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The SpaceDrive Project – Overview of Revolutionary Propulsion Efforts at TU Dresden

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Abstract

Interstellar propulsion within a human lifetime is the ultimate challenge for space travel to which no technological solution exists as of today. Traditional concepts such as solar sails or photon rockets require gigantic energy sources and may only enable nano-scaled spacecraft to go on a one-way trip. At TU Dresden, we are looking into non-traditional approaches for revolutionary propulsion by building a unique infrastructure to test and investigate claims on new propellantless thrusters as well as to explore new ideas in that area. 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 that warrants a closer examination. The second concept is believed to generate transient mass fluctuations in a piezo-crystal stack that creates non-zero time-averaged thrust. Within the SpaceDrive project, a number of unique thrust balances and sensors are under development that can reliably detect tiny forces for such devices, which are powered by high voltages and high frequencies including two different classical torsion balances, a double-pendulum balance as well as a new superconducting levitating friction-free balance. In addition, a number of complementary experiments are carried out, such as direct measurements of mass-fluctuations in a dedicated rotating dynamic test stand. This paper will give an overview on our program and a summary of the latest results.

Keywords: Breakthrough Propulsion, Propellantless Propulsion, EmDrive, Mach-Effect-Thruster, Thrust Balance

Nomenclature

a	-	Acceleration [m/s^2]
g	-	Gravitational acceleration [m/s^2]

Abbreviations

DC	-	Direct Current
DUT	-	Device-Under-Test
MET	-	Mach-Effect Thruster
RF	-	Radiofrequency

1. Introduction

Aspirations of pushing human space exploration beyond our solar system are prohibited by the classical method of propulsion that requires propellants. There exist relatively few concepts of propellantless propulsion with our current understanding of physics; a simple photon rocket, or beamed propulsion as envisioned by Breakthrough Starshot [1]. The former has a theoretical thrust efficiency of 3.3 nN/W, while the latter only offers the possibility of a fly-by trip to the nearest star.

The purpose of the SpaceDrive project is to investigate unconventional means of propulsion for efficient interstellar travel [2]. Here we are following three important paths:

1. Development of balances with a sensitivity that is going beyond the current state-of-the art and allowing to power a variety of devices on that balances ranging from high voltage to high frequencies without affecting the balance itself. By accumulating experience in characterizing balance-device interactions, our group can validate claims of propellantless propulsion that seem to challenge our understanding of physics.
2. Testing the claims of propellantless-propulsion devices.
3. Performing complementary experiments targeting possible variations of mass, which is the key for a propellantless-propulsion scheme, as well as other relevant claims.

First, this paper describes four balances currently used at the institute to measure minute thrust. Then, a summary of the latest measurement campaigns for two of the tested peer-reviewed claims is presented: the Mach-Effect Thruster (MET) and the EmDrive.

Finally, four additional ongoing experiments are described consisting of a direct measurement of the mass change for the MET experiment, the Biefeld-Brown effect, a version of the Kaluza-Klein theory, as well as the relationship between temperature and mass.

2. Overview Thrust Balances

2.1. Introduction

Thrust measurement and validation for devices weighing more than one kilogramm can be performed using a variety of instruments. The most commonly used balance is a hanging pendulum balance. These balances can support large thrusters and typically achieve resolutions of around 100 µN, down to a few µN [3]. The biggest disadvantage is the change in behavior for thrusters having different masses. Using gravity as the restoring force, these balances are quite sensitive to shifts in the center of mass [4].

Torsion balances, on the other hand, are not influenced by gravity as long as the rotational axis is aligned with the gravitational field. In that case, relying solely on the torsional spring rate of the pivot, a better resolution is achieved with minimal complexity. The two most important parts of a torsion balance are the pivot, which provides the necessary restoring force, and the beam displacement reading. These two components determine the resolution of the balance [4]. Another important parameter is the moment of inertia of the beam, which, in relation with the pivot's spring constant, determines the response time of the balance. The torsion balances will also react to center of mass shifts e.g. triggered by thermal expansion, because the rotational axis will never be perfectly aligned with the gravitational field.

Having three anchoring points to the device platform, the double-pendulum balance is less sensitive to the shifts in the center of mass of the tested device. The construction, however, is a bit more complex than the torsion balance.

The instruments mentioned above all have a mechanical connection that ultimately limits the deflection of the device. Another variation is a rotation balance with a pivot consisting in a permanent magnet levitating over a superconductor cooled at cryogenic temperature, which leads practically friction-free thrust validation over a full rotation. This allows to verify if a thrust is really produced by the device or due to external influence (e.g. the Earth's magnetic field).

By operating our devices on all different thrust balances, we will be able to identify the real thrust cause and/or gain confidence that the device works as claimed. This full investigation is still ongoing and has not been finalized.

2.2. Torsion Balance v5

Our first torsion balance (Figure 1a) is used for large devices-under-test (DUT) with a mass of up to 10 kg (+10 kg counterweight mass for electronics) [5]. It uses two E-20 pivots by C-Flex and results in a calibration constant of around 7 µN/µm. Damping is done by an eddy-current brake, which consists in moving a copper plate between two neodymium magnets fixed to a U-shaped steel bracket. Electrical power is supplied through four coaxial, liquid contacts and the calibration is done with a LA05-05-000A voice coil by BeiKimco. Additionally, it has a separate, low-cost liquid feedthrough for radio frequency (RF) power. The beam, as well as the two experiment boxes are shielded with 0.5 mm thick mu-metal plates to reduce the influence of electromagnetic interactions.

