Summary
of the
Argonne Workshop on High Gradient rf

J. Norem
Argonne National Laboratory

LINAC 2004
August 19. 2004

fact
Muon Collaboration

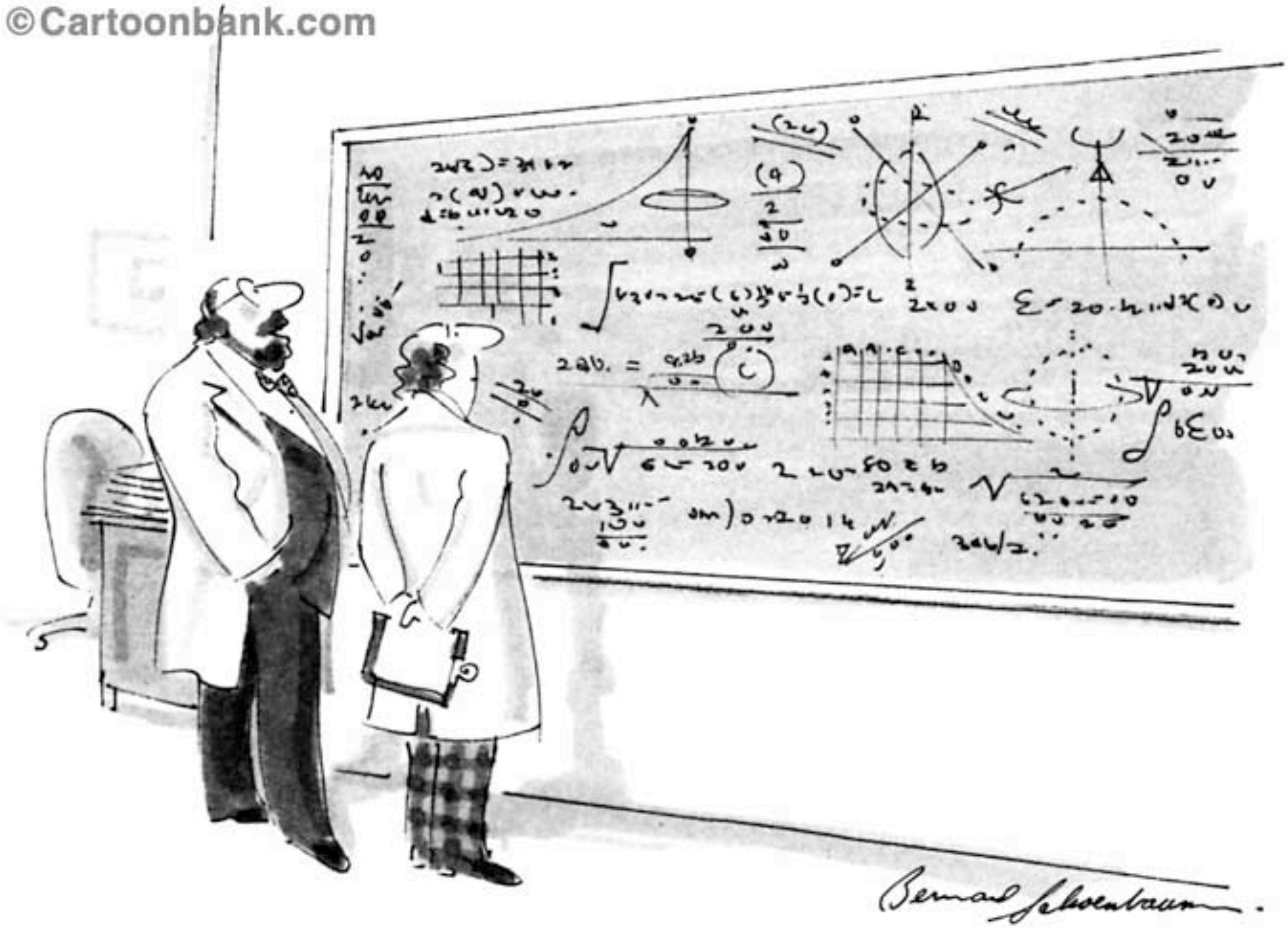
This talk will:

- Summarize the results presented at the workshop.
- Highlight things not covered at LINAC 2004
- Identify some open issues and questions in the physics of breakdown.

Note that:

- Many of the participants of the workshop are here.
- The workshop reached no collective conclusions.

1, Recent Results



"Oh, if only it were so simple."

Superconducting rf Development

A. Matheisen, K. Saito

High gradient SCRF requires:

- Materials and fabrication
  - High quality Nb
  - Improved cavity fabrication

- Tools
  - BCP for E_{acc}~ 30 MV/m E_{peak} 60 MV/m
  - Electropolishing for E_{acc} = 35-40 MV/m E_{peak} = 70-80 MV/m
    - Gives improvement on surface /cleaning quality
  - High pressure rinsing to fight field emission
    - BUT ! Facility has to be under control /intensive QC necessary

- Sequences and personnel structure
  - Preparation sequences are tested
  - Test set up for assembly

  - Well trained personnel !!!

- New cavity shape may give more gradient.

NLC Structure Tests

C. Adolphsen

Linac 2004 summarizes this work, . . . a year ago the summary was:

- Three generations of X-band structure tests show the need to operate at power levels below damage threshold (60-80 MW at 400 ns)
  At this limit surface fields vary significantly:
    - 110 MV/m for the 1.8-m Structures
    - 140 MV/m for the H-Series Structures and up to
    - 195 MV/m for the T-Series Structures.

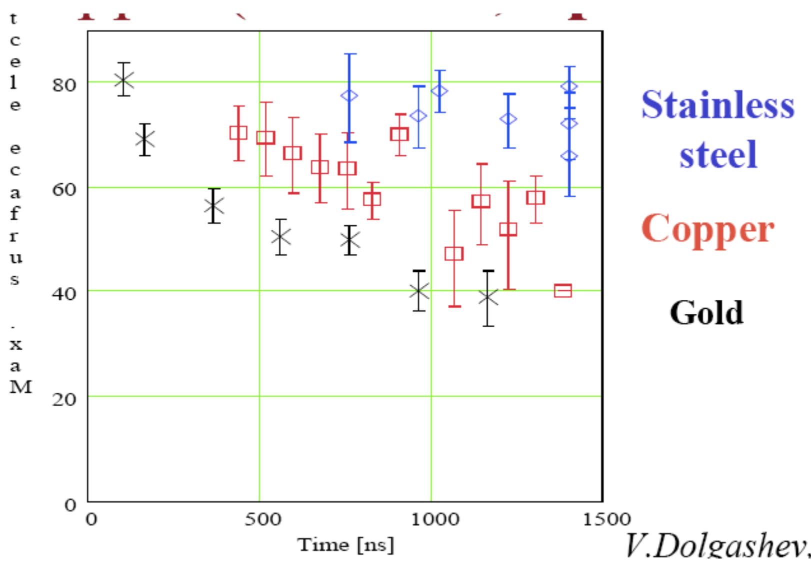
- Have tested a structure with essential NLC/GLC features that basically met 65 MV/m performance requirements (within spec at 60 MV/m).

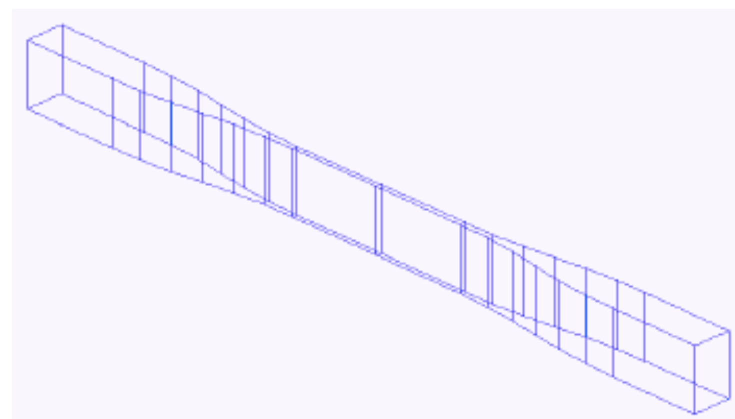
- Adopted a lower power design for NLC/GLC –building eight for a system test.

- Still do not have basic understanding of source of breakdown or its relation to pulse heating –we encourage fundamental studies of these issues.

Breakdown Experiments

- Breakdown seems to be a mysterious process, with no clear theory that enables understanding of the phenomenon.
- Most of the experimental work is done with complicated structures that make interpretation of the data very hard.
- Used waveguides of copper, gold and SS. Low and high magnetic field.

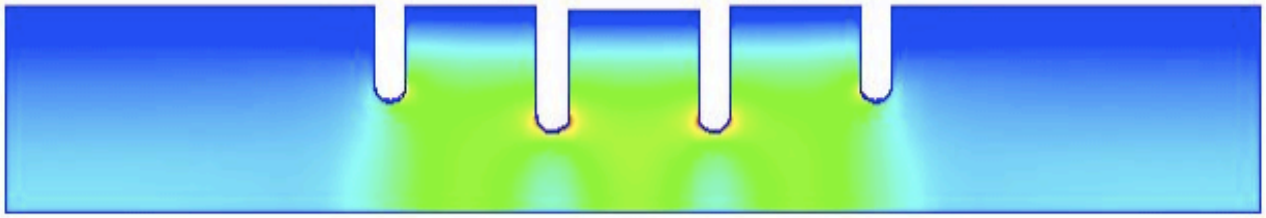




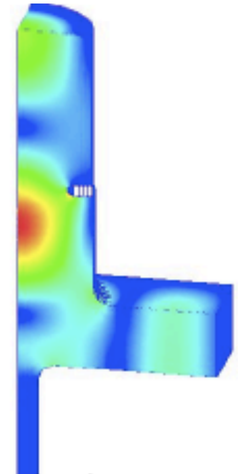
V.Dolgashev, S.Tantawi

THP67

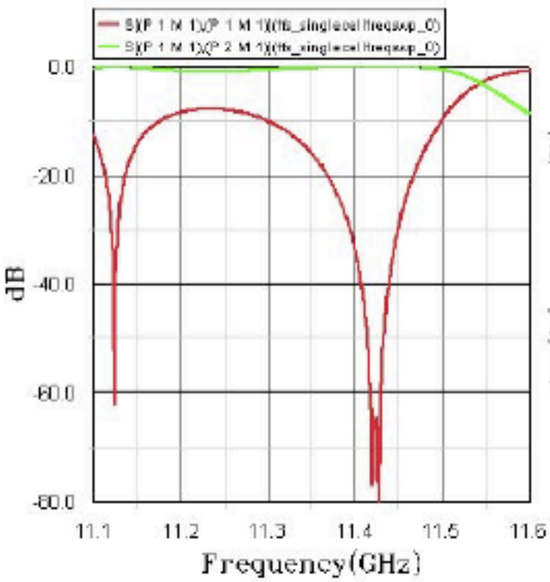
Single-Cell TW Structure for RF Breakdown Experiments



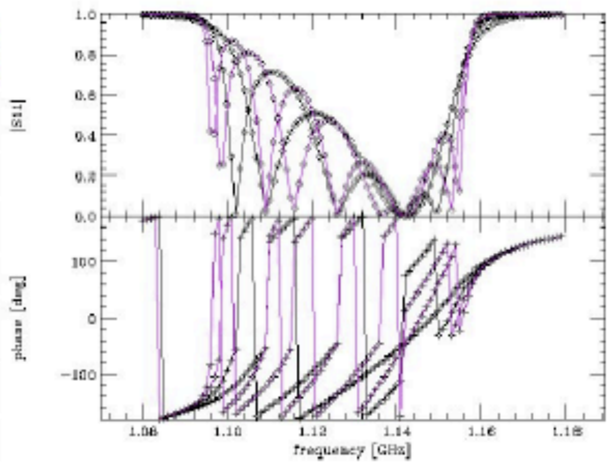
Plot of electric field amplitude in a single vg/c~0.05, traveling-wave accelerator cell flanked by matching cells.



