RF Experiments and Modeling, Can we make "Breakdown and Field Emission-Free" cavities?

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ANL/HEP

NFMCC Collaboation Meeting
1/26/09

Many people have contributed to these results.

Normal Conducting

A. Hassanein	Plasma Phys	Purdue
Z. Insepov	Fracture kenetics	ANL/MCS
A. Moretti	RF	FNAL
A. Bross	RF, instrumentation	FNAL
Y. Torun	RF, instrumentation	IIT
D. Huang	RF, Instrumentation	IIT
R. Rimmer	cavity design, expts.	JLab
D. Li,	cavity design, expts.	LBL
M. Zisman	Expt design	LBL
D.N. Seidman	High E / materials	Northwestern U
S. Veitzer	Plasma modeling	Tech-X
P. Stoltz	Plasma modeling	Tech-X

Superconducting

M. Pellin	ALD, expts	ANL/MSD
G. Elam	ALD, expts.	ANL/ES
J. Moore	ALD, expts.	MassThink LLC
A. Gurevich	SCRF theory	NHMFL
J. Zasadzinski	SC theory and exp	IIT
Th. Proslier	SC theory and exp	IIT
L. Cooley	SCRF	FNAL
G. Wu	SCRF	FNAL

Outline

- We have immediate problems:
  MICE needs working, high gradient cavities with little field emission.
  NFMCC needs increased gradients.

- New experimental results this year.

- OOPICX Pro modeling
  New threshold for breakdown, and many predictions of experimental properties.

- Other modeling

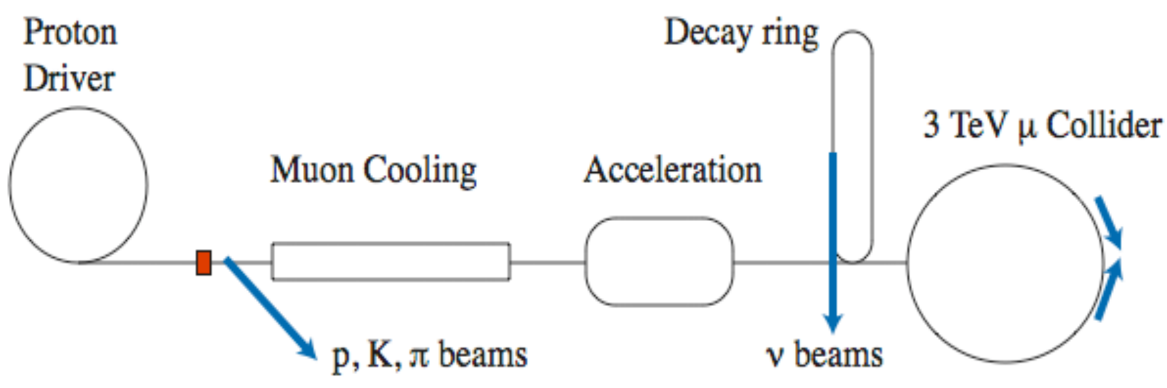
- ALD for SRF (and NCRF)

- "Breakdown-Proof" cavities a program to get there

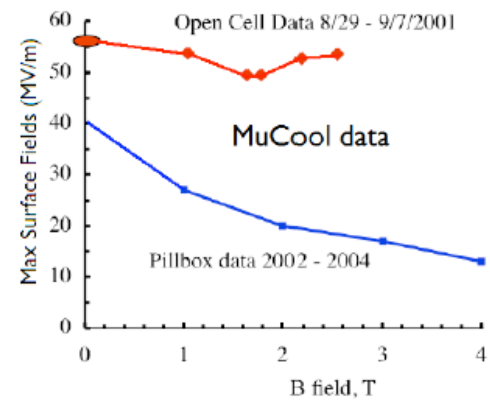
- To Do:

The Neutrino Factory and Muon Collider (NFMCC) Program

The goal:



The problem:



Muon cooling needs high gradients at low frequencies - in B fields.
MICE needs to cure Dark Current / Breakdown Problems.

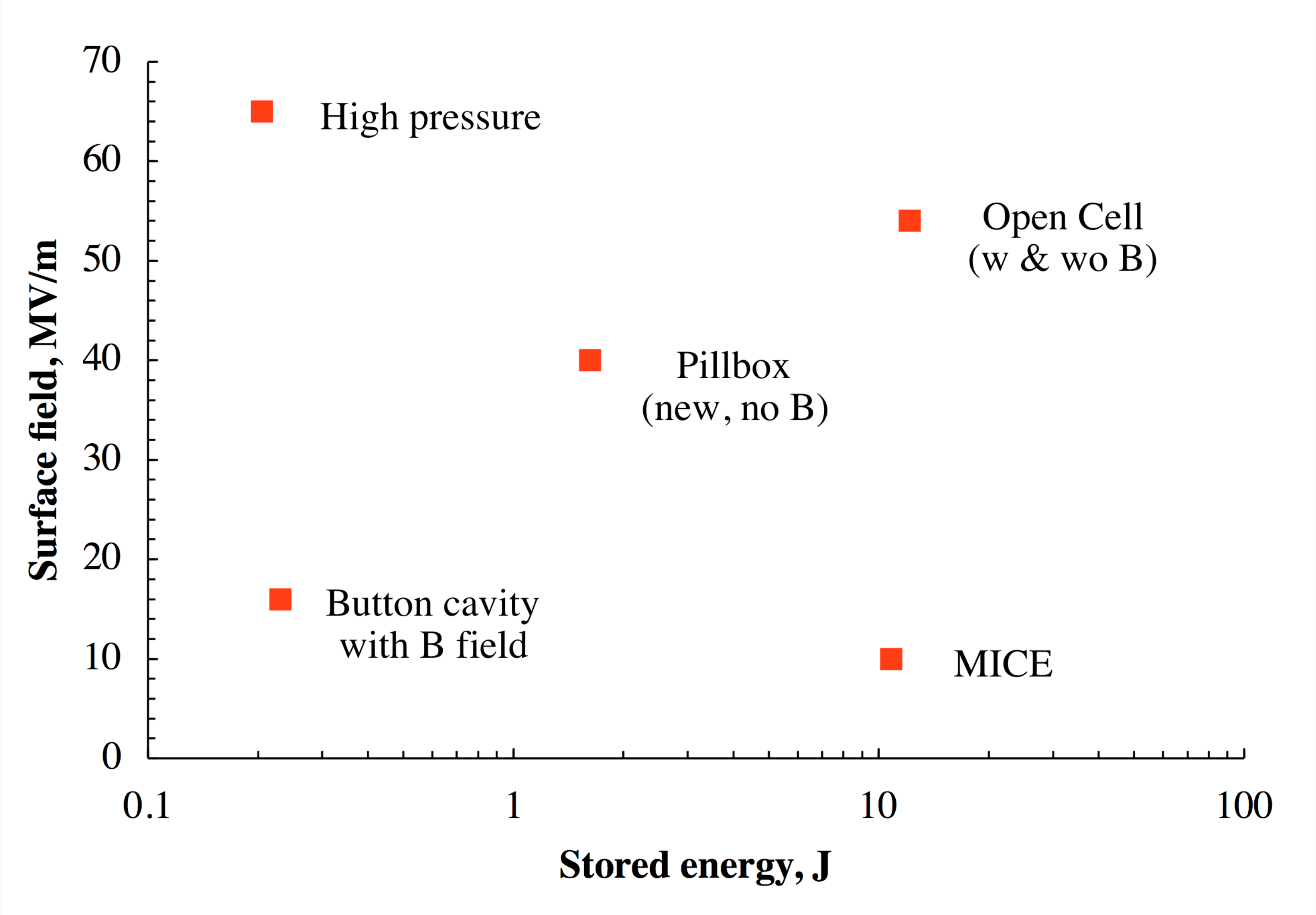
RF Expts started in 2000 – we look mostly at FE dark currents and X rays.

Many papers, new models and methods of analysis.

This work has high priority, many collaborators.

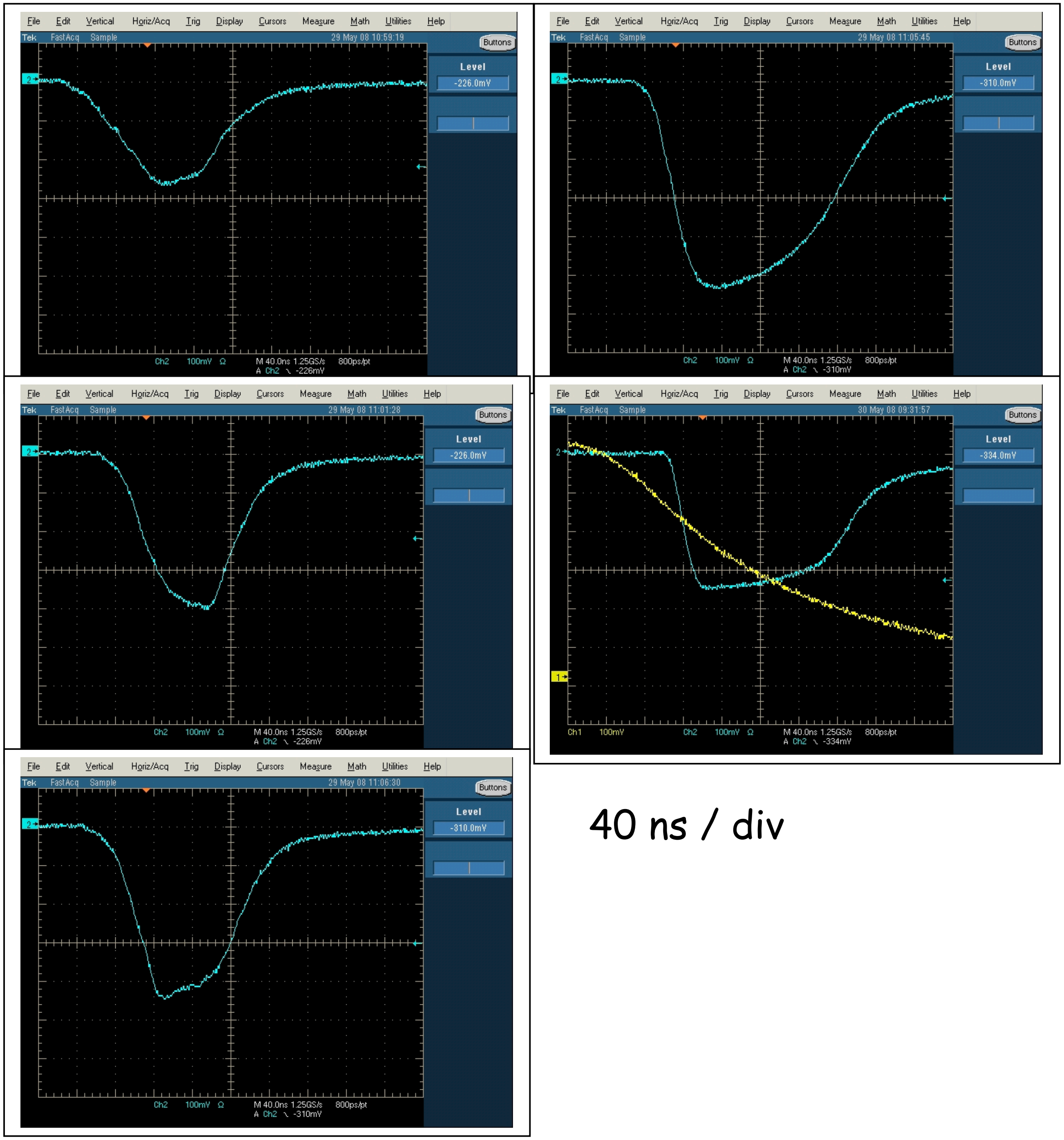
Like CLIC and ILC, we need better NCRF and SRF, our B fields complicate things.
Atomic Layer Deposition (ALD) should control all rf surfaces.

Our experimental program does not cover all the ground.



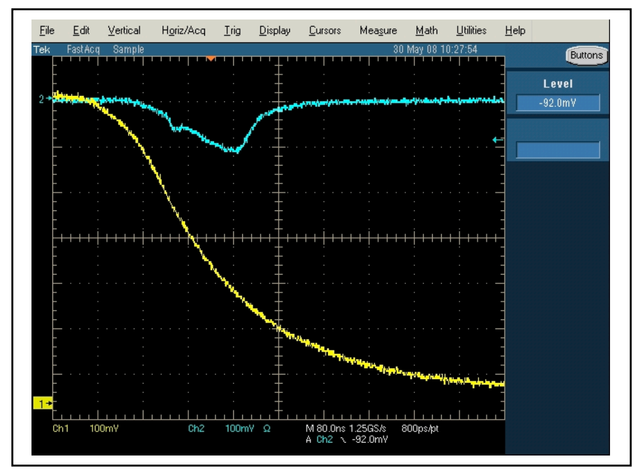
- Modeling is required to fill the gaps and understand the data, and show what we need.

RF breakdown: x ray pulses from the pillbox



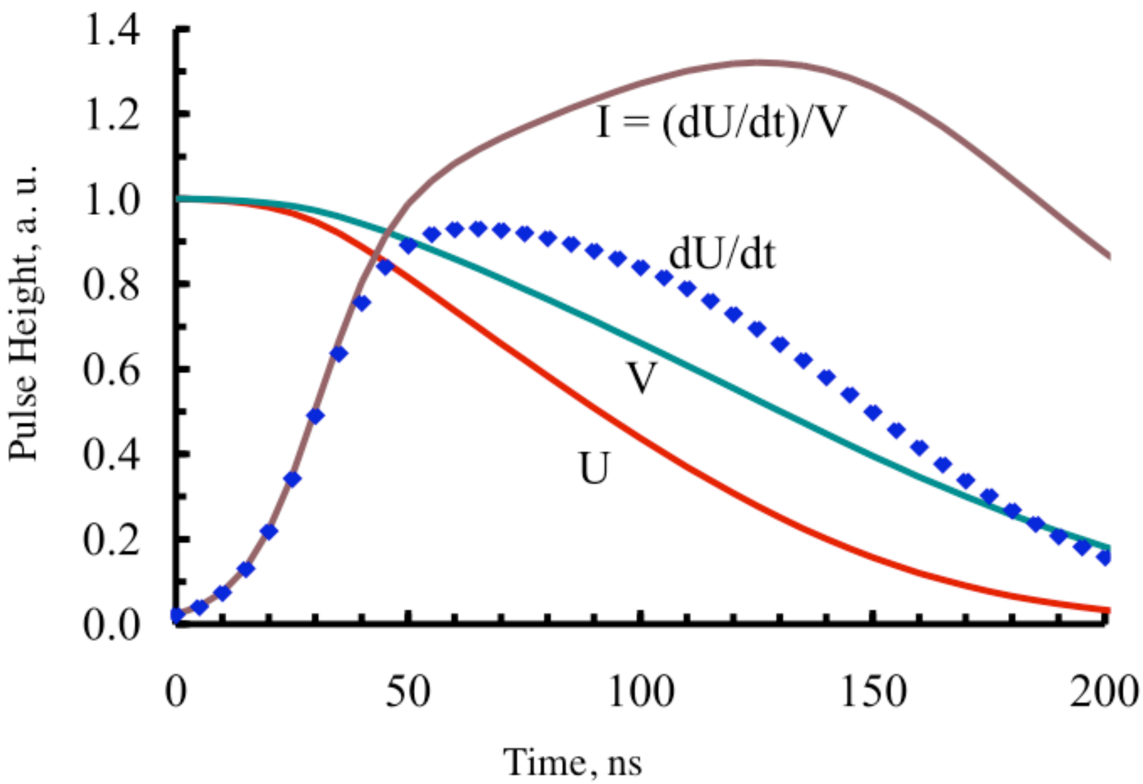
40 ns / div

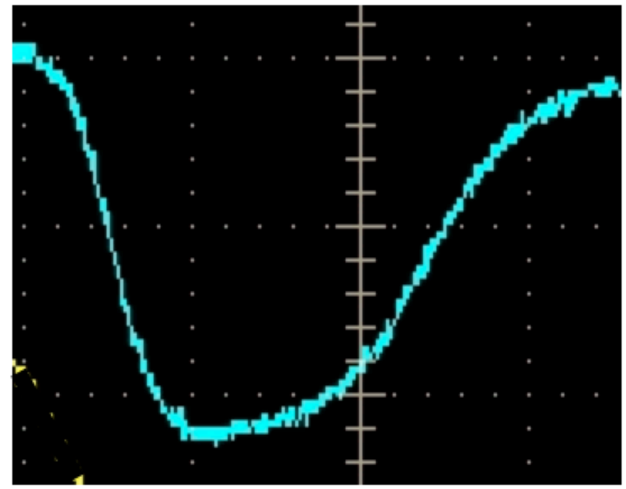
80 ns / div



What is happening?

