9-2-2014

Dual-defect Model of Electrostatic Discharge in Polymeric Dielectrics

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Recommended Citation

Allen Andersen and JR Dennison, "Dual-defect Model of Electrostatic Discharge in Polymeric Dielectrics," Invited Seminar, Physics Colloquium, Utah State University, Logan, UT, September 2, 2014.

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2014 USU Physics Colloquium

Acknowledgements

UtahState UNIVERSITY

Support & Collaborations

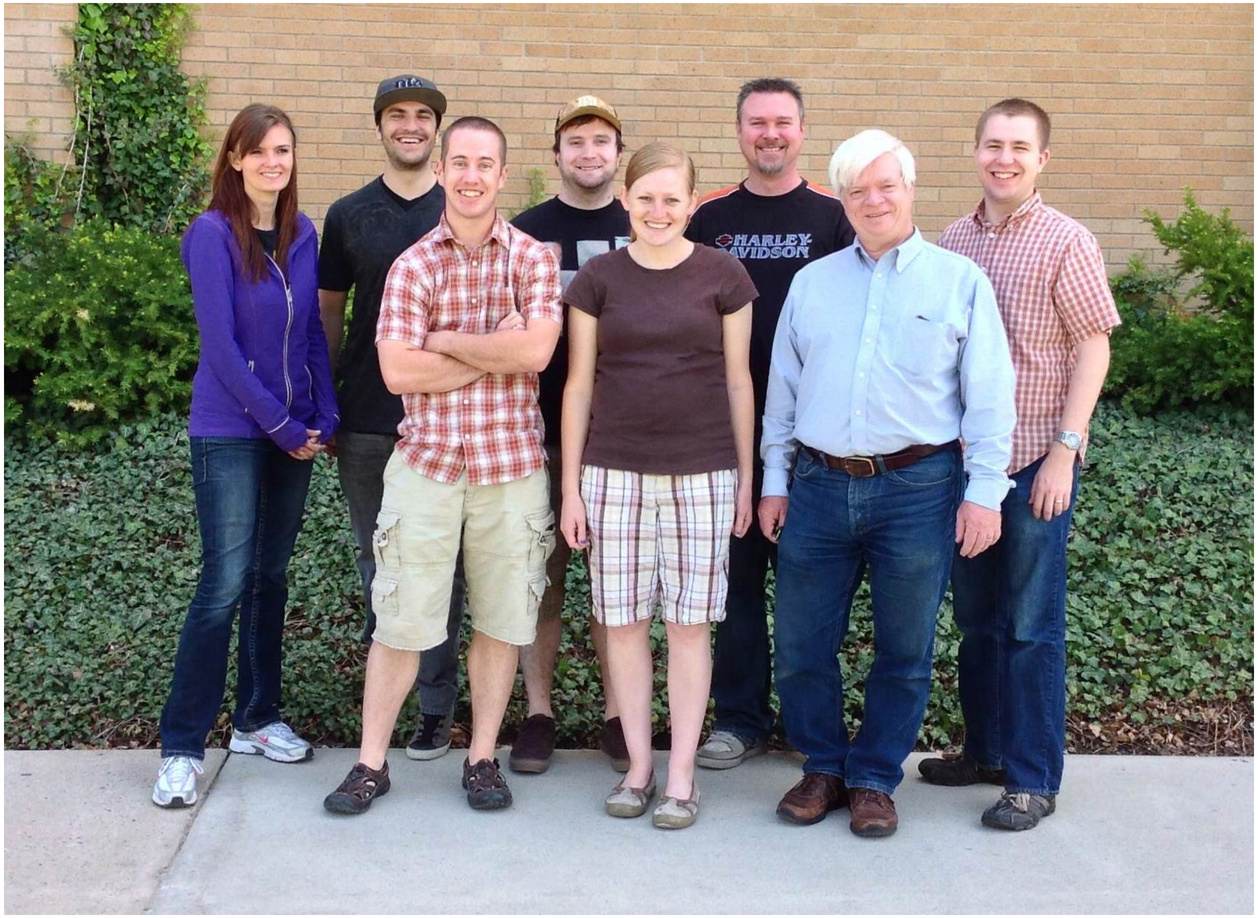
JWST (GSFC/MSFC)
USU Blood Fellowship
NSTRF Fellowship

Alec Sim

Charles Sim

Jodie Gillespie

Greg Wilson

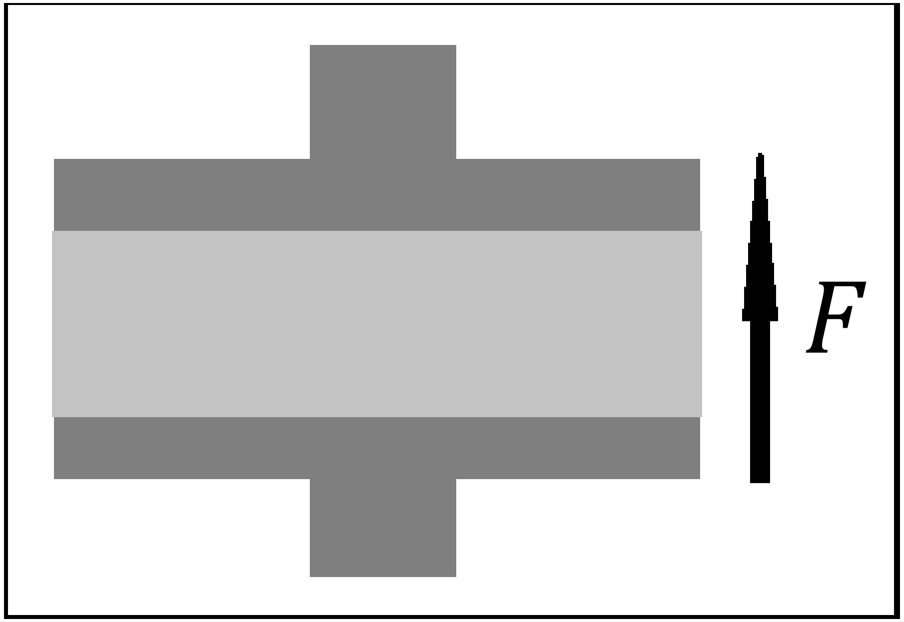


USU Materials Physics Group

My Selected Works

USU MPG Webpage

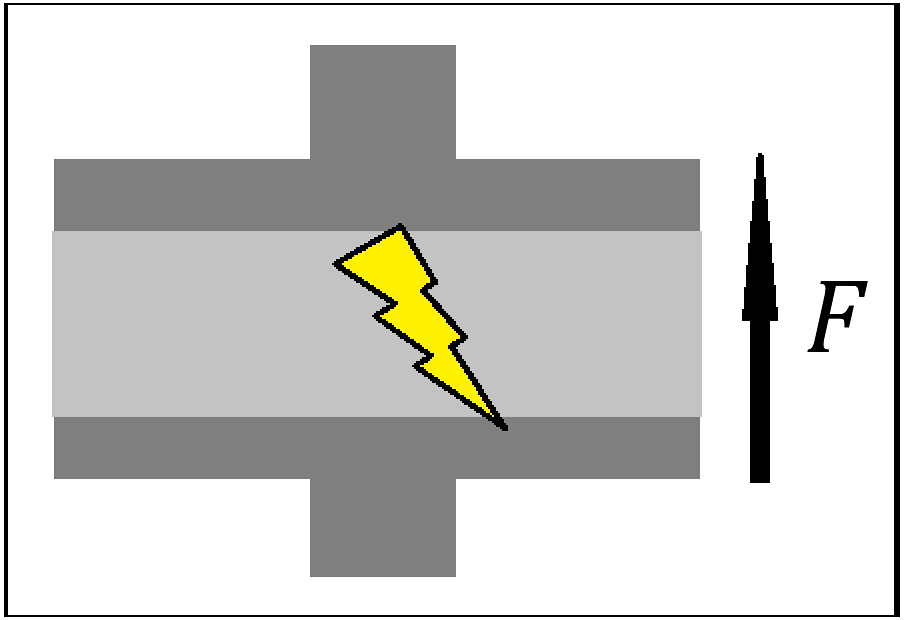
Introduction—What is ESD?



Consider a simple parallel plate capacitor.

- At low fields current flow is restricted.

Introduction—What is ESD?

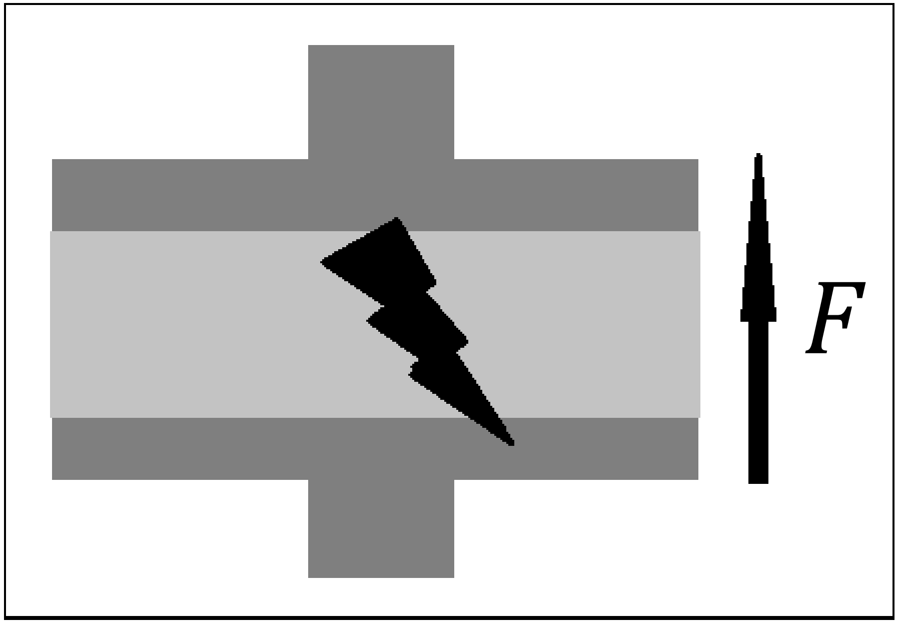


Consider a simple parallel plate capacitor.

- At low fields current flow is restricted.

- At high enough fields or after long times the insulator can breakdown.
- Large currents can flow.

Introduction—What is ESD?

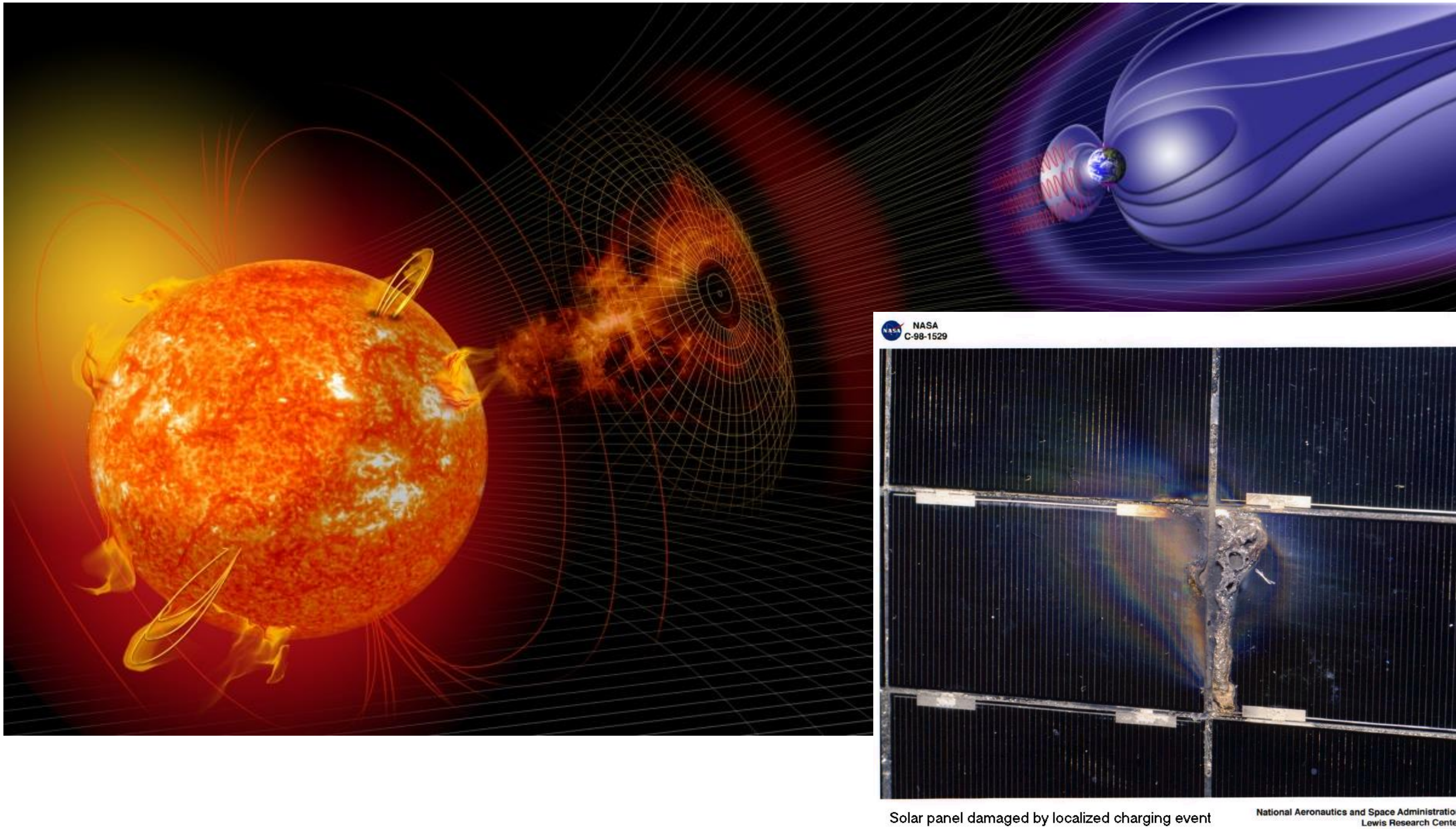


Consider a simple parallel plate capacitor.

- At low fields current flow is restricted.

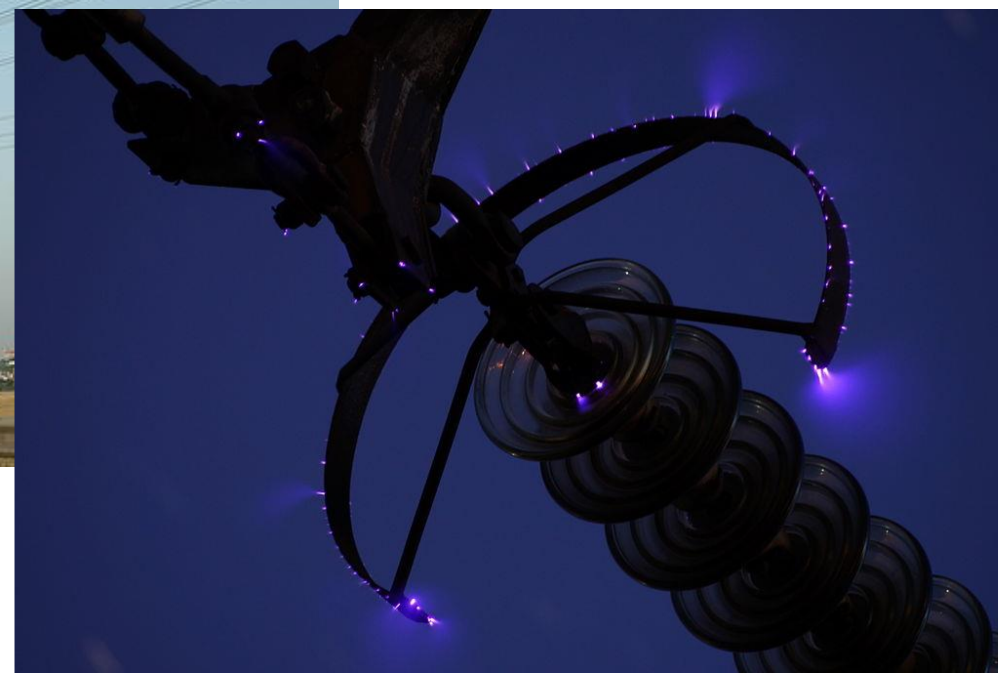
- At high enough fields or after long times the insulator can breakdown.
- Large currents can flow.
- Electrostatic discharge (ESD) is a permanent, catastrophic failure of a dielectric material.
- What was an insulator is now essentially a conductor in the system.

Why should we care about ESD?



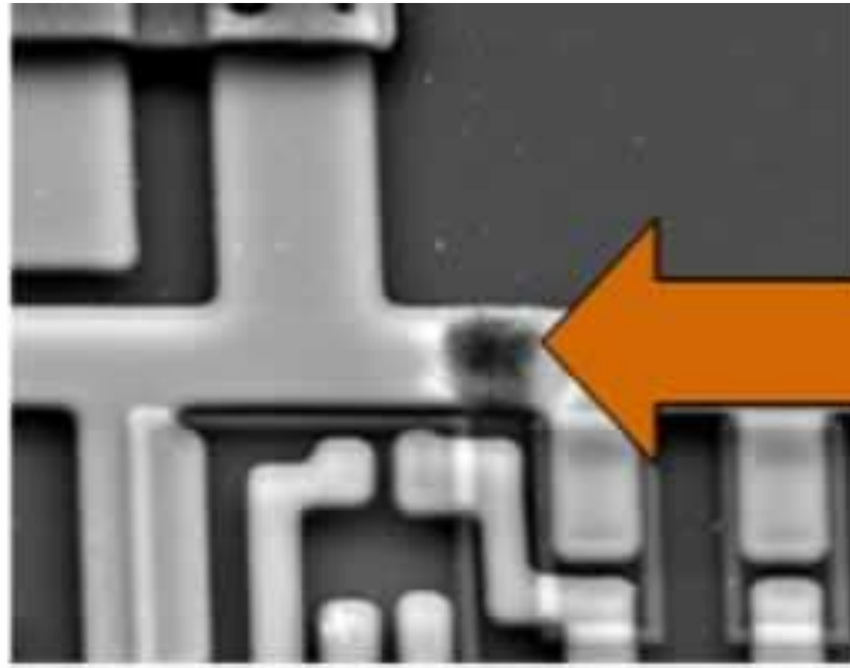
- **ESD is one of the most common and most devastating results of the interaction of spacecraft with the space plasma environments.**

Why should we care about ESD?



