Electric
solar
wind
sail

ESAIL D23.2
Tether vacuum-testing setup

Work Package: **WP 23**

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1. Introduction

The E-sail tether is subject to the harsh conditions of interplanetary space. In addition, during E-sail operation it is biased to +20 - 40 kV positive potential with respect to the surrounding solar wind plasma, which causes solar wind electrons to bombard its surface. This E-sail specific electron bombardment possibly causes adverse changes of the tether or its coating material. Some of the tether space compatibility properties will be studied theoretically or using computer simulations. Those studies will be reported on the deliverable D23.3. This document will report the design of the experimental setup which will be used for testing the durability of the tether in laboratory.

2. Tether vacuum testing

2.1. Tether wire

The tether to be used in E-sail is developed by University of Helsinki. The tether will be a *Heytether* construction made out of one 50 µm main wire and several 25 µm auxiliary wires, which are periodically bonded to the main wire with ultrasonic bonding technique to increase the micrometeoroid tolerance of the tether structure. The baseline material choice for the tether is aluminium. The tether manufacturing and tether coating developments are made in work packages 2.1 and 2.2. The tether structure is not relevant for testing the materials and coatings. Therefore for simplicity a single 25 µm aluminium wire will be used for testing. Other wire materials will be tested if necessary.

2.2. Test motivation

The most important things impacting the life-time or durability of the tether and it's coating are temperature and the direct effects of the electron bombardment. The main emphasis of the study will be on the testing of the coating materials on the tether, but bare tether wire will also be tested. The equilibrium temperature of the tether in space depends highly on the emissivity of the tether surface material. The temperature affects the material properties of the load bearing aluminium wire, for example creep, tensile strength and other mechanical properties. The life-time of some of the possible coating materials is also highly dependent on the tether temperature. The changes in temperature might cause peeling of the coating material due to differences in thermal expansion coefficient. The coating material may also be sensitive to high energy electron bombardment the tether will experience in space. The emissivity properties have to be preserved through the mission so that failure due to over-heating can be prevented.

The emissivity of the tether is the only material parameter affecting the thermodynamics, which can't be looked up from the material data sheets. The other parameters are rather well known. The emissivity depends highly on the surface preparation, oxide thickness on aluminium in case of bare tether wire, and on the specific properties of the coatings. The emissivity measurement has to be made also after and during the electron bombardment. Therefore the only way to study the emissivity of bare and coated tethers is to use an experimental approach.

An experimental setup has been designed and partially already prepared for measuring the emissivity and making the electron bombardment in the same vacuum chamber. In this way the emissivity of the tether wire can be measured after bombardment without exposing the tether to air, which could cause oxidation or other changes in the aluminium wire or the coatings. The testing will be done using a 30 cm high, 60 cm diameter vacuum chamber with many ports for the necessary voltage feed-troughs for tests (see figure 1). The objective of this work is to perform the emissivity tests at the vacuum of $<10^{-7}$ mbar in order to minimize the effects caused by the residual gases.

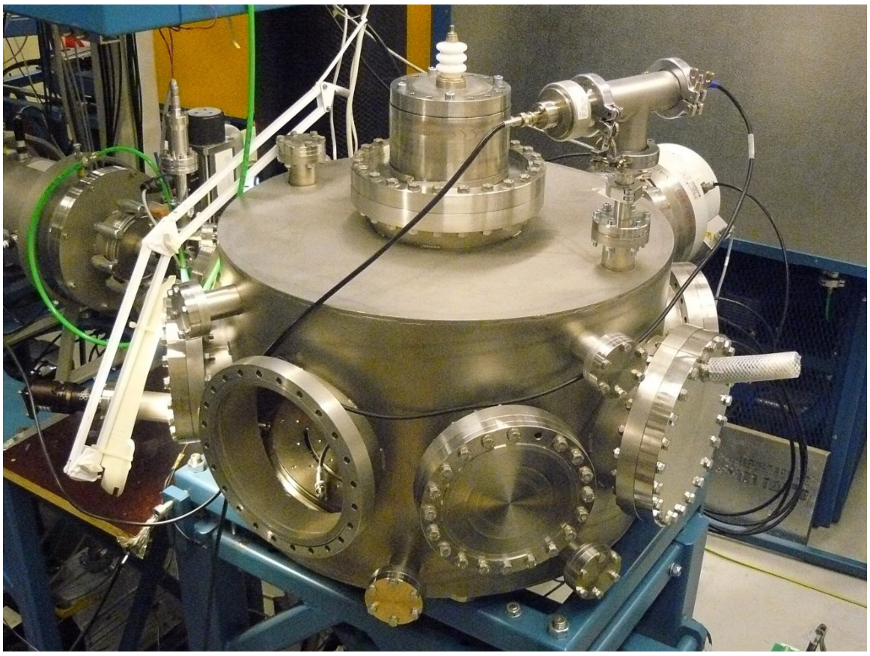

Figure 1. The vacuum chamber for making the tether testing.