2.3. Torsion Balance v6

The second torsion balance Figure 1b) was designed for light devices with masses lower than 1.5 kg resulting in higher resolution and shorter response times [6]. The lower mass of the DUT means a smaller pivot can be used. This balance uses two A-20 pivots by C-Flex, resulting in a calibration factor of around 0.34 µN/µm and a natural frequency of 0.067 Hz (period of 15 s). It also uses an eddy-current brake to damp the oscillations and four coaxial liquid contacts for power transmission. The calibration is done with a LVCM-010-013-01 voice coil by Moticont. In combination with the laser interferometer IDS3010 from attocube, a measurement noise of 2 to 10 nN can be achieved at a sampling frequency of 10 Hz.

The null test is an integral part of a test campaign to validate propellantless propulsion. In our case, the test consists in applying a force along an axis which should not result in any thrust: for instance, along the beam, or vertically pushing down on the beam. By applying a known force using our voice coil mounted parallel to the beam, the balance showed a response consisting in only 0.2% of the applied force. The response to the applied force is, as expected, very low, and is due to the beam not being perfectly parallel to the ground. Thus, aligning the theoretical thrust axis of the DUT with the beam should show significantly reduced force measurements, compared with the DUT oriented perpendicular to the beam in the horizontal plane.

Another null test consisted in a pulse test with a resistor and 0.8 A DC current. Although the results show a clear thermal drift due to heating of the resistor, the absence of switching on-off transients seem to eliminate the influence of electromagnetic interaction on the balance measurements.

2.4. Double Pendulum Balance

The first development to compare the results is a counterbalanced inverted pendulum thrust stand

(Figure 1c). Three main columns support the axial load of two base plates. The DUT is placed on the top plate while it is counterbalanced with weights on the bottom plate. The main columns are connected with the plates with a total sum of nine torsional springs that enable a deflection of the parallelogram, which depends on their stiffness. This type of balance counteracts the difficulties in center of mass shifts due to its bearing orientation. In case the center of mass is not aligned with the rotational axis of the system or shifts while the thruster is operating, solely the period of oscillation changes due to its pendulum-like behavior. Compared to the torsional type thrust balance these shifts do not lead to undesired deflections that indicate measurement errors.

This type of balance does not operate with the high resolutions of torsional type thrust balances, but eliminates many of its undesired interactions with the environment.

2.5. Rotation Balance

To clearly identify the presence of thrust we developed a new kind of rotation-based thrust balance. Its core function is to measure the change in angular acceleration of a magnetically levitated testbed inside a vacuum chamber onto which the thruster applies a torque [7]. This measurement principle is advantageous because mechanical work can be visualized directly. Previous measurement errors like center of mass shifts or vibration of balance components should not influence this type of balance. Instead, the most crucial objective is to enable full rotation of high rotating masses with thrust forces down to micronewtons. Therefore, the balance is based on magnetic levitation with high-temperature superconductors to provide a frictionless rotational degree of freedom around which the thrust concepts can accelerate in a space-like environment (see Figure 1d).

3. Mach-Effect-Thruster

3.1. Introduction

The MEGA drive or MET, invented and built by James F. Woodward, consists of a multi-layer piezoelectric stack, sandwiched between two different masses, that aims at producing thrust through the application of power in the Low Frequency range (Figure 2) [8]. Although the underlying principle remains unclear, peer reviewed literature mentions an observed thrust around 1-3 µN for an applied voltage of 200 V at a frequency around 36 kHz [9]. A detailed test description and previous measurement results within the SpaceDrive project can be found in Refs. [5], [6].

3.2. Experimental Setup

Experiments at TU Dresden used the same amplifier electronics and DUT as supplied by Woodward, and were performed on the torsion balance described in section 2.3, in a vacuum chamber with $8 \cdot 10^{-2}$ mbar atmosphere. For comparison purposes, the tests were repeated using in-house electronics that consist in dedicated power amplifiers (Figure 3). The MET was tested using different mounting configurations: the vibration isolation yoke from Woodward, and a direct gear connection with a copper heat sink (Figure 4). Frequency sweeps in a range of 24-48 kHz, and fixed frequency pulses of 16 s duration were commanded. The DUT was tested in four different orientations to examine the balance's response. In addition, beam vibration was observed with increased sampling frequency in a few cases.

3.3. Experimental Summary

Overall, the force observed on our torsion balance when driving the MET at the recommended frequency remained at least one order of magnitude below the claimed force. On the copper block and gear mounting, with Fullerton electronics, the switching on-off transients with an amplitude of 30 nN were observed to reverse with DUT orientation, but no steady force was observed (Figure 5a). With the DUT parallel to the balance beam, the same phenomenon was observed, although no thrust was expected (Figure 5b). Beam vibration observation with higher sampling frequency first revealed a 20 Hz sinusoidal disturbance of unknown origin, which is normally averaged out by the attocube software. Moreover, a 500 Hz vibration appears superimposed when the device is powered (Figure 6). The observation of vibration is independent of the mounting used. The amplitude of vibration is correlated with the resonances of the loaded MET and the magnitude of the force observed in the experiments. Furthermore, the resonances of the system differ when connecting the MET to different amplifiers. These observations indicate a correlation between the Woodward effect and vibrational artefacts.

