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Effects of Voltage Ramp Rates on Electrostatic Field Strength in Highly Disordered Insulating Materials

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I. Introduction

The primary objective of this work investigated the dependence of electrostatic field strength for spacecraft materials on voltage ramp rate, by applying an increasing electrostatic field until electrostatic breakdown occurred. At high enough electrostatic fields or after long times, insulators can breakdown, causing large current flow through the material: this breakdown is called electrostatic discharge (ESD). Enhanced understanding of prolonged exposure to high static electric fields (DC aging) of insulating materials based on expanded experimental studies is critical to understand the physics of highly disordered insulating materials, as well as for applications in spacecraft charging, high voltage DC power transmission cables and switching, thin film dielectrics, and semiconductor devices and sensors [2].

For many real spacecraft charging situations, the standard tests with rapidly increasing applied fields do not provide an appropriate measure of the likelihood of failures [3]. ESD breakdown is the main cause of failures and anomalies attributed to the spacecraft charging interactions with the space environment [1].

Initial tests on the polymeric material Kapton E^{TM} (PI) found that at ramp rates two or three orders of magnitude lower than the maximum recommended rate, F_{ESD} was lower than at rapid rates by a factor or two or more (see Fig. 3). This suggests that tabulated values of F_{ESD} which have been used by the spacecraft charging community can substantially overestimate F_{ESD} in common slowly evolving spacecraft situations.

This motivated similar measurements on additional materials reported here.

II. Theory

A common mean field approximation for breakdown that considers only mean defect energy,ΔG_{def} , and mean defect density, N_{def} is the Crine model [5,6].

$$P_{def} = \frac{2k_B T\Delta t}{h} e^{\frac{-\Delta G_{def}}{k_B T}} \sinh\left[\frac{\varepsilon_0 \varepsilon_r F^2}{2k_B T N_{def}}\right] \qquad (1)$$

A first order approximation for how F_{ESD} depends on the ramp rate dV/dt, comes by assuming that the ratio at two different ramp rates is the same for breakdown fields and the probability of breakdown. Setting the ratio of (1) evaluated at $\Delta t = \Delta t_{step}$ and $\Delta t = 1\ s$ equal to the ratio of the experimental ramp rate *r* over $r_0 = 1$ and recalling that $\sinh^{-1} x = \ln\left(x + \sqrt{1 + x^2}\right)$ we find

$$F_{ESD}(r) \approx \sqrt{1.1346\, F_{ESD}(r_0)^2 \ln\left(r + \sqrt{1 + r^2}\right)} \qquad (2)$$

Note: (2) corrects a typographical error found in [4]. This approximation is quite simple but as it neglects much of the ramping process.

For incremental voltage step-up tests the breakdown probability, P_{BD}, becomes

$$P_{BD} = 1 - \prod_{j=1}^{V/\Delta V} [1 - \alpha\Delta t \sinh[\beta(j\Delta V)^2]] \qquad (3)$$

III. Methods and Results

Standard step-up voltage tests [8] were performed in a custom high vacuum chamber (<10^{-3} Pa base pressure) at room temperature (see Fig. 1) [7]. Samples were placed between a metal sample mounting plate and six highly polished Cu high voltage electrodes, using recommended ~0.4 MPa uniform clamping pressure [8]. For ramp rate tests, voltage was incrementally increased at a constant time intervals until breakdown occurred, which was evident by an abrupt current increase followed by a ohmic linearly current above breakdown set by limiting resistors.

