Normal-conducting high-gradient rf systems
Part 2

Walter Wuensch, CERN

Lecture structure

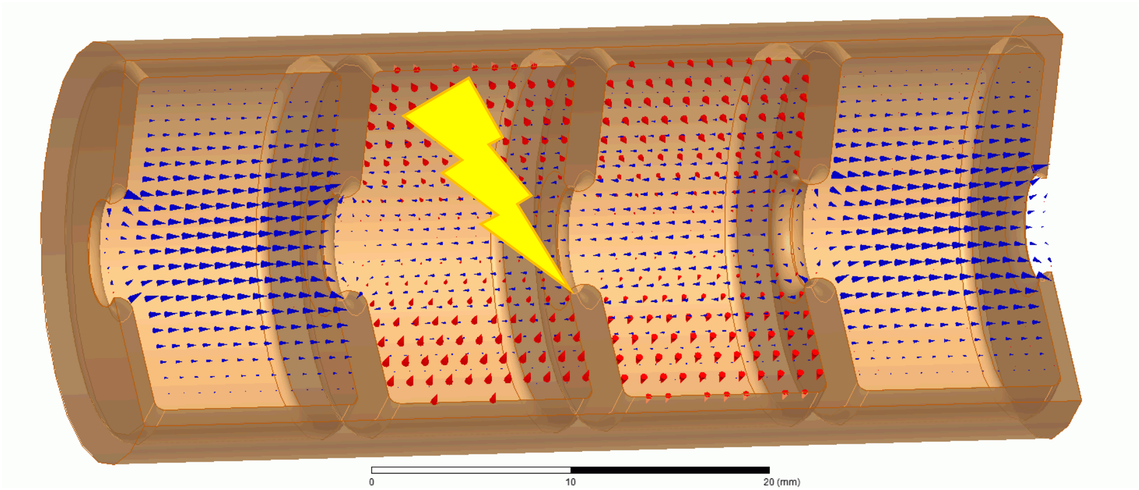
1. Basic concepts of travelling wave accelerating structures
2. High peak rf power production and manipulation
3. High field phenomena in accelerating structures

Now – The thrilling world of high gradients!

Complexity

- The underlying equations for the acceleration equations we have seen are Maxwell's equations and the Lorentz force – linear equations!
- When we raise the power we put in a structure, increasing the surface fields, we encounter a whole range of new phenomena.
- These phenomena include field emission and vacuum arcing and pulsed surface heating which, in various combinations, affect the beam and can damage a structure.
- We need to consider:
  - Electromagnetism
  - Material science
  - Plasma physics
  - Quantum mechanics - field and photo emission

Vacuum arc, a.k.a. breakdown

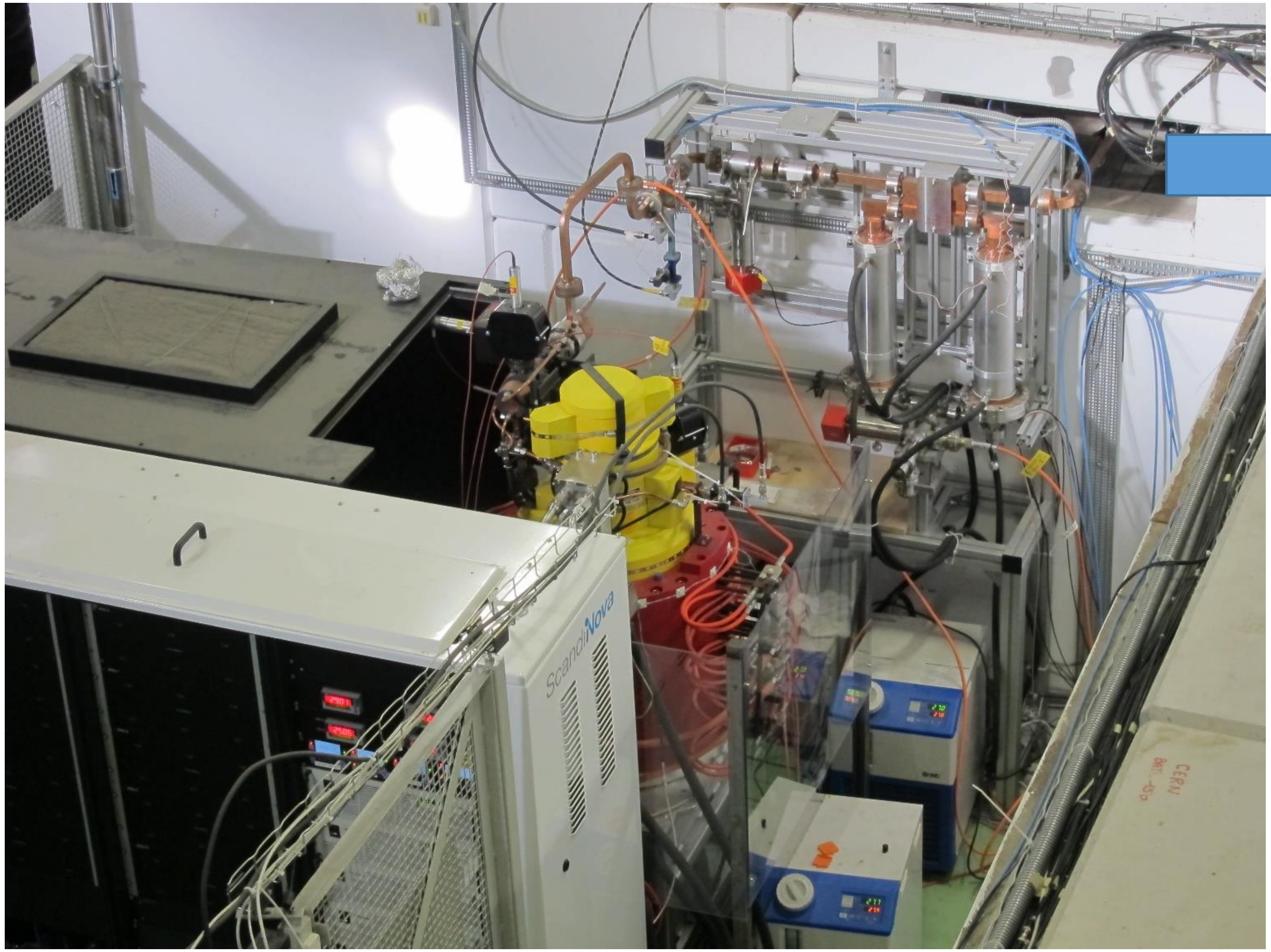


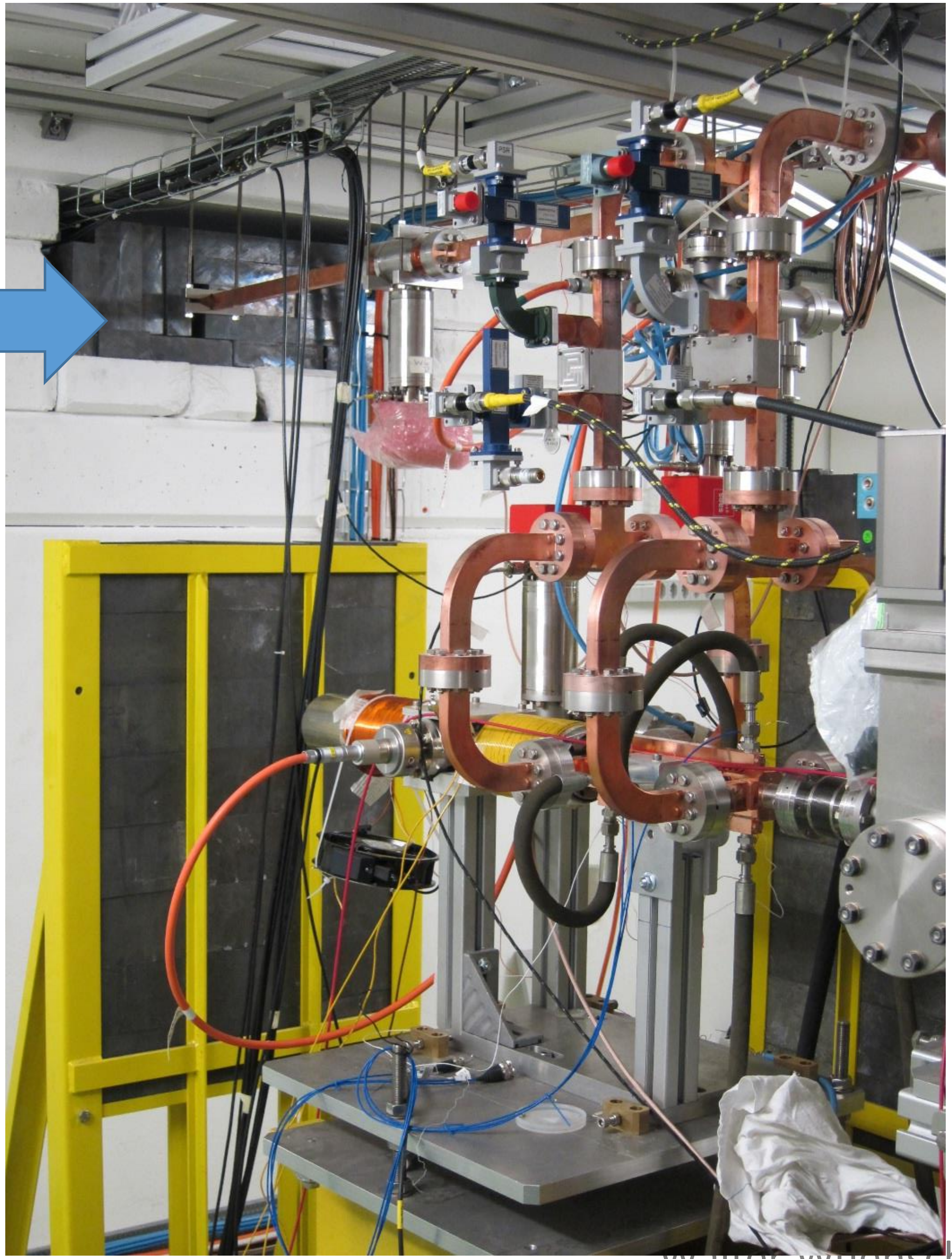
Some (round) numbers to keep in mind:

Average accelerating gradient - 100 MV/m
Peak surface electric field – 220 MV/m
Input power - 50 MW
Pulse length - 180 ns
Pulse energy of 12 J.

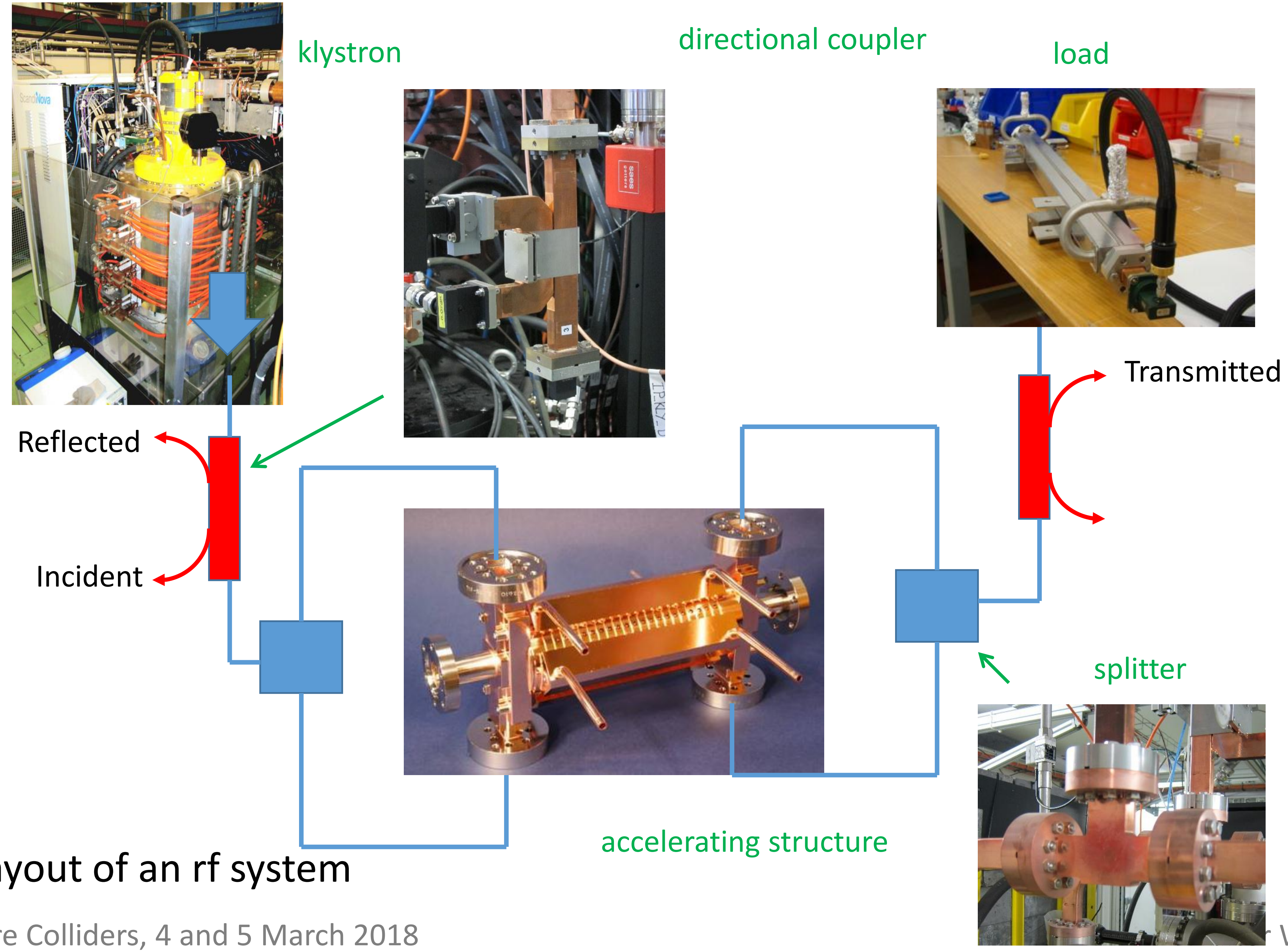
How do we experience breakdown in an rf system?
First introduce system.

This klystron modulator unit feeds…





this accelerating structure.