2.3. Emissivity measurement setup

The basic idea for measuring the emissivity is to first heat up the tether wire under measurement with a high current, while measuring the voltage drop across the wire in the same time. If the emissivity of the wire is assumed to be independent of temperature, the resistance of the wire can be used to calculate the temperature. The emissivity can be determined from the equilibrium temperature of the wire. If the emissivity is not constant in the temperature range, the temperature dependence can be measured by making a series of measurements with different heating currents. Another way of measuring the emissivity is to use the decay of the wire resistance after the heating current has been switched off. This can be done by using a low measurement current for determining the resistance.

The preparation for the emissivity measurement was made by developing a software for calculating the dynamic behaviour of the temperature distribution in the tether wire under the test. The wire length was chosen to be about the maximum, which can fit in the chamber (0.5 m). The wire was observed to reach the melting point of aluminium at about 100 mA of current. The maximum temperature of the wire as a function of time with different heating currents is shown in figure 2. The spatial temperature distribution of temperature on the wire is shown in figure 3 for the case in which the heating current was 25 mA. The wire was observed to be long enough and the end effects to be negligible for the required accuracy of the measurement. The conductive and radiative heat losses of the system are 3.3 mW and 39 mW, respectively, when the equilibrium temperature was reached using the heating current of 25 mA. The calculation assumed an emissivity of 0.1.

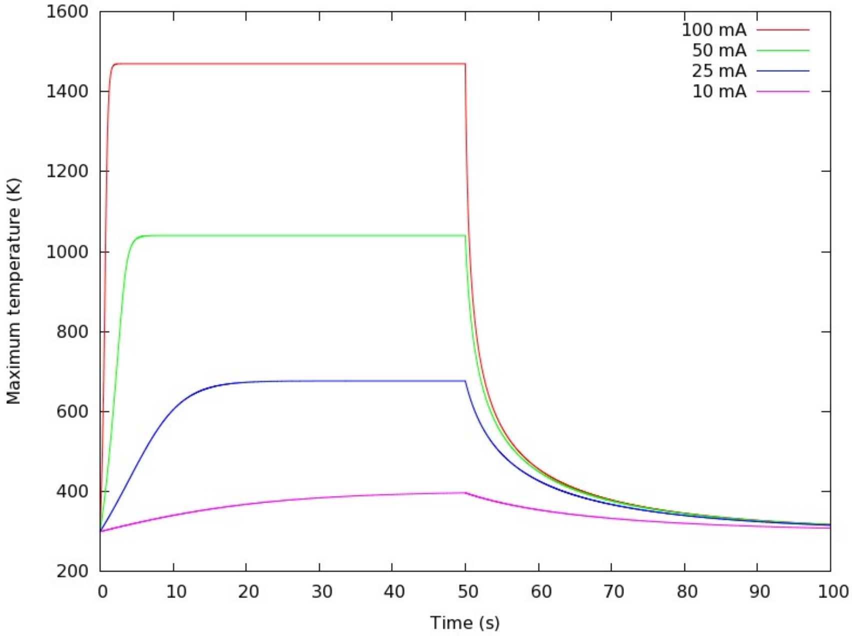

Figure 2. Maximum (central) temperature of the wire as a function of time with different heating currents. The heating current is switched off at t=50 s.

