A Model of RF Vacuum Arcs

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Vacuum arc theory is unsettled after more than 120 years.

Vacuum arcs were isolated by Millikan and Michelson in 1900.

Lord Kelvin proposed an Electrostatic Discharge model in 1904.
Predicted ~10 GV/m local BD threshold.

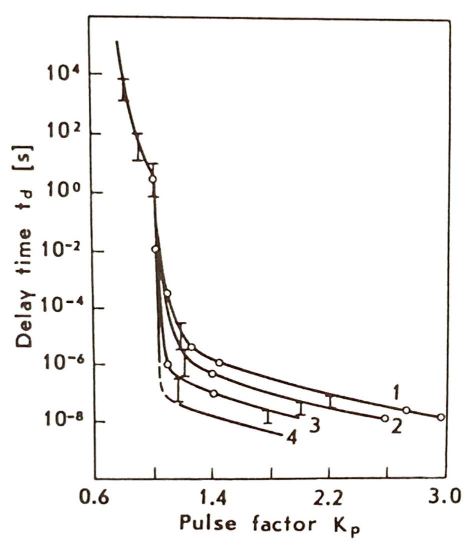
Most Vacuum Arc studies are aimed at component reliability.

The Explosive Electron Emission (EEE) model doesn't fit RF data very well.

DC predictions:

- Long BD delay times (~μs)
- Weak field dependence
- Unicorn horn asperities

which are not seen in RF.



Mesyats & Proskurovsky 1989

Fig.2.2. Breakdown delay time as a function of the pulse factor for steel electrodes with gap spacing d = 15 (*1*), 10 (*2*), 5 (*3*), and 1 mm (*4*) [2.59]

The EEE model explains DC systems, with some problems.

Juttner criticized all models in 2001.

> … In the literature the theoretical treatment prevails, but many theories are built on unsafe experimental ground. . . . Also, the interpretation of measurements is sometimes heavily disputed by the experimenters. Therefore, at present no model is generally accepted, and this review cannot avoid a personal view.

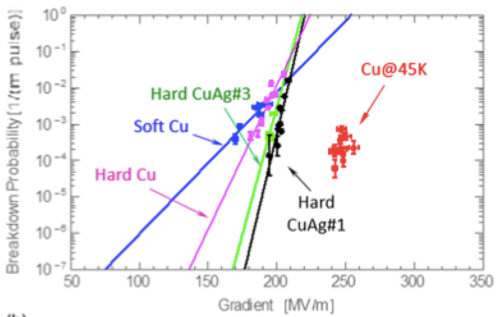
RF is different.

- There are more variables than measured quantities in arc experiments.
- RF experiments are unique: short pulse length, low duty cycle.
- A wide range of frequencies makes data comparisons difficult.
- Surfaces can be inaccessible.

RF Expts show sharp thresholds, fast BD times, little damage.

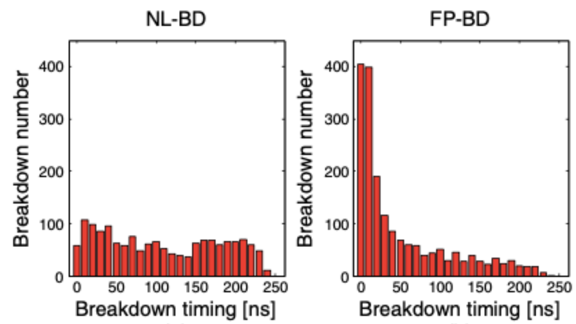
Experiments at high frequencies see:

BDR ~ E^{30}



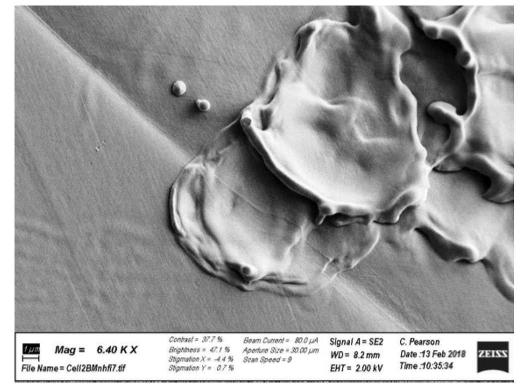
CERN, SLAC

fast triggers



CERN 2017

smooth surfaces



SLAC 2017

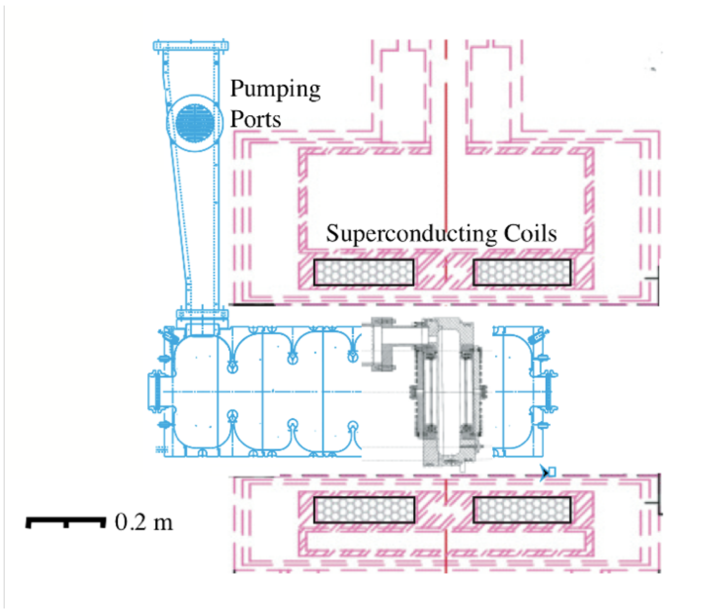
These are not predicted by the EEE model.

Our arc model is based on 805 MHz experiments at FNAL.

We had removable plates, high B fields, new diagnostic techniques, different cavity systems, experienced plasma modeling, and SEMs.

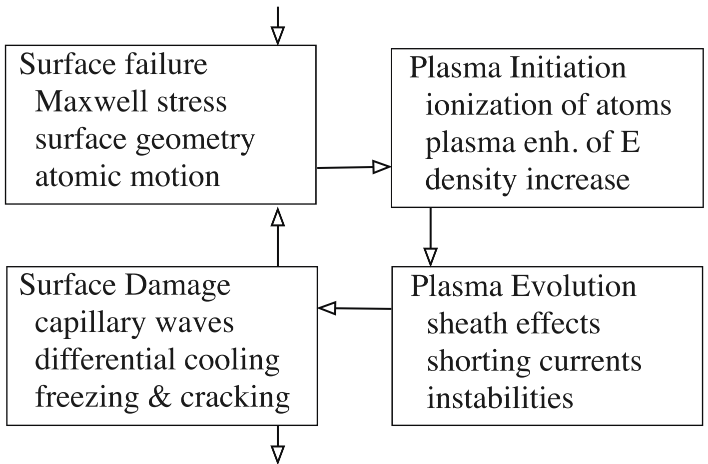
The tests were part of the Muon Accelerator Program, aimed at producing a system for cooling muons (2001 – 2012+).

There are more experimental options at lower frequencies.



We understand RF arcs from our own data and modeling.

