The SpaceDrive Project – First Results on EMDrive and Mach-Effect Thrusters

BARCELO RENACIMIENTO HOTEL, SEVILLE, SPAIN / 14 – 18 MAY 2018

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KEYWORDS: Breakthrough Propulsion, Propellant-less Propulsion, EMDrive, Mach-Effect Thruster

ABSTRACT:

Propellantless propulsion is believed to be the best option for interstellar travel. However, photon rockets or solar sails have thrusts so low that maybe only nano-scaled spacecraft may reach the next star within our lifetime using very high-power laser beams. Following into the footsteps of earlier breakthrough propulsion programs, we are investigating different concepts based on non-classical/revolutionary propulsion ideas that claim to be at least an order of magnitude more efficient in producing thrust compared to photon rockets. Our intention is to develop an excellent research infrastructure to test new ideas and measure thrusts and/or artefacts with high confidence to determine if a concept works and if it does how to scale it up. At present, we are focusing on two possible revolutionary concepts: The EMDrive and the Mach-Effect Thruster. The first concept uses microwaves in a truncated cone-shaped cavity that is claimed to produce thrust. Although it is not clear on which theoretical basis this can work, several experimental tests have been reported in the literature, which warrants a closer examination. The second concept is believed to generate mass fluctuations in a piezo-crystal stack that creates non-zero time-averaged thrusts. Here we are reporting first results of our improved thrust balance as well as EMDrive and Mach-Effect thruster models. Special attention is given to the investigation and identification of error sources that cause false thrust signals. Our results show that the magnetic interaction from not sufficiently shielded cables or thrusters are a major factor that needs to be taken into account for proper µN thrust measurements for these type of devices.

1. INTRODUCTION

Interstellar travel is one of mankind's biggest dream and challenge. Rockets routinely put spacecraft into Earth's orbit, however Tsiolkovsky's equation puts a strong limit on the achievable Δv if onboard propellant is used, even using advanced materials and futuristic engines. For example, even nuclear propulsion with a specific impulse of 10,000 s or more (nuclear pulse, combined electric/nuclear, fusion propulsion, etc.) requires a propellant mass on the order of the mass of our sun to propel a spacecraft to our nearest star within our lifetime [1].

Recent efforts therefore concentrate on using propellantless laser propulsion. For example, the proposed Breakthrough Starshot project plans to use a 100 GW laser beam to accelerate a nano-spacecraft with the mass of a few grams to reach our closest neighbouring star Proxima Centauri in around 20 years [2]. The technical challenges (laser power, steering, communication, etc.) are enormous but maybe not impossible [3]. Such ideas stretch the edge of our current technology. However, it is obvious that we need a radically new approach if we ever want to achieve interstellar flight with spacecraft in size similar to the ones that we use today. In the 1990s, NASA started its Breakthrough Propulsion Physics Program, which organized workshops, conferences and funded multiple projects to look for high-risk/high-payoff ideas [4]. The project culminated in a book that summarized the ideas studied and presented a roadmap with unexplored areas to follow up [5].

Within the SpaceDrive project [6], we are currently assessing the two most prominent thruster candidates that promise propellantless propulsion much better than photon rockets: The so-called EMDrive and the Mach-Effect thruster. In addition, we are performing complementary experiments that can provide additional insights into the thrusters under investigation or open up new concepts. In order to properly test the thruster candidates, we are constantly improving our thrust balance facility as well as checking for thruster-environment interactions that can lead to false thrust measurements.

Our goal is to falsify if these thrusters work as claimed and to identify and understand the working mechanisms that could enable to upscale them towards flight applications. This paper will review the first results so far.

2. SpaceDrive Project

2.1 Thrust Balance

Testing of propellantless propulsion concepts requires a highly sophisticated thrust balance that must be able to reliably detect very small thrust with a resolution down to the nano-Newton range, block electromagnetic interactions as much as possible and limit any balance-vacuum chamber wall interactions. Vibration and thermal expansion/drifts are the two most important artefacts that must be carefully isolated to obtain reliable measurements.

The basis for our measurements is a torsion balance in our large vacuum chamber (0.9 m diameter, 1.5 m length) that has undergone various improvements over more than 4 years. A thrust produces an angular displacement that can be measurement by a laser interferometer. We use two C-flex E-20 torsion springs with a high enough sensitivity (2x0.0033 Nm/°) to achieve sub-µN resolution while supporting enough weight on the balance arms. The vacuum chamber uses a vibration isolated Edwards XDS35i scroll pump and a Pfeiffer 2300 L turbo pump to reach a vacuum down to the 10^{-7} mbar range. For the tests on the EMDrive and Mach-Effect thruster, only the scroll pump was used with a vacuum level of 10^{-2} mbar, which was sufficient to suppress buoyancy for quicker turnaround times. The vacuum chamber is fixed to a separate concrete block that is mounted with vibration isolation to decouple it from the vibrations in the building's foundation (see Fig. 1). Based on our prior experiments with Mach-Effect and EMDrive thrusters, an upgraded balance has been built with the following features:

