The design of high-voltage insulators for spacecraft traveling wave tubes

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ABSTRACT

As part of a study on high-voltage design concepts used in microwave tube technology, a number of different insulator designs are studied. This work clearly demonstrates the presence of surface charge and its effect on the voltage holdoff performance and the conditioning process. Insulators may be characterized by the breakdown voltage (before and after conditioning), the conditioning speed, and the dependence on surface charge.

Insulators with anode field enhancements give the best performance. Field enhancements at the cathode side are less harmful if stepped insulator shapes are chosen. Effective conditioning requires at least a limited number of breakdowns. With sufficient conditioning breakdowns all insulator geometries tested reached an averaged breakdown field exceeding 12 kV/mm.

1. INTRODUCTION

The present generation of spacecraft traveling wave tubes (TWT's) suffers from spurious discharges and tube failure as a result of high-voltage breakdown. Supported by the European Space Agency, we have studied the high-voltage design concepts used in microwave tube technology [1]. The objective of this work was to provide guidelines for future tubes, operating at increased frequency and power (and consequently at increased voltage).

The most promising opportunities for improving the high-voltage performance of microwave tubes are in our opinion field control and conditioning techniques. The choice of materials is often limited by additional requirements (vacuum and thermal properties, machinability, etc.). Although possibly promising material treatments such as doping and coating have been suggested [2], the literature shows a lack of data on their long term behavior, whereas stability is of major concern.

Earlier we have reported on field control techniques for improving existing designs [3,4,5]. Here we present the results of a more fundamental study of insulator geometries. From problem areas, encountered in actual designs or in literature, we have derived a number of test geometries for experimental investigation. The tests include sensitive DC current and partial discharge measurements, breakdown voltage measurements and time-resolved measurement of current and optical emission during breakdown. Also different conditioning procedures have been studied experimentally.

We will emphasize the role of surface charge in the breakdown process and in the conditioning process. We will discuss how the insulator shape affects not only the electric field in the cathode triple junction (field control), but also whether, and how much, surface charge is deposited.
rent during breakdown. Time-resolved optical emission during breakdown is measured with a detection system involving photomultiplier tubes, and the necessary optics. The bandwidth of the time-resolved measurements is 600 MHz.

The high-voltage source and most diagnostics are controlled and monitored by a personal computer. For inspection of samples an optical microscope and a Scanning Electron Microscope (SEM) are available. State of the art EMC measures are taken to ensure reliable and interference-free measurements in the presence of flashovers, partial discharges, switched mode power supplies and other sources of interference.

3. TEST SAMPLES

The test samples used are shown in Fig. 2. All samples are machined out of circular disks of 40 mm diameter and 5 mm thickness, made of Wesgo AL300 alumina, metallized at top and bottom side with MoMn and Ni, and gold-plated. The outer surfaces are carefully machined under clean room conditions. The disks are subsequently cleaned in flowing ethanol of 70°C, dried and stored in dry nitrogen. Before the experiments the samples are conditioned. With an optical microscope and a SEM samples were inspected in different stages of production, as well as before and after experiments.

Figure 2. Insulator geometries used in the present study (asymmetric shapes denoted * are tested both ways). Insulator thickness 5 mm, radius 20 mm.

4. CONDITIONING

Spacecraft traveling wave tubes are usually conditioned with voltage conditioning, possibly combined with heat treatment. It is well known that the conditioning effect is lost when a component is exposed to air. This is usually ascribed to the adsorption of oxygen or water to electrode or insulator surfaces. We have observed that conditioning becomes more effective if a few breakdowns are permitted. Our experiments further show that the conditioning effect may also be lost when the component is exposed to low pressure dry nitrogen. When nitrogen was admitted to samples after voltage application, discharges were observed caused by the charges accumulated at the insulator surface. These observations indicate that the loss of conditioning effect upon exposure to nitrogen is related to the removal of surface charge.