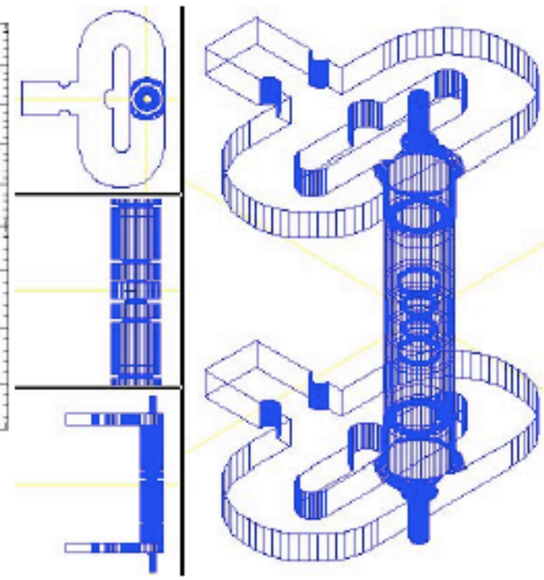
Electric field snapshot in _ geometry of TM_{01} launcher with viewport.



Simulated frequency response.



Traveling-wave periodic structure match demonstrated with mode-matching code by doubling, tripling, and quadrupling center cell.

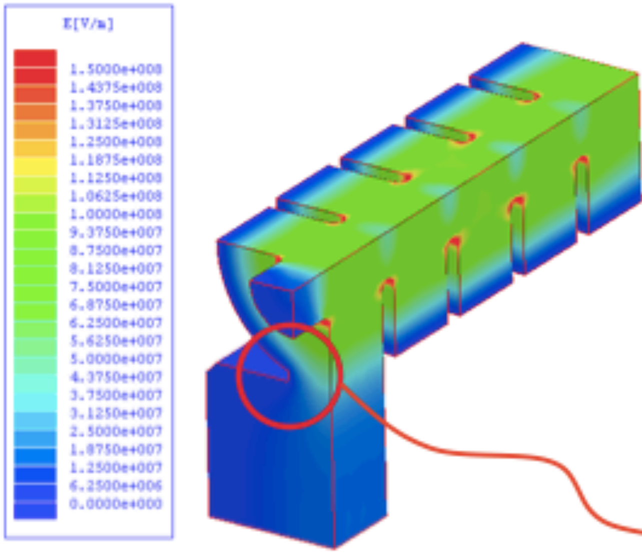


Experimental assembly: TM_{01} launchers with matched single TW cell.

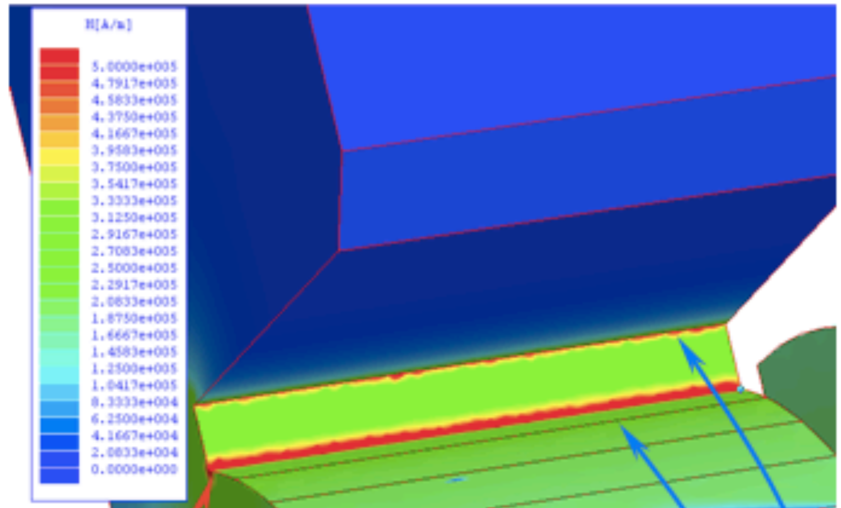
Magnetic Fields, Power limits

V. Dolgashev

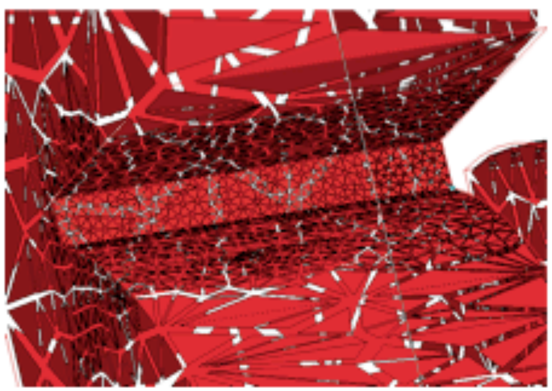
Field distribution in T53VG3 coupler



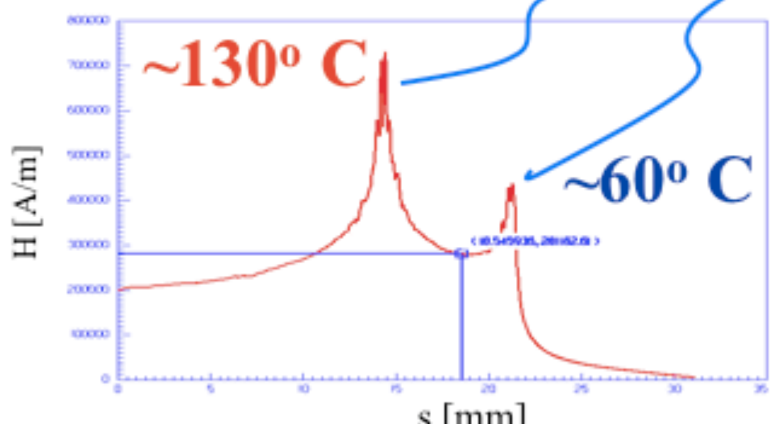
Surface **electric** field distribution, max. field in the coupler cell 140 MV/m, power 48 MW



Surface **magnetic** field distribution, field on a flat part of the coupler iris ~0.28 MA/m



Mesh



Surface **magnetic** field

NLC/ GLC Surface Studies

S. Harvey

- Slip Lines

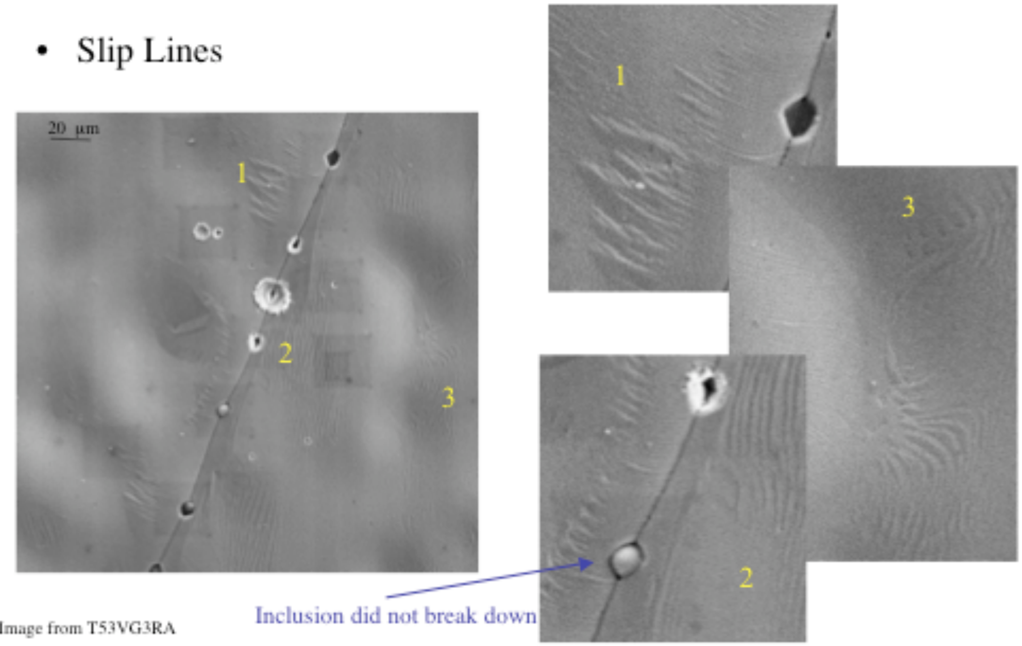
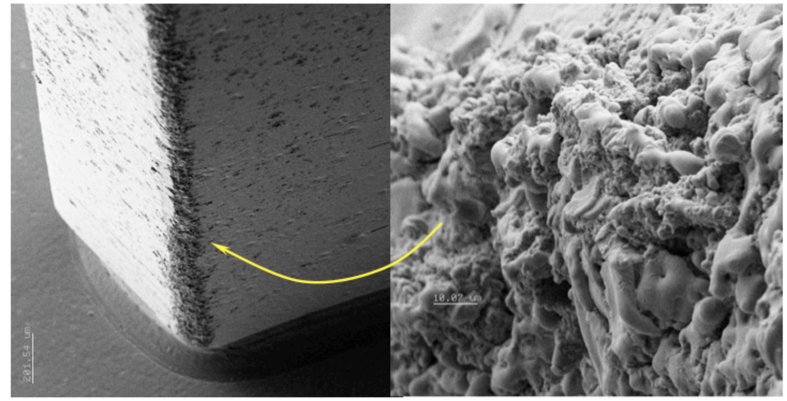
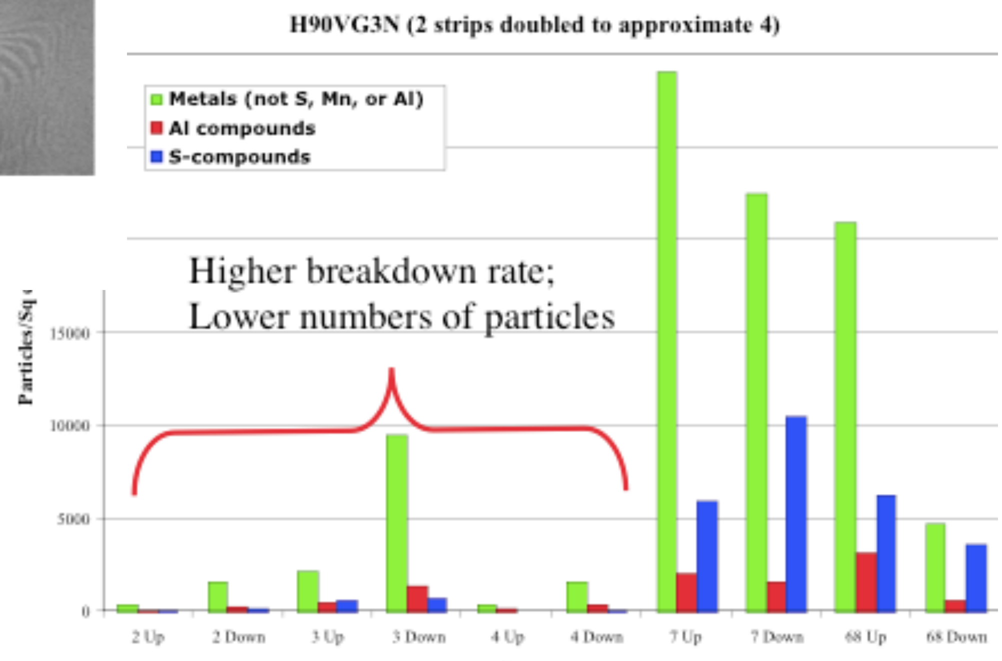


Image from T53VG3RA

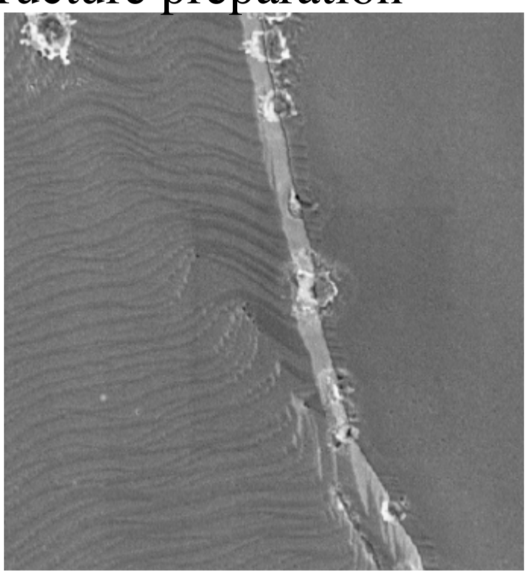
Typical edge damage on the cell side of the Horns