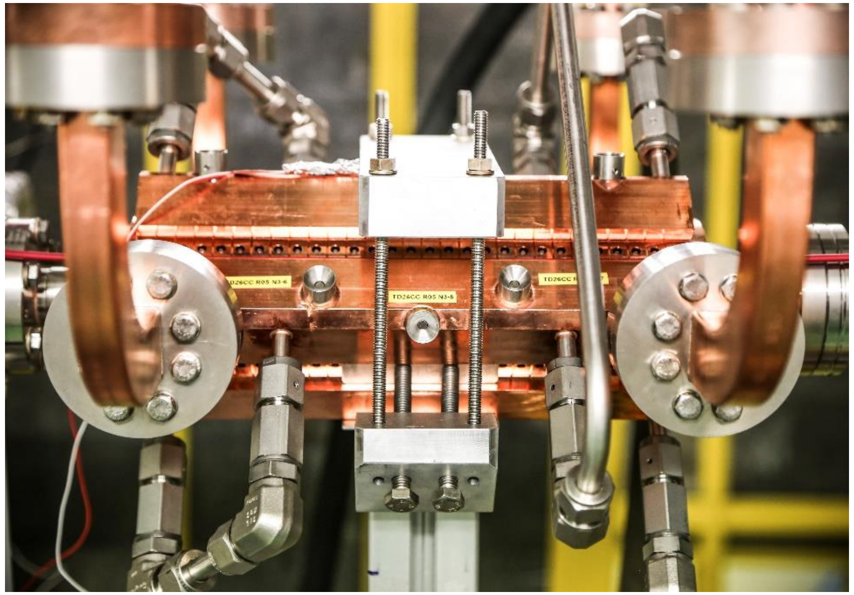


The basic layout of an rf system

rf signals

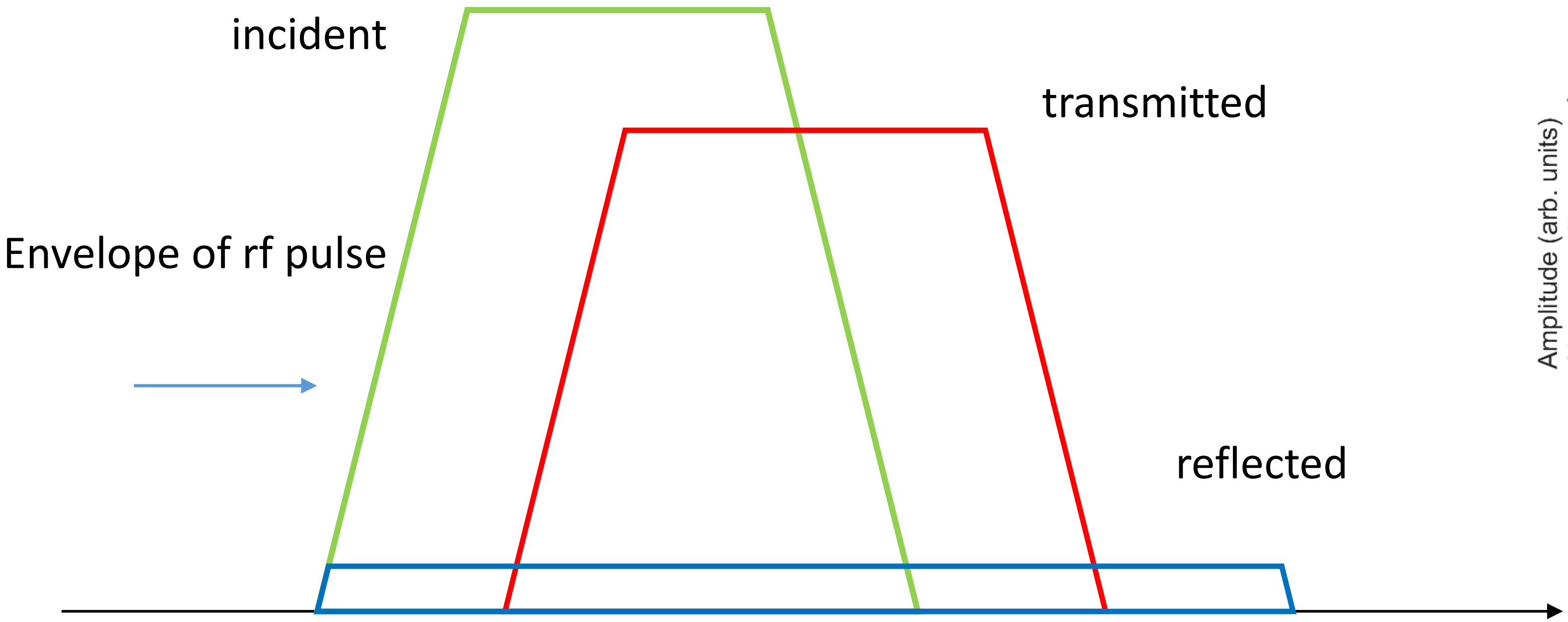
incident power

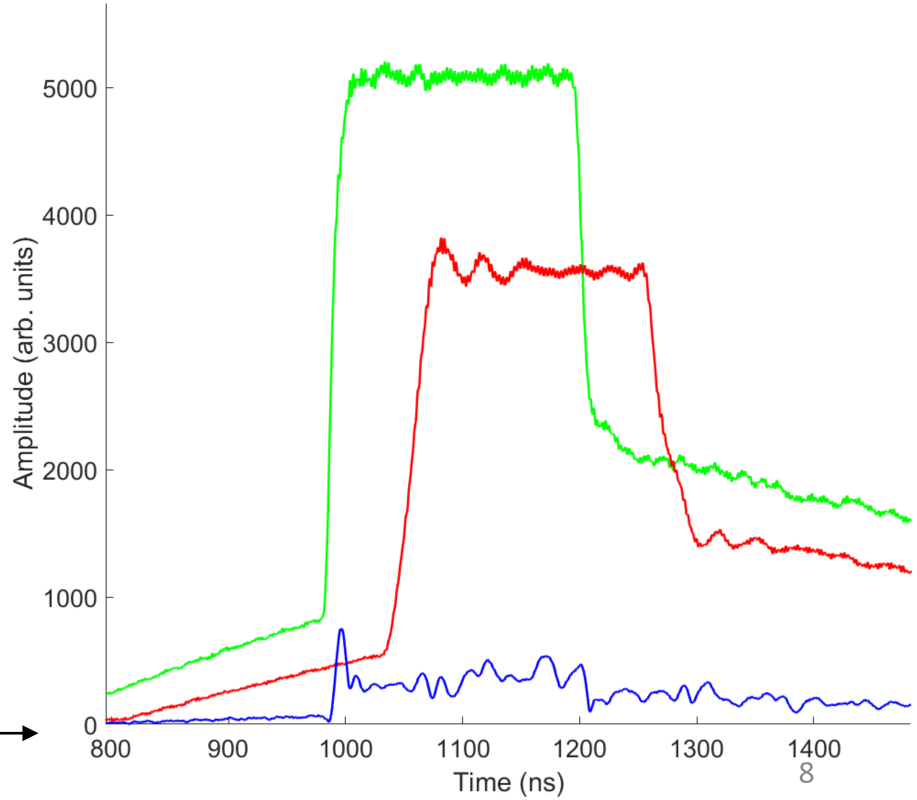
reflected power



transmitted power

From CLIC XBoxes

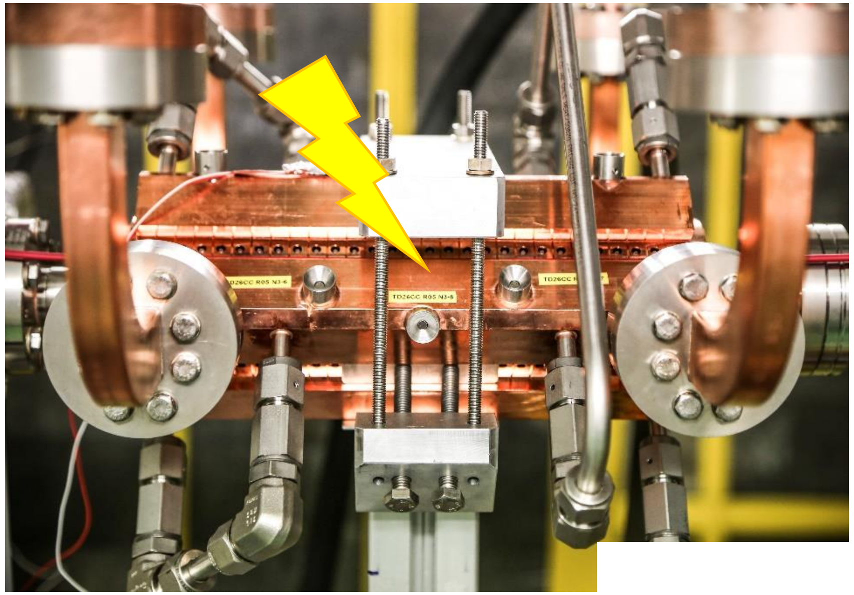




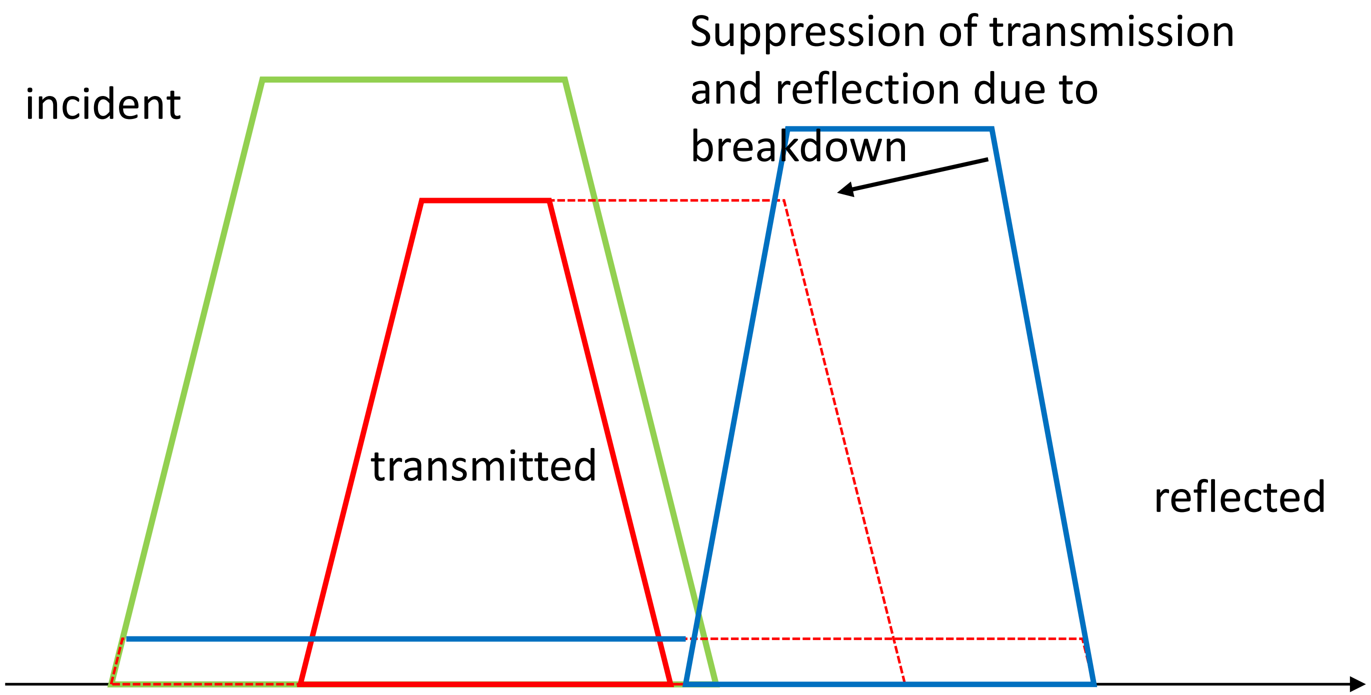
rf signals

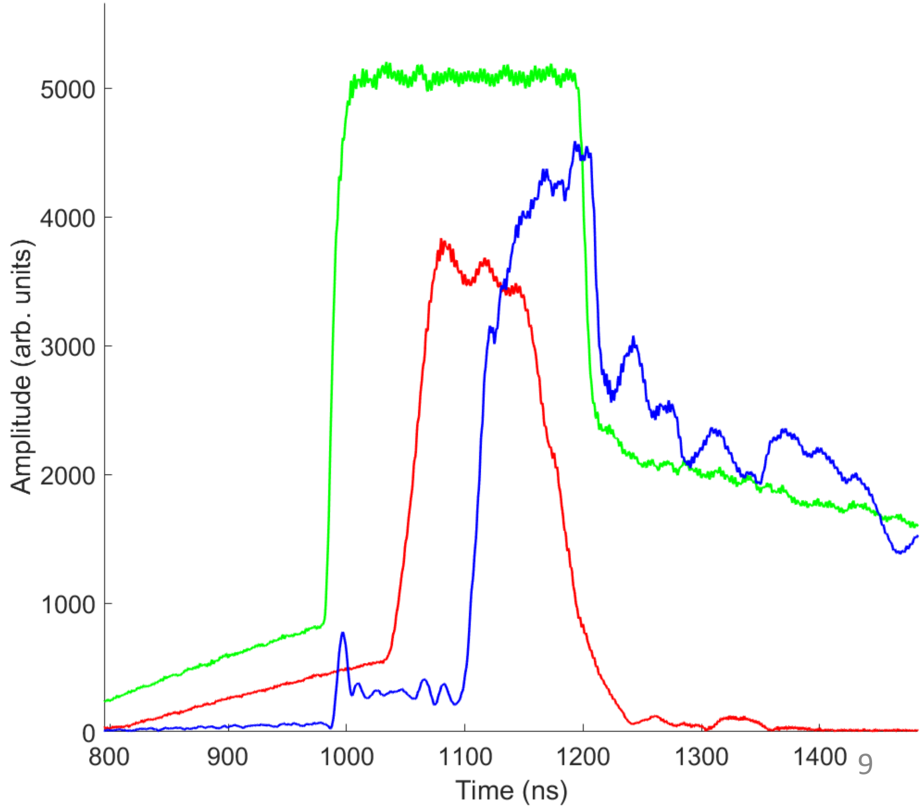
incident power

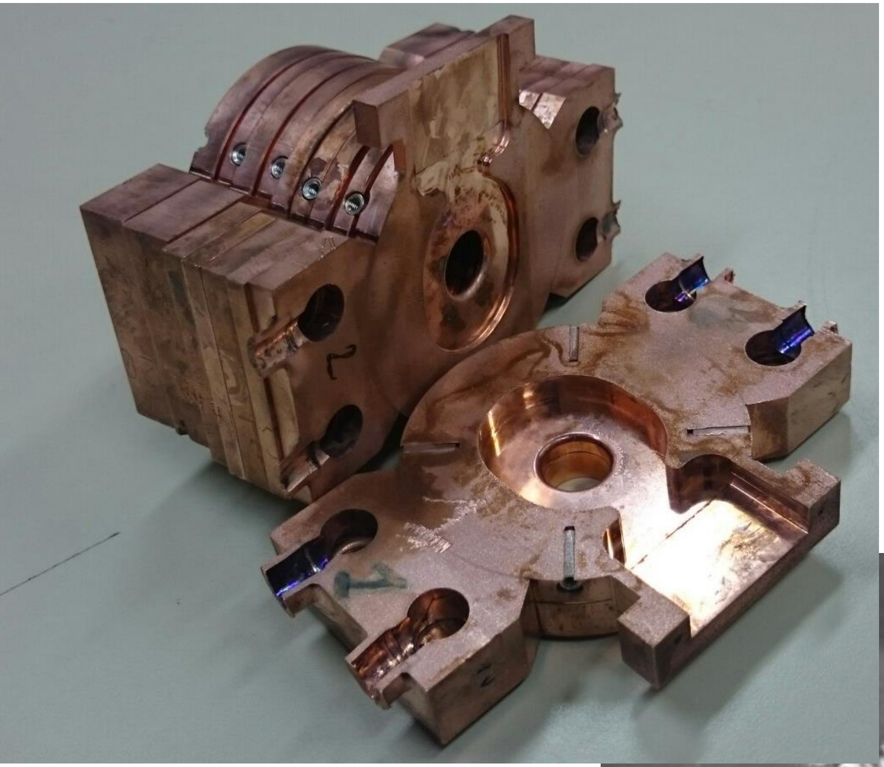
reflected power



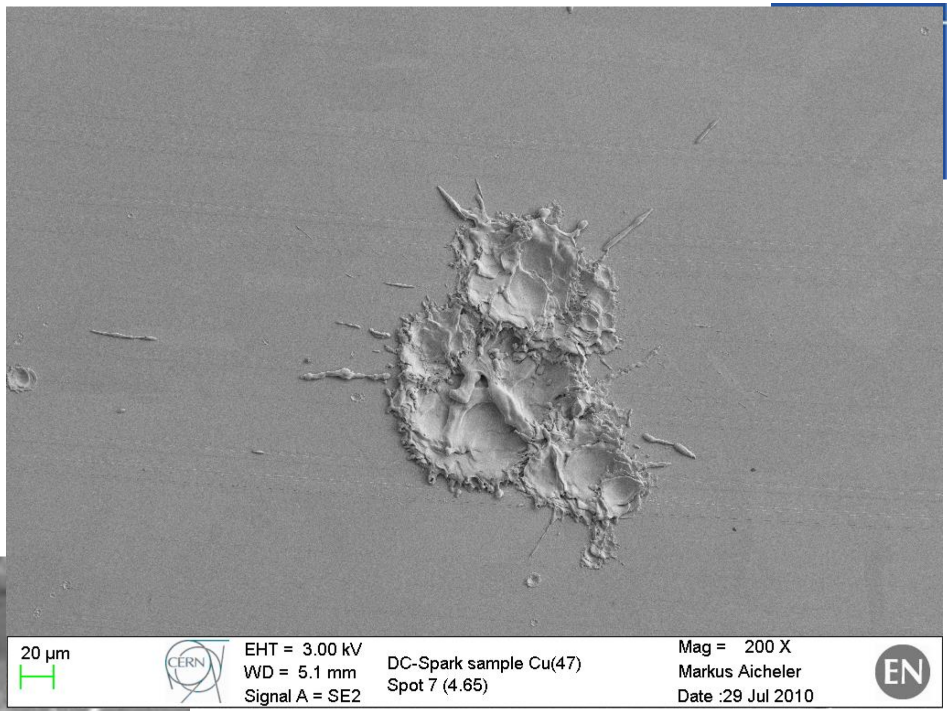
transmitted power

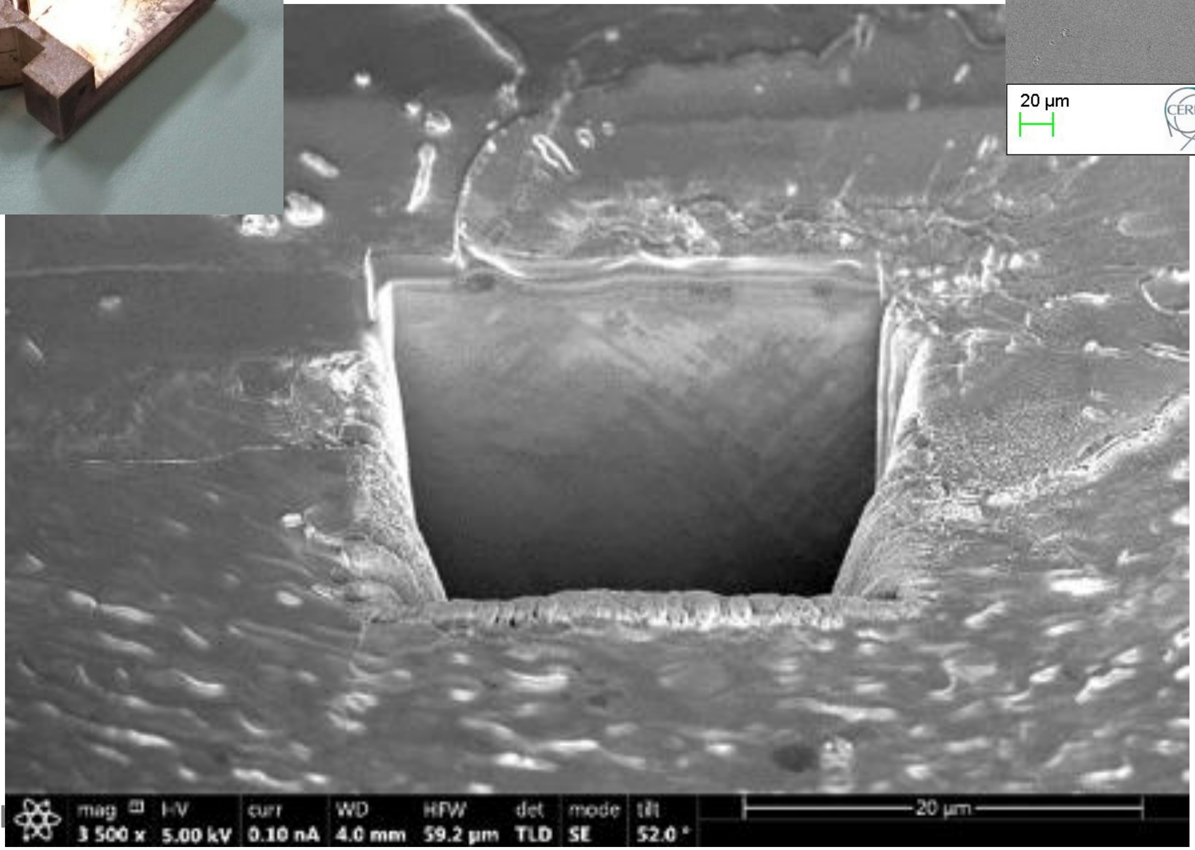






And with electron microscopy





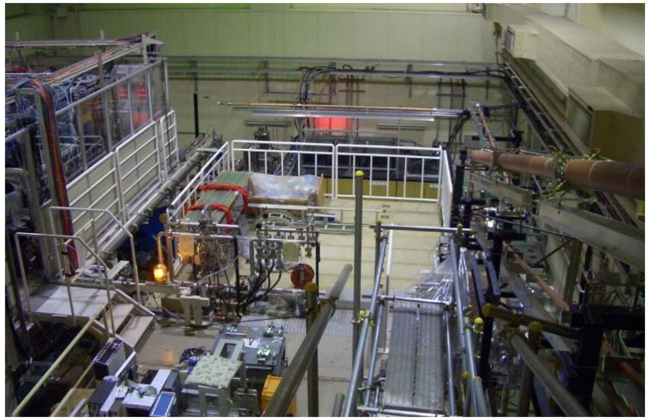
CLIC klystron-based X-band test stands around the world

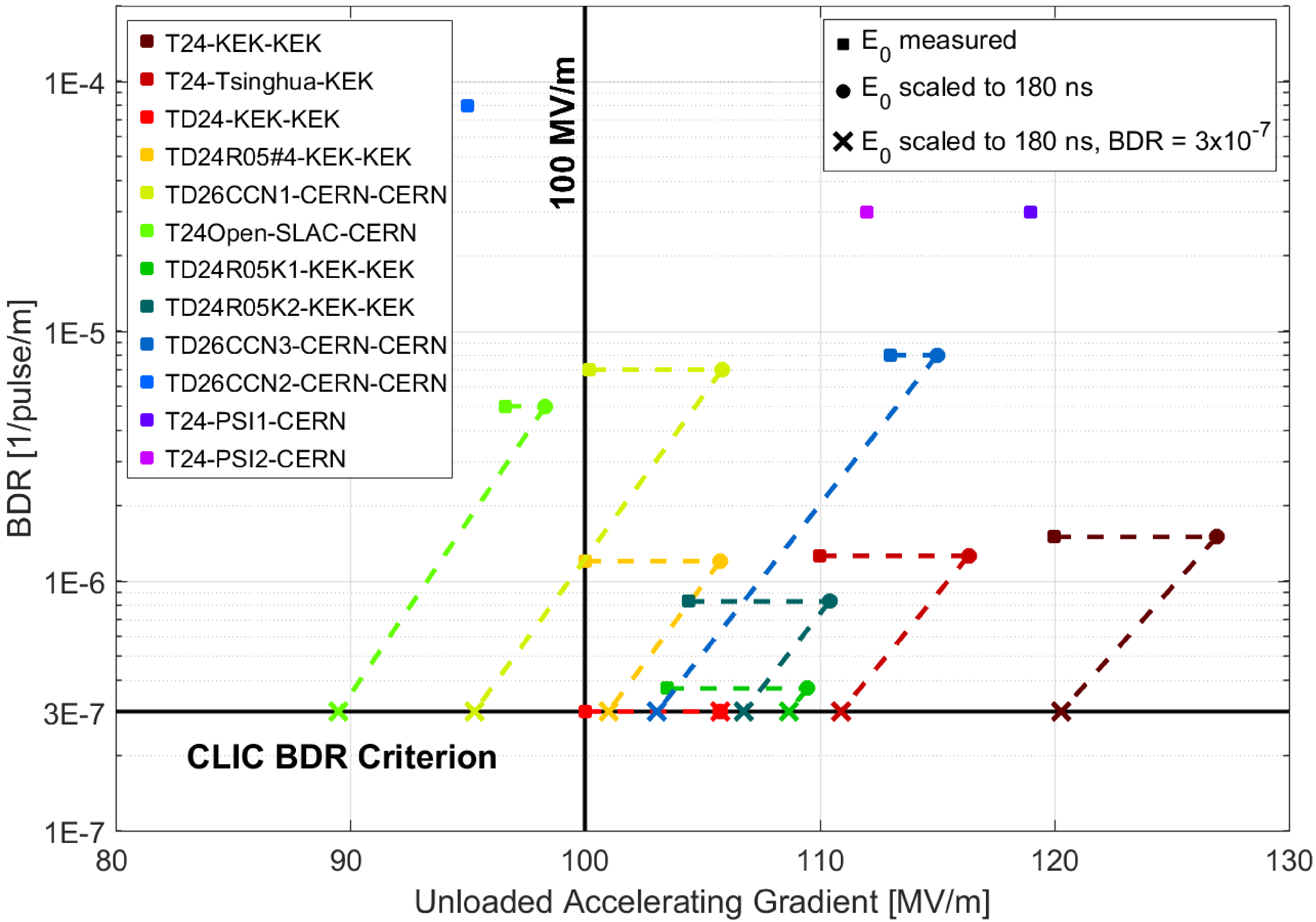
XBox-1: 50 MW, 50 Hz

XBox-2: 50 MW, 50 Hz

XBox-3: 50 MW, **400 Hz!**

NEXTEF
KEK




T24-KEK-KEK
T24-Tsinghua-KEK
TD24-KEK-KEK
TD24R05#4-KEK-KEK
TD26CCN1-CERN-CERN
T24Open-SLAC-CERN
TD24R05K1-KEK-KEK
TD24R05K2-KEK-KEK
TD26CCN3-CERN-CERN
TD26CCN2-CERN-CERN
T24-PSI1-CERN
T24-PSI2-CERN
E_0 measured
E_0 scaled to 180 ns
E_0 scaled to 180 ns, BDR = $3x10^{-7}$
100 MV/m
CLIC BDR Criterion
BDR [1/pulse/m]
1E-4
1E-5
1E-6
3E-7
1E-7
80
90
100
110
120
130
Unloaded Accelerating Gradient [MV/m]

Overview

Here is an overview of the breakdown process and the big questions so you have context as the lecture proceeds.
Breakdown is highly complex and multi-scale phenomenon so we need to zoom in and out of the problem – nm to mm, nsec to μsec, nA to 100 A etc.
We also need to look at practical effects and their physical explanation.

Breakdown steps:

- Applied electric field causes electron and neutral atom emission from cathodic surfaces.
- This emission is concentrated at sites which are surface features and, in the early stages of operation, contaminants.
- Electrons ionize neutral atoms.
- Ions are accelerated back to the cathode.
- The ions sputter more, starting avalanche that leads to a plasma just above surface.
- Plasma sheath forms, setting up multi GV/m surface fields and strong electron emission.
- Electrons interfere with rf transmission.

Some of the big questions:

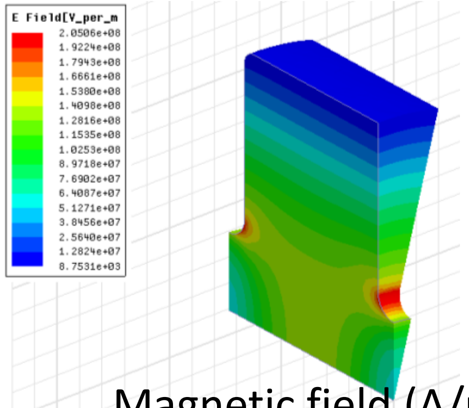
- Why does gradient and surface field depend so much on rf geometry?
- What is evolving during conditioning and what exactly is getting better?
- What is the origin of breakdown rate vs gradient and pulse length dependencies?
- What is the nature of the sites which will lead to breakdown?
- What drives the statistics of breakdown occurrence?
- What is the nature of the breakdown sites and what is the origin of the β correction?

Dependence of gradient on rf geometry

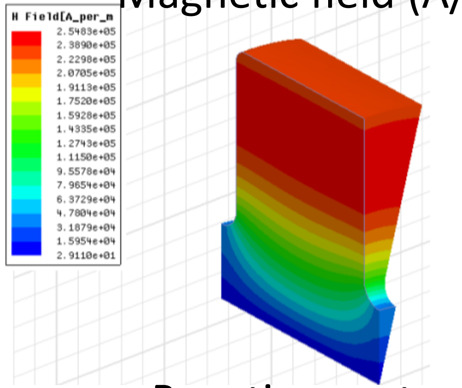
- Different design structures achieve different gradients. Big question for us have been:
  - Can we quantify the dependence of achievable accelerating gradient on geometry?
  - Where does such a geometrical dependency come from?
- Trying to understand, derive and quantify geometrical dependence has been a significant effort because an essential element of the overall design and optimization of the collider, especially through interaction with beam.
- You might think that breakdown is determined by surface electric field, but it turns out to be more complicated than that.

