POWER AND SIGNAL TRANSFER TECHNOLOGY FOR HIGH-TEMPERATURE APPLICATIONS

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ABSTRACT

The BepiColombo mission is the 5th cornerstone of the Cosmic Vision scientific programme of the European Space Agency (ESA). It mainly consists of two scientific spacecraft, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO), which are dedicated to the study of the planet Mercury and its magnetosphere. Both share the same carrier to Mercury, where the satellites are deployed to their respective orbits.

The challenge for the solar array drive mechanisms as needed for the BepiColombo mission is to provide a reliable electrical, mechanical and thermal interface between the solar array and the spacecraft, while being exposed to the high-temperature environment near Mercury. In particular, the rotary joint dedicated to electrical power and signal transfer becomes a very critical item under these conditions.

The paper will summarise the survey of material candidates for rotary joint application in the context of the BepiColombo mission. Furthermore, it will elaborate on the results of the development tests performed with the breadboard and engineering models of such a high-temperature rotary joint.

As a 1st step, promising material combinations for a slip-ring based solution were tested with an adapted vacuum tribometer, which is typically used for conventional pin-on-disc tests, however in vacuum and optionally at elevated temperatures (up to 300 °C). The adaptation of the tribometer has comprised electrical aspects (specifically, in-situ measurement of the electrical contact resistance) as well as the use of a wire brush instead of a pin as contact element.

In a 2nd step of the activity, the selected material couples were evaluated in the form of real slip-ring components integrated in a breadboard model.

A comprehensive test campaign with an engineering model has been the 3rd step of the development, which included numerous mechanical and electrical performance tests (for instance, start-up and running torque, dielectric strength, insulation resistance, and susceptibility to arcing and corona effects) as well as environmental (vibration, shock & thermal vacuum cycling), and finally a life test in vacuum.

Via the hardware development and test approach as outlined above, the viability of a slip-ring based hardware solution for power and signal transfer at high temperature has been successfully demonstrated, which is considered an enabling factor for BepiColombo and other missions with similar requirements.

1. INTRODUCTION

The challenge for the solar array drive mechanism (SADM) needed for the BepiColombo mission is to reliably operate in the high temperature environment of Mercury transferring the electrical power and the pedal position from the solar array to the spacecraft bus. In particular the rotary joint through which the power, date and the solar array pedal position are to be transferred, become very critical under these conditions.

In principle the work summarised in this paper can be divided into 3 steps:

- Survey of materials (testing of promising and selection of best material pairings)
- Breadboard Model (BB) tests (evaluate selected material pairings in shape of real component)
- Engineering Model (EM) tests (demonstrate ability of the EM to survive in worst case – thermal/vacuum environment without malfunction)

2. MATERIAL SCREENING: EXPERIMENTAL DETAILS, TESTS AND RESULTS

Elements with sublimation temperature lower than 300 °C are not capable for BepiColombo mission. Thus, materials containing Zn, Cd, Mg, for example can't be selected. Promising material pairings were tested tribologically in a vacuum tribometer with which friction, wear and also electrical contact resistance was measured. Generally, pin on disc and brush on disc configurations were tested.

Pins: Ag835, Ag/MoS2, CuMMC (different compositions of Cu, Sn, MoS2 and Cf, s. [1-3])
Brushes: Different Au-based alloys and coatings

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Discs: Ag835, CuMMC (different compositions of Cu, Sn, MoS_2 and Cf, s. [1-3]), different Au-based materials and coatings

The <u>test facility</u> (UHV – Tribometer, Pin-on-disc type) enables the investigation of sliding friction according to standardised pin-on-disc or ball-on-disc geometries in air, inert gases and under vacuum.

Technical data:

Environments	air – inert gases – vacuum (10^{-6} mbar)
Temperature range	-100 to +300 °C
Rotation speed	0.01 to 500 rpm
Measurement	Friction, Linear Wear (+/-2 µm), Contact Resistance
Data acquisition	automatically by means of PC

<u>Specimen preparation</u>

Both discs and pins were cleaned by ultrasonics using first acetone and secondly ethanol. After drying in air, they were mounted into the tribometer (s. Fig. 1). Evacuation was started immediately afterwards.

<u>Test</u>

To achieve the desired environment following steps were done:

- Air: for controlled humidity, a humidifier was used. Test is started immediately after reaching desired level.
- Vacuum: tests were started after reaching a vacuum level less than 5.10^{-6} mbar.