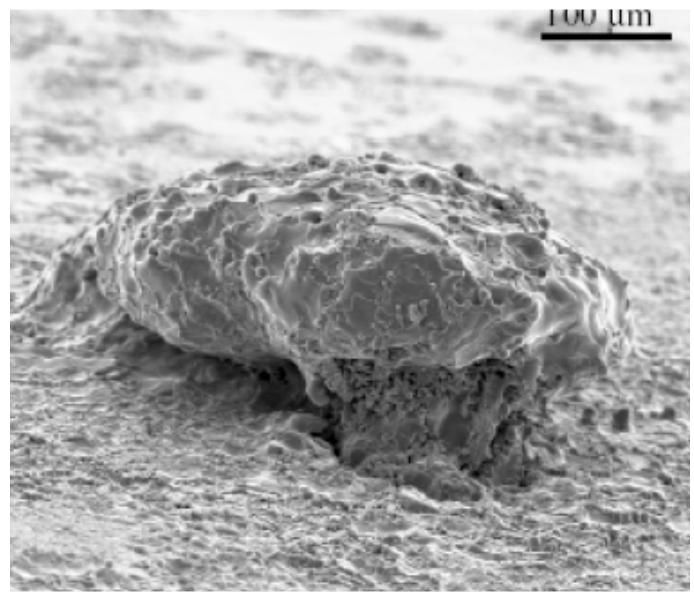


H90VG3 – chemical distribution. Recent data.



- No visible particle residue in most craters.
- An overwhelming majority of particles do not break down.
- Large particles (> 50 μm) catastrophic when they occur.
- Most breakdown events must have unidentified causes.
- Autopsies => clean-room technique is essential to reducing particles that lead to breakdowns.
- Non-native contamination (Mn, Cr) can be added in the last steps of structure preparation





Gradient Limitations

S. Dobert

- Looked at breakdown rates and maximum gradients as a function of many parameters.

Breakdown probability and damage threshold depends on:

- pulse length ($\tau^{-1/3}$)
- surface field (exp)
- input power (~exp)
- RF- surface (~A_s)
- Material parameters ($T_m^{0.77}\ C_p^{0.53}\ D_m^{0.29}$)*
- clean fabrication and handling helps

*DC-tests: M.J. Mulcahy et al. ARPA No. 517 1969

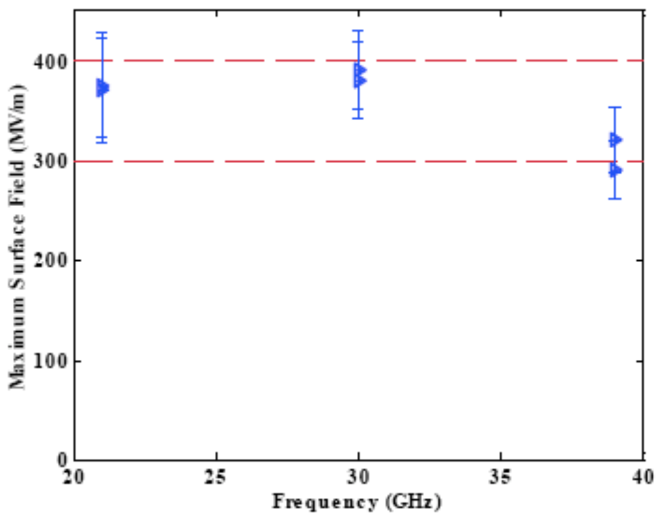
(Fowler-Nordheim: $E_{eff} = Es * \beta$ -> 7 GV/m = 170 *40)

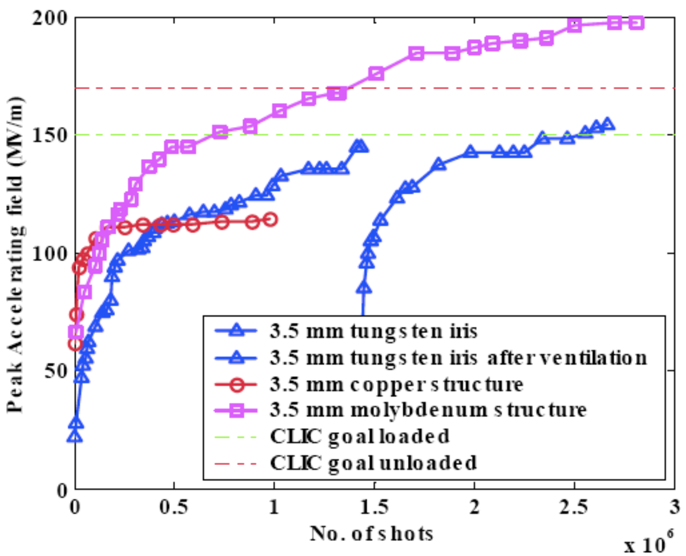
- See WE101

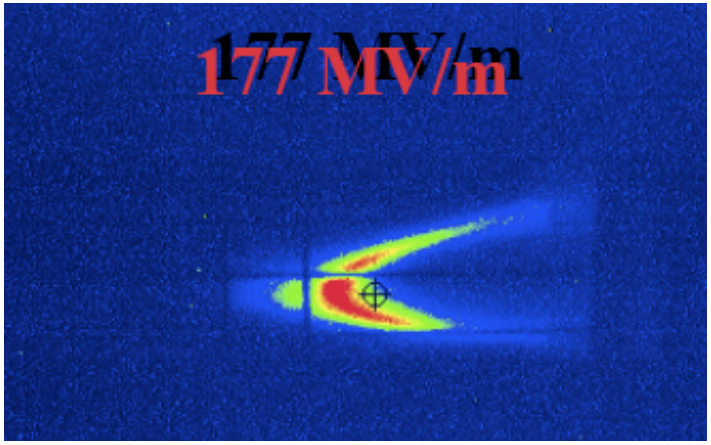
CLIC Tests

W. Wuensch

- The CLIC test facility can do unique measurements.
- The facility is being extended to
- Data show no significant frequency or temperature dependence to breakdown.
- Tungsten vs. molybdenum vs. copper.
- No dependence of breakdown rate on temperature.
- THP34



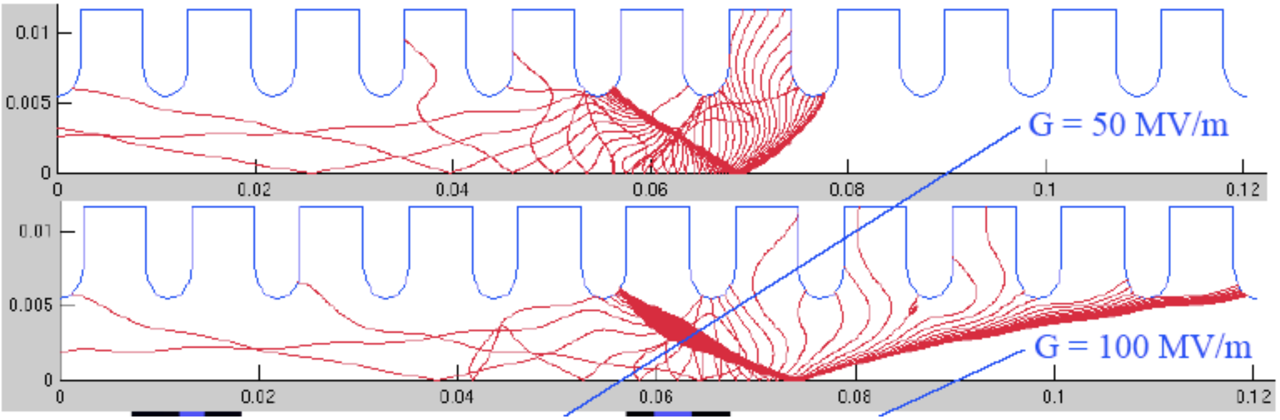




Dark Current Simulation

V. Ivanov

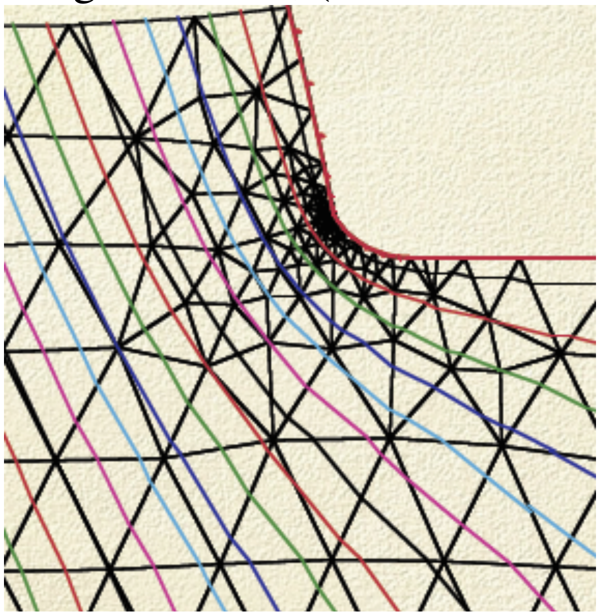
- Detailed calculations of dark current trajectories, capture, and secondary prod.

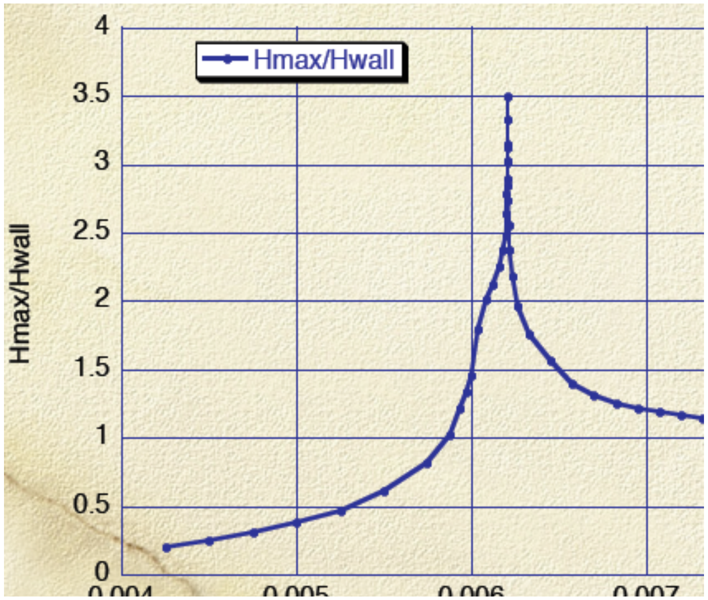


Calculating Fields near Corners

Y. Iwashita

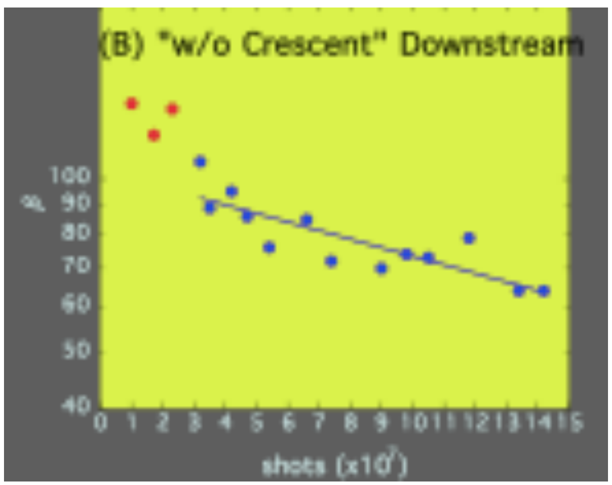
- Calculating the magnetic field, (and the enhanced surface current density), is important.
- TUP95