Geometric dependency

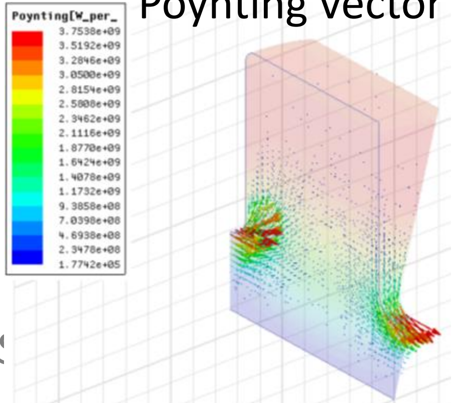
Electric field (V/m)

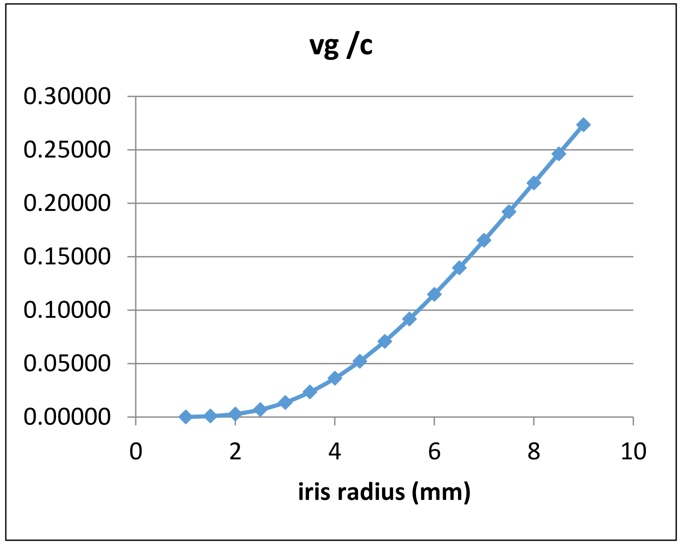


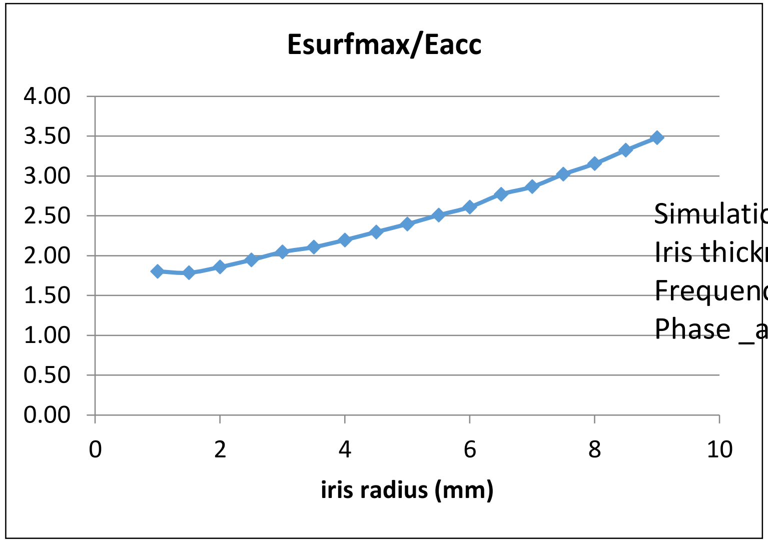
Magnetic field (A/m)



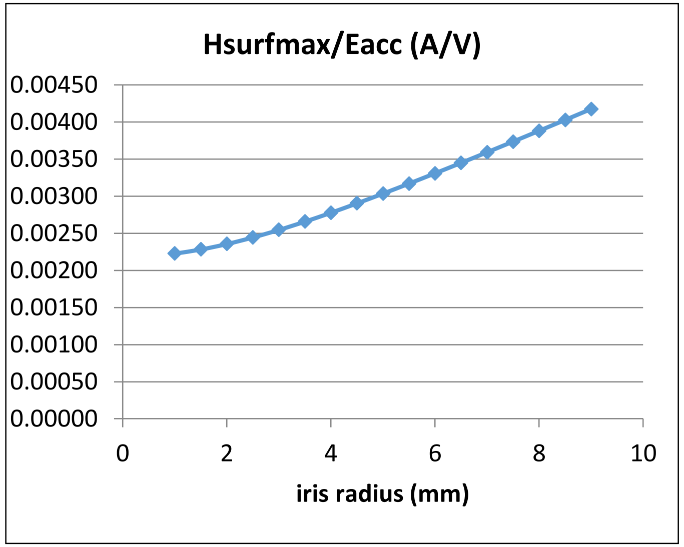
Poynting vector (W/m^2)

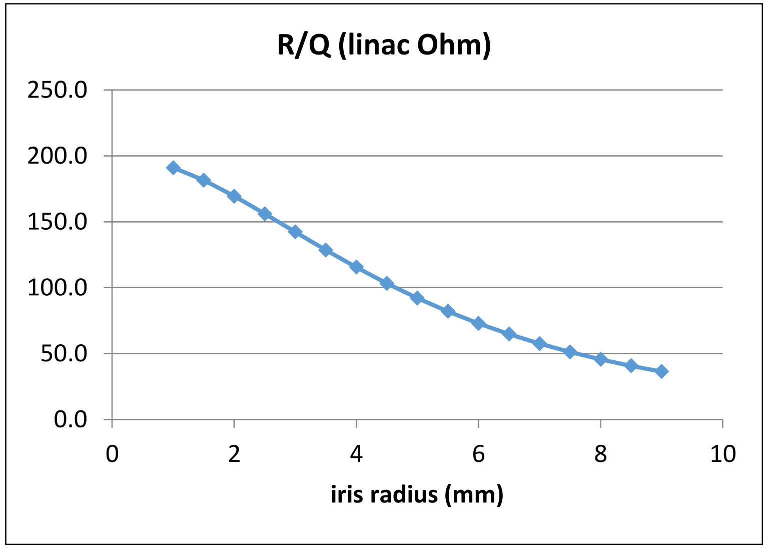






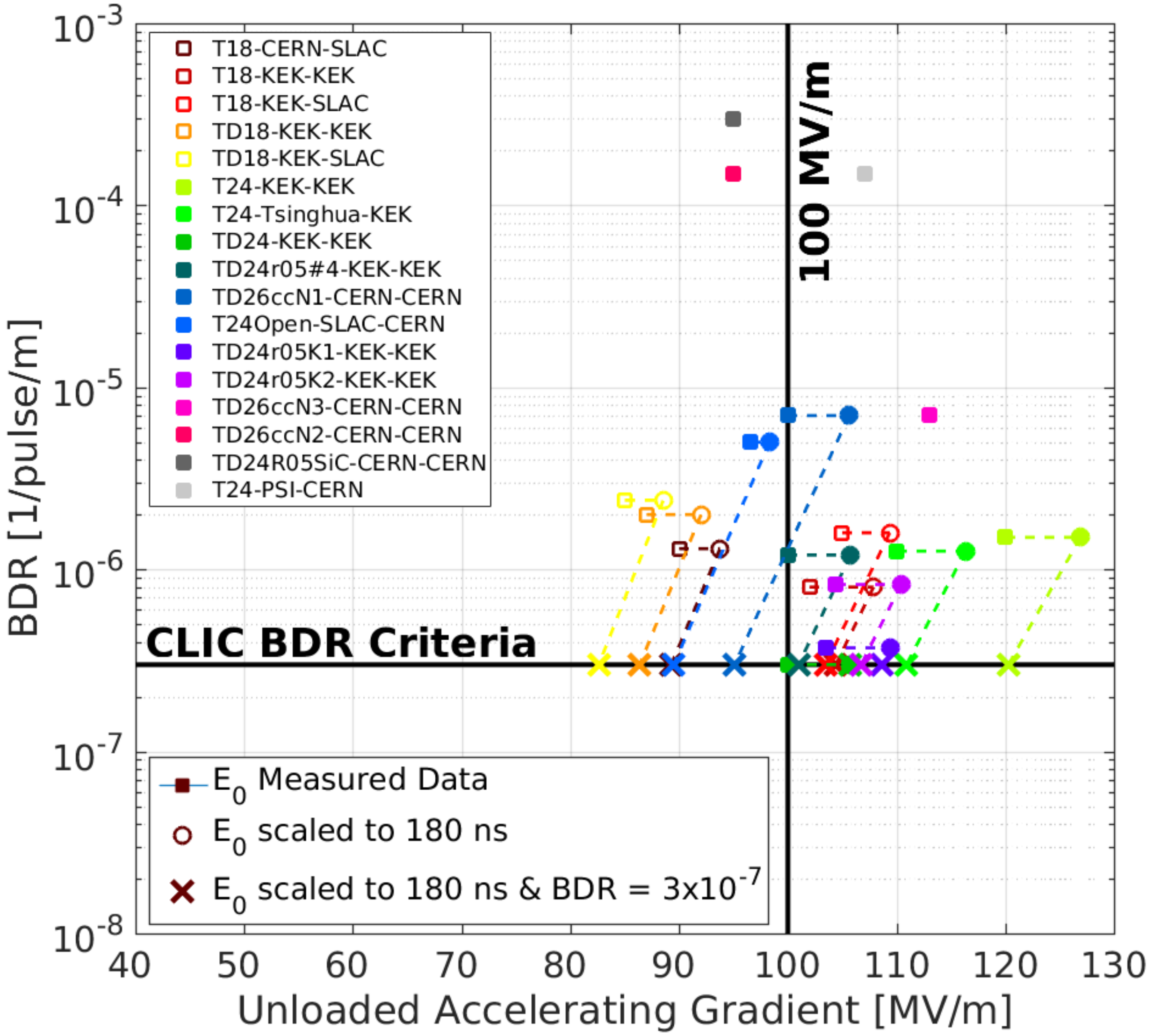
Simulation in HFSS12
Iris thickness: 1.66mm
Frequency: 11.424GHz
Phase _adv/cell: 120 degree





Performance of two different series of structures.

The important point is that the accelerating gradient, and maximum peak surface electric field is different at the end of the tests.
When including more structures, the effect is even more pronounced.

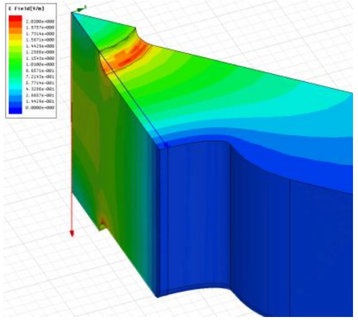


This has resulted in the development of two power-density based design criteria:

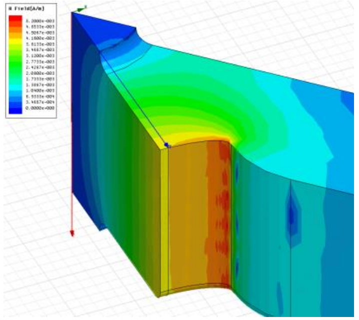
$$\frac{P}{\lambda C} = \text{const}$$

global power flow

E_s/E_a



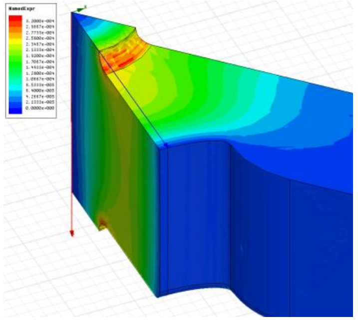
H_s/E_a



$$S_c = \text{Re}(\mathbf{S}) + \frac{1}{6}\text{Im}(\mathbf{S})$$

local complex power flow

S_c/E_a^2



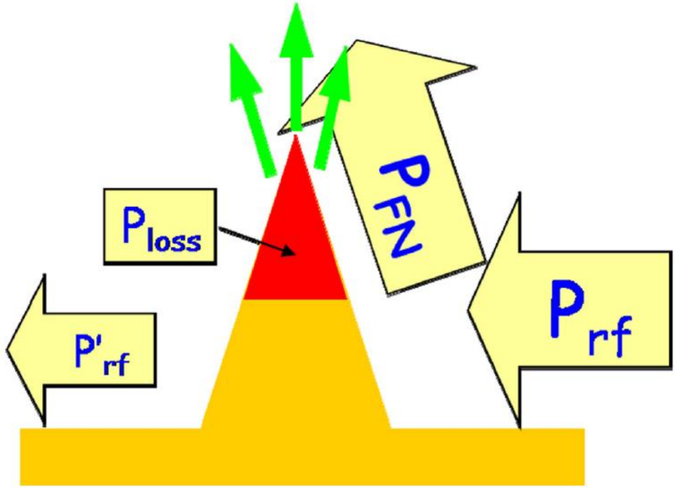


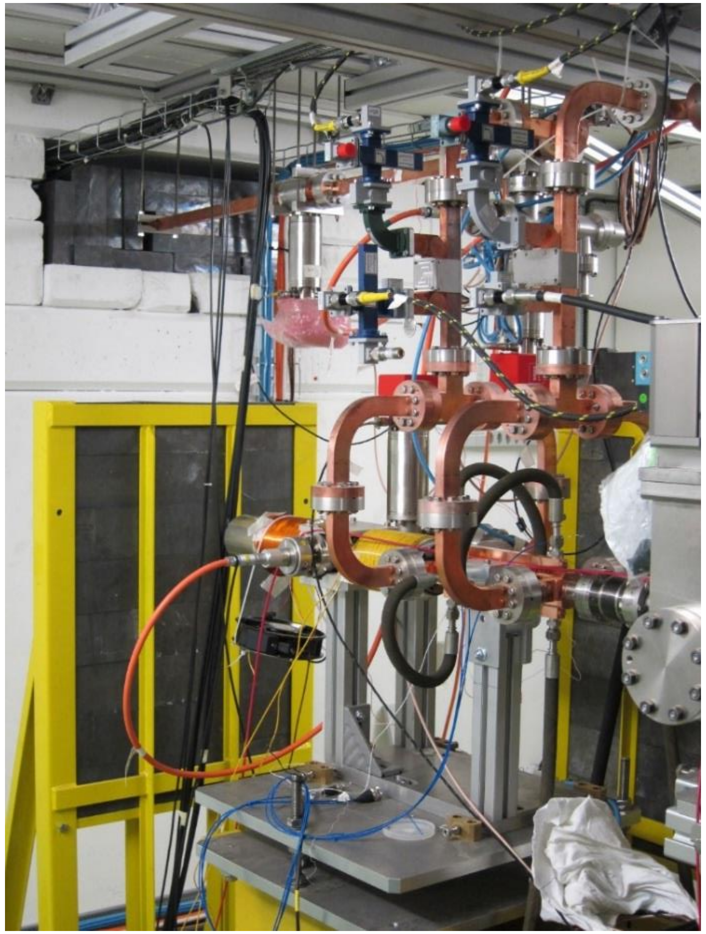
FIG. 9. (Color) Schematic view of the power flow balance near the tip.

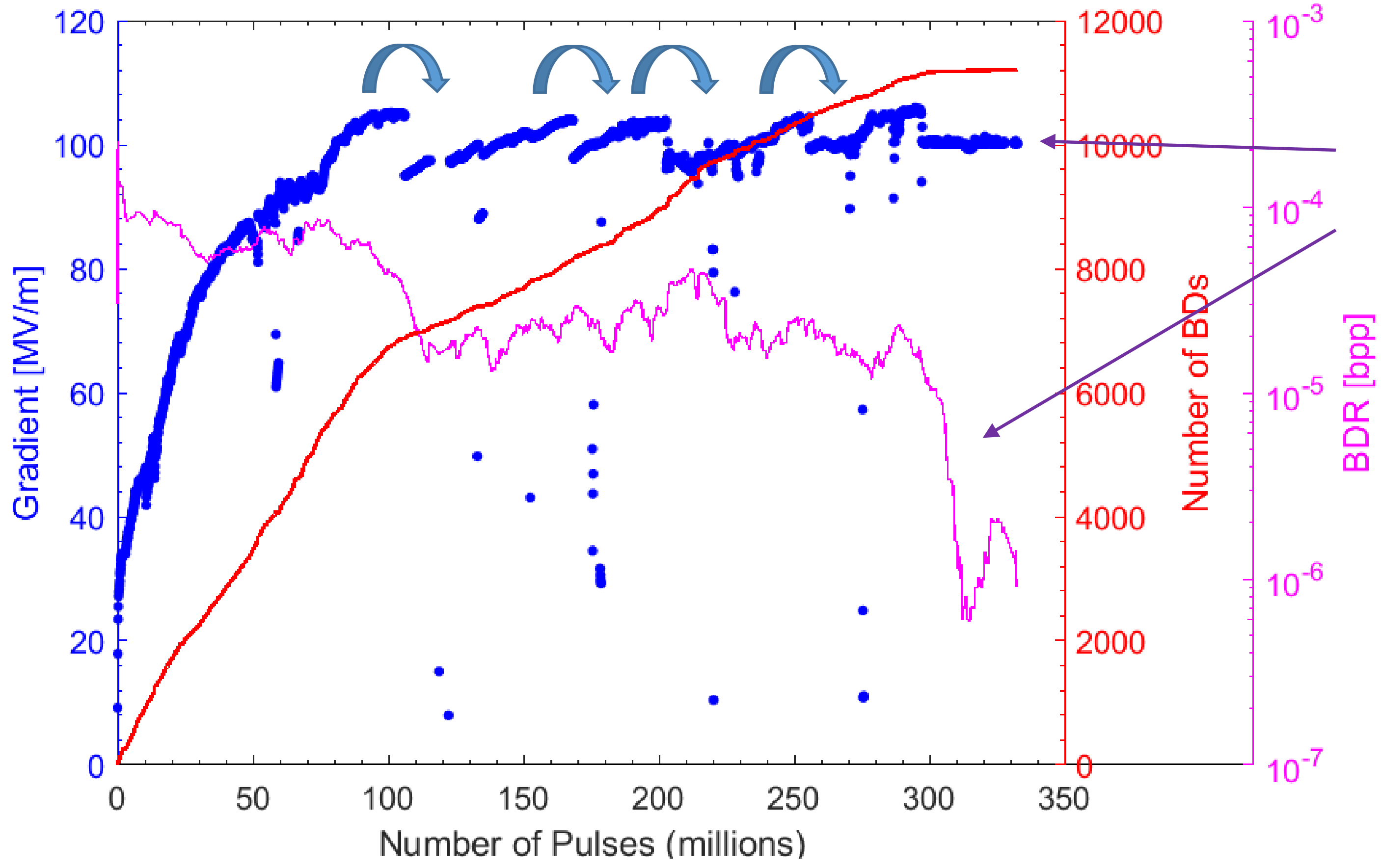
S_c is typically the quantity which dominates the design of high-gradient travelling wave structures.

A. Grudiev, S. Calatroni, and W. Wuensch, *New local field quantity describing the high gradient limit of accelerating structures,* Phys. Rev. ST Accel. Beams 12, 102001 (2009)

Conditioning

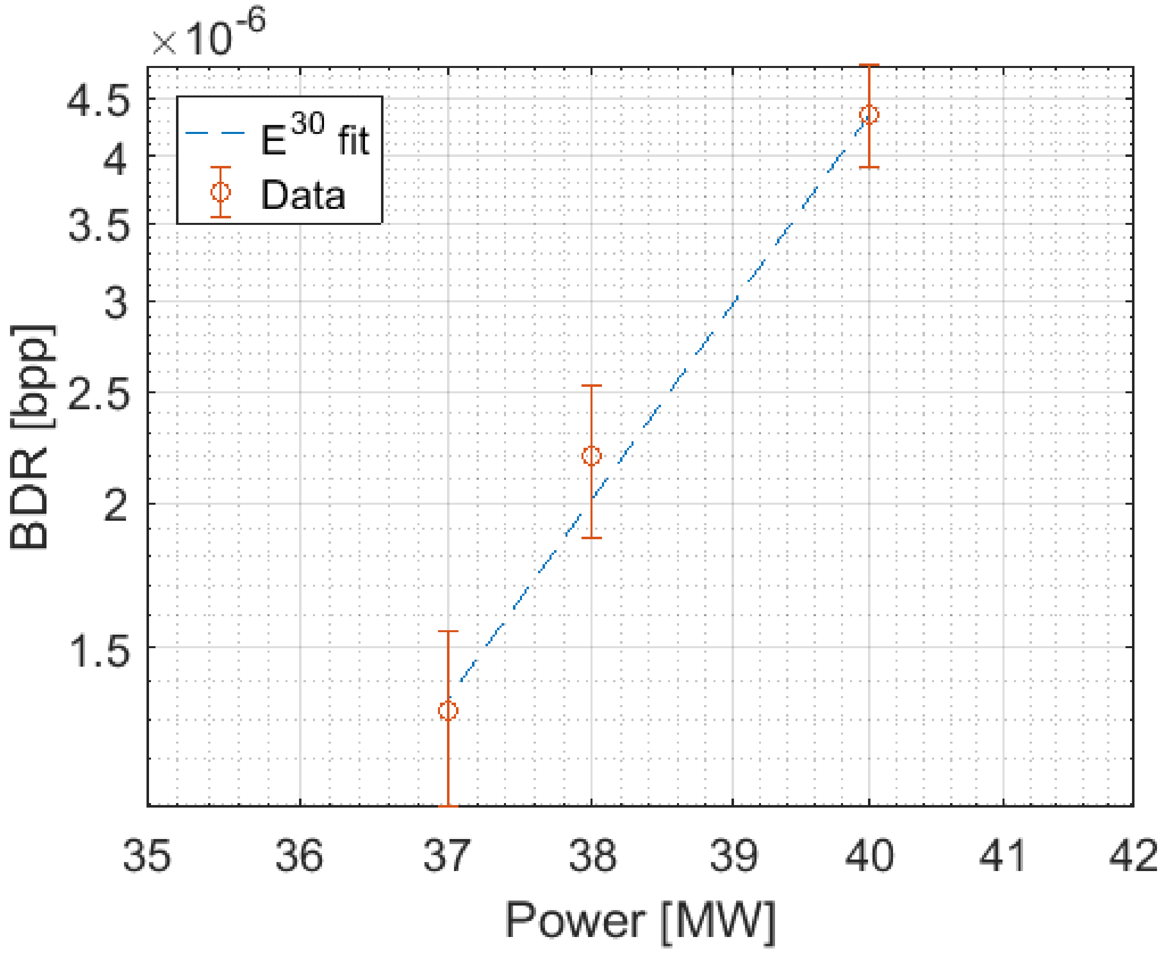
Accelerating structures do not run right away at full specification – pulse length and gradient need to be gradually increased while pulsing. Typical behaviour looks like this:





4 million pulses per day at 50 Hz

BDR dependence



Data taken in XBox-2 with TD26CC structure, T. Lucas

Regularly observed dependence:

$$BDR \propto E^{30}\tau^{5}$$

Physical model based on defect formation

$$BDR \propto e^{\frac{-E^{f}+\varepsilon_0 E^2 \Delta V}{k_b T}}$$

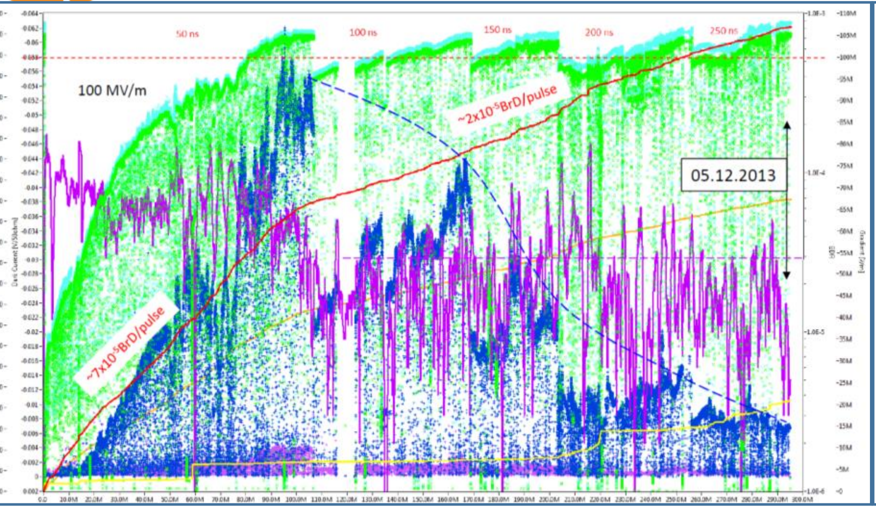
$$E^{f} = 0.8\ eV$$

$$\Delta V = 0.8 \times 10^{-24} m^{3}$$

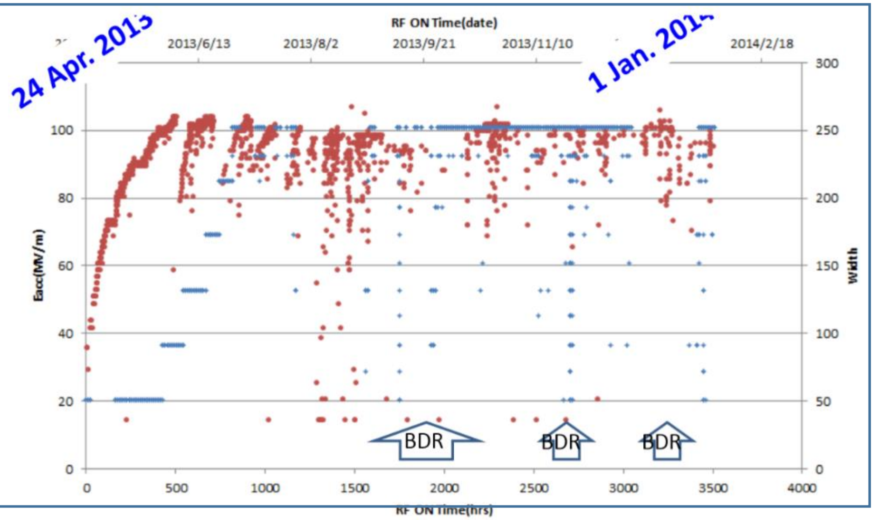
K. Nordlund, F. Djurabekova, *Defect model for the dependence of breakdown rate on external electric fields*, Phys. Rev. ST Accel. Beams 15, 071002 (2012)

Comparison of three similar structures

TD26CC (XBOX-1)



TD24R05#4 (NEXTEF)

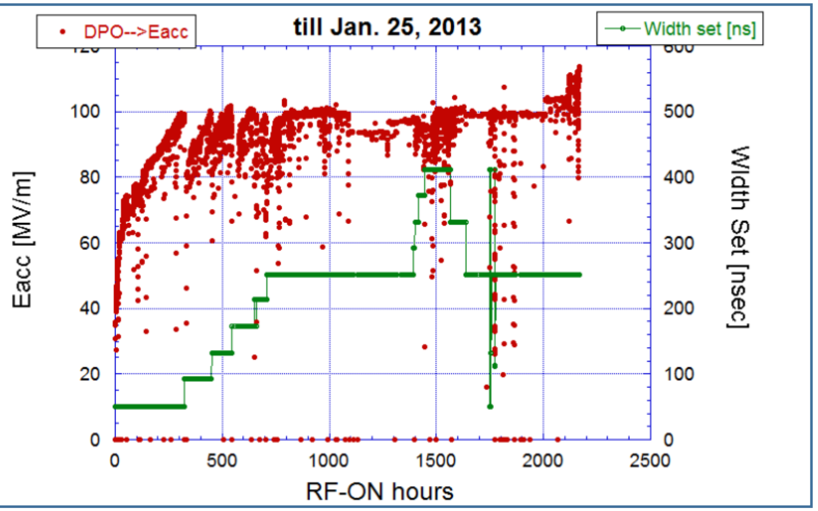


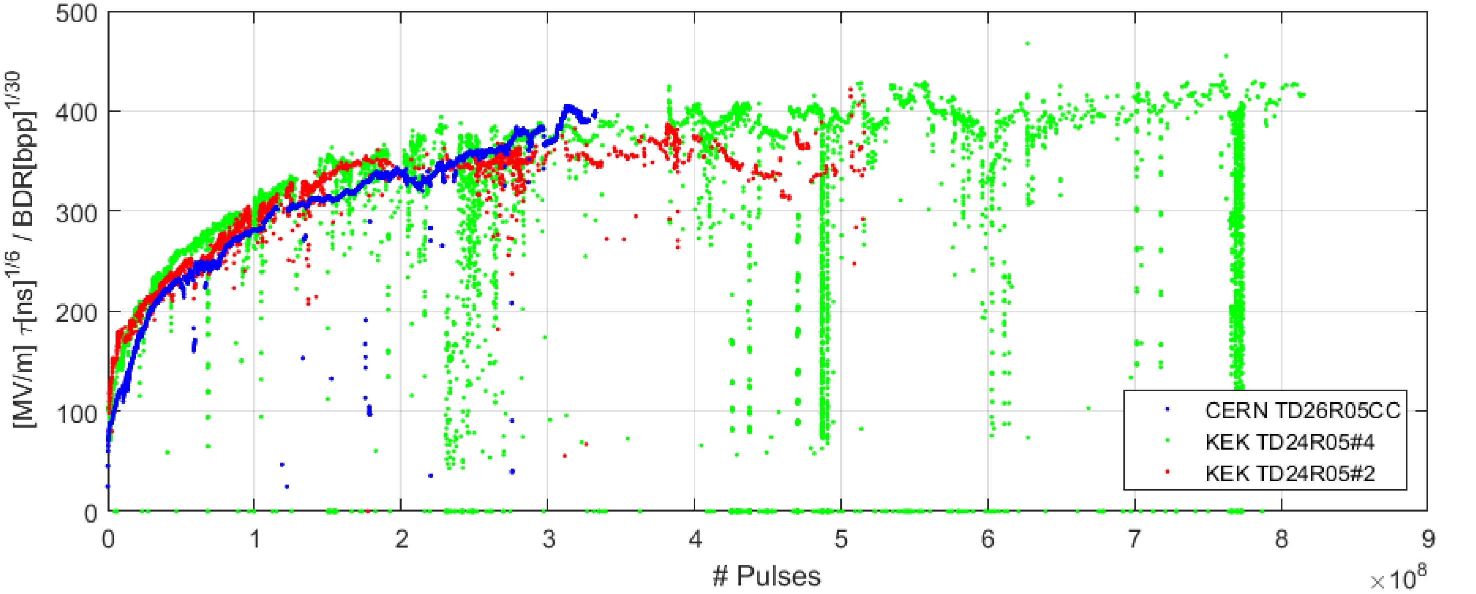
We normalize by:

$$BDR \propto E^{30}\tau^{5}$$

And get

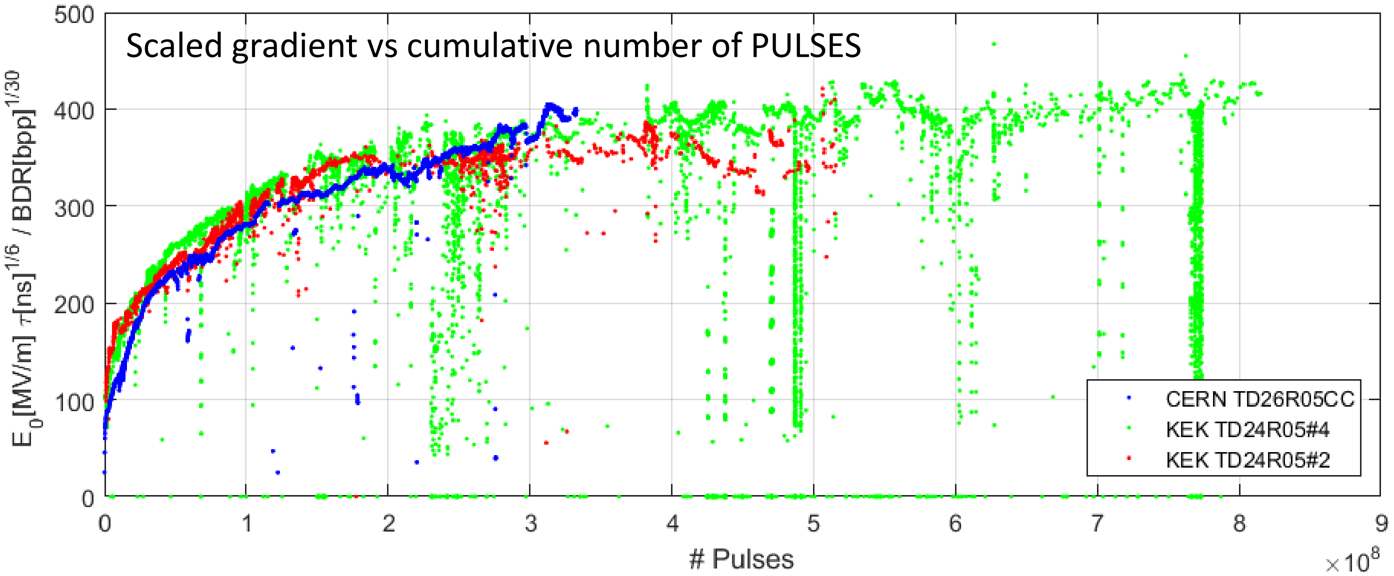
TD24R05#2 (NEXTEF)



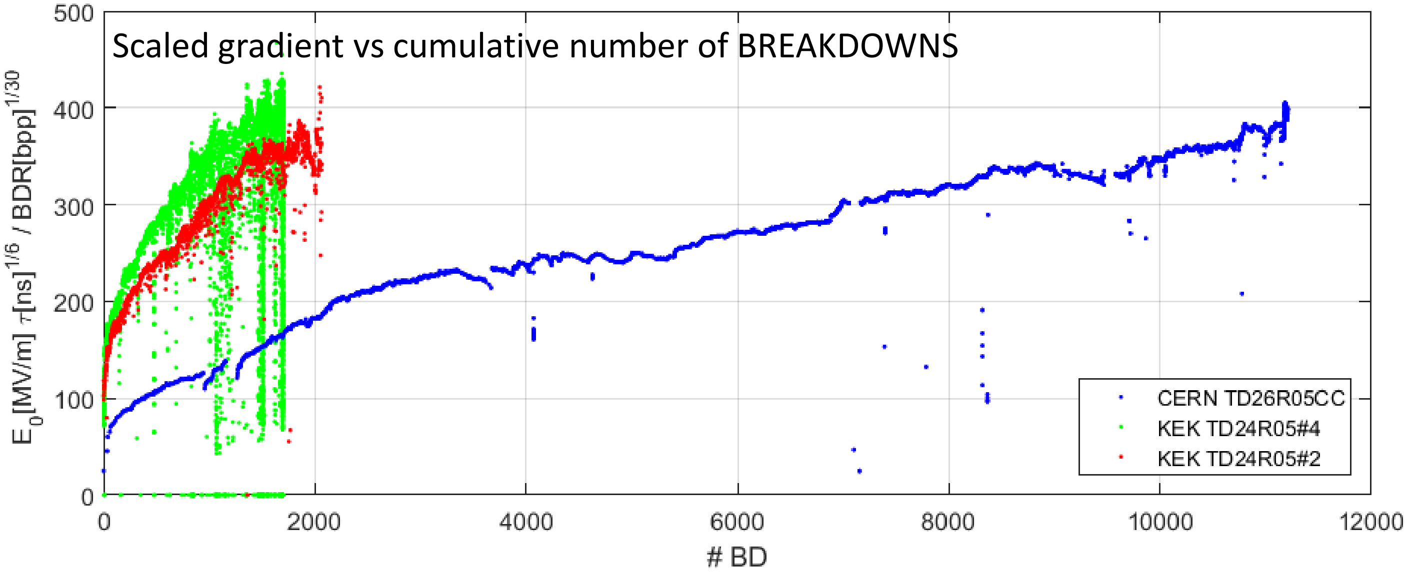


Interpretation: Conditioning is a reproducible process which implies a well defined physical mechanism.

Comparing conditioning



vs. number of pulses

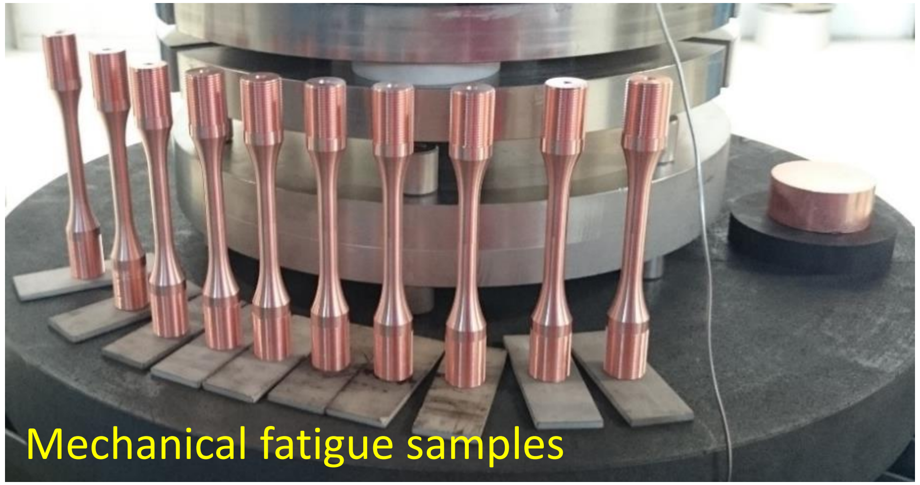


Interpretation – conditioning proceeds as the number of pulses *not* the number of breakdowns. This implies a steady modification of the structure for each pulse.

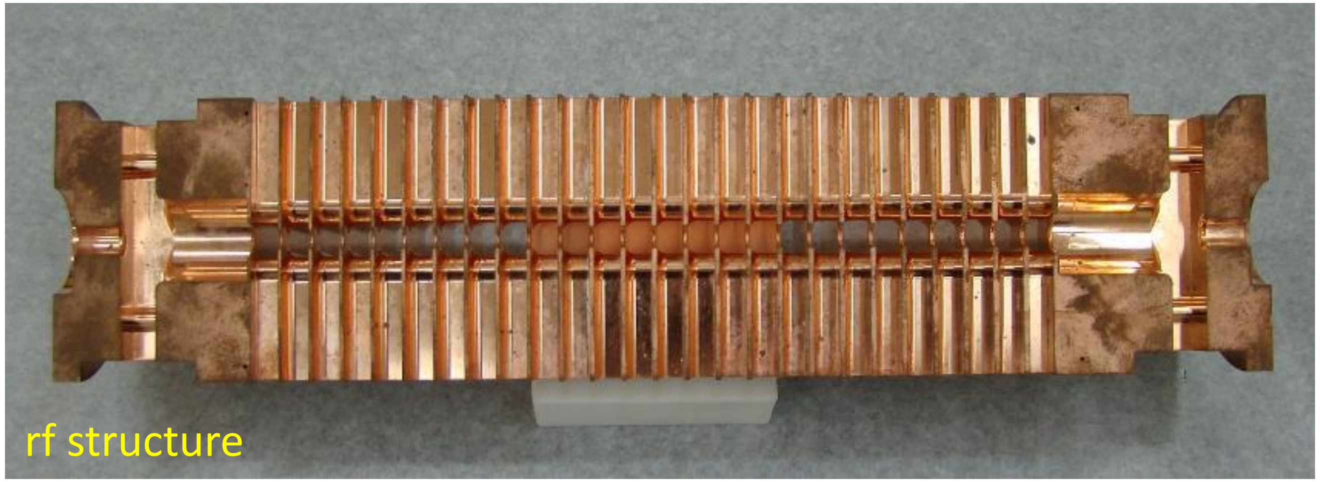
vs. number of Breakdowns

Alberto Degiovanni, Walter Wuensch, and Jorge Giner Navarro, *Comparison of the conditioning of high gradient accelerating structures*, Phys. Rev. Accel. Beams 19, 032001 (2016)

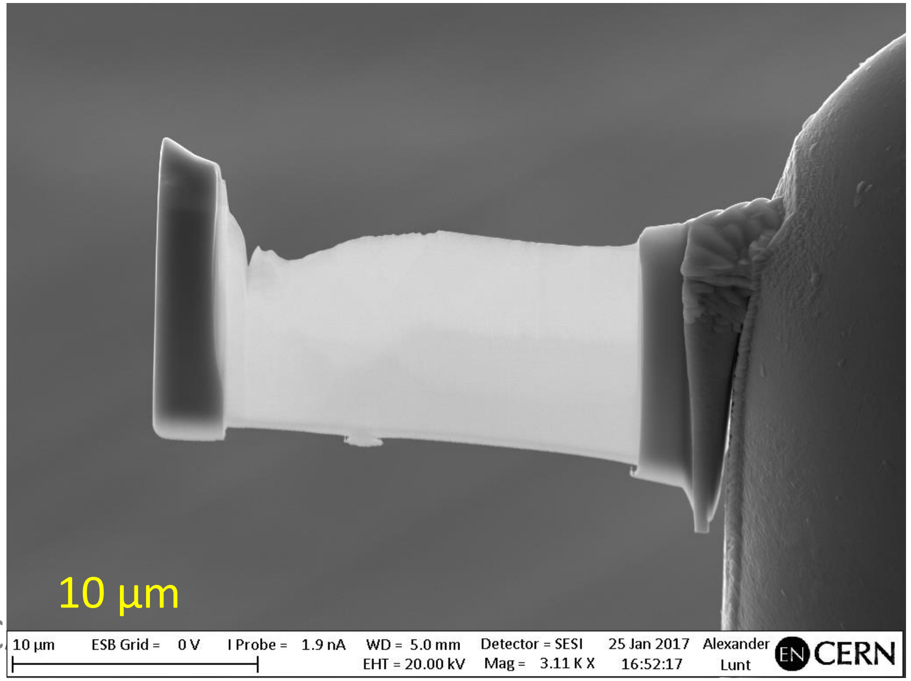
Comparison of mechanical and rf samples



Mechanical fatigue samples



rf structure

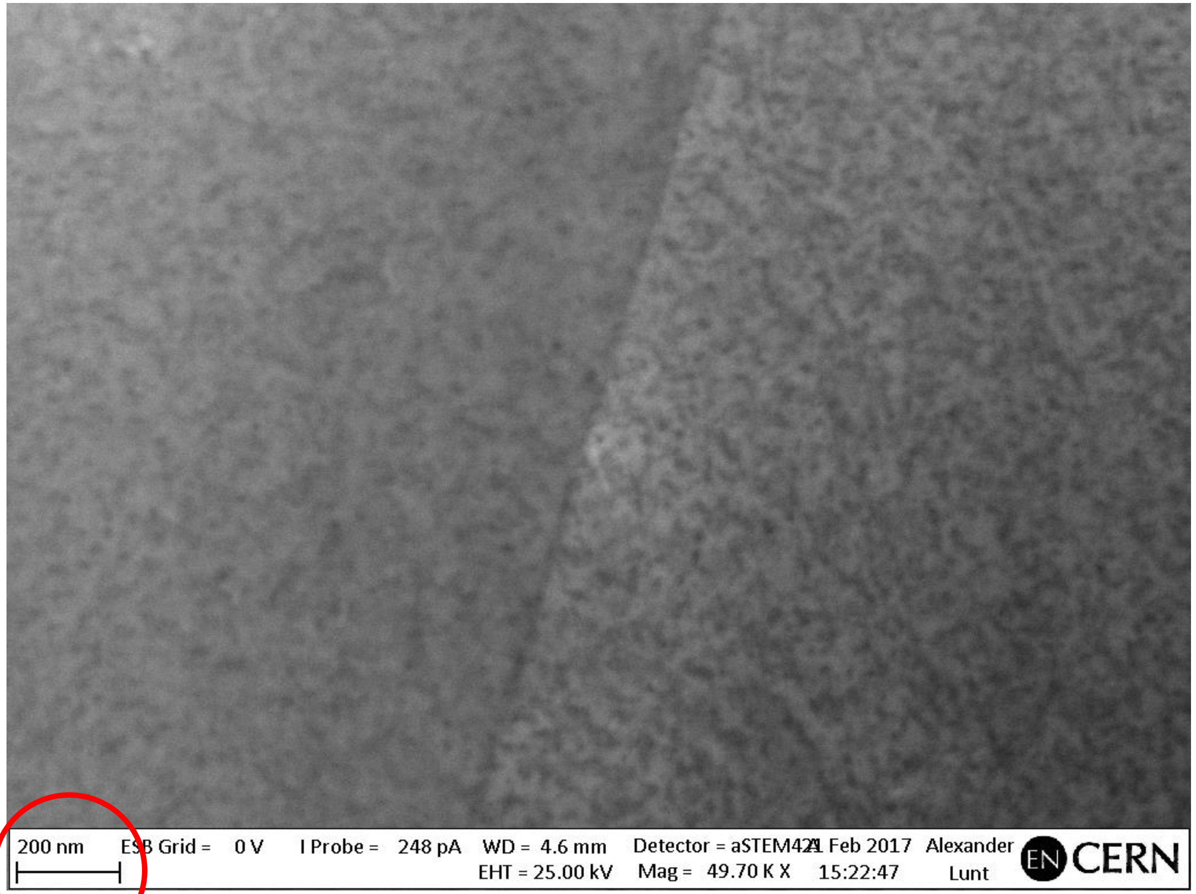


10 µm

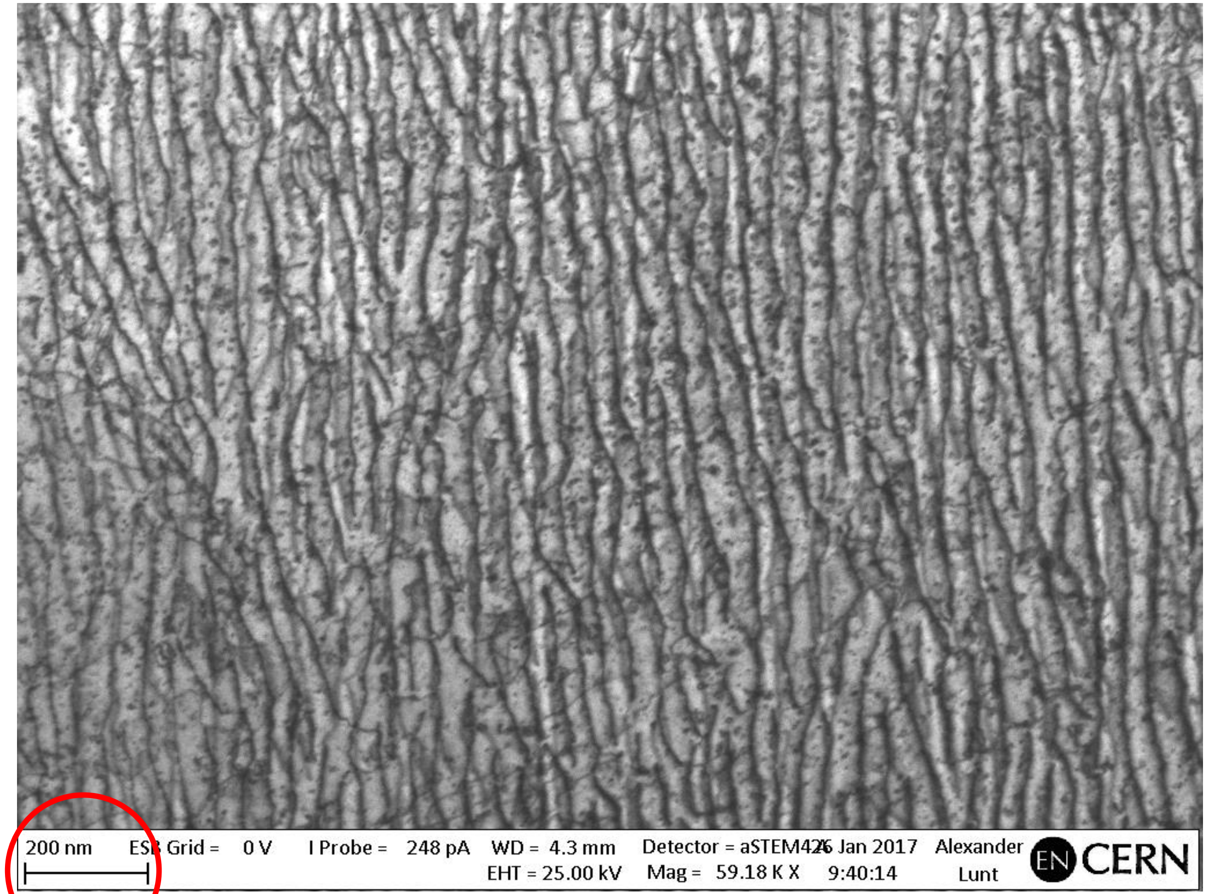
Experiment:

1. Build rf structure, standard procedure with 1040 °C bonding, and mechanical sample with same heat treatment.
2. Condition rf structure and fatigue mechanical sample.
3. Compare material state before/after/between using advanced microscopy techniques: FIB cutting lamella and image using STEM and TEM.