- **ESD and coronal discharge in high voltage power transmission can cause parasitic current leaks and total failure of components.**

Why should we care about ESD?



- Any electronic device exposed to high fields is vulnerable to ESD. The problem does not scale linearly due to quantum tunneling. In Si/SiO_2 transistors the insulating layer is only a few atoms thick.

$$d_{circuit} \approx 10^{-3}\,m \rightarrow V_{ESD} \approx 10^4\,V$$

$$d_{MOFSET} \approx 10^{-8}\,m \rightarrow V_{ESD} \approx 1\,V$$

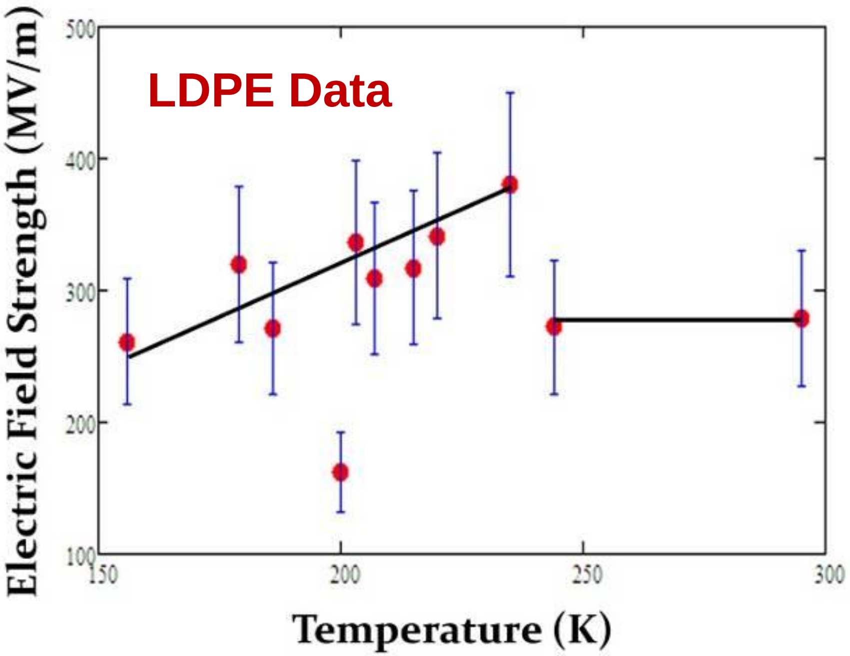
Why should we care about ESD?

- **Dielectric strength values are listed in engineering handbooks but how well are they known?**
- **Standard ASTM tests apply 500 V/s until breakdown.**
- **ESD depends on many environmental factors such as temperature, humidity, charge rate, surrounding medium (air or vacuum), etc.**
- **The term “dielectric constant” is misleading.**

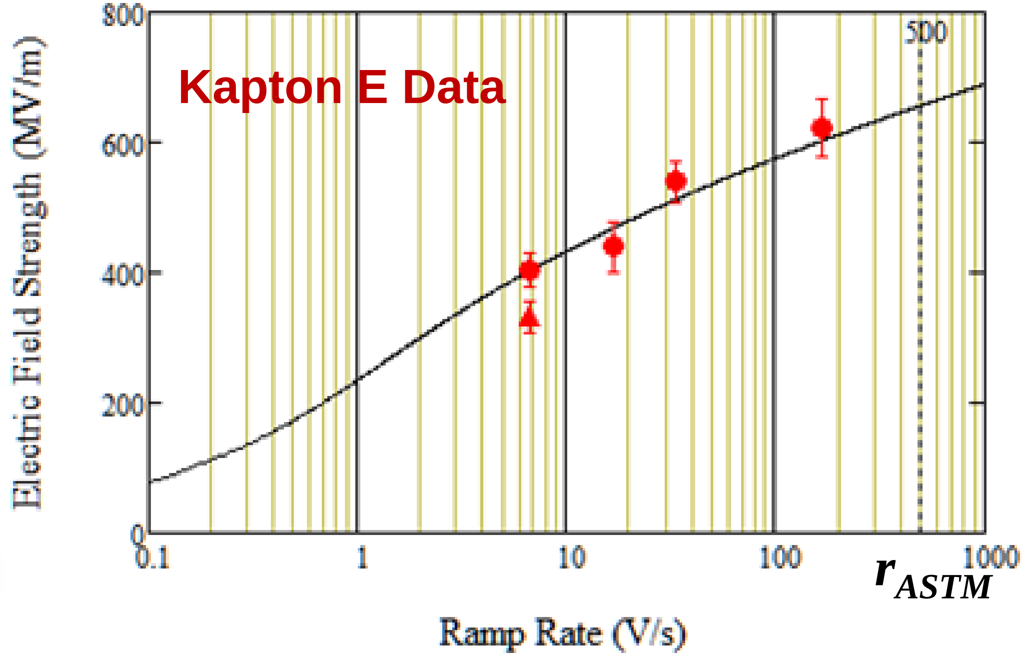
Substance	Dielectric Strength (MV/m)
Helium (relative to nitrogen)[2]	0.15
Air [3]	3.0
Alumina[2]	13.4
Window glass[2]	9.8 - 13.8
Silicone oil, mineral oil[2][4]	10 - 15
Benzene[2]	163
Polystyrene[2]	19.7
Polyethylene[5]	19 - 160
Neoprene rubber[2]	15.7 - 26.7
Distilled water[2]	65 - 70
High vacuum (field emission limited)[6]	20 - 40 (depends on electrode shape)
Fused silica[7]	25–40 at 20 °C
Waxed paper[8]	40 - 60
PTFE (Teflon, extruded)[2]	19.7
PTFE (Teflon, insulating film)[2][9]	60 - 173
Mica[2]	118
Diamond[10]	2000
PZT	10–25[11] [12]
Vacuum	10^{12}

Breakdown Test Dependence on T and dV/dt

F_{ESD} Temperature Dependence



F_{ESD} Ramp Rate Dependence



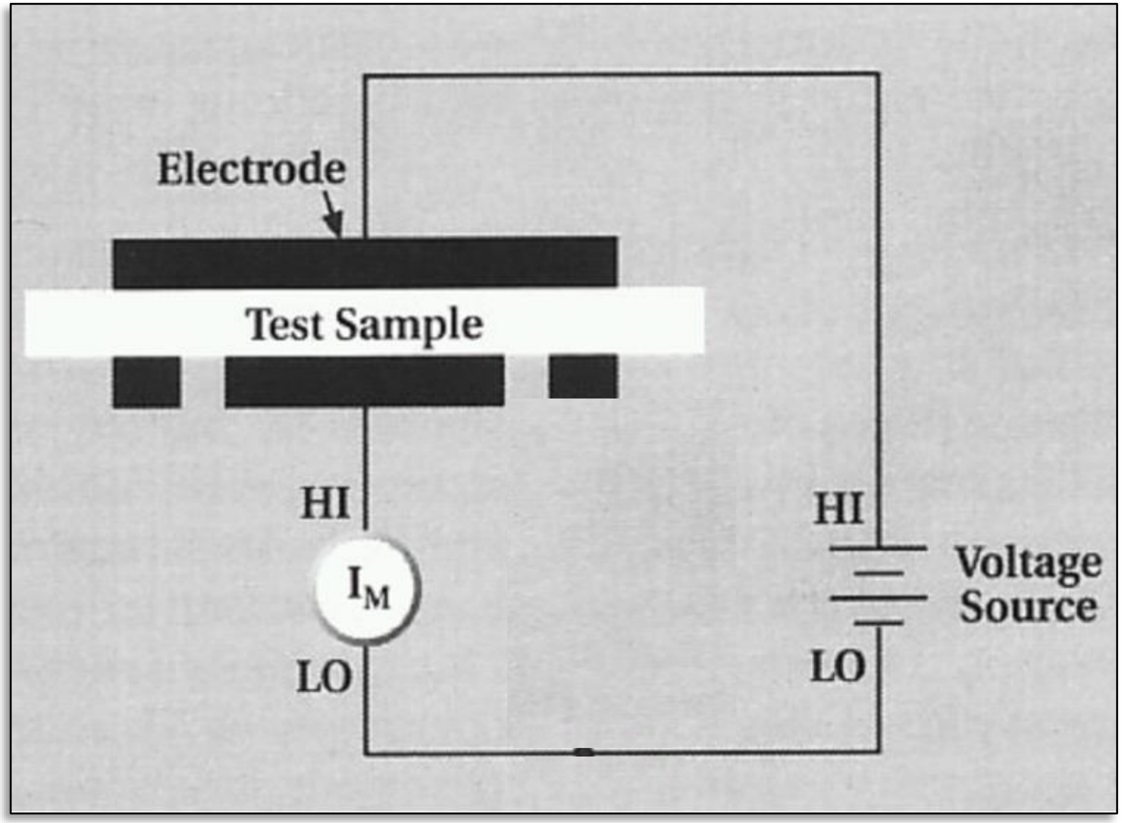
F_{ESD} depends significantly on both temperature and ramp rate.

- ASTM D3755 standard tests recommend a 500 V/s ramp rate until breakdown.
- However these test are not very repeatable and tend to overestimate breakdown strengths for slower ramp rates.
- Slow (even VERY SLOW) ramp rate better model real charging applications.

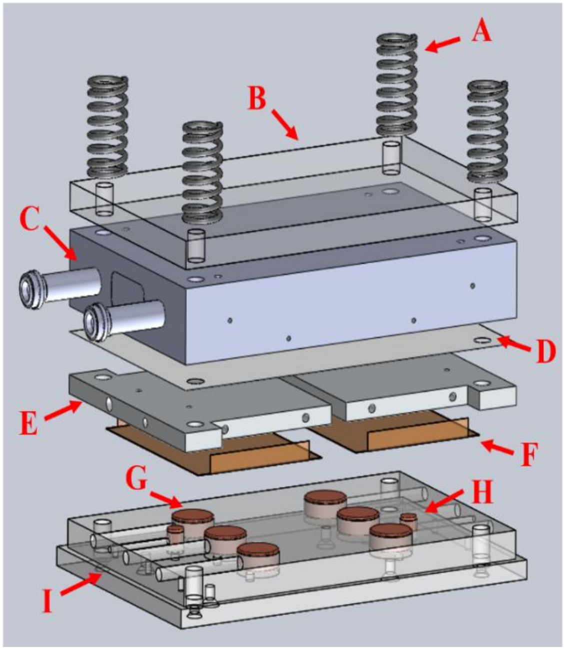
USU ESD Test System

Simple Parallel Plate Capacitor Test System

- V <30 kV and F <1000 MV/m
- ~100 K < T < 350 K
- Vacuum <10^{-3} Pa.
- Long test times up to days



USU ESD Test System



ESD Test Assembly:

(A) Adjustable pressure springs,
(B) Insulating layer
(C) Cryogen reservoir,
(D) Thermally conductive, electrically isolating layer,
(E) Sample and mounting plate,
(F) Sample
(G) HV Cu electrode
(H) Cu thermocouple electrode,
(I) Insulating base.

Simple Parallel Plate Capacitor Test System

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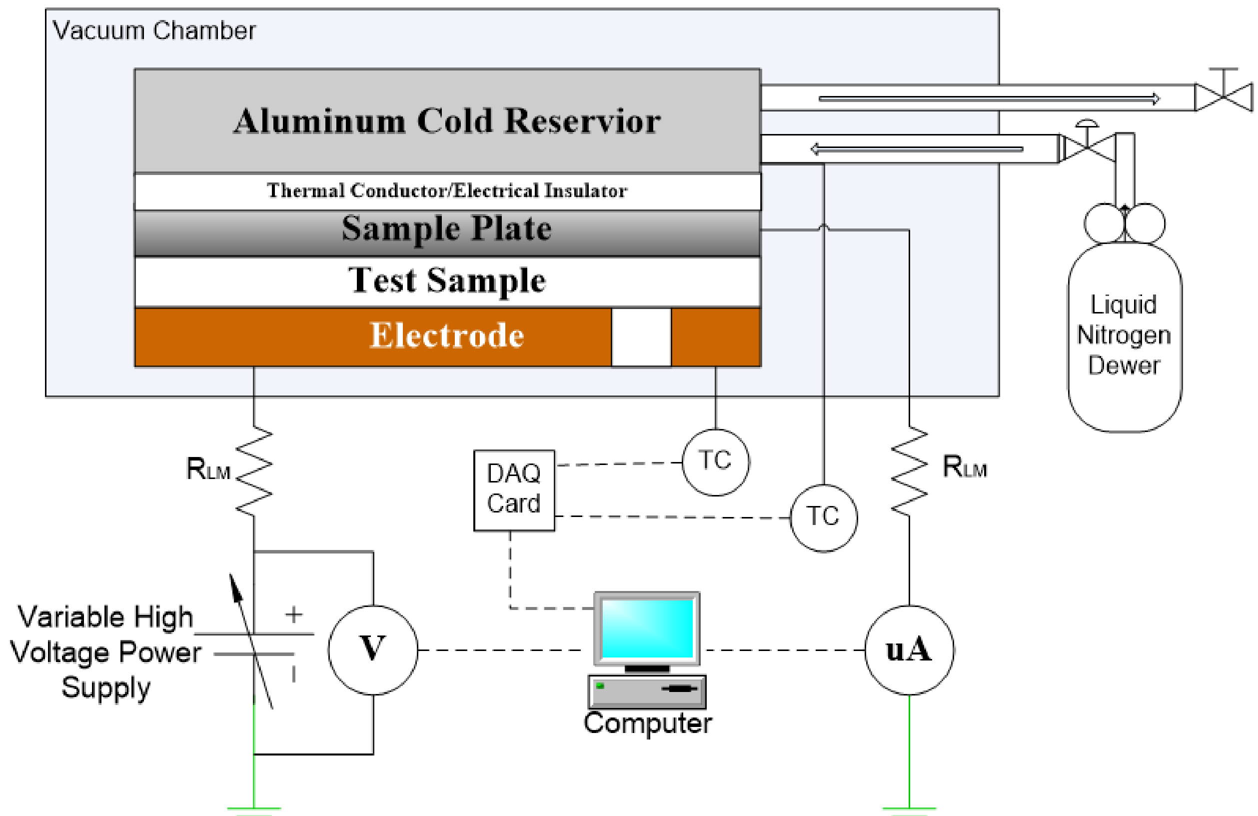
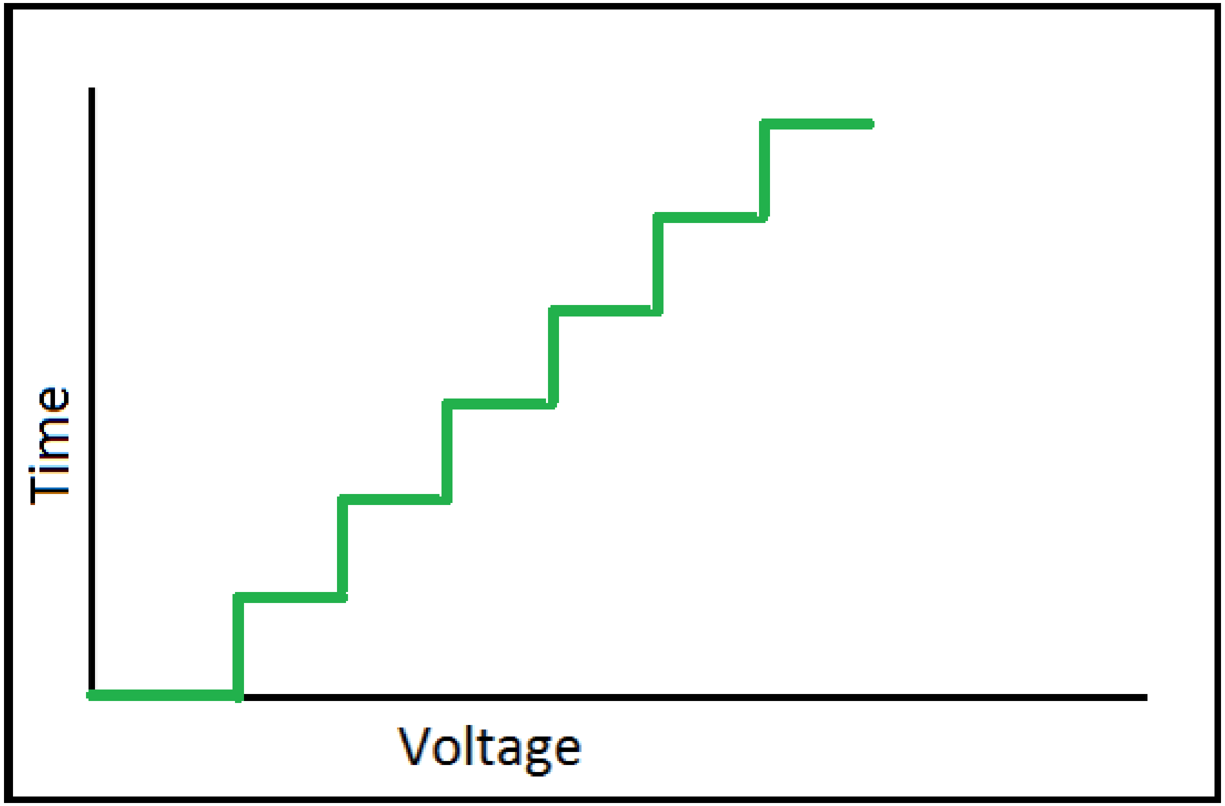
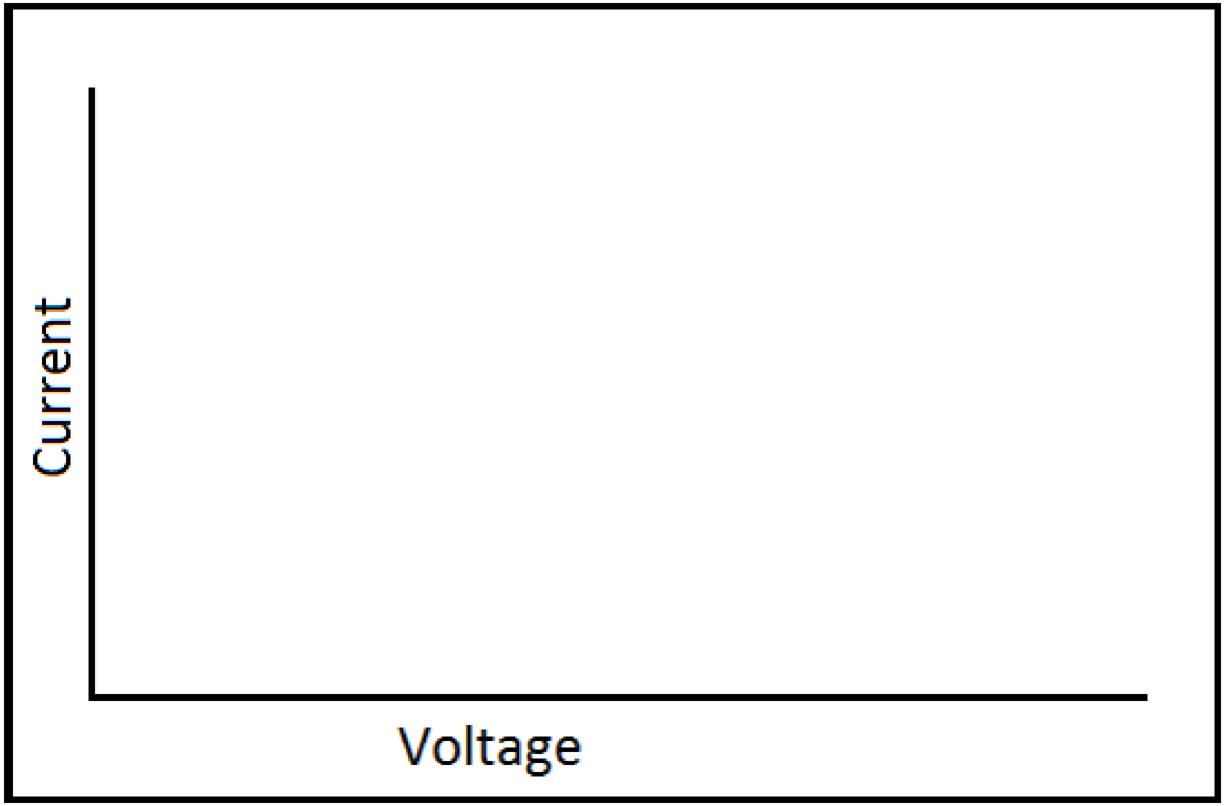