- A total weight of up to 25 kg of thruster and electronics can be installed on the balance. There are two separately-shielded boxes on each side: one for the thruster assembly and one for the electronics and data acquisition.
- Thrust noise reduced to the nano-Newton range with a sub-Nanonewton resolution. We use the attocube IDS 3010 laser displacement sensor with pm resolution to digitally read out the balance position.
- Variable damping using eddy-currents and permanent magnets. A stepper motor can change the position of a copper disc to adapt the strength of damping.
- Stepper motors to level the balance once it is completely set-up inside the vacuum chamber.
- Stepper motors to change the orientation of the thruster. This enables us to investigate e.g. shifts in the center of gravity due to thermal expansion by changing the thruster direction from forward to backward and observing the change in the thrust measurement. All this can be done inside the vacuum chamber without breaking vacuum and changing any cables that can influence the analysis.
- Two different calibration techniques, one using a voice coil and one using electrostatic combs that provide constant thrusts by applying a defined current (coil) or voltage (comb) which was calibrated with a dedicated setup using a Sartorius AX224 balance.
- Complete shielding of the balance arm and thruster/electronics boxes using high permeability Mu-metal.
- Wireless control of experiment by on-board data acquisition using either Weeder modules or a LabJack T7 Pro using an infrared serial port. This allows analog input/output, digital control of relays as well as temperature measurements on the balance. In addition, we added infrared cameras that can detect overheating of the electronics and the thruster.
- Four pairs of liquid-metal-contacts with twisted, paired cables to supply the balance and experiments with power and other data signals (see Fig. 2).
- LabView program that can operate and control the complete vacuum facility, thrust balance and experiments. A script language is used to automate the whole experiment, from calibration to measurement. This procedure ensures repeatable measurements and allows to check the validity of the balance calibration and perform signal averaging and filter operation to obtain very low noise signals.

A picture of the vacuum chamber as well as the schematic of the balance is shown in Fig. 1. All calibration and thruster experiments are executed using profiles with a down-time (sector 1), a ramp-up (sector 2), a constant thrust (sector 3), a ramp-down (sector 4) and again down-time (sector 5) interval. Each profile can be checked individually and data processing like drift compensation or filtering can be applied. Drift compensation can be done with many different options like using a linear or polynomial fit through sector 1 and 5 and subtraction from the profile. Since the thrusters heated up during testing, a thermal drift compensation technique was used where first a linear fit is performed in sector 1 and 5 and a straight line is used to connect the end of sector 1 to the beginning of sector 5 to account for any thermal drifts (see Fig. 5). Profiles can be repeated many times and a signal averaged plot can be computed that can drastically reduce noise and increase signal confidence.

An example of a one µN calibration pulse is shown in Fig. 3 using our voice coil. The low noise (<10 nN) as well as the damping and drift elimination is clearly evident. We performed calibration pulses along a wide range with small steps as shown in Fig. 4 that shows the high linearity of our balance. This figure also shows how the calibration constant (µN/µm) changes for different setups with different weights. A calibration is automatically performed before and after each thrust measurement to check for any changes in the balance sensitivity.

2.1 EMDrive

The EMDrive is a concept developed by Shawyer [7] in which microwaves are directed into a truncated resonator cavity/frustum which is claimed to produce thrust. He believes that the radiation pressure is different at the small and large ends which results in a net thrust force [8]. This was highly criticized as not being compatible with electromagnetism and conservation laws [9]. Alternative theories have appeared [10]–[12], however, the community remains highly sceptical on the theoretical grounds of this concept.

On the other hand, there is a significant amount of experimental data available with tests both on a normal/knife-edge [13],[14] as well as on a torsion balance [15]–[17]. Initial concern concentrated on buoyancy effects due to testing in air, however, the more recent tests in high vacuum [17], especially NASA's latest test results by White et al [16] revealed that air is not an issue. Several experimental artefacts still need to be examined and higher quality thrust data must be obtained in order to validate the production of thrust. Thermal drifts were especially significant in the latest reported test by White et al. [16] and possible magnetic interaction with feeding cables has yet to be assessed.

We built a frustum cavity with the same inner dimensions as in White et al [16], however, instead of hand-cut copper sheets and copper plated PCBs, our cavity geometry was manufactured from 1.5 mm thick copper sheets that were pressed into the correct geometry (see Fig. 6). Afterwards, the inner surfaces were polished. We used standard SMA/N-Type connectors throughout all components. A picture of our loop antenna (1.5 mm wire, 15 mm radius) is also shown in Fig. 6 as well as the complete EMDrive with cavity and all related electronics on one side of the torsion balance. Because of the size of the cavity, we could not encapsulate it yet with Mu-metal sheets to reduce possible magnetic interactions. This will be crucial in the next step as we will explain below.

The resonance frequencies and Q-factors of the cavity were analysed using an Anritsu MS46121B vector network analyser. Using a Maury 1878B 3-stub tuner, we matched a frequency of 1865 MHz and obtained Q-factors from 20,000 – 300,000+ (unloaded) depending on the peak (see Fig. 7). This is similar and even higher than the values reported by White et al [16] and should lead to at least similar thrust values if not more as the Q-factor is believed to be directly related to the generated thrust [7]. COMSOL simulations were carried out to simulate the generated modes within the cavity and to find the optimum position for the antenna (see Fig. 8).

The EMDrive setup is shown in Fig. 9 which consists of a frequency generator/oscillator (Mini-Circuits ZX95-2041-S+), a voltage-controlled attenuator (Mini-Circuits ZX73-2500-S+), a 50 W amplifier (RF Systems EMPower 1164), a bi-directional coupler (Mini-Circuits ZGBDC35-93HP+) with power-meters for input and reflected output (Mini-Circuits ZX47-40-S+), an optional fixed 40 dB attenuator (Mini-Circuits BW-40N100W+), the Maury 3-stub tuner and the cavity. All these components could be operated in vacuum without modification (a small venting hole was present in the cavity and one screw was removed from the Mini-Circuits components), however, we were cautiously operating them only up to a power of 2 Watts to prohibit overheating (several thermocouples are used to monitor the temperature). The optional 40 dB attenuator allows to reduce the power by a factor of 10,000 that goes into the cavity without changing cables or setup. This provides a powerful "zero-thrust" measurement capability. Our software features resonance frequency tracking to compensate for frequency shifts during operation.