Mechanical fatigue – STEM images



After heat treatment



200 nm

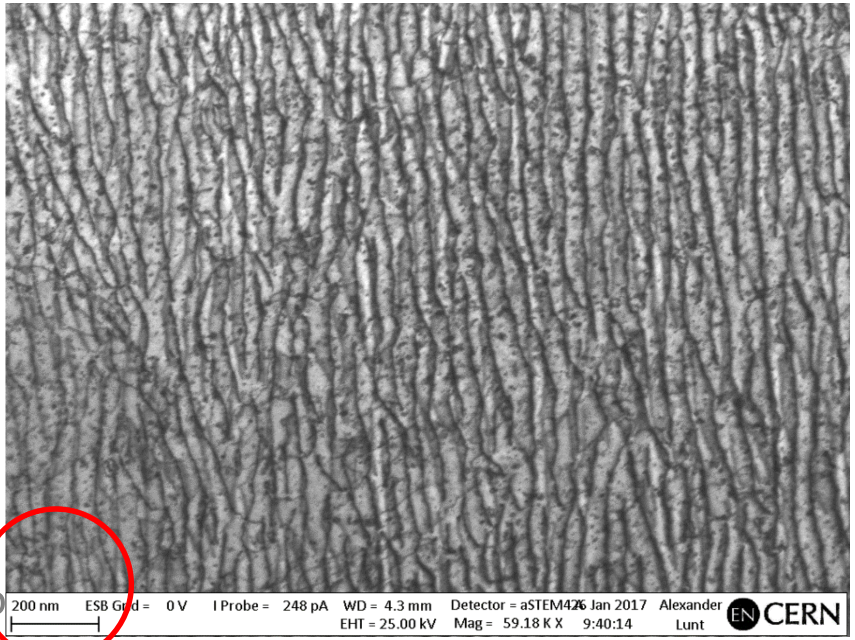
After mechanical fatigue

Formation of dislocation patterns characteristic of hardening.

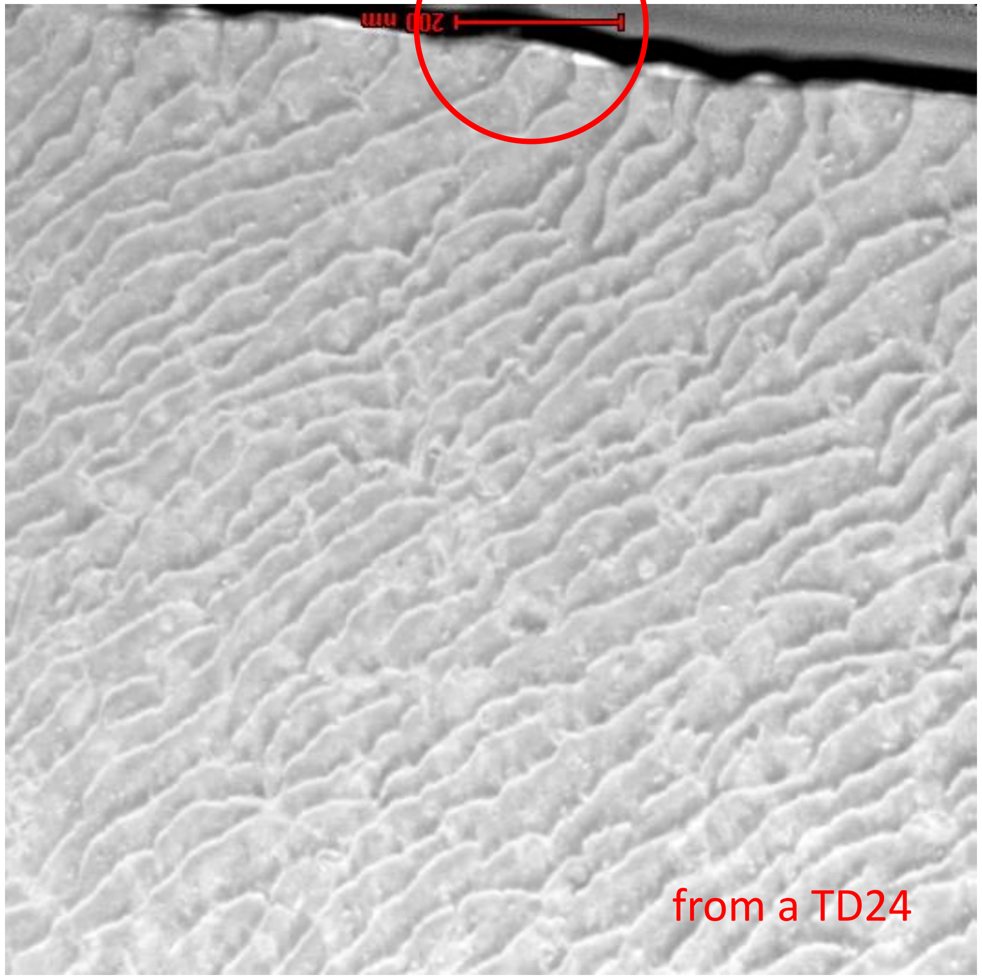
E. Rodriguez Castro

Comparison of mechanical and rf samples

200 nm



200 nm



After rf conditioning, high E field region – TEM image

A. Yashar, I. Popov

Interpretation

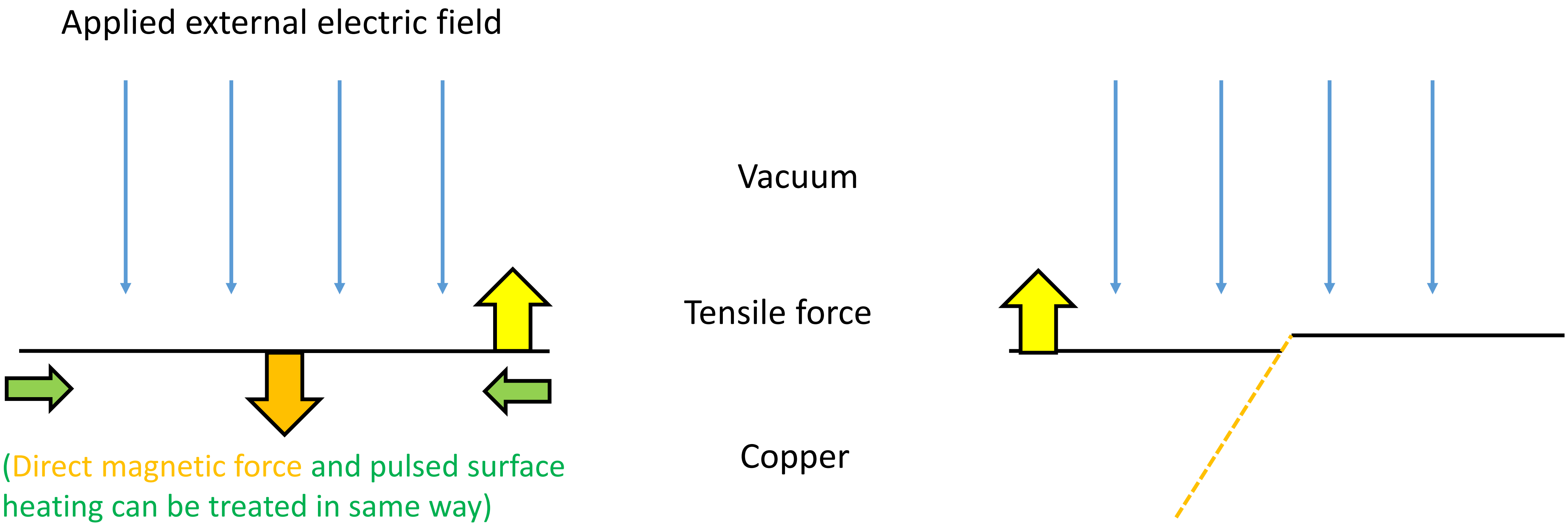
RF operation at high fields produces dislocation patterns similar to fatigue implying:

- A hardening process occurs during conditioning,
- Dislocation dynamics, formation and movement, are central to high-gradient behaviour.

Some numbers:

- Electric field stress is $\sigma = \frac{1}{2}\varepsilon_0 E^2$ so for 250 MV/m surface field, 270 kPa – for perfect flat surface.
- The onset of plastic behaviour in Cu is of the order of kPa, so well above already at 100 MV/m surface field.
- Speed of sound in copper is .38 mm/100 ns, so bulk phenomenon.

Simplified picture



- Tensile stress induces plastic behaviour, i.e. creates dislocations.
- Dislocations move to surface to reduce energy.
- Projection of dislocation on surface in nucleation point for continuation of breakdown process, last section and Flyura's presentation.

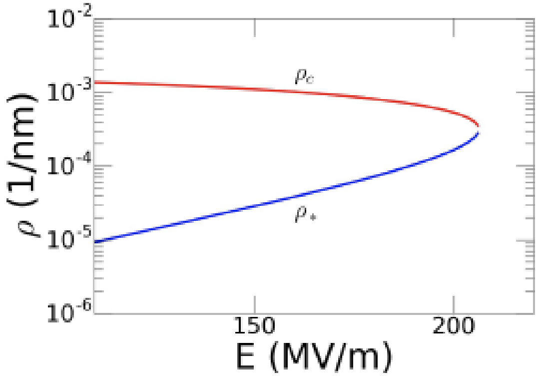
The mathematics behind dislocation dynamics

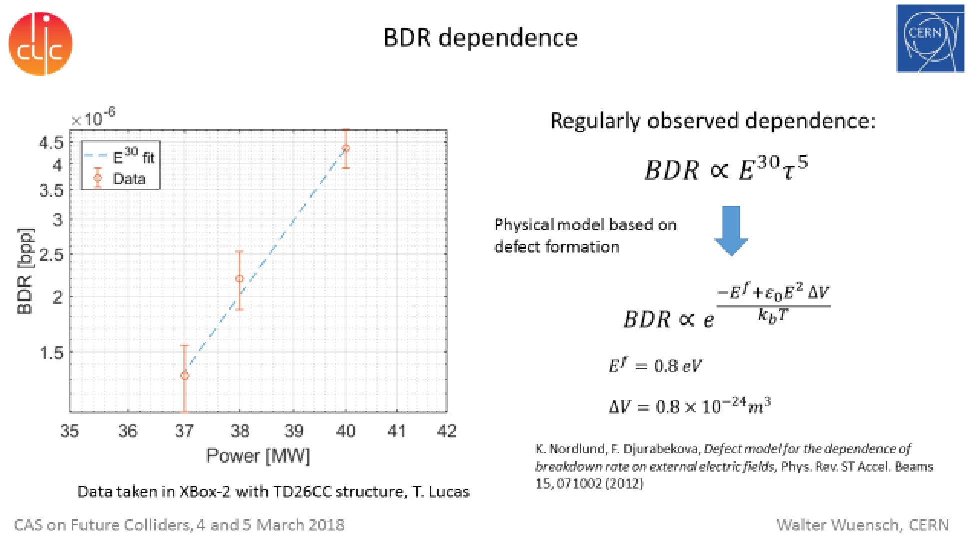
Describing mobile dislocation population evolution:

$$\dot{\rho}^{+} = \frac{25\kappa C_t}{G^2 b}(\rho + c)\sigma^2 e^{-\frac{E_a - \Omega\sigma}{k_B T}}$$

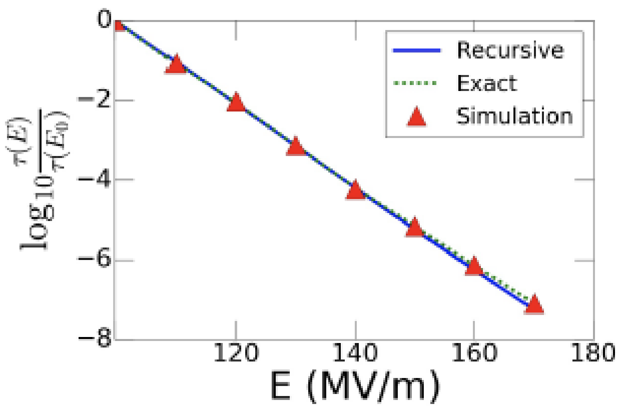
$$\dot{\rho}^{-} = \frac{50\xi C_t}{G}\sigma\rho(c + \rho)$$

$$\sigma = \beta\epsilon_0 E^2/2 + ZGb\rho$$





Leads to an exponential decay:

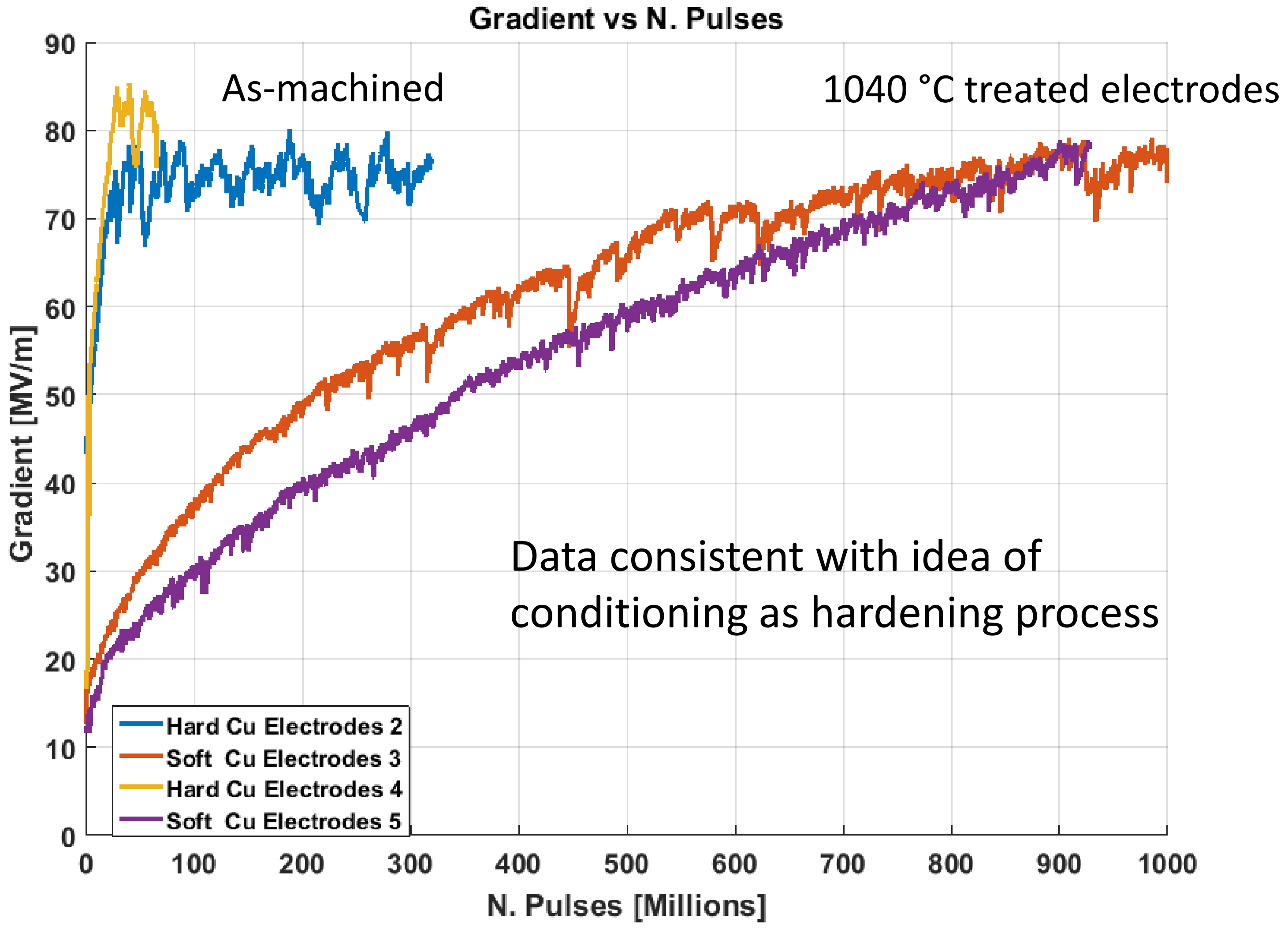


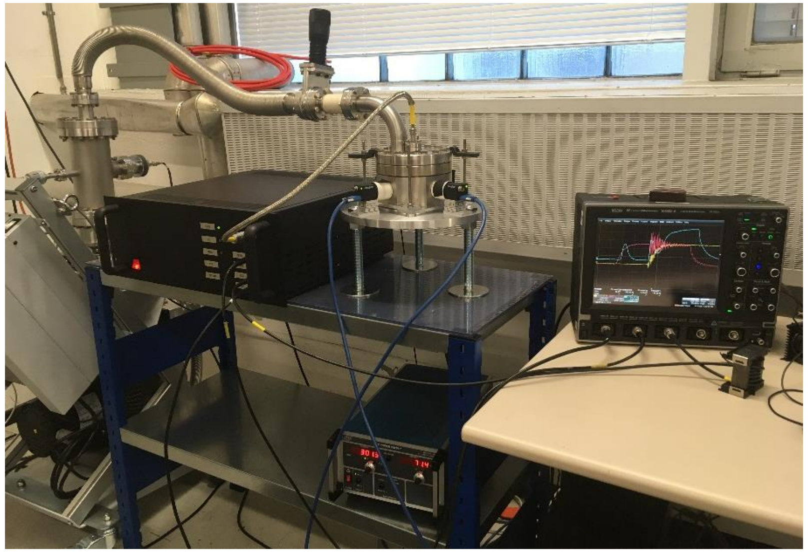
$$\tau \sim e^{-\gamma\frac{E}{E_0}}$$

Y. Ashkenazy and E. Engelberg

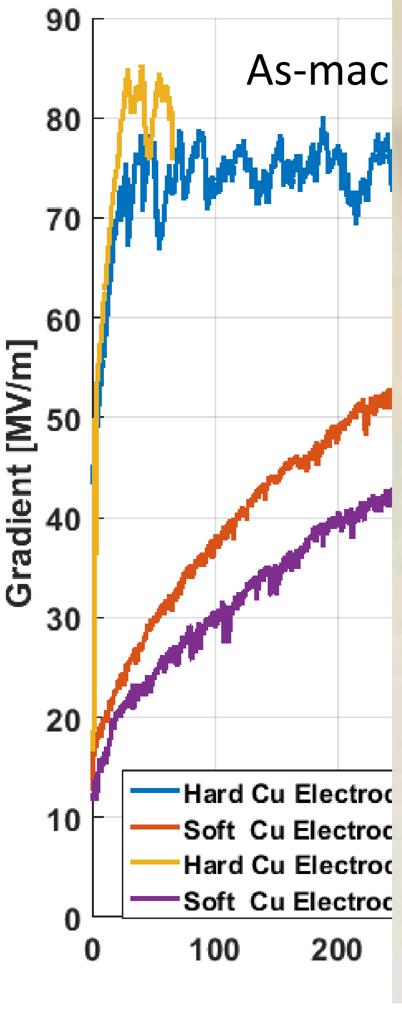
Accepted for publication in PRL

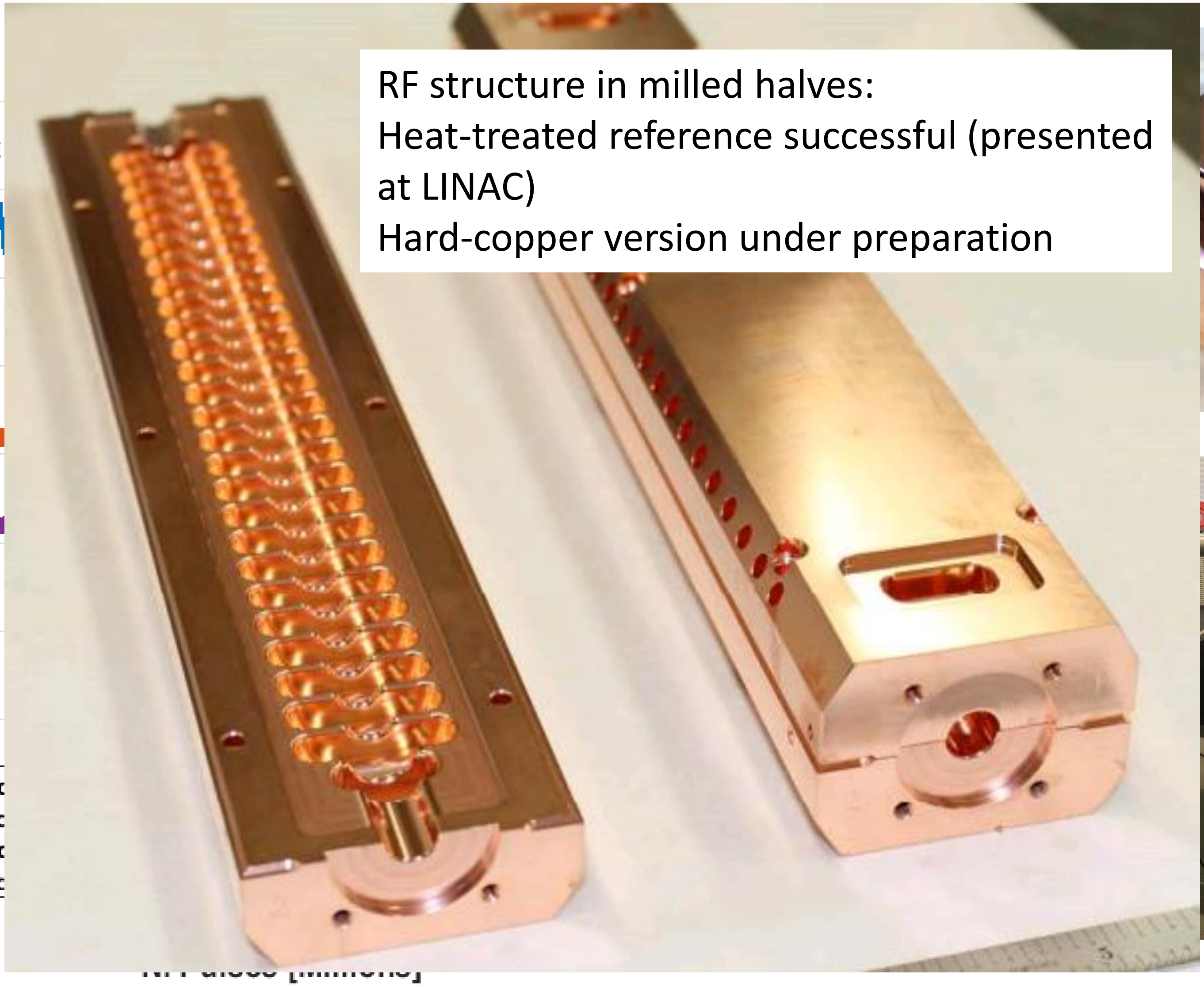
Hard vs. soft copper in pulsed dc system



