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Towards a new slip ring design for the next generation of high-power satellites: a plasma-physics challenge

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The aerospace community is continuously pushing forward the limits of space technology to meet the future scientific challenges, and the upcoming market demands. This requires a constant effort in promoting and coordinating dedicated R&D programs years before the application of the corresponding product becomes necessary. During the last decade, the possibility of increasing the current satellite operating voltages of 30 - 100 V up to 300 - 600 V has been one of the hot topics under investigation. This upgrade mostly aims at reducing the power-to-mass ratio, and therefore the cost, for the next generation of satellites equipped with ion and Hall high-power thrusters [1]. At the same time, this impacts the satellite design on multiple levels, including the safe operation of key components that must be assured for the whole operating life of a satellite. The main risk associated with voltages in the range of a few hundreds of volts is the electrical breakdown [2, 3, 4, 5], which has been already observed in the past at the solar panel level [6]. Electrical breakdown is one of the fundamental topics in plasma physics, playing an important role in science and technology with various applications, such as electrical relays, spark gaps for automotive, and X-ray tubes. When not controlled, it can lead to destructive events with the consequent failure of the associated components, which is generally avoided by improving the electrical insulation of the high voltage conductors with respect to the reference ground. However, this can be extremely complicated in satellites because of charge build-up, up to being not compatible for a specific component that features exposed high-voltage parts like the Slip ring Assembly. The SRA is a key element in the power transmission line of a satellite, allowing for the current transfer from the rotating solar panels to the main body of the satellite. In the standard cylindrical configuration, this is achieved by gold-plated brushes slipping on gold-plated rings, stacked inside a conducting housing at the ground reference voltage of the satellite, as shown in Fig. 1 (a), and schematically illustrated in Fig. 1 (b). This configuration is prone to gas breakdown on multiple length scales, from ~ mm between adjacent rings, to ~ 10 cm over the full length of the ring stack. According to the Paschen's law, this corresponds to critical pressure values in the range 10^{-1} - 10 mbar, which is necessarily encountered by the satellite from atmospheric pressure before launch to high vacuum during the de-pressurization phase. To mitigate this potential failure, a first discussion between Beyond Gravity (at that time RUAG Space) and the Swiss Plasma Center (SPC - at that time CRPP) started in 2010, triggering the RETS project, with the support of the European Space Agency, within the framework of a PhD project at the SPC (2010 - 2013) [7]. At first, the SRA was simplified down to the most relevant components in a mockup to investigate the breakdown mechanism in a cylindrical geometry: three conducting rings arranged in a stack and separated by two insulating rings, with a high voltage applied to the central ring, while ground-

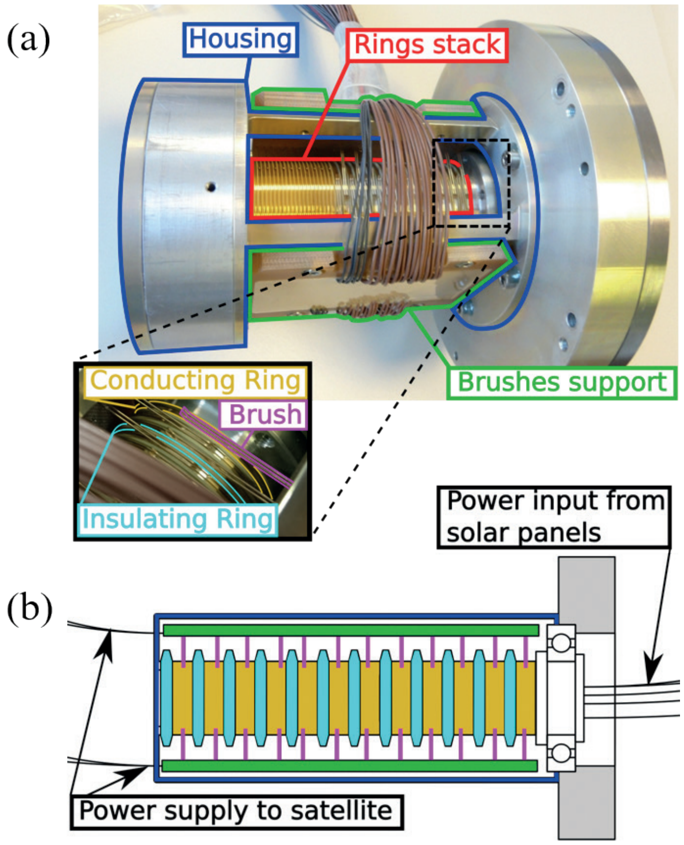

Figure 1: (a) Photograph of a cylindrical slip ring [7]. The conducting housing is partially removed to show the slip ring components such as brushes, and conducting and insulating rings. (b) Schematic of the slip ring with the colours of the components corresponding to the labels in (a).

Acronyms

APRIOM	**A**dvanced sli**P** **RI**ng for high v**O**ltage **Mech**anism.
ARTES	Advanced Research in Telecommunications Systems.
BBM	Bread Board Model.
HV-EPSA	High Voltage Electrical & Power System Architecture.
LDs	Limiting Discs.
RETS	Robust Electrical Transfer Systems.
SPC	Swiss Plasma Center.
SRA	Slip ring Assembly.
TRL	Technological Readiness Level.