Using the stepper motor, we could rotate the thruster on our balance such that it points in different directions. In our setup, 0° direction means a positive thrust direction (going from the large back area on the cavity to the smaller front area), 180° direction means a reversed or negative thrust direction and 90° means that the thruster points parallel to the balance arm, which should result in zero thrust.

Fig. 10 shows thrust measurements for our EMDrive in all directions with around 4 µN at an amplifier power level of 2 Watts, which corresponds to an amplifier current of around 2.5 A. The maximum temperature on the amplifier was going up to 75 degrees. The Q factor in this case was 50,000 (unloaded). This leads to a thrust-to-power ratio of around 2 mN/kW, which is nearly double compared to White et al [16] who measured 1.3 mN/kW for a Q factor of 40,900 (their absolute thrust value was 80 µN for 60 W of power). The thrust direction also seems to reverse for the 180° direction. However, at 90° we see a similar thrust as in the 180° direction, where we should expect zero thrust. Even more importantly, if we keep the 0° direction but use the 40 dB attenuator to reduce the power that goes into the cavity by 5 orders of magnitude, the thrust signal nearly remains the same as without the 40 dB attenuator.

This clearly indicates that the "thrust" is not coming from the EMDrive but from some electromagnetic interaction. Although we used twisted or coaxial cables as much as possible, some magnetic fields will eventually leak through our cables and connectors. Considering the magnetic field strength of the Earth's magnetic field of 48 µT with an inclination of 70° in middle Europe, a few centimeters of cables and a current of 2 A (similar to what is needed to power the amplifier), we obtain Lorentz forces of a few µN, which is similar to our observed "thrust" values. We therefore suspect, that the interaction of the power feeding for the amplifier with the Earth's magnetic field masked any real thrusts that could be below our observed value. In a next setup, we are enlarging our experiment box such that the cavity and amplifier configuration can be completely shielded with Mu-metal sheets to greatly reduce this artefact. However, such shielding was not present in any of the previous tests (e.g. in White et al [16]) which should be carefully re-analysed [18].

Note that we did not implement a dielectric disc in our cavity so far which was used in the configuration from White et al [16], although positive tests were claimed to have been carried without such discs too. After our setup improvement, we will try a dielectric disc configuration, different geometries as well as higher power levels.

2.2 Mach-Effect Thruster

The second concept to be studied in detail is the so-called Mach-Effect thruster which is being developed by J.F. Woodward since the 1990s and more recently by H. Fearn [19]–[22]. It is based on one interpretation of Mach's principle (inertia here is due to mass out there), that inertial mass is due to the gravitational interaction with the whole universe [23]. Woodward and others showed that linearized general relativity theory with time-varying solutions and Sciama's analysis altogether leads to mass fluctuations that can be up to 11 orders of magnitude higher for typical devices than classically expected from $E=m.c^2$ [24].

In the Mach-Effect thruster, a stack of clamped piezo crystals is excited using a frequency in the tens of kHz range. According to Woodward, this energy oscillations leads to transient Machian-mass variations that can lead to time-averaged stationary thrusts if they are properly pushed and pulled with the correct frequency and phase. This is believed to happen thanks to the piezoelectric and electrostrictive material properties of piezo crystals. Although at much smaller amplitudes, electrostriction happens at twice the applied frequency and at a 90° phase shift, which is required for stationary thrust [22],[24]. A large brass reaction mass can amplify this effect. A schematic sketch of the thruster as well as an actual thruster and a corresponding ANSYS model is shown in Fig. 11. We are working on analytical as well as finite element models to accurately predict the oscillation movements on the thruster (verified using laser vibrometry) in order to predict and enhance the thrust produced.

In order to operate the thruster, we built an amplifier based on the Apex PA04 amplifier that has a frequency range of up to 180 kHz (measured in our setup), 150 W and a voltage capability of 150 Vpp (voltage and power may be doubled using two amplifiers in bridge mode). This is significantly better compared to the audio amplifiers used so far that cut the power close to the thruster operating frequencies (≈35 kHz) [22],[25].

Fig. 12 shows the frequency response spectrum for a recent thruster supplied to us by Woodard and Fearn. The first resonance frequency is at 31 kHz. Our software can control the amplifier with various options such as using arbitrary waveforms (sine wave or e.g. mixed signals with single- and double-frequency signals at a proper phase shift) using a Picoscope 2405A oscilloscope that has an arbitrary waveform output. The current, voltage and phase signals are read back into the computer. Most importantly, we implemented a tracker that adapts the frequency e.g. to track for maximum current (=power). We can therefore operate always at resonance even if the thruster warms up during operation, which causes resonance frequency shifts.

The thruster was mounted inside the measurement box with Mu-metal shielding. The amplifier electronics were outside, and a liquid-metal feedthrough was used to power the thruster on the balance. Fig. 13 shows thrust results in all three directions (0°, 90° and 180°) for 150 Vpp and an applied sine wave at 31 kHz in vacuum. The apparent thrust has a value of 0.6 µN and indeed reverses for 180° and moreover also vanishes at 90° as expected. However, when we moved the thruster box back to the 0° direction and manually flipped only the thruster to 180°, while leaving all power cables the same, the thruster signal remained the same as in the 0° direction. This again indicates that there must be some electromagnetic interaction or thermally induced center of mass shift that is masking any real thrust value.

Woodward measured a steady thrust with this thruster of around -1.2 µN for 400 Vpp as well as large switching thrust transients during on-off. Previous data suggests a V^4 scaling of thrust with applied voltage [21]. We therefore expect only 0.02 µN which may be present in our thrust data but masked by electromagnetic/thermal issues. In a next step, we need to increase our voltage and reduce our thermal and electromagnetic interactions to safely assess this thrust range.

