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Experimental test of whether electrostatically-charged micro-organisms and their spores contribute to the onset of arcs across vacuum gaps

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Recently it was proposed [L. R. Grisham, A. von Halle, A. F. Carpe, Guy Rossi, K. R. Gilton, E. D. McBride, E. P. Gilson, A. Stepanov, T. N. Stevenson, Physics of Plasmas **19** 023107 (2012)] that one of the initiators of vacuum voltage breakdown between conducting electrodes might be micro-organisms and their spores, previously deposited during exposure to air, which then become electrostatically charged when an electric potential is applied across the vacuum gap. This note describes a simple experiment to compare the number of voltage-conditioning pulses required to reach the nominal maximum operating voltage across a gap between two metallic conductors in a vacuum, comparing cases in which biological cleaning was done just prior to pump-down with cases where this was not done, with each case preceded by exposure to ambient air for three days. Based upon these results, it does not appear that air-deposited microbes and their spores constitute a major pathway for arc initiation, at least for exposure periods of a few days, and for vacuum gaps of a few millimeters, in the regime where voltage holding is usually observed to vary linearly with gap distance.

Although the voltage gradient which can be reliably sustained across a vacuum gap between two metallic conductors without arcing is the most significant constraint in the design of electrostatic accelerators and in related applications, the physical mechanisms responsible for the onset of electrical arcs between electrodes have remained unclear. Proposed mechanisms have included field emission of electrons from surface imperfections, the growth of whiskers that enhance field emission of electrons, emission of ions from surfaces, and the acceleration of electrically charged clumps, presumably of oxide, from one electrode to the other. [2 - 16] The clump model yields the best agreement with the generally observed scaling of voltage holding with the vacuum gap distance, namely, but suffers from the fact that oxides are tightly bound to their surfaces, and thus not easily detachable for acceleration.

Recently, it was proposed [1] that some or all of the "clumps" of the clump model might be microbes such as bacteria, bacterial spores, fungi, and fungal spores. They are ubiquitous in air, and thus constantly being deposited upon exposed surfaces, they are appropriately sized, [17,18] with dimensions of microns, they are in most cases only weakly attached, if attached at all, to the surfaces on which they land, and they readily acquire an electrostatic charge, especially as spores.

If microbes and their spores deposited from air, as hypothesized, play a significant role in initiating at least some electrical arcs between metallic electrodes in vacuum, then one way to test this hypothesis would be to explore whether changes in the timing of the final cleaning of the electrodes comprising a high voltage vacuum gap relative to when the electrodes are put under vacuum is associated with changes in the number of high voltage conditioning shots required to reach the nominal operating voltage for the vacuum gap. The results of this test should also serve as evidence of whether a relatively simple change in experimental protocol, which could be readily implemented in at least some practical applications, might produce significant operational benefits.

In order to keep the experiment as simple and inexpensive as possible, the configuration used was comprised of two 3.175 cm diameter hardened stainless steel spheres, separated by a gap of 3.15 mm. They were installed in the Princeton ion source test stand, an aluminum vacuum enclosure with dimensions of roughly 2.6 x 0.9 x 0.6 meters, evacuated by a turbo-molecular pump to a pressure generally in the range of 4.5×10^{-7} to 1×10^{-6} Torr. The negative electron-emitting sphere was suspended from a porcelain vacuum feed-through, while the anode sphere was supported by an aluminum plane grounded to the test chamber, resulting in a vacuum test gap surrounded by vacuum. Using spheres to form the vacuum gap meant that the alignment would be simple, and the required experimental time short, since the area at the opposing surfaces of the spheres subjected to the highest fields would be small.

The electrical system consisted of a low current 100 kV power supply, with a crowbar circuit in parallel with the vacuum gap defined by the two spheres. The crowbar circuit turned off the output of the high voltage supply, and fired a crowbar to divert the current away from the test gap to instead flow through a thyristor switch when a current surge was detected flowing across the vacuum gap between the two spheres. After some testing, the trip level was set to 700 micro-amperes for the crowbar circuit, as this appeared to be above the system electrical noise, but low enough to preclude significant surface damage to the spheres. In order to limit the stored energy available to a fault, there was only was only about 25 cm of electrical path length between the crowbar and the negative electron-emitting sphere. When triggered the thyristor switch reduced the voltage across the vacuum gap between the spheres from full voltage to 0 volts in about 10 microseconds, roughly the same sort of timescale over which the crowbars for ion beam accelerators typically operate.

Accordingly, the experiment was designed to simulate the way in which accelerator grids are often conditioned up to their intended operating voltage, but with a much smaller area at the highest electrical field than is usually the case, and with a robust material for the electrode surfaces to reduce the chances of damage, in combination with the crowbar circuit to limit the energy that could be dissipated during a voltage breakdown across the test vacuum gap.