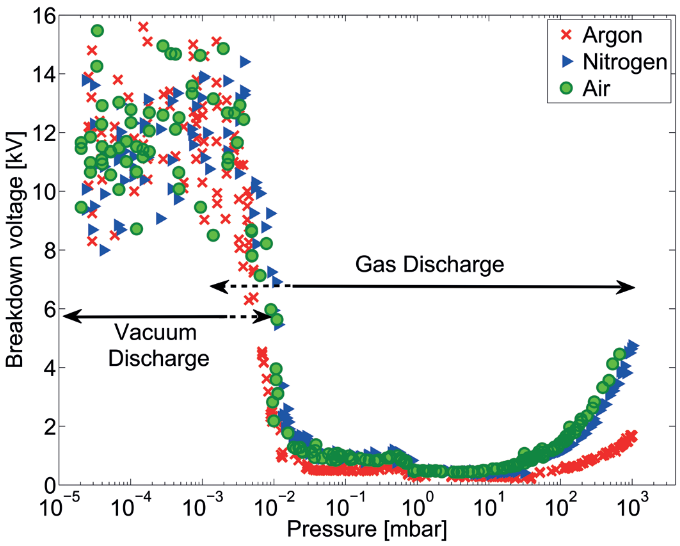

Figure 2: Measured dc breakdown voltages for the ring assembly from 2 × 10^{-5} to 10^3 mbar in different gases [7].

ing those at the sides. Experimental studies were performed by varying several parameters, namely the operating gas (Argon, Nitrogen, Air), the conductor rings thickness, the insulating rings diameter and thickness, the voltage polarity, as well as the voltage frequency (from DC, to the kHz range). These allowed to define the pressure range of interest for gas breakdown, and the safe region of operation in terms of breakdown voltage, as shown in Fig. 2, with a more detailed differentiation between different kind of discharges, such as negative and positive coronas, or arcs, by using optical emission spectroscopy. Numerical investigations were performed in parallel by developing a 2D COMSOL model. This confirmed that the observed breakdown voltage minimum measured in Fig. 2 at ~ 300 V over the wide range of intermediate pressure is due to the SRA complex geometry, where multiple path lengths are available as the most favorable gap over which breakdown can occur: the low (high) pressure thresholds for gas discharges are given by the longest (shortest) electric field path length. The RETS project established the experimental and theoretical basics of gas breakdown physics of SRAs for the follow-up High Voltage Electrical & Power System Architecture project in 2016, within the Horizon 2020 framework, during which an innovative passive technical solution to inhibit gas breakdown at low pressures was developed. Analyzing the low pressure branch of the measured breakdown curves, which features electrical breakdown between the high-voltage electrode and the conducting housing (vacuum chamber), the diameter of the adjacent grounded rings (from now on referred to as Limiting Discs) was increased to act as a partial Faraday screen of the HV ring. This is significantly reducing the electric field intensity towards the housing (vacuum chamber), as confirmed by COMSOL simulations. The proximity of the grounded LDs is counter-intuitive from the point of view of vacuum breakdown, but this approach effectively inhibits gas breakdown, which occurs at voltages much lower than for vacuum breakdown, leading to an increase of the safe operating pressure range of the satellite slip ring by two orders of magnitude, as can be observed from the breakdown curves in Fig. 3 [9]. To increase the breakdown minimum voltage of a SRA from ~ 300 to 600 V, the grounded LDs configuration was modified by passively biasing the two LDs with a series of resistances, to keep their voltage roughly a half of that applied to the central HV ring, as in the schematic of Fig. 4 (a). This technical solution was tested both in the first SRA mock-up, as well as in the test SRA of Fig. 4 (a ,b), as can be observed in the breakdown curves in Fig. 5. A Technological Readiness Level 3 was attained, corresponding to the experimental proof of concept, with the technology validated in a laboratory. In 2020, the Advanced sliP RIng for high vOltage Mechanism project started within the Advanced Research in Telecommunications Systems program, in a joint collaboration between Beyond Gravity and the SPC of the EPFL, as a follow-up of the HV-EPSA project. The main aim was to reach a TRL level 5 - 6, namely having the technology validated and demonstrated in a relevant environment. The SPC optimized the system's geomet-