- X ray data show how energy leaves the cavity. Relativistic electrons can take most.



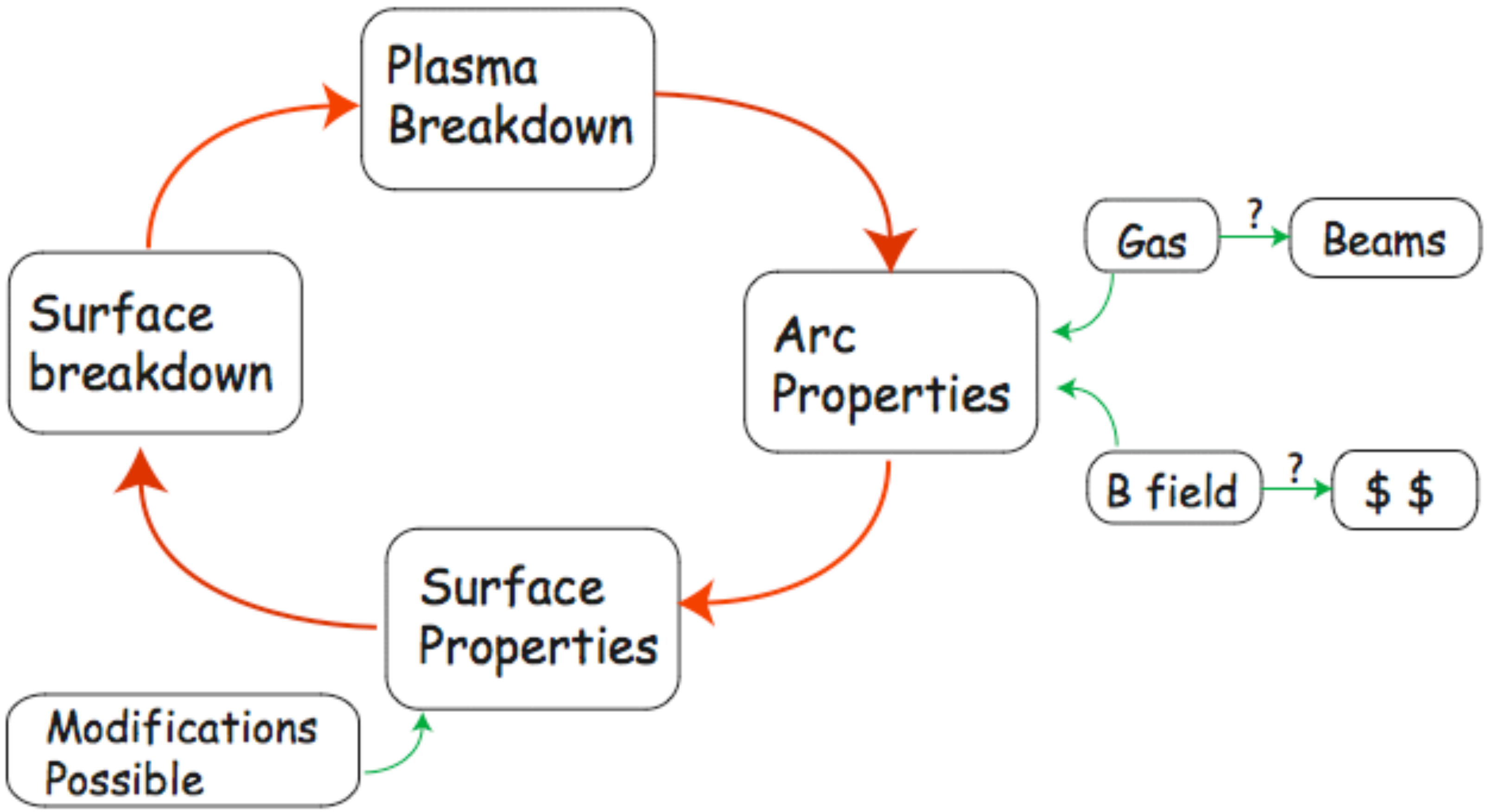


At the MTA our 805 MHz pillbox has:

- Stored Energy ~ 1 J
- Electron energy ~ 4 MeV
- Electron current ~ 4 A, (40,000 (?!) times the field emitted currents)

The big picture

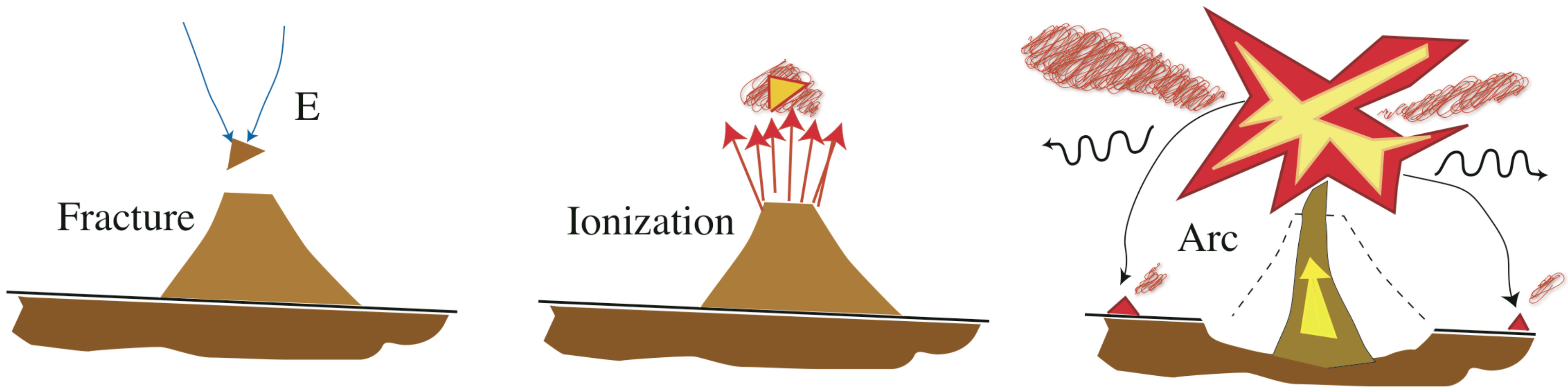
- The maximum field is a result of complex interactions., some uncontrollable.



- Intervening in these processes are difficult.

- Field emission – same problem, different effects.

What starts the arc, and how does it develop?

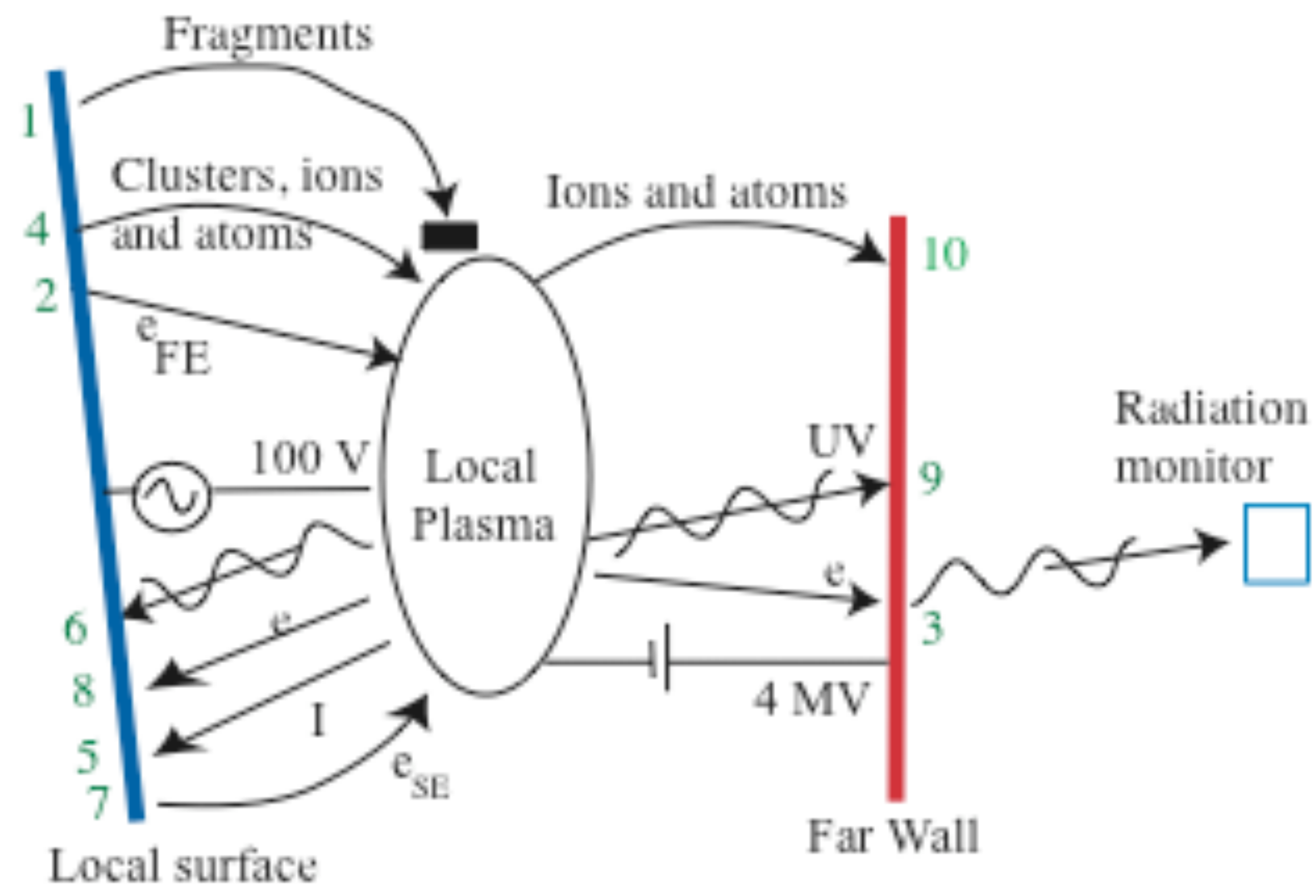


- Average fields in these cavities can be 30 – 50 MV/m = E_{surf}
- X rays show small asperities have much larger fields, E_{local} ~ 7 GV/m.
- We assume an enhancement factor $\beta = E_{local} / E_{surf}$
- At 7 GV/m tensile stress is comparable to copper's tensile strength.

We can describe the breakdown arc more precisely.

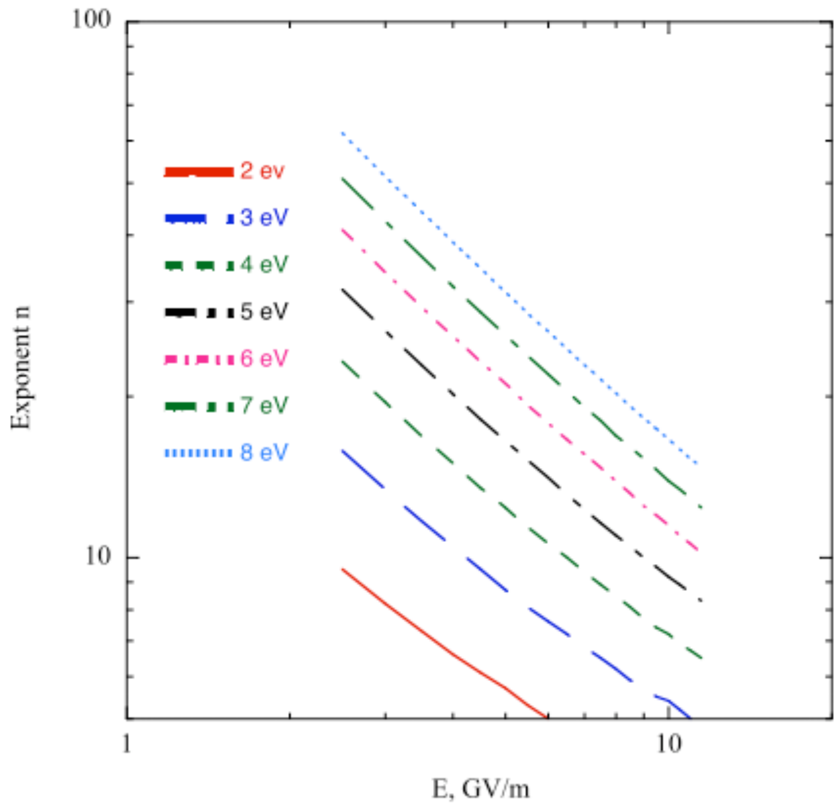
They seem to look like this:

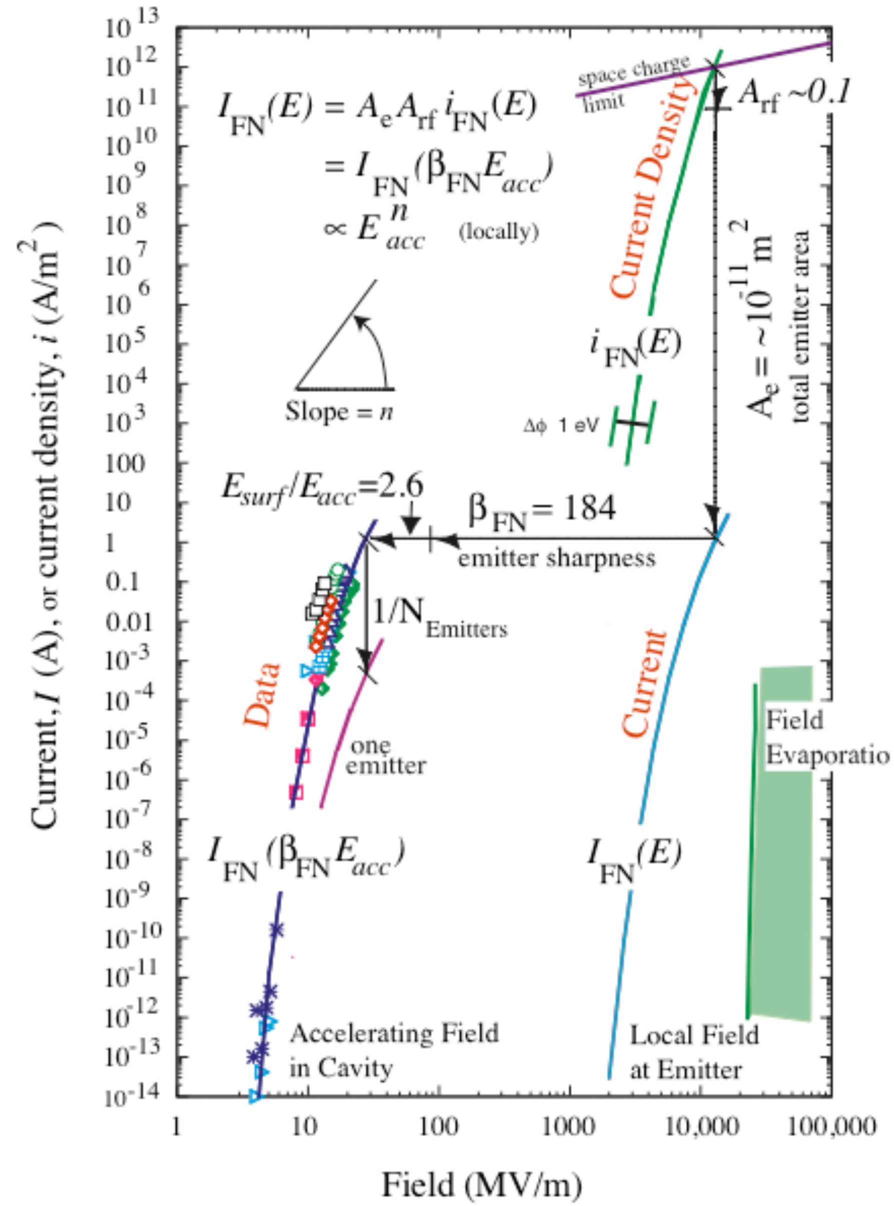
With lots going on inside.