Typical ESD Step-Up Test Results

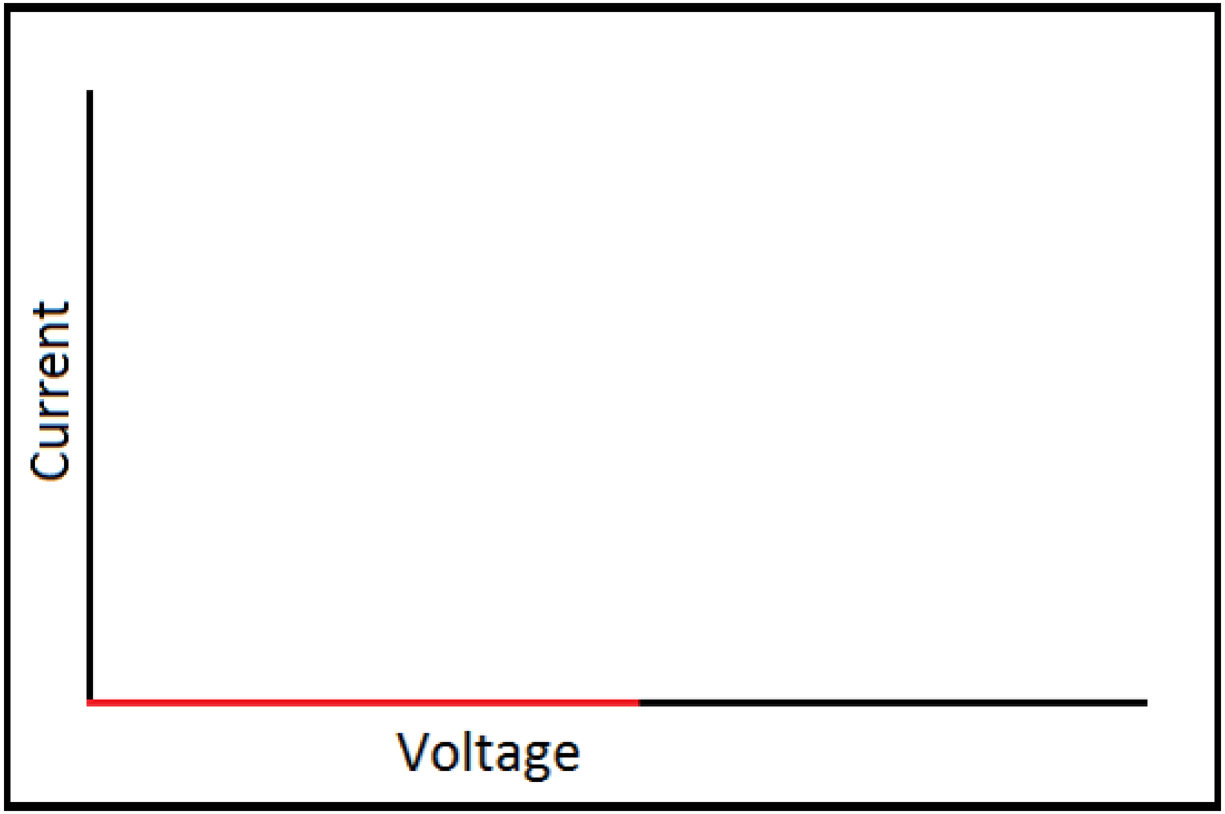


Slower ramp rates of ~20 V/4s lead to lower F_{ESD} and greater repeatability than 500 V/s ASTM standard tests.

Typical ESD Step-Up Test Results

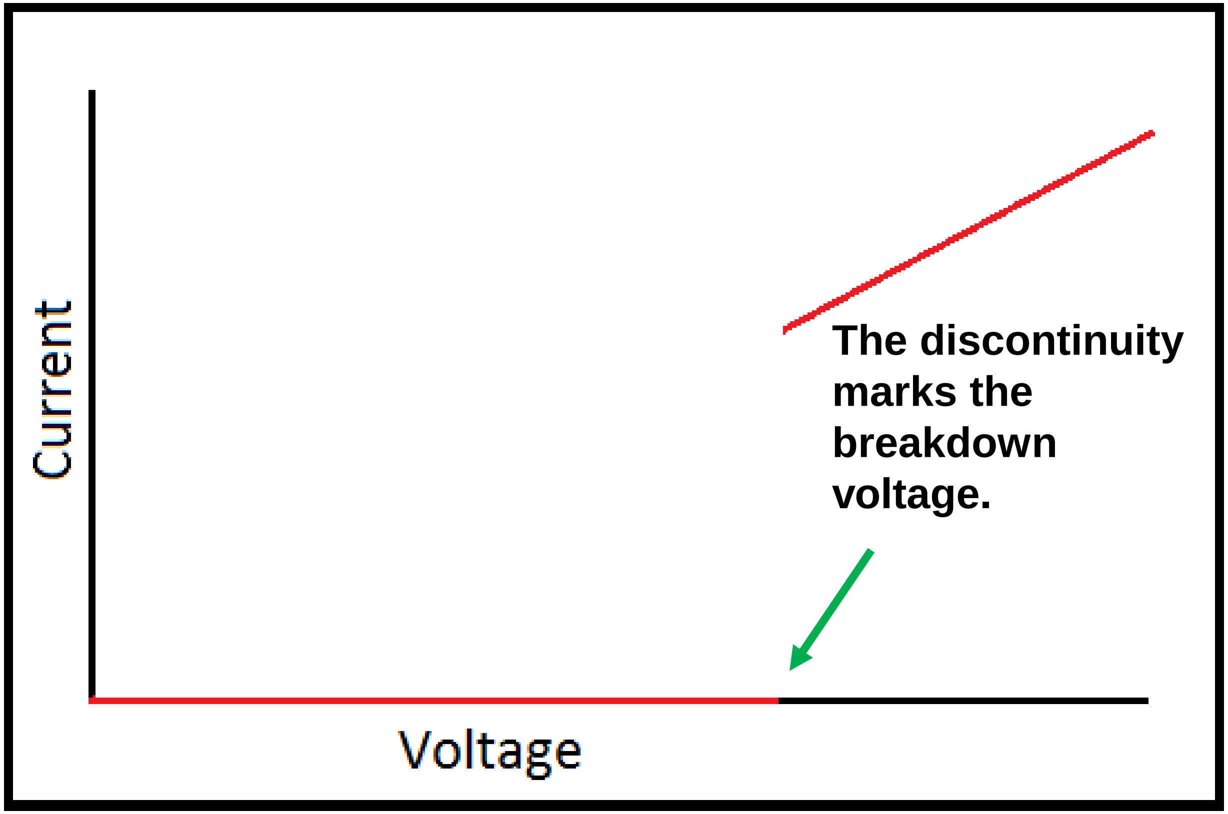


Typical ESD Step-Up Test Results



As voltage begins to increase no measurable current flows through our circuit.

Typical ESD Step-Up Test Results

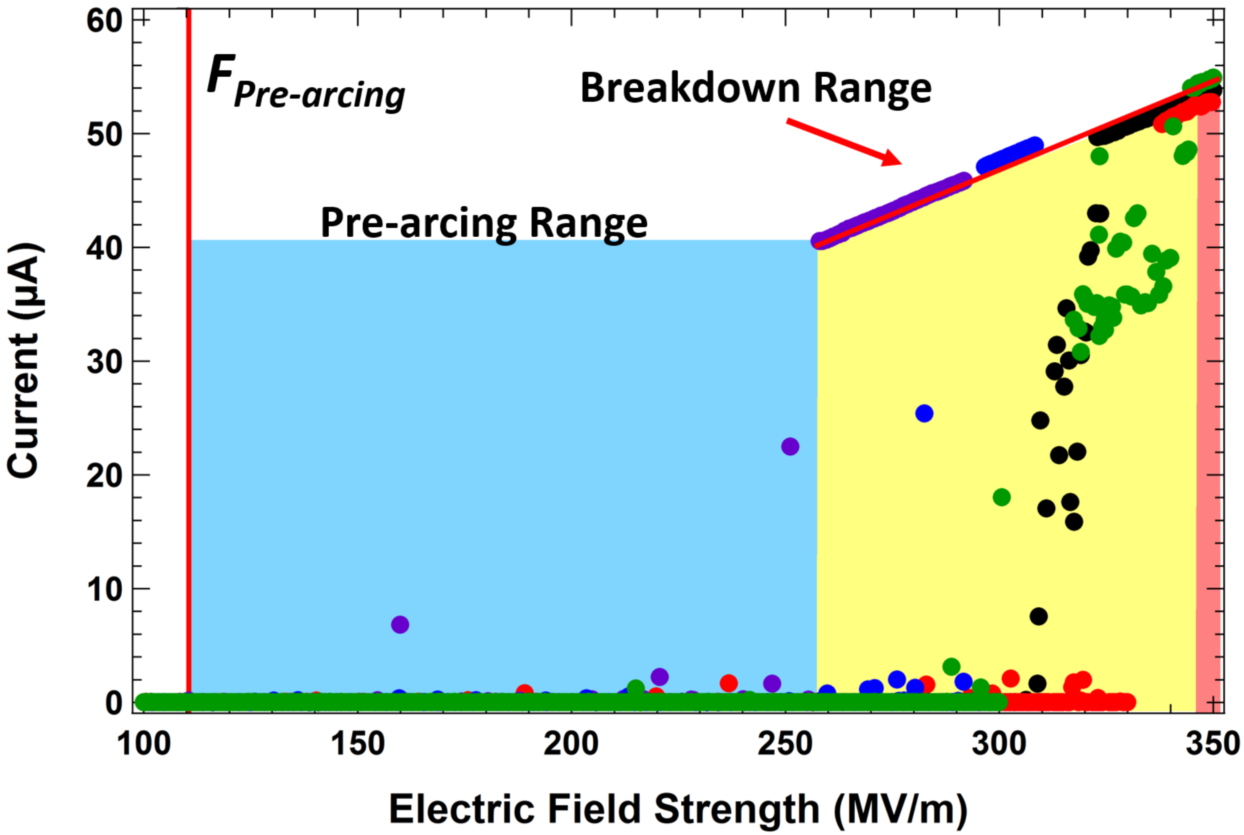


• At some high voltage the insulator breaks down allowing the free flow of current through the material.

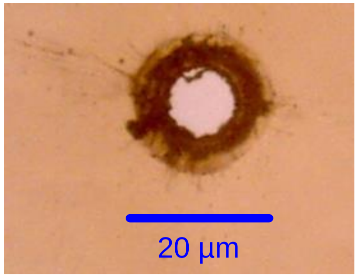
• The slope of the breakdown current is given by the current limiting resistors in the circuit according to Ohm's law.

$$V = IR_{lm} \Rightarrow \frac{I}{V} = {R_{lm}}^{-1}$$

Typical ESD Step-Up Test Results



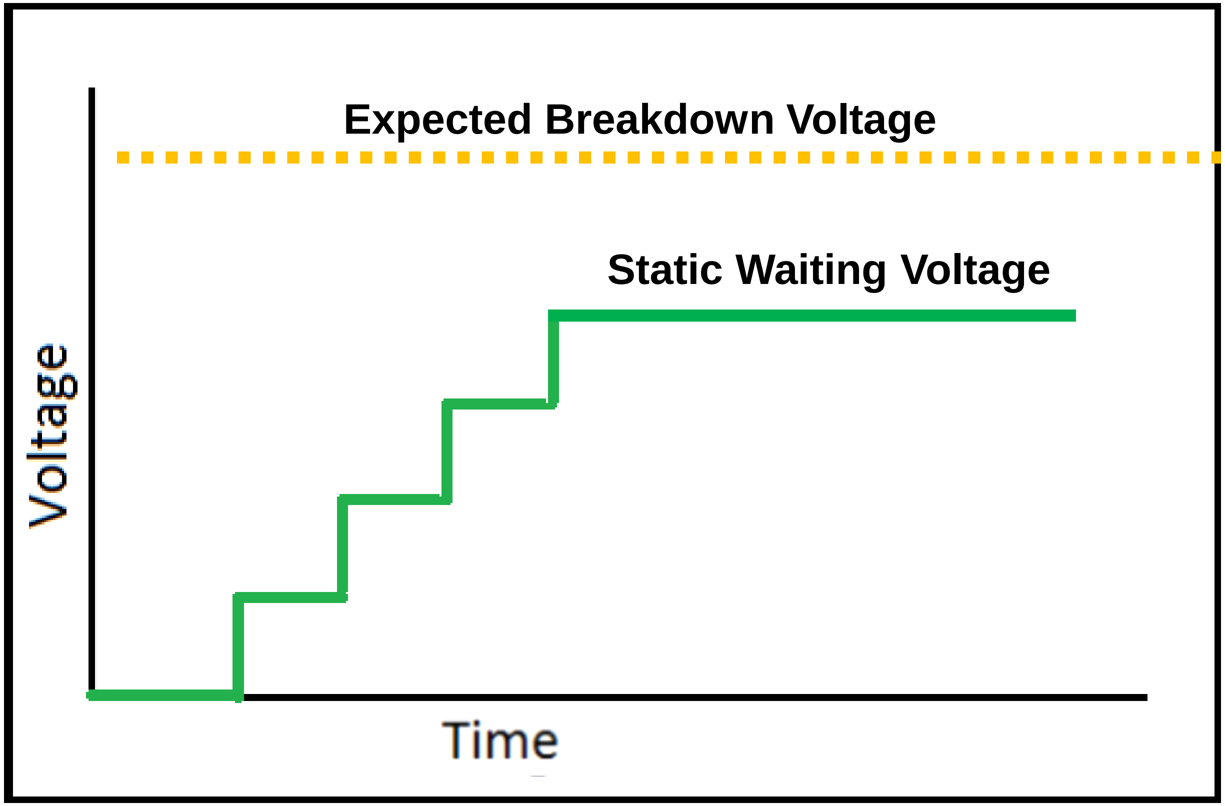
Thermoplastics
(LDPE)



Thermoset plastics
(Kapton)

