Room Temperature rf
High Gradients: Physics, rf design and Technology
When Maxwell’s equations just aren’t enough

General Introduction
and
Part I: Introduction to the Main Effects which Limit Gradient

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General Introduction

The objective of the next three hours of lectures is to familiarize you with the main issues related to designing and running a normal conducting linac with a high accelerating gradient.

In the past, issues such as achievable gradient, high-power rf design and structure preparation were dealt with primarily through recipes based on experience.

However the importance of high-gradient for a multi TeV linear collider motivates us to understand the phenomenon more deeply.

Consequently a significant effort has emerged to understand, quantitatively and in detail, high-gradient limits and dependencies.

In these lectures I will describe our understanding of the main features of high-gradient and high-power phenomenon.

A word of caution before we dig in,

High-gradient and high-power phenomena are very complex, and the relevant physics spans a wide scale.

We'll cover distance scales from nanometers to centimeters, currents from picoamps to kiloamps etc.

Consequently you will not see a formal derivation of high power rf phenomenon like you've seen in the subjects that Erk and Alexej have covered. We speak in terms of a multi-scale model.

There are many subjects which are the subjects of ongoing research so consequently I cannot tell you that the truth looks exactly like this and that, which may be what you expect from me.

But there is a lot we do understand now, and we have been able to identify key questions, set up a common way of speaking, organize our thinking – this is what I would like to communicate to you.

In my view the subject is quite fascinating.

All this is relevant for linear colliders, but is also used in other applications which require higher performance acceleration including medical accelerators and X-FEL's.

Part I: Introduction to the main effects that limit gradient

Part II: Deeper into the physical processes of breakdown

Part III: Breakdown in rf structures and design for high gradient

Part I: Introduction to the main effects that limit gradient

There are a number of effects which appear in cavities above certain field levels and which disturb normal cavity operation.

We will make a relatively superficial survey of these effects before addressing the most important one for linear colliders, **breakdown**.

The effects organized by main origin are:

Electric field ⟺ Magnetic field

Electric field	Magnetic field
• Dark current	• Pulsed surface heating
• Multipactor	• Average power
• Breakdown	

Dark Current

Dark current is an old term in physics/engineering which traditionally refers to two phenomenon:

1. Initial current in a gas tube before there is any emitted visible light.
2. Background current in a photo-multiplier (and these days CCD) tube when no incident light is present.

In an rf accelerating cavity it refers to electron currents emitted from the cavity surface in regions of high electric field through *field emission* in a regime which is more or less stable from pulse to pulse – i.e. without a breakdown.

Field emission occurs through quantum-mechanical tunneling and is described by the Fowler-Nordheim equation. The basic physics is that electrons tunnel through the potential barrier given by the surface of a metal when an external electric field is applied.

The Fowler-Nordheim equation for field emission

$$I = \xi E^{2} e^{-6.53\times 10^{3}\varphi^{3/2}/\beta E}$$

We'll come back to this equation in more detail in the breakdown section.

Once the current is emitted it is accelerated and decelerated by the electric field and deflected by the magnetic field according to the Lorenz force,

$$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right)$$

The resulting trajectories in an rf cavity are very complex. Generally most of the dark current collides with the wall within the same or adjacent cell.

If the electric fields are high enough, electrons can be captured in an rf “bucket,” accelerated and potentially transported over many cells and even structures. This **dark current capture limit** is given by,

