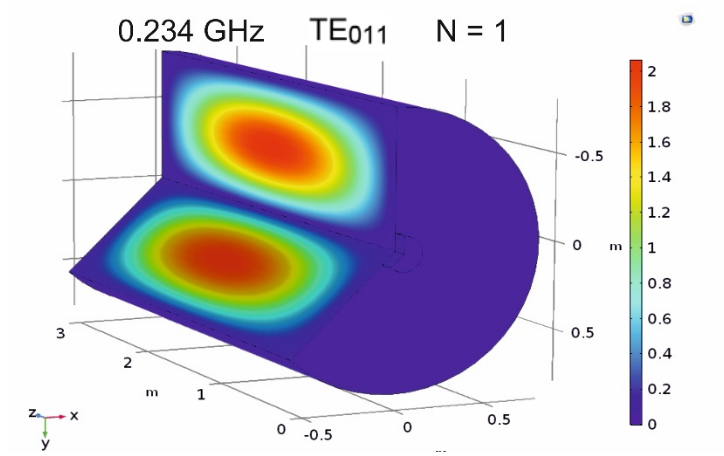

Fig.3. Modal distribution in a cylindrical resonator

II.Anechoic chamber combined with a vacuum vessel

For full compliance EMC tests, an RF absorber chamber is required which is flanged to a vacuum tank in order to be able to measure the ion thruster in active operation. The thruster unit is surrounded by an RF transparent measuring cylinder (Fig. 4), which must remain open towards the vacuum tank for beam extraction. This results in the problem of keeping high-frequency disturbances, coupling in from the tank by vacuum pumps, measuring electronics etc. away from the transparent cylinder inside the anechoic test chamber. First considerations to insert a HF screen transparent for the beam between cylinder bottom and vacuum tank were rejected. The divergence of the ion beam would prevent the beam from passing through the HF honeycomb. On the other hand, alternative wire meshes would be quickly destroyed by sputtering of the beam and unwanted metallic sputter residues would be deposited in the measuring cylinder. The solution would be to move the RF-absorbing honeycomb to the center of the vacuum tank, directly behind the beam dump.

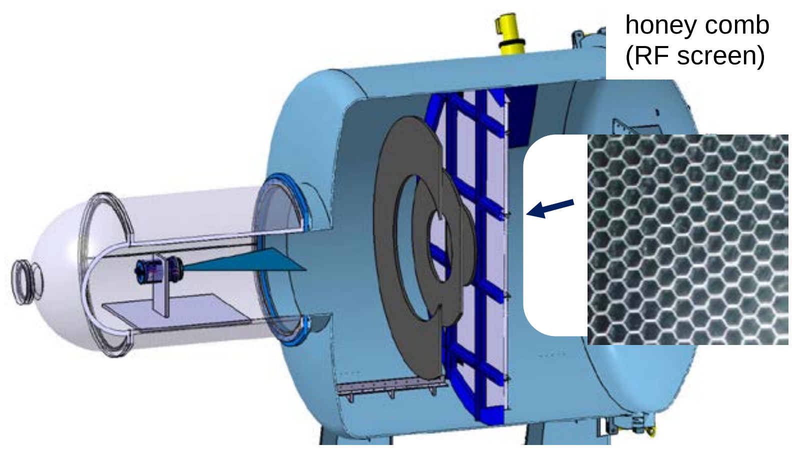

Fig.4. RIT Thruster and vacuum vessel with honeycomb

An optimization of the honeycomb with regard to high RF attenuation with minimal obstruction of the gas flow is necessary.

A. Attenuation of the Honeycomb

Since honeycomb elements act as a non-conducting microwave waveguide as RF attenuation, the diameter of each honeycomb element must be small compared to the smallest test wavelength (= highest frequency) still to be shielded. This is 40GHz according to MIL-461G. The theory of waveguides requires that the diameter must be smaller than half the cut-off wavelength of the maximum test frequency.