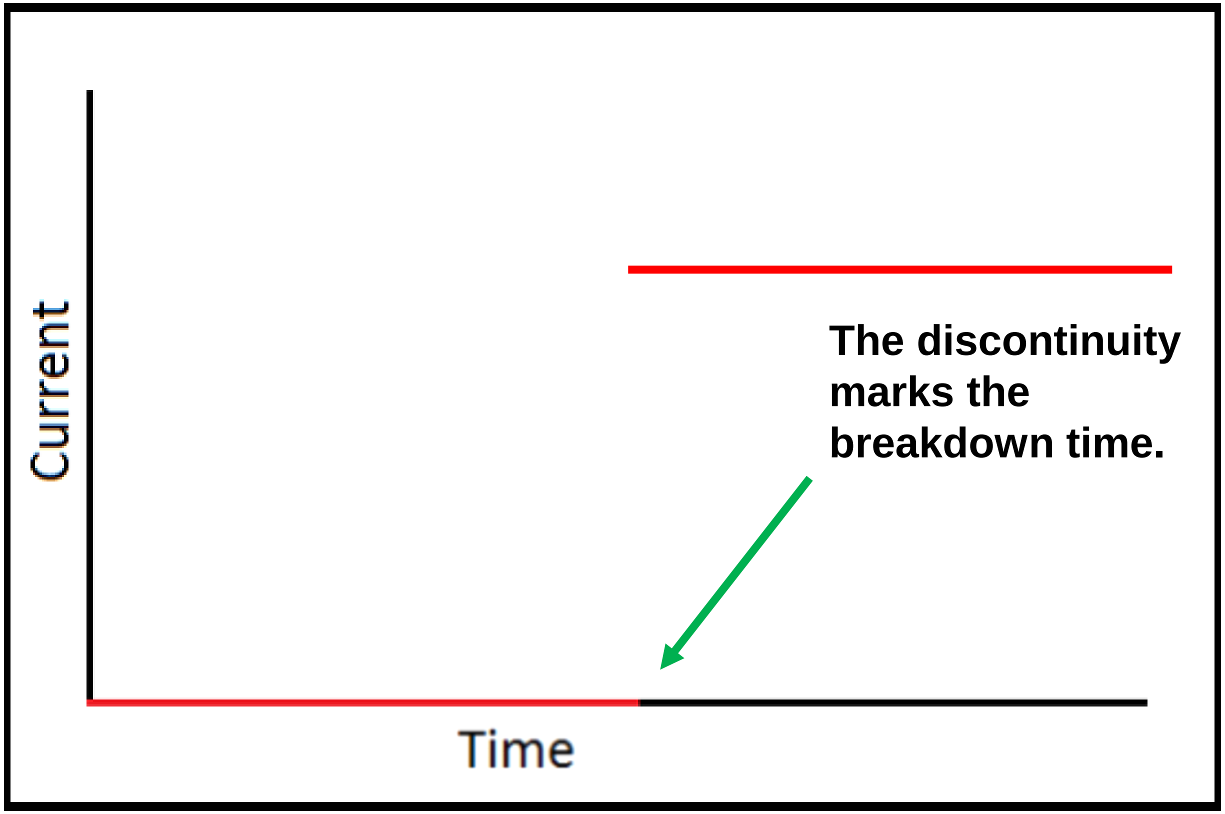
- **Slower ramp rates of ~20 V/4s lead to lower F_{ESD} and greater repeatability.**
- **Observed transient pre-breakdown current spikes.**
- **Slope after breakdown results from current limiting resistors given by Ohm's law $\frac{I}{V} = \frac{1}{R}$.**

Typical ESD Endurance Time Results



We can ramp up to some voltage below the expected breakdown value and wait for eventual breakdown.

Typical ESD Endurance Time Results

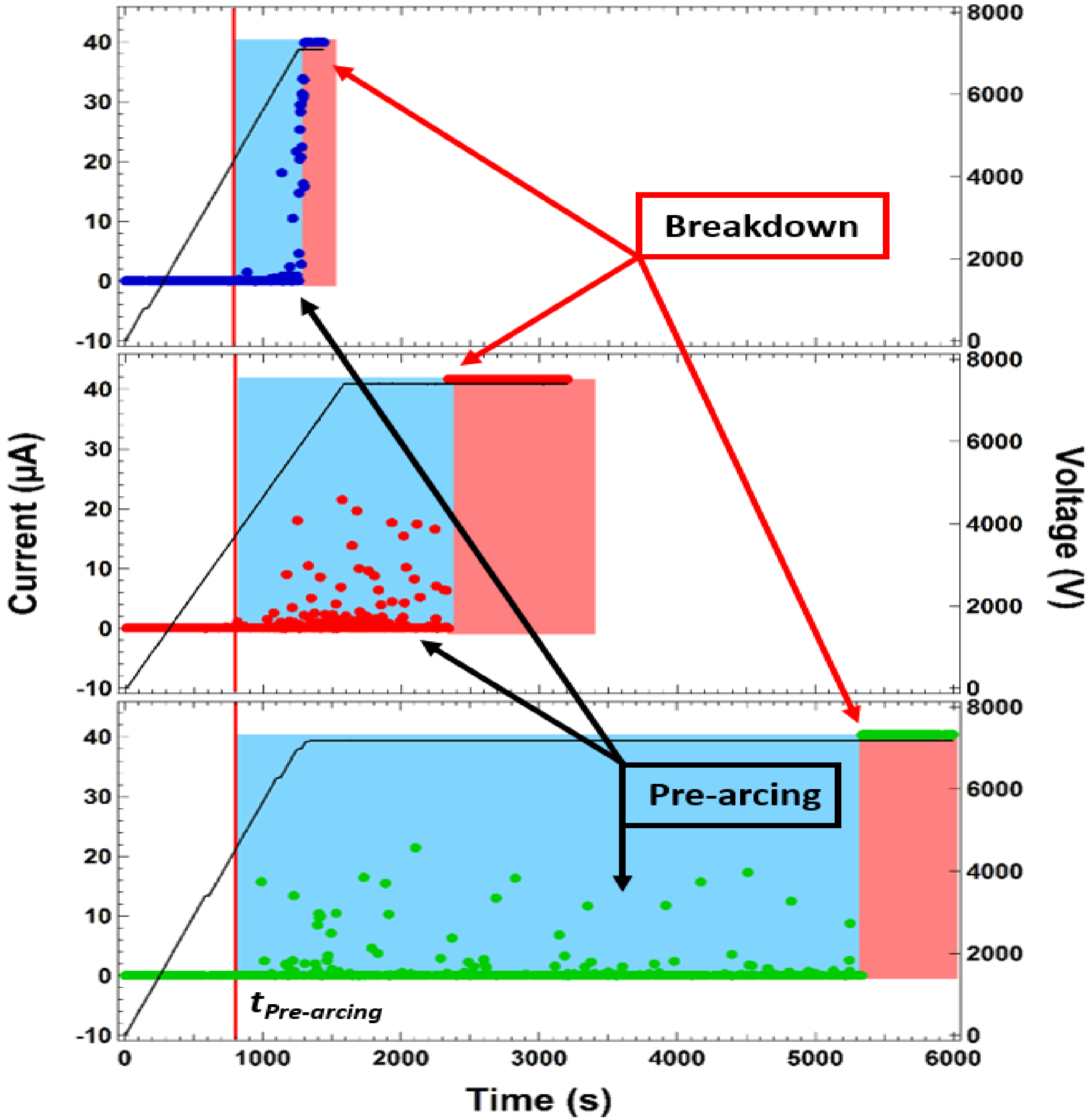


The sample is ramped to some fraction of the average breakdown field and time to breakdown is observed.

Static Voltage Endurance Time Testing

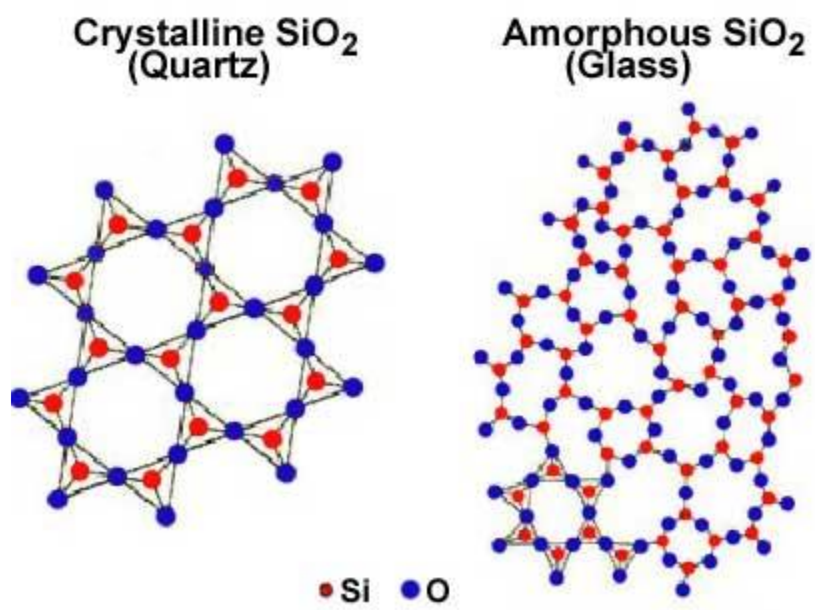
- Pre-breakdown arcs are again observed.

- Occasionally samples break down before the waiting voltage is reached.



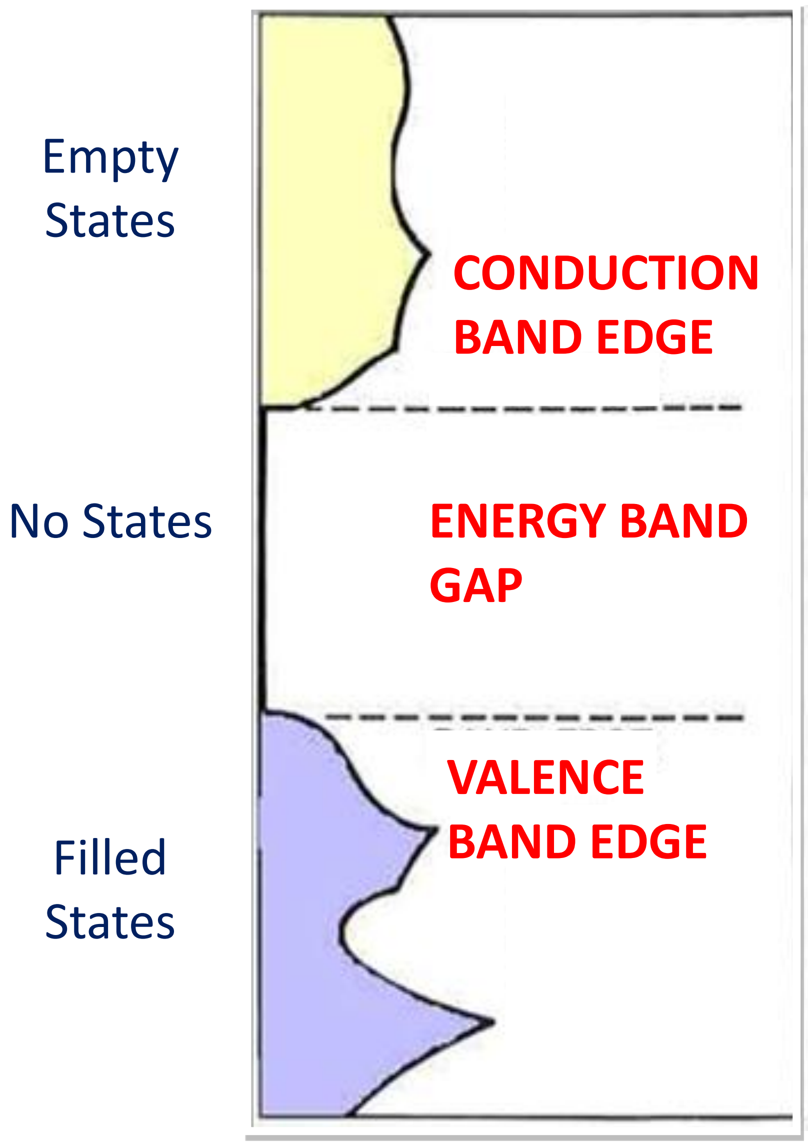
Physics of Highly Disordered Insulating Materials

- **What is the physics behind ESD properties of highly disordered insulating materials?**
- **We need to relate observations to what is happening on the level of the atomic structures of the materials in question.**
- **Begin with what is known about ordered materials and see what happens as defects are introduced.**



Defect Theory of Highly Disordered Insulating Materials

Ordered Materials



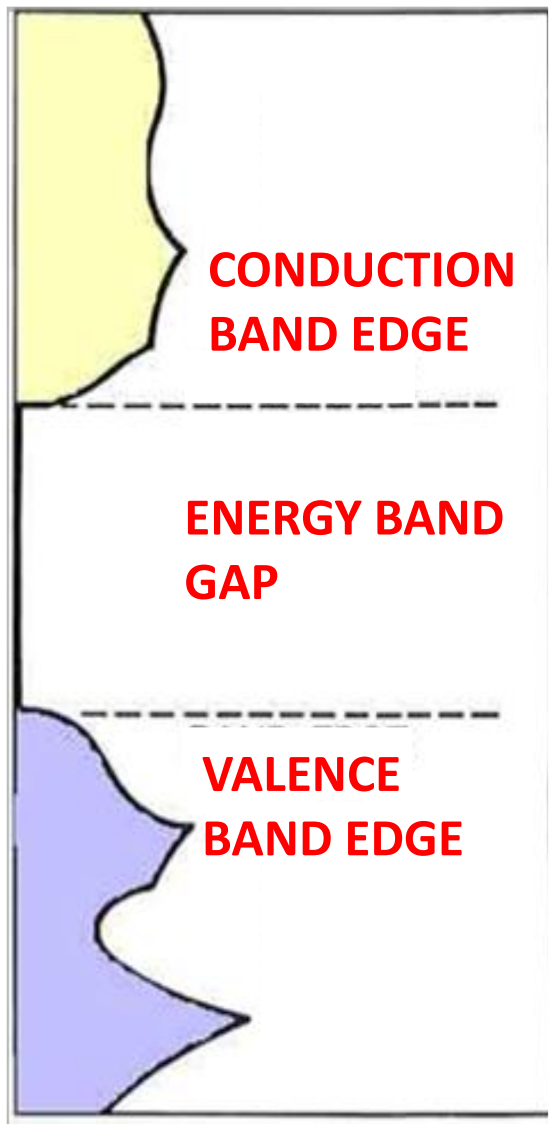
Defect Theory of Highly Disordered Insulating Materials

Ordered Materials

Empty States

No States

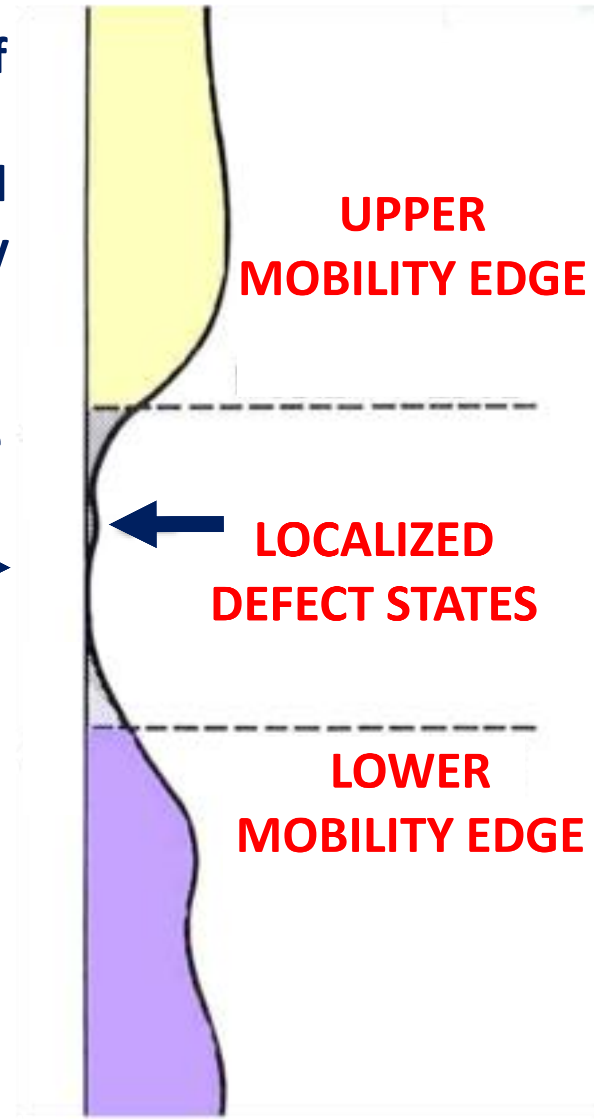
Filled States



The effect of disorder spatially and energetically introduces localized states in the bad gap.

The density and occupation of defects determine electrical properties.