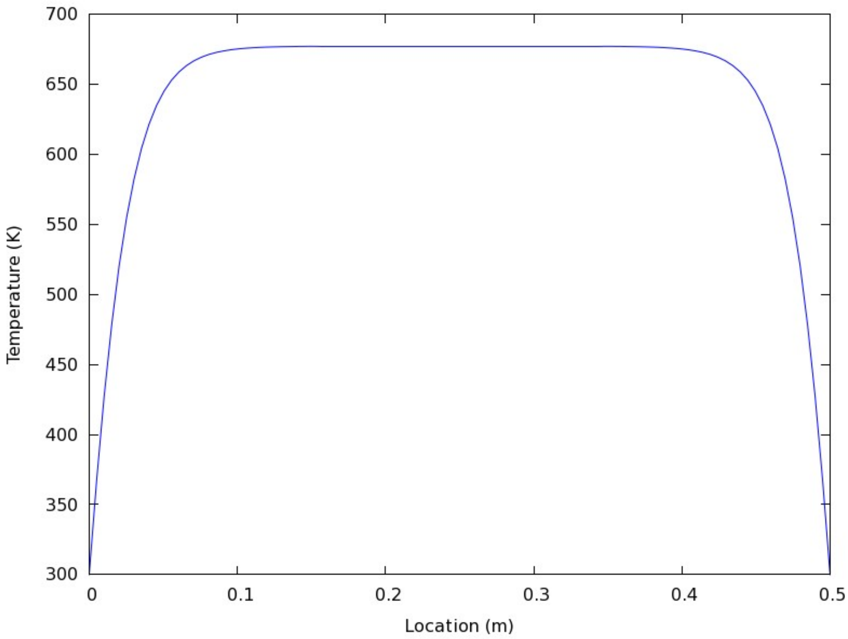

Figure 3. The spatial temperature distribution of the wire with 25 mA heating current.

The emissivity measurement set up and the necessary electronics was designed using the results from the computational study. The same computer program can be used for determining the emissivity value by matching the simulations to the experimental results.

The emissivity measurement setup has a rail with screw holes for mounting insulated wire clamping plates of different lengths. The maximum length of the tether wire which can be tested using the set up is 470 mm (see figure 7. for a view of the measurement set up). Two measurement wires are connected to each wire clamping plate for a total of four wires. Two of the wires will be used for feeding current through the tether wire and two measurement wires will be used for measuring the voltage across the tether wire. This setup is known as four-wire resistance measurement circuit. A specially developed circuit shown in figure 4 has been developed for the measurement. The circuit is connected to a PC for controlling and data acquisition. The heating current can be varied from 0 to 50 mA and current for resistance measurement from 0 to 100 µA. The unit has two switchable scales for voltage measurements: 0 to 10 V for use with heating current and 0 to 10 mV for use with low currents.

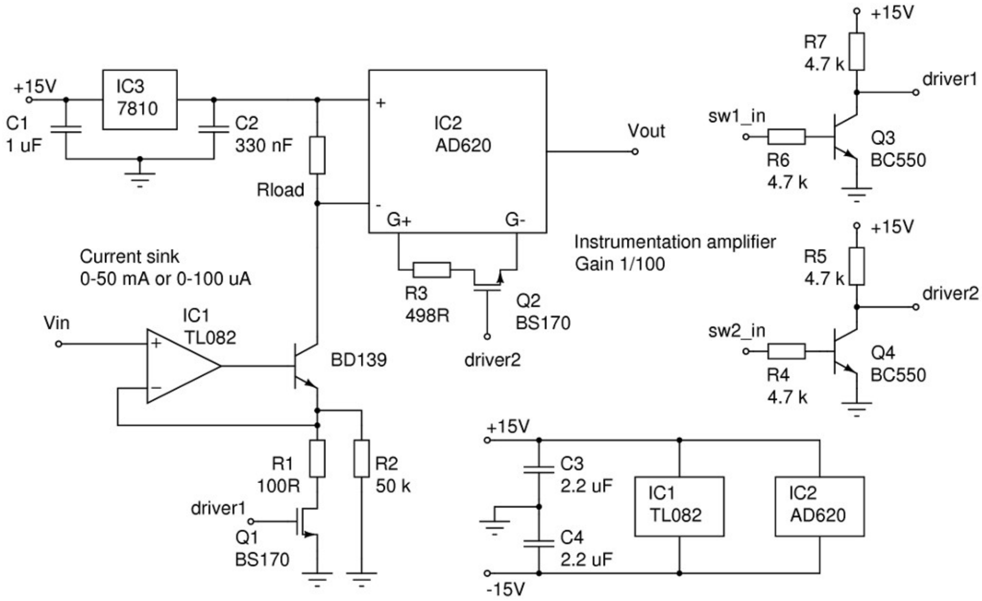

Figure 4. Circuit schematics of electronics developed for emissivity measurement.

The setup for the emissivity measurement is ready for first tests. The method of data analysis will be determined after first experimental data is produced with bare aluminium wire. This value will be used as a reference point for the emissivity.

