Studies of Electrical Breakdown Processes across Vacuum Gaps

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The Maximum Electric Field Gradient which can be Reliably Sustained Across a Vacuum Gap Between Two Conductors Is a Basic Design Constraint of All Electrostatic Accelerators

- **Constrains such important design parameters as:**

1. **Minimum accelerator length**

2. **Strength of electrostatic lenses**

3. **Current density which can be controlled within a channel**

Efforts to improve voltage holding have focused on smoothing surfaces, and then conditioning with controlled sparks.

Efforts to Augment Voltage Gradients in Vacuum Gaps Have Been Impeded by an Imperfect Understanding of the Physical Processes Important in Vacuum Breakdown

- Two main models for onset of vacuum breakdown:

1. Electron emission from negative electrode (field emission from micro-projections, photoemission, and secondary emission)

Problems:

Simple electric field model would predict linear dependence of sustainable voltage with gap distance, rather than the square root dependence observed for gaps greater than a cm.

Fails to explain why electro-polished electrodes usually need conditioning (would seem to be same spark erosion process)

2. Acceleration of charged clumps from the electrodes, producing plasma upon impact

Problem:

Predicts correct voltage-distance scaling, but concept of charged pieces of electrode or electrode oxide breaking off and accelerating enough to produce plasma cloud seems somewhat physically implausible

Some Possible Reasons Why Vacuum Electrical Breakdown Seems Puzzling

1. Half of the force balance has traditionally been left out of the description of electron field emission; only electric field is considered, not the self-magnetic field of the electron current

    Self-magnetic field will focus the current channel and be kink-unstable; probably give different distance scaling

2. Maybe the clumps of clump theory are actually bacteria or bacterial spores:

    Ubiquitous unless special precautions taken

    Can persist in vacuum for many years

    Readily accumulate electrostatic charge

    Loosely attached to surface, so easily detached by field

    Appropriate size (a few microns)

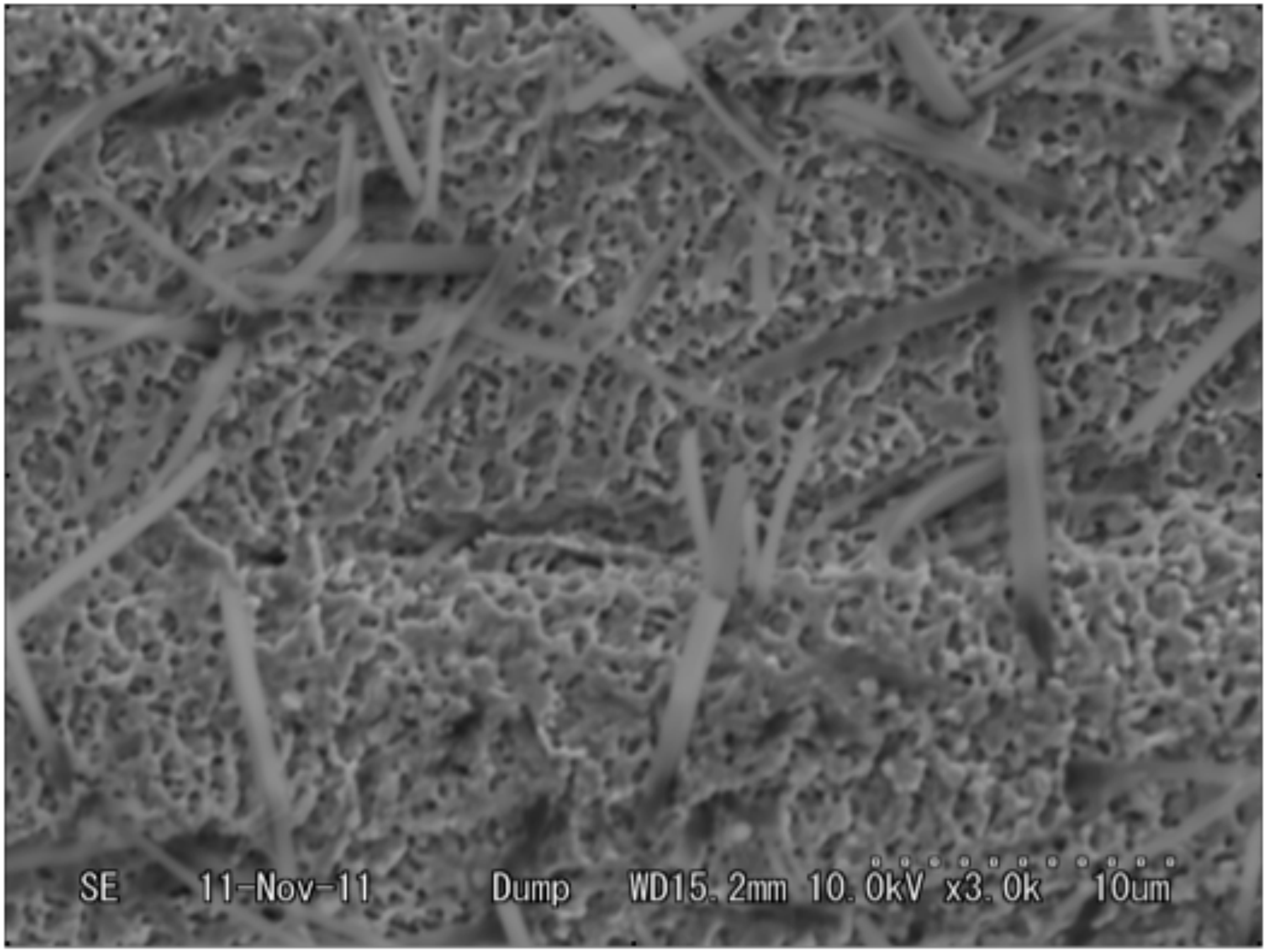
3. Maybe electro-polishing and conditioning are really doing two different things:

    Electro-polishing smoothing surface by spark erosion

    Conditioning perhaps also removes bacteria and spores

4. Maybe several processes responsible for breakdown

Bacteria or Spores on a Copper Beam Dump

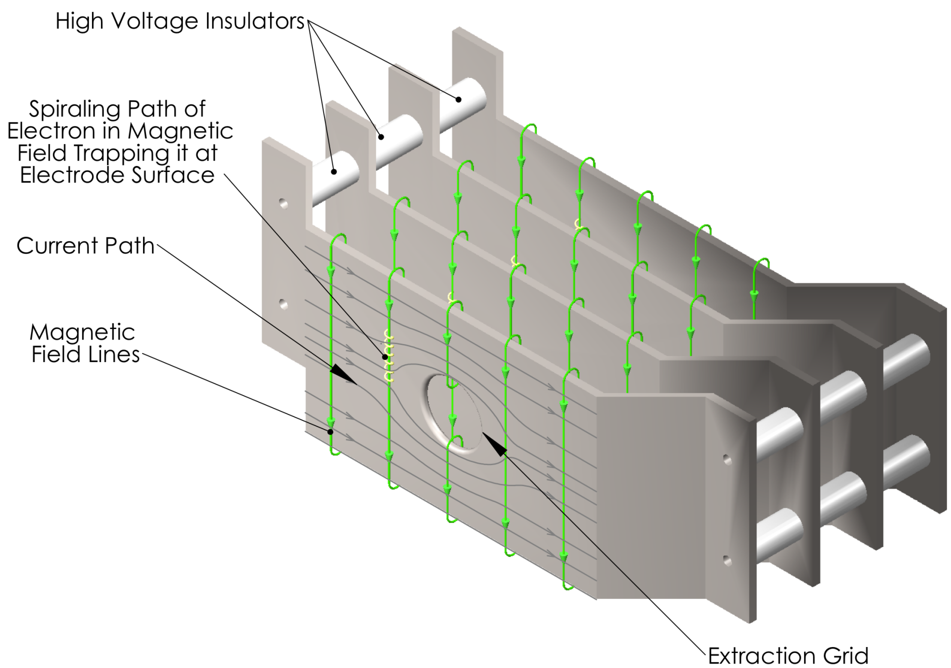


Magnetic Insulation with Appropriate Topology Might Improve Voltage Holding in Electrostatic Accelerators IF Field Emission of Electrons is the Principle Instigator of Vacuum Electrical Breakdown

To differentiate between electron emission and clumps as breakdown instigators:

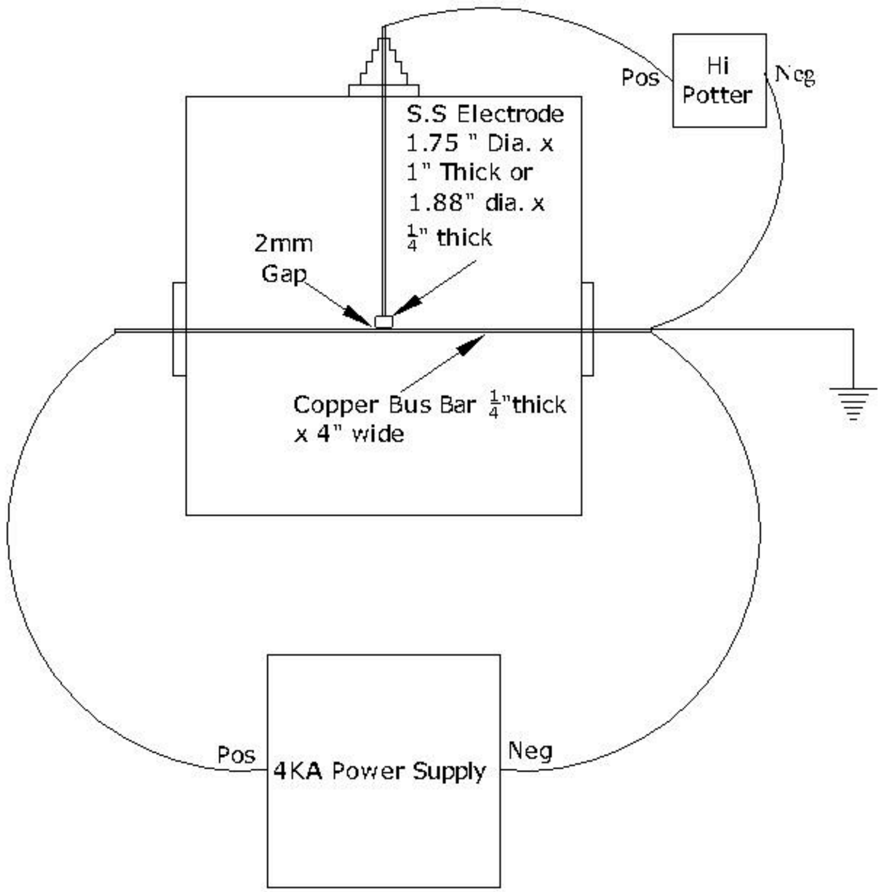
- Attempt to mitigate breakdowns by passing large current through a negative electrode on one side of a vacuum gap to produce enveloping magnetic field
- Magnetic field needs to be strong enough to prevent electrons from leaving surface and picking up energy from electric field.
- Spontaneous field emission should be most responsive to magnetic insulation because electrons are born at electrode temperature
  - At room temp of 1/40 eV; 240 G produces electron gyroradius of 2.2 x 10^{-3} cm to reduce mobility of electrons within electrode and at surface; charged bacteria or other clumps would have vastly larger gyroradii, so unmagnetized
  - This field (at negative electrode surface) was used in initial PPPL experiment

Magnetic Field Is Everywhere Parallel to Surfaces of Electrodes and Their Conducting Support Structures



Exploratory Low Budget Experiment Conducted on Princeton 100 kV Test Stand

- Produced magnetic field with surface magnitude of 240 gauss enveloping negative side of vacuum gap by flowing 4 kA along copper busbar with high voltage applied across gap between and stainless steel probe disk



Outcome of Initial Experiment

- **No increase of sustainable electric field seen across small vacuum gaps of a few mm with maximum magnetic field of 240 gauss enveloping the negative electrode**

- **Possible explanations:**

  High voltage supply had no crowbar to quickly divert breakdown current, so electrode were damaged every shot, changing surface conditions

  Magnetic field was too low (was chosen to be practical for applications on large area grids such as for ITER)

  Field emission of electrons is not principle breakdown mechanism , but instead charged clumps or bacterial spores, which would have huge gyroradii and thus be unimpeded by enveloping field

Integrated Program to Understand Physics of Vacuum Breakdown

Repeat magnetic insulation with better equipment and much higher enveloping magnetic field so can use it to differentiate between electron emission and charged clump (or bacterial spore) emission as primary breakdown instigator

- Planned Improvements:

Previous high voltage supply had no crowbar to quickly divert breakdown current, so electrode were damaged every shot, changing surface conditions; will purchase new supply with fast crowbar on output

Magnitude of original magnetic field enveloping negative electrode was chosen to be practical for large area accelerators; for next experiment aimed at understanding physical mechanism of breakdown instigation, magnetic field will be increased by an order of magnitude (use same high current supply, but decrease width of tested part of negative electrode by 10 to correspondingly augment current density.

- Couple with theory program using HIF beam codes to model magnetic self-field of electrons emitted from surface and arc dynamics

Extend Experimental Scope to Include Contributions of Bacteria and Bacterial Spores to Vacuum Electrical Breakdown

- Find a sterilization technique which removes most bacteria and spores from electrodes and nearby surfaces (inspect with appropriate microscope)

- Repeat tests of voltage holding under vacuum in test stand to compare voltage holding of electrodes with and without sterilization

- Combine with enveloping magnetic field to see whether combination of sterilization (removal of bacteria and spores) and enveloping magnetic magnetic field improves voltage holding more than either technique by itself

- If experimental results support bacterial breakdown hypothesis, try to model dynamics of charged bacteria and spores

If This Exploratory Program is Successful

- Should result in a better understanding of the physical processes which determine voltage holding across vacuum gaps

- Informed by the experimental program, theory effort to produce a better description of the dynamics of vacuum breakdown

- Perhaps have a basis to increase reliable voltage gradients in some accelerator applications, and to reduce time required for accelerator conditioning

- Even if neither technique produces improvements, still should achieve something by reducing the range of possible mechanisms for instigation of breakdown