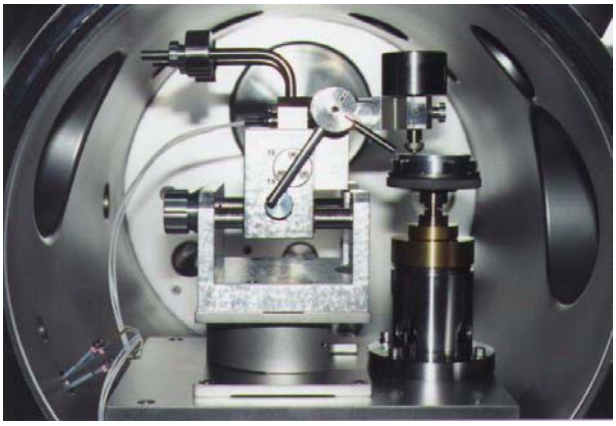


Fig. 1: Vacuum tribometer (inside view)

After reaching the desired environment, the friction test was started as soon as the desired temperature was reached; typical deviations were +/- 5 °C. The test was stopped, if the desired test duration (e.g. distance or cycles) was achieved.

Used electrical devices:

Function	Device name	Serial number
Current source	EA-PS 5065-10	15130115
Amperemeter	Keithley 2000	583944
Voltmeter	Keithley 2700	809841

<u>Analysis</u>

Surface roughness and wear tracks were measured with an optical profiler for 3D-topographies. Surface morphology was studied by means of SEM (Scanning electron Microscope). Main objective was to determine eventually destructions of surfaces. This included also investigation of material transfer by EDX (Energy dispersive X-ray analysis).

Test results include plot of friction and contact resistance as function of distance. A PC acquired beside that environmental data. From the plots, the test was divided in running-in and steady state. For both parts, peak and mean values of friction coefficient were calculated. The plot of linear wear is qualitative, but can be calibrated by use of total wear volumes. Total wear rates were calculated from wear volumes. Resistance was evaluated by means of voltage and current measurement. Current was changed between cascade (50 mA, 0.5 A, 1.5 A, 2.5 A alternated for example) and constant current (2.5 A for example). For testing of brushes instead of “pins” the tribometer was adapted accordingly.

<u>Pin on Disk (POD) test set-up</u>

In Fig. 2 a sketch of the typical POD test set-up is shown. The rotating heating plate (= disc holder) is powered via a rotating shaft by means of an electrical motor placed outside of the vacuum chamber. By means of Aluminium nitride plates it is thermal connected and electrical isolated to the disc which is mounted on the heating plate with a carrier. The pin is heated separately. The temperature of both samples and of the heating plate is acquired with thermocouples. Between the pin and the disc the electrical resistance is measured with four-wire-technique.

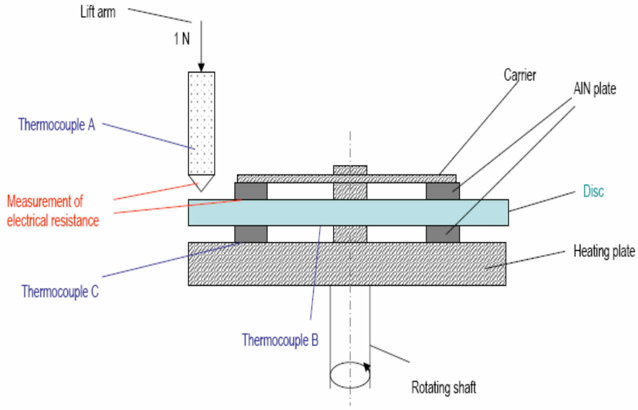
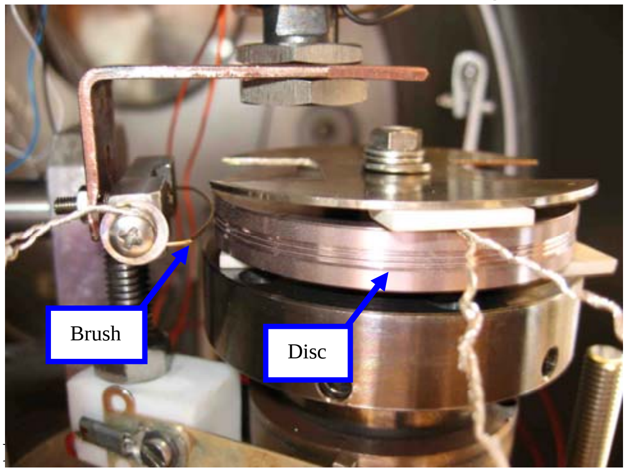