We measured the initial conditions with x rays.

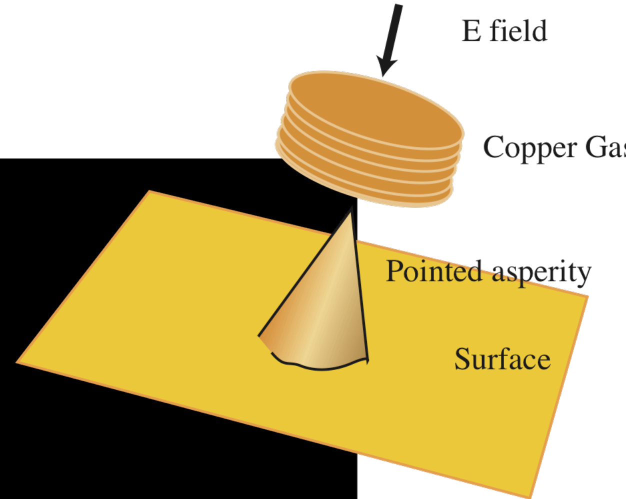
- FN can be approximated by $I = E^n$.
- The local surface field = f(n, ϕ).~7 GV/m

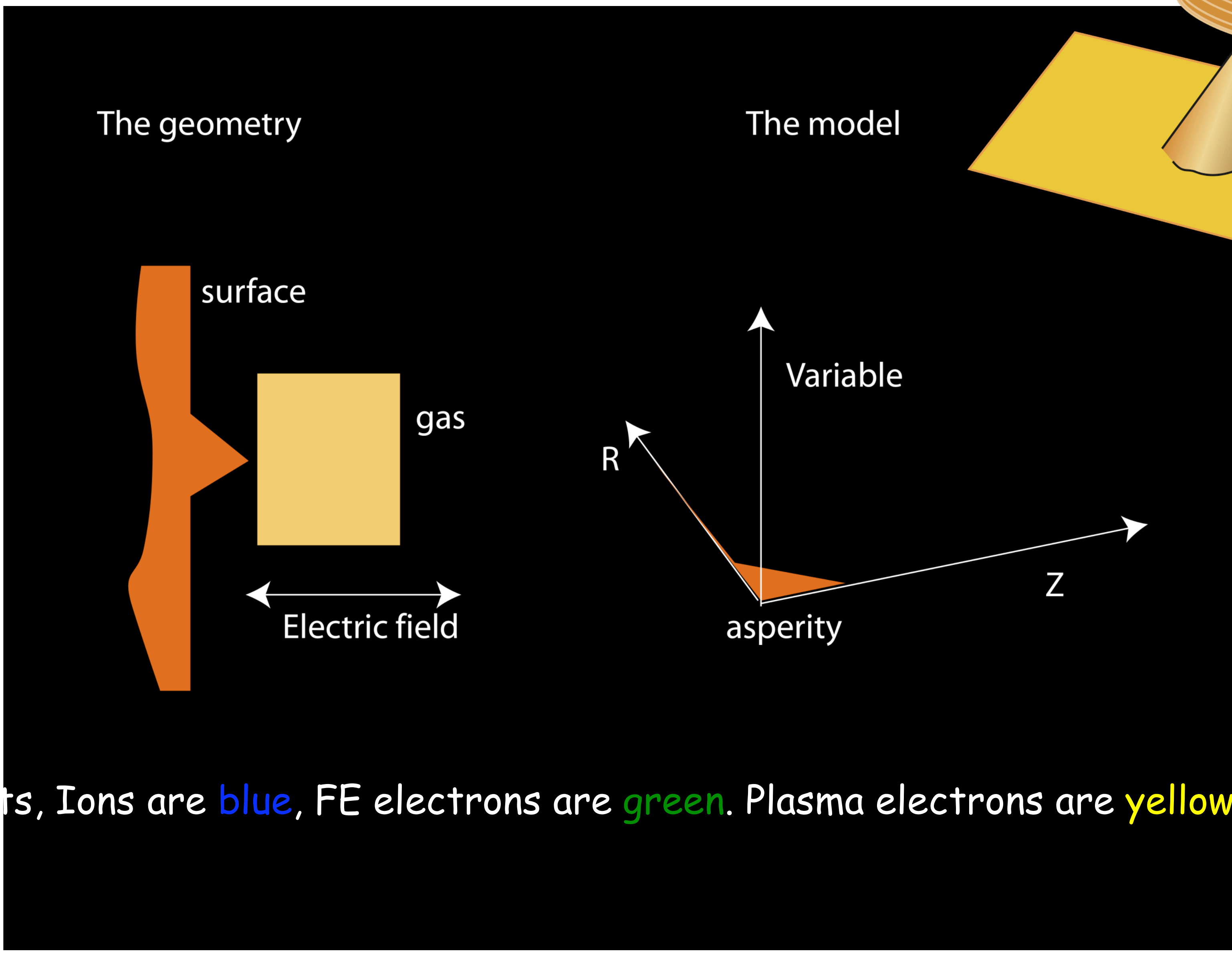




OOPIC Pro shows how the arc develops

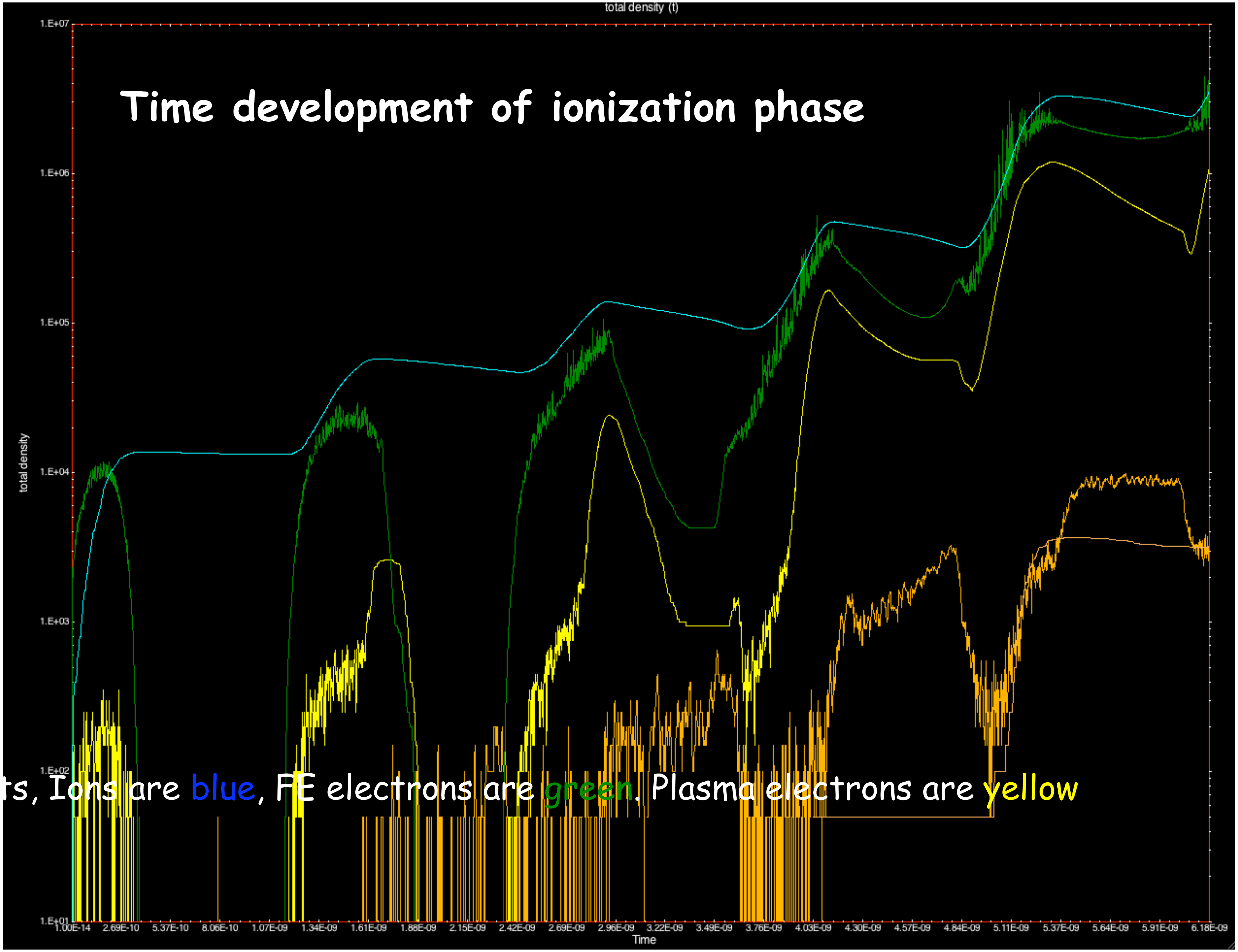
- We use a simple geometry





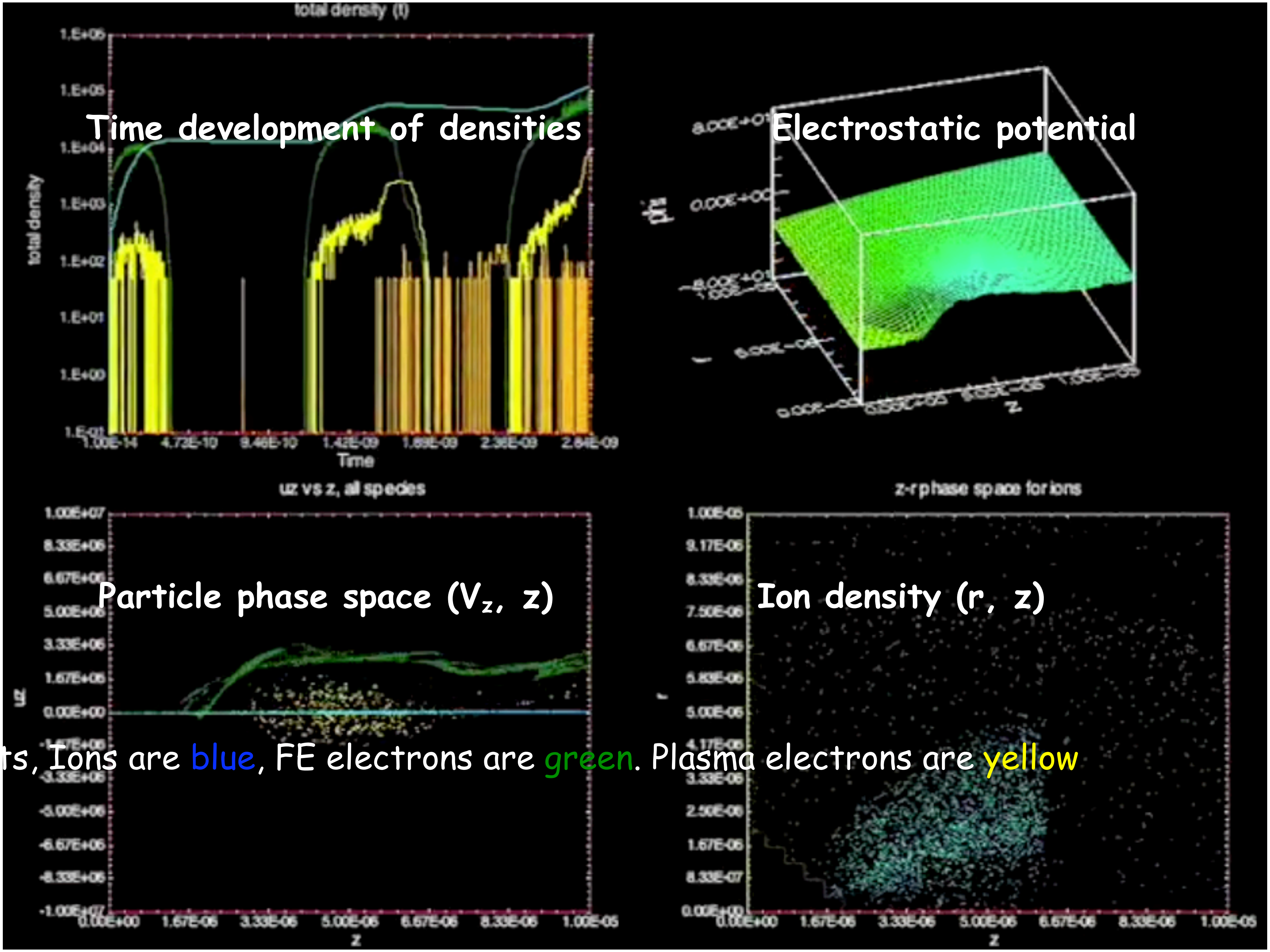
In plots, Ions are blue, FE electrons are green. Plasma electrons are yellow

OOPIC Pro generates an enormous volume of data.



In plots, Ions are blue, FE electrons are green, Plasma electrons are yellow

A movie shows how what happens in the first few ns.

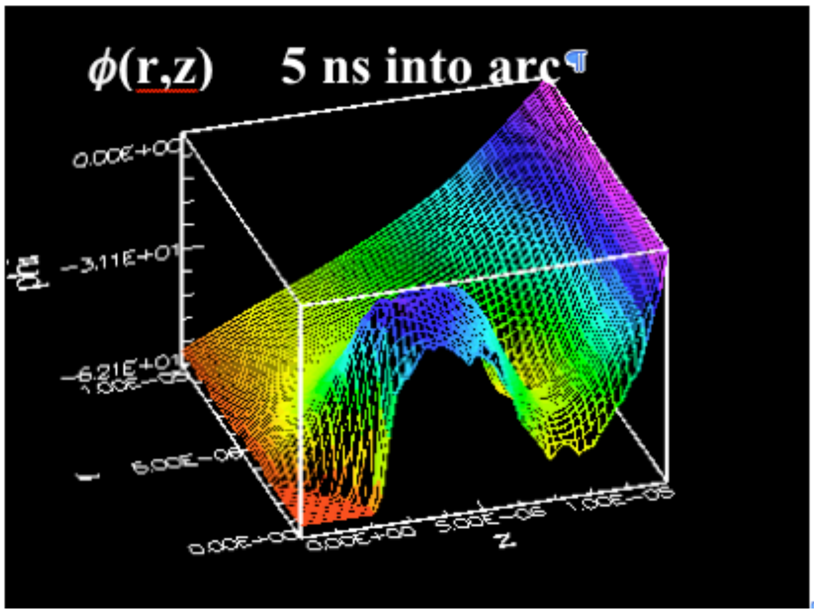


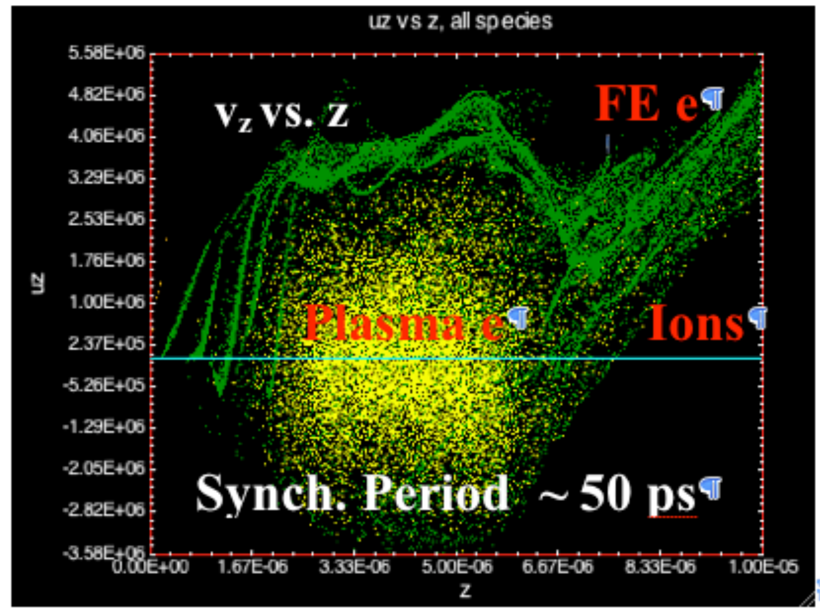
In plots, Ions are blue, FE electrons are green. Plasma electrons are yellow

FE electrons are not the only source of ionization.