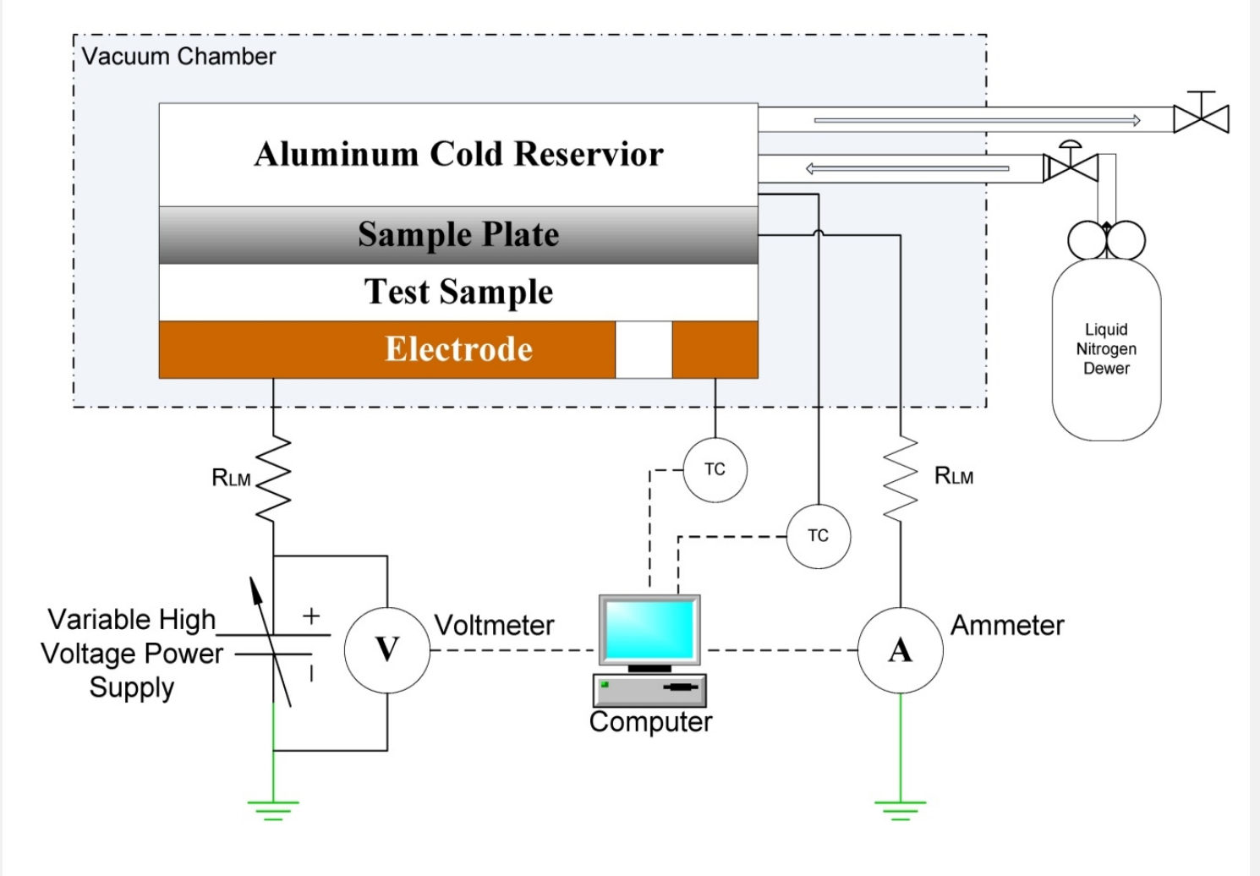

Figure 1. Schematic of ESD test chamber.

Figure 2 shows three step-up tests done at slow, medium, and fast ramp rates. Ramp rates shown in Fig. 2 vary from 20 V per 4 s up to 2000 V per 4 s [4]; standard protocols suggest rates less than 500 V/s [7].

Between 3 and 6 tests were done at each ramp rate; each point in Fig. 3 shows the average and standard deviation of the tests at a given ramp rate. Figure 3 shows the breakdown field versus ramp rate for three polymeric materials, Kapton E^{TM} (PI), Kapton HN^{TM} (PI), and biaxially oriented poly-propylene (BOPP). Also shown are the average F_{ESD} and a fit based on Eq. (2).