We have compared the effect of the following three conditioning procedures to identical sets of samples (see Fig. 3):

- **Stress-conditioning.** The voltage is raised in steps of 10 kV, and remains at each level for 10 minutes. After the first breakdown the voltage is ramped to breakdown 10 times.
- **Ramp-conditioning.** The voltage is ramped to breakdown 10 times. Then the voltage is raised in steps of 10 kV, and remains at each level for 10 minutes until breakdown occurs.
- **Step-conditioning.** The voltage is ramped to breakdown. The voltage is then set at 90% of this first breakdown voltage for 5 minutes, and is increased by 5% every 5 minutes until a next breakdown occurs. The voltage is then set at 90% of this second breakdown value, and so on, until 11 breakdowns have occurred.

Figure 4 shows the improvement of the holdoff performance during conditioning, and the subsequent breakdown behavior. After step-conditioning the breakdown voltage shows the fastest rise and the smallest spread. In the present work therefore the step-conditioning procedure is used, however with a total number 6 breakdowns rather than 11 in order to minimize the risk of failure during conditioning.

5. RESULTS AND ANALYSIS

The results of DC-current measurements and partial discharge measurements during and after voltage steps are presented elsewhere [1,6,7] and will be briefly summarized here. Upon a voltage step the DC current rises fast and decays to an end value in a few minutes. The measured current is corrected for the displacement current \( \frac{dQ}{dt} \). A transient charge is derived by integration of the measured current, after the constant end-current is subtracted. The derived charge divided by the voltage change is approximately constant, and is the same for a voltage rise and for a voltage drop. The charge per kV voltage change is however clearly dependent on the insulator shape. Partial discharges occur mainly during voltage changes. The amount of charge again depends on the insulator shape. The results of both diagnostics indicate that the insulator surfaces are charged and discharged upon stepwise voltage changes. A possible explanation of the DC current behavior in terms of polarization relaxation (a bulk mechanism) is contradicted by the clearly different response of different sample shapes.

The most direct evidence of the presence and the role of surface charge is provided by breakdown experiments before and after surface charge has been removed. The voltage is repeatedly ramped to breakdown with 1 kV/s (with the external coupling capacitor removed). Upon breakdown the voltage is reset to zero, and ramped again to breakdown after a time delay of 3 seconds. The measurements are stopped when the breakdown voltage has reached the maximum supply voltage of 60 kV. Then the surface charge is removed. For this purpose dry nitrogen is admitted to a pressure beyond the minimum of the Paschen curve (to about 10 mbar), with no voltage applied. The vessel is pumped down again and a second series of breakdown measurements is performed. During nitrogen exposure we have observed optical emission and partial discharge activity, indicating that the surface is actually being discharged. An example of such a break-
Figure 3. Applied voltage (kV) versus time (minutes) for the conditioning procedures tested. Here each conditioning procedure involves a total of 11 breakdowns, in the actual experiments only 6 breakdowns are allowed.

down voltage measurement is given in Fig.5. The breakdown voltage increases to about 4 times its initial value, and falls back upon exposure to nitrogen. In the series of breakdowns after exposure the insulator is conditioned much faster than in the first one. These measurements clearly prove that surface charge may dramatically affect the holdoff performance and the conditioning process.

Important insulator parameters are the breakdown voltage (before and after conditioning), the conditioning speed, and the dependence on surface charge. Figure 6 shows the minimum breakdown voltage (before conditioning or nitrogen exposure) for different insulator shapes. A field enhancement at the anode side, as in samples 4b, 5b, 6b and 10b, gives the highest breakdown voltage. Note that at a given voltage the integral \( \int E \, dl \) is constant and a field enhancement at the anode causes a field reduction at the cathode. For a field enhancement at the cathode side we note that a 45° angle (as in samples 4a and 8) causes a lower breakdown voltage than geometries with a smaller angle (as in sample 7) or with stepped shapes (as in samples 2, 5a and 6a); these shapes (2, 5a, 6a, 7) collect surface charge effectively, thereby reducing the cathode triple junction field.

