Physics of breakdown in vacuum cavities

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Why even talk about breakdown physics?

1. **Context:** Next session is about instrumentation, simulation, and data analysis. But what are we looking for and what can we expect to learn?
2. **Optimization:** We have limited time and resources during the next 2-3 years. We'd better know what we're doing.
3. **Planning:** What's next for the MTA?

Breakdown is an open problem. What can we all agree on?

Observables

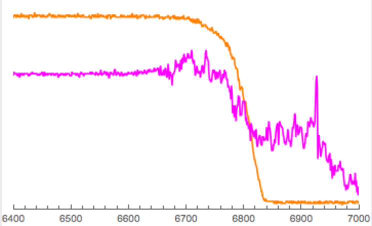
- Transmitted power drops, reflected power spikes. (Next slide.)
- Charge transport shorts the cavity. Stored energy drops.
- Sparks can cause damage. Acoustic signal too: {**audio**}
- X-rays detectable before and during an event.
- Light from plasma spot and spark before/during/after.
- Spike in vacuum pressure.

Surface Phenomena

- Sparks obliterate the features we'd like to observe.
- Surface degradation (needles? cracks?) leads to Fowler-Nordheim currents.
- Proper conditioning leads to a stable (metastable?) surface.

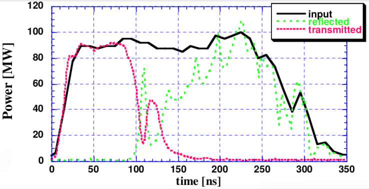
Breakdown waveforms

MICE @ 210 MHz (Preliminary)



Pickup signal, forward power.
40 ns per bin

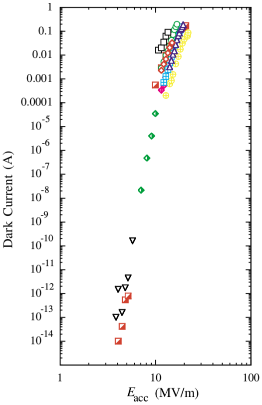
SLAC @ 14.2 GHz



Dolgashev & Tantawi, SLAC-PUB-10499

c.f. M. Leonova's talk earlier today for a more detailed description of MICE cavity waveforms.

Characterization of dark current in 805 MHz cavities



J. Norem *et al.*, PRST-AB 6, 072001 (2003). Dark current measurements in a six-cell 805 MHz cavity.

Fowler-Nordheim current density $i(E)$

$$i(E) = \frac{A_{\mathrm{FN}}(\beta E)^2}{\phi} \exp\left(-\frac{B_{\mathrm{FN}}\phi^{3/2}}{\beta E}\right)$$

From F-N log-log plot, we get:

- Total emitter area, # emitters
- Emitter duty factor (∼0.1 here)
- Field enhancement factor β
- $I \sim E^n$, estimate n

These are probably estimates, not measurements.

What theories exist to explain breakdown?

I know of no "end-to-end" theory that explains all phenomena, starting with surface evolution and ending with spark current density. Better question: What *flavors* of theory exist?

1. Nanoscale surface evolution
2. Electron/ion distributions
3. Cavity-scale processes

You are free to form your own opinions of these theories. I'm presenting a brief overview of the field, not my personal favorites.

A great resource:

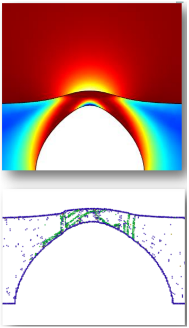
2013 International Workshop on Breakdown Science and High Gradient Technology (HG2013)

`http://indico.cern.ch/event/231116/timetable/#20130603`

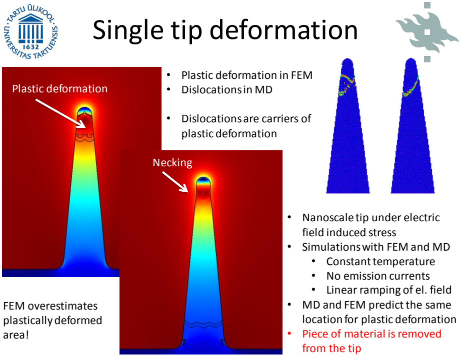
Nanoscale surface deformation

V. Zadin *et al.*, *Multiphysics simulations of surface under electric field*, Proc. HG2013

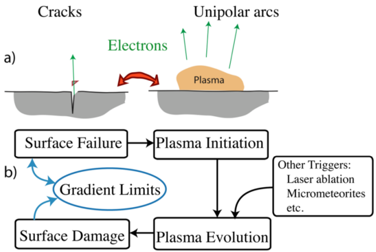
http://indico.cern.ch/event/231116/session/1/contribution/15