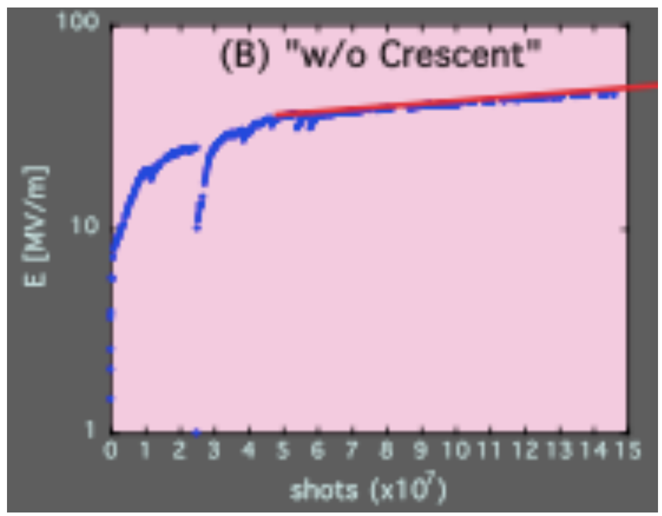


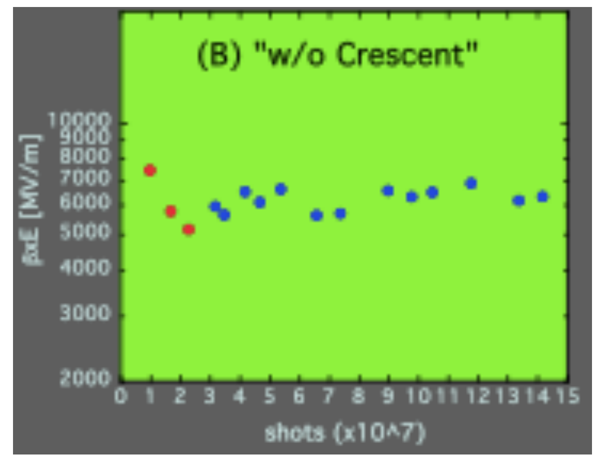


KEK 2856 MHz Cavity Development

- This work included a detailed study of the effects of high power rinsing.
- Rinsing produced full gradient in 1/2 the time and 1/3 the dark currents.
- During the conditioning period although the β was decreasing and the accelerating field was increasing, the product remained the same, ~6 - 7 GV/m.
  - independent of treatment.





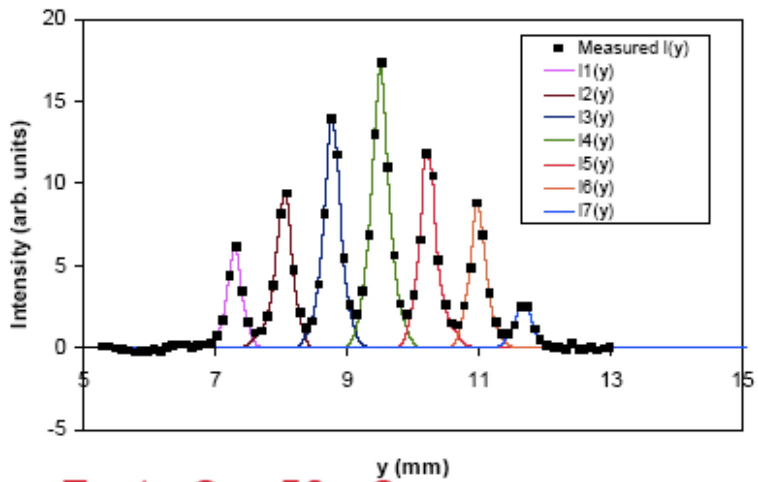


Enhancement factor * Surface field = 6 - 7 GV/m

17 GHz rf Gun Development

M. Shapiro

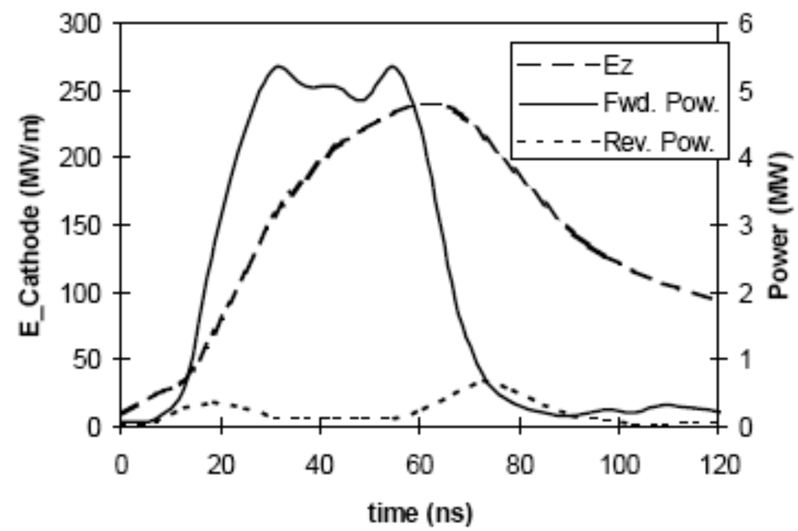
- Operation of a photo cavity at 17 GHz.



Expt.: Q ≈ 50 pC, $\tau \approx 1$ ps

E = 0.8 MeV

RF Filling

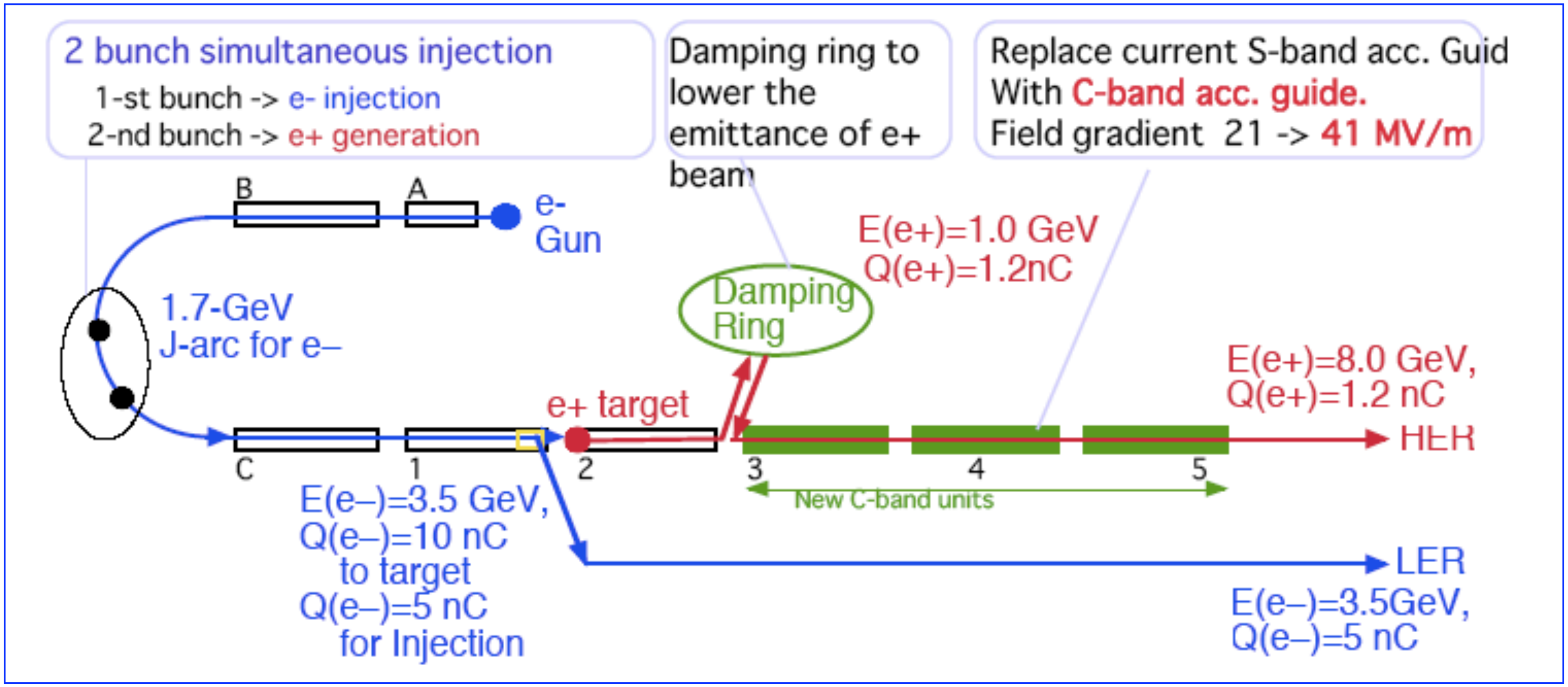


- Up to 200 MV/m peak field achieved (Highest achieved in an RF gun)
- Limited by breakdown.

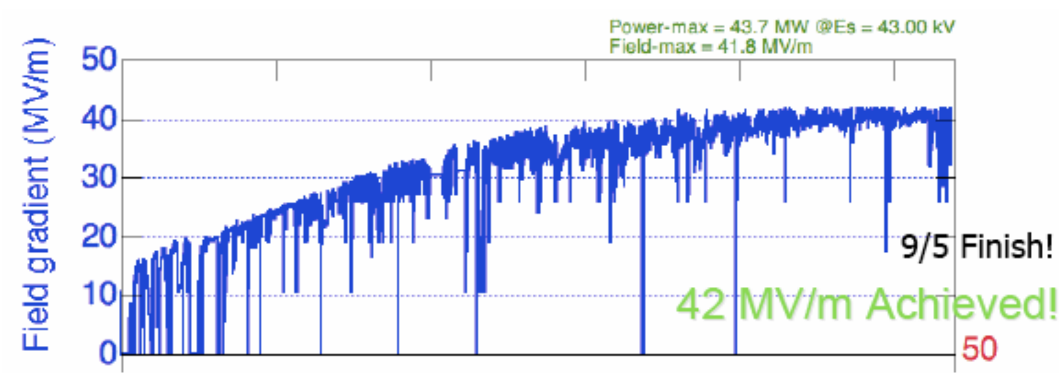
C band structures

S. Fukuda

- This is a large project to increase the energy of the Super KEKB injector



- The structures are operating as required after conditioning for about two months.



Cell Preparation for High Field Stuctures

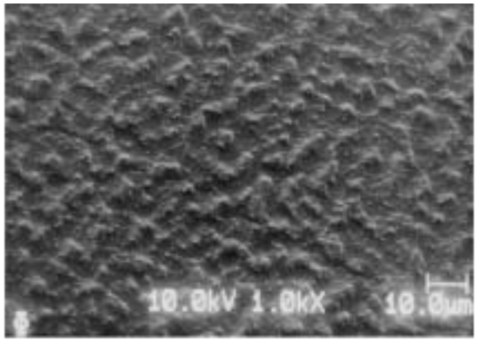
T. Higo

A systematic study of improvements in the copper surface.

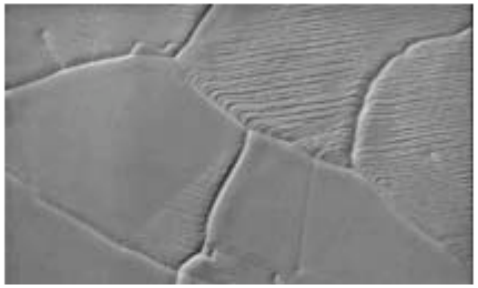
- Diamond turning without kerosene but with N_2
- Chemical etching following SLAC procedure
- Electro-polishing SCC process
- High temperature vacuum baking
- High temperature hydrogen furnace cycle
- Rinsing with pure-water jet irradiation

Tested to some extent
To be studied

- SEM view of copper surface exposed to hydrogen or VAC furnace at ~950C.