3. Conclusions

The SpaceDrive project aims at developing cutting-edge measurement equipment to thoroughly test the latest EMDrive and Mach-Effect thruster models, the two most promising revolutionary thruster concepts that are presently under investigation at various labs. Our thrust balances shall provide the necessary resolution and investigate electromagnetic and thermal artefacts to obtain reliable measurements in order to confirm or refute the claimed thrusts.

First measurement campaigns were carried out with both thruster models reaching thrust/thrust-to-power levels comparable to claimed values. However, we found that e.g. magnetic interaction from twisted-pair cables and amplifiers with the Earth's magnetic field can be a significant error source for EMDrives. We continue to improve our measurement setup and thruster developments in order to finally assess if any of these concepts is viable and if it can be scaled up.

In addition, a number of complementary experiments are carried out to investigate e.g. Machian-mass variations with an alternative rotary setup [6].

At least, SpaceDrive is an excellent educational project by developing highly demanding test setups, evaluating theoretical models and possible experimental errors. It's a great learning experience with the possibility to find something that can drive space exploration into its next generation.

Acknowledgements

We gratefully acknowledge the support for SpaceDrive by the German National Space Agency DLR (Deutsches Zentrum fuer Luft- und

Raumfahrttechnik) by funding from the Federal Ministry of Economic Affairs and Energy (BMWi) by approval from German Parliament (50RS1704). We would also like to acknowledge the support from J. Heisig, W. Stark, C. Holzapfel, J. Woodward and H. Fearn for their contributions to the ongoing experiments.

References

[1] Tajmar, M., *Advanced Space Propulsion Systems*, Vienna: Springer Vienna, 2003. doi:10.1007/978-3-7091-0547-4

[2] Daukantas, P., “Breakthrough Starshot,” *Optics and Photonics News*, vol. 28, 2017, pp. 26–33.

[3] Lubin, P., “A Roadmap to Interstellar Flight,” *JBIS - Journal of the British Interplanetary Society*, vol. 69, 2016, pp. 40–72.

[4] Millis, M. G., “NASA Breakthrough Propulsion Physics Program,” *Acta Astronautica*, vol. 44, Jan. 1999, pp. 175–182. doi:10.1016/S0094-5765(99)00045-4

[5] Millis, M. G., and Davis, E. W., eds., *Frontiers of Propulsion Science*, Reston ,VA: American Institute of Aeronautics and Astronautics, 2009. doi:10.2514/4.479953

[6] Tajmar, M., Kößling, M., Weikert, M., and Monette, M., “The SpaceDrive Project – Developing Revolutionary Propulsion at TU Dresden,” *International Astronautical Congress*, 2017, p. IAC-17,C4,7-C3.5,10,x38595.

[7] Shawyer, R., “Second Generation EmDrive Propulsion Applied to SSTO Launcher and Interstellar Probe,” *Acta Astronautica*, vol. 116, 2015, pp. 166–174. doi:10.1016/j.actaastro.2015.07.002

[8] Shawyer, R., “A Theory of Microwave Propulsion for Spacecraft” Available: https://www.newscientist.com/data/images/ns/av/shawyertheory.pdf

[9] Costella, J. P., “Why Shawyer’s ‘electromagnetic Relativity Drive’ Is a Fraud” Available: http://johncostella.webs.com/shawyerfraud.pdf

[10] Grahn, P., Annila, A., and Kolehmainen, E., “On the Exhaust of Electromagnetic Drive,” *AIP Advances*, vol. 6, Jun. 2016, p. 65205. doi:10.1063/1.4953807

[11] McCulloch, M. E., “Testing Quantised Inertia on Emdrives with Dielectrics,” *EPL (Europhysics Letters)*, vol. 118, May 2017, p. 34003. doi:10.1209/0295-5075/118/34003

[12] Montillet, J.-P., “Theory of the EM-Drive Based on Mach-Lorentz Theory,” *Proceedings of the Estes Park Advanced Propulsion Workshop*, H. Fearn and L. Williams, eds., Mojave: Space Studies Institute Press, 2017, pp. 111–126.

[13] Shawyer, R. J., “Technical Report on the Experimental Microwave Thruster” Available: http://www.emdrive.com/FeasibilityStudytechnicalreportissue2.pdf

[14] Shawyer, R., “Technical Report on the Development of a Microwave Engine for Satellite Propulsion” Available: http://www.emdrive.com/DemonstratorTechnicalReportIssue2.pdf

[15] Brady, D., White, H., March, P., Lawrence, J., and Davies, F., “Anomalous Thrust Production from an RF Test Device Measured on a Low-Thrust Torsion Pendulum,” *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 2014, p. AIAA 2014-4029. doi:10.2514/6.2014-4029

[16] White, H., March, P., Lawrence, J., Vera, J., Sylvester, A., Brady, D., and Bailey, P., “Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum,” *Journal of Propulsion and Power*, vol. 33, Jul. 2017, pp. 830–841. doi:10.2514/1.B36120

[17] Tajmar, M., and Fiedler, G., “Direct Thrust Measurements of an EMDrive and Evaluation of Possible Side-Effects,” *51st AIAA/SAE/ASEE Joint Propulsion Conference*, 2015, p. AIAA 2015-4083. doi:10.2514/6.2015-4083

[18] Li, A. Y., and Li, S. A., “An Experiment About Parallel Circuit And The Lorentz Forces On Wires” Available: http://arxiv.org/abs/1510.07752

[19] Woodward, J. F., “A New Experimental Approach to Mach’s Principle and Relativistic Graviation,” *Foundations of Physics Letters*, vol. 3, Oct. 1990, pp. 497–506. doi:10.1007/BF00665932

[20] Fearn, H., Zachar, A., Wanser, K., and Woodward, J., “Theory of a Mach Effect Thruster I,” *Journal of Modern Physics*, vol. 6, 2015, pp. 1510–1525. doi:10.4236/jmp.2015.611155