$$E_{crit} = \frac{\pi m_0 c^2}{e\lambda}$$

$$= 5.3 \frac{f}{1GHz}$$

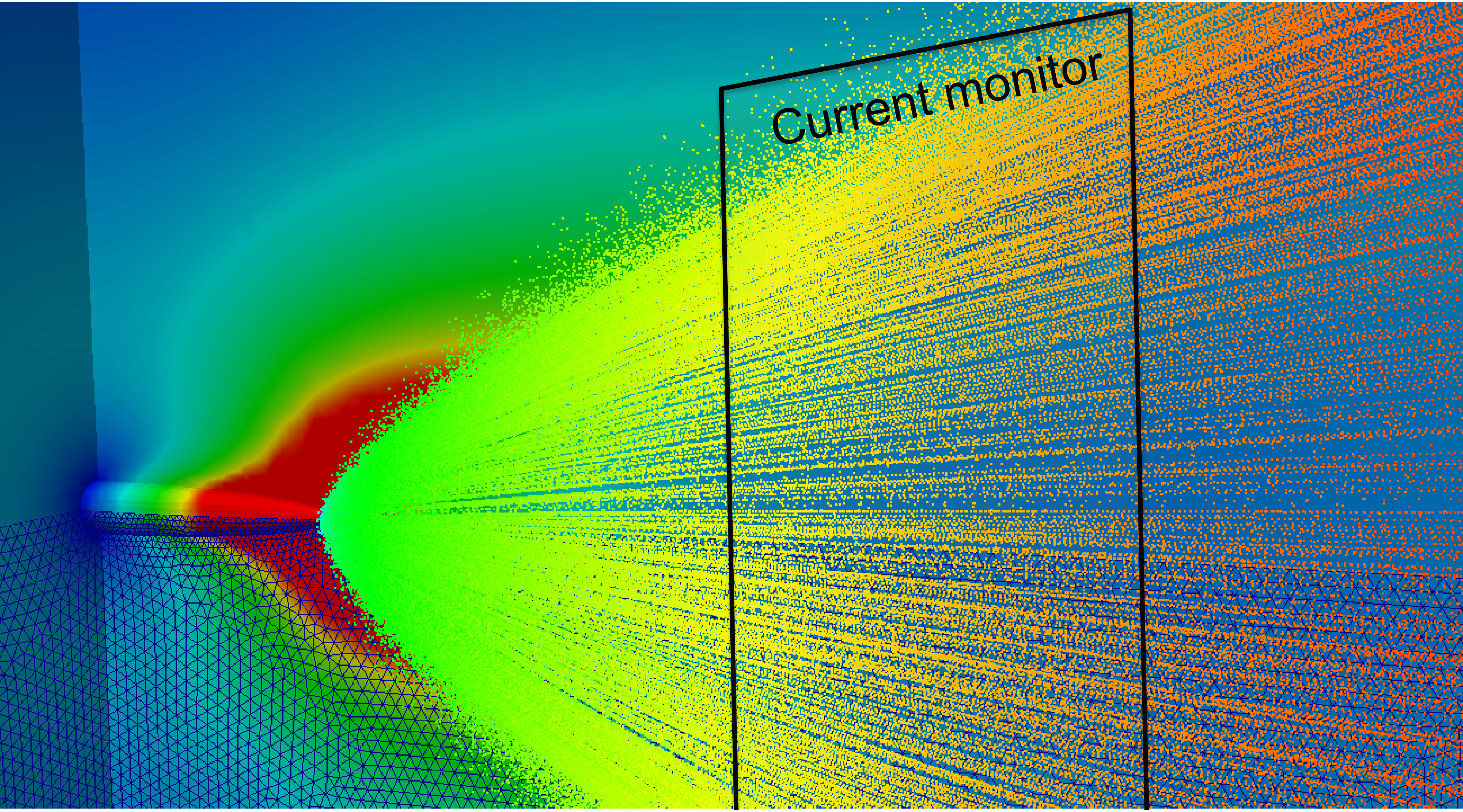
Examples: ILC, 1.3 GHz, runs about 4 times the dark current capture limit, and CLIC, 12 GHz about 1.5.

The effect of dark current is to,

1. Generate background X-rays from bremsstrahlung.
2. Captured dark current can generate an even higher energy background.
3. The dark current screws up diagnostics readings like beam position measurements.
4. A dynamic pressure rise occurs through **electron stimulated desorption**.
5. Lower the *Q* in a superconducting cavity.