4. EmDrive

4.1. Introduction

The EmDrive (Figure 7-8), invented by Roger Shawyer, is an asymmetrical copper cavity resonator that aims at generating thrust through the application of electromagnetic power in the microwave regime. The underlying principle is controversial. Our investigations are based on the experimental arrangement described by NASA's Eagleworks Laboratory [10] and recommendations of the inventor. A detailed test description and previous measurement results within the SpaceDrive project can be found in Refs. [5], [11]. The most recent tests were aimed at increasing the power supplied to the cavity, and at understanding the high-frequency processes present in the system when transmitting RF-power to the cavity.

4.2. Experimental Setup

First, impedance matching was performed with the help of a three stub-tuner, and included all coaxial components and feedthroughs after the external circulator (Figure 9). Here, the natural frequencies of the whole system were observed to be consistent with the previously determined resonance frequencies of the cavity. Using this method, up to 25 W of power were presumably supplied to the cavity.

Then, a simpler, symmetrical cavity equipped with a sensor loop antenna opposite the emitter loop antenna was tested as a null test article. The cylindrical cavity presented a clear, isolated resonance frequency in a range of 1.9 to 2.0 GHz, and proved that RF power could reach the cavity with proper tuning of the antennas.

The high reflectivity of the liquid-metal feedthrough at higher frequencies (approx. 3dB loss at 2GHz) was observed to lead to oscillations in the system and thus power losses between the cavity and the feedthrough. A more thorough analysis of the frequency-dependent behavior of the Galinstan feedthrough will be performed with a 2-port VNA.

In addition to our last reported measurements on the torsion balance, preliminary tests were performed with the EmDrive placed on the rotation balance, described in section 2.5, (Figure 8). The balance pivot was not yet levitating using the superconductor, but hanging from the cardanic suspension and resting on a ball bearing. This configuration can only detect forces that overcome the friction in the bearing, forces that can deflect the cardanic suspension, as well as center of mass shifts due to thermal expansion.

4.3. Experimental Summary

The measurement process proceeded by switching the EMDrive into operational mode at two distinct position of the rotating structure (Figure 10). The first measurement was conducted at the starting position at an angular position defined as 0°. With 5 W of power commanded to the EMDrive and a measured power within the cavity of 2 W at a frequency of 1984 MHz at the second resonance frequency, the angular sensor detected a motion of around 1 millidegree. A corresponding thrust cannot be calculated because the moment of inertia of the system was not calibrated for these preliminary function tests. Raising the commanded power to 10 W lead to a corresponding increase in the angular signal. It is important to mention, that these measurements have yet to be confirmed in future measurements. Firstly, the rotation balance was not levitating and therefore was not able to rotate at all with µN forces. And secondly, our tilt sensor showed a clear signal change when the EMDrive was on such that the observed rotation is most probably due to a thermal effect that resulted in a small tilt which moved the rotation arm. Details can be found in Ref. [7]. Tests with the frictionless bearing will follow soon.

5. Other Experiments

5.1. Mass fluctuation on rotating test stand

The idea for a rotating test stand for a direct measurement of Machian mass fluctuations without the need for a torsion balance was originally proposed by Woodward [12]. We designed our own version with enhanced sensitivity (Figure 11). The feasibility of measuring fluctuations in the mass of a piezo-stack driven with 100 V at 30 kHz and rotated with 60 Hz, equivalent to an acceleration of a 1000 g's, was investigated. This experiment showed evidence of the high non-linearity in the piezo-stacks built by Woodward. A large second harmonic signal was observed without rotation of the stack and led to poor resolution in the mass fluctuation measurement. The next experiments will aim at measuring mass fluctuations coming from a rapid oscillation in electric potential energy in capacitors, which should involve much smaller mechanical vibrations.

5.2. Biefeld-Brown Effect

The Biefeld-Brown effect was discovered in the late 1920s and claims that an asymmetric pair of electrodes will generate thrust towards the smaller electrode when a high voltage is applied [13]. Later it was found out, that this is not a reactionless force, but the electric field ionizing the surrounding air and creating an ion wind [14]. However, Brown himself and other researchers still claim to measure a force even in vacuum if a discharge (e.g. vacuum arc) takes place [15]–[17].

To examine this claim we have built a device which can support different kinds of electrode geometries at variable distances, with the option to hold a gas at atmospheric pressure, to provide a steady discharge current, or to be evacuated instead. The device was then put on the thrust balance described in section 2.2 inside a surrounding vacuum of 10^{-6} mbar to measure for the appearance of a force while charging up the electrodes with high DC voltages. The presented configuration in this paper has a group of metal tubes as cathode and a group of thin corona needles as anode (Figure 12a). During the experiments, the voltage of the cathode was ramped up until the current reached -180 µA, at a voltage of up to -17 kV. This current is made up of ion winds - charged particles of the air inside the device being accelerated towards the electrodes by the electric field. This wind is inside the device and should not generate a response of the balance besides a small change of the center of mass.

The results (Figure 12b) show the detection of a transient force of 1 μN at the beginning and 1 μN force at the end of the measurement. For the duration while the current was constant at – 180 μA, no force was detected within 100-200 μN. This test was repeated by turning the device on the balance, showing a similar result (Figure 12c). This shows that the on-off transient is most likely an artefact. Our results improve previous measurements by many orders of magnitude [14]. Testing with more geometries are still ongoing.