[21] Fearn, H., Rossum, N. van, Wanser, K., and Woodward, J. F., “Theory of a Mach Effect Thruster II,” *Journal of Modern Physics*, vol. 6, 2015, pp. 1868–1880. doi:10.4236/jmp.2015.613192

[22] Woodward, J. F., *Making Starships and Stargates*, New York, NY: Springer New York, 2013. doi:10.1007/978-1-4614-5623-0

[23] Sciama, D. W., “On the Origin of Inertia,” *Monthly Notices of the Royal Astronomical Society*, vol. 113, Feb. 1953, pp. 34–42. doi:10.1093/mnras/113.1.34

[24] Tajmar, M., “Mach-Effect Thruster Model,” *Acta Astronautica*, vol. 141, Dec. 2017, pp. 8–16. doi:10.1016/j.actaastro.2017.09.021

[25] Buldrini, N., “Verification of the Thrust Signature of a Mach Effect Device,” *Proceedings of the Estes Park Advanced Propulsion Workshop*, H. Fearn and L. Williams, eds., Moja: Space Studies Institute Press, 2017, pp. 83–88.

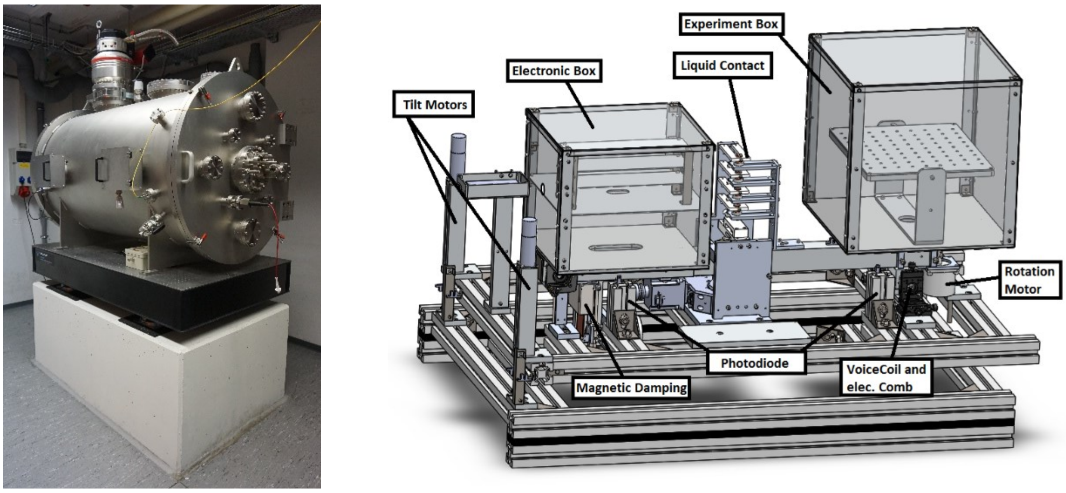


Fig. 1 Vacuum Chamber on Concrete Block (Left) and Schematic Sketch of Thrust Balance (Right)

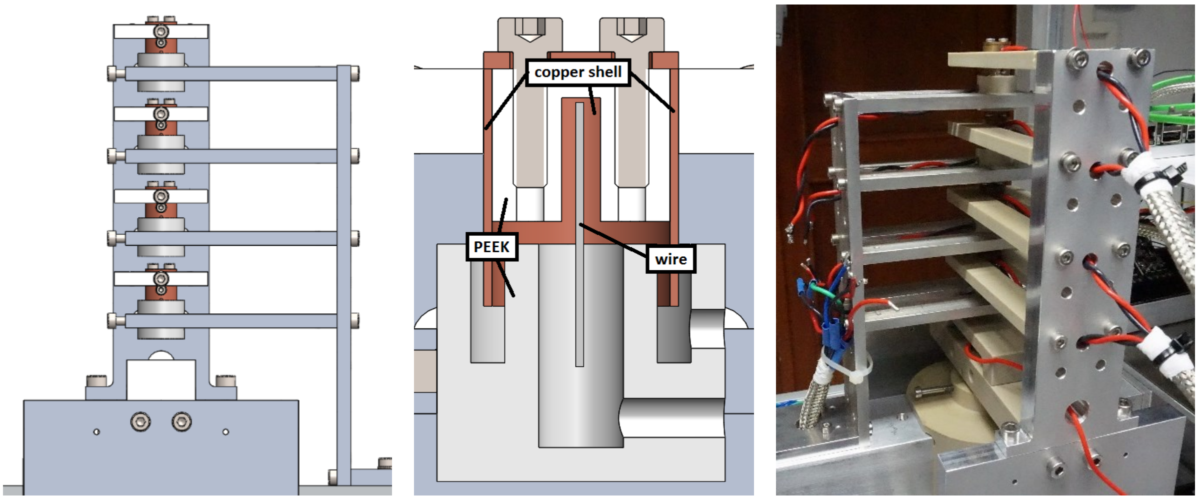


Fig. 2 Liquid Metal Contacts

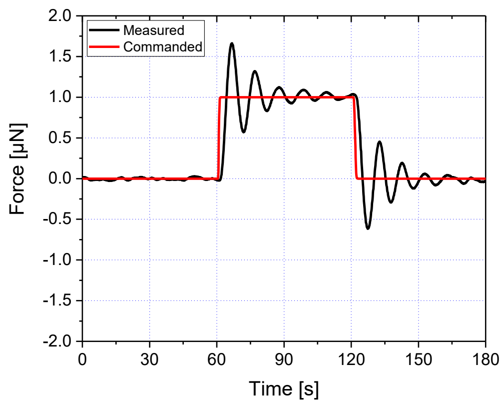


Fig. 3 Voice Coil 1 µN Step Response (200 Profiles Averaged)