Open to VAC furnace



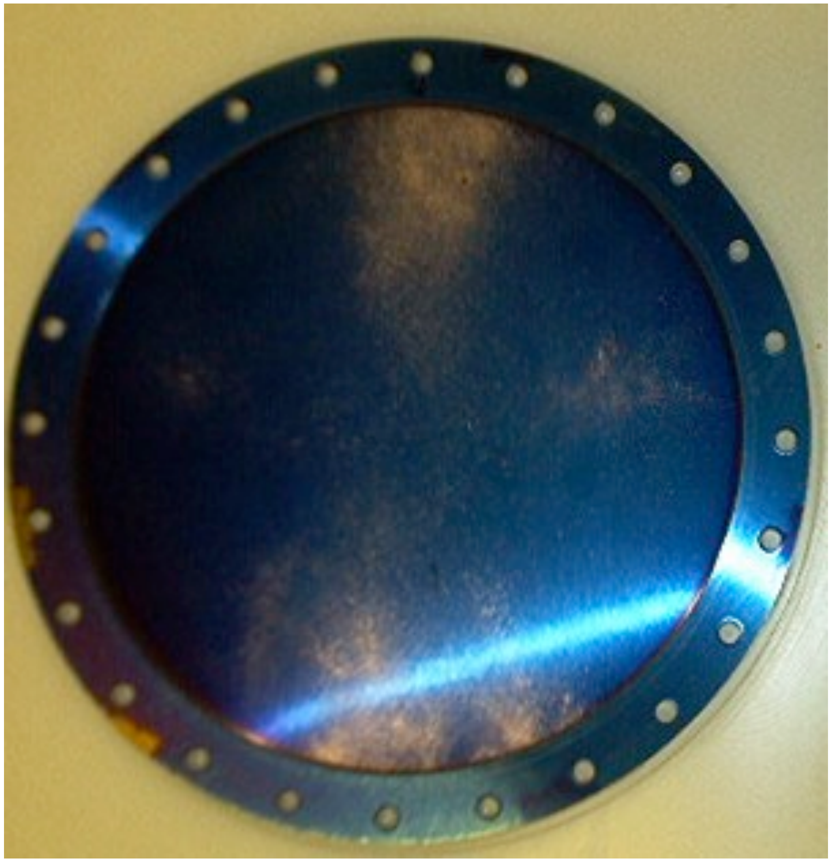
VAC furnace with Cu cap

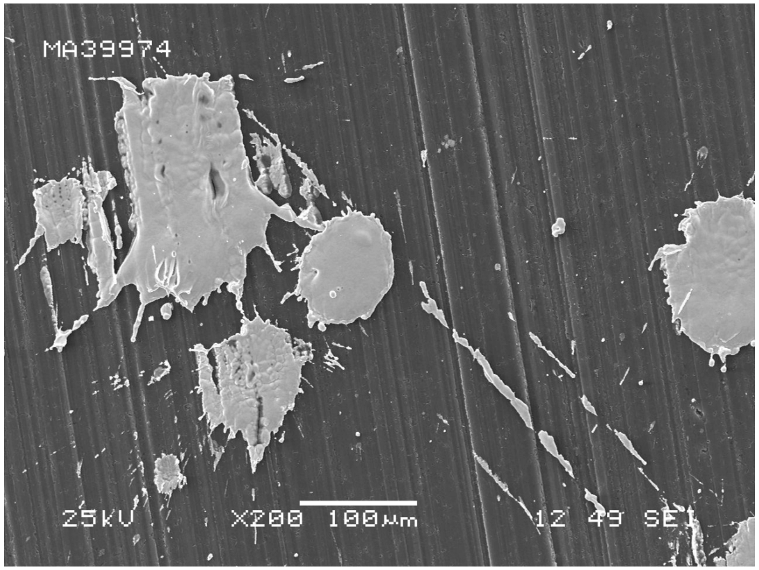
Results with Be and High Magnetic Fields

A. Moretti

- Muon cooling systems will use Be windows and high (0 – 5 T) magnetic fields.

- The Be was undamaged, but covered with copper splashes.



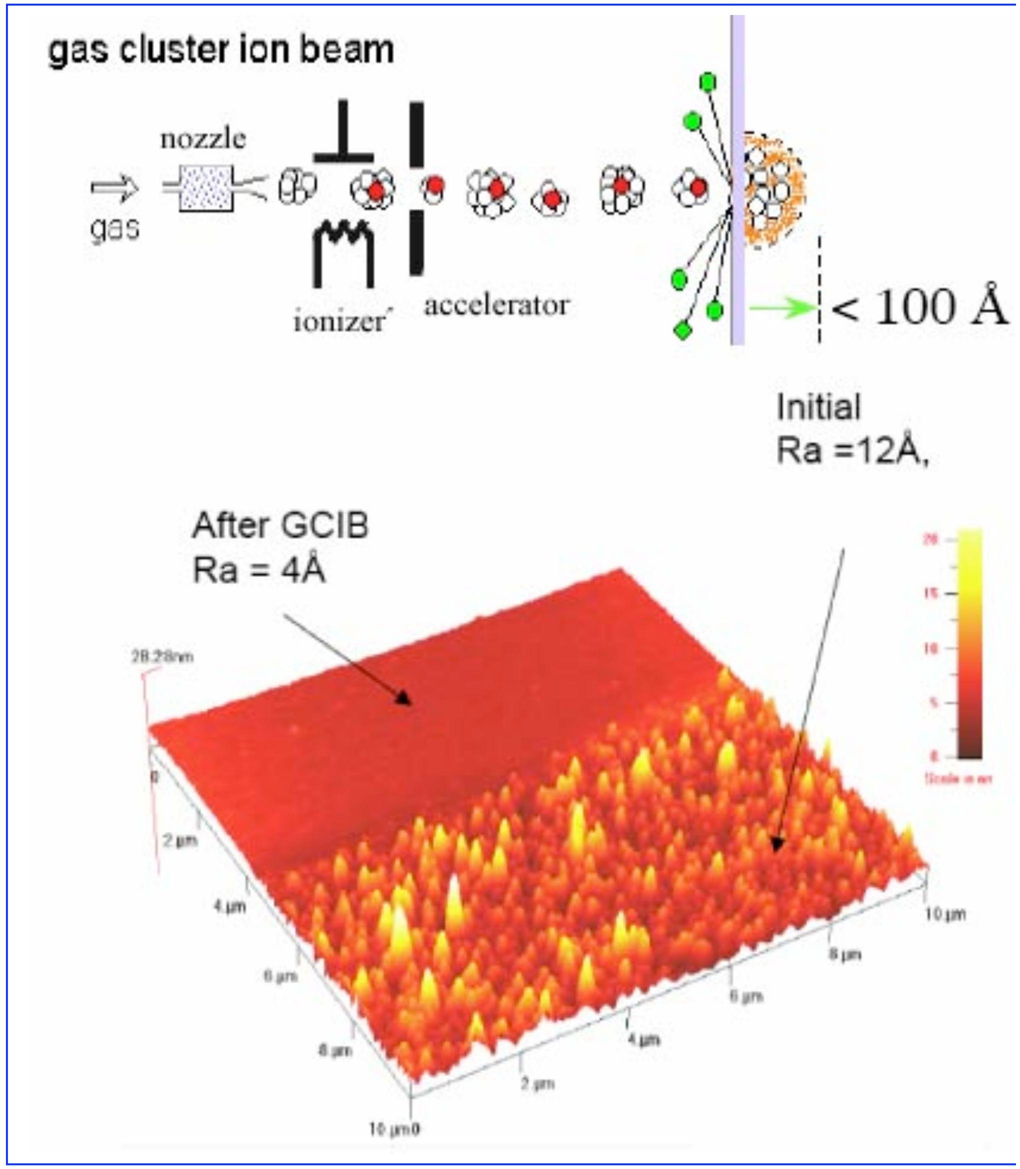


- Magnetic field results reported in TU204.

Gas Cluster Ion Beams (GCIB)

Z. Insepov

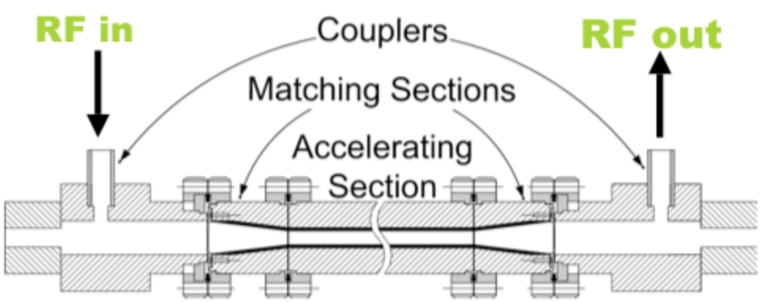
- Developed by Epion Corp., Billerica Mass.
- This is proven technology.
- Used in the Semiconductor industry.
- Can be used to smooth copper.
- Tests underway with Cornell &SLAC.

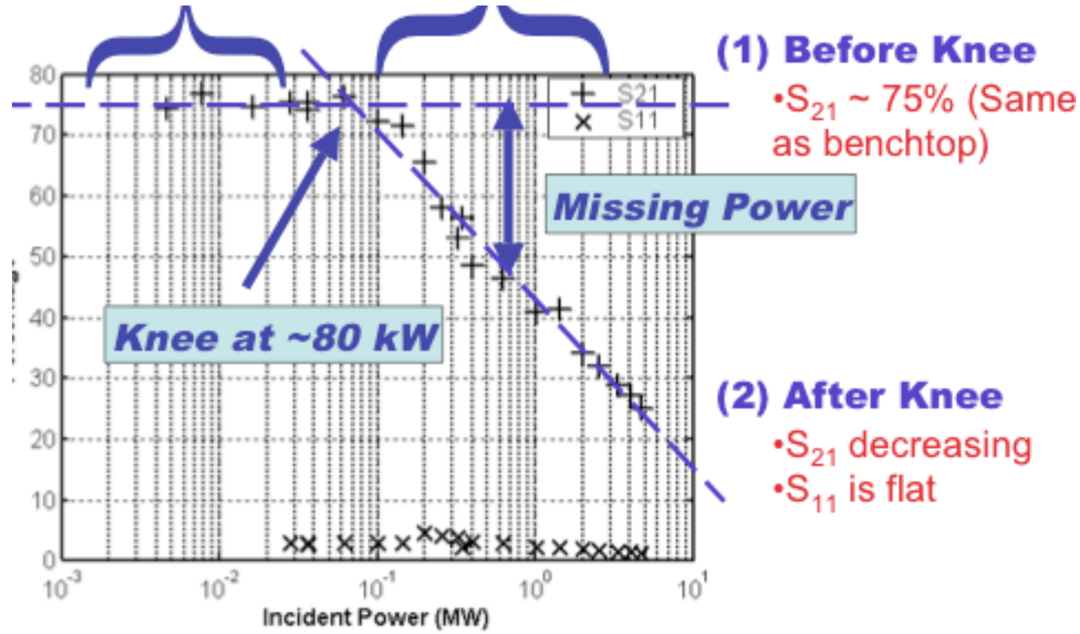


Dielectric Breakdown

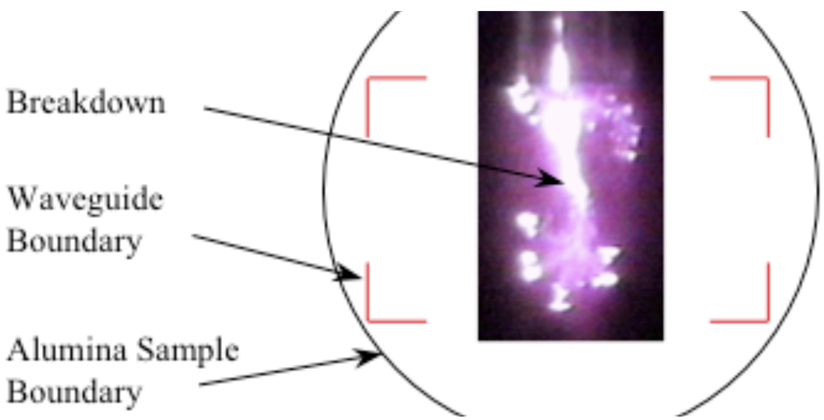
Y.Y. Lau, A. Neuber, J. Power

- Dielectric structures are being studied as possible high gradient accelerators.
  - Recent results have been limited by arcing and multipactor., TiN works.
- **Experiments at X band**