For the required attenuation > 100dB up to the highest test frequency, a maximum diameter of a honeycomb element of approx. $a = 3mm$ is admissible. Common honeycomb constructions use 1/8" = 3.175mm. Since the dB attenuation increases proportionally with the depth of the honeycomb, a depth of ½ inches is required for frequencies up to 20GHz, and even 1 inch for 40GHz. The wavelength for this frequency is

$$\lambda = \frac{c}{f} \approx \frac{300 \cdot 10^6 \frac{\mathrm{m}}{\mathrm{s}}}{40 \cdot 10^9 \frac{1}{\mathrm{s}}} = 7{,}5\ \mathrm{mm}\,,$$

which would result in a diameter of

$$a = \frac{\lambda}{2} = \frac{7{,}5\ \mathrm{mm}}{2} = 3{,}75\ \mathrm{mm}\,.$$

Based on these values, a simulation model with diameters slightly below and above this value has been set up to observe the attenuation properties of a rectangular honeycomb plate. Instead of simulating a source that emits spherical waves with a single frequency and using a receiver as an infinitesimally small point, the the overall ability of the structure to damp electromagnetic waves is represented by using a rectangular plane source whose transmission area spans approximately the honeycomb area, so boundary effects are minimized which allows us to simulate the component itself rather than disrupting side effects.

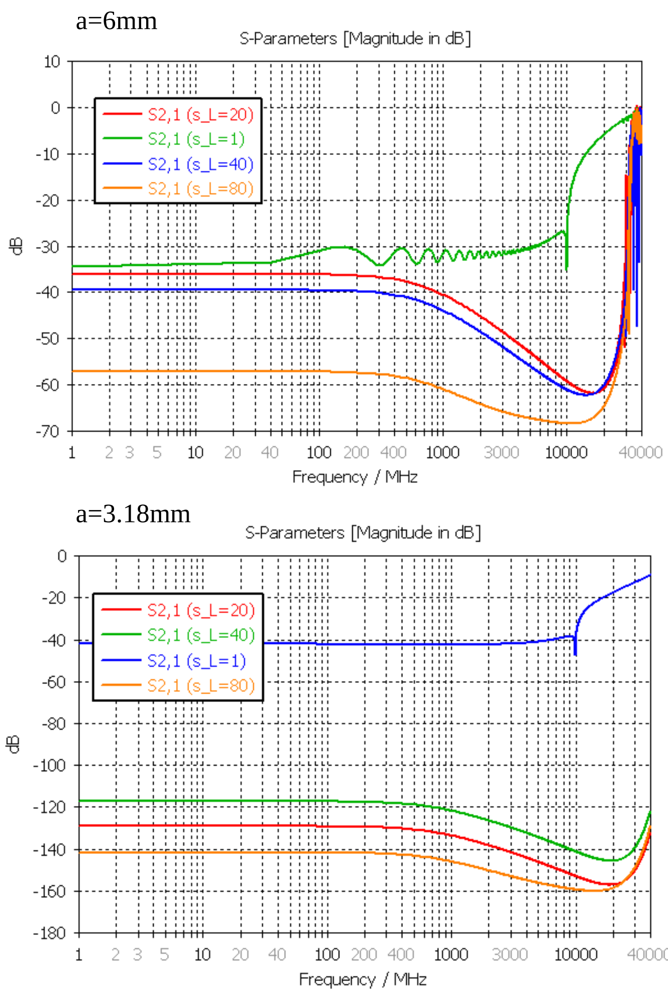

Fig.5. Attenuation frequency responses for varied lengths

Therefore, a simulation model was created to determine the broadband attenuation of an incident electromagnetic wave. Instead of working with voltages and currents, we use scattering parameters (s-parameters). They are adequate to describe the RF properties of arbitrary structures. In our case, the s-Parameter s_{21} represents the transmission factor between the source and the sink. The description is given in the form of a Bode diagram which shows the attenuation for a sinusoidal signal with the corresponding frequency. Because each signal can be represented as a superposition of sinusoids, this representation is more meaningful than the simulation with individual frequency points.

For waveguide elements used to attenuate waves, there are mathematical relationships to describe their frequency response. With $\lambda_0 = 2a$ and $\lambda_k = \frac{c_0}{f_k}$ we can calculate the damping coefficient per unit length [Wolfsperger]

$$\alpha = \frac{2\pi}{\lambda_k}\sqrt{1 - \left(\frac{\lambda_k}{\lambda_0}\right)^2}\,,$$

The resulting attenuation of a honey comb element with the length l is calculated by

$$a[\mathrm{dB}] = 20\log(e^{\alpha l}) = 8.686\,\alpha * l$$

When we use a diameter of $a = 3$ mm, we get a $\lambda_k = 6$ mm which corresponds to a frequency of $f_k = 50$ GHz. The attenuation formula is valid for $f_0 < 0.8\, f_k$. Now we can calculate the attenuation for certain discrete wavelengths/frequencies.