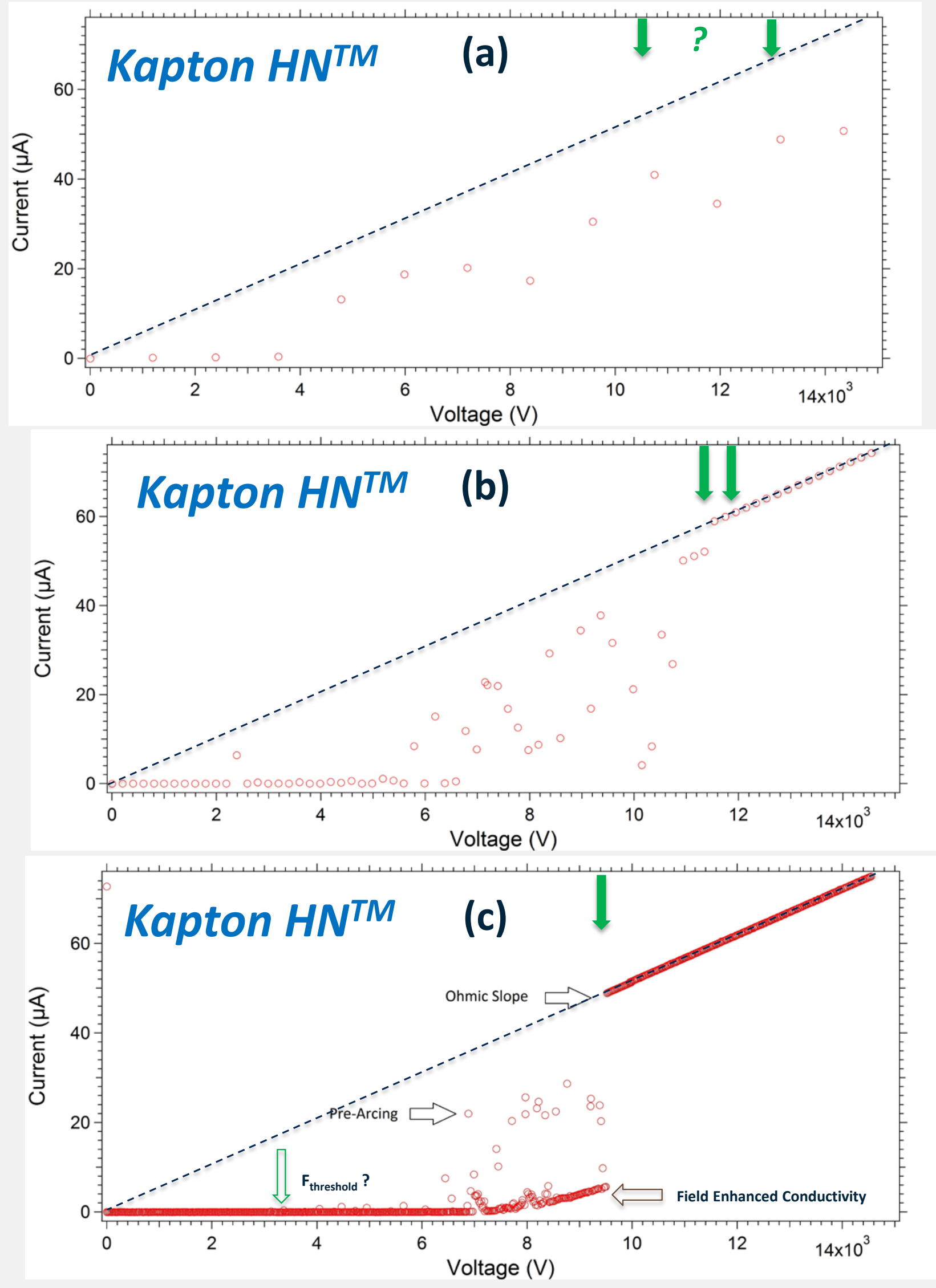

Figure 2. Comparison of representative step-up voltage tests of Kapton HN™ at fast, medium and slow ramp rates. (a) 300 V/s (1200 V per 4 s), (b) 100 V/s (400 V per 4 s), and 5 V/s (20 V per 4 s) test. Arrows indicate range of F_{ESD}.