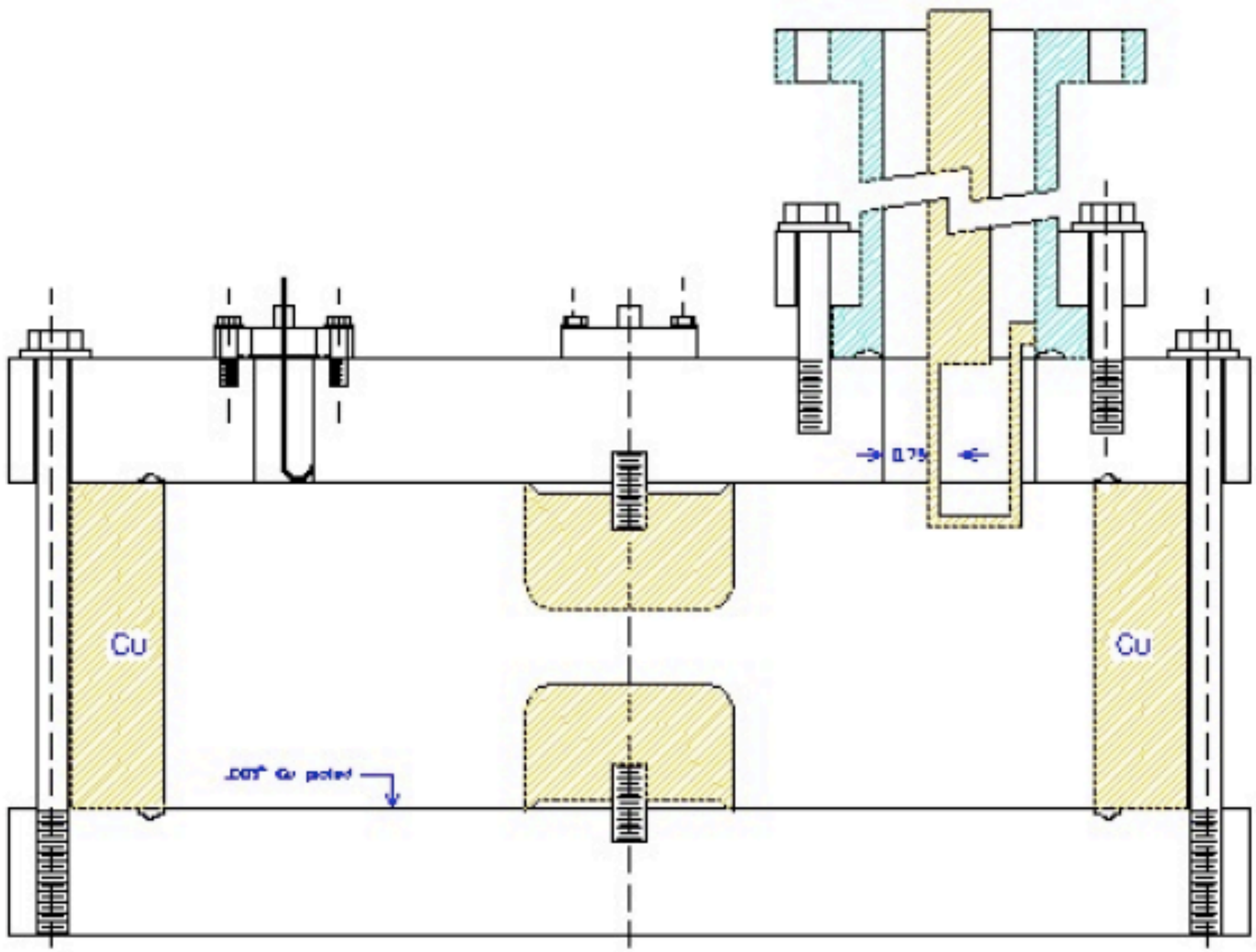
- **Experiments with S band resonator**



High Pressure Breakdown

R. Johnson

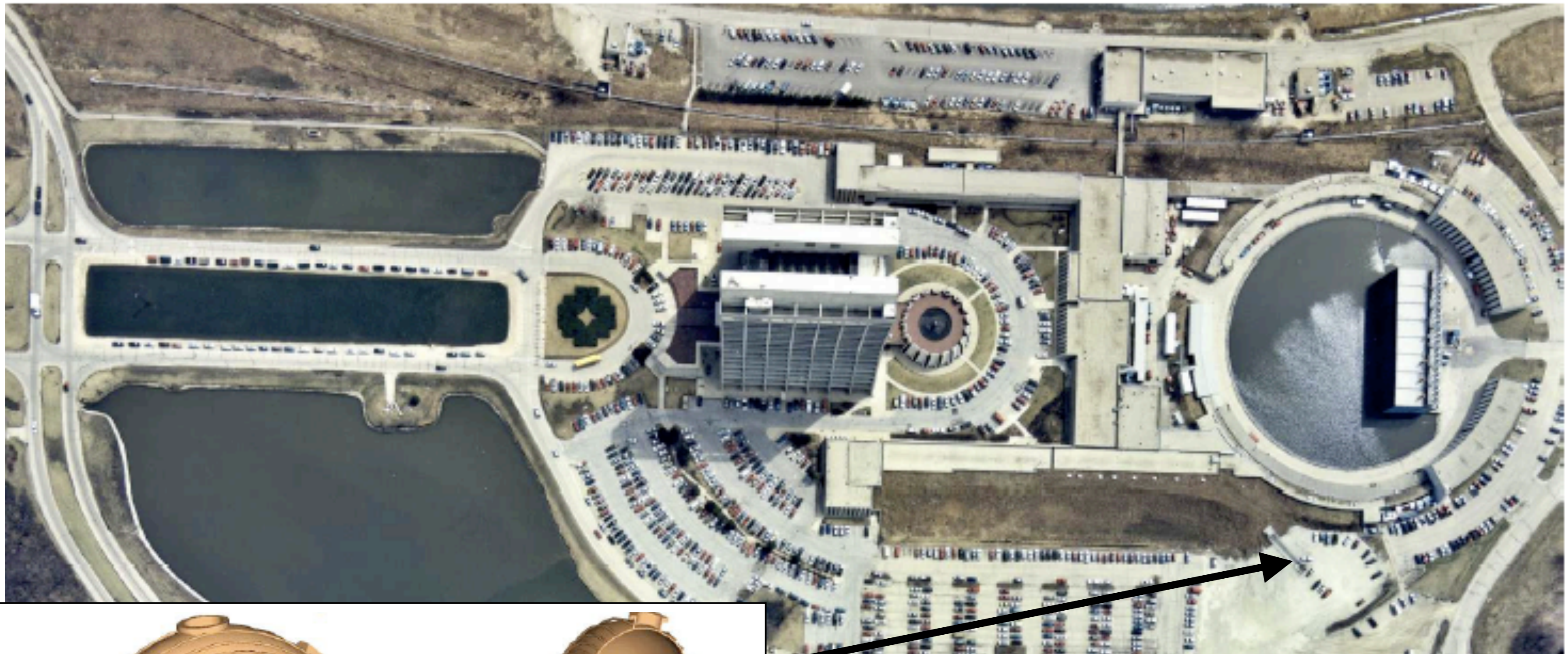
- Muons Inc. has an aggressive experimental program underway (TU203).



201 MHz Cavity Development and Testing

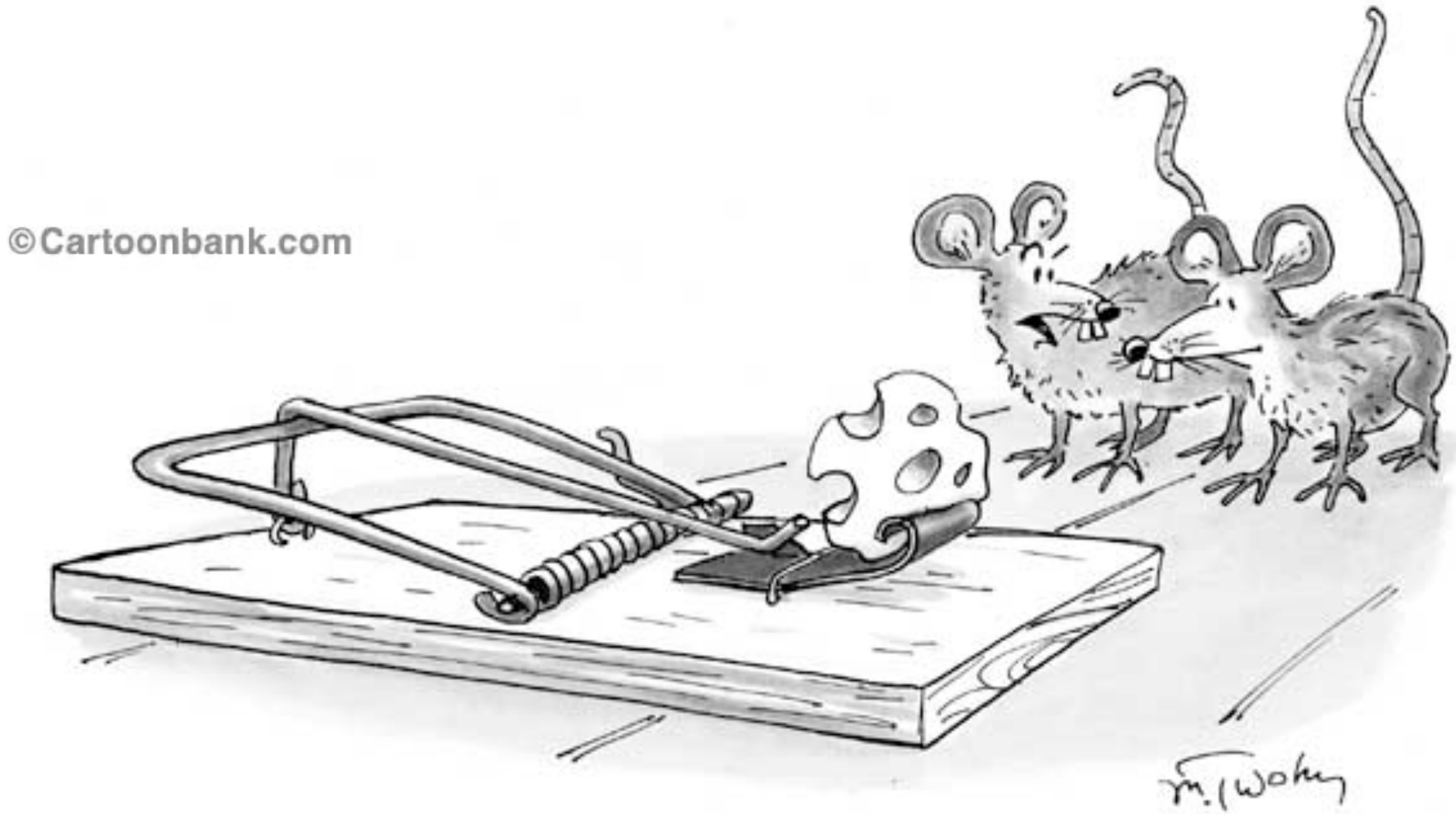
D. Li, M. Popovic

- The Muon Collaboration is setting up a new area to test a low frequency cavity.