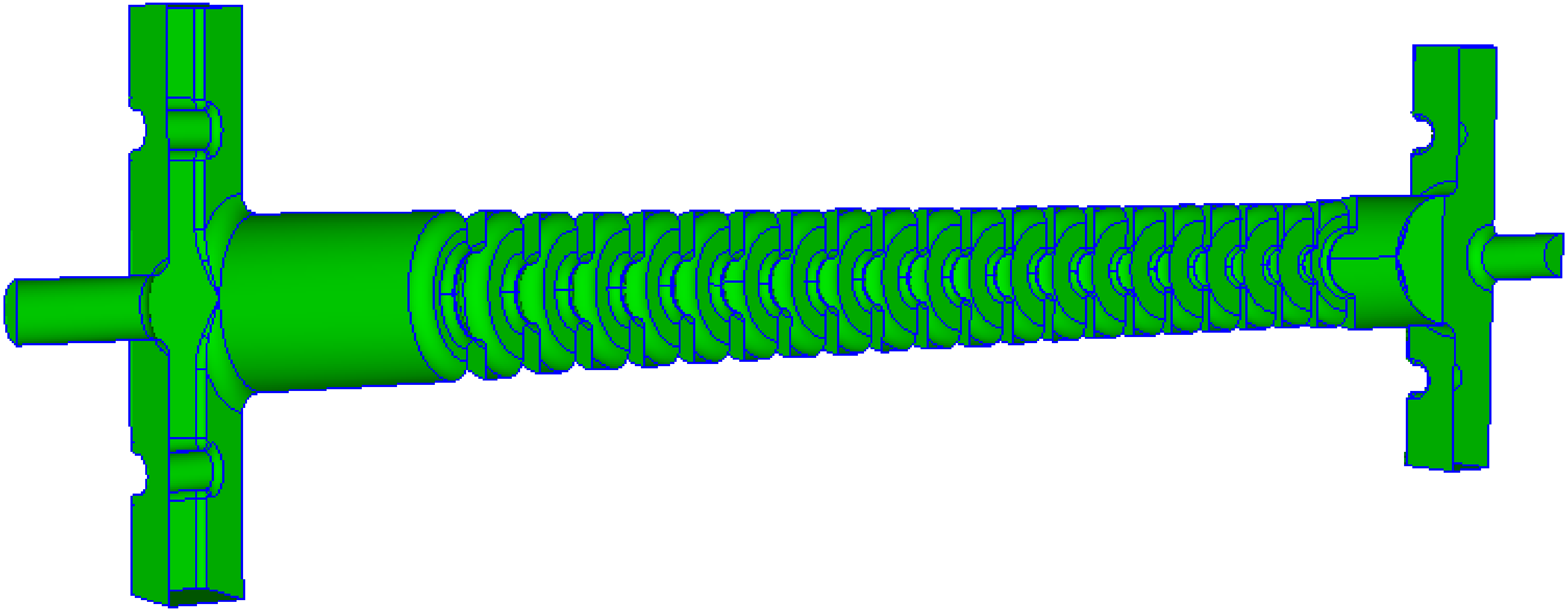
Most ominously for normal conducting machines, the high enough field emission which underlies to dark currents can lead to **breakdown**.

Pic3P Field Emitter Space-Charge Modeling



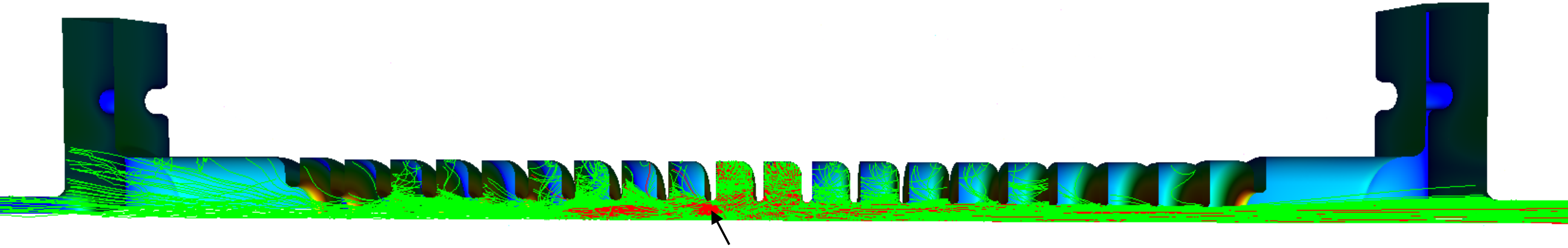
space-charge field |E| in vertical symmetry plane
electrons colored by momentum