5.3. Enhanced Kaluza-Klein Theory

Another planned test is the replication of an experiment, which tries to confirm an enhanced Kaluza-Klein type scalar-tensor theory of gravity [18]. The main idea is to create a magnetic field with a solenoid, which applies a force to a suspended, dielectric material. The material will then show a displacement and/or a rotation, although the material should not react to a magnetic field. The original experiment by Mbelek used a concave mirror on a torsion wire to reflect a light beam onto a ruler so the rotation of the mirror could be measured. The solenoid had a mu-metal core and could be turned on or off [19].

Our setup consists of a dielectric wire, which holds a glued-on dielectric mirror (Figure 13). The wire is connected to a stepper motor to align the mirror and to calibrate the measurement. The mirror is used to reflect two lasers of an interferometer to measure the rotation and displacement of the mirror.

The solenoid is mounted on a motorized linear translation stage to change the alignment of the coil and the mirror. According to the theory, this can be used to negate the effect. Due to problems with the setup and the low permeability of the solenoid, no final results are currently available.

5.4. Mass-Temperature Change

The theory of relativity suggests, that the mass of two iron spheres heated up by 100 K grows with an order of 10^{-14} per Kelvin [20]. One of the first measurements performed on this matter, measured an effect of less than $-2 \cdot 10^{-6}$ per Kelvin [21]. More recent experiments by Dmitriev seem to confirm this measurement with a negative correlation value of $-1 \cdot 10^{-6}$ per Kelvin [22].

To further investigate this behavior, it is planned to repeat the test for different materials, negate the effect of buoyancy, by performing the test in vacuum and increase the effect, by increasing the mass of the test objects and by increasing the temperature difference up to 600 K.

The setup (Figure 14) consists of a weight measurement system, a heater and a cooling system. The weight measurement system is either a calibrated voice coil, which lifts the test mass and a laser interferometer, or a commercial balance modified for operation in vacuum. The heater around the mass is designed to increase the temperature of the test object up to 800 °C through radiation. The heater itself is surrounded by a system of pipes, which contains running water to shield the vacuum chamber and the weight measurement apparatus from the heat. First results will be available soon.

6. Conclusion

Several ideas for efficient, propellantless space propulsion for rapid interstellar travel were described and tested within the framework of the SpaceDrive Project. The paper shows progress in the development of different thrust measuring devices and in analyzing device-environment interactions in the laboratory.

First, two torsion balance configurations were characterized, having a very high force resolution: the one for test devices weighing as much as 10 kg has a resolution of roughly 20 to 100 nN, and the other one for devices weighing up to 1.5 kg has a resolution of 2 to 10 nN. Then, as an alternative to the torsion balance, a double pendulum balance was designed and built, but remains to be characterized. Its foreseen advantage lies in its relative insensitivity to center of mass shifts. Lastly, a rotation balance using a levitating superconductor as a pivot was described and the resolution of its angular sensor was verified in a preliminary experiment with the EmDrive.

Recent measurements for the MET and the EmDrive performed on torsion balances were then summarized. Beam deflection during MET experiments show switching on-off transients reversing with device orientation of very small magnitude. However, the same displacement magnitude is observed when turning the DUT on the beam by 90° in a way that should not show a force. A beam vibration of 500 Hz was observed while performing the experiment under diverse conditions. The amplitude of the vibration correlated with the beam deflection observed during the test, as well as the resonances of the system.

For the EmDrive, although a higher power was supplied to the cavity, the presence of a thrust force could still not be confirmed. Clear thermal effects can be observed, as well as non-repeatable phenomena during frequency sweeps, for one device orientation, that could originate from center of mass shifts on the torsion balance. The power oscillation behavior of the RF transmission system was examined more closely but requires further investigation.

The status of complementary experiments was also presented. Trying to measure the mass fluctuations in a PZT stack using rotation showed limitations due to the relatively large non-linearity in the piezo-actuator at higher voltages near resonances. A sealed Biefeld-Brown experiment was performed in vacuum and did not show a steady-state thrust as claimed. Other experiments including a test for the enhanced Kaluza-Klein theory and a measurement of mass at high temperature are still under way. Lastly, experiments with the MET and the EmDrive need to be performed on other types of balances such as the described rotation and double pendulum balances for a definitive conclusion.