Fig. 2 Schematic view of POD test set-up

Brush on Disk (BOD) test set-up
Generally the set-up of BOD tests correspond the POD test set-up described above. The disc mounting is completely the same. The only difference is the brush holder. The brush bracket with the brush is screwed on an adapter clip which is mounted on the usual pin holder. With a micrometer device inside the chamber the whole pin holder was brought to the disc. After achieving electrical contact between brush and disc, the way to reach a specified load (which is known from a force-distance measurement performed before) is done by the micrometer device. The electrical resistance is also measured between the disc and the brush. The wire for measurement of the resistance is clamped by means of a nut between the bracket and the adapter clip on which the bracket is mounted. This point was elevated because it is well accessible and without any problems to contact. Any offset error is for all samples the same and consequently, it isn't relevant for the material choice. Brush and disc mounted in vacuum tribometer is shown in Fig. 3:



Test Parameters

Configuration	Pin on Disc / Brush on Disc
Radius of Pin	2.5, 4 and 6 mm (spherical tip)
Current	0 – 2.5 A
Motion	Oscillating
Speed	0.026 and 0.028 m/s e.g.
No. of turns	4000
Environment/Temperature	RT in air and in vacuum, 150 °C in vacuum, 300 °C in vacuum

Measurement set-up
For model testing a pin-on-disc system was used: The pin and the Wire resp. represented the brush, the disc represented the slip ring. The aim was to measure friction force and contact resistance and to assess life time of the material combinations.

Test Results
Generally, the measurement results are to be classified in friction coefficient μ and contact resistance R. Both are very crucial for the evaluation of suitable material pairings for the BepiColombo mission. Only material pairings are suitable with low friction coefficient AND low contact resistance in vacuum and at high temperatures (up to 300 °C). For selection of a material pairing the mean of the friction coefficient must not be higher than 2 **and** the maximum value of the friction coefficient must not be higher than 2.5 **and** the mean contact resistance had to be lower than 100 mOhm. With this selection the following table is obtained, in which the most promising material pairings with their mean friction coefficient and their contact resistances measured with a current of 2.5 A during 300 °C tests in vacuum are shown.

Brush / Track	R [mOhm]	μ (mean)
Au coated brush / Au coated disc	55	1.77
Au coated brush / CuMMC disc	44	0.61
CuMMC pin / Au coated disc	14	0.28
CuMMC pin / Ag835 Disc	10	0.29

Because a brush-solution was preferred, the breadboard and EM were manufactured with the two most promising brush combinations shown in the table.

3. BB + EM TESTING: EXPERIMENTAL DETAILS

Tests of BB and EM were performed in a thermal vacuum chamber as shown in Fig. 4.

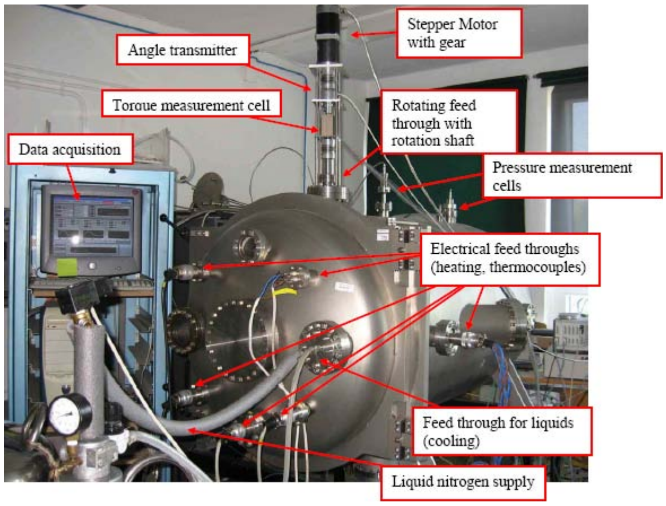


Fig. 4 Thermal vacuum chamber

Thermocouples were applied on the test samples as depicted in Fig. 5. For simplicity of the test set-up the rotor was fixed with an adapter to a heating plate and all cables on the rotor side were connected with the EGSE. The stator was connected to the rotating shaft and was moving. The cables on the stator side were connected such that adjacent ways were used for forward and return current. In Fig. 6 a heating pot placed around test specimen in thermal vacuum chamber is shown. In the top of the picture the rotating shaft can be seen. Fig. 7 shows the test set-up isolated with Al-foil ready for tests.