Disordered Materials



Mean Defect Model for Single Defect Species

Utah State University

Hoping Probability with F and T

with F against F

$$P = \nu e^{-\left(\frac{\Delta G - q_e a_o F}{2k_B T}\right)} - \nu e^{-\left(\frac{\Delta G + q_e a_o F}{2k_B T}\right)}$$

$$P = 2\upsilon e^{\frac{-\Delta G}{k_B T}} \sinh\left(\frac{q_e a_o F}{2k_B T}\right)$$

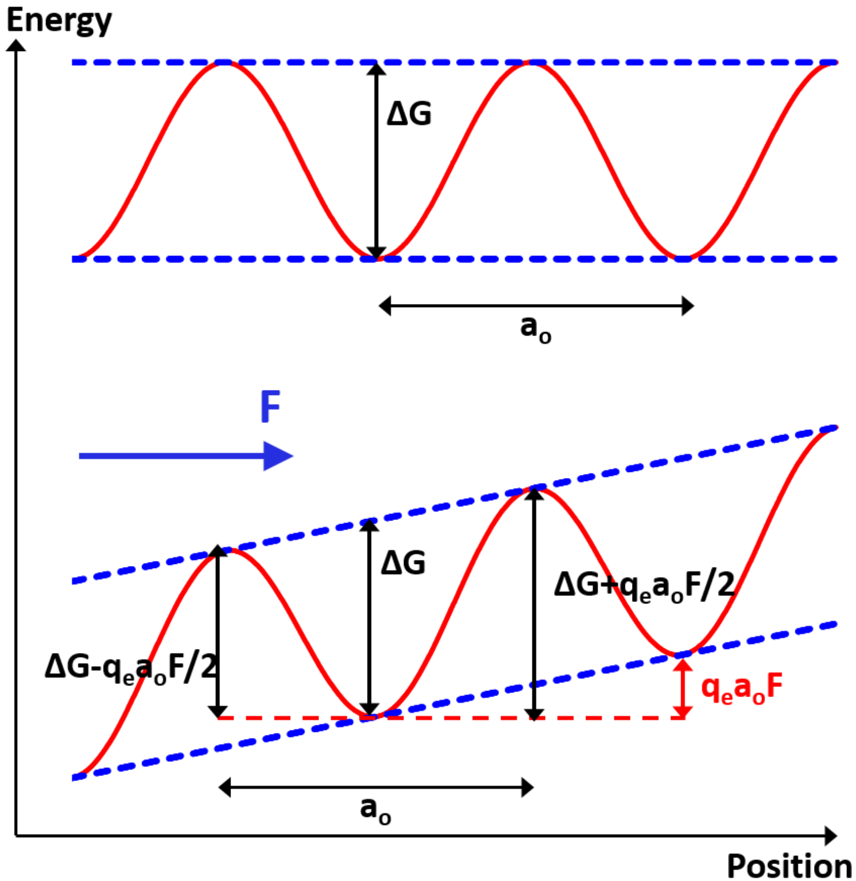
Time with F and T

$$t = \frac{1}{2\upsilon} e^{\frac{\Delta G}{k_B T}} \operatorname{csch}\left(\frac{q_e a_o F}{2k_B T}\right)$$

where

$$E_{strain} = \frac{1}{2}\varepsilon_r \varepsilon_0 F^2 \Delta V$$

$$\Delta V = a_o^3 \equiv 1/N_{def}$$



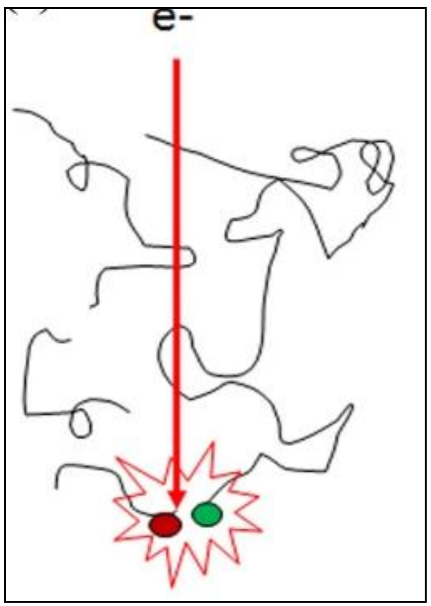
Endurance Time with F and T

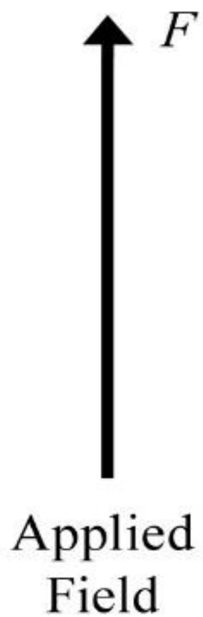
$$t_{en}(F,T) = \left(\frac{h}{2k_b T}\right)\exp\left[\frac{\Delta G_{def}(F,T)}{k_b T}\right]\operatorname{csch}\left[\frac{F^2 \varepsilon_0 \varepsilon_r}{2k_B T\, N_{def}(F,T)}\right]$$

Dual Defect Model: Defect Mode Examples

In order to predict full endurance time, we need a (slightly) more sophisticated model with two types of energetic defects.

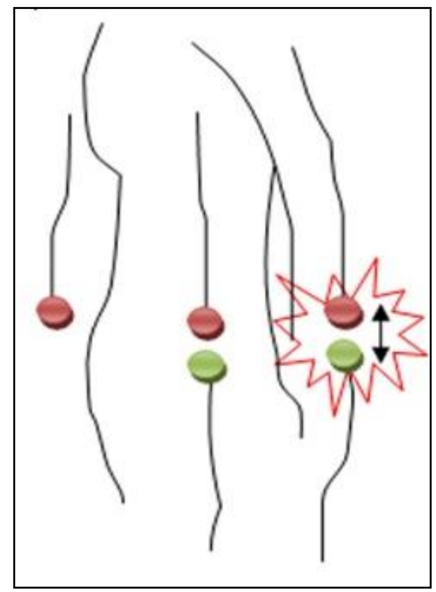
Type A Reversible Defects





- Primarily responsible for observed transient pre-breakdown arcs but can cause ESD.
- Energetically ~ $k_B T_{Room}$
- Can be thermally annealed
- Strongly T dependent: thermally annealable
- Lower T can reduce recovery
- Due, for example, to charge injection, impact ionization, or kink formation.

Type B Irreversible Defects



- Primarily responsible for complete ESD breakdown
- Energetically >> $k_B T$ for any operational temperature for material.
- Essentially non-recoverable.
- Due, for example, to chain bond breaking from direct stress.

Dual Defect Model: Voltage Step-Up

Probability of ESD at a given field and temperature after some wait time.

$$P_{def}^{Tot}(\Delta t, F, T) = \sum_{i=A,B} P_{def}^{i} = \left(\frac{2k_B T}{h/\Delta t}\right) \sum_{i=A,B} \exp\left[\frac{-\Delta G_{def}^{i}}{k_B T}\right] \sinh\left[\frac{\varepsilon_o \varepsilon_r F^2}{2 N_{def}^{i} k_B T}\right]$$

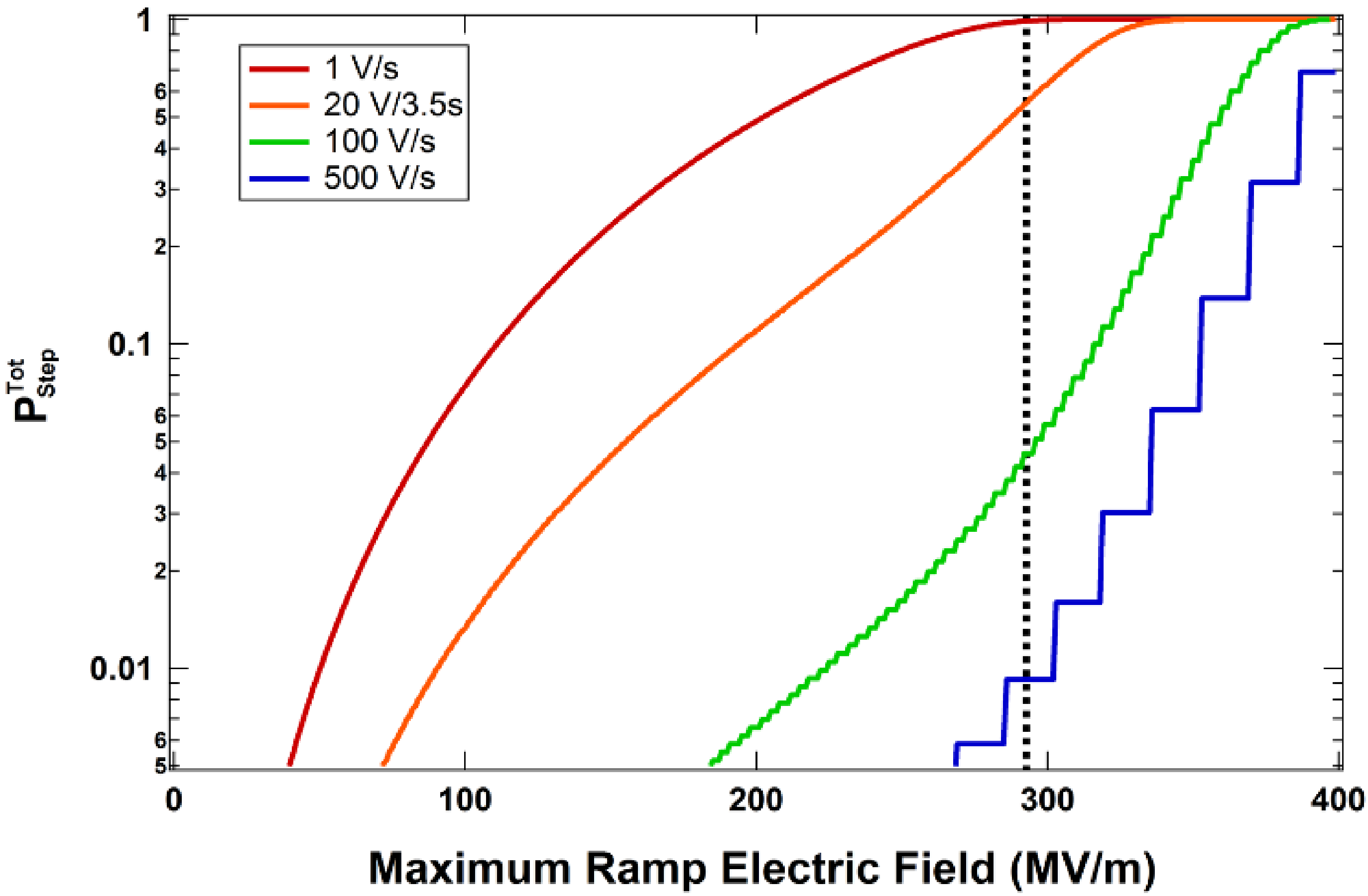
Probability of a sample surviving N_{step} number of ΔV voltage steps.

$$P_{survive}^{Tot}(\Delta t_{step}, N_{step}, \Delta V_{step}, T) = \prod_{j=1}^{N_{step}} \left[1 - P_{def}^{Tot}\left(\Delta t_{step}, \frac{j\Delta V_{step}}{D}, T\right)\right]$$

Probability of a ESD after N_{step} number of ΔV voltage steps.

$$P_{step}^{Tot}(\Delta t_{step}, N_{step}, \Delta V_{step}, T) = 1 - P_{survive}^{Tot} = 1 - \prod_{j=1}^{N_{step}} \left[1 - P_{def}^{Tot}\left(\Delta t_{step}, \frac{j\Delta V_{step}}{D}, T\right)\right]$$

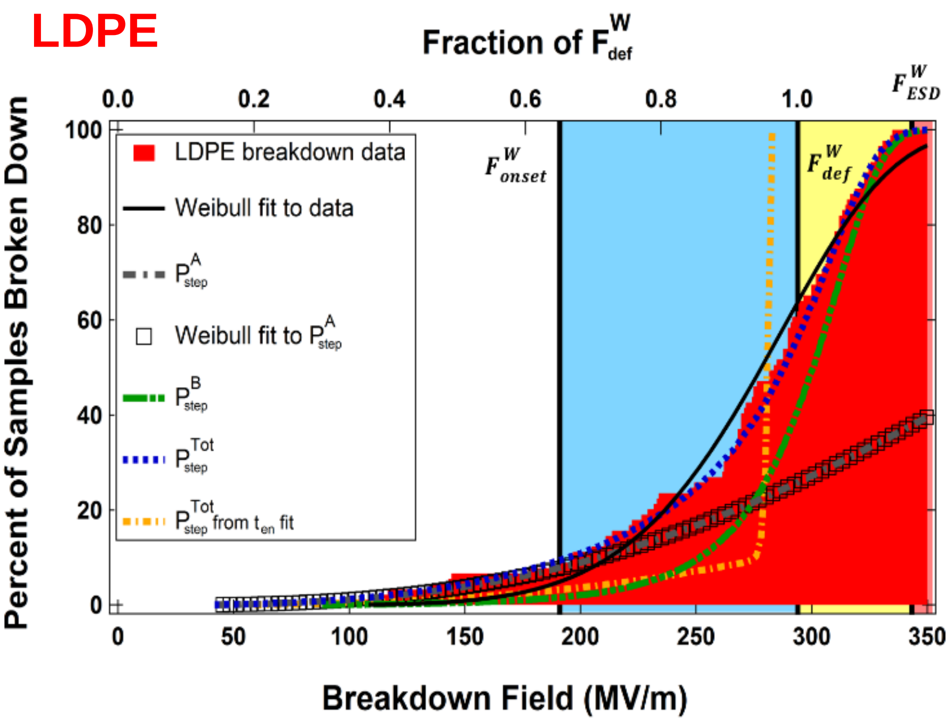
Dual Defect Model: Ramp Rate

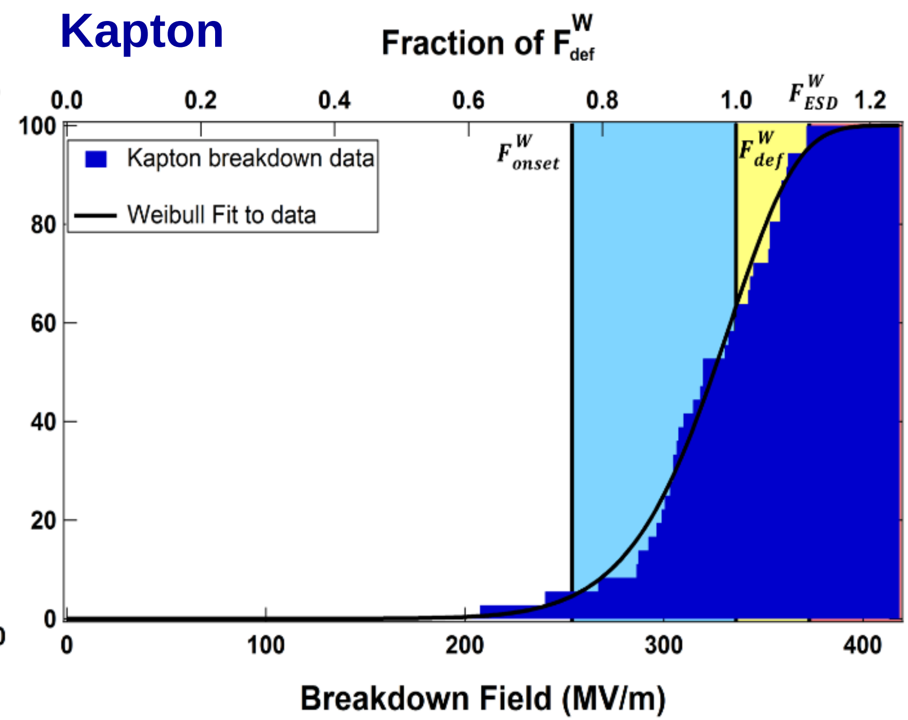


Probability of a ESD after N_{step} number of ΔV voltage steps for four different ramp rates (ΔV/ Δt_{step}). Note the drastic differences in the probability of breakdown at the same field.

$$P^{Tot}_{step}(\Delta t_{step}, N_{step}, \Delta V_{step}, T) = 1 - \prod_{j=1}^{N_{step}} \left[1 - {}_{P^{Tot}_{def}}\left(\Delta t_{step}, \frac{j\Delta V_{step}}{D}, T\right)\right]$$

Dual Defect Model: Weibull Distribution





ESD breakdown is a stochastic process, not simply just an average value with some uncertainty. Our dual defect model can be approximated by a Weibull distribution.

$$P^{Tot}_{step} \approx P^W_{def}\ (F) = 1 - \exp\left[-\left(F/F^W_{def}\right)^{\beta}\right]$$

The Weibull distribution is commonly fit to ESD step-up tests.