T18vg2.6 Structure



- Structure being tested at KEK and SLAC
- Simulation Code: (ACE3P)
  - S3P - S-Parameter & Fields
  - Track3P- Particle Tracking

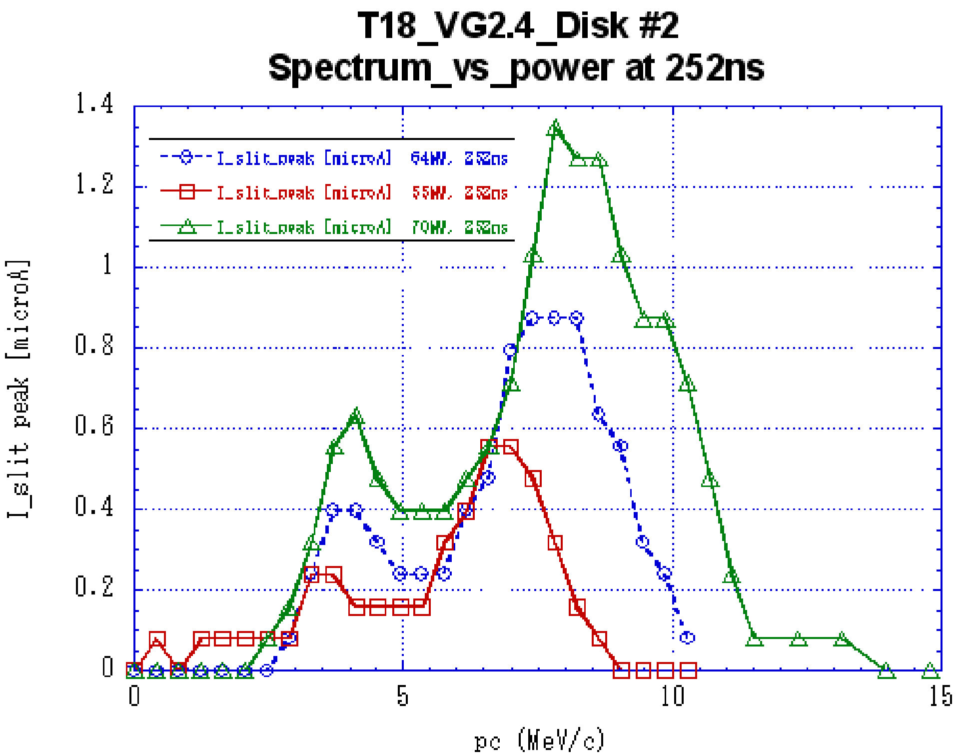
Dark Current Emitter Simulation

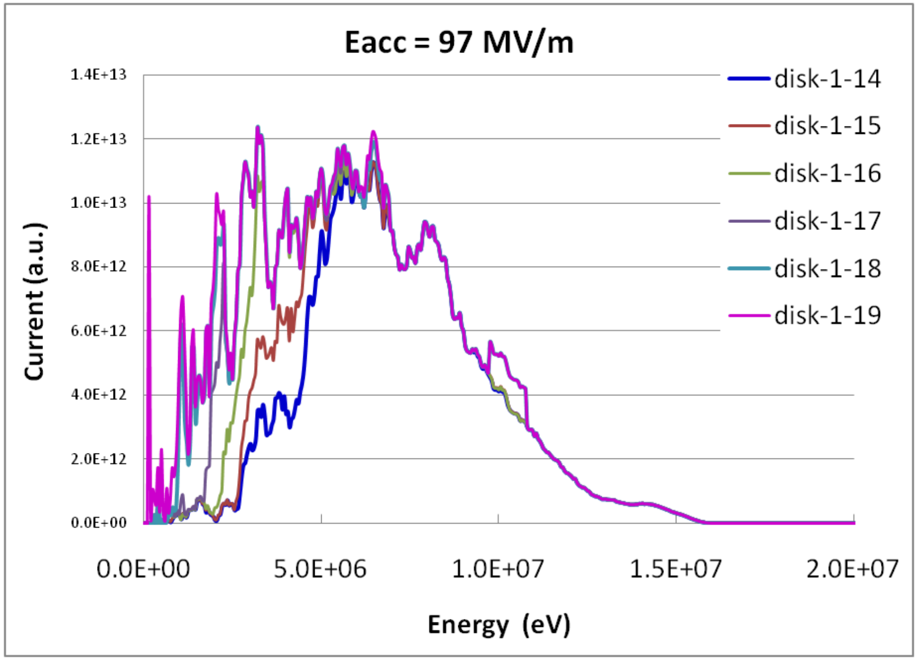


Emitted from
iris #6

- Intercepted electrons - dark current heating on surface
  - Deposited energy into the wall results in surface heating
- Captured electrons: energy spectrum
  - Emitter (disk) location - energy
  - Emitter density on disk – amplitude

Dark Current Spectrum Comparison





Measured dark current energy spectrum at downstream

Simulation Eacc=97MV/m. dE/E=0.1, zbp=2.9m

Differences?