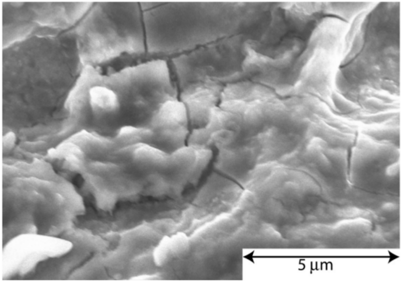


FEM (top) and MD (bottom) model of *E*-field strain near voids.



Z. Insepov and J. Norem, JVSTA 31, 011302 (2013).

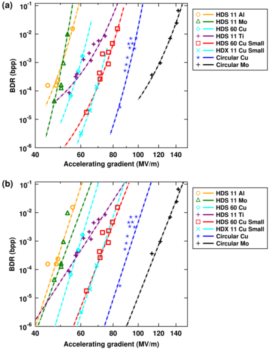




- Surface cracks cause field enhancement
- Local failure of surface nucleates plasma spot
- Unipolar arcing, damage

Dislocation dynamics and critical phenomena

K. Nordlund and F. Djurabekova, PRST-AB 15, 071002 (2012).
M. Assaf and B. Meerson, Phys. Rev. E, 021116 (2010).

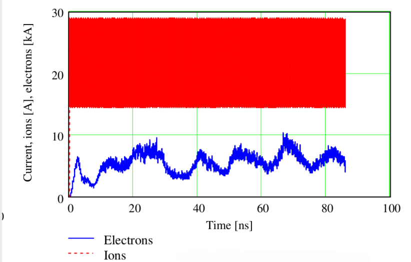


Nordlund and Djurabekova, 2012.
(a) Model fit to data; (b) Conventional power law fit to same.

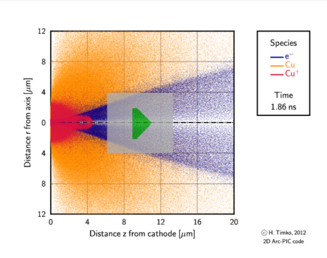
- Assumption: Material failure when mobile dislocations pile up at the metal surface.
- Extinction of a metastable stochastic population via intrinsic noise.
- Thermodynamic model of defect formation, incorporates RF heating effects.

Electron/ion distributions during field emission and breakdown

V. Dolgashev, 2003 MICE RF Workshop



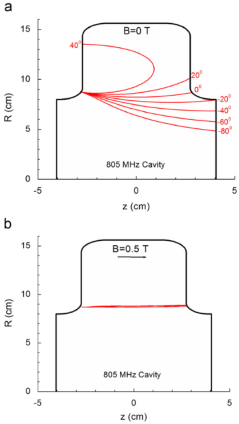
K. Sjobak, HG2013



http://indico.cern.ch/event/231116/session/1/contribution/16

- Space-charge-limited e^{-} emission
- Cu ion current needed to disrupt transmitted power
- Neutral Cu introduces drag

Breakdown in solenoidal B-fields



D. Stratakis *et al.*, NIMA 620 (2010) 147-154.

- Field emission focused by external B-field into a beamlet.
- Emittance reduction tapers off above $\sim$0.5 T.
- Beamlet causes cyclic fatigue over multiple RF periods.
- c.f. D.P. Pritzkau and R.H. Siemann, PRST-AB 5 (2002) 112002.
- Arguably, we have seen this behavior from the All-Seasons cavity and the old pillbox with gridded windows.

Parting Thoughts

- Reminder: Our objectives over the next 2-3 years are clear and they leave little room for academic breakdown studies. This talk is meant to give context for upcoming work and to give guidance during data analysis.
- Too much physics for a 15 minute talk! We could spend all week talking about this. See me offline if you're curious.
- Many of these are compatible.
- We're working to identify ways the MTA can be used in this field.