201.25 MHz cavity conceptual design

2. Modeling of Breakdown

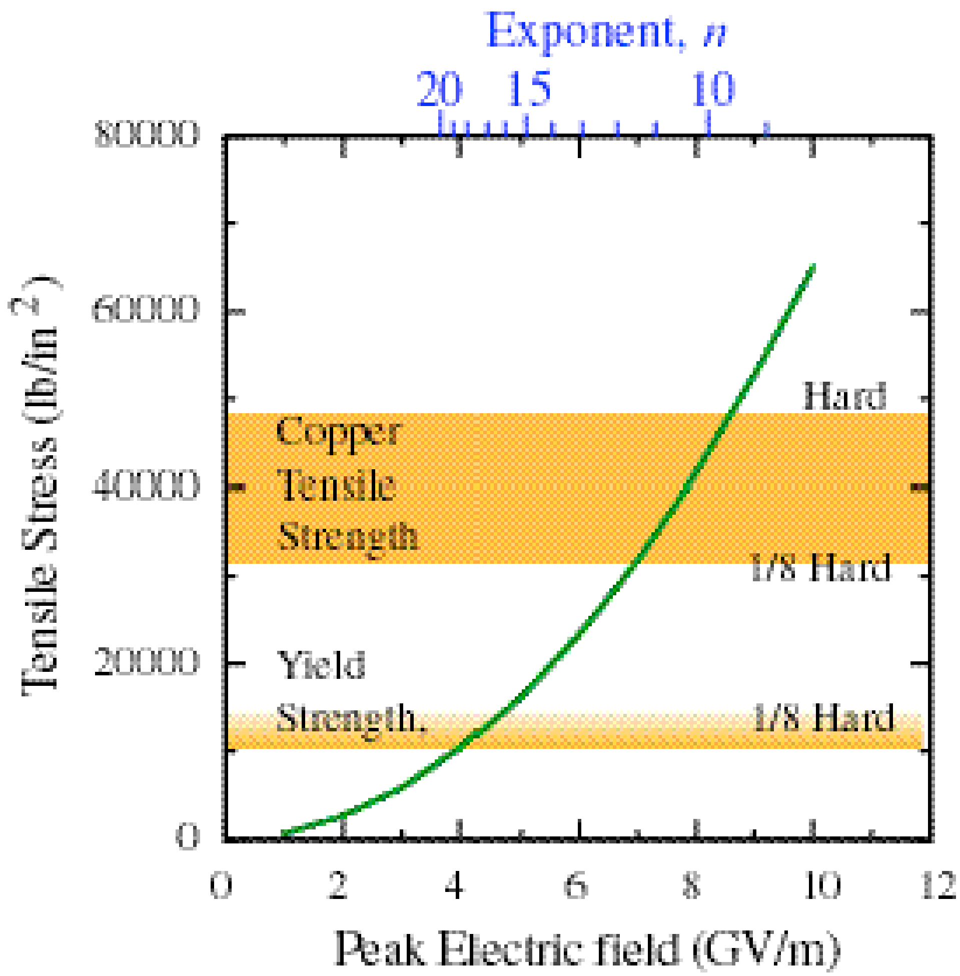


"Careful—it might be a trap!"

Breakdown and Tensile Stress,

J. Norem, I. Konkashbaev

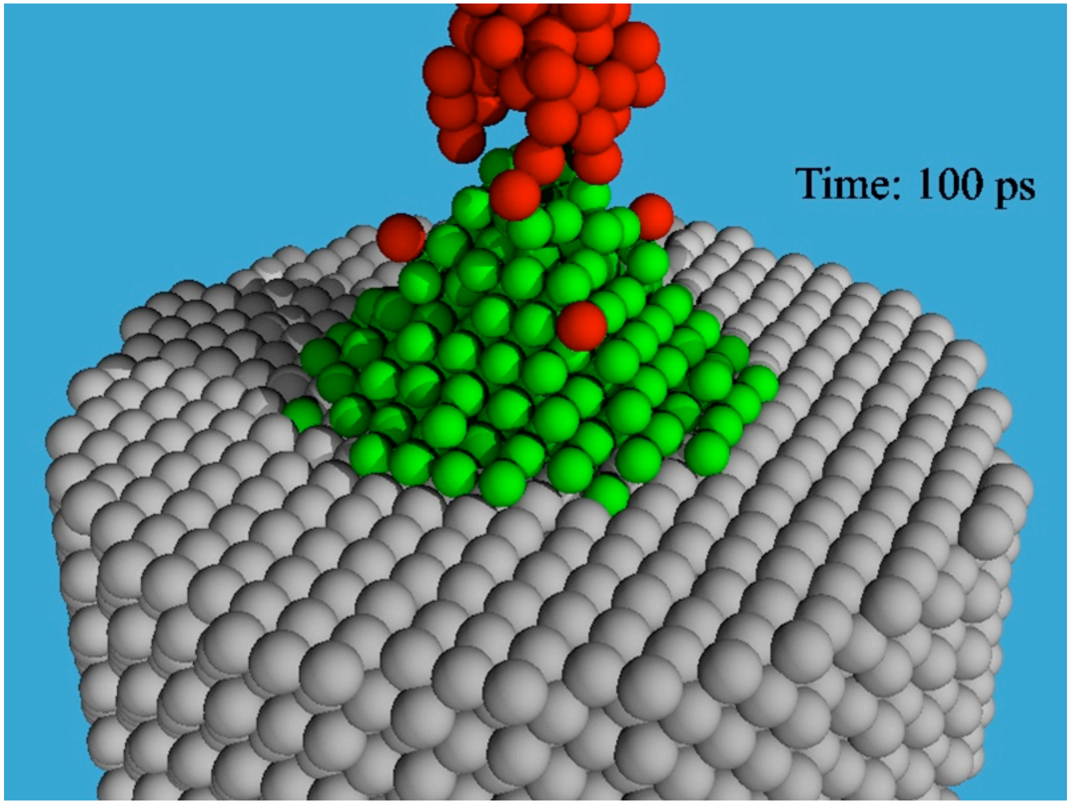
- All cavities and DC systems seem to breakdown around 6 – 10 GV/m.
- This is the approximate tensile stress limit for Copper.



Cluster Emission at High Fields

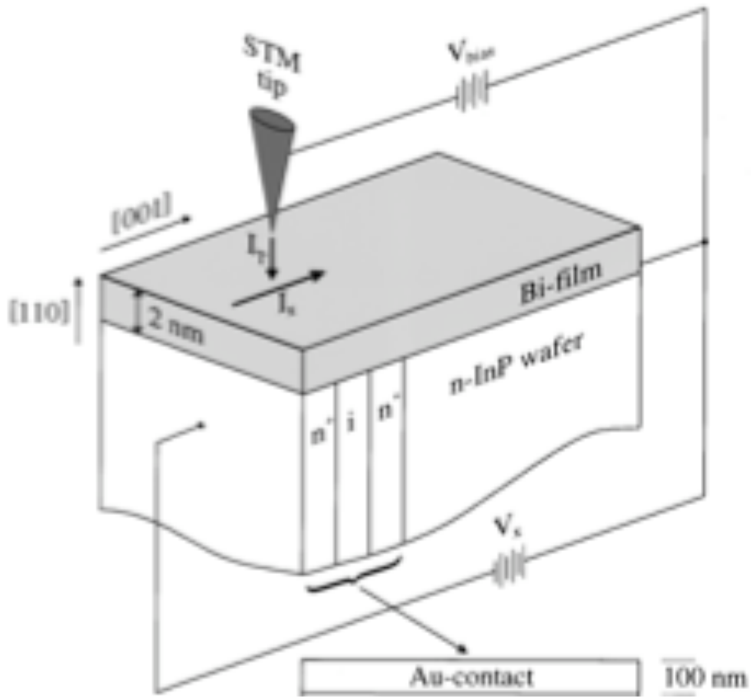
Z. Insepov

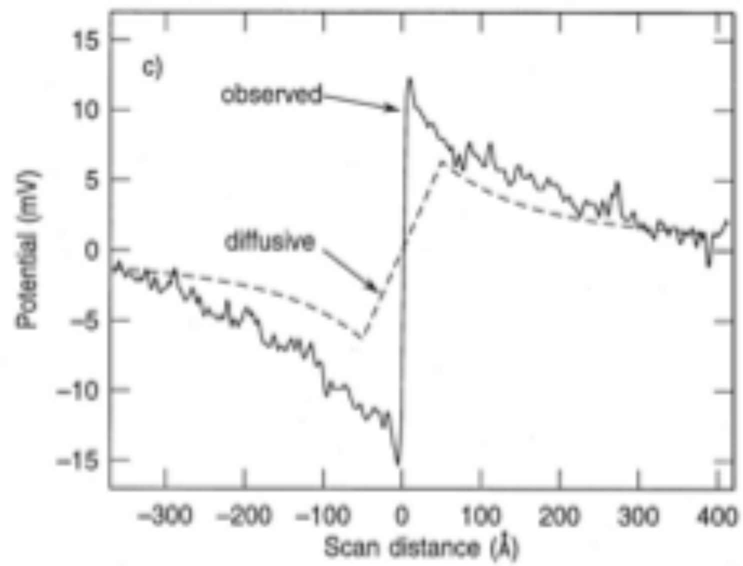
- Surfaces can emit single ions at high fields – at a fairly constant rate.
- Clusters can also be emitted by field emitters – these heat efficiently.
- Calculations done at a number of temperatures and fields.



High Current Densities

- When high current densities meet obstructions, very high fields can be produced.
- These fields can be seen with a scanning tunneling potentiometer.





Briner et.al. Phys Rev B 54, R5283 ('96)

Breakdown and Plasma Spots

P. Wilson

Initiation of Breakdown event:

1. A plasma spot is triggered at a field emission site

2. The surface area surrounding the plasma spot is heated by the back-bombardment.

3. Additional plasma spots can form in the neighborhood of an initial spot,

4. The combined heating exceeds the melting point

5. A macroscopic plasma ‘cloud’ then forms over the molten area. capable of emitting several kiloamperes of electrons and ~ten amperes of copper ions.

- Predictions of pulse length, electric field and material dependence.

Figure of Merit for Surface Melting

Metal	Cu	Au	Mo	SS	W	Nb	Be	Cr	Rh
$x_D^2/(x_p K T_m)\times 10^4$	1.24	2.96	0.73	0.75	0.84	0.72	0.32	0.55	0.94