Measured dark current spectrum details would depend on the number of emitters on the disks

Z. Lee, SLAC

Animations of field emission and dark currents

Multipactor

Multipactor is a special condition of dark current where, in a particular place in a cavity, electron trajectories connect one or two emission/impact sites over a specific number of half rf cycles.

This resonance condition, combined with **secondary electron emission**, results in the discharge phenomenon called multipactor.

Two- point multipactor,
low magnetic field,
parallel gap,
integer number of rf cycles.

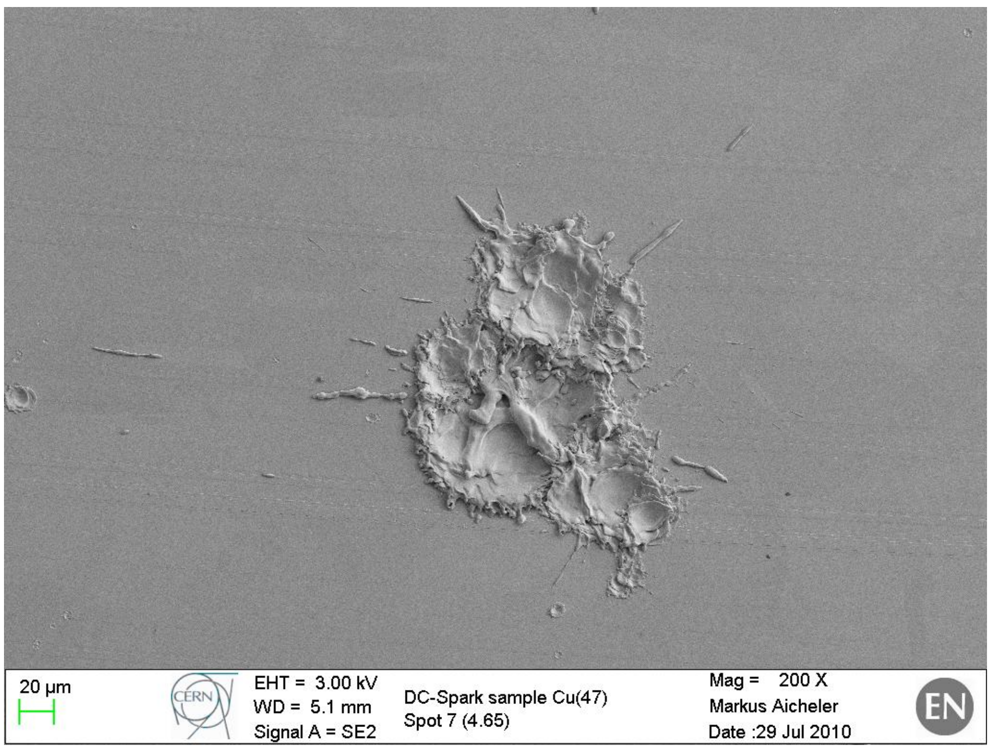
Single- point multipactor,
high magnetic field,
single surface,
odd number of half rf cycles.