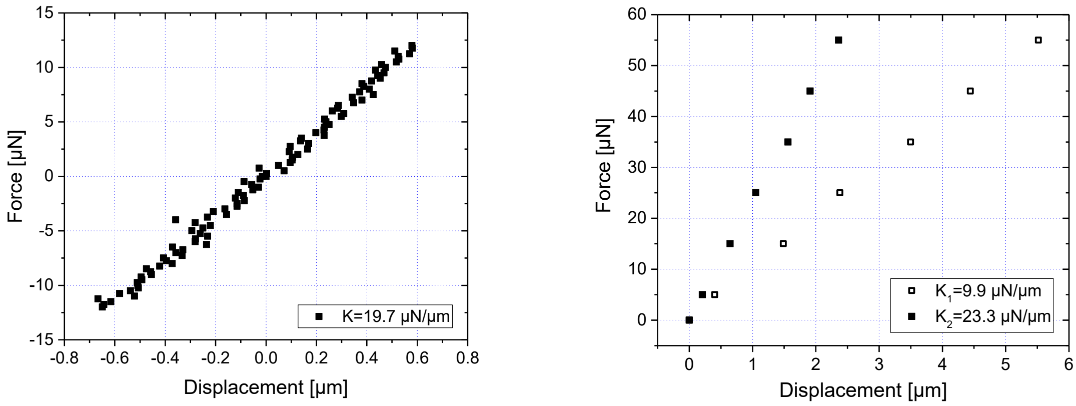


Fig. 4   Calibration Linearity: 0.25 µN Steps (Left) and Different Slopes for Different Setups/Weights (Right)

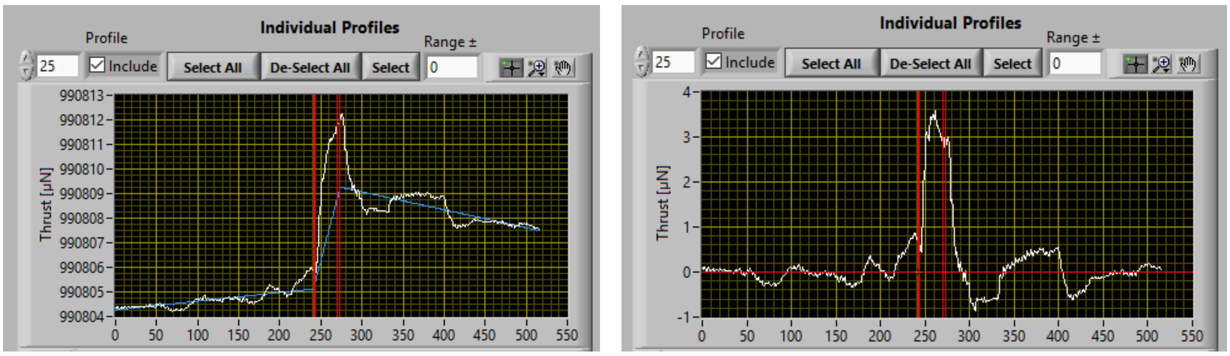


Fig. 5   Thermal Drift Compensation: Original Thrust Profile (White) and Drift Compensation Fitting Line (Blue) – Left, Compensated Thrust Profile without Thermal Drift – Right

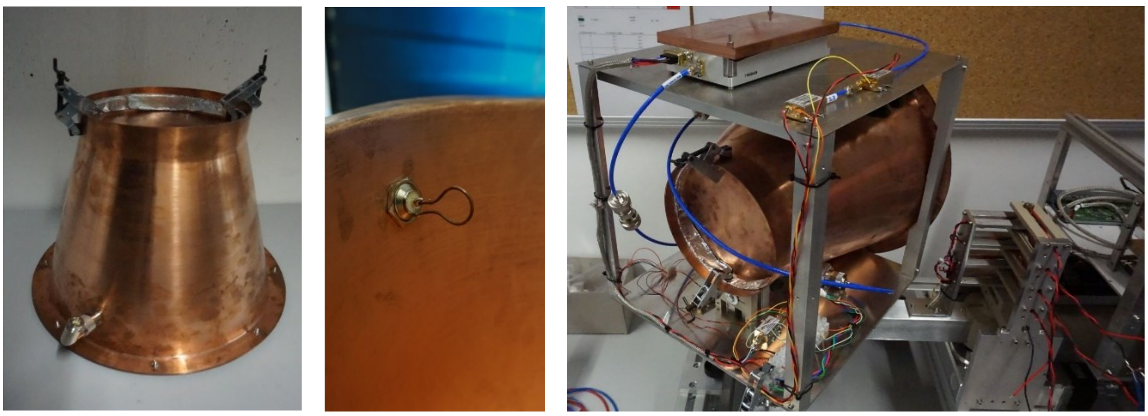


Fig. 6   EMDrive Thruster: Cavity (Left), Antenna (Middle) and On Balance (Right)

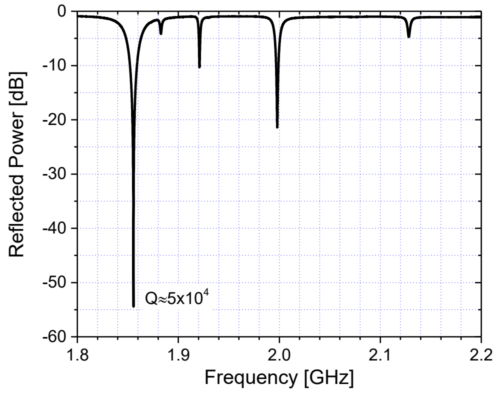


Fig. 7 Cavity S11 Reflection Plot from Vector Network Analyzer (Matched 1865 MHz via 3-Stub Tuner)