- $P^W_{def}(F^W_{onset}) \equiv 0.0455$ **or 2σ below** F^W_{def} **(beginning of blue regions)**
- $P^W_{def}\left(F^W_{def}\right) \equiv 0.632$ **(beginning of yellow regions)**
- $P^W_{def}\left(F^W_{ESD}\right) \equiv 0.9545$ **or 2σ above** F^W_{def} **(beginning of red regions)**

Dual Defect Model: Static Voltage Endurance Time

ESD Probability for Step-Up Process

$$P_{step}^{Tot}(\Delta t_{step}, N_{step}, \Delta V_{step}, T) = 1 - \prod_{j=1}^{N_{step}} \left[1 - P_{def}^{Tot}\left(\Delta t_{step}, \frac{j\Delta V_{step}}{D}, T\right)\right]$$

ESD Probability for Full Experiment

$$P_{SVET}^{Tot} = P_{step}^{Tot} + P_{def}^{Tot}$$

Corrected Endurance Time Formula

$$t_{en}^{Tot}(\Delta t_{step}, N_{step}, \Delta V_{step}, T)$$

$$= \left(\frac{h}{2k_B T}\right)\left[\sum_{i=A,B} \exp\left[\frac{-\Delta G_{def}^{i}}{k_B T}\right] \sinh\left[\frac{\varepsilon_0 \varepsilon_r N_{step}{}^2}{2k_B T\, N_{def}^{i}}\right]\right]^{-1} \times$$
$$\left\{\prod_{j=1}^{N_{step}} \left[1 - \left(\frac{2k_B T}{h/\Delta t_{step}}\right) \exp\left[\frac{-\Delta G_{def}^{B}}{k_B T}\right] \sinh\left[\frac{\varepsilon_0 \varepsilon_r \left(\frac{j\Delta V_{step}}{D}\right)^2}{2k_B T\, N_{def}^{B}}\right]\right]\right\}$$

Dual Defect Model: Static Voltage Endurance Time

ESD Probability for Step-Up Process

$$P_{step}^{Tot}(\Delta t_{step}, N_{step}, \Delta V_{step}, T) = 1 - \prod_{j=1}^{N_{step}} \left[1 - P_{def}^{Tot}\left(\Delta t_{step}, \frac{j\Delta V_{step}}{D}, T\right)\right]$$

ESD Probability for Full Experiment

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Corrected Endurance Time Formula

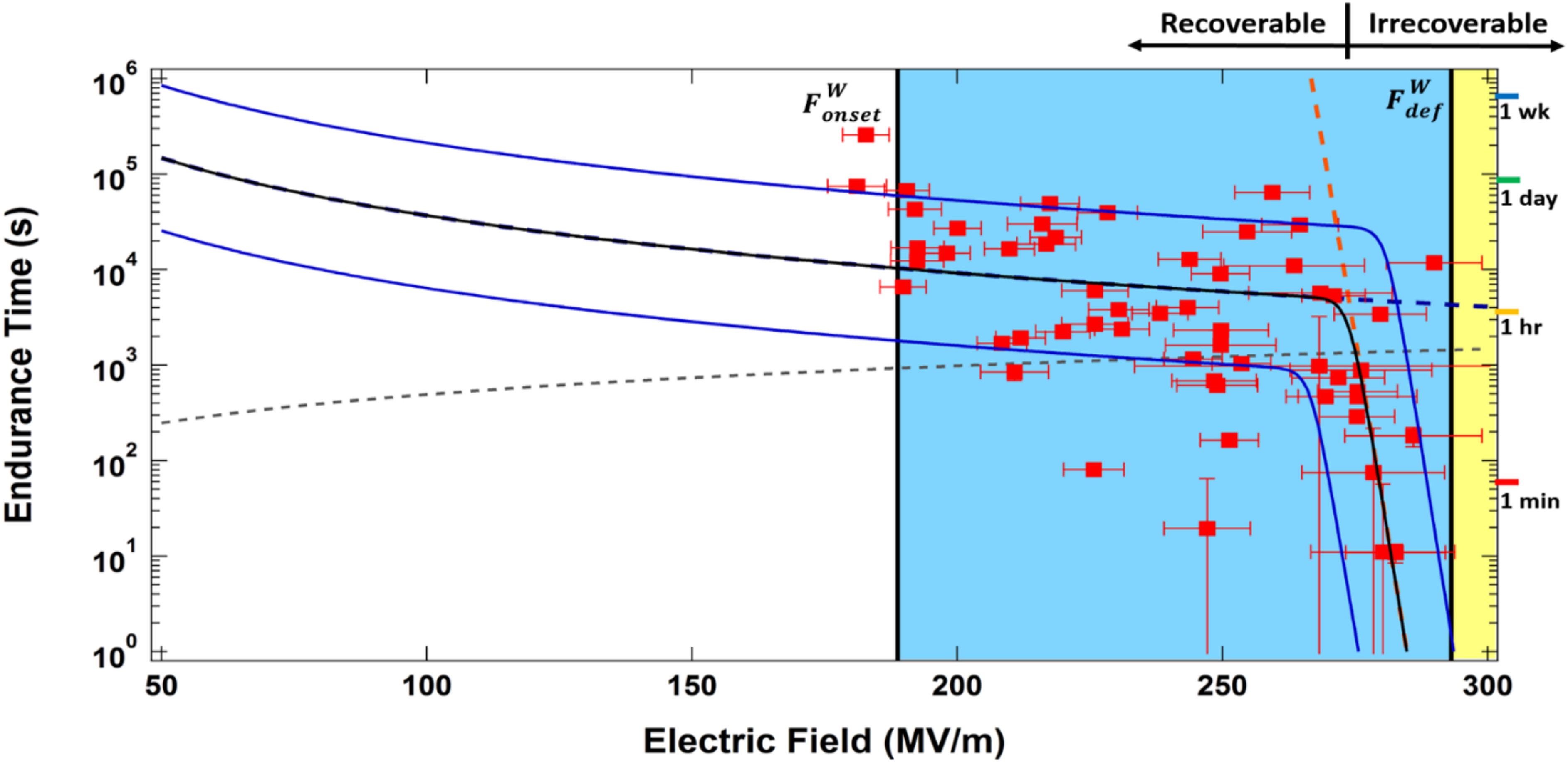
$$t_{en}^{Tot}(\Delta t_{step}, N_{step}, \Delta V_{step}, T)$$

$$= \left(\frac{h}{2k_BT}\right)\left[\sum_{i=A,B} \exp\left[\frac{-\Delta G_{def}^i}{k_BT}\right]\sinh\left[\frac{\varepsilon_0\varepsilon_r N_{step}{}^2}{2k_BT\,N_{def}^i}\right]\right]^{-1} \times$$

$$\cancel{\left\{\prod_{j=1}^{N_{step}}\left[1-\left(\frac{2k_BT}{h/\Delta t_{step}}\right)\exp\left[\frac{-\Delta G_{def}^B}{k_BT}\right]\sinh\left[\frac{\varepsilon_0\varepsilon_r\left(\frac{j\Delta V_{step}}{D}\right)^2}{2k_BT\,N_{def}^B}\right]\right]\right\}}$$

Depending on the ramp rate this term can sometimes be neglected since it can be ~1 for most values of V_{wait}.

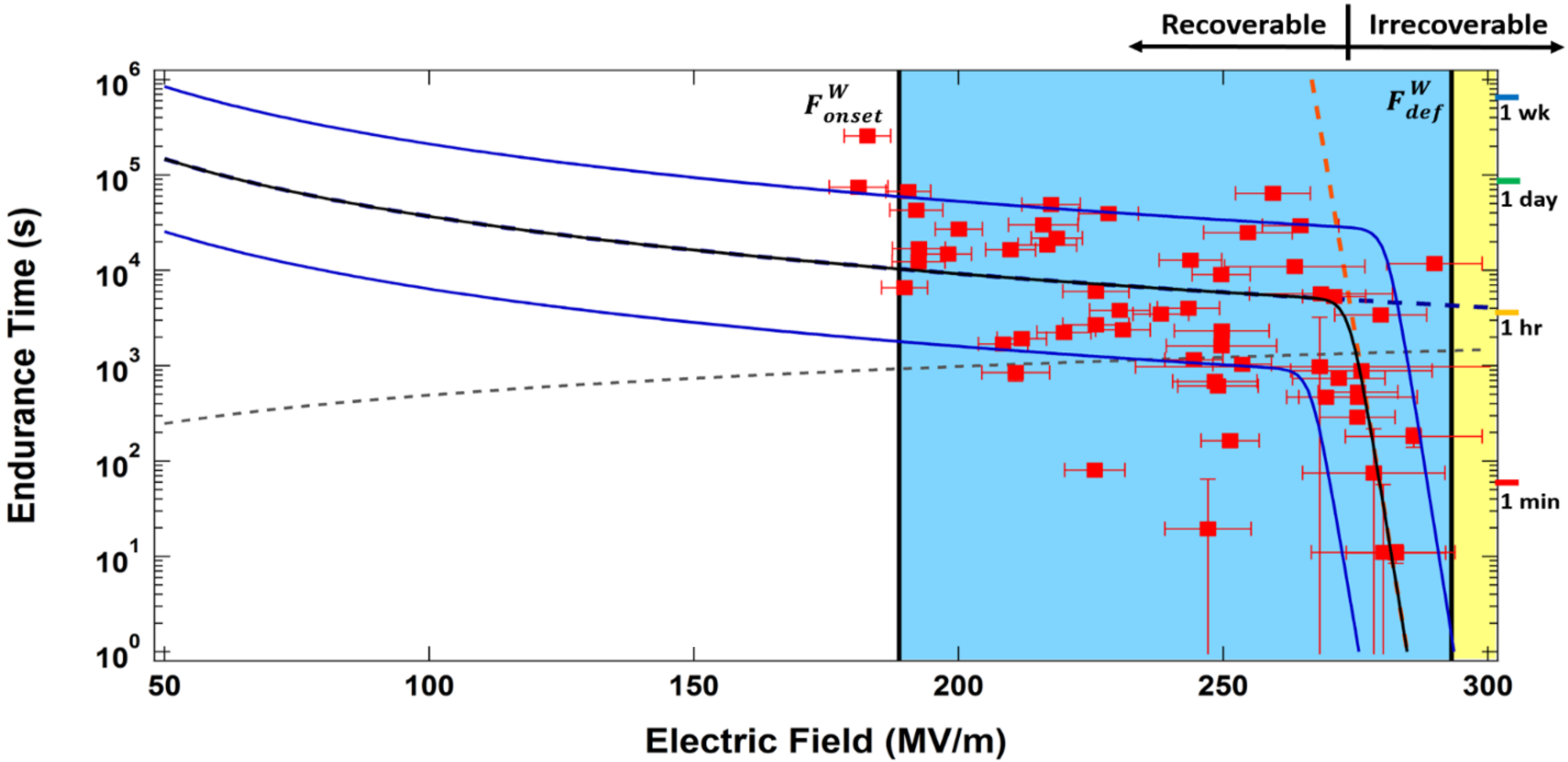
Dual Defect Model: Fit to LDPE Endurance Data



Values for defect energies (ΔG_i) were taken from independent measurements and the defect densities (N_i) were used as fitting parameters. The density values obtained were physically reasonable. Blue lines encompass a ±5% uncertainty in ΔG_i. The grey dotted line shows the ramp time to the static field.

$$t_{en}(\Delta t_{step}, V_{step}, V_{wait}, T) = \left(\frac{h}{2k_B T}\right)\left[\sum_{i=A,B} \exp\left[\frac{-\Delta G_i}{k_B T}\right] \sinh\left[\frac{\varepsilon_0 \varepsilon_r \left(\frac{V_{wait}}{D}\right)^2}{2N_i k_B T}\right]\right]^{-1}$$

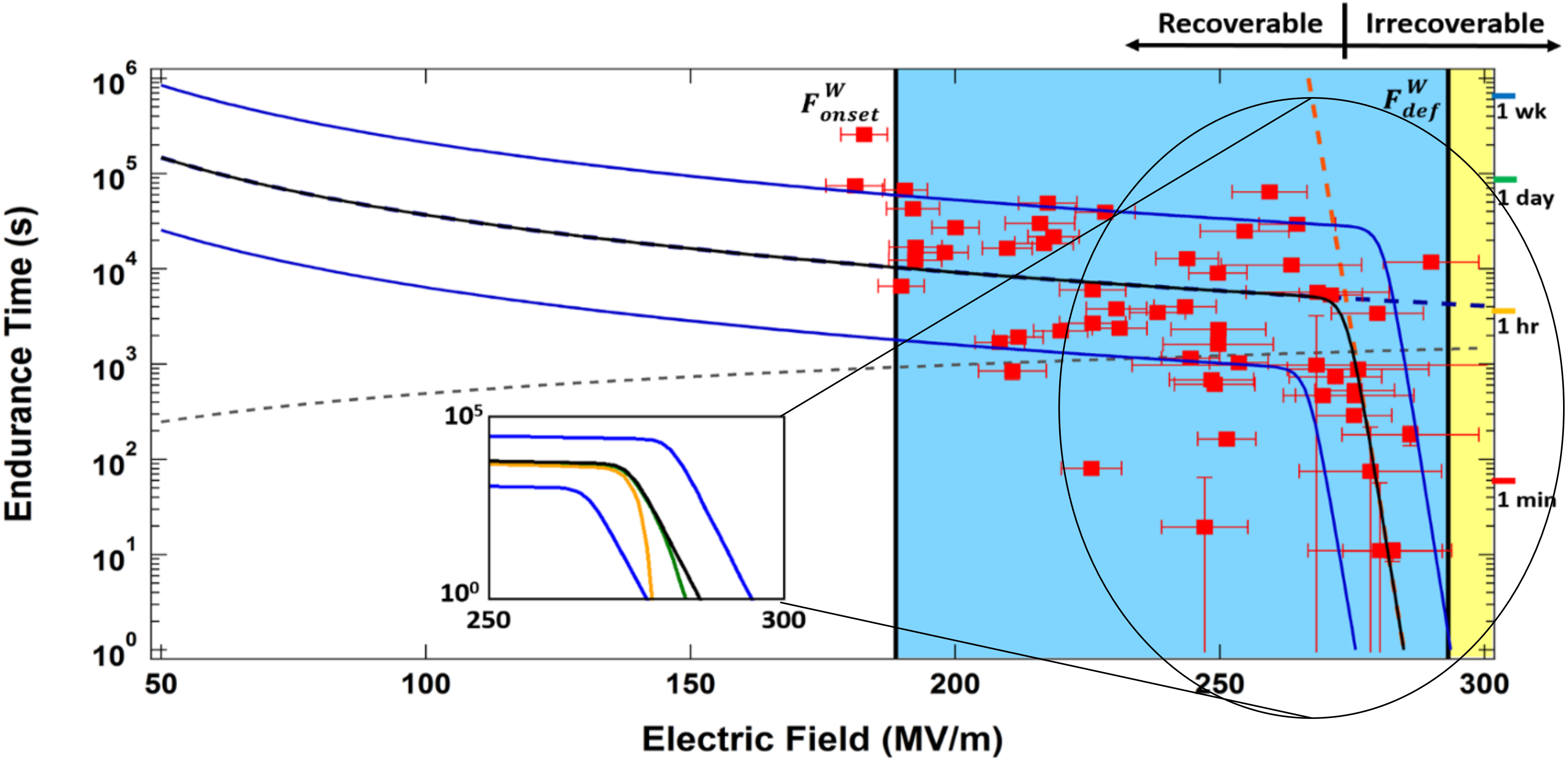
Dual Defect Model: Fit to LDPE Endurance Data



Even with large inaccuracies in ΔG_i and N_i we need both Type A and Type B defects to fit the data.

$$t_{en}(\Delta t_{step}, V_{step}, V_{wait}, T) = \left(\frac{h}{2k_B T}\right)\left[\sum_{i=A,B} \exp\left[\frac{-\Delta G_i}{k_B T}\right] \sinh\left[\frac{\varepsilon_0 \varepsilon_r \left(\frac{V_{wait}}{D}\right)^2}{2N_i k_B T}\right]\right]^{-1}$$

Dual Defect Model: Fit to LDPE Endurance Data

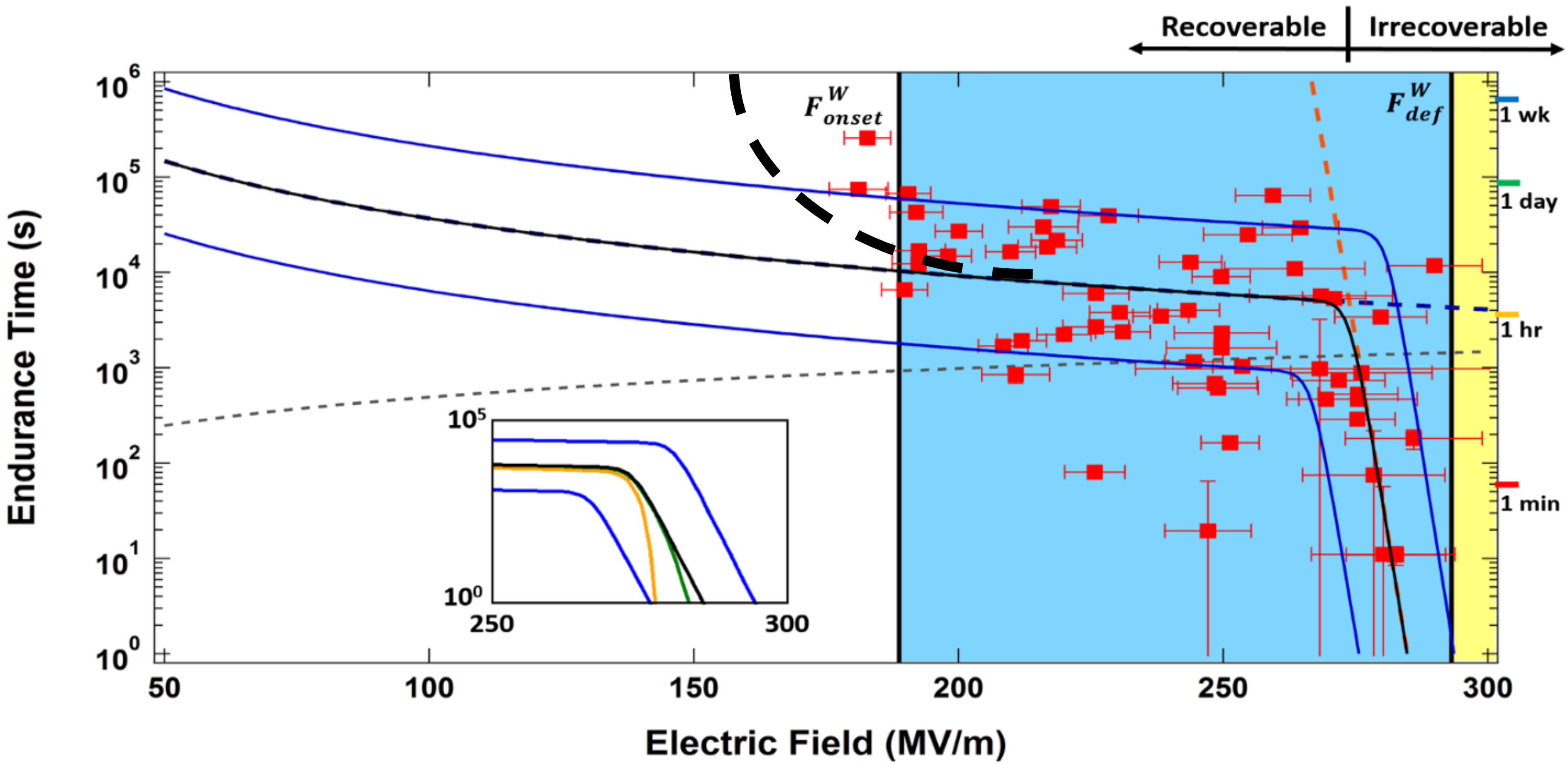


The inset shows the affect of assuming the static field for the step process (yellow line) and the correctly weighted step process (green line).

$$t_{en}(\Delta t_{step}, V_{step}, V_{wait}, T) = \left(\frac{h}{2k_B T}\right)\left[\sum_{i=A,B} \exp\left[\frac{-\Delta G^{i}_{def}}{k_B T}\right] \sinh\left[\frac{\varepsilon_0 \varepsilon_r {N_{step}}^2}{2k_B T\, N^{i}_{def}}\right]\right]^{-1} \times$$

$$\left\{\prod_{j=1}^{N_{step}}\left[1 - \left(\frac{2k_B T}{h/\Delta t_{step}}\right) \exp\left[\frac{-\Delta G^{B}_{def}}{k_B T}\right] \sinh\left[\frac{\varepsilon_0 \varepsilon_r \left(\frac{j\Delta V_{step}}{D}\right)^2}{2k_B T\, N^{B}_{def}}\right]\right]\right\}$$

Dual Defect Model: Fit to LDPE Endurance Data



The lower field data perhaps indicates that the curve should asymptotically go to infinity at some threshold field. This is a feature of some other models. Further data acquisition is needed in this regime and theoretical work to account for the dynamic density and occupation of states.