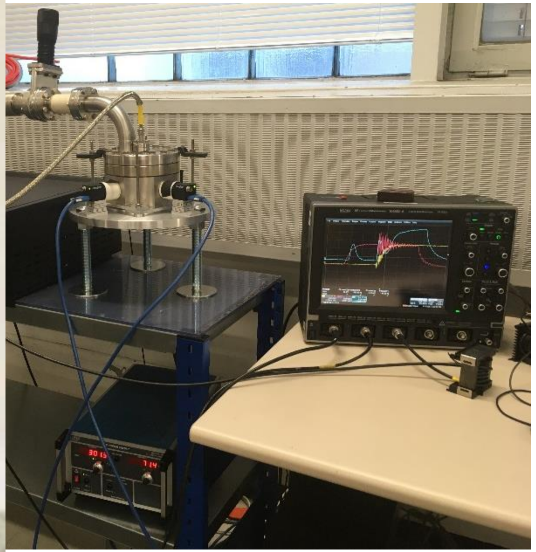


Hard vs. soft copper in pulsed dc system



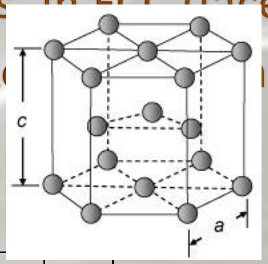


RF structure in milled halves:
Heat-treated reference successful (presented at LINAC)
Hard-copper version under preparation

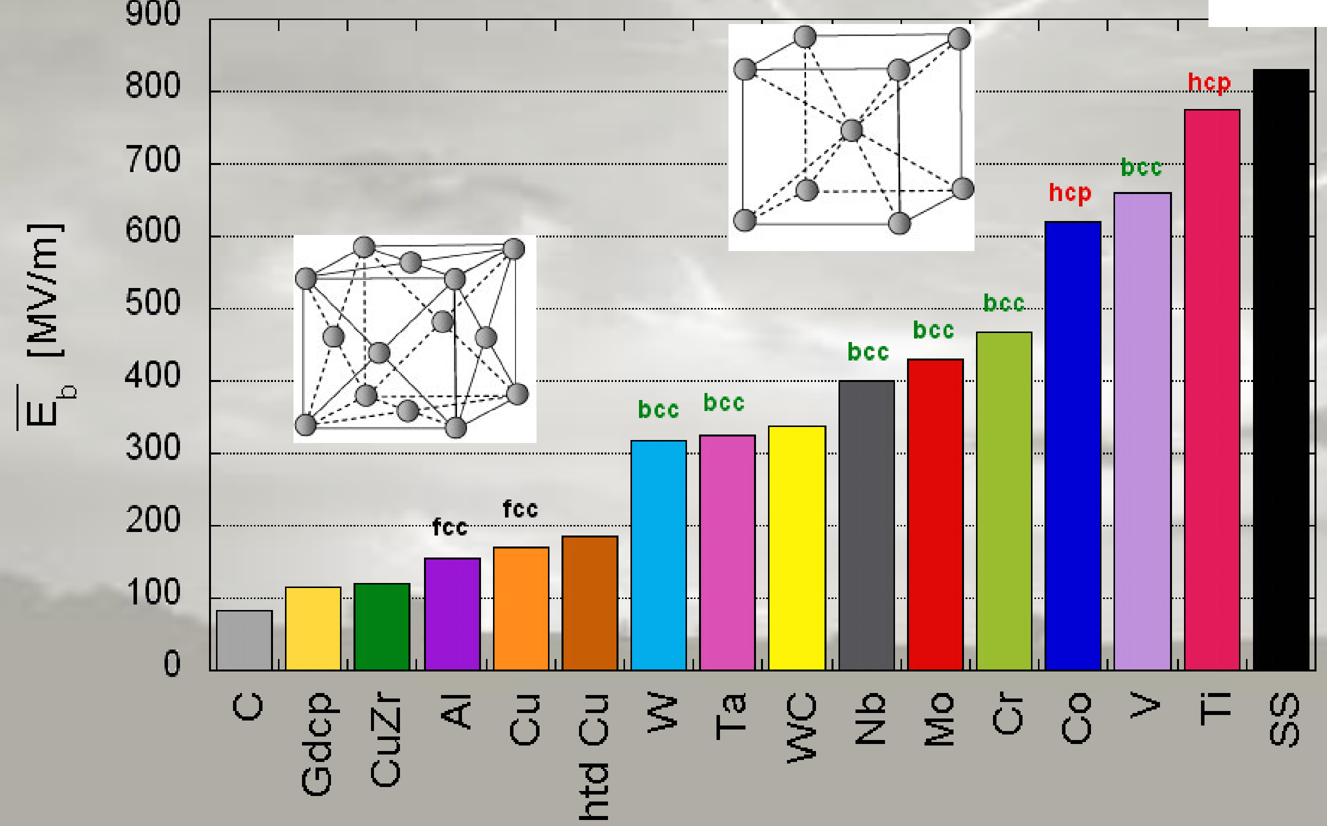


What are the field emitters?
Why do we look for dislocations?

- The dislocation motion is strongly bound to the atomic structure of metals. In FCC (face-centered cubic) the dislocation are the most mobile and HCP (hexagonal close-pack... hardest for dislocation mobility.

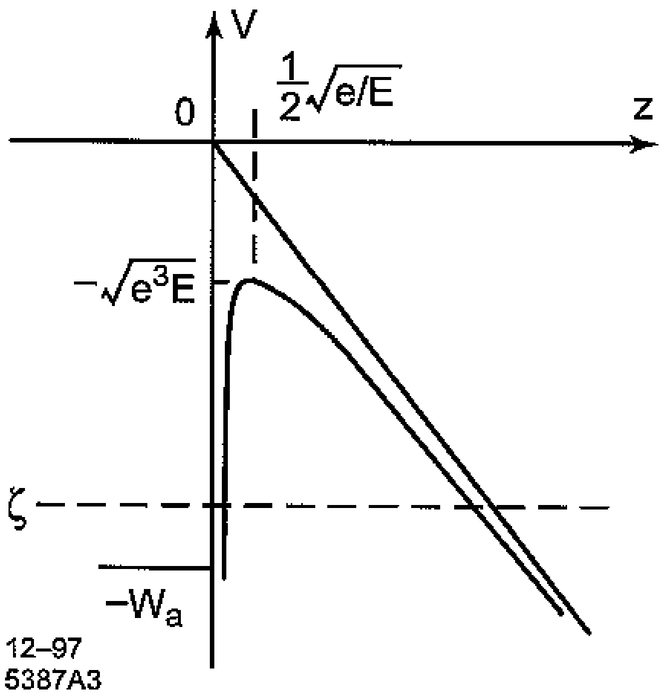


A. Descoeudres, F. Djurabekova, and K. Nordlund, DC Breakdown experiments with cobalt electrodes, CLIC-Note 875, 1 (2010).



Field emission

- A sufficiently strong surface electric field causes electrons to emitted from a metal surface. This is described by the Fowler-Nordheim equation.
- Functional form fits experiments perfectly, but there is an ever present need for a correction factor β, which is typically 30, and can be much higher. Attributed variously to small geometric features, locally lower work function and contaminants.



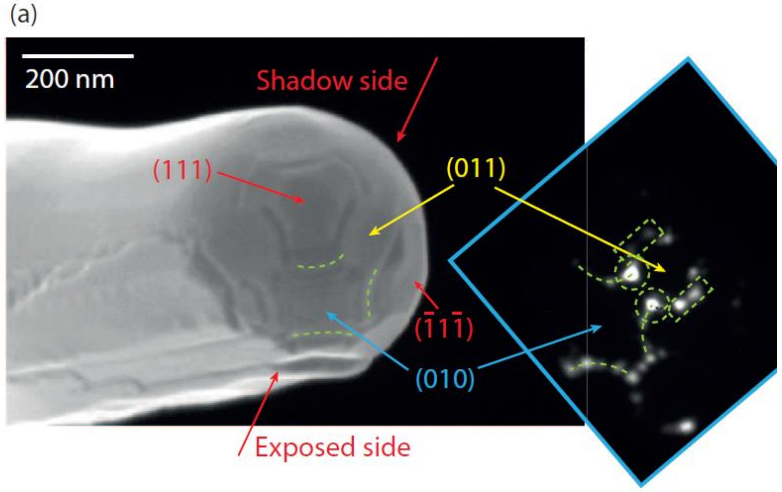
$$I = A_e \frac{1.54\times10^6 \beta^2 E^2}{\varphi} e^{10.41\varphi^{-1/2}} \times e^{-6.53\times10^3\times\varphi^{3/2}/\beta E}$$

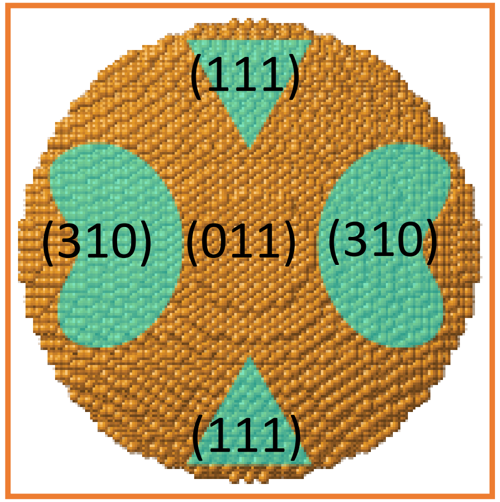
$$= \xi E^2 e^{-6.53\times10^3 \varphi^{3/2}/\beta E}$$

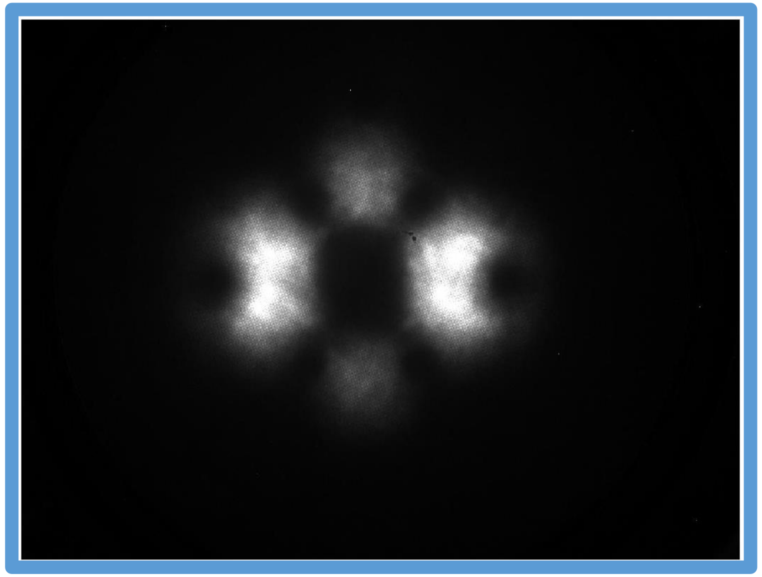
Units: [I]=A, [E]=MV/m, [A_e]=m^2, [φ]=eV and [β]=dimensionless

Values: φ = 4.5 eV for copper

Example of growth of nano-sized field emitter







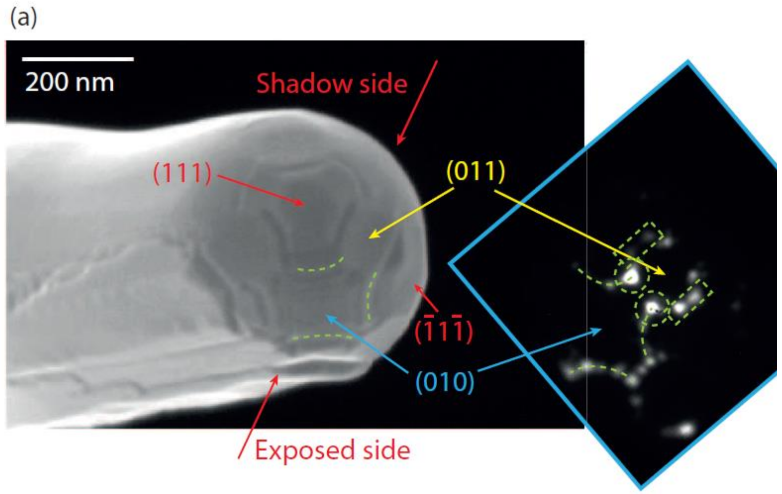
Tungsten tip used in ultra-fast electron diffraction.

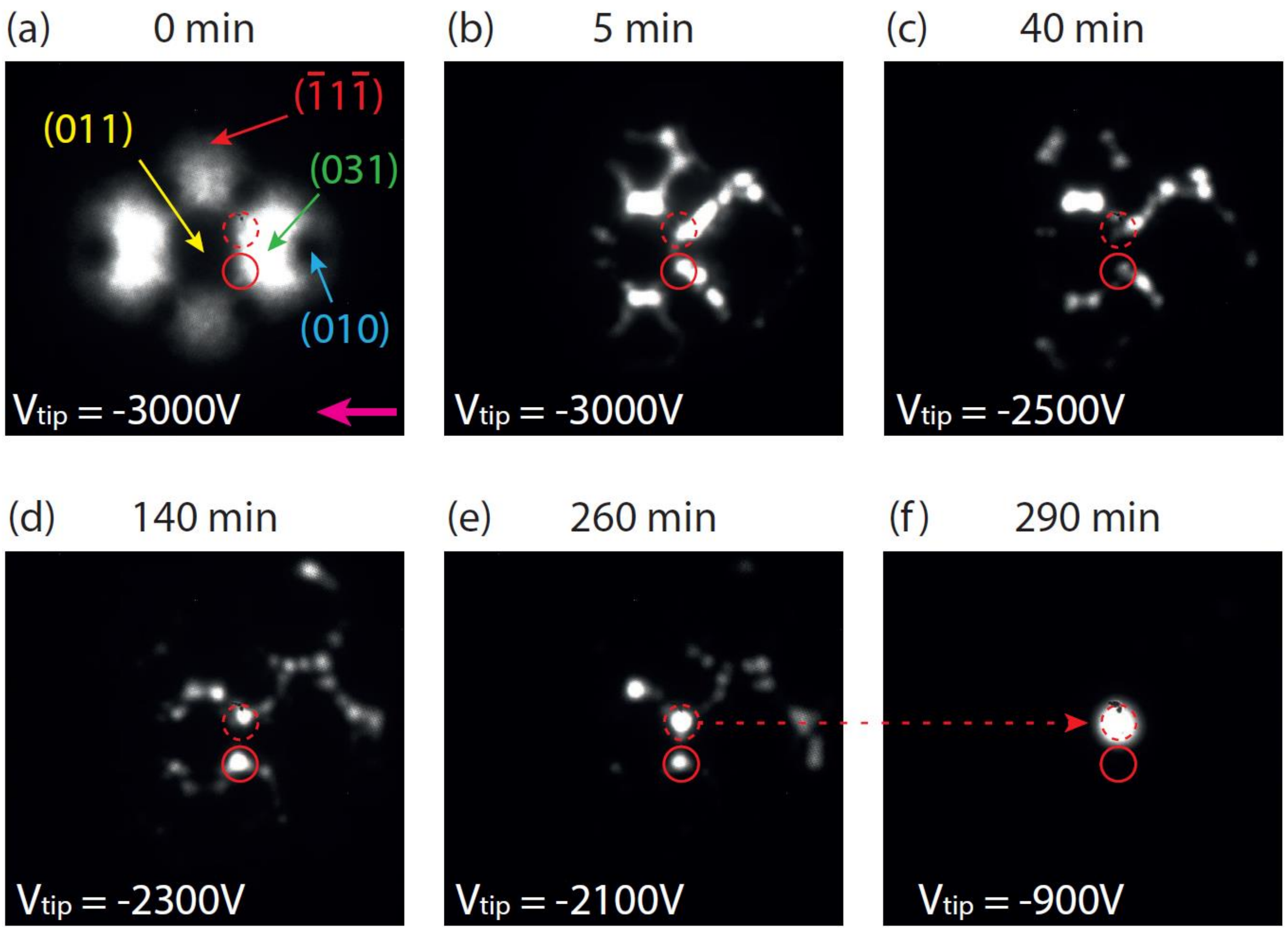
Tips deteriorate under laser pulsing but:

- Small area to uniquely identify characteristics of field emission sites
- Intense femtosecond fields opportunity to benchmark molecular dynamics and kinetic Monte Carlo codes

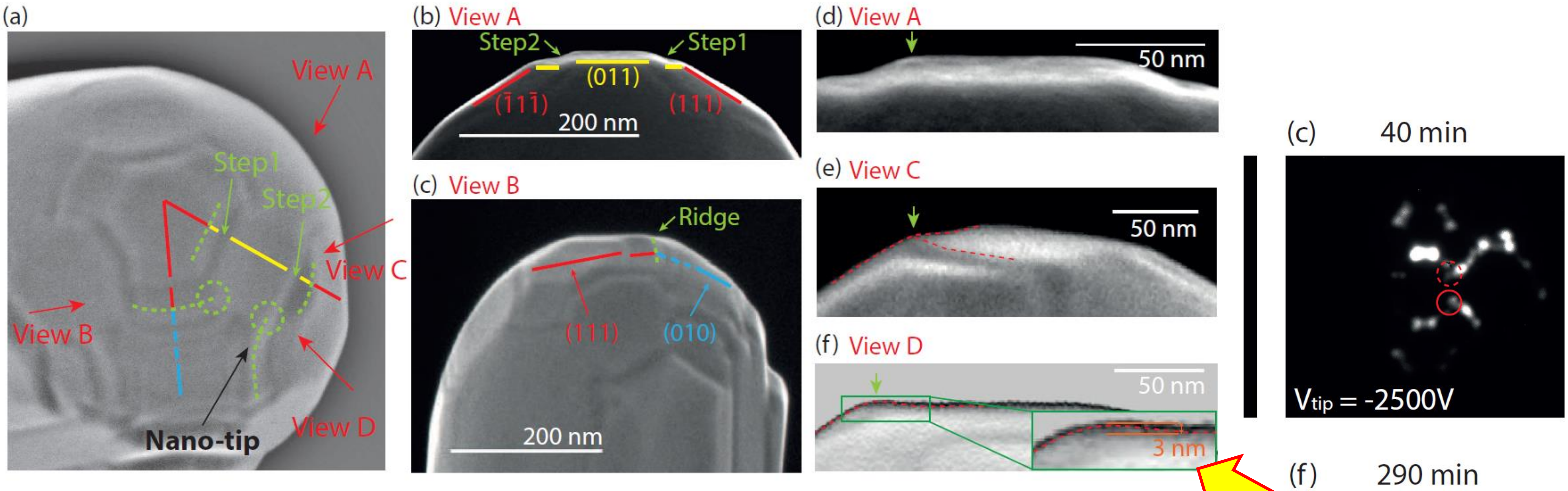
Hirofumi Yanagisawa, et. al. *Laser-induced asymmetric faceting and growth of a nano-protrusion on a tungsten tip*, APL Photonics 1, 091305 (2016); doi: 10.1063/1.4967494