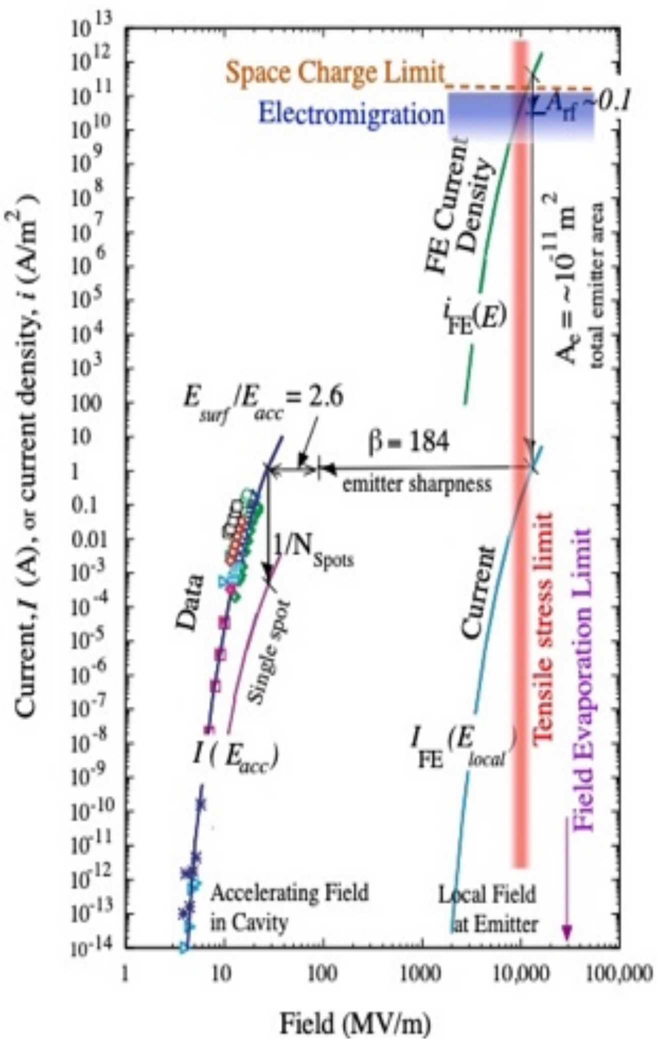
The arc model has four stages.



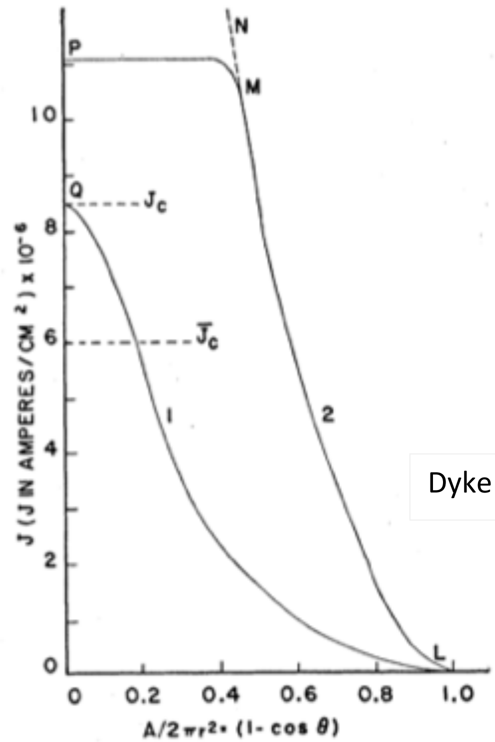
	Mechanism	Time scale
<u>Trigger</u>	Surface Failure	< 0.1 ns Electrostatic > 50 ns EEE
<u>Ionization</u>	FE + Atoms → plasma	~ 10 ns
<u>Evolution</u>	Unipolar arcs, FE shorting currents	10 ns - DC
<u>Damage</u>	Differential cooling, cracks	100 ns – 5 μs