- These arcs are high beta, inhomogeneous, non – equilibrium, cold, weakly ionized, non-neutral, collisional, inertially confined plasmas with two weakly interacting electron populations

- Electrons trapped in the potential well of the ions circulate around at energies that are sufficient to create more ionization – and the sheath potential increases the gradient to draw electrons out of the emitter at phases other than E_{max}.

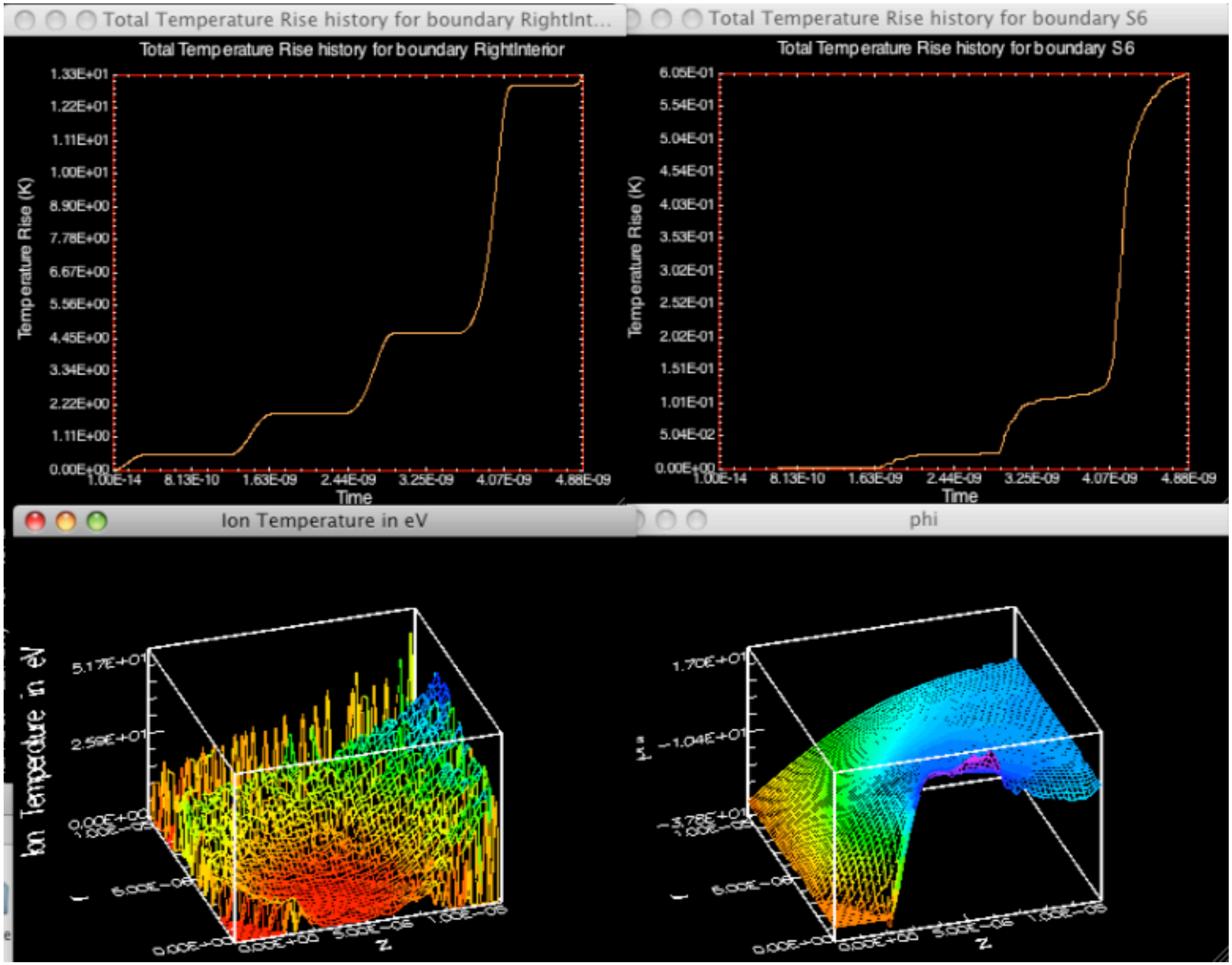




- The net result is that field emitted currents are: 1) enhanced and, 2) extend over a larger range of rf phase.

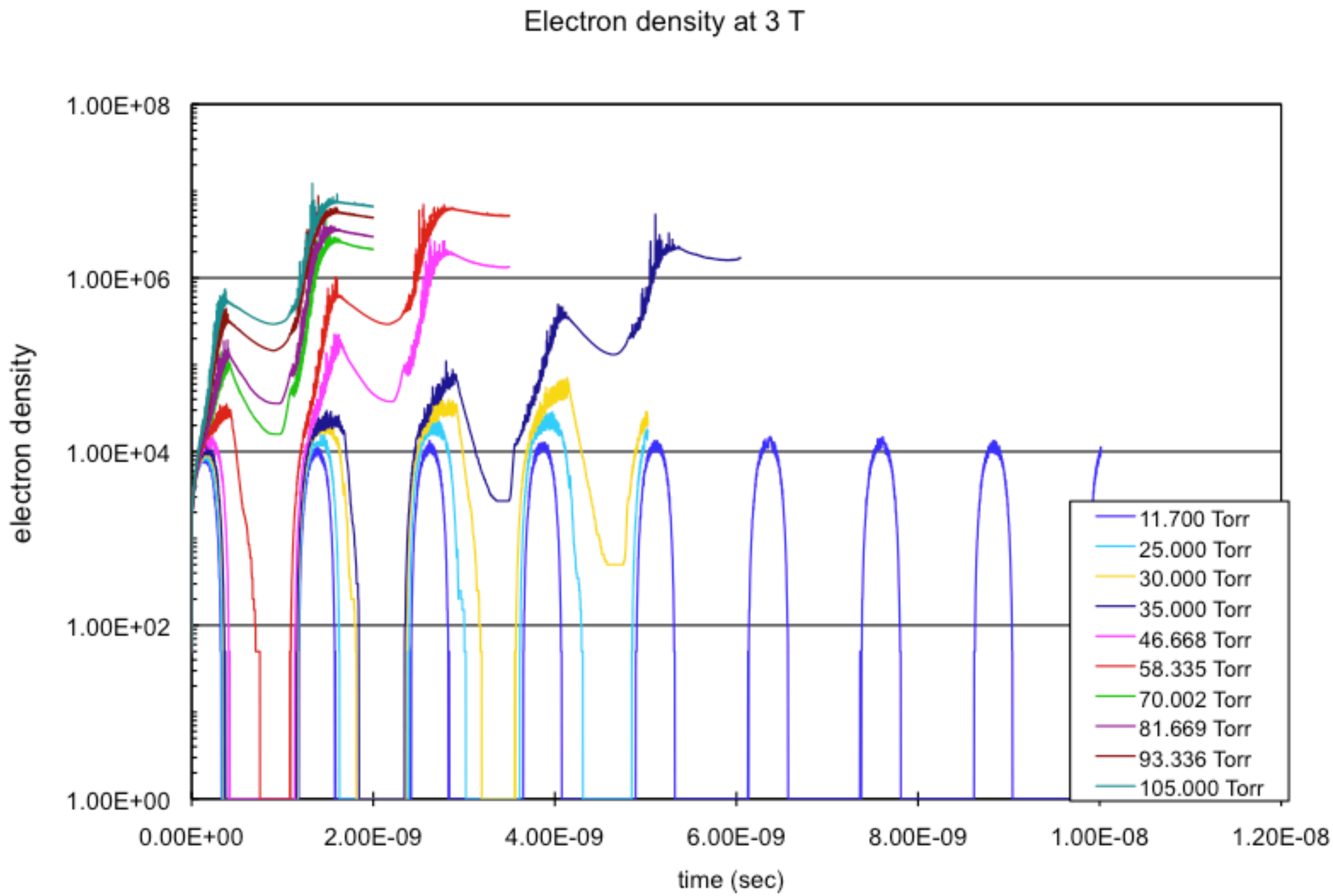
The code also gives plasma properties and thermal loadings.

- at 4.9 ns



We can also measure a threshold for breakdown.

- Dazhang's data gives a breakdown threshold pressure of ~ 30 Torr Cu gas. (@7GV/m)



This gives the number of neutral atoms required for BD.

- Depth of gas ~ 3 μm.

- Radius of gas cloud ~ 3 mm.

- pressure ~ 30 Torr

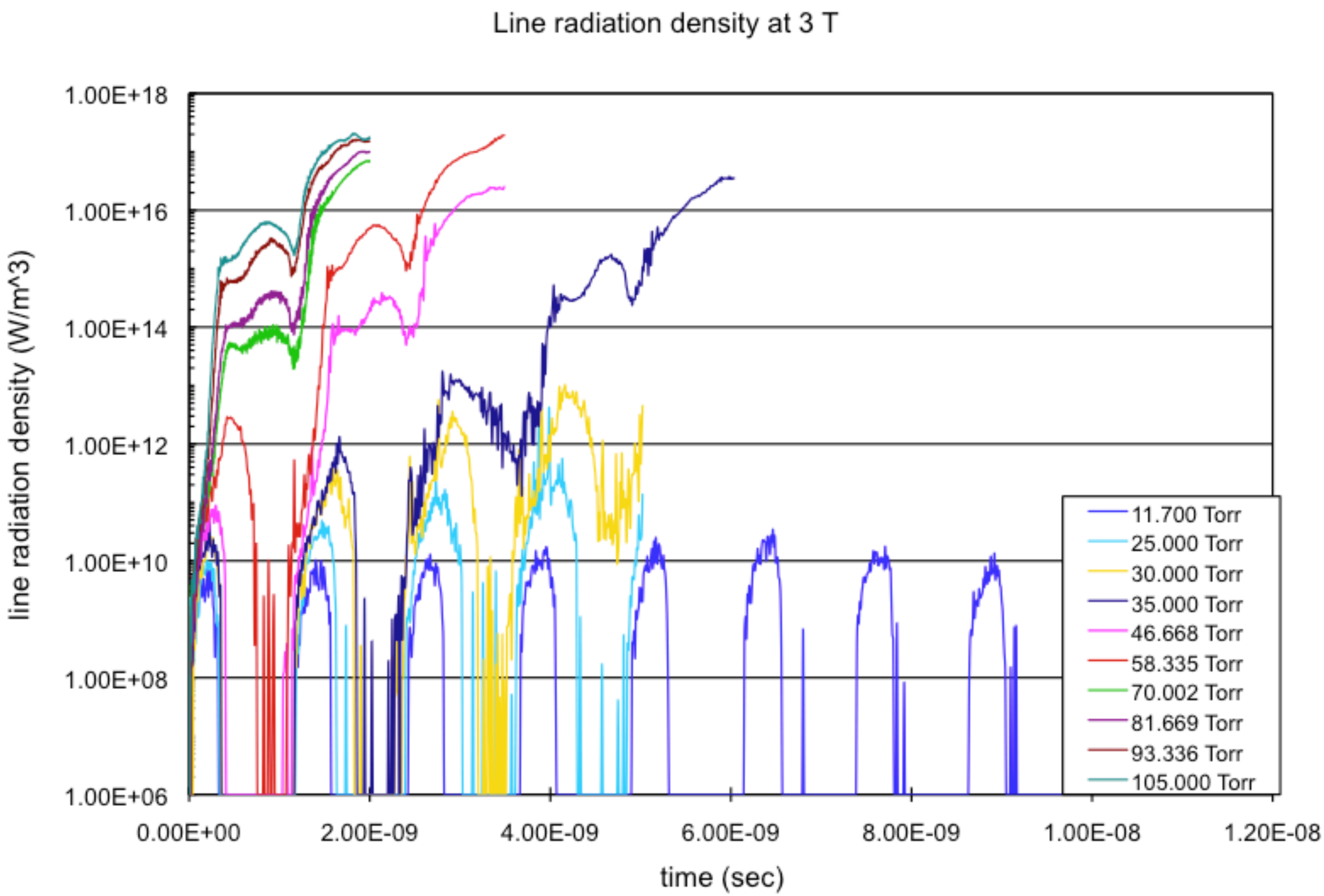
  ➜ minimum amount of neutral gas ~ 10^6 atoms,

  ~ a reasonable fraction of an atomic monolayer.

- (Copper holds on to one monolayer of oxide at high fields.)

OOPIC Pro also generates optical radiation produced in BD.

- Dazhang's data

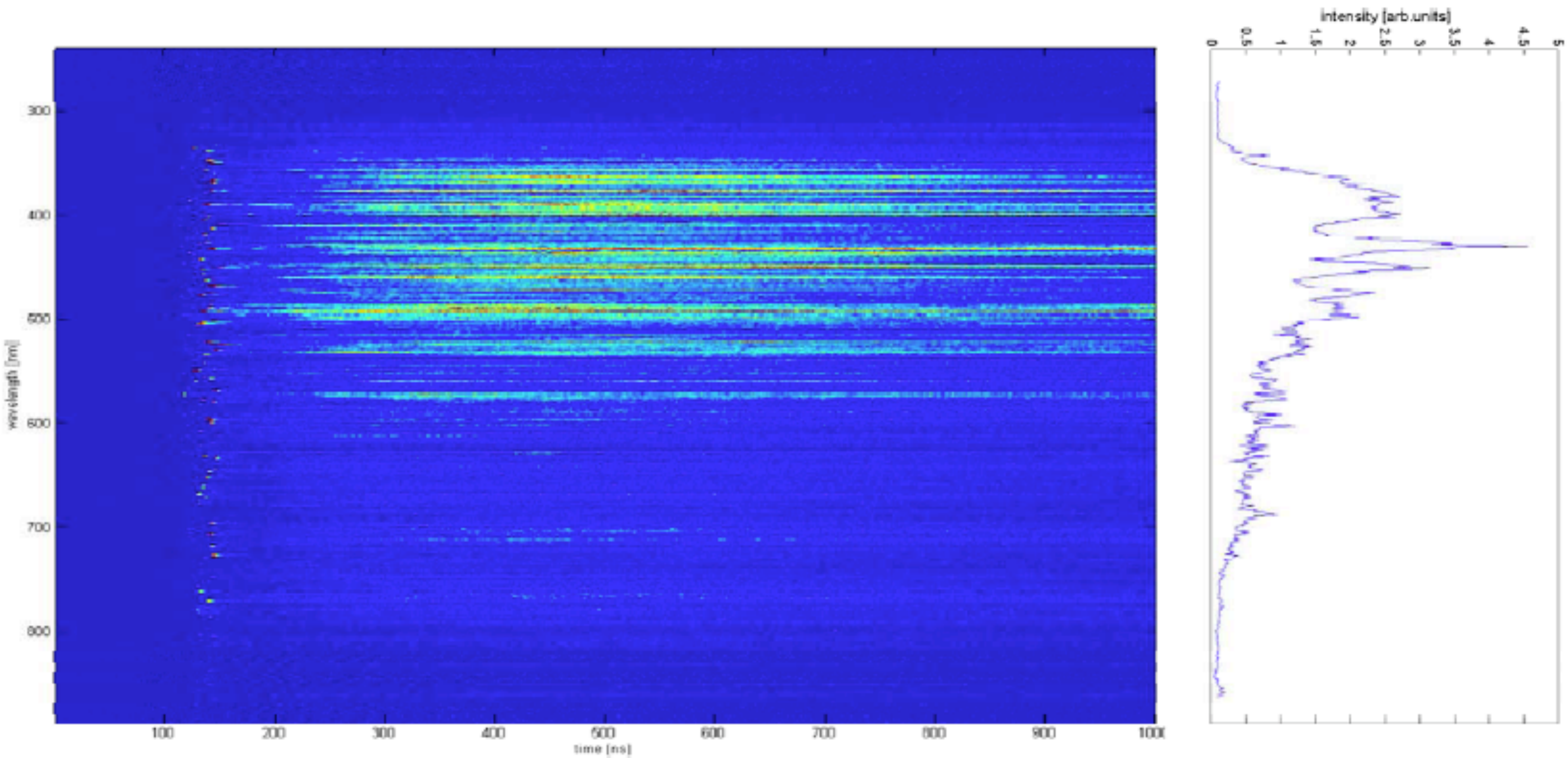


The optical radiation can be checked with experiment

- Moses Chung is developing optical instrumentation at Fermilab

- Jan Kovermann has been working with optical signals at CERN.