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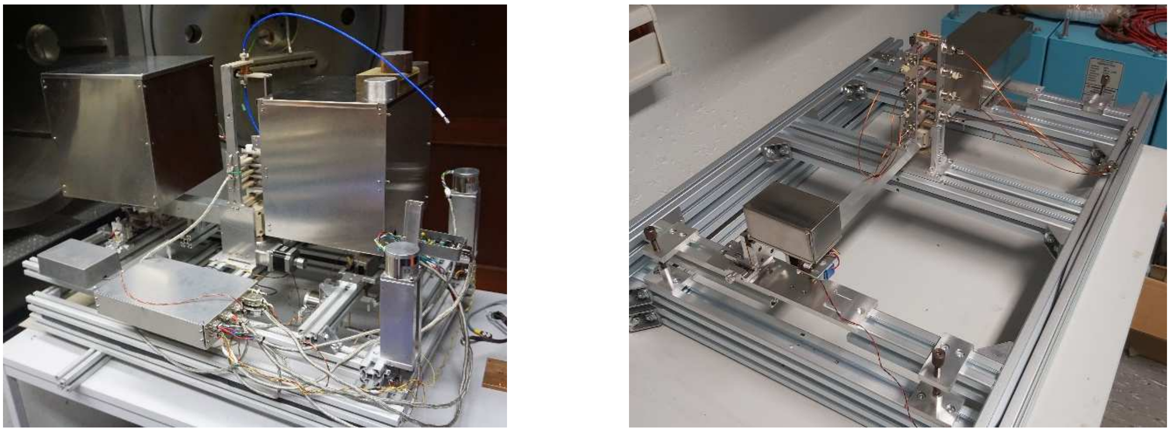
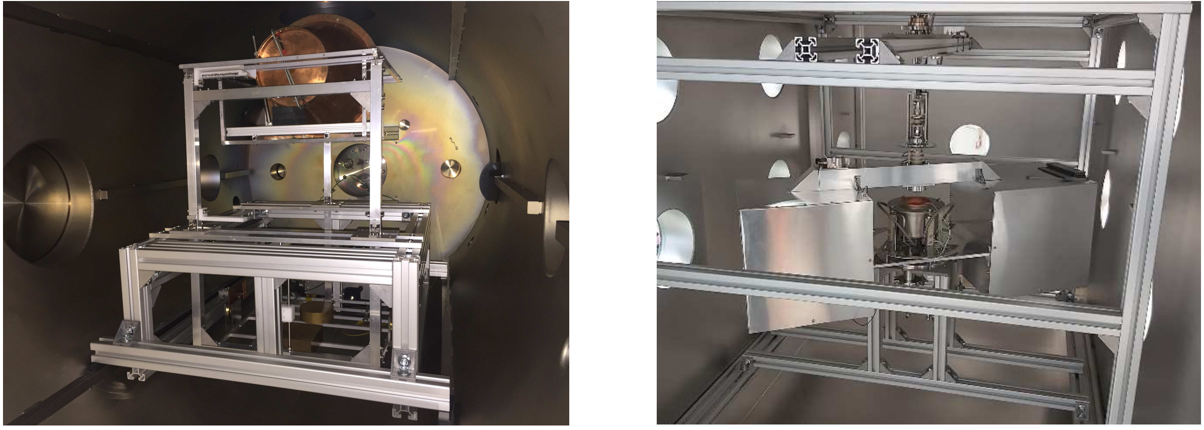


a) Torsion balance v5

b) Torsion balance v6

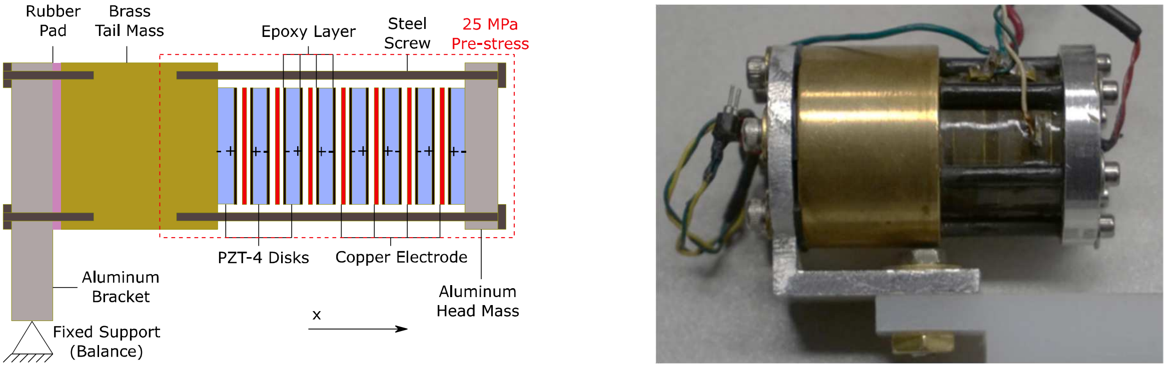
c)



d) Double pendulum balance

e) Rotational balance

Figure 1: Overview of thrust balances



a) Schematics of MET

b) NS5 provided by Woodward

Figure 2: Mach-Effect Thruster [6]