See for example G. Bienvenu, "An investigation on the field emitted electrons in travelling wave accelerating structures," NIM A320 (1992). A number of codes are capable of simulating this effect through tracking.

Breakdown

At a sufficiently high level of surface electric field, an emission point will undergo a phase transition, driven by some combination of the heating from the emission current and the stress from the high electric field.

This phase transition is a dramatic avalanche phenomenon which includes atomic evaporation, ionization, back-bombardment of ions, formation of a plasma spot, a plasma sheath, enhanced emission current, surface melting, macroscopic power absorption etc.

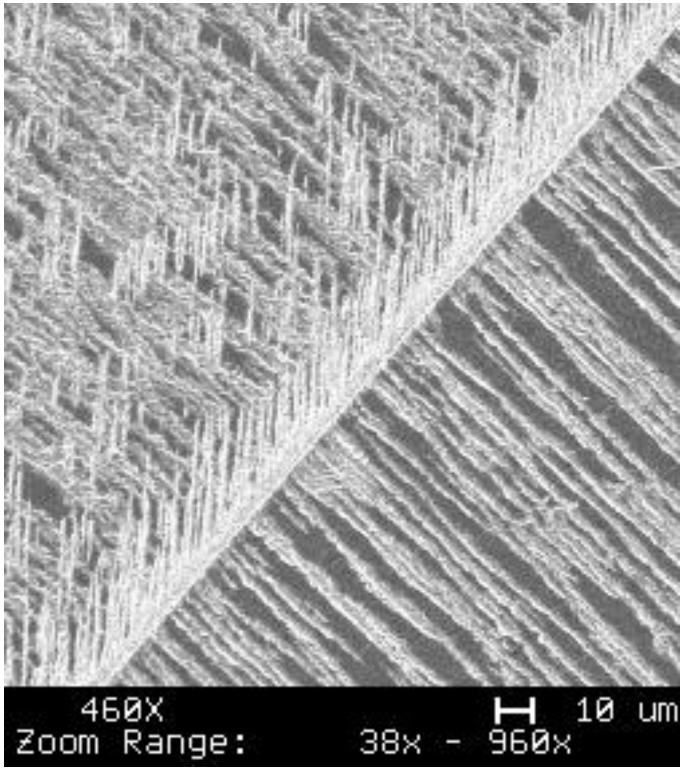


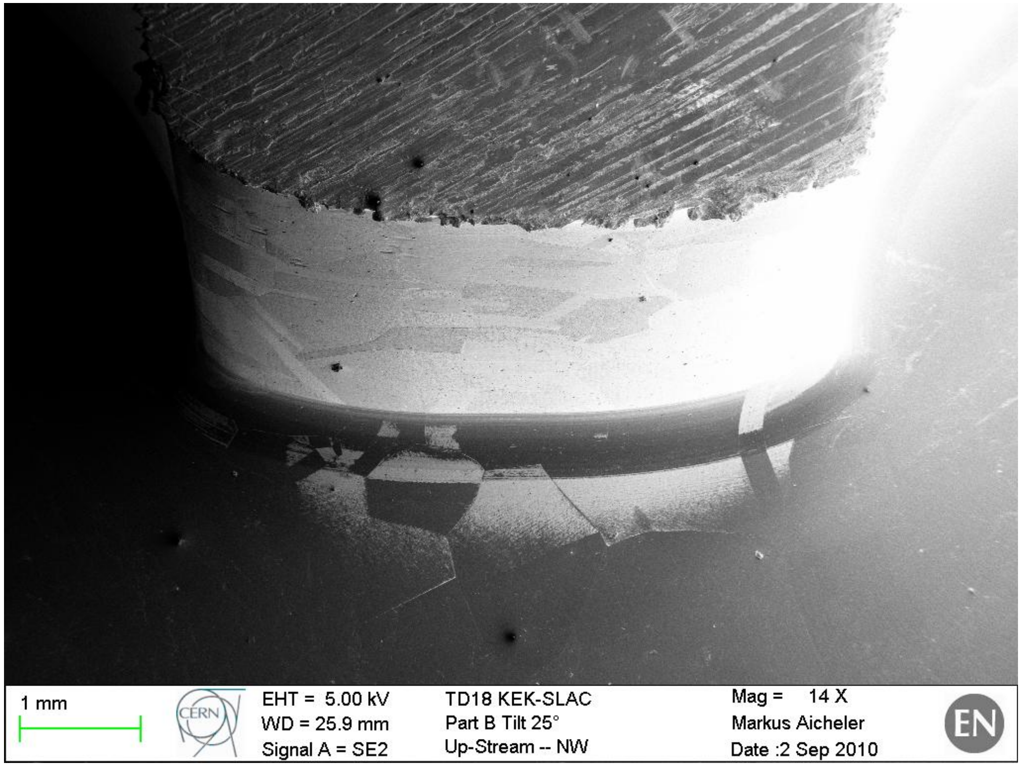
The details vacuum breakdown will be covered extensively in next section. This is one of the two the main effects which limit gradient in accelerating structures.