Diagnostics applied to RF and DC



Example: DC spectrum measured for Cu electrodes with existing setup

The code describes only the first 6 ns at present. Mods required.

- This limits the predictions that can be made and tested.

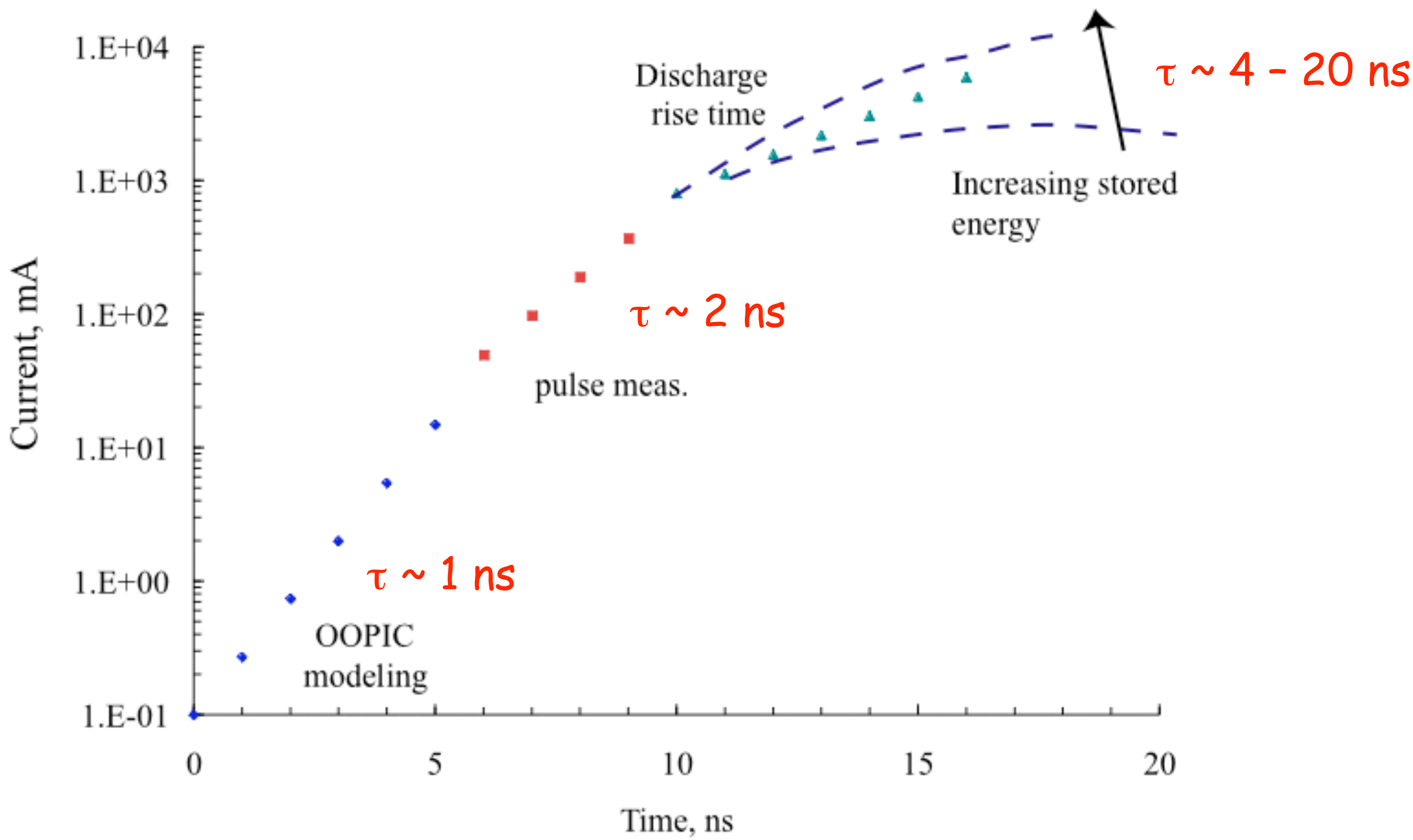
- The plasma is still weak after 6 ns. It gets ~ 1000 times stronger

- All the usual instrumentation looks at the X-rays or photons around P_{max}.

- It is possible to extrapolate some parameters, however.

We can compare measured and predicted rise times.

We can look at rise times of the shorting current pulse.
- The initial few ns have been modeled in detail in OOPIC Pro.
- The end of the breakdown event was measured with x rays.



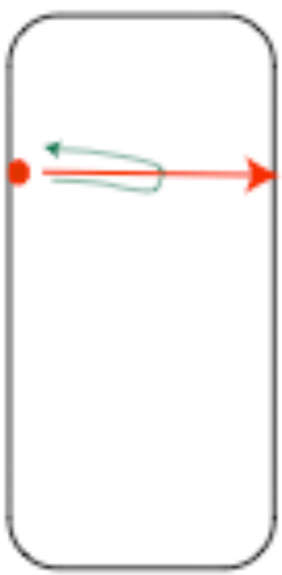
The big question: Why did the open cell cavity work so well?

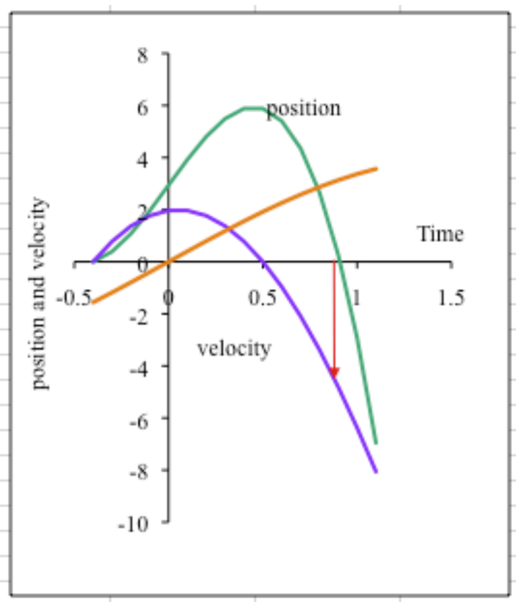
- The arc seems to confined by the B field, making hotter spots.

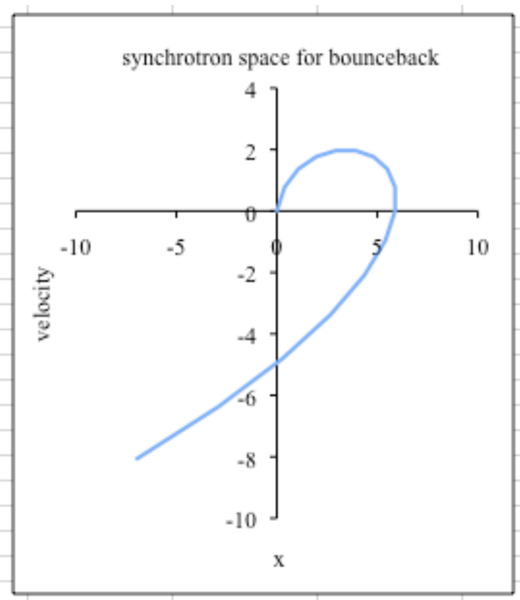
- The plasma particles however, are evidently not confined very well.
  Plasma pressure seems much greater than field energy.

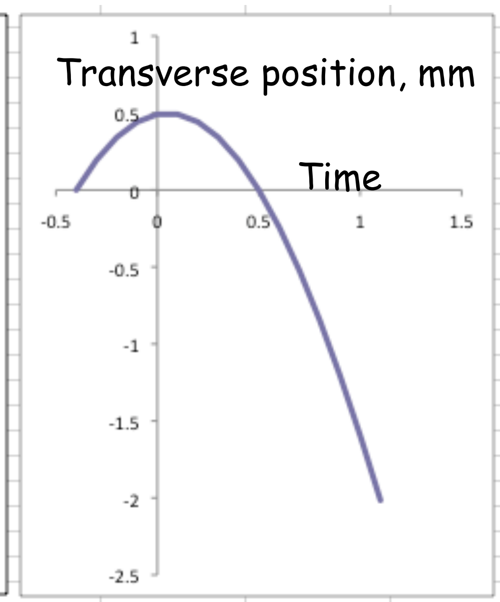
- The trajectory of the shorting current is partially driven by ExB forces

- High current beams emitted near E=0 will return to the arc region – asymmetrically deflected by ExB drifts





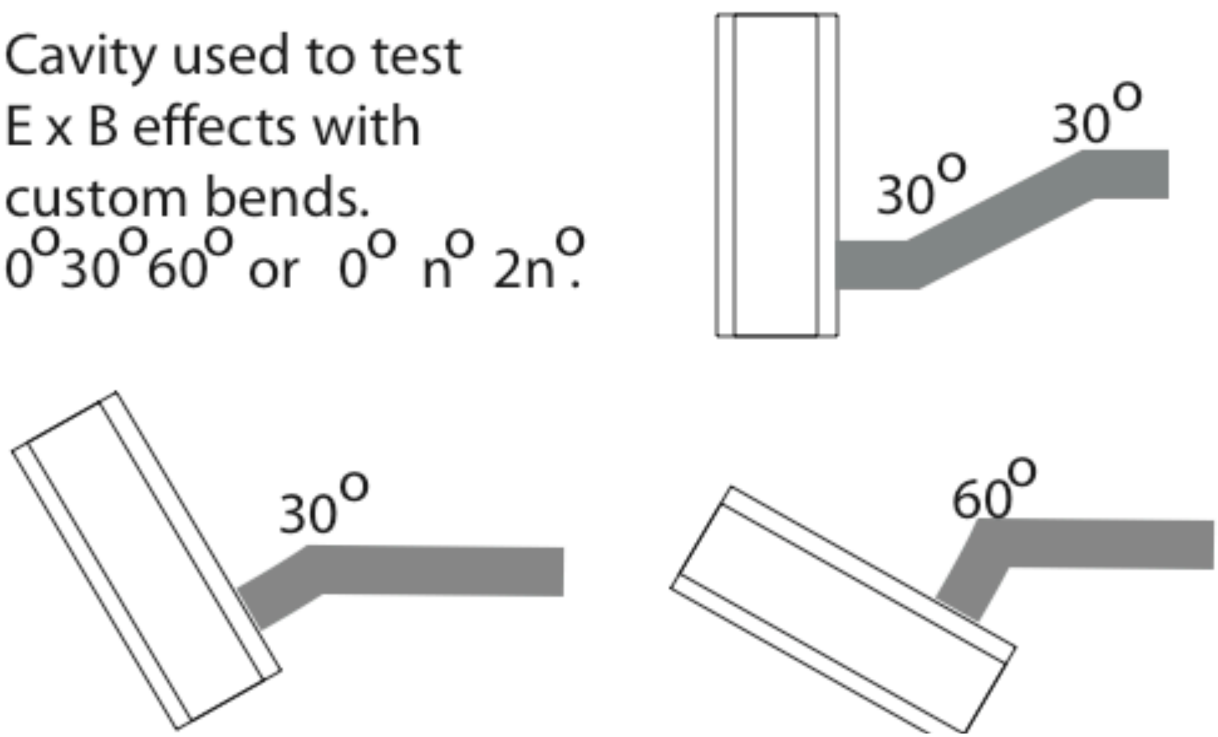




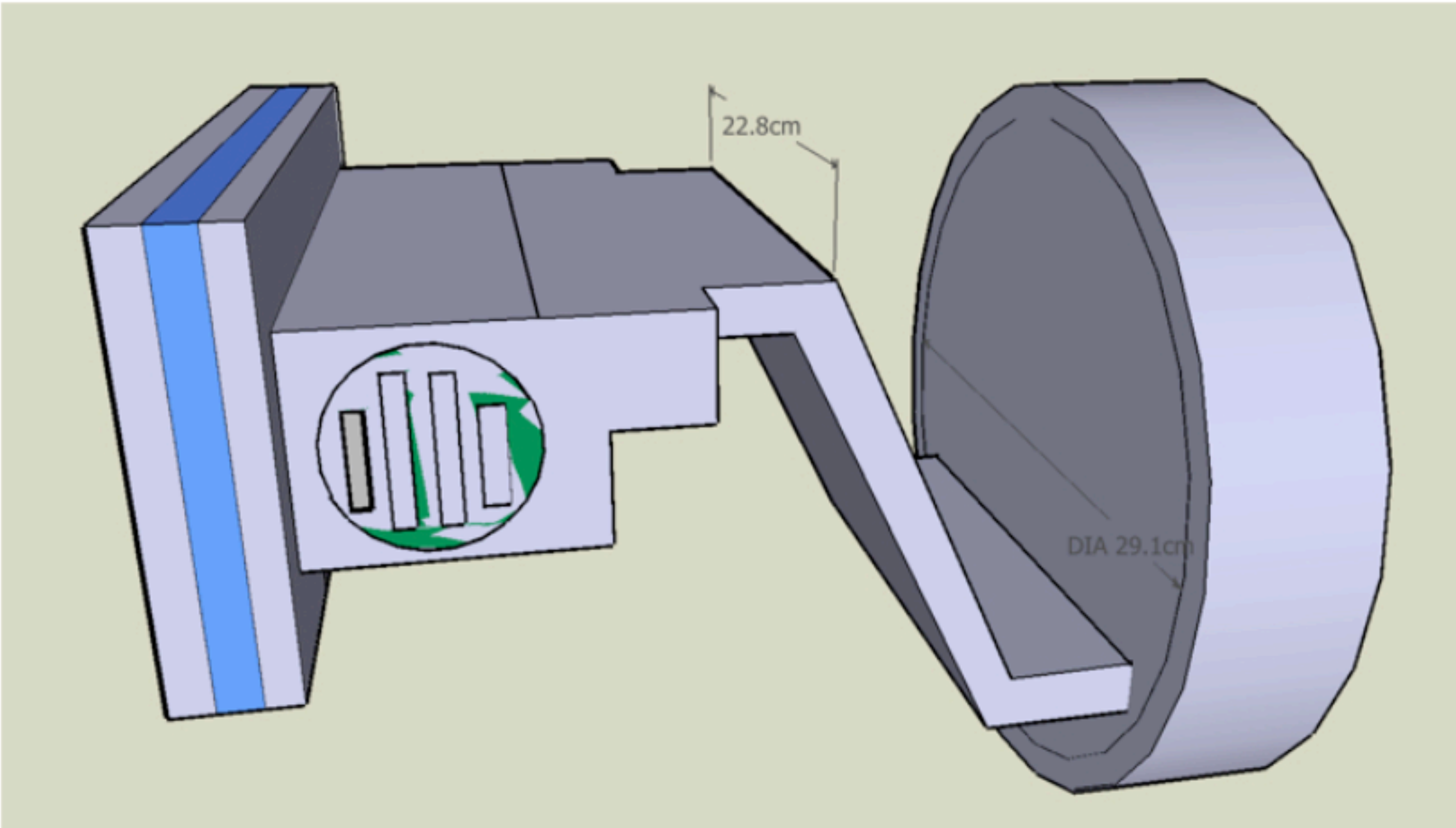
Magnetic field orientation has not been systematically studied.

- Magnetic fields will:
  Perturb electron orbits to change the trigger mechanism,
  Change the temperature and sheath potential of the plasma,
  Make the discharge sensitive to the orientation of the solid surface,
  Cause the plasma to drift perpendicular to the fields.

- It would be desirable to have a simple geometry, i.e. a pillbox..



We can do this with a series of new cavities.



- The cavities should be similar, and cheap.

We also have some useful results from Molecular Dynamics (MD)

- Z. Insepov has extended his modeling of tensile failure of asperities.

- With magnetic fields, but no currents, the fragments come off spinning.