Trigger

Compare data and mechanisms

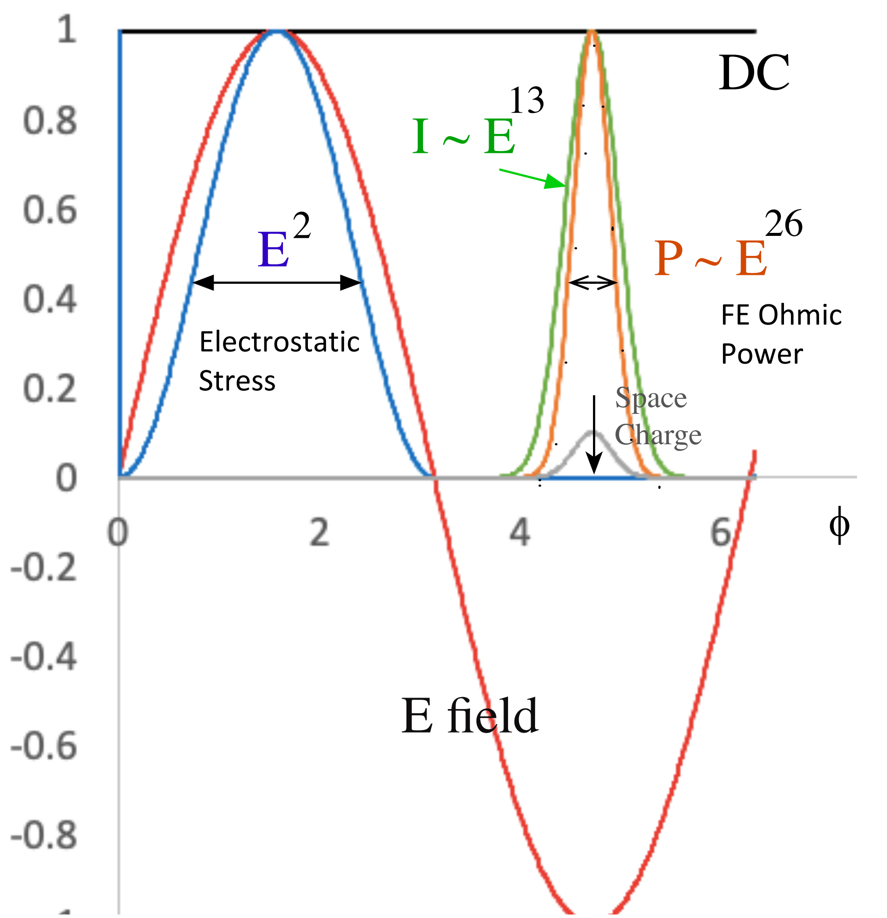


Space Charge Limit reduces surface field.

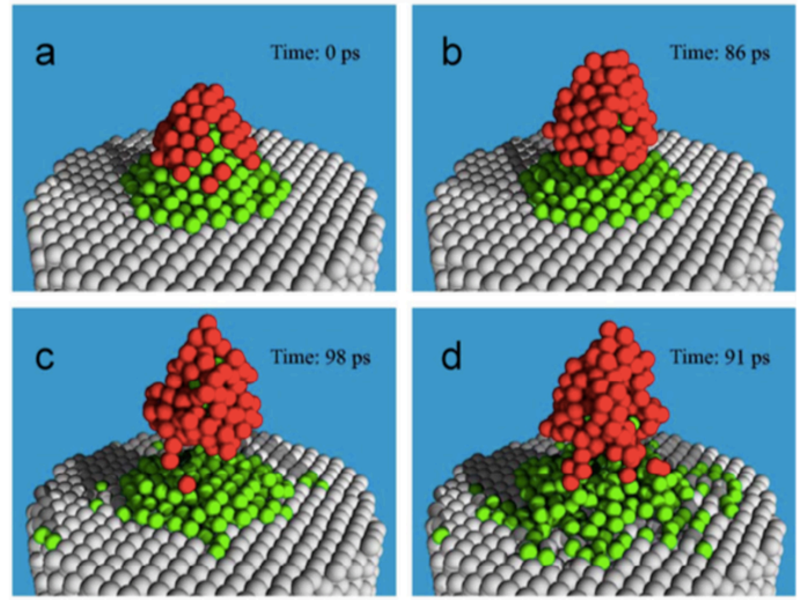


Dyke & Trolan, 1953

RF reduces heating by 0.076.