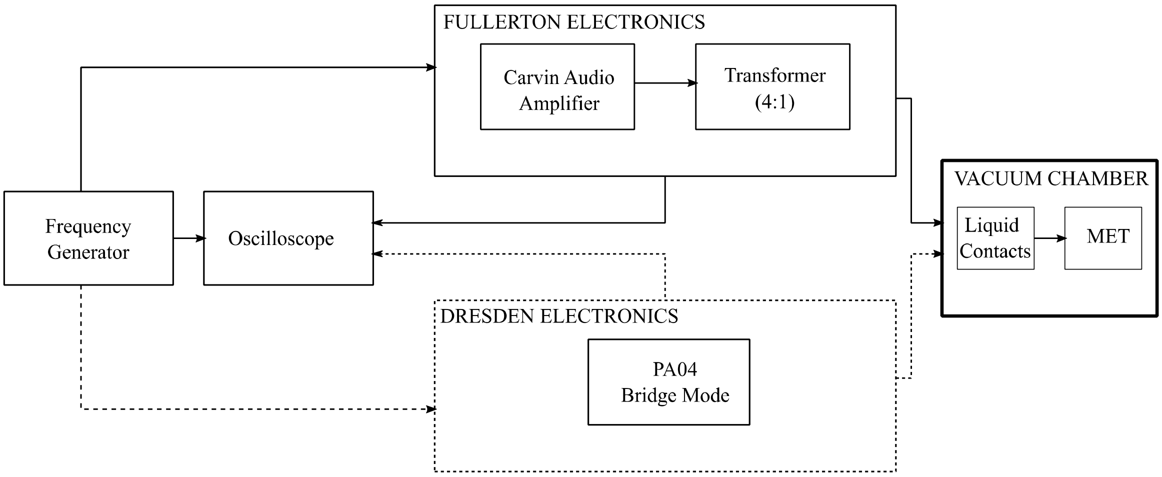


Figure 3: Schematics of both electronics for the MET [6]

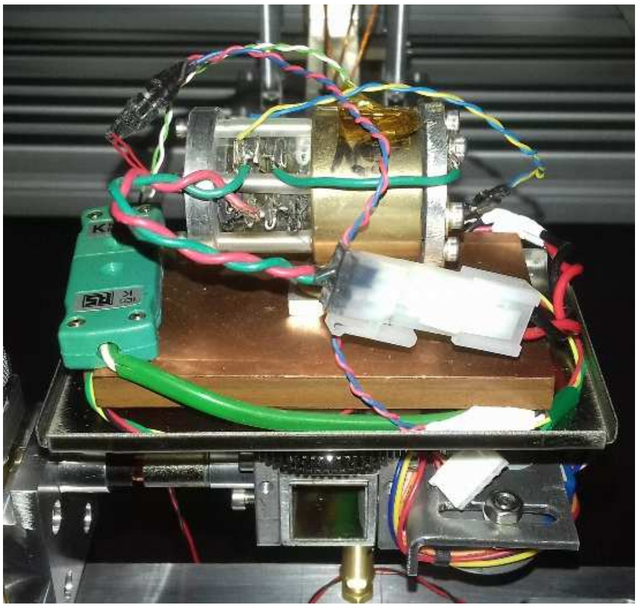
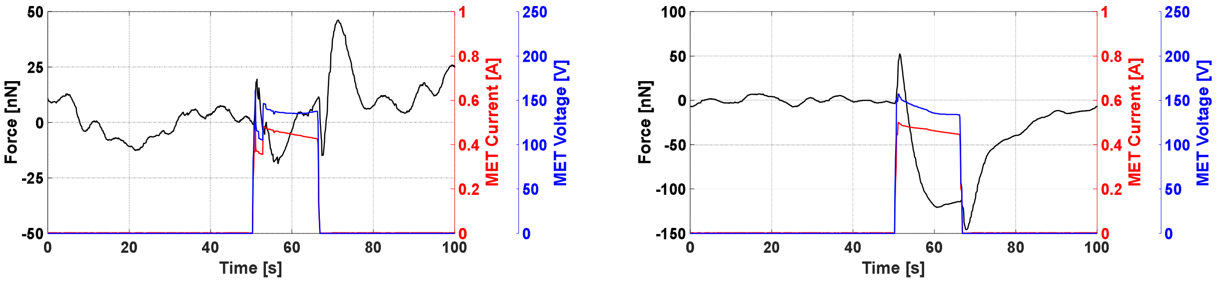


Figure 4: Setup on balance v6 [6]



a) 0° with Fullerton electronics, 36.0 kHz

b) 90° with Fullerton electronics, 36.0 kHz

Figure 5: MET measurement results [6]

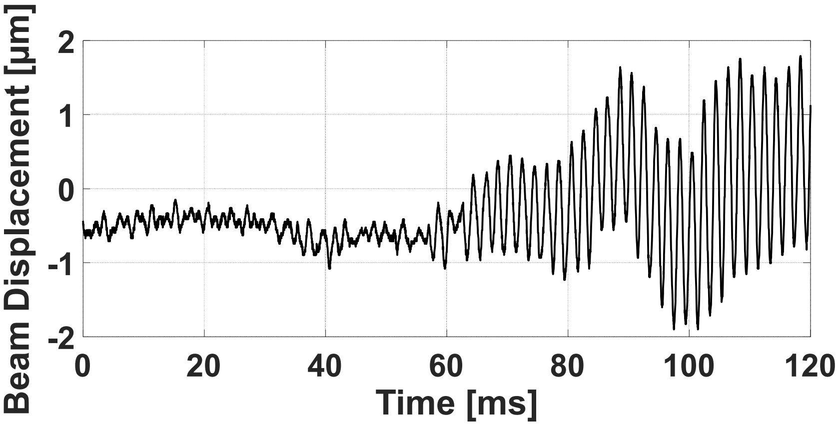


Figure 6: Beam vibration analysis of NS5 with Dresden electronics (-90° orientation) [6]