- He is doing other things:

Ion sputtering

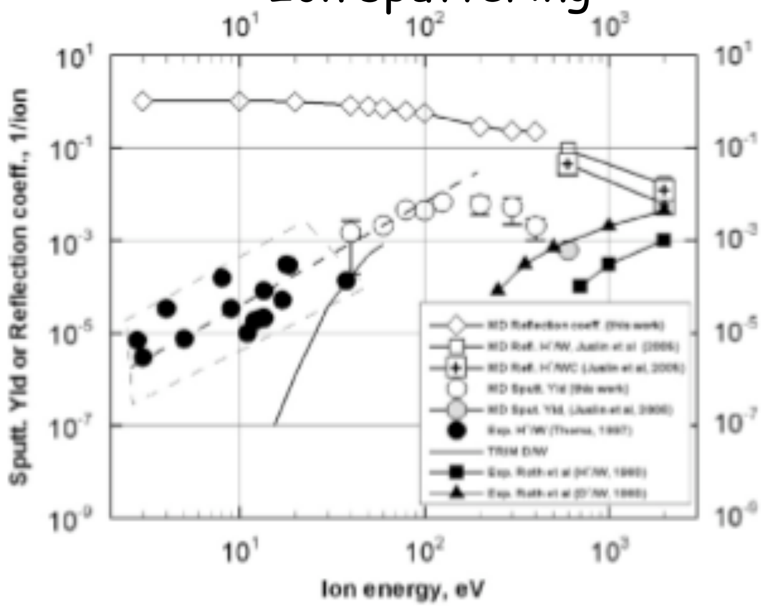
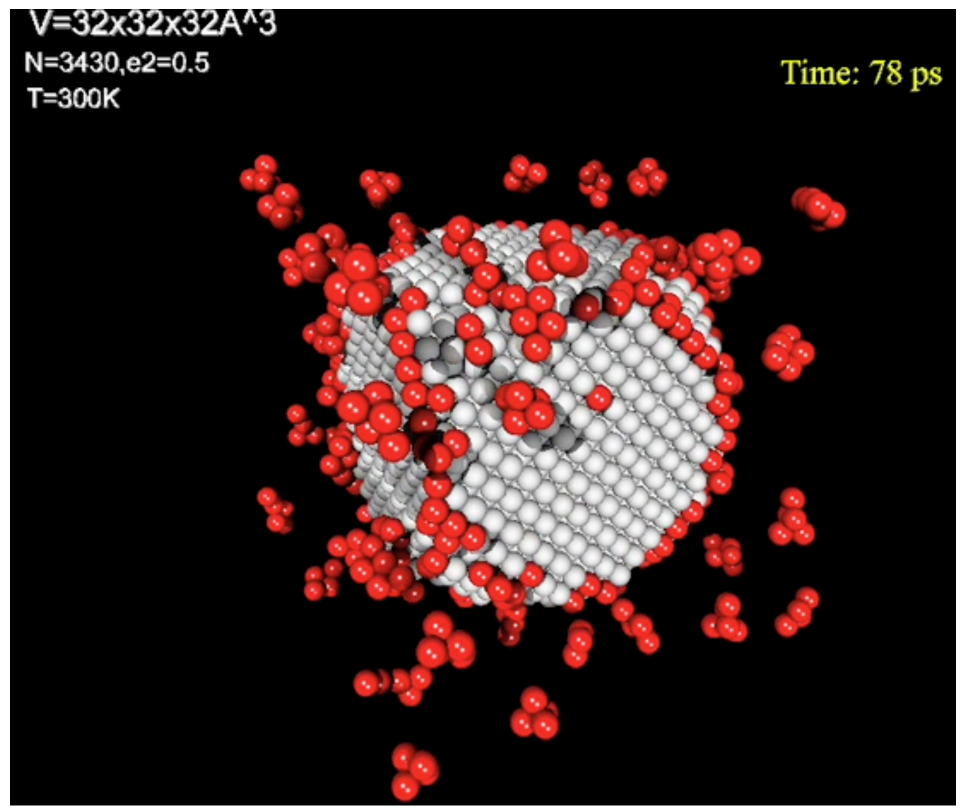


Fig. 3. Comparison of the sputtering yields and reflection coefficient of H^+ ions on a W (1 0 0) surface calculated in present work (open circles and open diamonds) with experimental data of Thoma et al. [17]—solid circles and Roth et al. [69]—solid triangles (H^+/W), solid squares (D^+/W), TRIM and with the reflection coefficients calculated by MD in [14] (open circles, circles with crosses), and a single calculated sputtering yield data point (gray diamond) at 600 eV [14].

Coulomb Explosions



We just submitted a large proposal to look at ALD for SRF.

People:

- Argonne, M. Pellin, J. Norem
- IIT, J. Zasadzinski
- JLab, R. Rimmer
- Fermilab, L. Cooley
- Northwestern, D. N. Seidman
- U of Chicago, S. Sibener
- NHMFL, A. Gurevich

Goals:

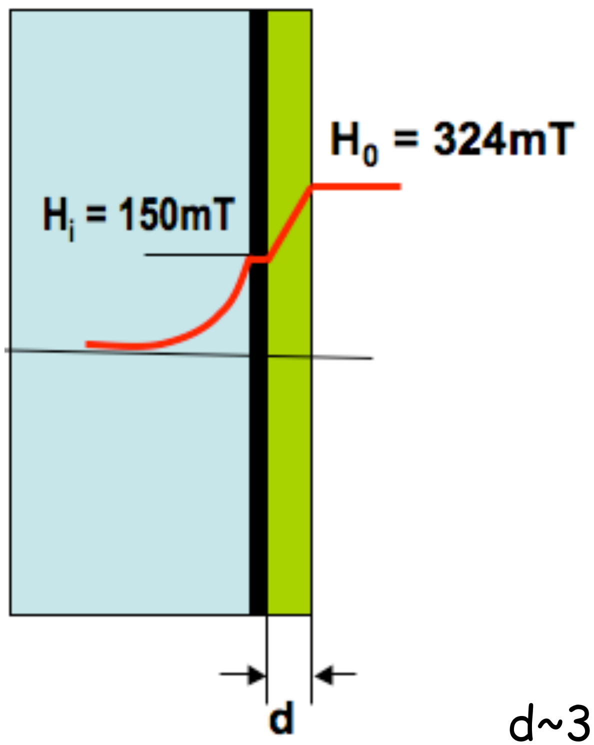
- What are the fundamental SRF performance limits?
- What are the optimum coating regimes for ALD materials?
- How far can ALD multilayers increase the maximum rf gradient?
- What is the optimum multilayer geometry?
- How can ALD be used to mitigate prosaic limitations (FE, multipactor)?
- Can ALD significantly decrease the cost of SRF linacs?

We, (Alex Gurevich) a cure for quench fields.

The primary niobium layer is covered with an insulator and superconductor.

The top layer has high T_c, screens quench fields from the bulk niobium.

Multiple layers permit almost arbitrarily large accelerating fields.



d~30-50nm

would give E_{acc} ~ 100 MV/m

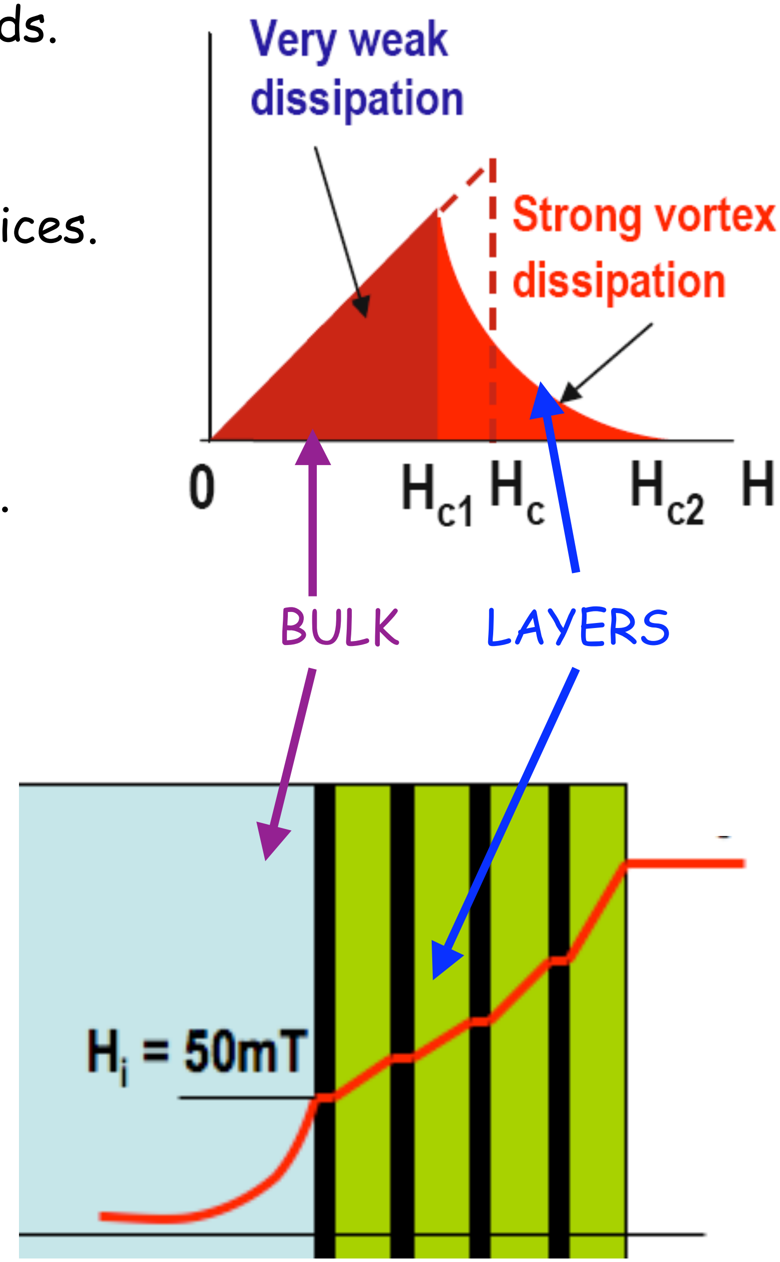
(A. Gurevich, A. P. L. 88. 012511 (2006))

Why layered superconductors can have higher quench fields.

- Vortices in superconductors move in AC fields.
  ⇒ rf losses.

- Nb can reach the highest field without vortices.
  ⇒ Use as bulk material.

- Vortices <u>aren't stable</u> in <u>thin layers.</u>
  ⇒ Use layers to "screen" fields from bulk.



- This is a hard geometry to construct.
  Nb is "bulk" material, i.e. 200 nm.
  Layers should be ~(10 – 30) nm
  Nanometer precision required for layers
  No shorts or voids in insulators.
  ALD can do it.

A. Gurevich. Appl. Phy. Let. **88** 012511, (2006)

Atomic Layer Deposition (ALD)

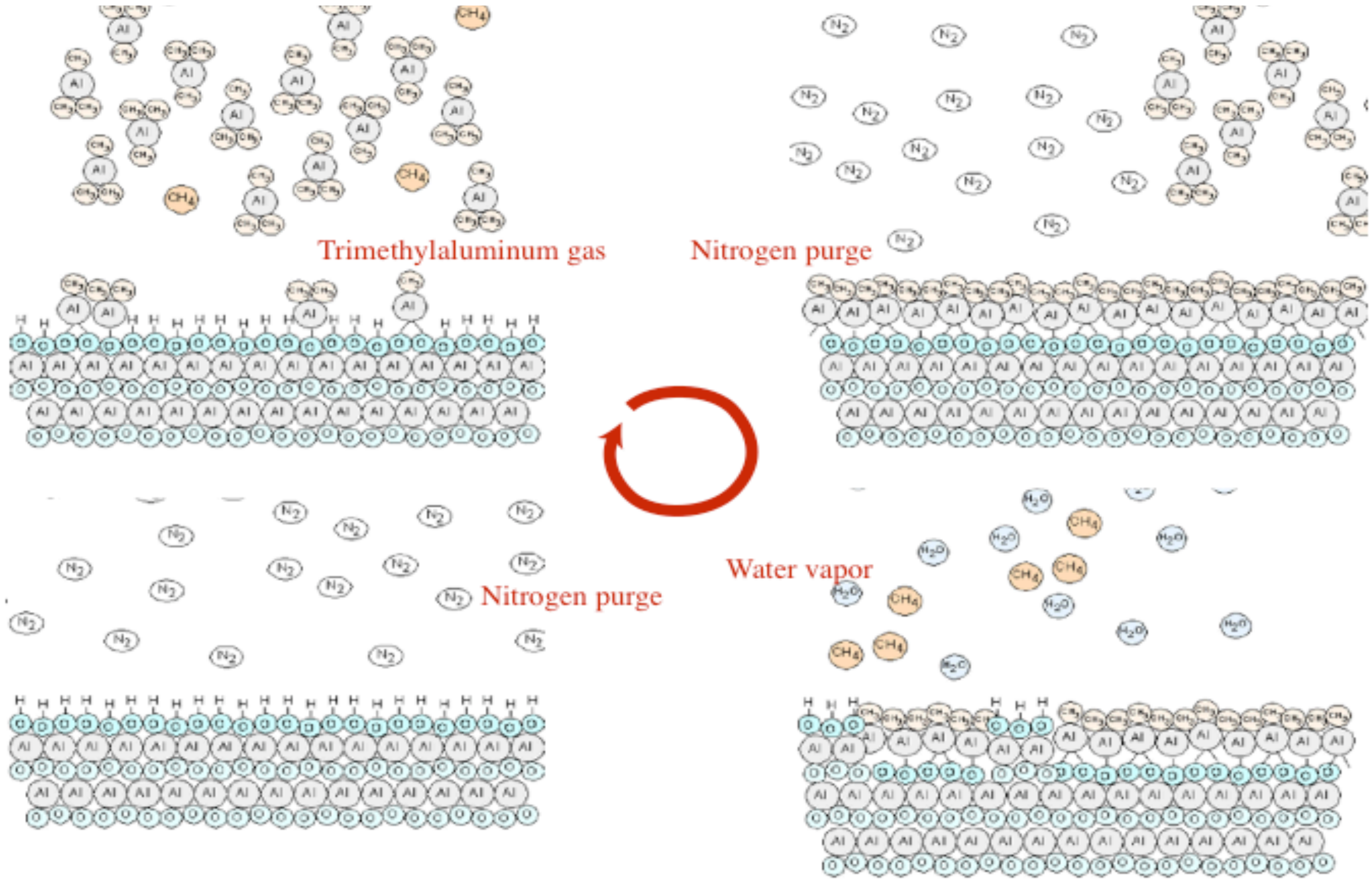
- Atomic Layer by Layer Synthesis: a method similar to MOCVD

- Used Industrially
  - Semiconductor Manufacture for "high K" gate dielectrics
  - "Abrupt" oxide layer interfaces
  - Pinhole free at 1 nm film thicknesses
  - Conformal, flat films with precise thickness control

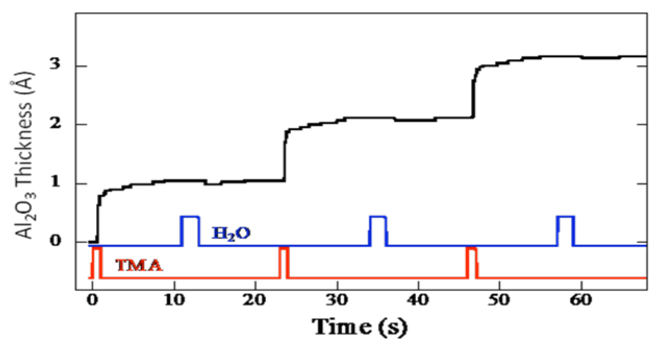
- Electroluminescent displays
  - No line of sight requirement
  - Large area parallel deposition
  - Large Surface area, high electric field applications

- Parallel film growth technique, (insides of large tubes).

Atomic Layer Deposition may be useful.