Pulsed surface heating

On each rf pulse, rf currents heat the cavity wall. This is referred to as **pulsed surface heating**. The consequence is that during an rf pulse, a thin surface layer is heated relative to the bulk material which results in a compressive stress.

The effect of many pulses, and corresponding compressive stress cycles, is to cause mechanical fatigue and surface damage.





Relations behind pulsed surface heating

Standard electromagnetic relations

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

$$R_s = \frac{1}{\delta\sigma}$$

$$P_{peak} = \frac{1}{2} R_s H_t^2$$

Thermal and mechanical relations

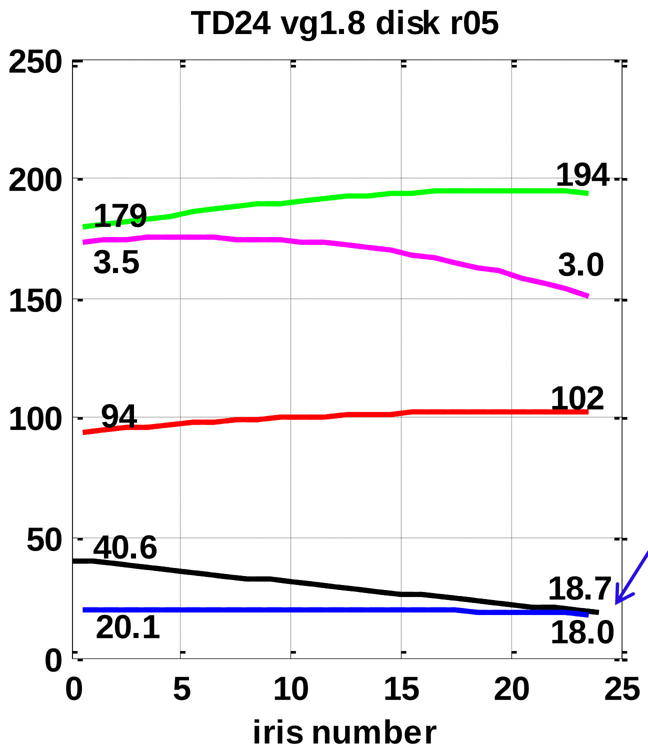
$$\Delta T = \frac{2\,Ppeak}{K}\sqrt{\frac{Kt_{pulse}}{\pi\rho C}}$$

K is the thermal conductivity
C is the specific heat

$$\sigma = \frac{E\,\alpha\Delta T}{1-\upsilon}$$

E is the elastic modulus
α is the coefficient of thermal expansion
υ is Poisson’s ratio