With $\lambda_0 = 7.5\text{mm} \triangleq 40$ GHz it is

$$\alpha_{40\text{GHz}} = \frac{2\pi}{6\text{ mm}}\sqrt{1-\left(\frac{6\text{ mm}}{7.5\text{ mm}}\right)^2} = \frac{0.628}{\text{mm}},$$

which results in an attenuation of

$$a_{40\text{GHz}}[\text{dB}] = 8.686\frac{0.628}{\text{mm}}12.7\text{ mm} \approx 69{,}3\text{ dB}.$$

For $\lambda_0 = 15\text{ mm} \triangleq 20$ GHz and $\lambda_0 = 30\text{ mm} \triangleq 10$ GHz, we get attenuations of

$$a_{20\text{GHz}}[\text{dB}] = 105.9\text{ dB}$$

and

$$a_{10\text{GHz}}[\text{dB}] = 113.2\text{ dB}.$$

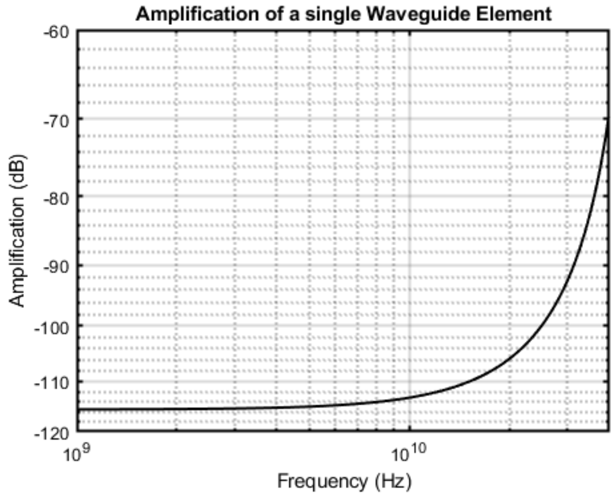

Fig.6. Negative Amplification for l=12.7mm, a=3mm

These relations imply that there is a basic attenuation which is dependent on the geometrical ratio l/a, so there is a contrarious influence of the length and the diameter of the single elements. In Fig. 6 we can see the plot of the attenuation for the given waveguide element.

The attenuation properties of a single waveguide element are suitable for achieving good shielding with little effort and simple scaling through the waveguide length. The practical implementation is an array of many parallel waveguide elements. Due to complex interactions, it is not possible to create a universal analytical description of the whole structure, which is why a numerical 3D simulation with CST was performed to verify the properties. The absolute wall/foil thickness for the single elements is not critical because the skin effect prevents the current at high frequencies to penetrate the material:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}.$$

The material of the structure is chosen in attention of the attenuation, robustness, corrosion resistance and cost. Common materials are aluminum, brass and different steels [7].

The simulation model is made of a quadratic honeycomb grid of parametrized geometrical dimension. As a material we have chosen brass because of its strong damping properties. We are interested in the influence of l and a. For very small l, the structure can be considered more as a lattice than a longish waveguide, so $l/a \ll 1$. Parameters used were $a = 3.18$ mm and $a = 6$ mm. For each of them, the length of the elements is varied at 1 mm, 20 mm, 40 mm and 80 mm. The results are shown in figure 5. In Figure 7 we can see an example field distribution for a single point in time in a cross-section plane of the model.

It has been found that increasing length has an improvement in damping properties to some extent, but this is somewhat non-linear. Furthermore, a constant l/a does not provide the identical damping characteristics. In this structure, the length of the comb-elements must be greater than their diameter, otherwise the attenuation gets worse.