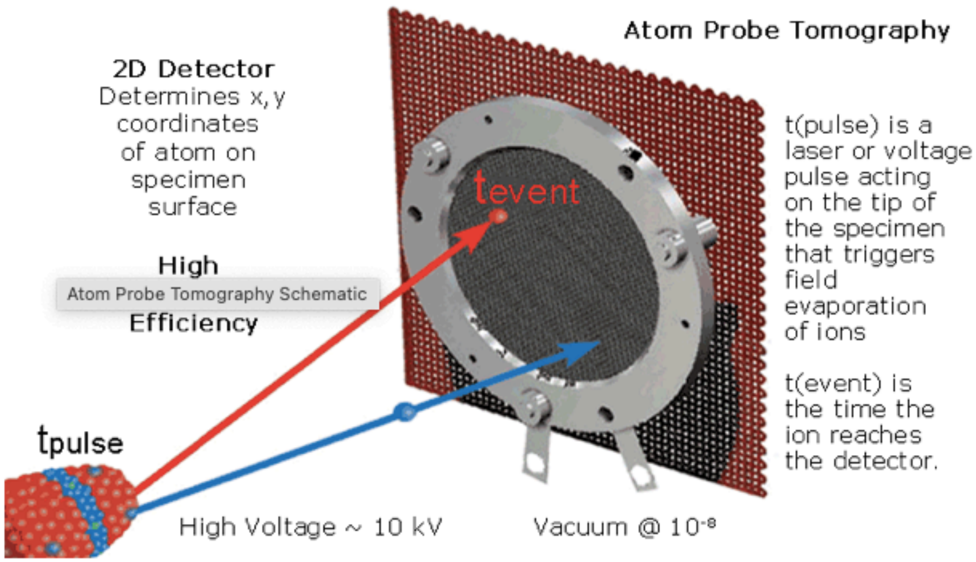


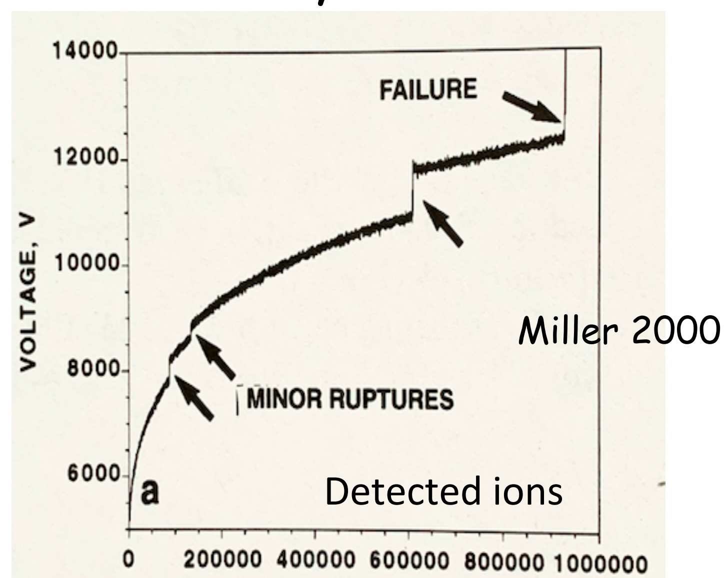
Electrostatic discharge < 0.1 ns



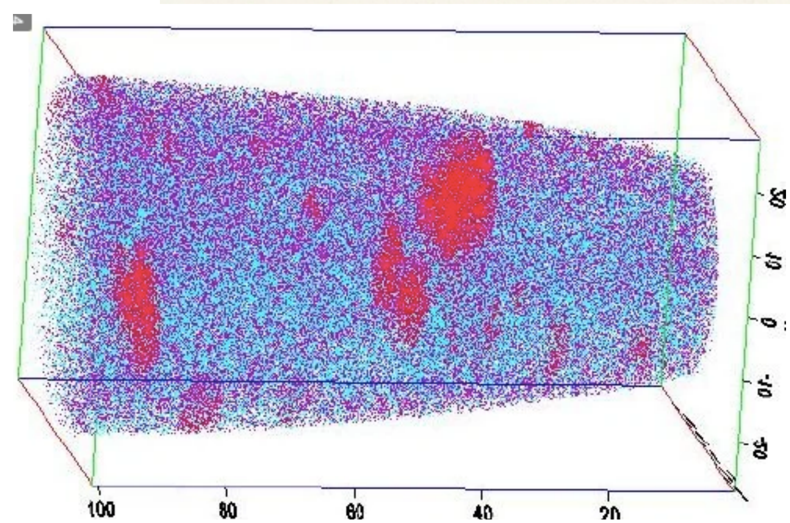
When FE space charge lowers the field at the asperity tips, the surface failure will occur when the surface is positive, and copper surfaces fail at ~30 GV/m in Atom Probe Tomography systems, with ns pulses.