Examples



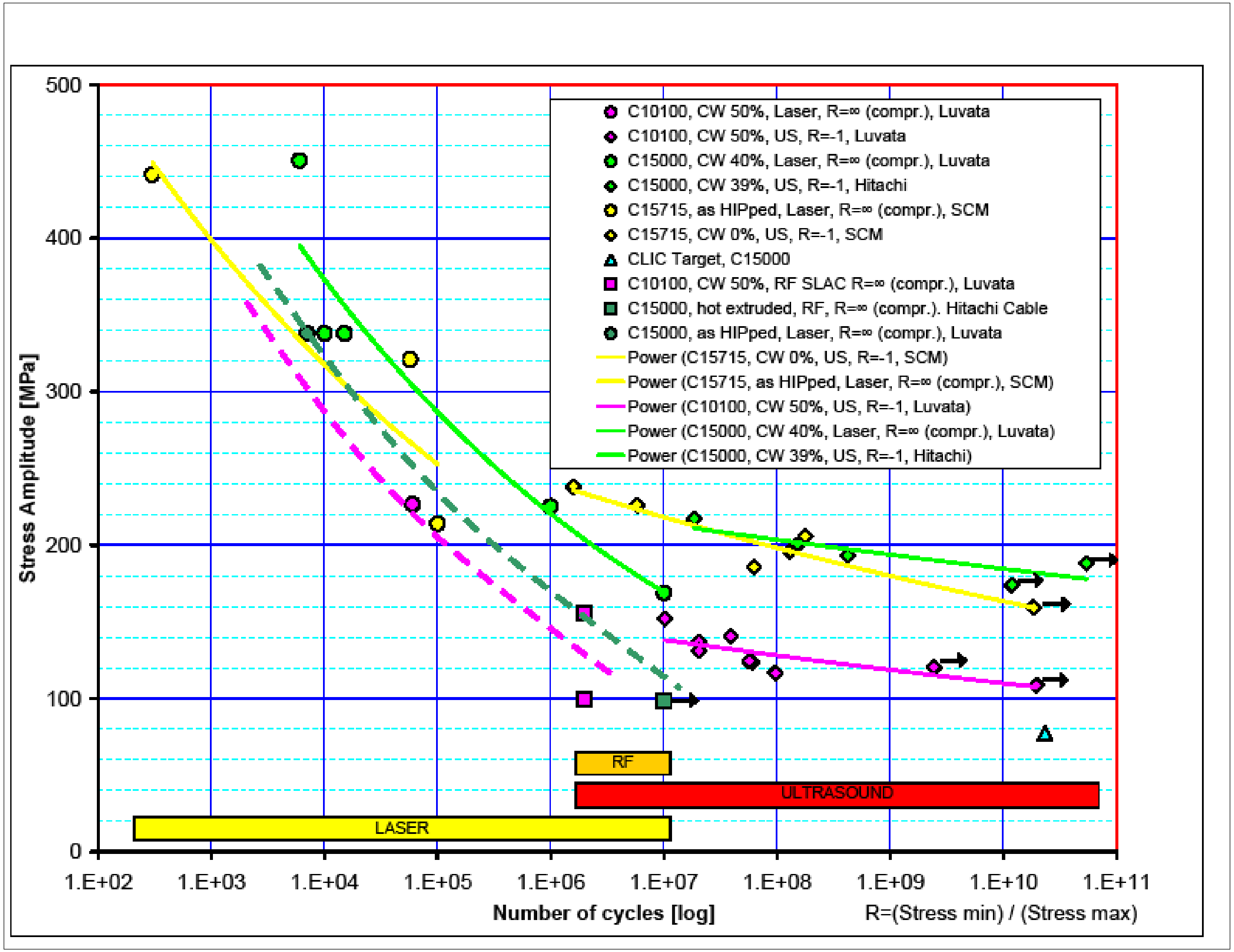
Various rf parameters for the CLIC nominal structure at 100 MV/m, 100 ns pulse length.

A pulsed surface heating temperature rise of 20 °C corresponds to a compressive stress of 68 MPa.

The yield strength for the annealed copper we have is 255 MPa.

But long before there is a fatigue effect from cyclical loading.

Wöhler curves for various types of copper relevant for rf cavities



From Samuli Heikkinen