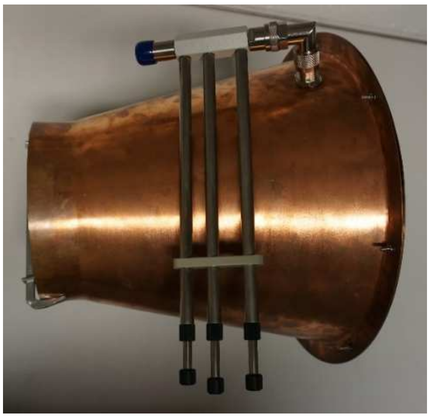


Figure 7: EmDrive with three-stub-tuner

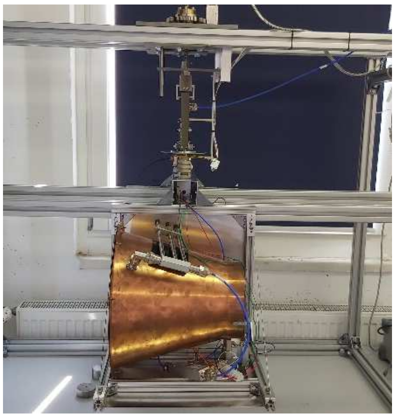


Figure 8: EmDrive on rotation balance without aluminium shielding

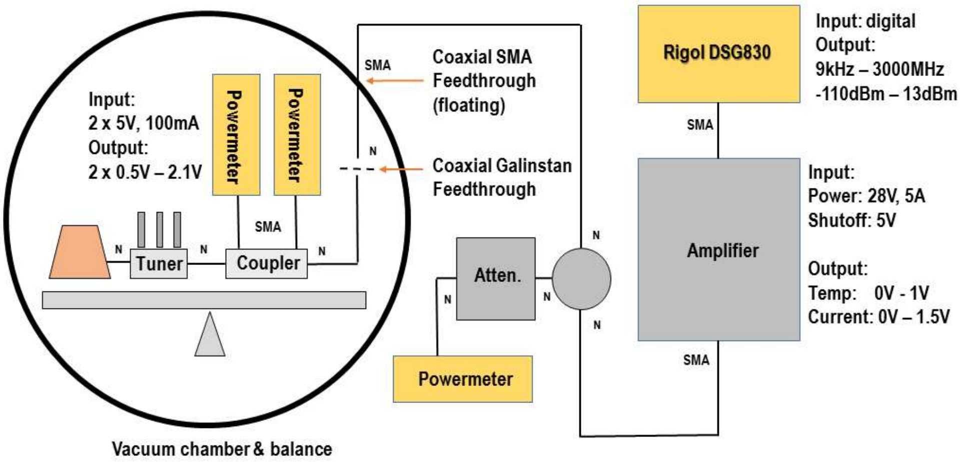
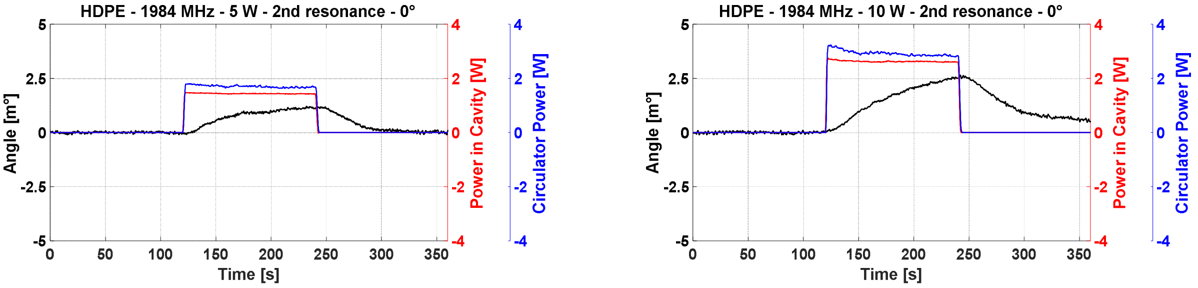
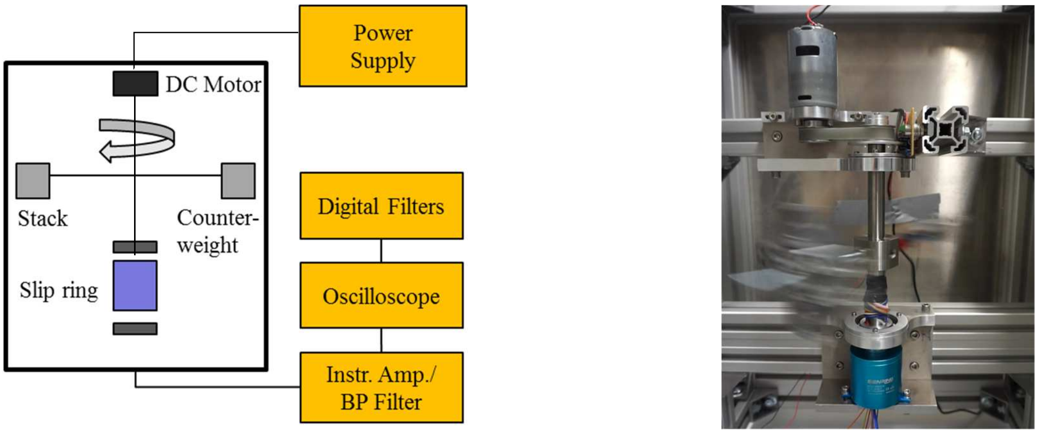


Figure 9: Schematics of electronics for EmDrive [6]