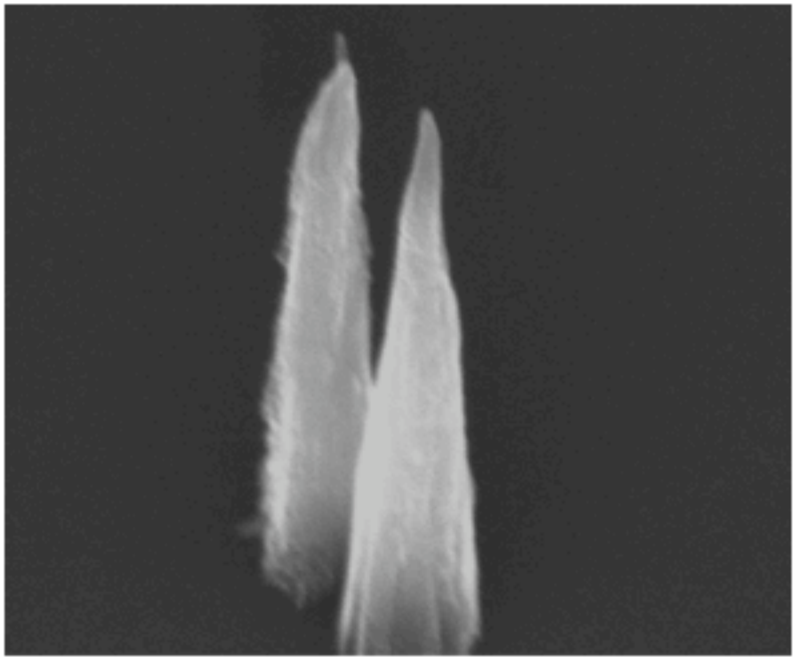
Quartz
Crystal
Microbalance



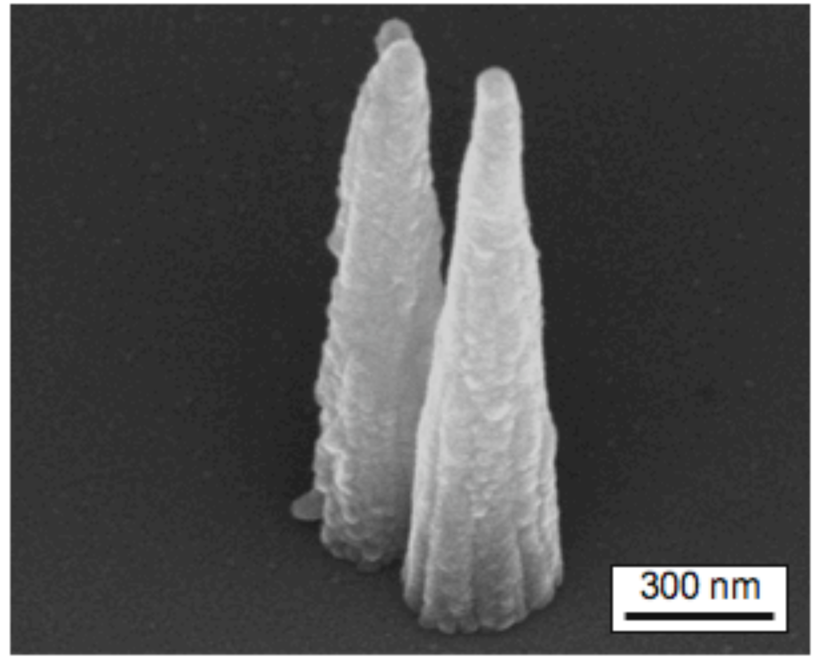
- Growth Occurs in Discrete Steps

ZnO ALD on Carbon Nanofibers

Before Coating



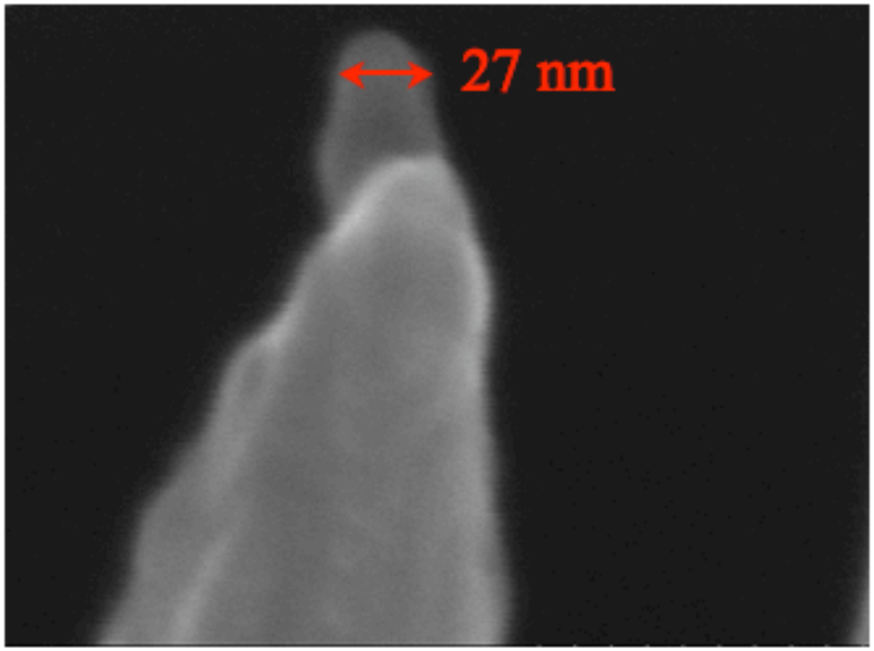
After Coating 15 nm ALD ZnO



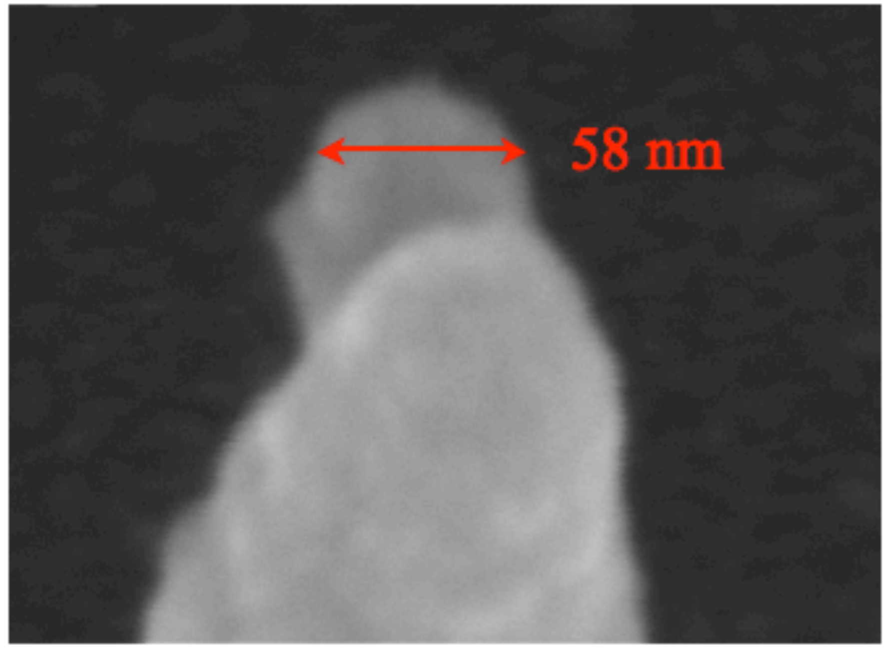
- ALD coats front, back, sides
- Conformal coating on all exposed surfaces

ZnO ALD on Carbon Nanofibers

- Before Coating

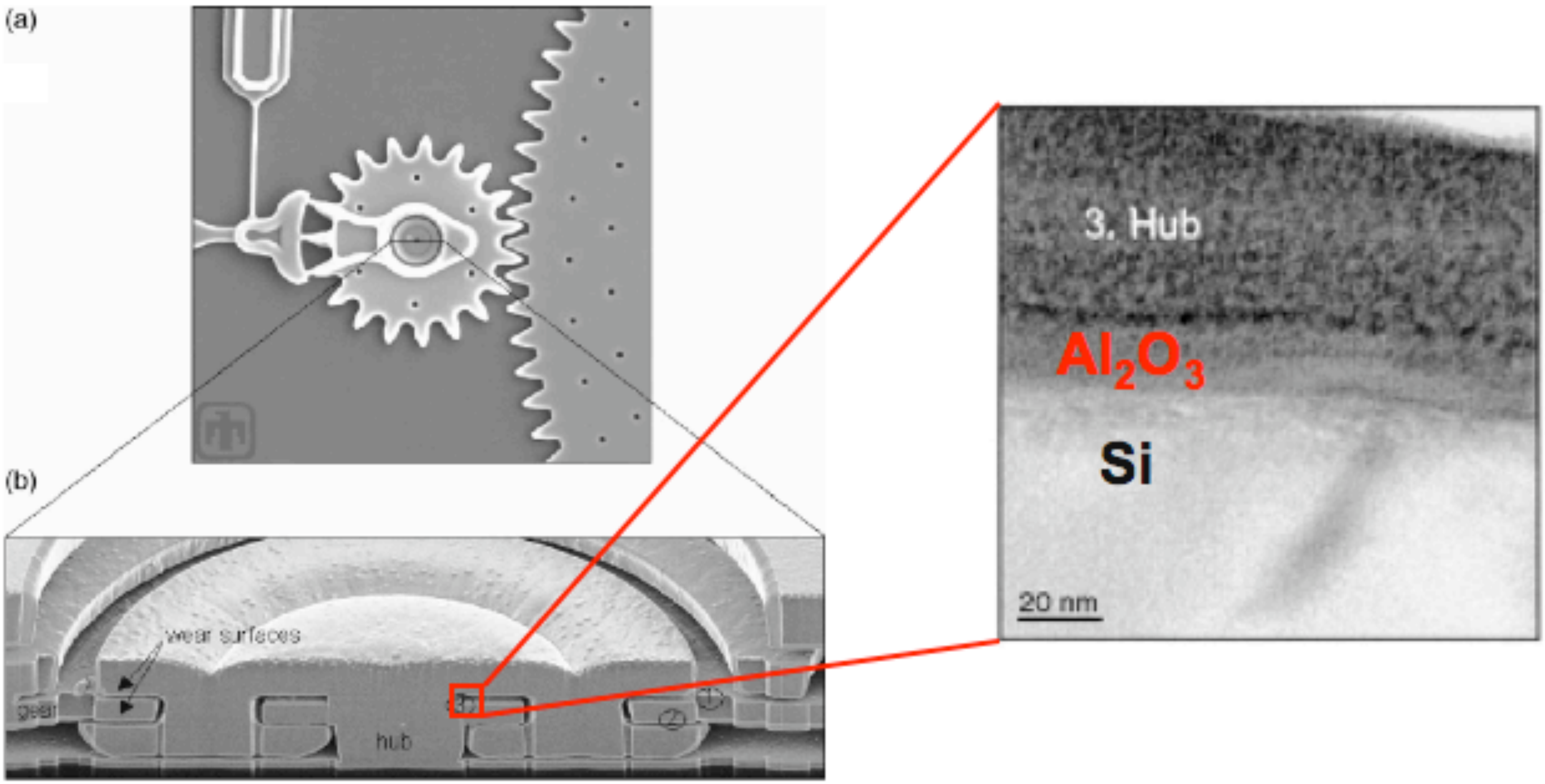


After Coating 15 nm ALD ZnO



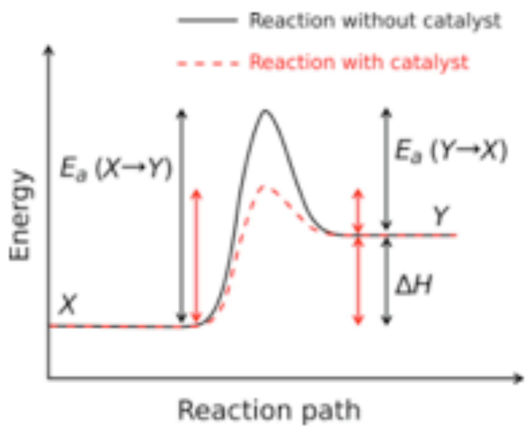
- Conformal coating on all exposed surfaces

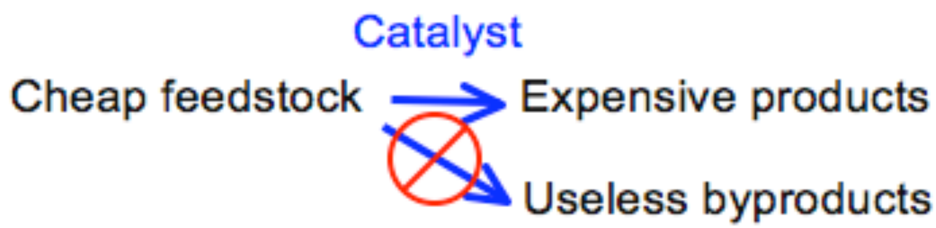
Al_2O_3 on MEMS Microengine Gears



- Conformal coating on all exposed surfaces
- Aspect ratio (channel length/width) ~80

What is a Catalyst?



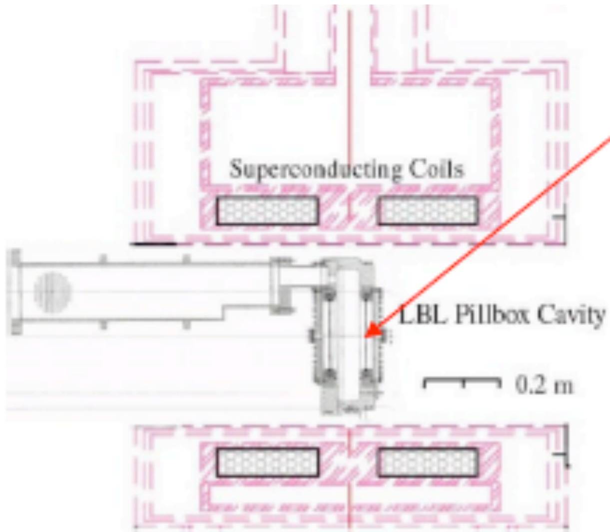


Huge Market for Catalysts:

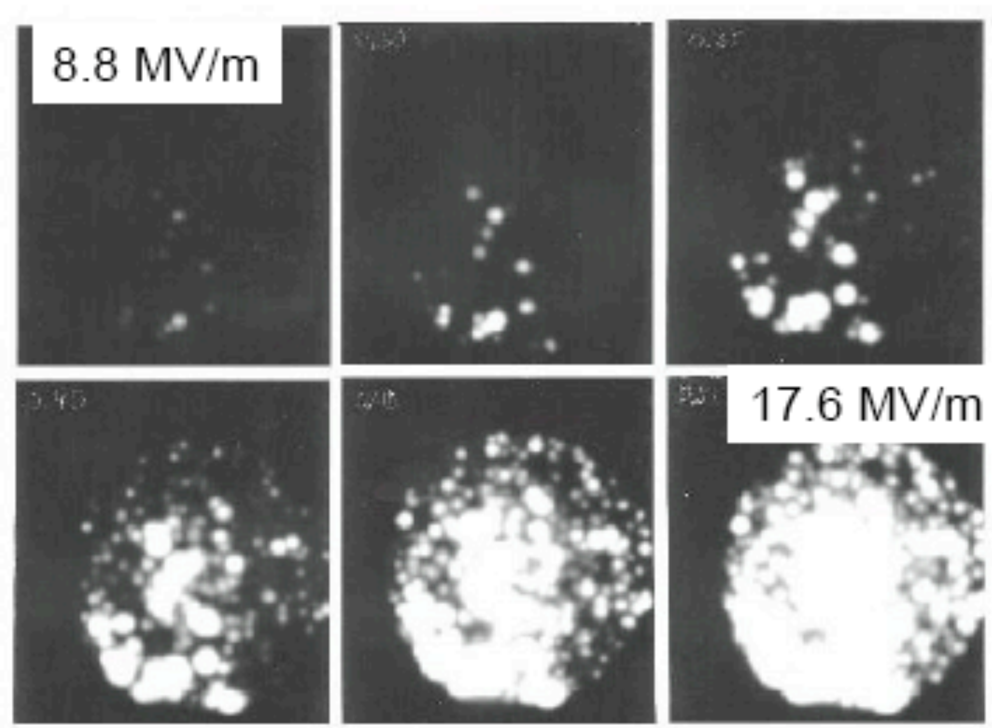
- More than 90% of all industrial chemical processes are catalytic.
  - 50% of gasoline from catalytic cracking
  - 100% of the NH_3 for fertilizer
- U.S. sales in excess of $500 billion per year.
- Fuel and chemical industry is the primary producer and consumer of energy
- Emissions reduction (catalytic converters)

We can measure the density spectrum of enhancement factors.

- From Dazhang's talk yesterday . . .