Atom probe tomography samples . .   . fail two ways,



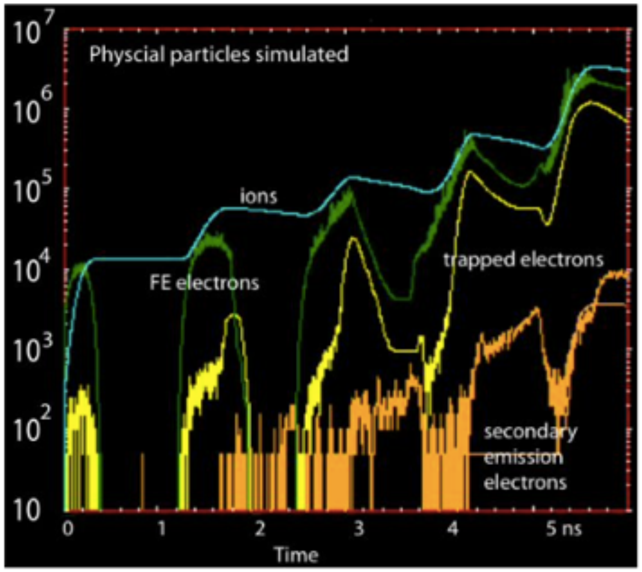


spoiling what should be good data.

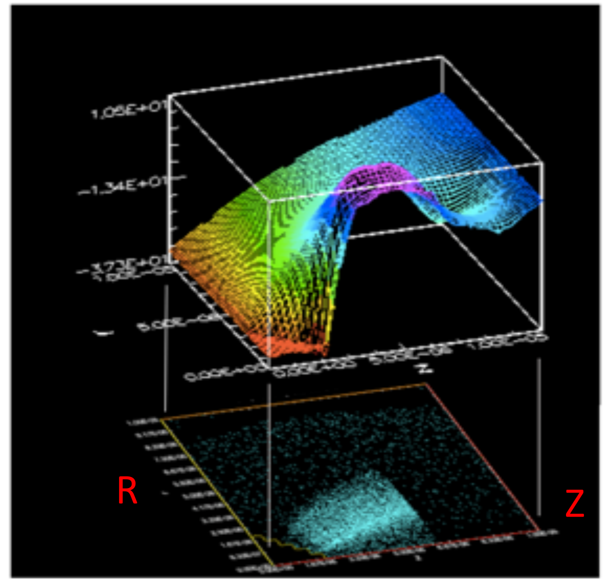


Ionization

Ionization takes ~ 10 ns.



A local plasma increases surface fields.