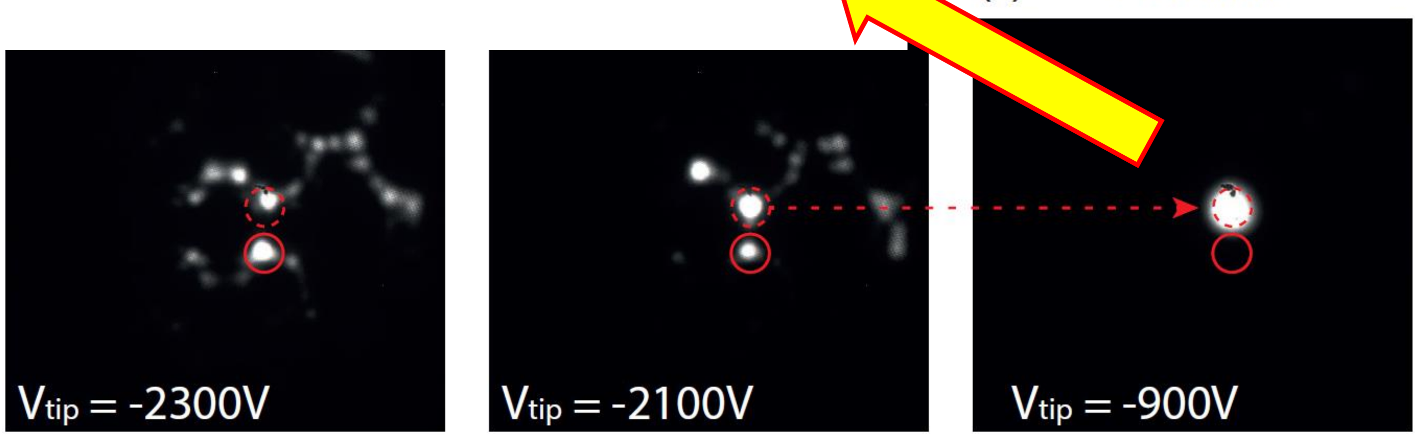
Evolution of field emission during laser pulsing



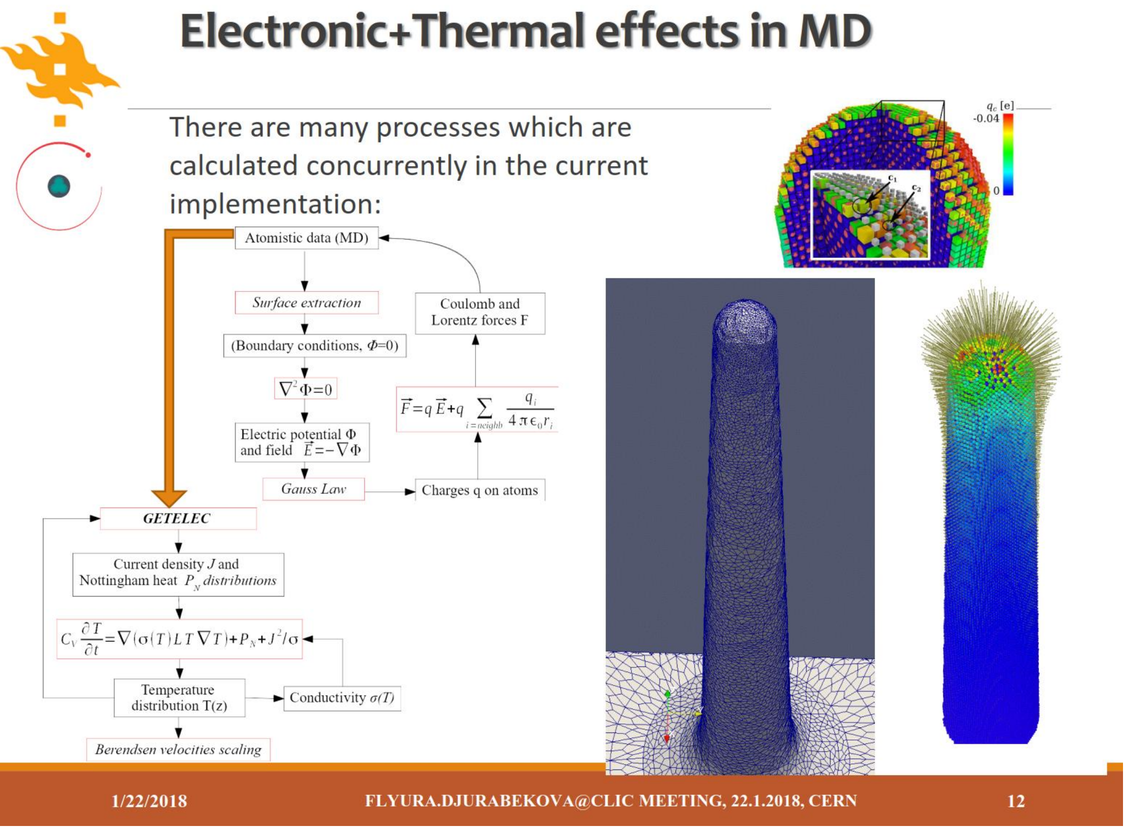


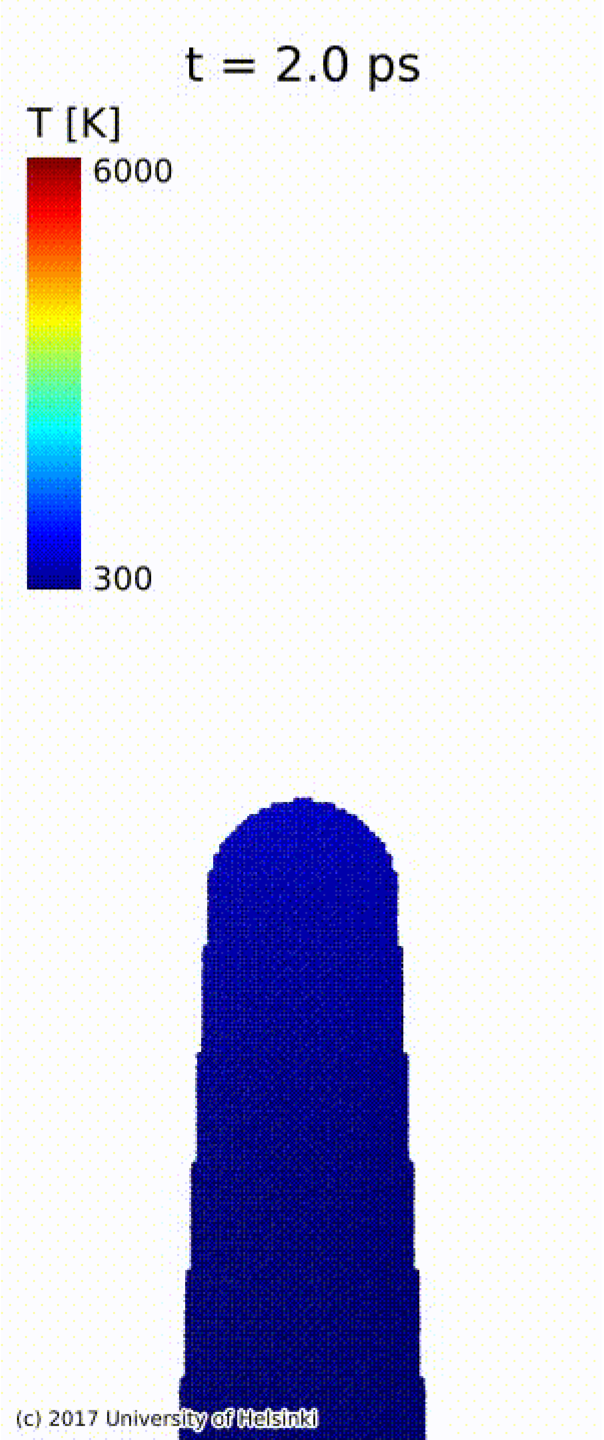
Identification of nm-sized emission site





Tip evolution

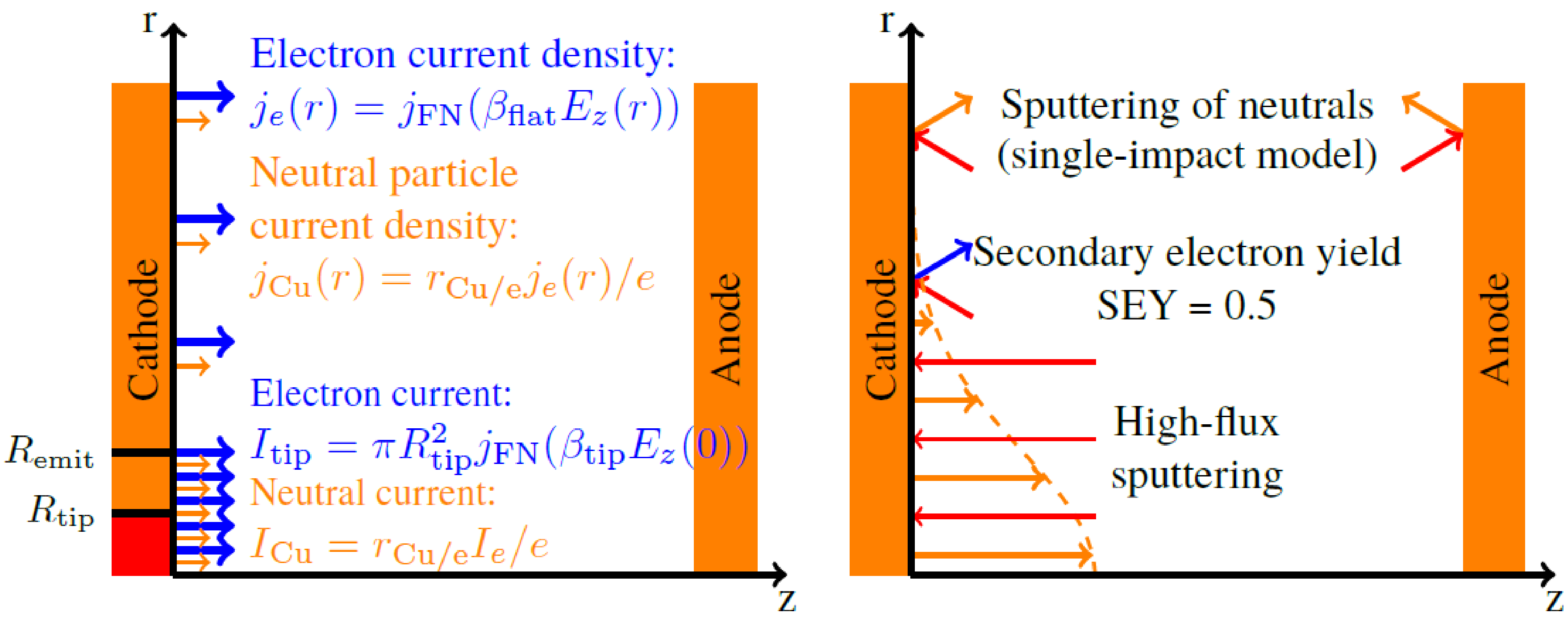




What’s going on inside.

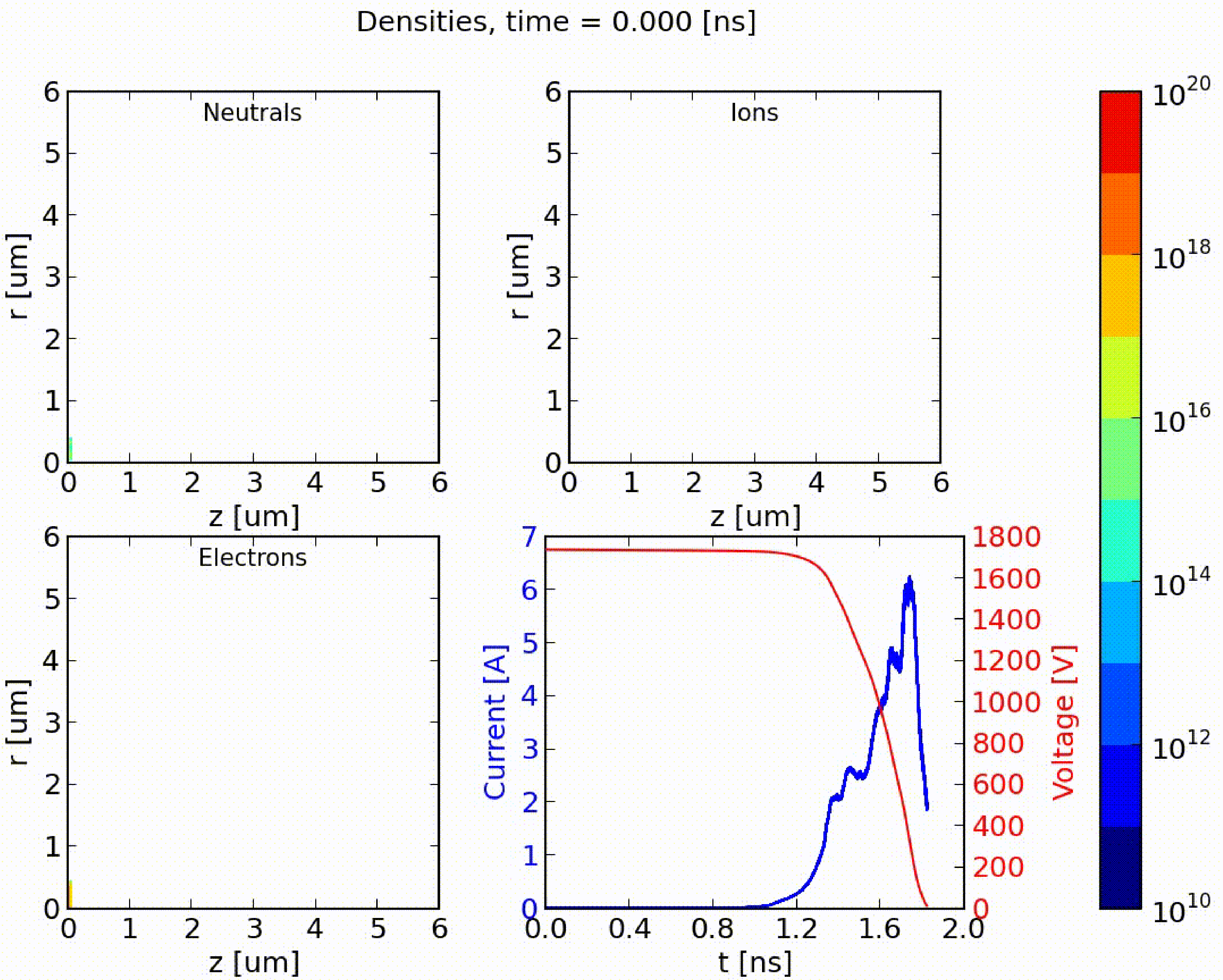
ArcPIC simulation of the onset of breakdown, starting from field emission and going through the formation of a plasma, a plasma sheath and dramatically rising emitted current.

The code is ArcPIC and simulates a 20 micron wide dc gap.



(a) Field emission and neutral evaporation.

(b) Sputtering and secondary electron yield.



Densities, time = 0.000 [ns]
Neutrals
Ions
Electrons
r [um]
z [um]
Current [A]
Voltage [V]
t [ns]
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}

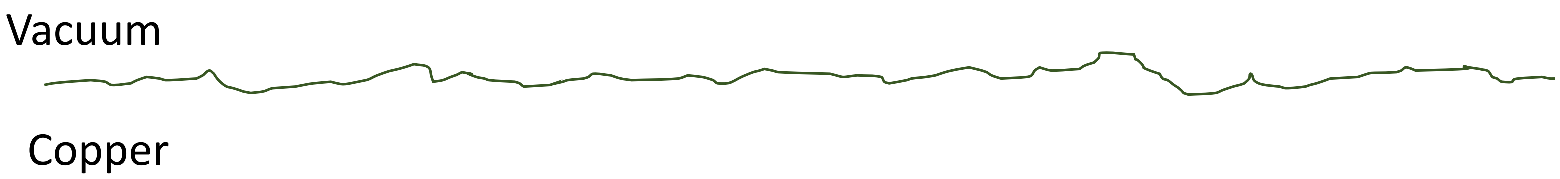
Cartoon summary of the steps which lead to breakdown

An overview of the breakdown process

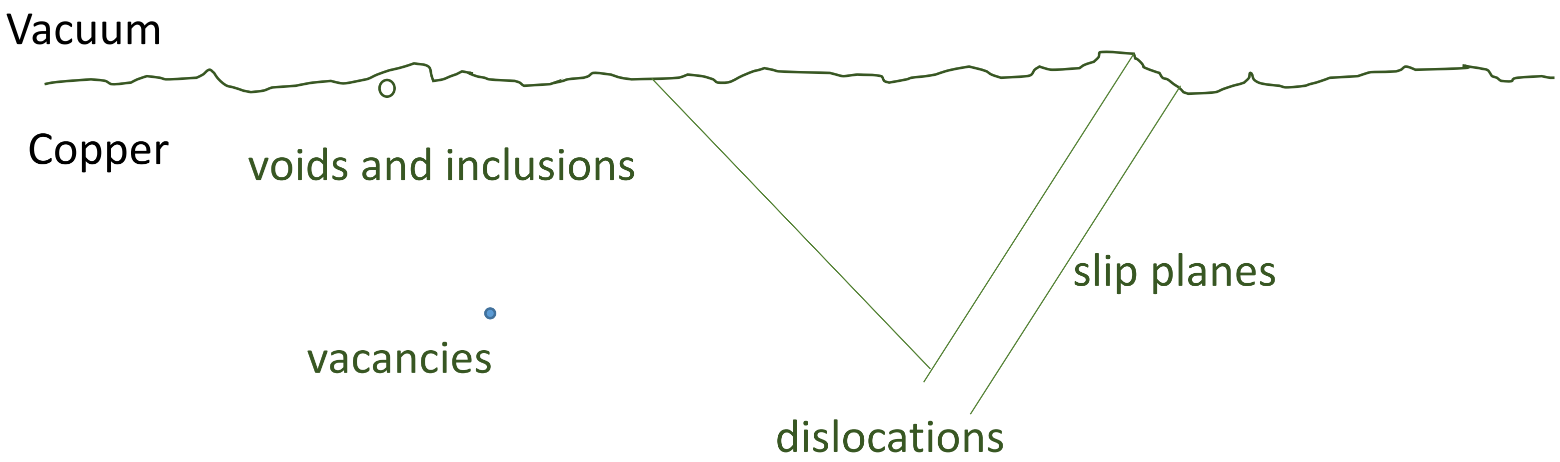
Vacuum

Copper

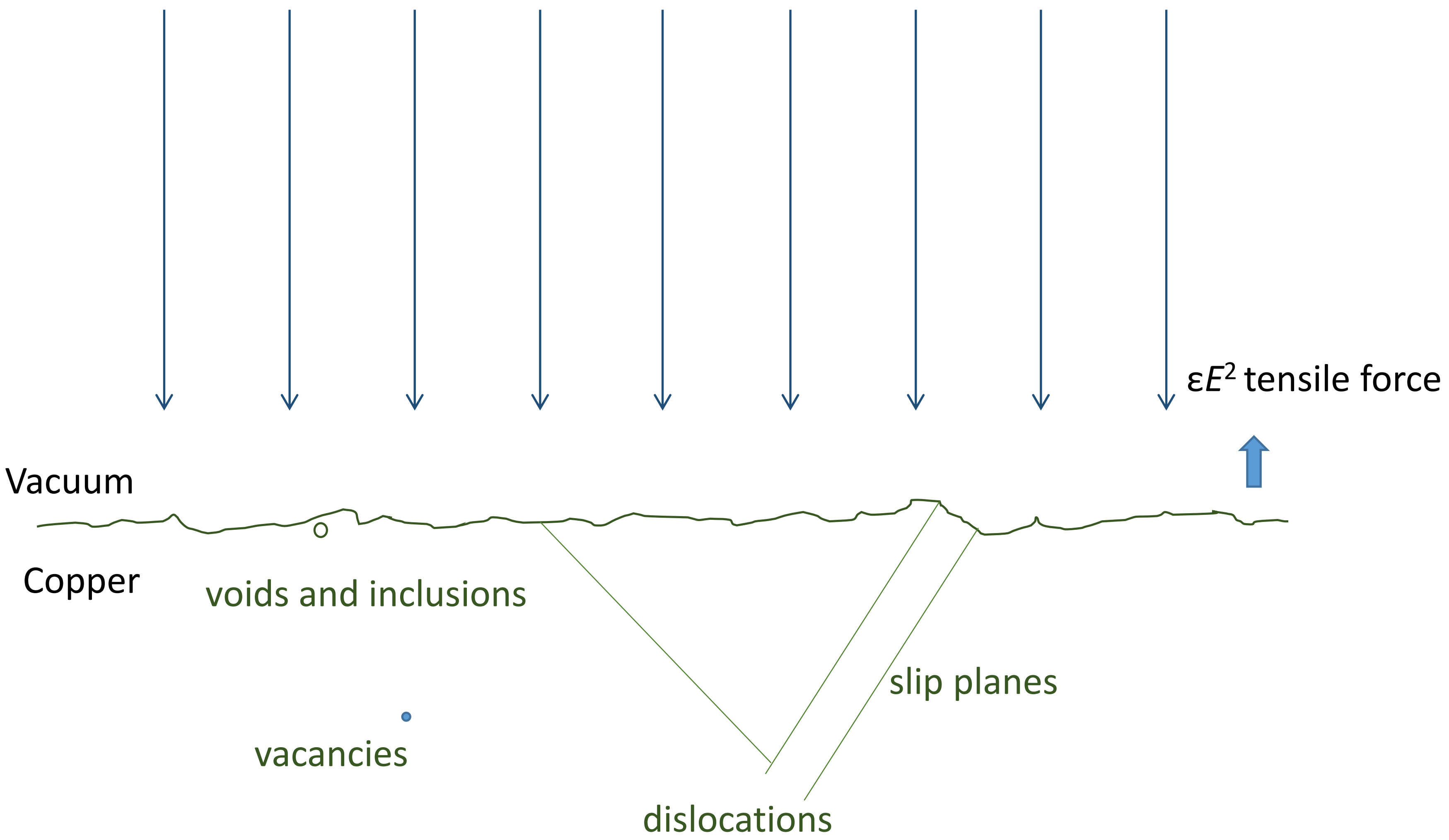
Actually real surfaces are imperfect



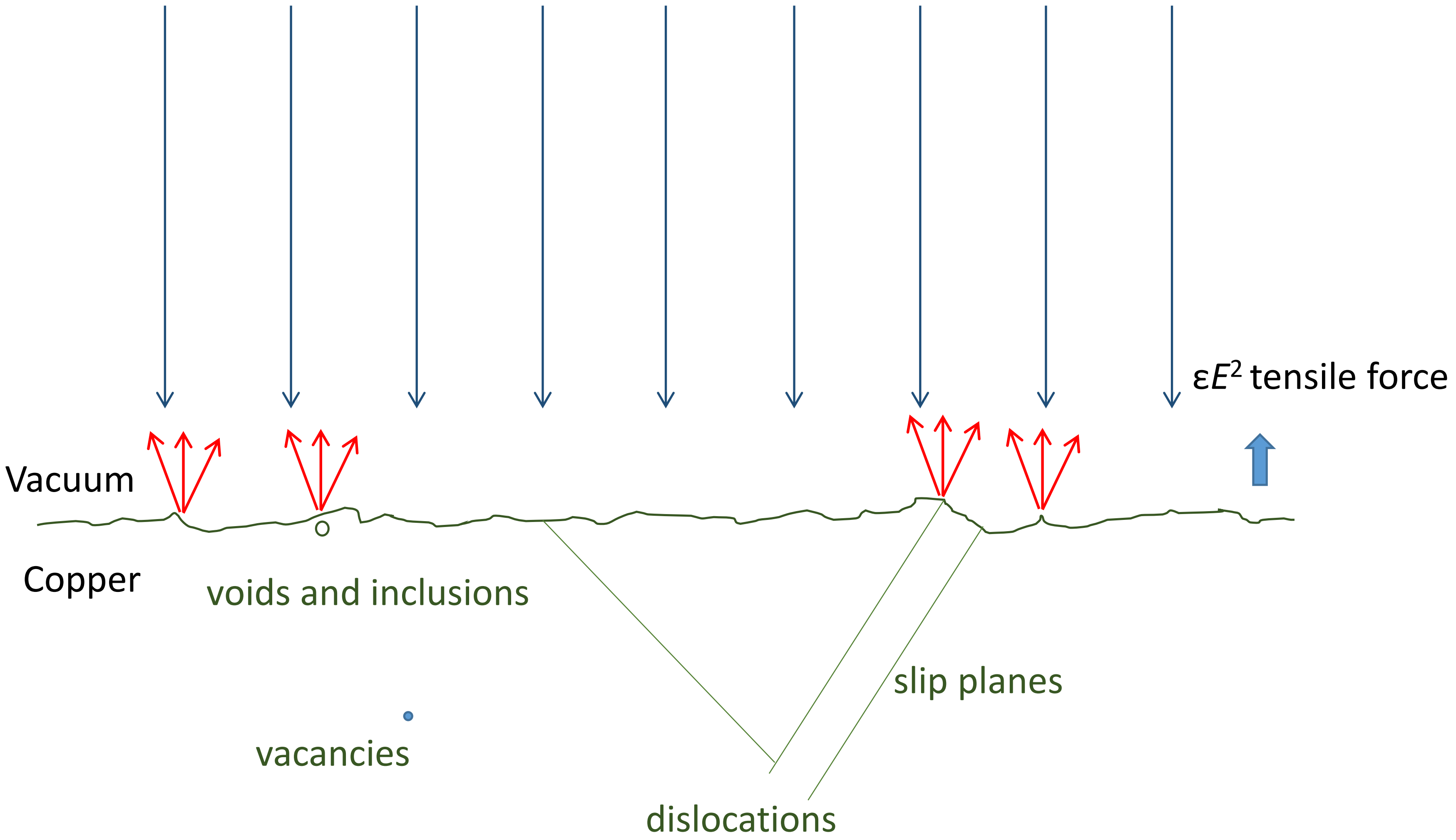
And the material below the surface isn't perfect either