Predicting the Endurance Time

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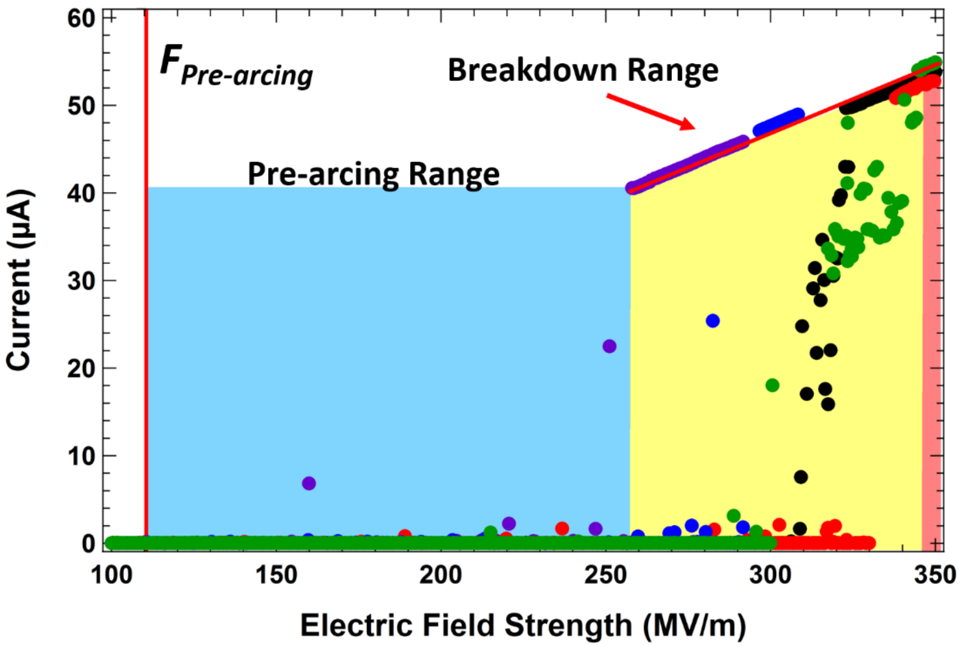
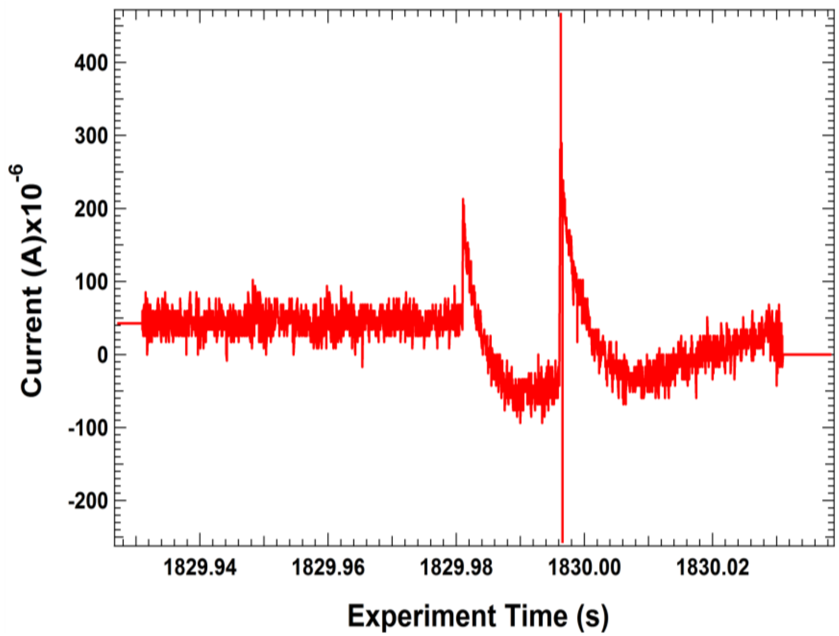
- What if the pre-arcing could tell us something? LDPE step-up tests had an average of 17 arc events. If the field where pre-arcs begins in related to the minimum breakdown field we might need only about half a day of instrument time to get a good estimate.

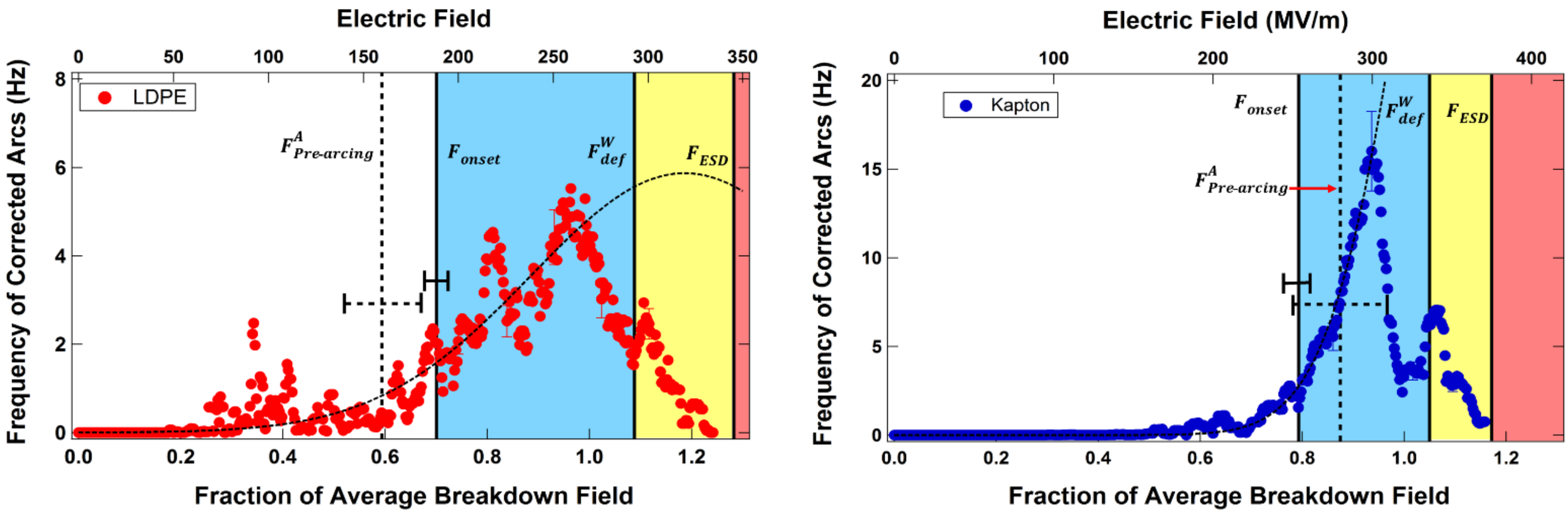
Pre-Breakdown Arcing





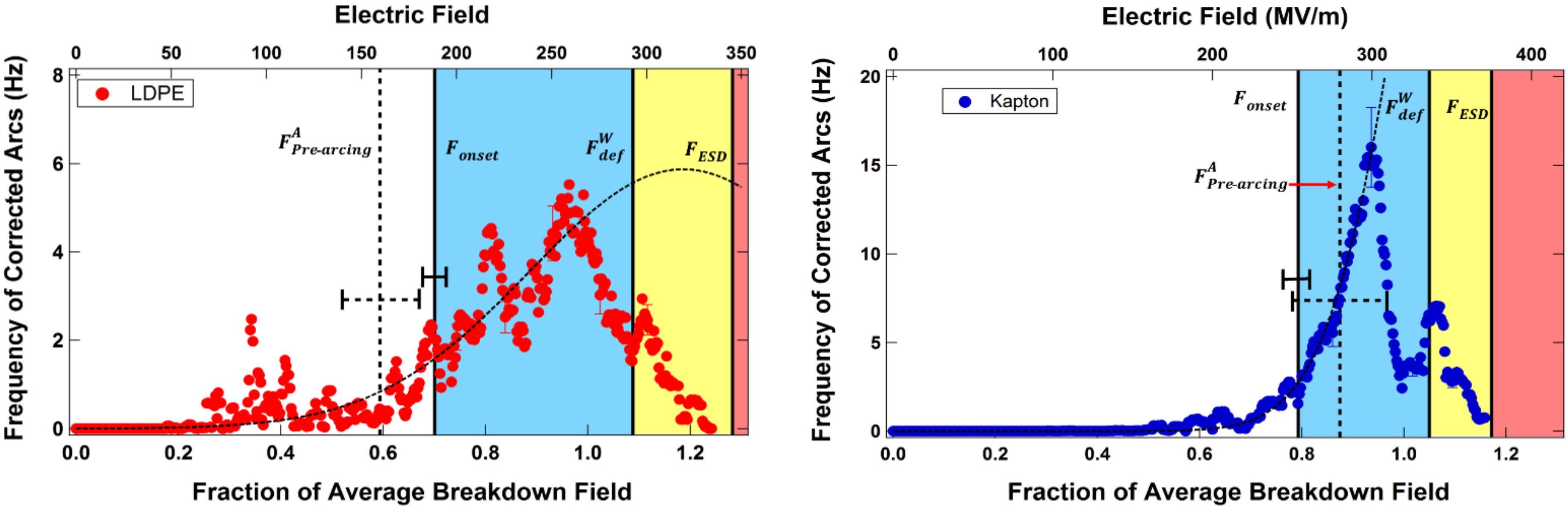
Pre-breakdown arcs were observed with an ammeter (~2 Hz) and with an oscilloscope (~10 kHz). We see occasions of several small arcs occurring faster than the ammeter can measure. This suggests that the larger amplitude arcs in the ammeter data represent current integrated over several small arcs.

Pre-Breakdown Arcing



For both LDPE and Kapton we see a main peak in the arcing frequency that corresponds to the crossover field between where Type A (recoverable) and Type B (irrecoverable) dominate.

Pre-Breakdown Arcing



Pre-breakdown arcing for 89 LDPE and 36 Kapton fit to a Gaussian function

$$f(F) = \frac{f_0}{\sqrt{2\pi}\Delta F} e^{\left(-\frac{(F-\bar{F})^2}{2\Delta F^2}\right)}.$$

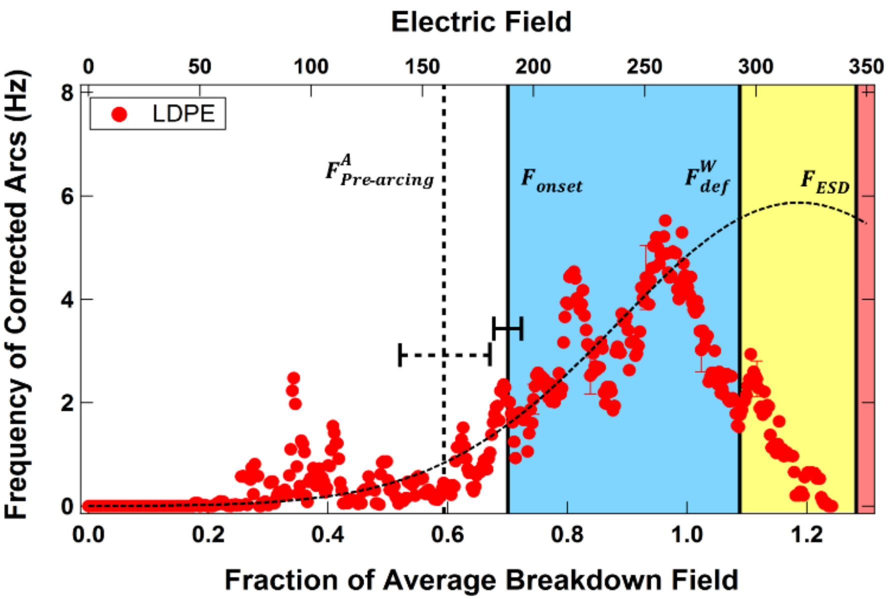
We define $\Delta F = \frac{1}{2}\left(\bar{F} - F^A_{Pre-arc}\right)$ **so that** $f\left(F^A_{Pre-arc}\right) = 0.0455.$

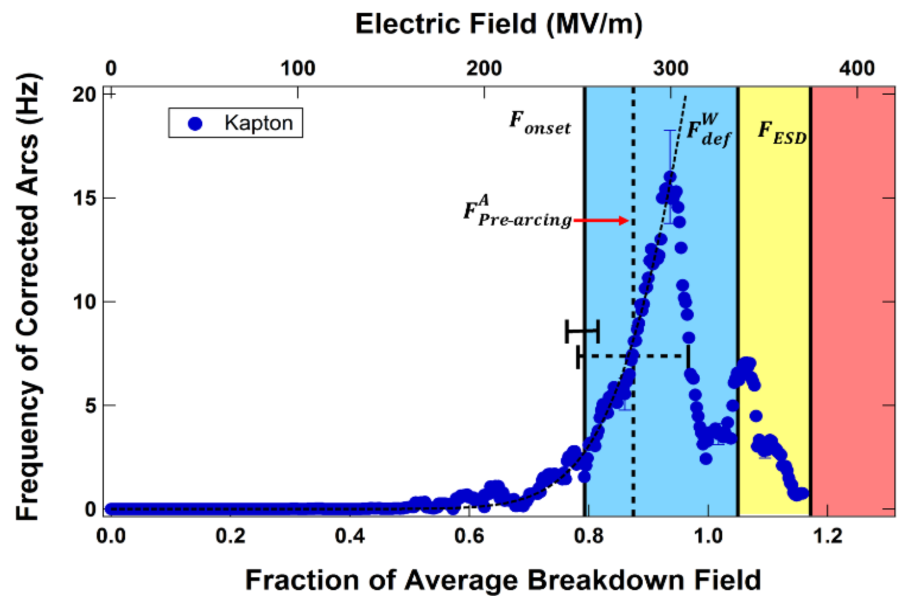
We can now quantitatively compare the field where ESD begins (*F_{onset}*) to the field where Pre-arcing begins ($F^A_{Pre-arcing}$).

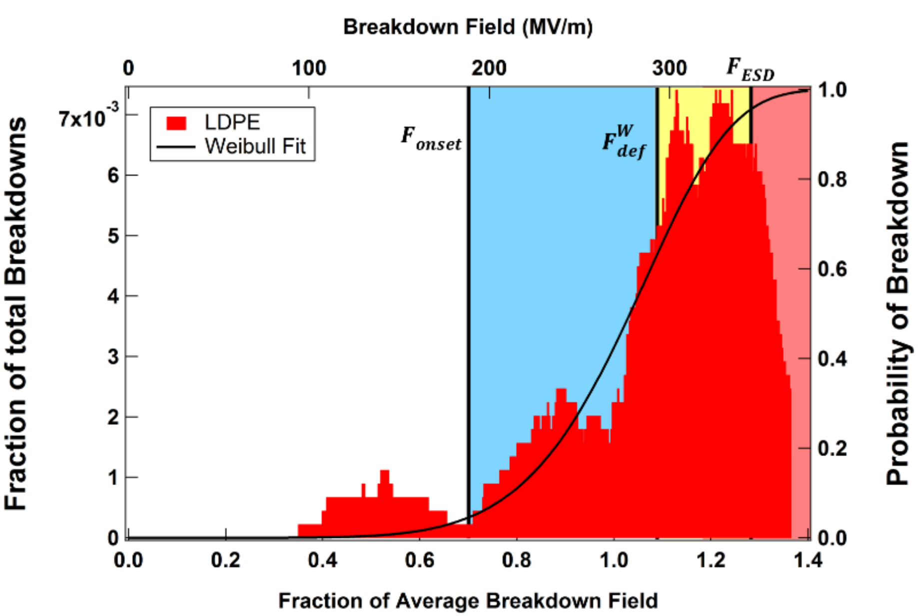
For LDPE $F^A_{Pre-arcing}$=160 ±20 MV/m ≈ F_{onset} = 189 ± 6 MV/m.