Figure 2 clearly shows that faster ramp rates yield less information than the slow ramp rates.

- Faster ramp rates are limited by the resolution of the voltage step size, which in the case of fast ramp rates is quite large [see Fig. 2(a)].
- In contrast, the smaller step size in the slower ramp rate tests results in higher resolution and more continuous data [see Fig. 2(c)].
- The higher resolution data from lower ramp rates tests [Fig. 2(c)] exhibits more detailed physical information, including pre-arcing [7], field enhanced conductivity and possibly a threshold breakdown field strength, $F_{threshold}$.
- Fig. 4 shows other information from slower ramp rate tests.

IV. Conclusions

- Initial Kapton E^{TM} ramp rate data showed strong dependence over a limit rage of ramp rates, consistent with a proposed mean field theory , Eq. (2).
- Subsequent ramp rate date for Kapton HN^{TM} and BOPP showed little ramp rate dependence. Kapton HN^{TM} and BOPP data are consistent with a single average F_{ESD}.
- More data for additional ramp rates, lower uncertainties at a given ramp rate, and more diverse materials are required to test the applicability and accuracy of the mean value, mean field [Eq. (2)] and incremental voltage step [Eq. (3)] models.
- Slower ramp rates:
  - Better approximate spacecraft charging situations, where charging is most often very slow,
  - Allow higher precision and accuracy determination of F_{ESD},
  - Produce data with more observable effects, such as pre-arcing and possibly field enhanced conductivity [7].
  - May result in significantly lower values of F_{ESD} for some materials.