2.4. Tether electron bombardment

The emissivity measurement setup is placed in the vacuum chamber so that an electron gun mounted to one of the DN160 CF ports can be used to provide the electron beam for bombarding the tether. A crude electron gun is going to be built for these experiments using an existing high-current feed-through for 1-1.5 mm diameter tantalum filament (shown in figure 5) and a newly designed two-electrode system for extracting the electron current in Child-Langmuir limited mode at about 1 keV energy. A preliminary design of the electron gun is shown in figure 6. More electron-optics simulations will be done before manufacturing.

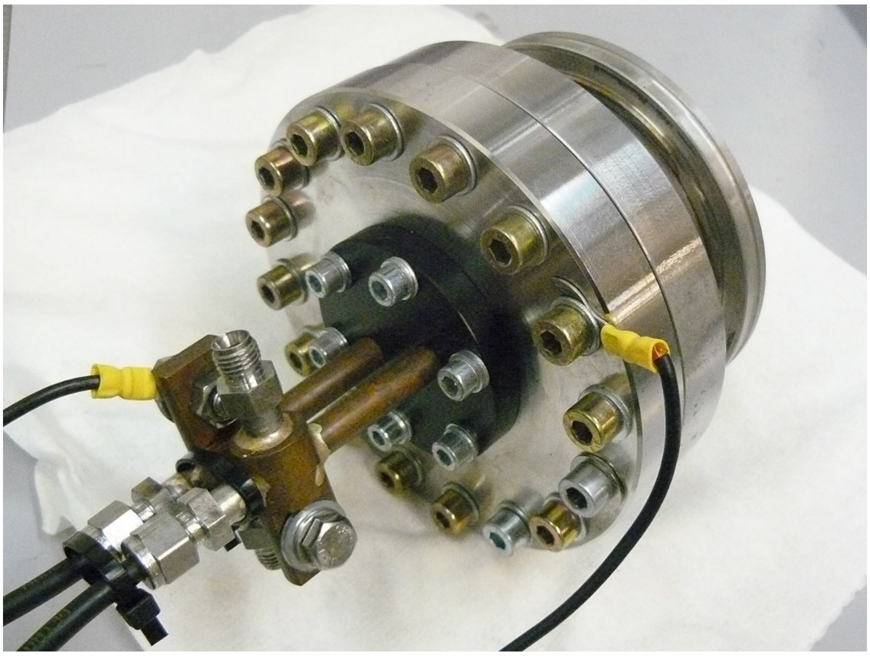

Figure 5. Filament vacuum feed-through for electron gun.

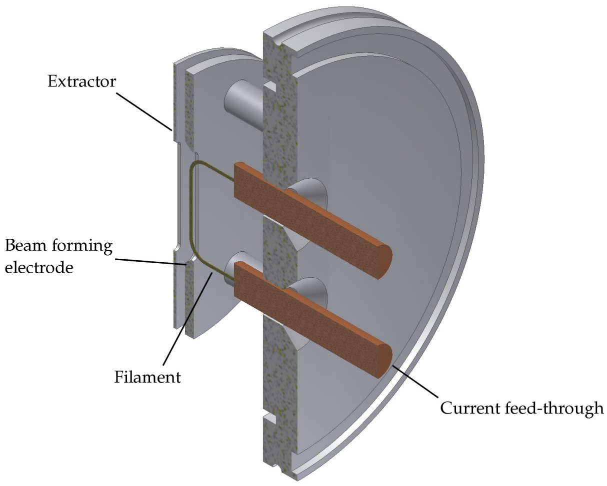

Figure 6. Preliminary design of the two-electrode slit-beam electron-gun.

The electron beam is collimated to cover about 20 cm part of the tether, after which the electrons will be accelerated towards the tether by the positive (up to 20 kV) potential of the wire. The entire tether can't be bombarded because of the geometrical limitations of the vacuum chamber in use. The exposed length has to be long enough in order to observe the changes in the emissivity value. The accurate dimensions of the collimator will be determined by measuring the electron beam uniformity once the electron gun is completed. Also, the situation is not geometrically the same as in space, because in the test the electron bombarding is more directional. Some electron bombarding also happens to the “back-side” due to the 20 kV acceleration after the collimator. The possibilities of exploiting this effect more will be studied further with more electron-optics simulations. See figure 7 for an illustration of the whole experimental setup.