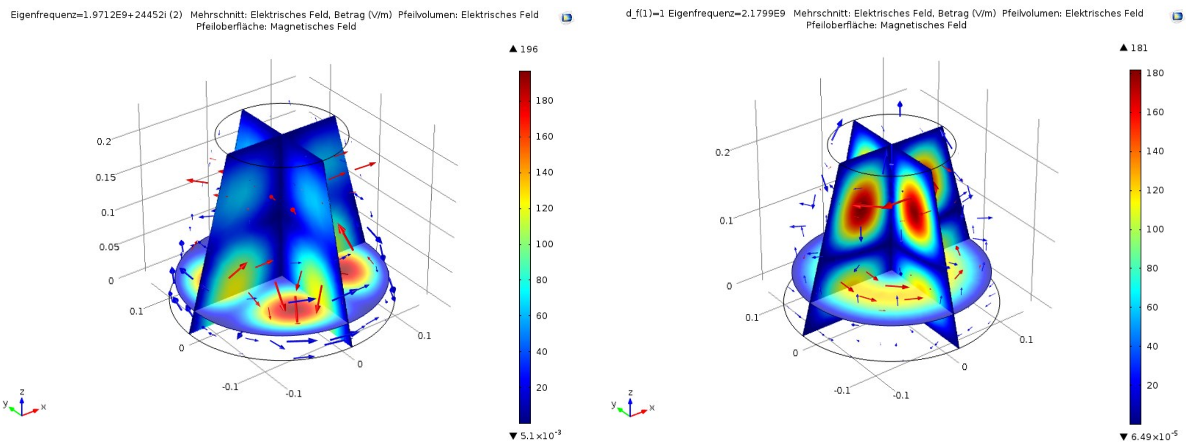


Fig. 8 EMDrive COMSOL Simulation (TM212@1971 MHz – Left, TE012@2179 MHz – Right)

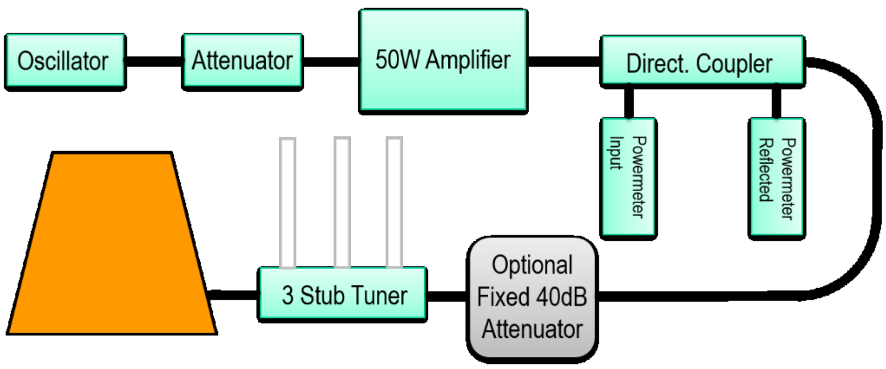
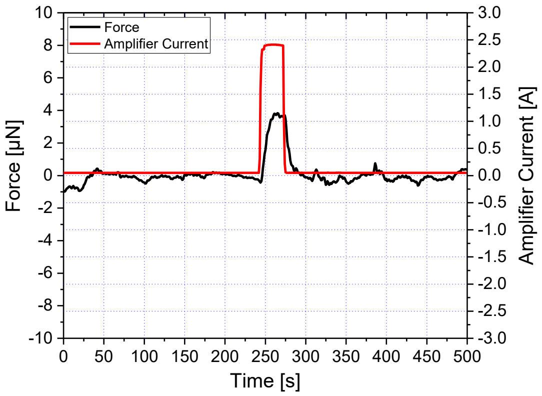
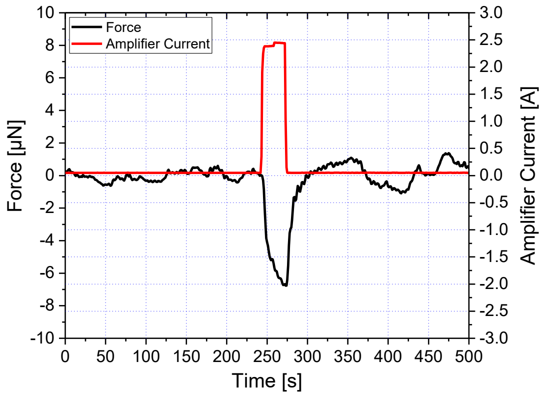