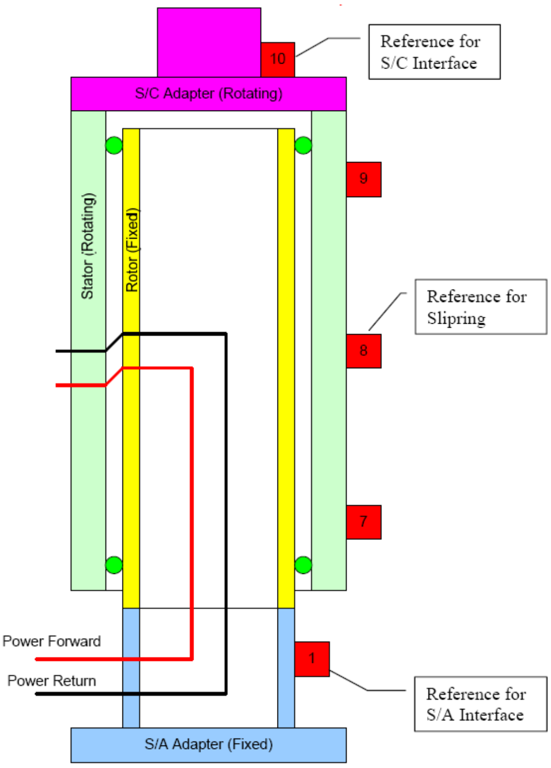


Fig. 5 Thermocouples on test specimen

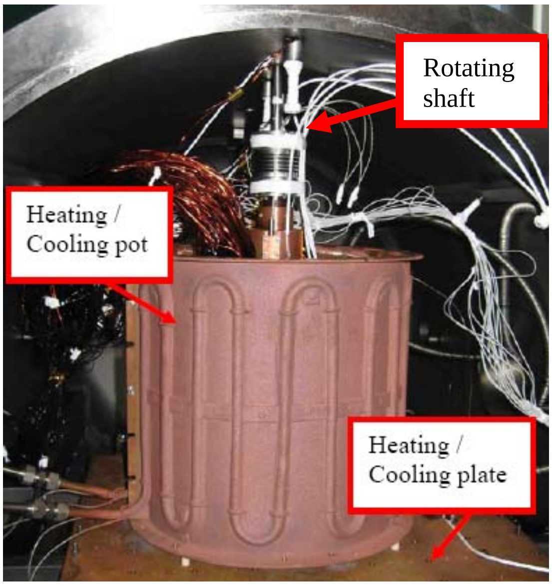


Fig. 6 Heating/Cooling pot placed around test specimen in vacuum chamber

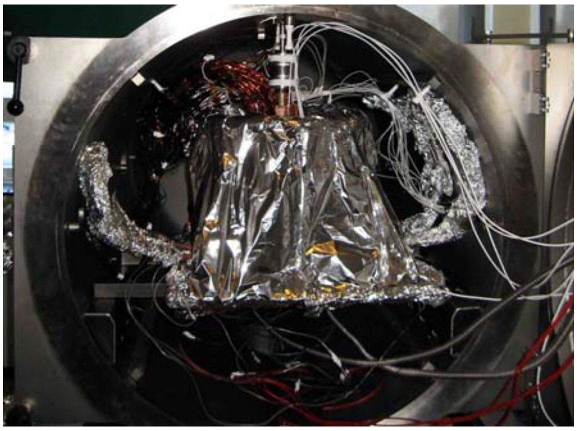


Fig. 7 Set-up isolated with Al-foil ready for tests

Wiring of test cables

In Fig. 8 the circuit diagram of wiring of test cables is shown. U_I(1, 3, 12) is the voltage with which the current of 1, 3 and 12 A resp. through the high precision measuring resistance R was measured. For 1, 3, 12 A different R's were used.