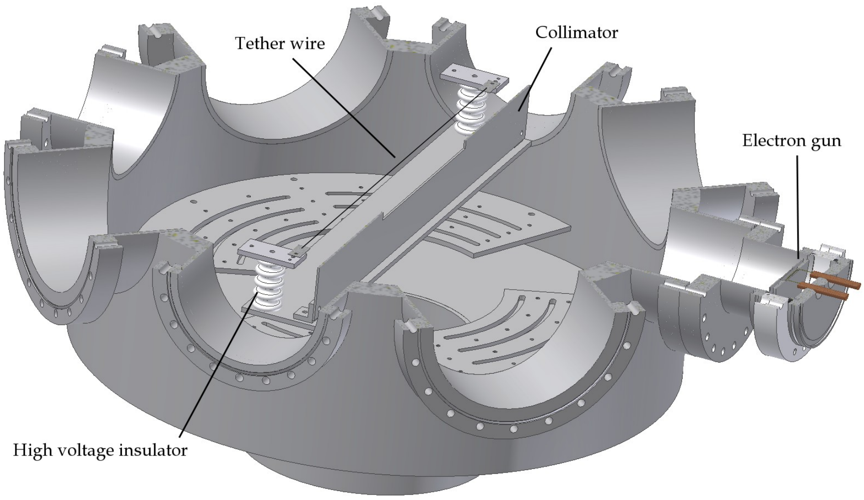

Figure 7. Section view of the vacuum chamber with equipment for emissivity measurements and electron bombarding.

The accelerated ageing-test will be done using the electron flux corresponding to the solar wind exposure of 5 years. It has been estimated that during the planetary mission the 20 km long tether will have the current up to 1 mA. The equivalent dose is 91 µA-day/m. During the accelerated ageing-tests the limiting factor will be the heat/temperature related properties of the wire. The temperature limit depends on the coating material, but for example assuming a 0.1 emissivity coefficient a 4 µA/m exposure at 20 keV will heat the wire with 40 mW, which rises the temperature to almost 700 K. In this case the exposure time would be 20 days. The bombarding flux has to be decided for each coating material, taking into account the necessary safety margin for the possible changes in emissivity coefficient during the afore-mentioned experiment. The planned method should be validated by doing ageing tests with different current levels and comparing the results.

2.5. Field emission tests

The tether wire will have about 200 MV/m electric field on its surface during operation in the solar wind. One of the possible phenomena affecting the life-time of the tether is the so-called ionic field emission. The tests will include a test for measuring the magnitude of the emission. The experimental test setup has a coaxial system with tether wire going through a grounded cylindrical electrode. The IV-curve of the system will be measured to estimate the amount of ions emitted from the tether.

3. Discussion

The emissivity experiments described above are fairly complicated and possibly will reveal factors which cannot be anticipated before the actual experimental work and further simulations. At this point three possible concern can be high-lighted:

1) coupled parameters concerning the accelerated ageing-tests,
2) effect of residual gas
3) adequate area of exposure.

The accelerated ageing-tests will be performed by using much higher flux of electrons compared to the flux the tether experiences in the space environment. As a result of this the temperature of the wire will also be higher than during the space missions. These two parameters cannot be separated (i.e. higher flux versus higher temperature) but possibly their effect can be estimated by varying the electron flux. Also, it is possible to study the effects of varying temperature during the emissivity tests prior to electron bombardment. This will be accomplished by measuring the tether emissivity after gradual heating procedure with varying currents.

The surface of the tether plays a critical role concerning the equilibrium temperature of the tether wire. The equilibrium temperature of the wire will increase if the emissivity of surface decreases. This has a strong impact on the life-time of the tether. As a consequence the emissivity properties of different tether surfaces/coatings have to be defined and the best possible material has to be found. The experiments will be carried out in the experimental chamber shown in figure 1. The unknown factor will be the surface oxidization caused by the residual gas. As an example the collisions caused by the residual gas will fully cover the material surface within few seconds if the vacuum has the pressure of 10^{-6} mbar. Because of this behaviour we are aiming the vacuum level as low as possible (less than 10^{-7} mbar).

During the emissivity experiments the tether length of 470 mm will be used. The quantitative results can be seen although the entire surface of the tether is not exposed to the electron bombardment. However, the accuracy of the results will possibly improve with the surface area exposed to the radiation. The area can be increased by using electrostatic wobbler deflectors and even by rotating the tether wire. However, this will greatly complicate the experimental set up and consequently the study will be started by using a less complicated approach.