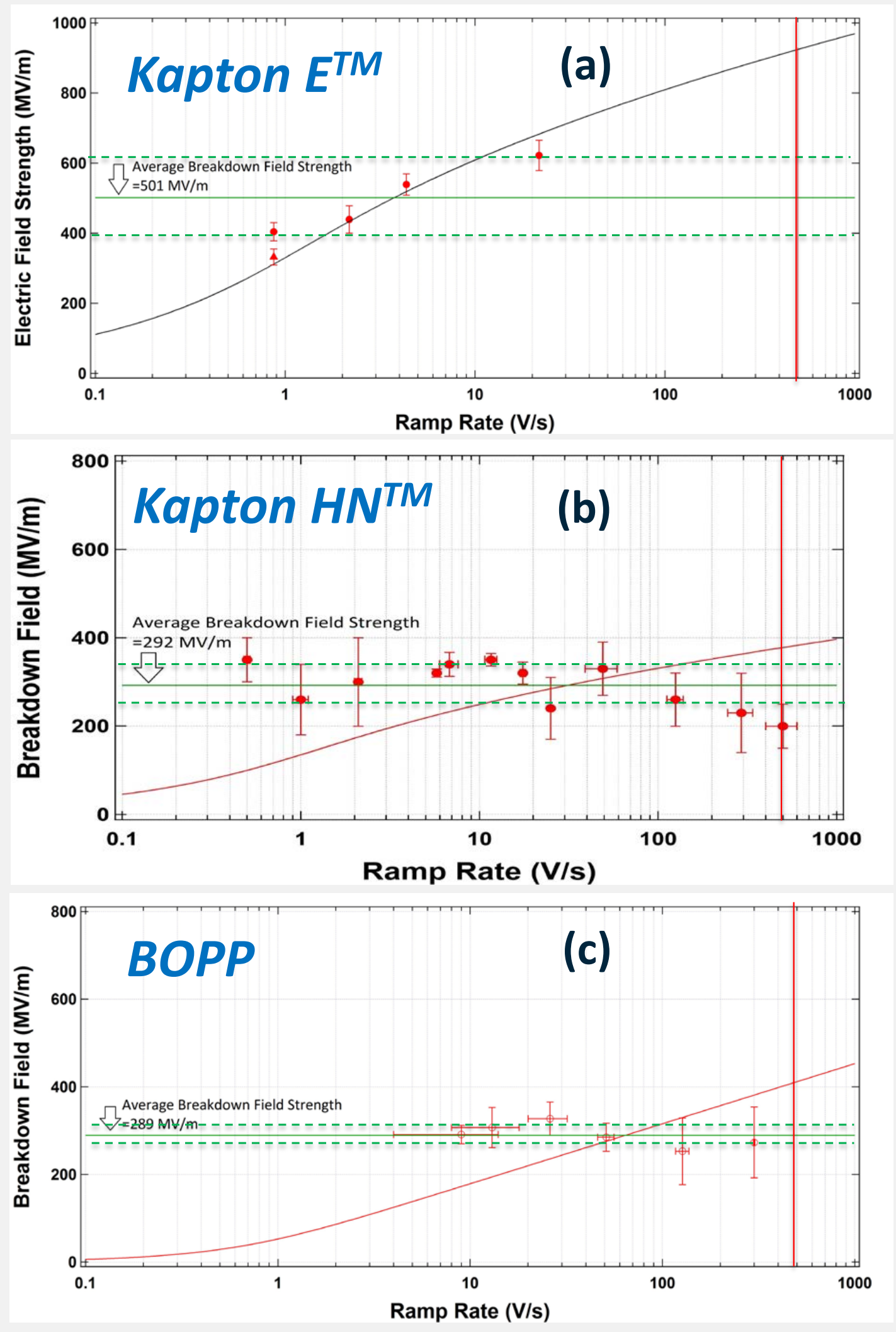

Figure 3. Breakdown field versus ramp rate for: (a) past tests on Kapton E^{TM}, (b) tests on Kapton HN^{TM}, and (c), new results for BOPP. Horizontal lines show the mean F_{ESD} and one standard deviation. Recommend maximum ramp rate of 500 V/s marked by the vertical red line.

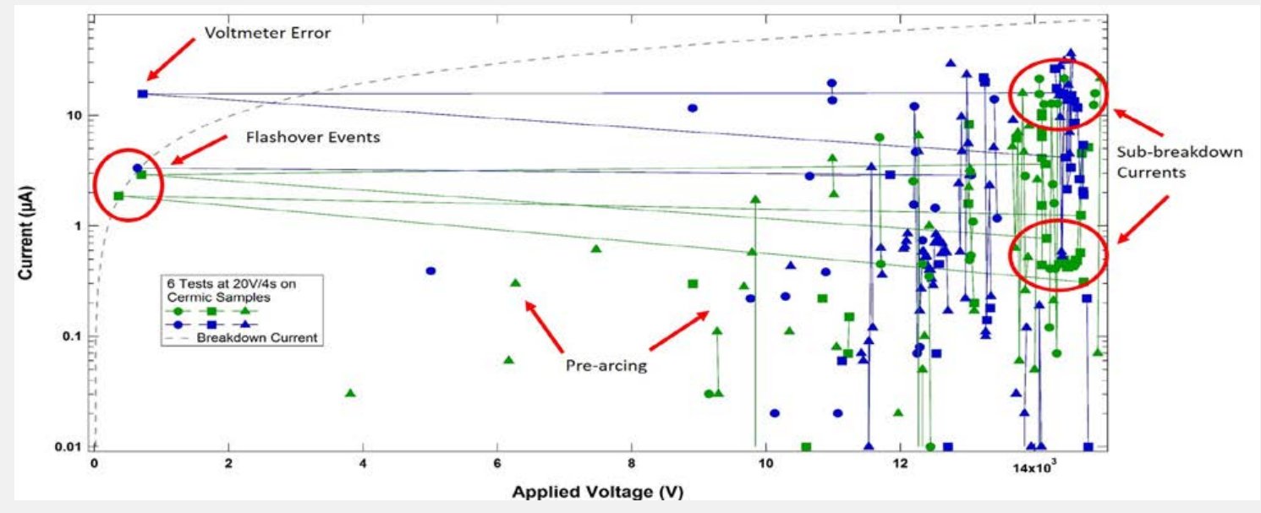

Figure 4. Additional features of step-up test visible with slow ramp rate data for Al_2O_3. Note logarithmic current axis.

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