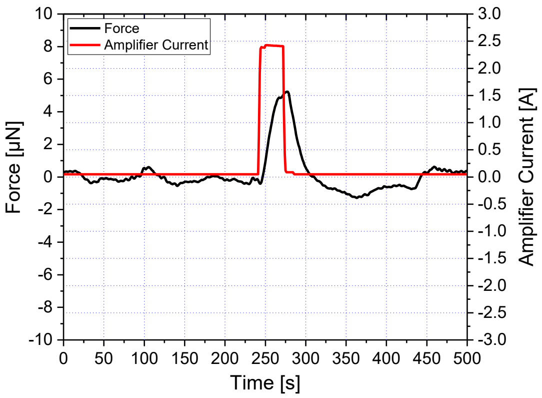
Fig. 9 EMDrive Setup



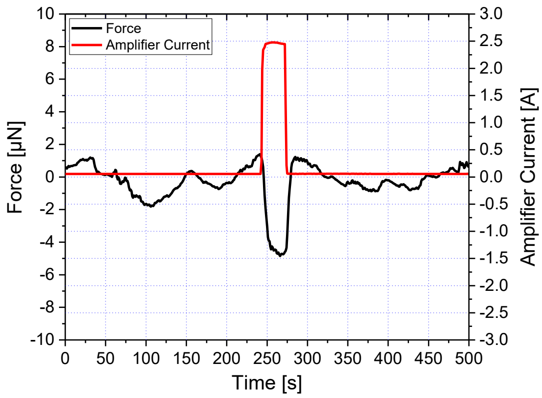
(a) Direction 0°



(b) Direction 180°

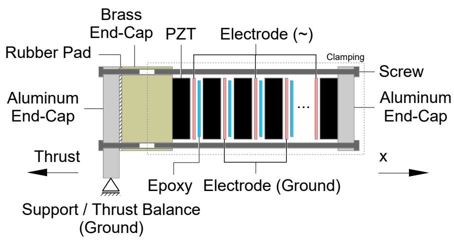


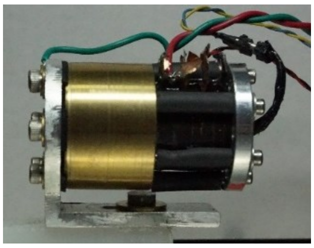
(c) Direction 0° with 40db Attenuator



(d) Direction 90°

Fig. 10 EMDrive Thrust Measurements with 2 W in Vacuum (10^{-2} mbar), 40 Runs Averaged





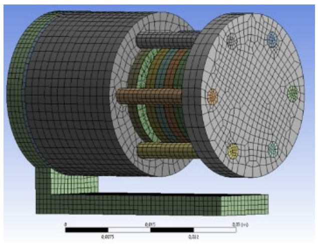


Fig. 11 Mach-Effect Thruster (MET): Schematic Sketch (Left) [24], Thruster under Testing (Middle) and ANSYS Model (Right)

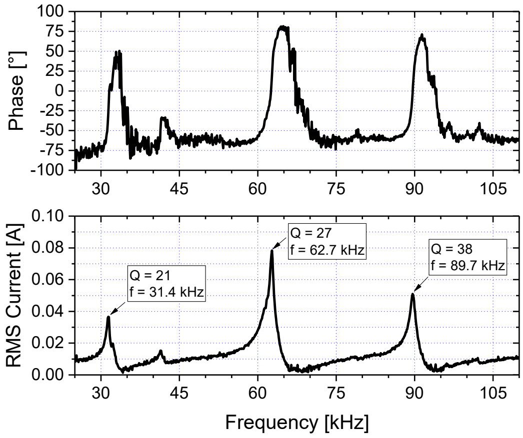
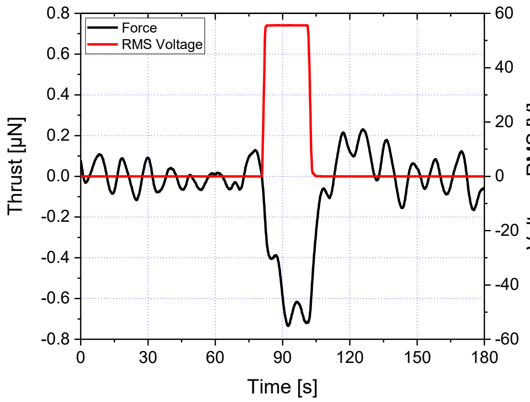
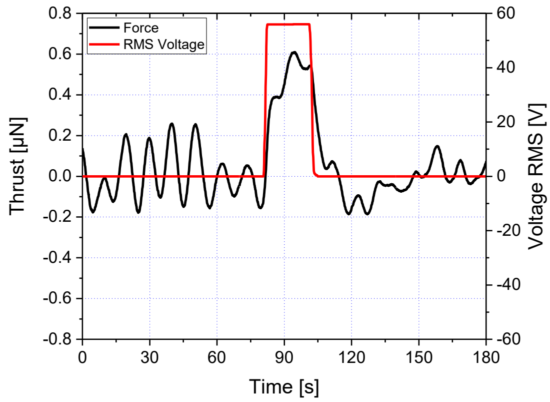


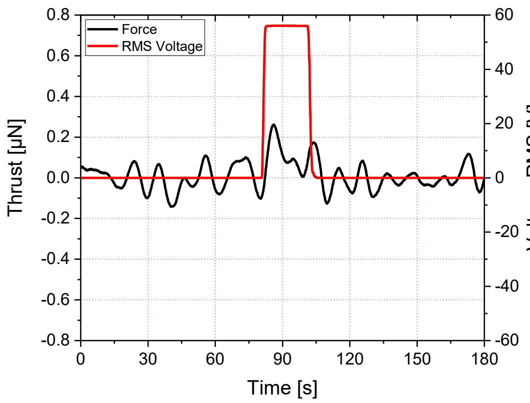
Fig. 12 Mach-Effect Thruster Spectrum



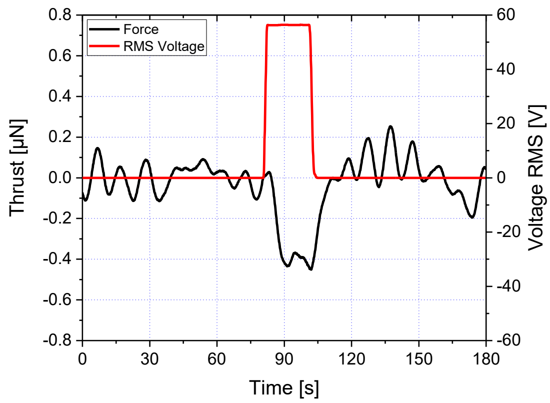
(a) Direction 0°



(b) Direction 180°



(c) Direction 90°



(d) Direction 180° - Only Thruster Rotated

Fig. 13 MET Thrust Measurements in Vacuum (10^{-2} mbar) at 150 Vpp, 200 Runs Averaged