All insulators tested reached a breakdown voltage of 60 kV. Figure 7 shows the first breakdown voltage.
after nitrogen exposure. For sample shapes with a field enhancement at the anode side (4b, 5b, 6b, 10b) the breakdown voltage hardly changes by nitrogen exposure: these samples hardly collect surface charge. For sample shapes with cathode field enhancements a difference is observed between stepped and non-stepped shapes. For non-stepped shapes (4a, 10a) much of the improvement is lost after exposure, whereas the stepped shapes (5a, 6a) show no or only a small deterioration. An explanation may be that non-stepped shapes rely heavily on surface charge in order to attain a high breakdown voltage, or that stepped shapes can be charged without breakdowns. It is not likely that non-stepped shapes are more easily discharged by N₂ than stepped shapes.

Figure 5. Measured breakdown voltage (kV) versus breakdown number for insulator 4a (geometry 4 from Fig.2 with field enhancement at cathode side). The left series (0-67) is recorded before, the right series (0-19) after exposure to low pressure nitrogen.

Figure 6. Minimum (usually first) breakdown voltage observed (kV), in ranking order. Two samples of each geometry were tested.

Figure 7. First breakdown voltage after N₂ exposure (kV), in ranking order. Two samples of each geometry were tested. The breakdown voltage before N₂ exposure equals the maximum supply voltage of 60 kV.

Figure 8 gives the number of breakdowns needed to reach a breakdown voltage level of 50 kV. Samples with an anode field enhancement (4b, 5b, 6b, 10b) reach this level fast due to the combined effect of a high initial breakdown voltage and a high conditioning speed. These shapes do not, or not efficiently, collect surface charge. The insulator shapes with cathode field enhancement improve more slowly, especially in case of a 45° slope (4a, compare also 7 and 8).

Figure 8. Number of breakdowns needed to establish a breakdown voltage of 50 kV, before (left bar) and after (right bar) N₂ exposure. The samples are ranked according to the number of breakdowns required before exposure. Each number is the average of two experiments.
The work presented clearly proves the presence of surface charge and its effect on the voltage holdoff performance and the conditioning process. Parameters describing the quality of insulators in vacuum are the breakdown voltage values (before and after conditioning), the conditioning speed, and the dependence on surface charge. Given sufficient conditioning breakdowns, all insulating geometries tested attain a high breakdown voltage. Insulators that rely on surface charge in order to have a high breakdown voltage should not be exposed to whatever gas, and should not be left without voltage applied for too long a time. For the samples used in this study the breakdown voltage was not affected when the voltage was switched off for a period of about 65 hours.

The effects of surface charge should be incorporated in the design. An important aspect is the conditioning process. If, in the conditioning process, one applies a sufficiently large number of breakdowns with limited energy, all geometries will reach a high breakdown voltage. If no breakdown conditioning is applied, the minimum or first breakdown voltage is decisive. In practice one would like to apply only a limited number of breakdowns, and therefore choose for a geometry with a high conditioning speed. Also in case of repetitive exposure to gases, or when the voltage is frequently switched off for long periods of time, a design with a high conditioning speed should be chosen. In terms of breakdown voltage, sensitivity to exposure or charge leakage, and conditioning speed, insulator geometries with field enhancements at the anode are superior. If cathode field enhancements are unavoidable, stepped shapes are recommended.

Breakdown conditioning, in particular step-conditioning, may drastically improve the voltage holdoff performance, and reduce the effects of uncontrolled, often microscopic, parameters. The main objection against breakdown conditioning at present is the fact that the discharge energy may be large and uncontrolled. Future designs could therefore aim at control of the breakdown energy, for example by subdividing assemblies and connecting the different parts by, for example, inductances which block the high-frequency current during a breakdown event. Important questions for future work are whether conditioning can be done more quickly, with simpler methods and in particular with fewer, or possibly no, breakdowns. Future work should reveal what is the optimum breakdown energy for conditioning if breakdowns are permitted.

References