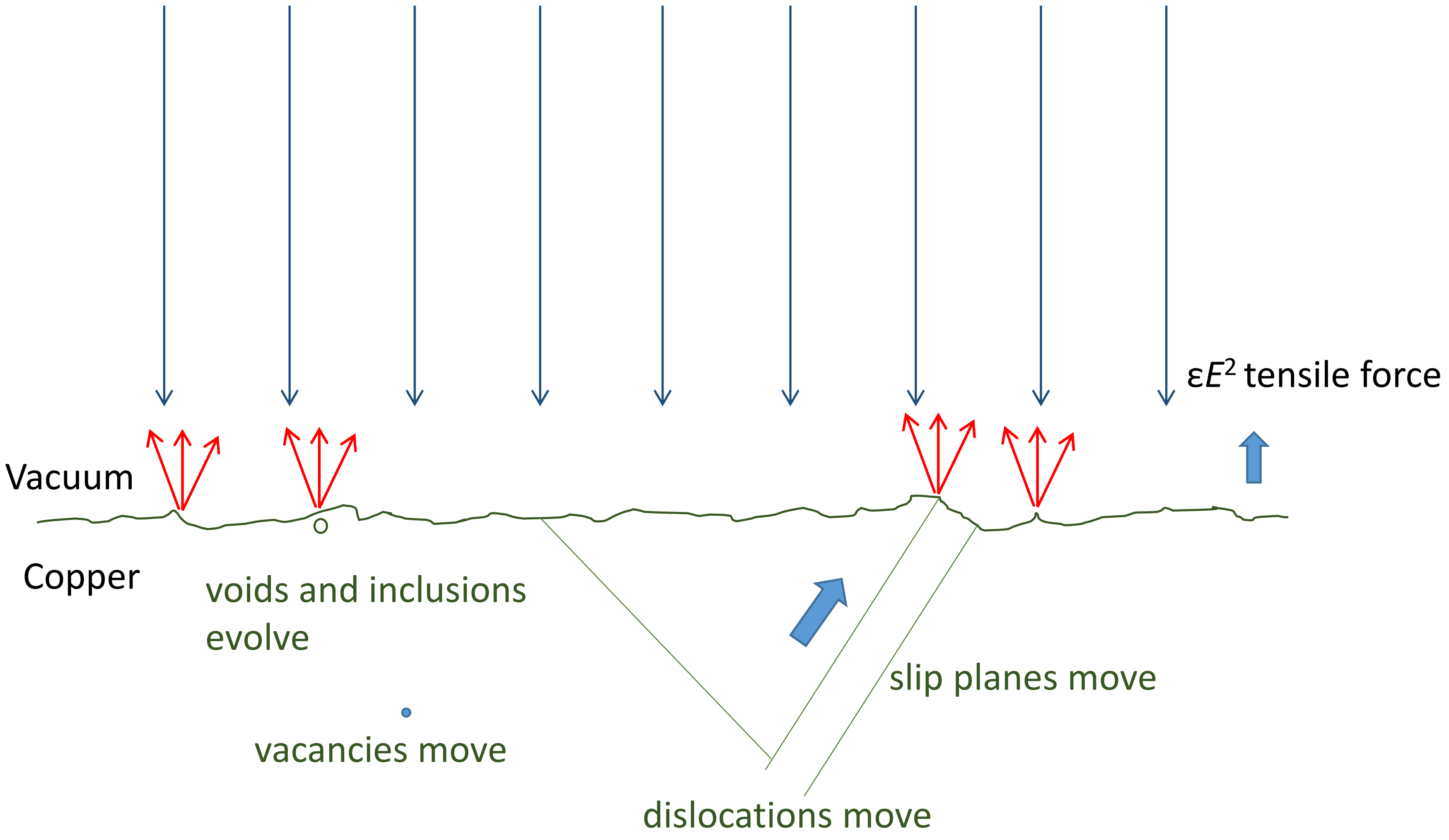
Add an external electric field, around 200 MV/m. Surface charges re-arrange themselves in fs. Surface experiences εE^2 tensile force.



Field emission current flows from metal into vacuum (Fowler-Nordheim) from local areas (O[10 nm]) of geometrical field enhancement and low local work function. There is a local field enhancement β of around 50-100. The total current from something like 0.1 mm^2 is a nanoAmp.



The external electric field causes the tensile stress and field emission current causes thermal induces stresses so the material imperfections and surface features evolve – plastic deformation.



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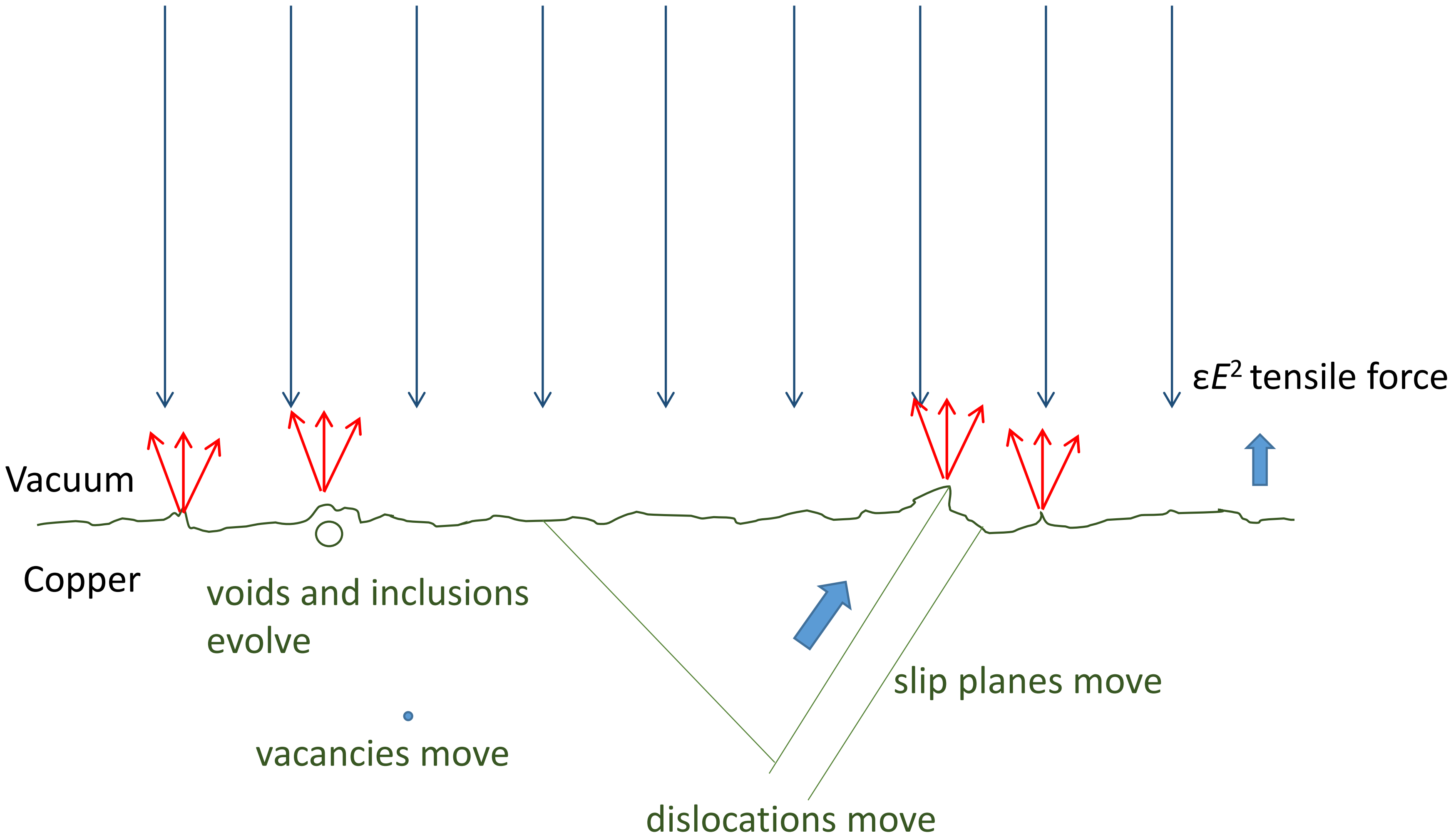
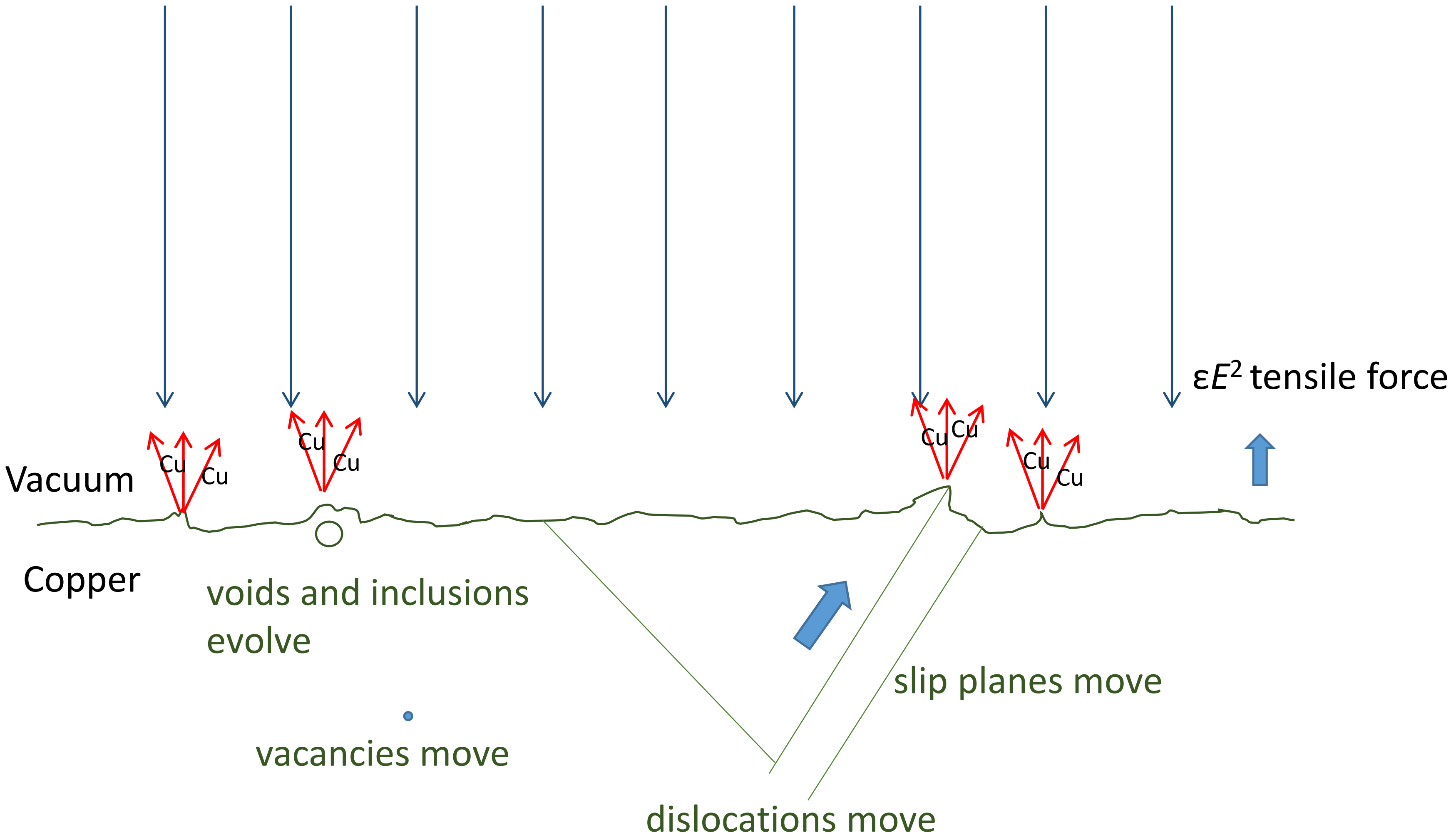
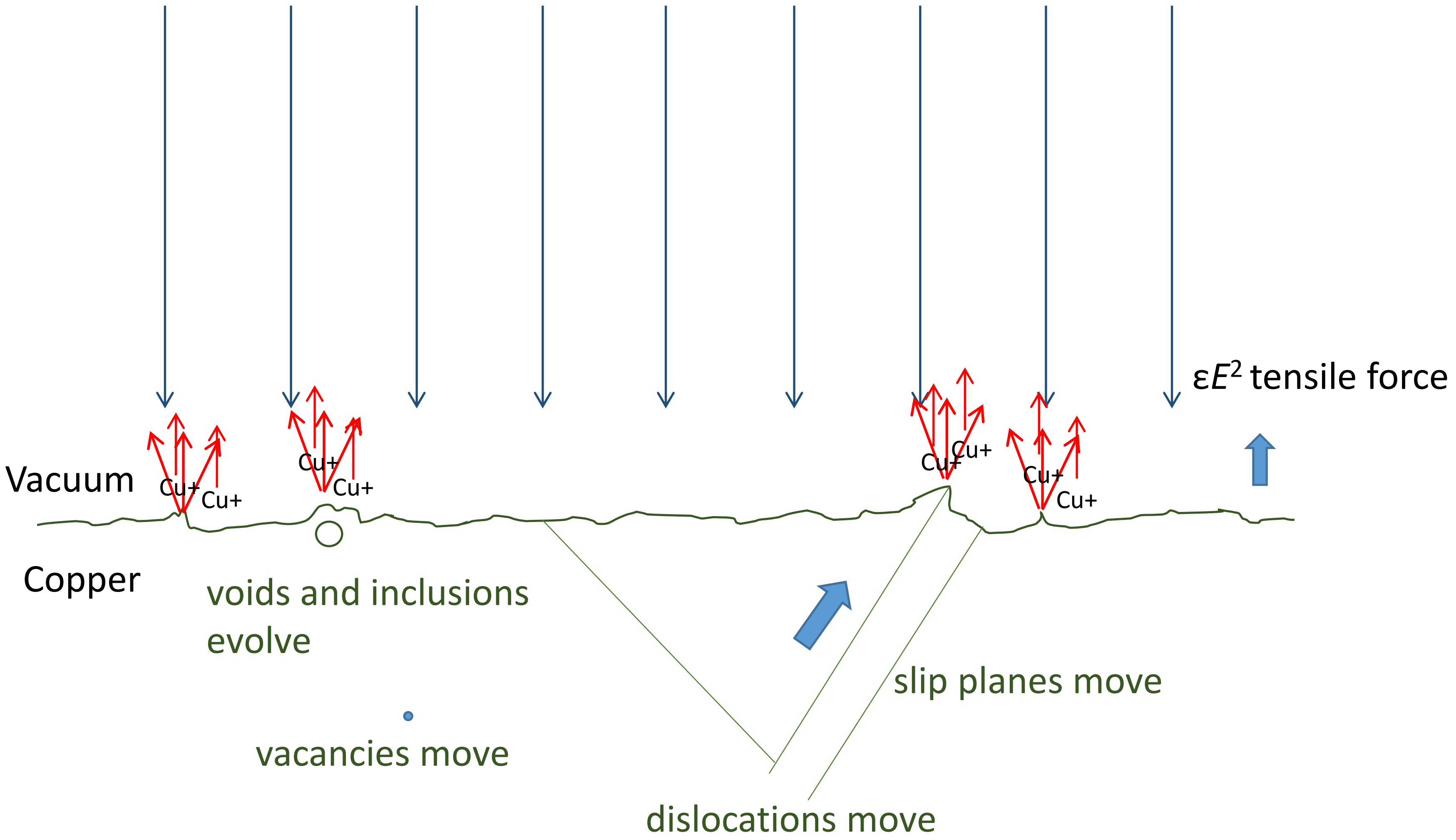


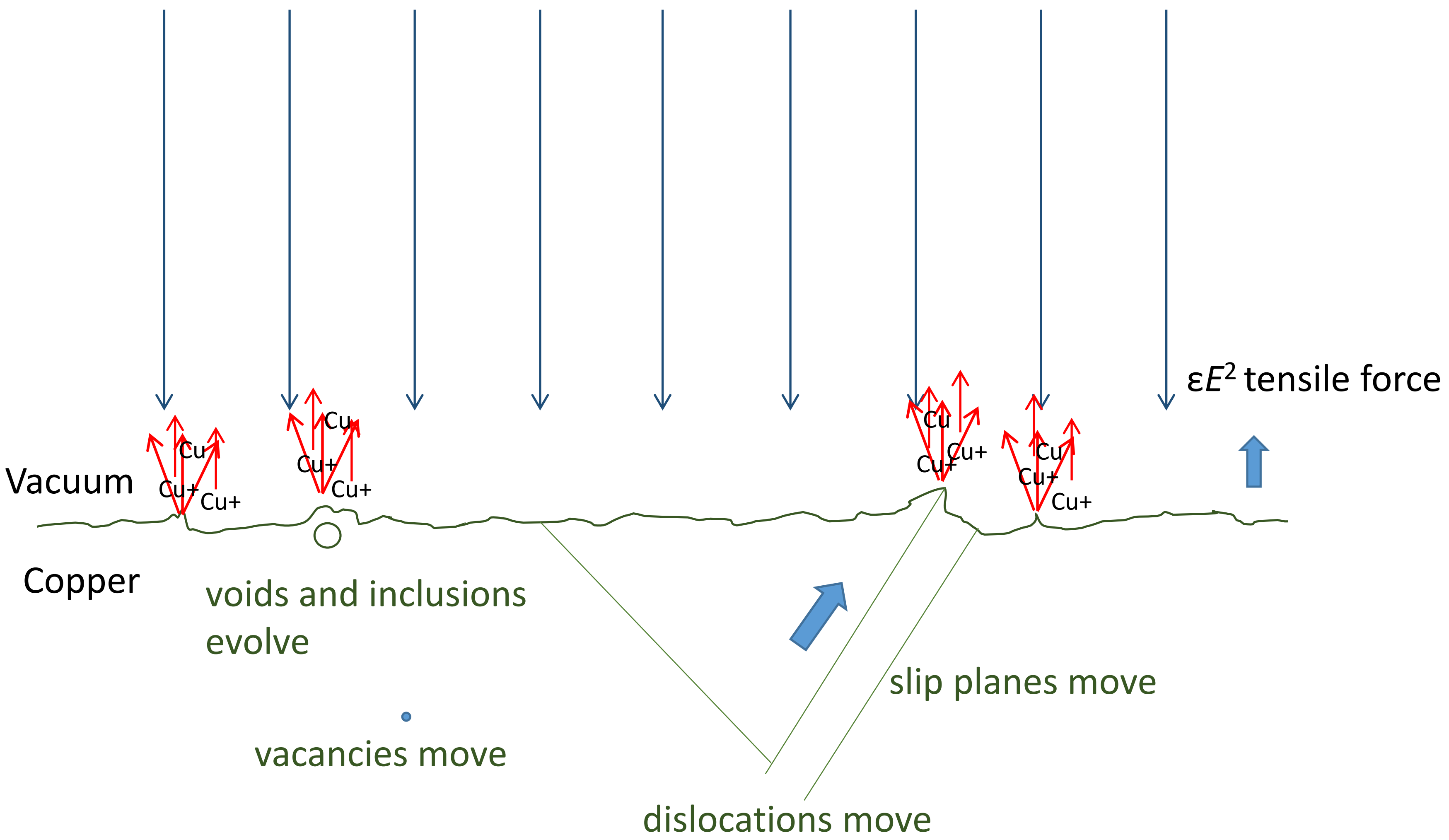
All the while, neutral copper atoms are coming off the surface field assisted evaporation.
The details of this process is process is a fundamental open question.



The copper atoms are ionized by the field emission current. the positively charged ions head to the surface and the electrons add to the emission current.



The copper ions hit the surface and sputter more copper in addition to that produced at by the original emission process.



One of these emission points, on some rf or dc pulse, at some point passes a threshold and the process runs away. We will now switch to a computer simulation of the run-away process.