Potential

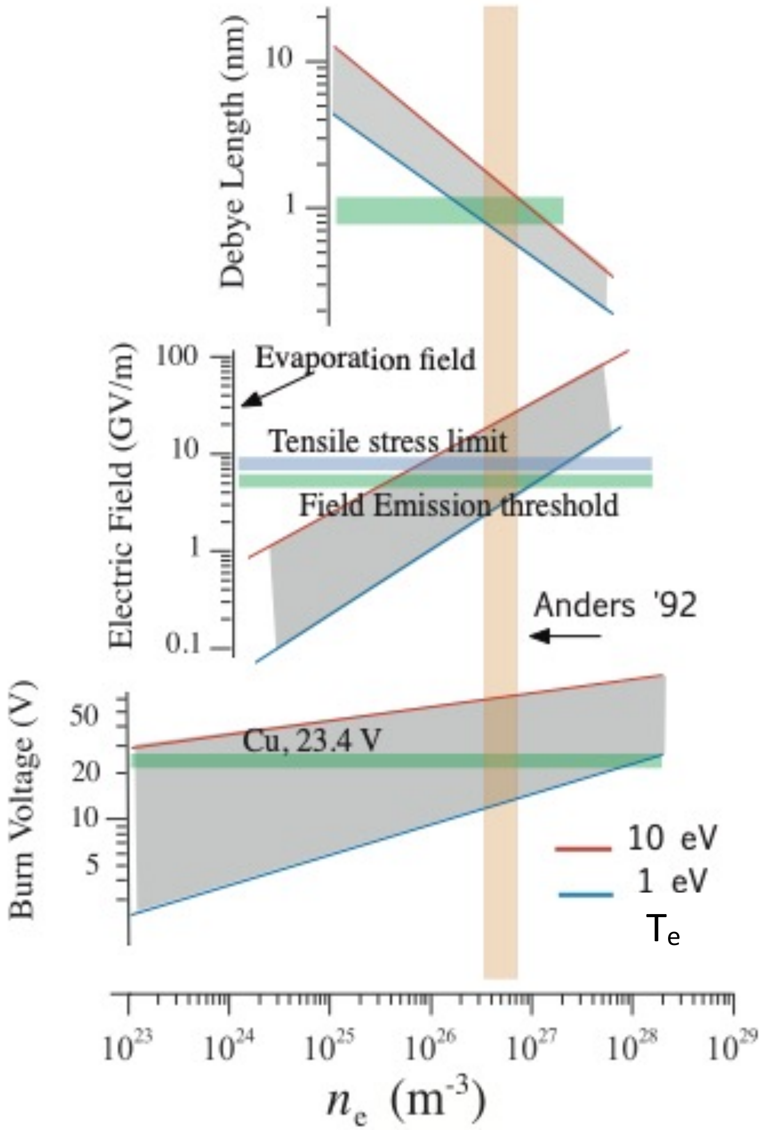
Plasma Ions

Unipolar arcs:

- Ions are inertially confined near surface.
- Some electrons escape, charging the plasma positive.
- Field emission maintains the electrons.
- Self sputtering and evaporation maintain ions.
- Image charge sticks the plasma to the surface.
- High densities are nonlinear.

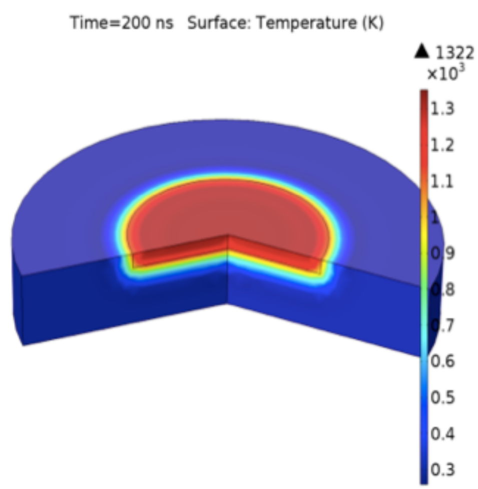
Plasma Evolution

The properties of the unipolar arc are determined by n_I and T_e



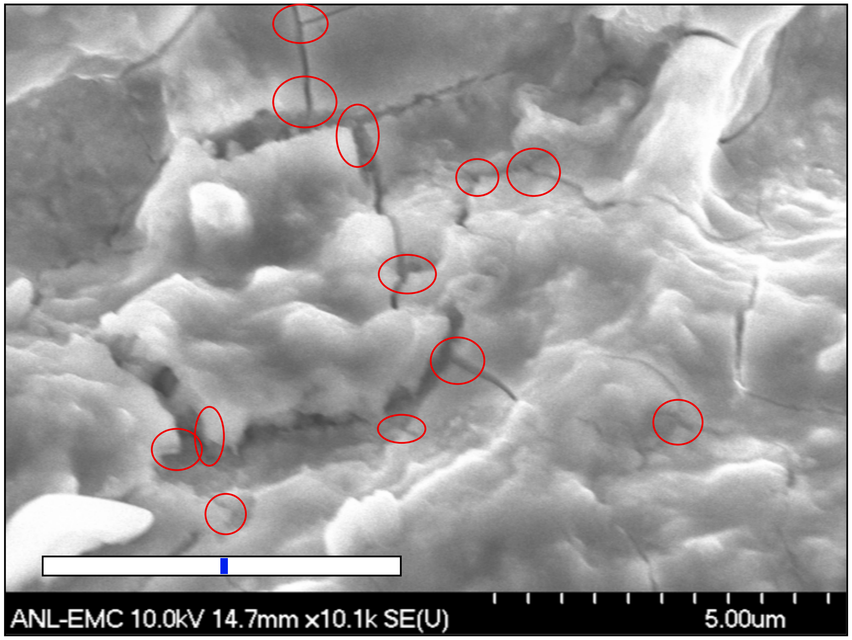
At densities > 6×10^{26} m^{-3}, the plasma becomes non-Debye, maintained by self-sputtering, evaporation and field emission.

The surface melts and heats up.