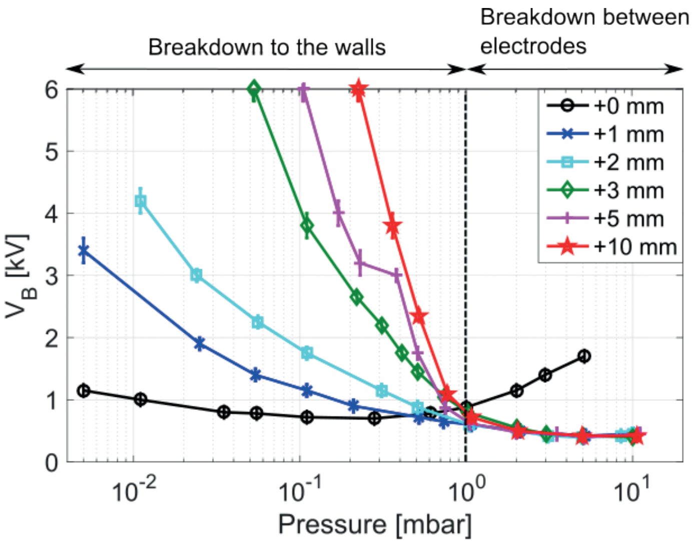

Figure 3: Breakdown voltage as a function of the gas pressure for different grounded discs. The black circles are for the HV-ring alone inside the vacuum chamber. The other measurements refer to the assembly with grounded limiting rings of increasing diameter [9].

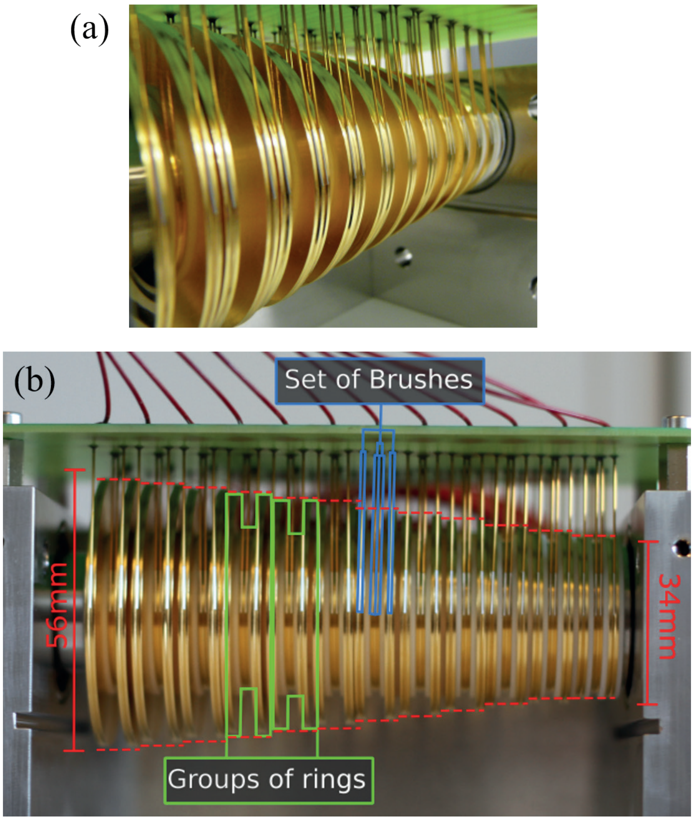

Figure 4: (a) Close-up view of the ring stack and the associated brushes of the test SRA shown in (b) from the side [10].

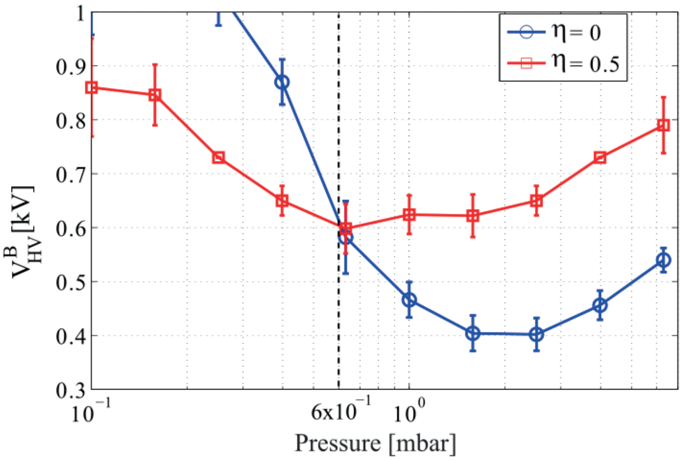

Figure 5: Breakdown curves of the HV ring for the test-SRA with 54 mm LDs: in blue circles, the case of grounded LDs (η = 0), in red squares the curve measured with the passively biased LDs (η = 0.5) [10].

rical parameters, both via experimental measurements, as well as COMSOL simulations, contributing to the finalization of the Bread Board Model design, which is representative of a real satellite slip ring featuring the new passively-biased LDs solution. Also, the breakdown mechanism in a scenario with transient voltages was explored at the SPC to define the limits of performance of the simple mockup. The BBM pictured in Fig. 6 was developed by Beyond Gravity and tested for 25.000 tours, taking into account that a Geo-satellite undergoes about 11.000 tours in 30 years of operation. Most importantly, the component was successfully operated at 10^{-5} mbar with 500 V, and 8 A (40 kW of equivalent power), as well as at 1 mbar, with 400 V and 8 A (32 kW of equivalent power). These tests confirmed the achievement of a TRL 5 - 6 for the passively-biased LDs solution, opening the way towards the design of a SRA prototype for the next generations of high-power thruster satellites.

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Figure 6: Picture of the BBM implementing the passively-biased LDs [source: Beyond Gravity].

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