The measurement cables (GSE), connected to the slip ring tracks, can be neglected in the voltage measurement. The calculation of resistance is performed with the formula R=U/I. It was assumed to be constant, but if not, one can still calculate with the measured values at the measuring point.

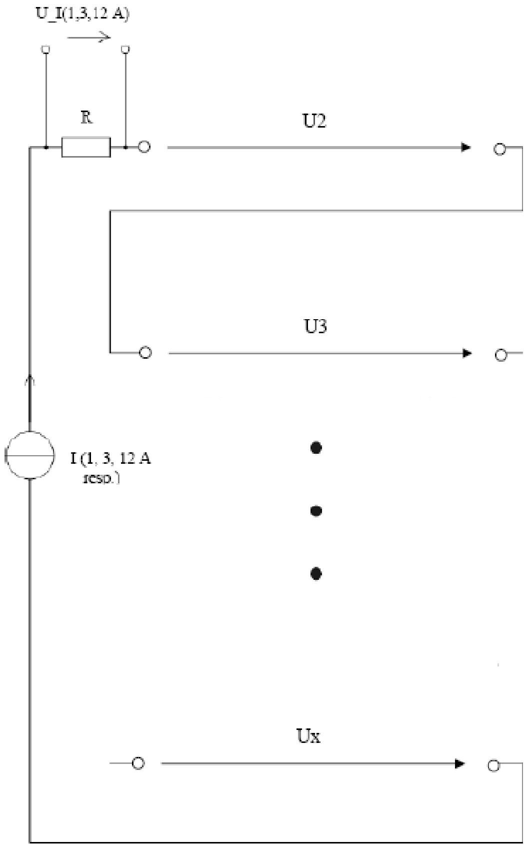


Fig. 8 Circuit diagram

4. BB TESTING: TESTS AND RESULTS

In the BB selected material pairings were mounted and tested. The purpose of the BB tests was to evaluate the selected material in the shape of a real component as foreseen to be used in the EM. The test provided feedback on the design of a typical slip ring/brush/isolator element.

It consisted of 6 tracks with the following function:

Track No.	Current
1	mass
2	12 A
3	3 A

Test parameters

The rotation schedule for BB testing is shown in Fig. 9:

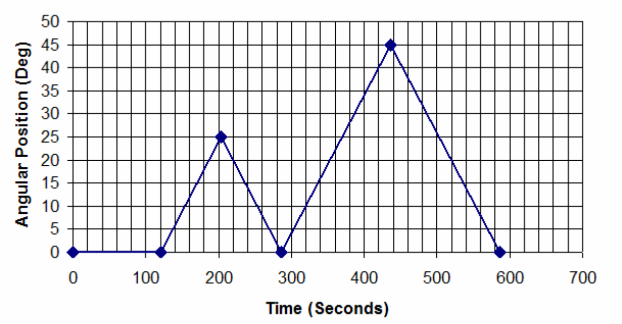


Fig. 9 Rotation schedule for BB test (i.e. 1 turn)

The test was performed in 2 phases:

- Phase 1: 2 weeks at 250°C (2000 turns)
  Intermediate inspection
- Phase 2: 1 day at 250°C (750 turns)
  3 days standby at 250°C
  2 days at 250°C (300 turns)
  1 hour at 300°C (5 turns)
  1 day at 250°C (750 turns)
  3 days standby at 250°C
  2 days at 250°C (300 turns)
  1 hour at 300°C (5 turns)
  1 hour at 250°C (5 turns)
  Final inspection

The total scheduled number of turns is 4100.

Test results

The di-electric strength/insulation resistance of the BB between its ways was measured at 100, 250 and 500 V DC. It was always >20 GOhm. Measurement of contact resistance during both phases is shown in Fig. 10:

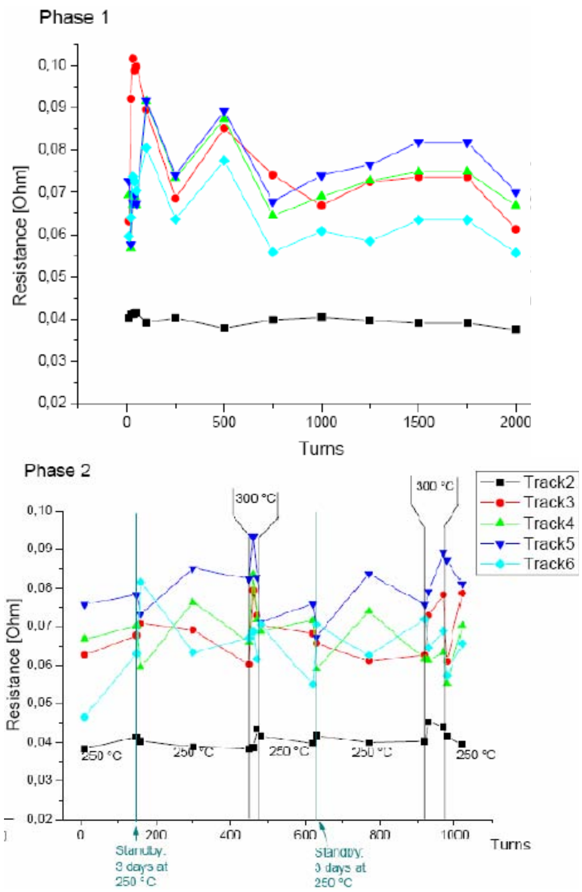


Fig. 10 Contact resistance vs. turns during BB-Test.

The test was interrupted after 3 days due to degradation of the mechanical performance (excessive torque). The test specimen was removed, inspected and the bearing was repaired. Resistance was in the same order of magnitude than measured during screening tests in the vacuum tribometer and remained constant during complete BB test duration. Track 2 showed the lowest resistance because it's the power ring with higher current (12 A instead of 3 A; therefore, track 2 was equipped with more brushes and cables).

5. EM TESTING: THERMAL CYCLING TEST

The test conditions were: Pressure $<10^{-4}$ mbar, Temperature change rate <20 °C/min, Stabilisation criterion: 1 °C/h. Dwell time at max/min temperatures: 2 h. After each stabilisation a functional test was performed (i.e. 11 turns during which torque of the EM and resistance of each track and was measured).

The following thermal conditions were applied:

Simulated Scenario	Cycles	Level	S/A Interface (Sensor 1)	Slipring (Sensor 8)
Cruise	4	max min	+140/+150 -165/-55	+152/+154 -60
Nominal orbit	4	max min	+216/+225 -61/-60	+149/+157 +64/+72
Survival	Steady	max	+243	+180

6. EM TESTING: LIFE CYCLE TEST

The test conditions were: Pressure <10^{-5} mbar, Current: 1, 3, 12 A resp., Rotation speed 20 deg/min, Resting time between turns 2 min. The life cycle (LC) test was divided in 6 phases. The angle to go ("travel"), the no. of turns and the temperature required and achieved are shown for each phase in the following table. Voltage and current and thus R was only measured when electrical contact between all rings and wires was working.

Phase	Travel (deg)			Turns		S/A Interface [°C]		Slipring [°C]	
	Required	Achieved	Resistance measured	Required	Achieved	Required	Achieved	Required	Achieved
1	-60/+60/-60	-60/+60/-60	-60/+60/-60	1736	1736	220	220	160	162
2	-40/+40/-40	-40/+40/-40	-60/+20/-60	761	761	-60	-59	65	67
3	-20/+20/-20	-20/+20/-20	-20/+15/-20	1736	1736	220	220	160	162
4	-60/+60/-60	-60/+60/-60	-60/+15/-60	1736	1736	220	220	160	161
5	-40/+40/-40	-40/+40/-40	-40/+15/-40	761	761	-60	-56	65	67
6	-20/+20/-20	-20/+20/-20	-20/+15/-20	1736	1736	220	220	160	164
Total				8506	8506				

Current and voltage was measured with 100 Hz during LC Test. After each turn the arithmetic mean, the maximum and the minimum value are stored in a file and is shown in Fig. 11 for ring no. 3. The peak to peak noise was derived and plotted vs. turns (for ring no. 3: Fig. 12).

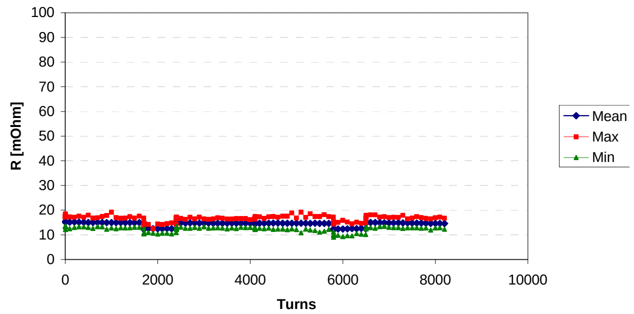


Fig. 11 Contact resistance (mean, maximum and minimum value) of ring no. 3 vs. turns during LC-Test.