- **Insert Polaroid film near the Be window**

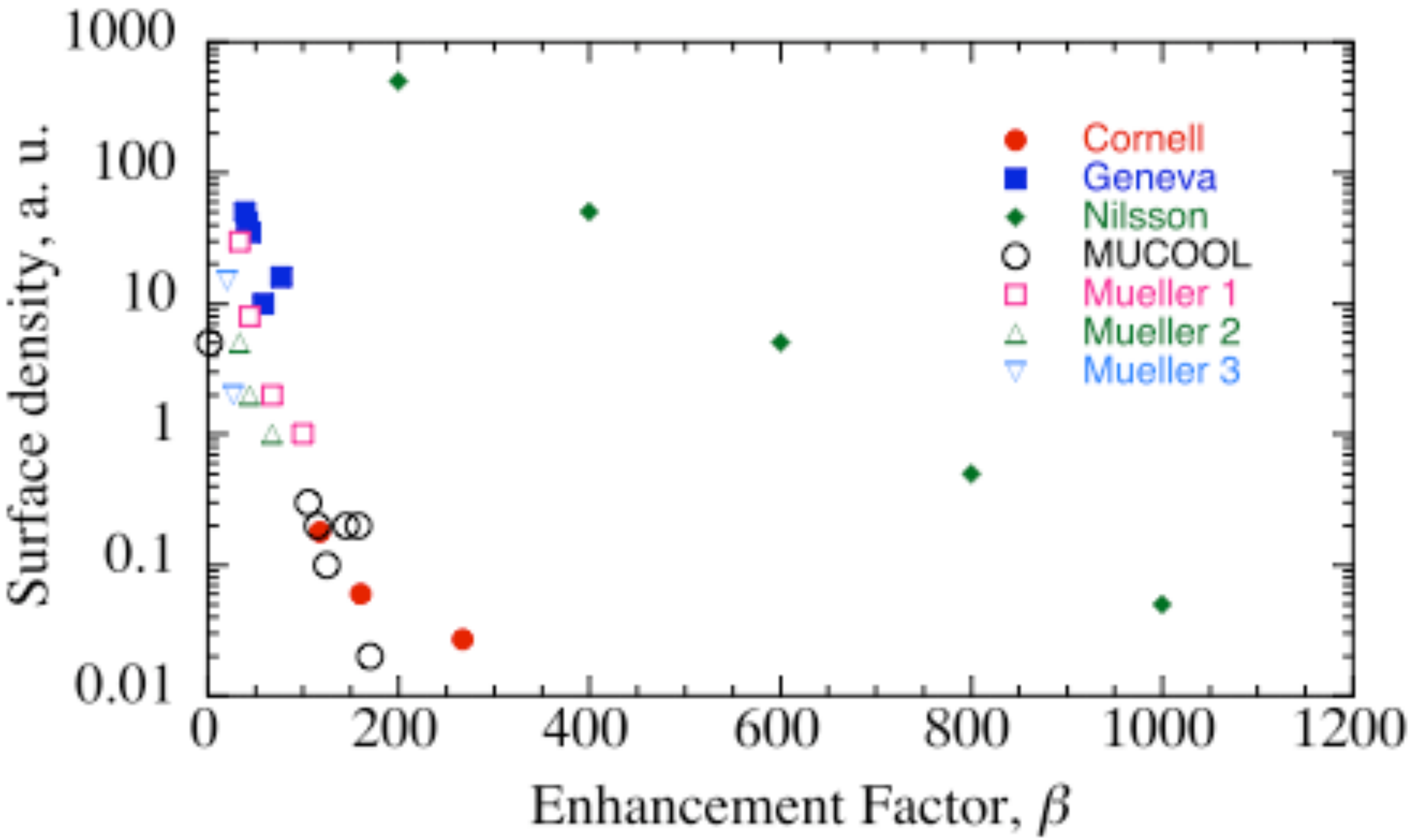


- **Direct pictures of how field emitters on the Be window change with RF field can be taken**

2009-1-25 D. Huang et al. NFMCC09, LBNL 8

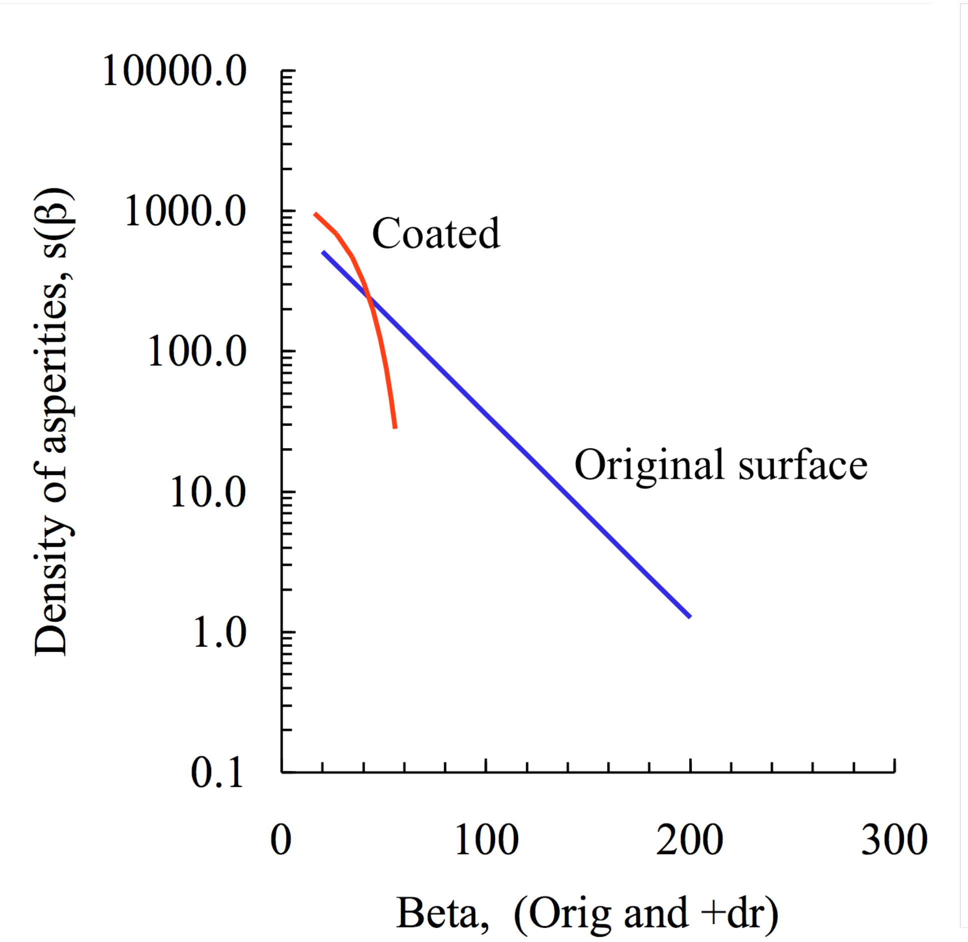
Our spectra agree with others.

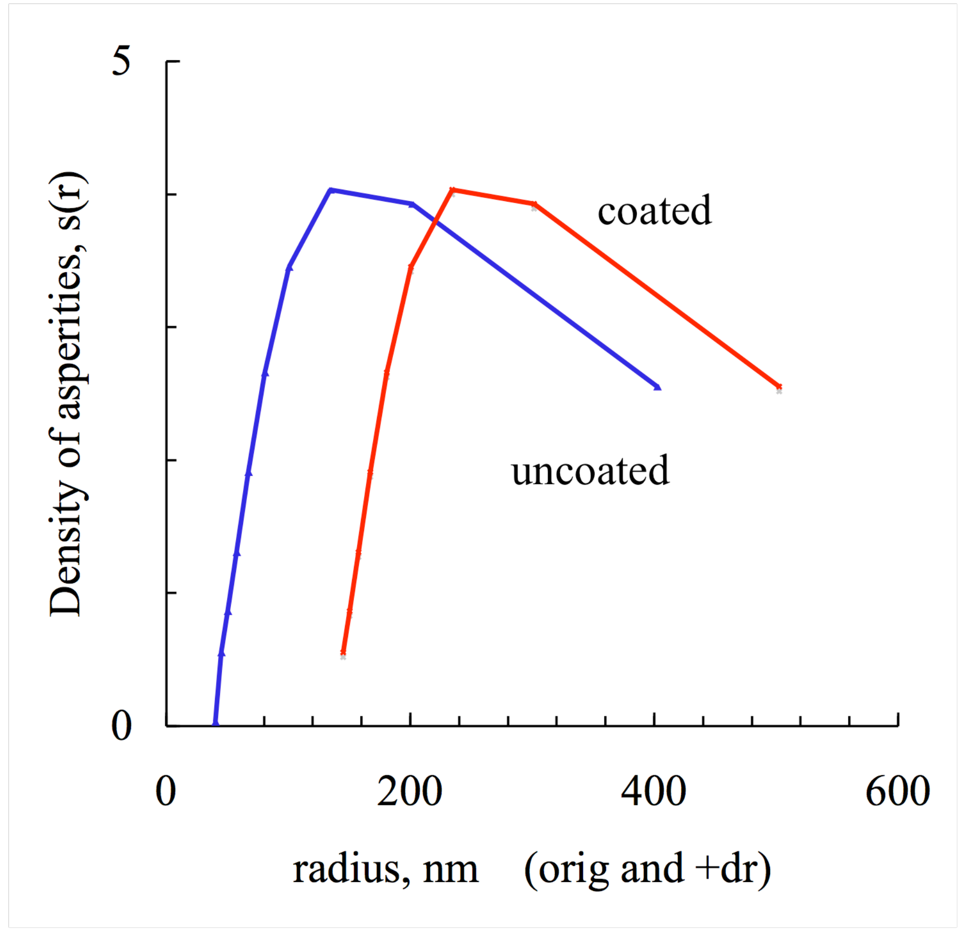
- We assume that the density of emitters looks like Ae^{-Cb}.
- A wide variety of data is consistent with this parameterization.



Smooth coatings can change the spectrum of enhancements.

- What is the effect of a ~100 nm conducting coating?

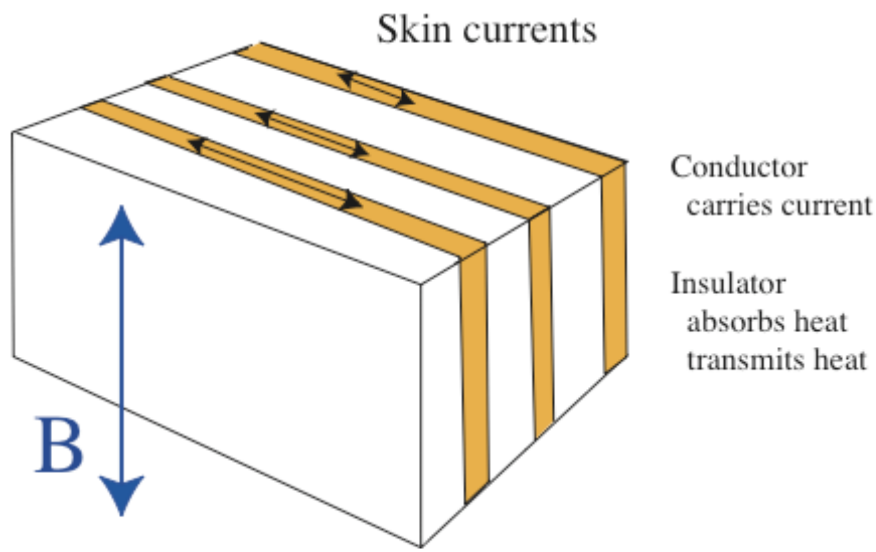


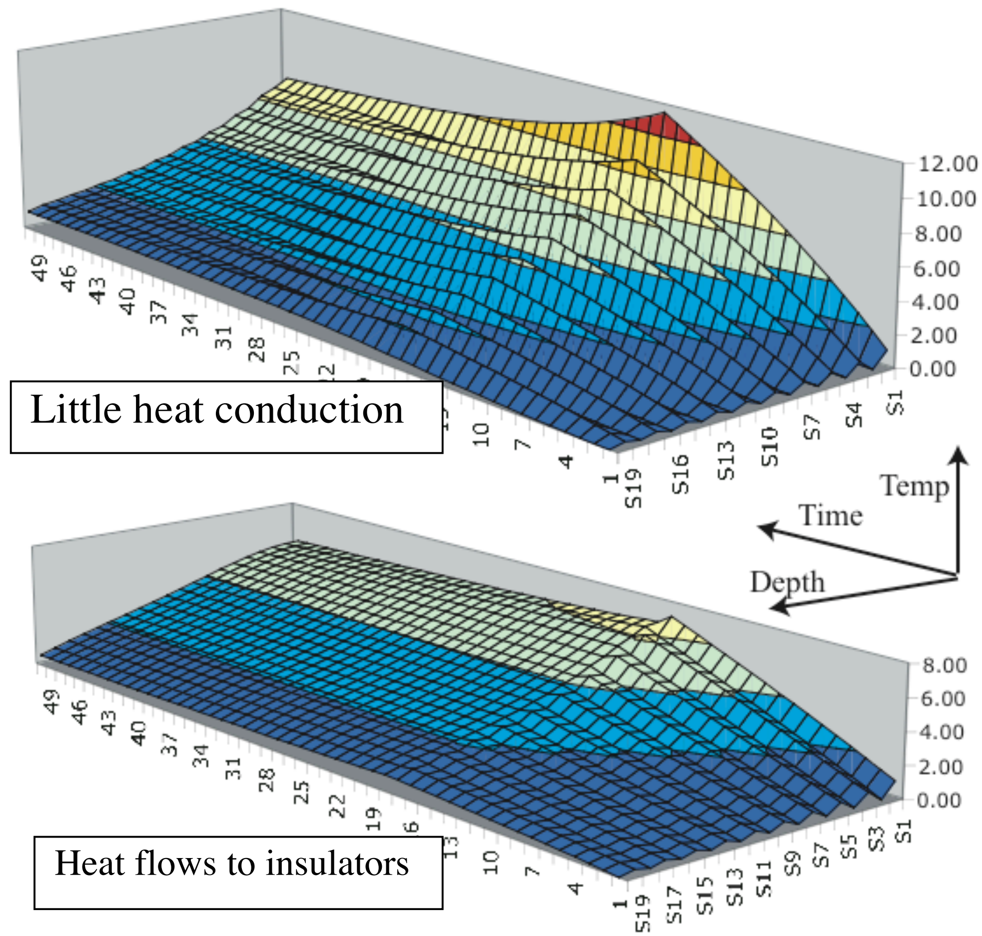


- This example should give three times higher rf gradients.

Surface layers can address pulsed heating in NCRF.

- You can build a composite material with different properties.

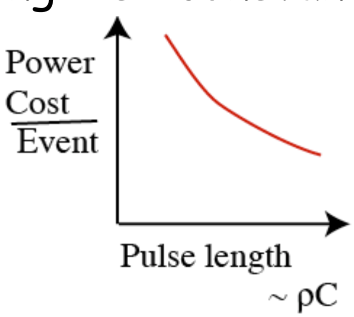




Since

$$\Delta T = \frac{H_t^2}{\sigma \delta}\sqrt{\frac{t}{\pi \rho C_\epsilon \kappa}}$$

everything else constant $\Rightarrow t \propto \rho C$.



With ideal materials this must work.

What happens with nanofabricated materials?

To do:

- Extend OOPIC Pro modeling to currents of ~10 A.

➜ Incorporate MD calculations in plasma simulation: Coulomb explosion, sputtering, creep, surface and oxide parameters.

- Systematic studies of shorting currents hitting arcs in B fields.

- Develop inclined cavity experiment

- Better define ALD experiments to produce "Breakdown-Proof" cavities.

Summary

The modeling effort is beginning to be productive.

The button test program has not been productive because
- The cavity stored energy was low
- Breakdown occurred elsewhere

It looks like high pressure cavities have the same limits as the open cell cavity
- They condition faster, perhaps because they have a much smaller active area.
- But they may have other problems (radiation induced resistivity, δ ray runaways)

We should look at:
- magnetic field effects
  - Surface orientation w,r,t B field,
  - Magnetic insulation,
  - More stored energy on buttons.
- In-Situ ALD
  - Dielectrics have more potential barrier,
  - Metals can lower the local fields, should cure Breakdown and field emission.