Under these circumstances, the ultimate voltage to which the gap could be conditioned should be independent of the cleaning sequence, but what might be expected to change, if removing air-deposited microbes and their spores just before vacuum pump-down reduces one significant instigator of voltage breakdown across vacuum gaps, is that the number of breakdowns required to condition the electrodes to their nominal maximum voltage should be reduced. This is because conditioning an accelerator reduces the originating sources of breakdown by applying controlled bursts of energy which may smooth micro-projections, remove or vaporize clumps of oxide or other electrode material, or, as hypothesized in [1] remove or vaporize microbes and their spores, the hypothesis under test in this experiment. Conditioning probably works though all these channels, as well as perhaps others, but if microbes and their spores deposited from the air constitute an appreciable contributing cause to electrical breakdown between metallic electrodes in vacuum, then time interval between when the electrodes are cleaned relative to when they are put under vacuum should affect the number of conditioning breakdowns required to bring the gap back to its nominal operating voltage.

After the steel test spheres were mounted on their support structures and the spheres and support structures were degreased with ethyl alcohol, which would have had the additional effect of removing microbial life-forms and their spores, they were allowed to sit in the air of a typical room (that Is, the air was not treated to any special controls) for three days, after which the two spheres and their supporting fixtures were installed inside the test stand, which was then immediately put under vacuum. The three day interval for exposure to air was meant to allow ample time for deposition of microbes and their spores from the atmosphere, as the literature suggested that such a time lapse was relatively long on the timescale of microbial deposition from indoor air. [19,20]

The protocol which was then followed consisted of applying high voltage across the gap between the two steel balls inside the vacuum, and raising the voltage until a current rise across the gap triggered the crowbar circuit to turn off the supply and divert the current through the thyristor switch to ground, then to reapply the voltage, but at a slightly lower voltage than that at which it had tripped (of order 2 – 4 kV), and then slowly raise the voltage again until the current again rose, tripping the crowbar circuit. Typically this process was repeated several times per minute, although there was no indication that it was sensitive to the interval between voltage applications over a range of intervals of lengths between a few seconds and a few tens of minutes.

The number of voltage applications, each terminated when a sudden current rise, indicating the onset of high voltage breakdown, was terminated and diverted by the crowbar circuit, was compared between test sequences before which the spheres were exposed to indoor air for three days without biological sterilization prior to being put under vacuum and test sequences before which the spheres were exposed to indoor air for three days, but then cleaned with ethyl alcohol just prior to being put under vacuum. The ethyl alcohol was squirted onto the smooth steel spheres in sufficient quantity so as to wash off loosely attached microbes, their spores, and any other small particulate matter, with vacuum pump-down then beginning within about 5 minutes so that the time available for subsequent re-deposition from the air was much shorter than the three days which constituted the standard exposure interval used for these experiments.

Once installed into the test stand, the steel spheres and their support apparatus were left undisturbed in order to maintain the alignment and gap distance between the spheres, which had separate support systems to simplify the isolation of the sphere at high potential relative to ground. When an experimental conditioning sequence was completed, flanges were removed to allow ambient indoor air to pass through three openings of about 10 cm diameter, two on one side of the test assembly and one the other side, for three days. At the end of the three day exposure period, either the flanges would be reattached and vacuum pump-down commenced, or the spheres would be washed with ethyl alcohol in place just before the flanges were replaced and pump-down commenced, depending upon whether the subsequent conditioning sequence was supposed to have or not have biological decontamination just prior to being put under vacuum.

For purposes of determining whether or not biological decontamination immediately before vacuum pumpdown produced a practically significant difference in voltage hold across a vacuum gap between metallic electrodes, the number of conditioning voltage applications required to reach a nominally stable operating voltage across the gap appeared to be a better measure of efficacy than the exact voltage ultimately reached across the vacuum gap, and is also probably the aspect which would be of most practical value if biological decontamination removed a major pathway for the onset of high voltage breakdown between electrodes in accelerators. This is because with a properly function crowbar system to protect the electrodes from serious discharge-induced damage, a given vacuum gap between two metallic electrodes should always reach about the same reliably sustainable voltage across that particular gap, regardless of the physical mechanism or mix of mechanisms which is leading to the onset of breakdowns, so long as the breakdowns deposit sufficient energy to eliminate the cause of the breakdowns (as indicated by a rise in voltage with successive breakdowns from the initial, unconditioned state of the electrodes), and so long as the crowbar circuit is limiting the energy into a breakdown enough to preclude electrode damage, which appeared to be the case.

After the experimental apparatus was installed in the test stand, some voltage applications were used to vary the threshold for the trip current, in order to determine the correct level so that it would not be tripped by noise or electron emission which was present even when breakdown was not in the process of starting. The current trip level for the crowbar circuit was varied from 300 to 800 micro-amps, with the determination eventually being made that 700 micro-amps was the most appropriate current level at which to trip the crowbar circuit, since it appeared to be above most of the circuit noise, but low enough to minimize or preclude damage to the electrodes. After this initial conditioning sequence with a variety of current trip levels was completed, the system was left under vacuum over the weekend, after which the first of the conditioning sequences using the standard protocol of voltage applications, each raised until the crowbar circuit tripped at 700 micro-amps, was begun. The typical period between voltage applications was 10 – 20 seconds.