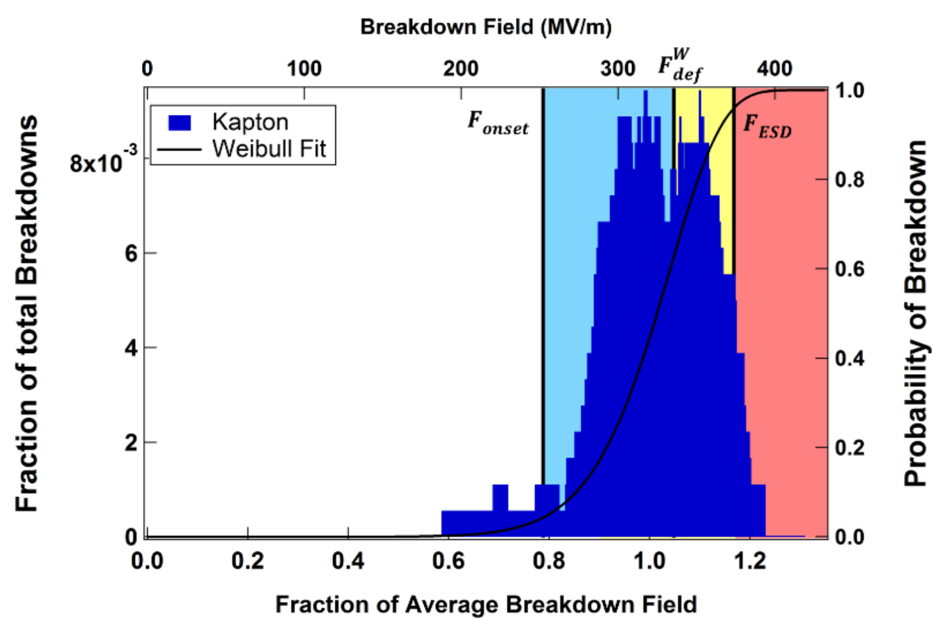
For Kapton $F^A_{Pre-arcing}$=280 ±30 MV/m = F_{onset}= 253 ± 8 MV/m within the uncertainty.

Pre-Breakdown Arcing

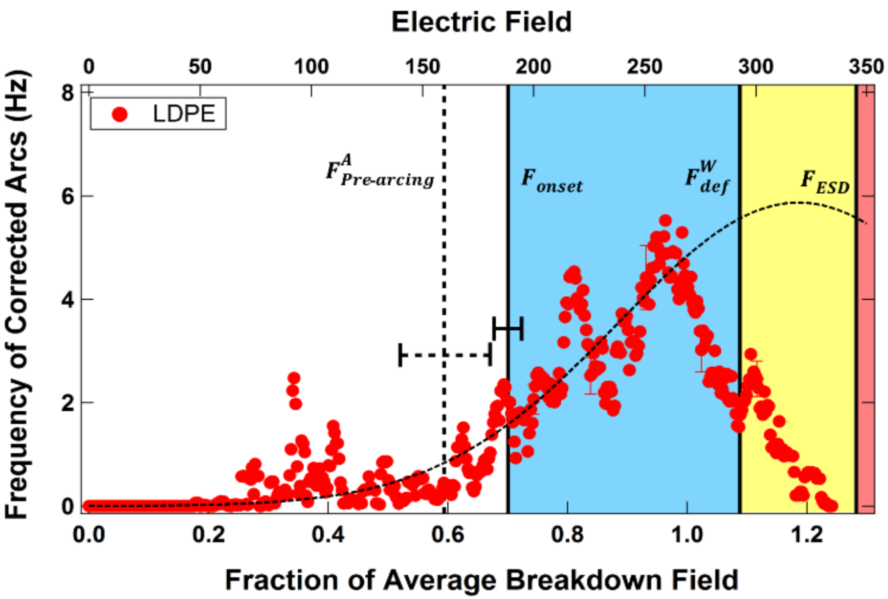


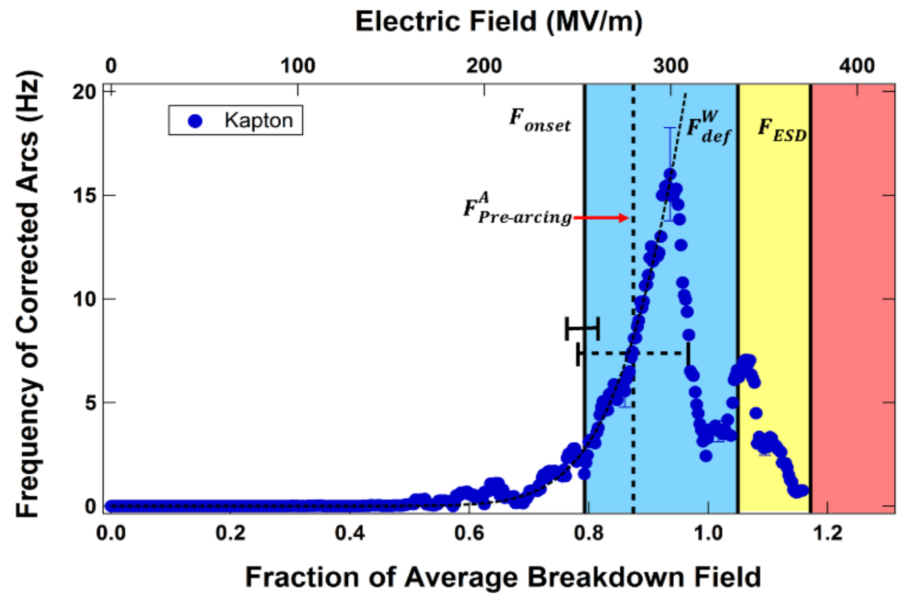






Material Comparison





Let's compare qualitatively the pre-arcing results for LDPE (thermoplastic) and Kapton (thermoset plastic).

We see pre-arcing and breakdown occurring at lower fields for LDPE which matches $\Delta G^A_{LDPE} < \Delta G^A_{Kapton}$.

We see similar high field behaviors for pre-arcing and breakdown in LDPE and Kapton which matches $\Delta G^B_{LDPE} \approx \Delta G^B_{Kapton}$ for carbon-carbon bonds.

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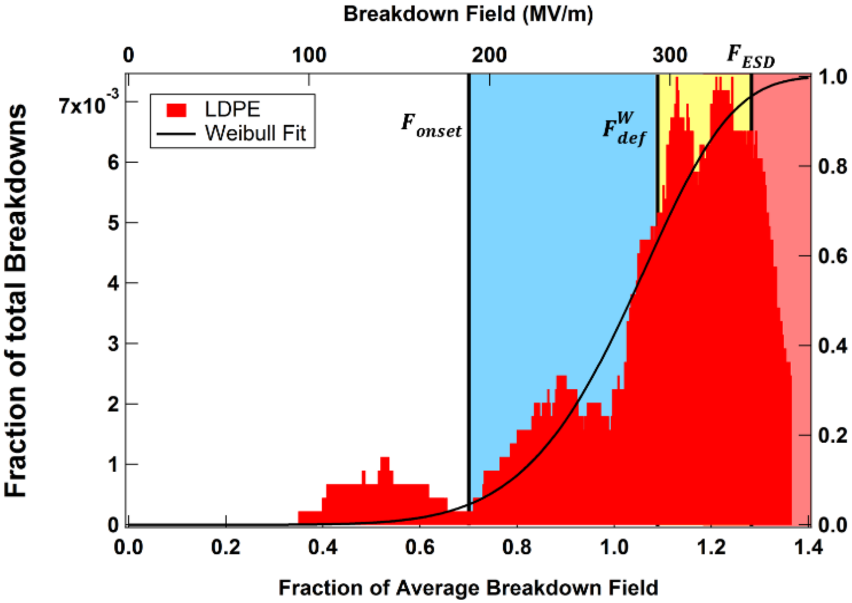

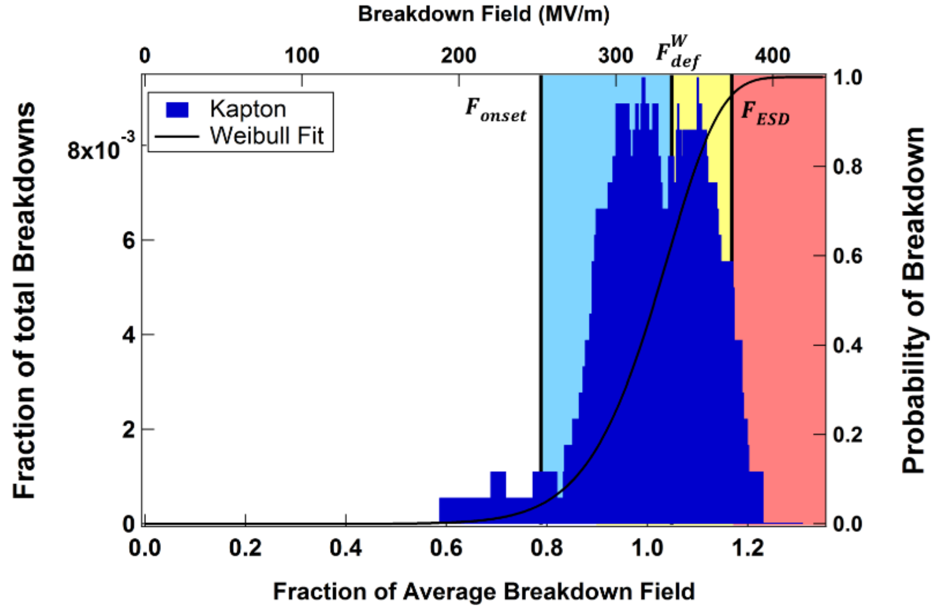

Let's compare qualitatively the F_{ESD} results for LDPE (thermoplastic) and Kapton (thermoset plastic).

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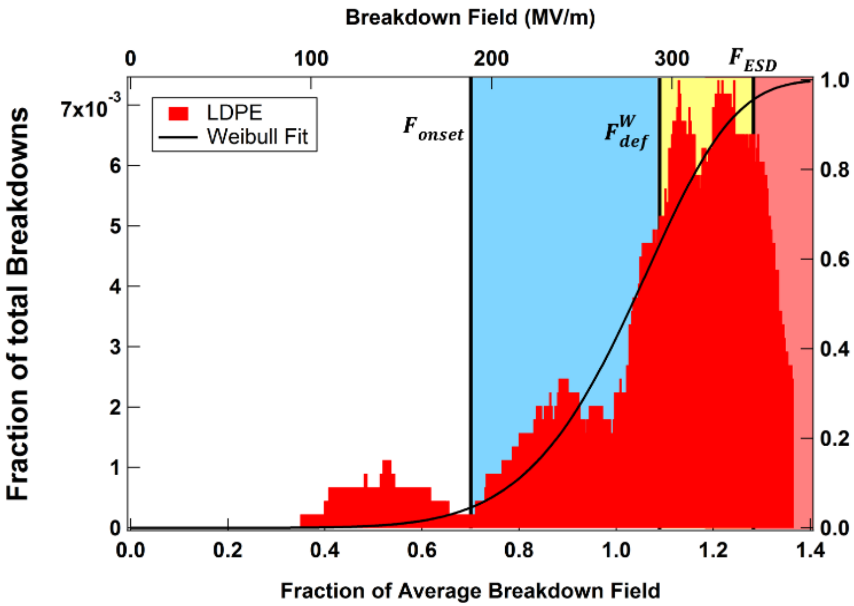
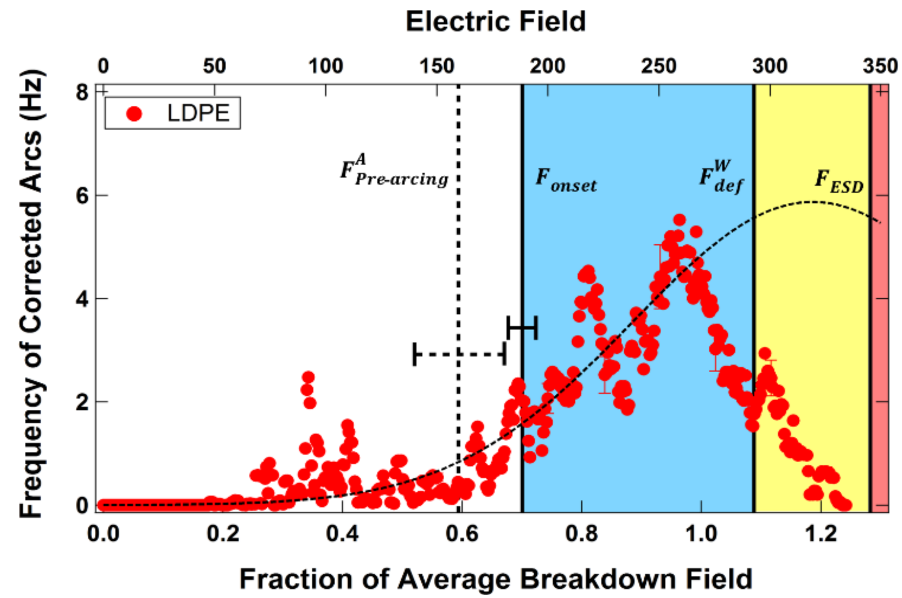
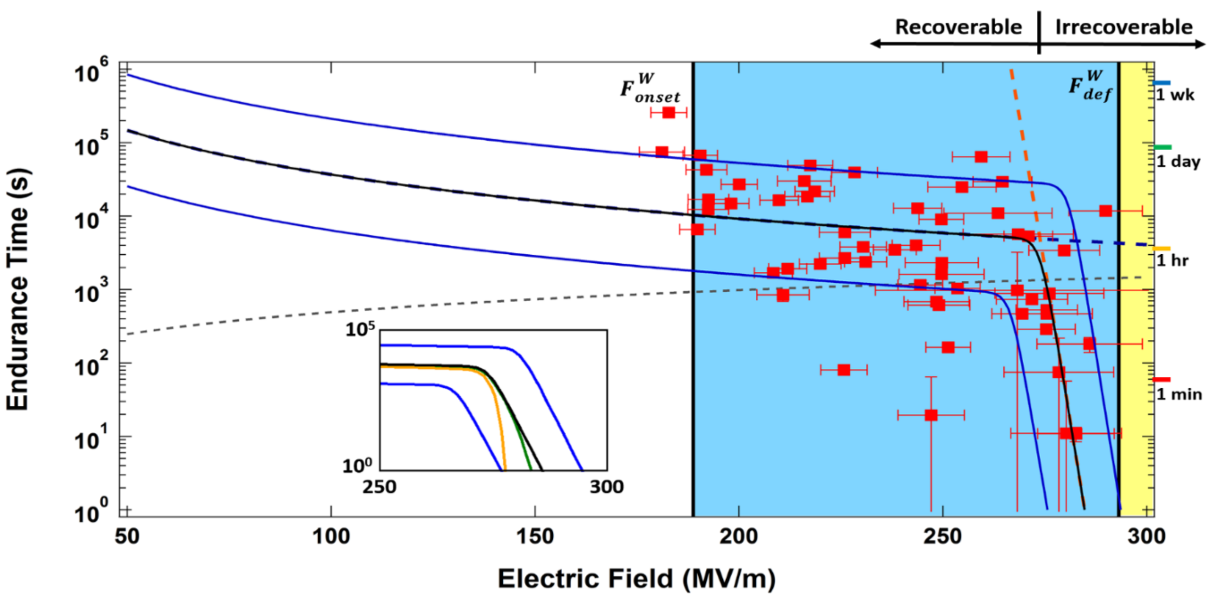
Predicting the Endurance Time







Voltage step-up, pre-breakdown arcing, and static voltage endurance time tests might all be telling us the same things.

Each scenario depends on the material defect energies, densities, and occupation.

Future Work

- Extend LDPE and Kapton data sets to longer endurance times.
- Explore other materials, with other defect distributions.
- Perform time endurance tests for materials without recoverable defect modes such as SiO_2. (We expect SiO_2 and other glassy or ceramic materials behavior to be drastically different because of different defect species and energies.)
- Expand temperature datasets to observe changes in breakdown fields, time endurance, and arcing thresholds.
- Expand model to include other (dynamic) density of state and defect occupation profiles.

Conclusions

- Electrostatic breakdown values are not simple–they depend on temperature, charge history, and material structure.
- The field for the onset of pre-breakdown arcing is a good estimate of the minimum breakdown field.
- Our dual defect model predicts behavior consistent with ESD measurements of pre-breakdown arcing, temperature- and ramp rate-dependent breakdown field distributions, and endurance times.

If you want to learn more about ESD…

Utah State UNIVERSITY

Allen Andersen and JR Dennison, "Pre-breakdown Arcing and Electrostatic Discharge in Dielectrics under High DC Electric Field Stress," *2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena*—(CEIDP 2014), (Des Moines, IO, October 19-22, 2014).

Allen Andersen, JR Dennison, Alec M. Sim and Charles Sim, "Measurements of Endurance Time for Electrostatic Discharge of Spacecraft Materials: A Defect-Driven Dynamic Model," 13th *Spacecraft Charging Technology Conference,* (Pasadena, CA, June 25-29, 2014).

Allen Andersen and JR Dennison, "Pre-breakdown Arcing in Dielectrics under Electric Field Stress," American Physical Society Four Corner Section Meeting, University of Denver, Denver, CO, October 18-19, 2013.

Allen Andersen and JR Dennison, "Electrostatic Discharge in Solids," Utah State University Physics Colloquium, Utah State University, Logan, UT, October 8, 2013.

Allen Andersen and JR Dennison, "Charge Transport and Electrical Degradation Research for Power Grid Applications," Utah State University Graduate Student Research Symposium, Utah State University, Logan, UT, April 12, 2013.

Allen Andersen, Charles Sim and JR Dennison, "Electrostatic Discharge Properties of Fused Silica Coatings," American Physical Society Four Corner Section Meeting, New Mexico Institute of Mining and Technology, Socorro, NM, October 26-27, 2012.

My Selected Works

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