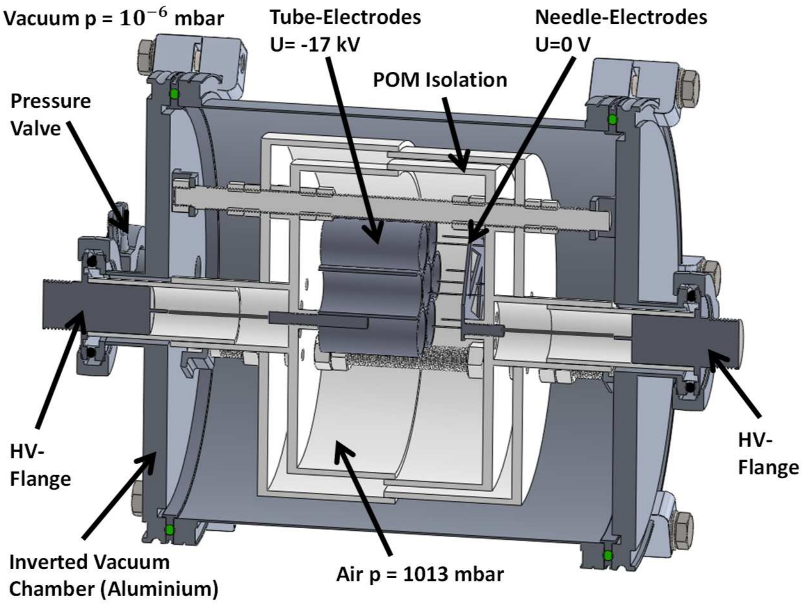
a) 0° b) 180°

Figure 10: EmDrive results on rotation balance [7]

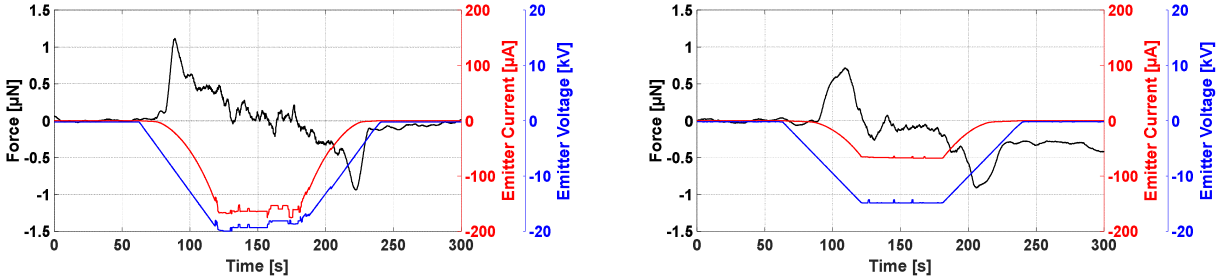


a) Measurement principle b) Experiment during rotation

Figure 11: Rotary mass fluctuation measurement setup



a) Cross-section for Biefeld-Brown experiment with tubes-needles



b) Results for tubes (-20 kV) – needles(GND) – 0°

c) Results for tubes (-15 kV) – needles (GND) – 180°

Figure 12: Biefeld-Brown experiment

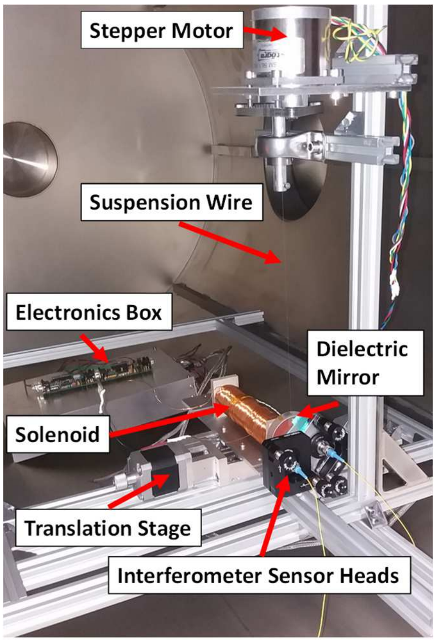


Figure 13: Setup for experiment on enhanced Kaluza-Klein theory

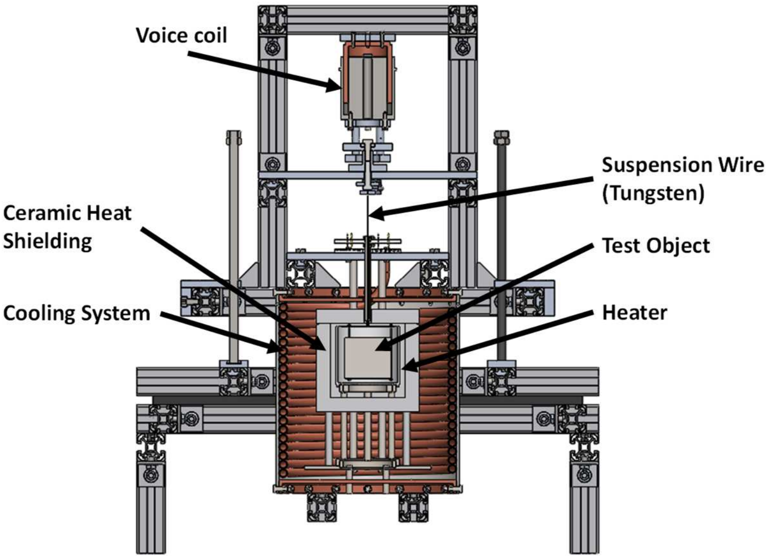


Figure 14: Cross section of the mass-temperature change experiment