After the first of the standard conditioning sequences, the vacuum chamber was exposed to indoor air for three days by removing flanges, as described earlier, after which the spheres were cleaned with ethyl alcohol in accordance with the technique earlier mentioned, and the chamber was immediately pumped down. After pumping overnight, the conditioning sequence was repeated as before, but with the difference being that this time the spheres had been decontaminated with ethyl alcohol just prior to going under vacuum. This was followed by another three day exposure to air, and then conditioning with no decontamination, and then another three days in air, followed by a repeat of the decontamination, and another conditioning sequence. Thus, the data gathered consisted of four sets of conditioning sequences, two taken without decontamination after exposure to air for three days, and two taken after three days of air exposure, with decontamination just prior to being put under vacuum.

The repetition of the conditioning cycles was intended to distinguish between any benefits derived from removing loosely attached microbes, spores, and non-biological micro-particles such as very fine dust just before pumpdown and more general factors such as repeated conditioning sequences. While of limited duration due to time constraints, this sequence of conditioning cycles should be adequate to determine whether the protocol produced significant benefits.

Figure 1 shows the results obtained over the course of the conditioning sequences. With a fast crowbar circuit to minimize damage to the electrodes due to the arcs which terminate each voltage application, it would be expected that about the same ultimate operating voltage would be achieved regardless of whether sterilization just prior to pump-down was significant or not significant. Where the benefit, if any, of sterilization should appear is in the number of conditioning pulses required to reach the limiting voltage of the vacuum gap. Conditioning sequences 1 and 3 did not have ethyl alcohol washing of the steel spheres after three days exposure to air, while sequences 2 and 4 did. While sequences 2 and 4, which were washed with alcohol just prior to vacuum pump-down, start at higher voltages and reach the peak voltage sooner than does sequence 1, which was not alcohol-cleaned just prior to vacuum pump-down, it is also the case that sequence 3, which was not cleaned with alcohol before pump-down looks as good as sequences 2 and 4 in terms of how many conditioning pulses are required to reach the maximum voltage gradient at which moderately stable operation is possible.

Accordingly, the conclusion of this experiment is that washing electrodes with ethyl alcohol just prior to vacuum pump-down does not significantly reduce the number of conditioning pulses required to achieve the optimum operating voltage across a vacuum gap. This suggests that air-deposited micro-organisms and their spores are not a major source of voltage breakdown instigation, or if they do play a significant role, it would only become important after much longer periods of exposure to air, or perhaps for significantly larger vacuum gaps separating the electrodes, where the scaling of voltage holding with gap distance is known to change from the linear regime which prevails at small gaps of a few millimeters, such as was used here due to facility and equipment constraints.

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References

[1] L. R. Grisham, A. von Halle, A. F. Carpe, Guy Rossi, K. R. Gilton, E. D. McBride, E. P. Gilson, A. Stepanov, and T. N. Stevenson, Physics of Plasmas **19** 023107 (2012).

[2] W. P. Dyke and J. K. Trolan, Phys. Rev. **89** (1953).

[3] R. H. Fowler and L. Nordheim, Proc. R. Soc. London **A119** 173 (1928).

[4] L. Nordheim, Proc. R. Soc. London **A121** 626 (1928).

[5] A. J. Ahearn, Phys. Rev. **50**, 238 (1936).

[6] L. C. Van Atta, J. Van de Graff, and H. A. Barton, Phys. Rev. **43**, 158 (1933).

[7] N. I. Ionov, Sov. Phys. Tech. Phys. **5**, 527 (1960).

[8] R. Amal, Ann. Phys. **10**, 830 (1955).

[9] J. G. Trump and R. J. Van de Graff, J. Appl. Phys. **18**, 327 (1947).

[10] L. I. Pivovar and V. I. Gordienko, Sov. Phys. Tech. Phys. **7**, 908 (1963).

[11] L. Cranberg, J. Appl. Phys. **23**, 518 (1952).

[12] G. P. Beukema, J. Phys. D: Appl. Phys., **7**, 1740 (1974).

[13] Yu. V. Medvedev, Plasma Phys. Rep. **36** 507 (2010).

(14) S. A. Barengolts, G. A Mesyats, E. A. Perelstein, Techn. Phys. **54** 1446 (2009).

(15) Y. Langlois, P. Chapelle, A. Jardy, F. Gentils, Journal of Applied Physics **109** 113306 (2011).

(16) I. J. Cooper, D. R. McKenzie, J. Appl. Phys. **99** 093304 (2006).

[17] R. G. Green and W. P. Larson, J. Infect. Dis. **30**, 550 (1922).

[18] B. S. Henry and C. A. Friedman, J. Bacteriology **33**, 323 (1937).

[19] I. Goh, J. P. Obbard, S. Viswanathan, Y. Huang, Acta Botechnol. **20**, 67 (2000).

[20] J. R. Puleo, M. S. Favero, G. S. Oxborrow, C. M. Herring, Applied Microbiology **30**, 786 (1975).

Figure Captions

1. Conditioning curves showing voltage achieved before the onset of voltage-holding breakdown as a function of the number of voltage applications. Series 1 and 3 are without biological decontamination of the electrodes after 3 days exposure to ambient air, while series 2 and 4 had biological decontamination just prior to pumpdown after 3 days of air exposure.

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