Simulations of Breakdown

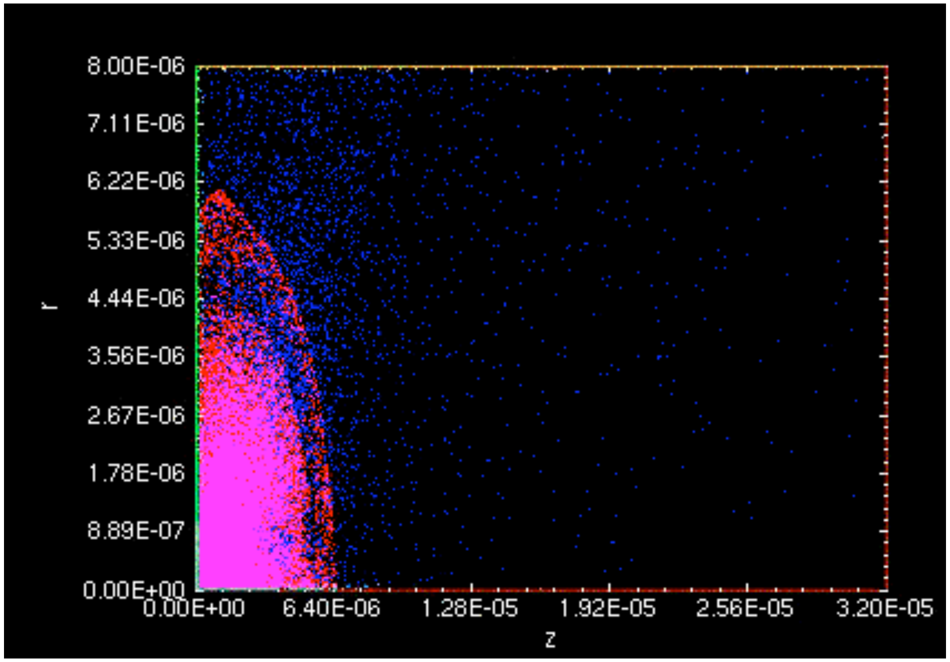
V.,Dolgashev,   G. Werner

Stages of Breakdown   TUP56

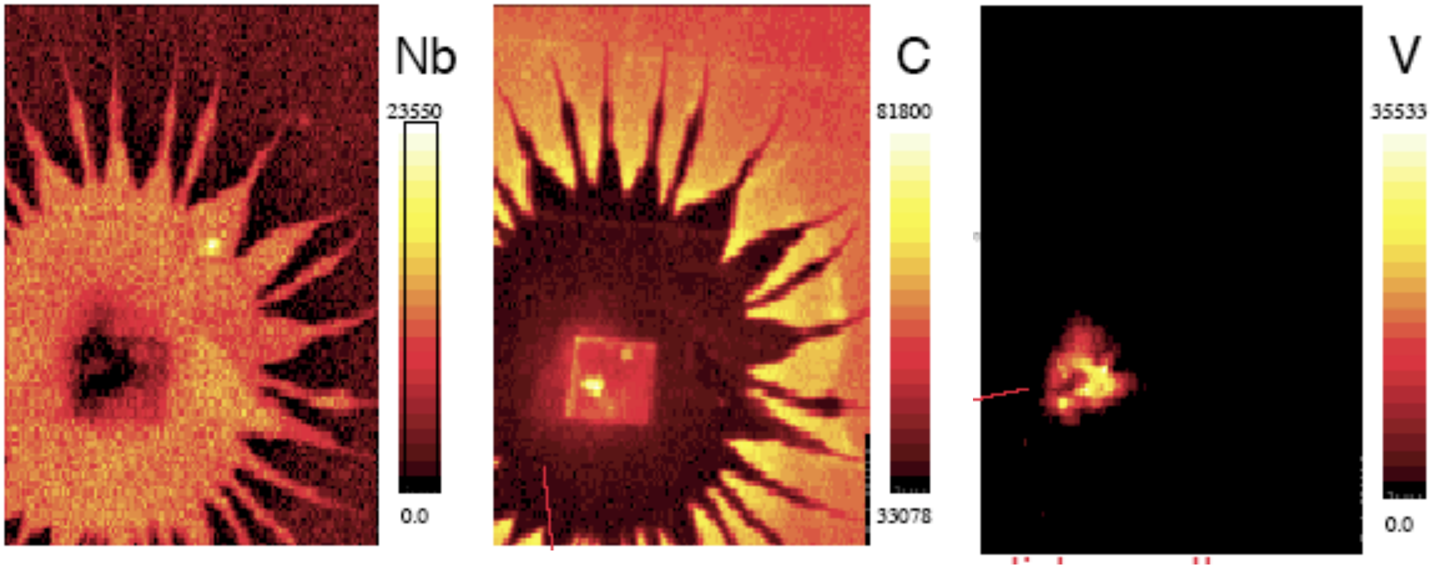
1. Enhanced field emission

2. Neutral vapor production
   Why so much so quickly?

3. Evolution of arc
   Expansion of plasma cloud
   Formation of starbursts and craters



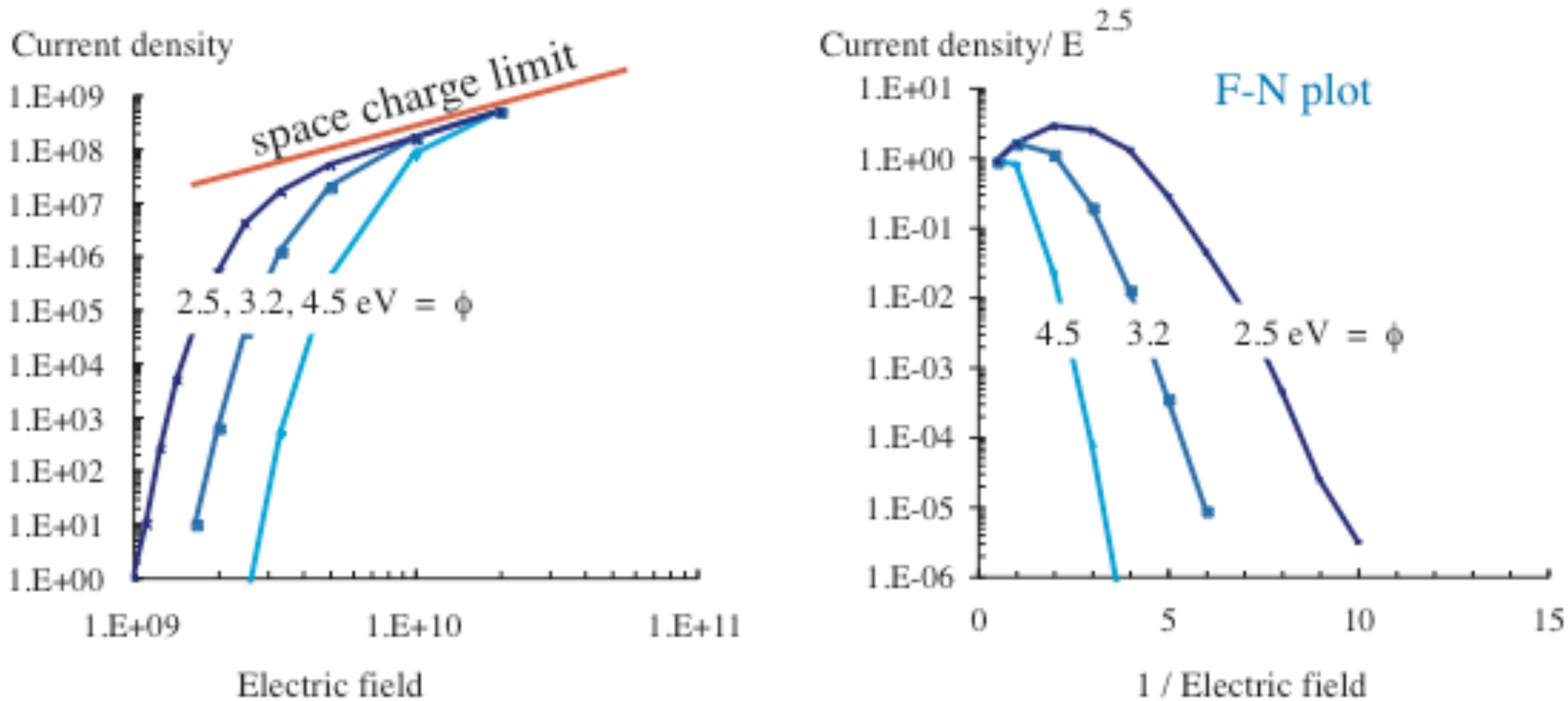
- Analysis of starbursts caused by V particle (Auger images).



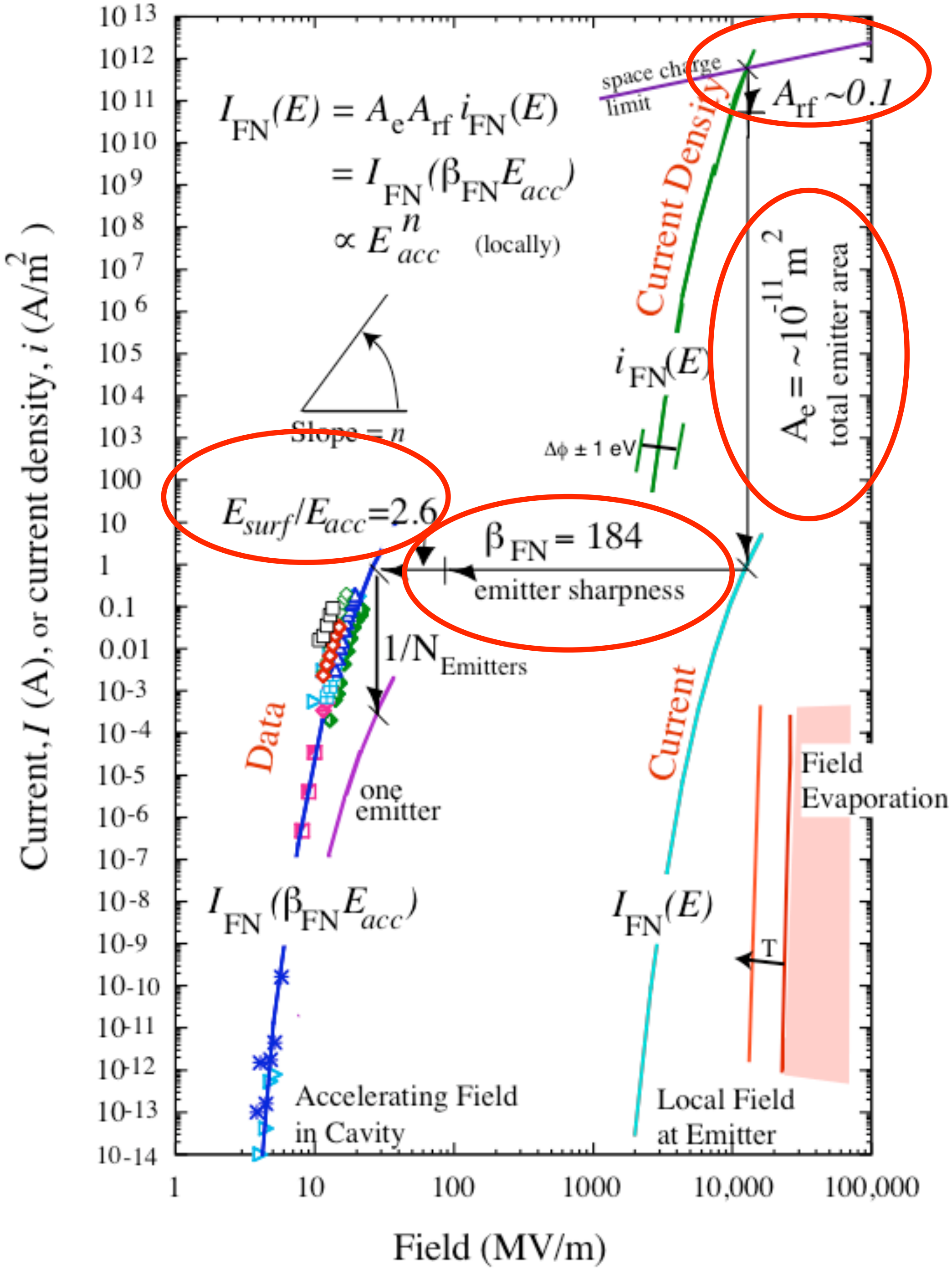
3. Misc. Questions and Comments

Fowler-Nordheim Plots (?)

- The standard way of analyzing field emission data is to use Fowler-Nordheim plots.
- They are non-intuitive.



Barbour, et.al. Phys. Rev., 92, 45 (1953), Dolan, Phys. Rev., 91, 510, (1953)



Current, I (A), or current density, i (A/m^2)
Field (MV/m)
$I_{FN}(E) = A_e A_{rf}\, i_{FN}(E)$
$= I_{FN}(\beta_{FN} E_{acc})$
$\propto E_{acc}^{\,n}$ (locally)
Slope = n
space charge limit
$A_{rf} \sim 0.1$
Current Density
$i_{FN}(E)$
$\Delta\phi \pm 1$ eV
$A_e = \sim 10^{-11}$ m^2
total emitter area
E_{surf}/E_{acc}=2.6
β_{FN} = 184
emitter sharpness
1/N$_{\text{Emitters}}$
Data
one emitter
Current
Field Evaporation
T
$I_{FN}(\beta_{FN} E_{acc})$
$I_{FN}(E)$
Accelerating Field in Cavity
Local Field at Emitter

Conclusions

- The physics of breakdown is not understood.

- Some of the basic processes may be similar:
  30 GHz, 11.4 GHz, 805 MHz, see βE = 6 - 12 GV/m local fields,
  superconducting, normal and DC systems affected by field emission,
  Field Ion Microscopes see sample failures at similar fields

- Huge power densities can be reached in microscopic volumes by
  high electric field: tensile stress limit / field emission
  high current densities: local Ohmic heating and E fields

- We need more good data and models.