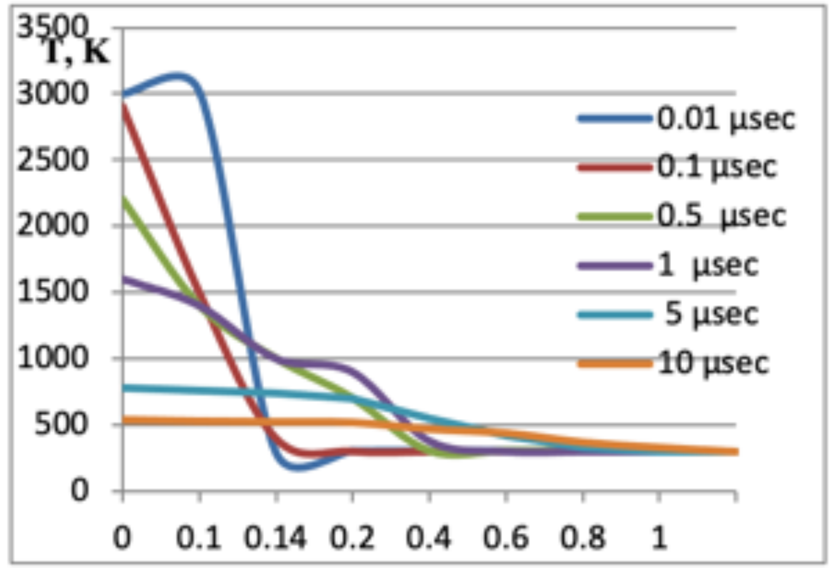


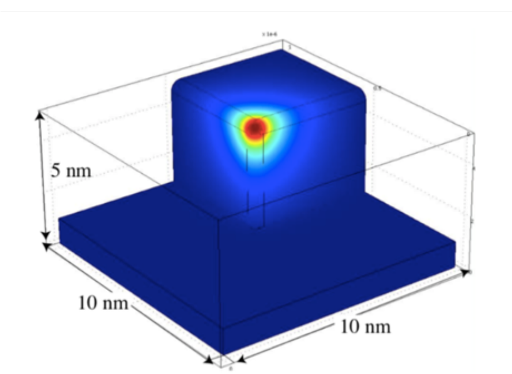
Surface Damage

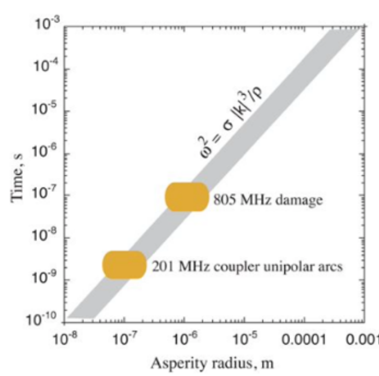
We see high β surface damage . .



. caused by differential cooling,







. . .with rectangular asperities and capillary waves.

Details

Breakdown without heating. In rf systems, surface heating is suppressed by the duty cycle of the field emitted currents. (If $I_{FE} \sim \boldsymbol{E}^{13}$, currents are reduced by 0.1, heating by 0.076.) Space charge can prevent negatively charged asperity tips from field emitting, so positive surfaces break down.

Electrostatic discharges should be very fast and almost independent of field just above threshold. Atom Probe Tomography is done in this regime, and sharp thresholds are seen.

Electromigration can alter the geometry. Iphones have ~10^9 transistors, and there are about 10^9 of them in use. They don't fail at current densities of $<10^{11}$ A/m^2 in copper, where the primary failure mode is known to be electromigration. BD may not be very sensitive to electromigration.

It is surprisingly hard to find good data on electrostatic discharges, since everyone spends all their effort avoiding it. Atom Probe people flush their data if a sample breaks down.

Conclusions for RF breakdown

Electrostatic fields trigger RF breakdown, not Ohmic heated unicorn horns.

Electrostatic discharges occur quickly, have a sharp threshold, and can be triggered by the tiny surface cracks we can see.

The model is consistent with the dependence of BD fields on pulse length, hardness and temperature. We expect these arguments apply to X Band systems, but have not produced a complete, self-consistent picture.

This necessary effort is not part of the General Accelerator R&D plan.

Our references:

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