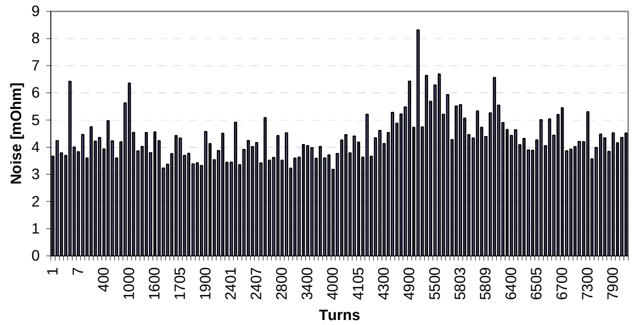


Fig. 12 Peak to peak noise of ring no. 3 vs. turns during LC-Test.

The **torque measurements** are not representative of the torque of the slipring since the test cables are attached between the slipring and the test chamber, creating a parasitic torque. The parasitic torque is an order of magnitude higher than the slipring torque and is angular travel and temperature dependent (cables are more flexible at higher temperature).

7. ARCING TESTS

Additionally, arcing- and corona tests were performed with BB and EM. The objective of the arcing test with BB was to evaluate the conditions under which arcing and corona discharge occurs. The tests were also performed in the thermal vacuum chamber described above. With conditions suggested for Arcing and Corona testing (500 V DC @ 2x10E-4 mbar) no glow discharge and no arcing was detected. Discharge only could be observed with extreme worst conditions (Ar-atmosphere, 3 to 25 mbar, 500 V DC) (s. Fig. 13). With EM the compliance with unfriendly environment with regard to arcing had to be checked and no discharge was observed (500 V DC @ 2x10E-4 mbar under vacuum).

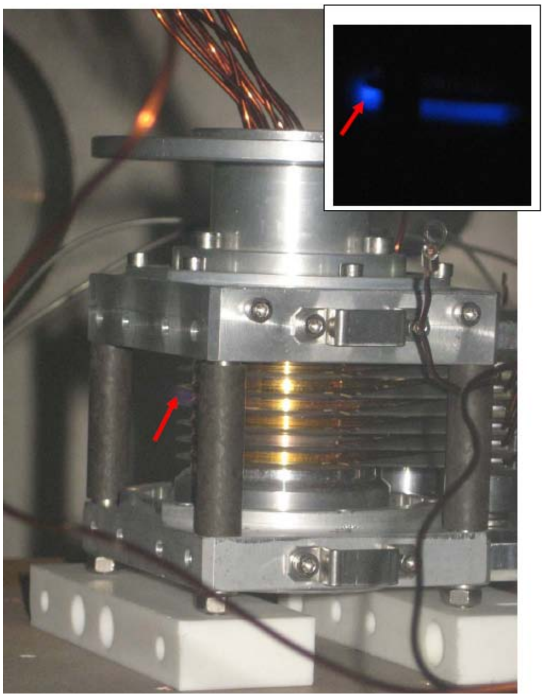


Fig. 13 BB during arcing test at worst case conditions.

8. CONCLUSIONS AND LESSONS LEARNT

1. In principle, the feasibility of a slipring solution for rotary joint for BepiColombo mission could be shown. Nevertheless there are still open questions (bearing, angular sensor, cables).
2. The first configuration of the BepiColombo HTRJ – BB containing 2 non lubricated bearings showed failure of the bearings after about 170 turns of the test. The second configuration of the BB – model contained only 1 bearing (Dicronite coated).
3. The contact resistance of all tracks of the BB remained nearly constant during the test procedure.
4. TC Test of EM: Mean values of resistance measured during functional tests didn't change significantly
5. LC Test of EM: Mean values of resistance and noise didn't change significantly with Au-based rings
6. Due to very stiff cables torque of sliprings couldn't be measured and contact of cable to CuMMC was broken.
7. Within the visual inspections no damage of the BB and the EM could be stated.

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