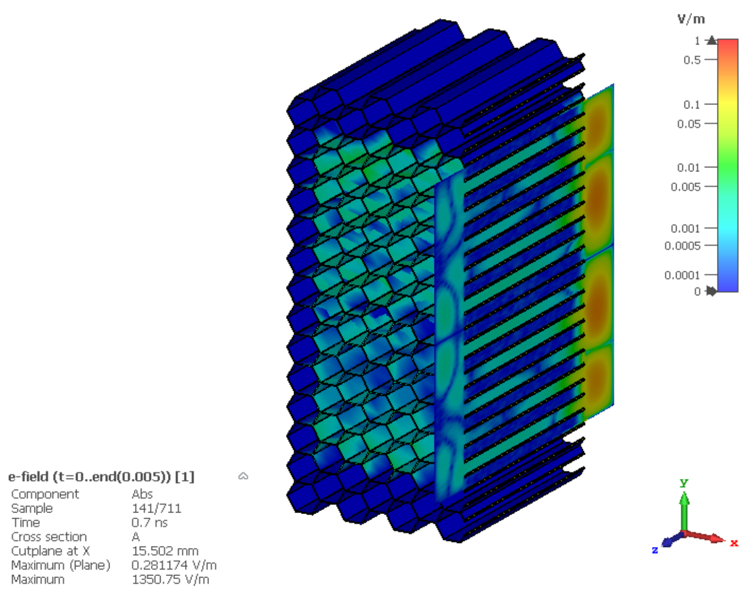

Fig.7. Example field distribution in the structure

B. Vacuum technology related considerations

The small honeycomb openings obstruct the gas flow necessary to maintain the vacuum in the tank (chamber1) in front of the test cylinder housing the ion thruster. The pressure in chamber 1 should not exceed a few 10^{-5} mbar, even at maximum ion current, to ensure a largely undisturbed beam. In this pressure range gas particles (Xenon) show molecular flow behavior. The honeycomb can be regarded approximately as a group of round pipes connecting the two tank compartments (chamber 1 and 2). For the calculation of the achievable pressure at a given pV flow q_{pV} (throughput) the following relationship exists [8]:

$$q_{pV} = \frac{\bar{c}}{4} \cdot A \cdot P \cdot (p_1 - p_2)\,.$$

with

$$\bar{c} = \sqrt{\frac{8\,k\,T}{\pi\,m_T}},$$

the mean particle velocity of Xenon at 20°C (293K) is 218 m/s. According to [8], the passage probability P for molecular flows through circular tubes (with diameter d and any length l) is calculated by

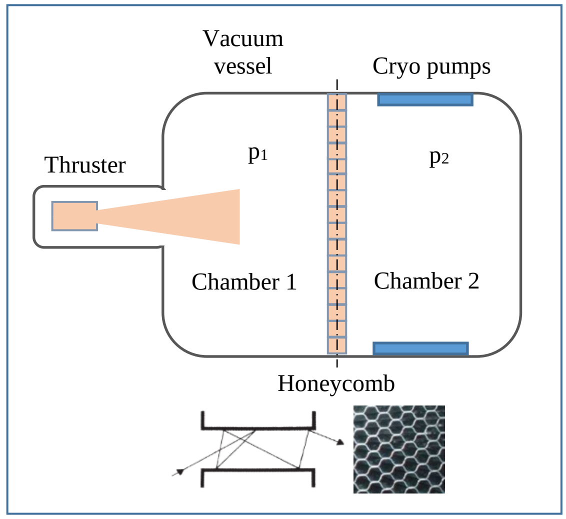

Fig.8. Structure of the Honey Comb arrangement

$$P = \frac{14 + 4\frac{l}{d}}{14 + 18\frac{l}{d} + 3\left(\frac{l}{d}\right)^2}.$$

eq. <1>

For $4 < l/d < 10$ the formula becomes P ≈ d/l with an accuracy of +-10%.

For suitable honeycomb dimensions with $4 < l/d < 10$ (e.g. $d = 1/8$“, $l = 1/2 \ldots 1$") eq. <1> can be converted to

$$p_1 - p_2 \approx q_{pV} \frac{4l}{c \cdot A \cdot d}$$

The test stand planned in Giessen has a vacuum tank diameter of 2.50 m. The planned honeycomb will have a flow cross-section A of approx. 1.8 m² and is operated with Xenon. With an assumed gas flow of 10 sccm (≈ 0.182 mbar l/s) and $d = 1/8$" and $l = 1$" ($l/d = 8$), a pressure difference of $1.48 \cdot 10^{-5}$ mbar is calculated. At a cryopump gasflow power of 27500 l/s (0.5 m² area) $p_2 = 0.66 \cdot 10^{-5}$ mbar. From this the final pressure will be: $p_1 = 2.08 \cdot 10^{-5}$ mbar - a reasonable operating pressure for ion thrusters.

III. Conclusions

The Reverberation Chamber is suitable as a supplement to the absorber chamber at higher frequency range. Due to the high quality of the Reverberation Chamber it offers advantages for immunity measurements in the high frequency range, since the RF power required to achieve the standard field strength of 20V/m is considerably lower than with the absorber chamber.

When using the more universal, but more complex absorber chamber with vacuum tank, a honeycomb chimney is suitable for shielding high-frequency interferences for almost perfect standard-compliant measurements. The concept presented here is currently being put into practice.

As expected, longer honeycomb chimneys provide the damping above 100dB required for standard-compliant measurements. The damping values achieved by calculation and simulation are essentially the same. For the simulated measurements it was shown that the transparency of the honeycomb chimney for xenon is sufficient under vacuum aspects.

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