CLIC Accelerating Structure Development

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Outline

- Overall objectives and issues
- Accelerating structure design and optimization
- High-power limits – breakdown and pulsed surface heating
- Recent high-power rf test results

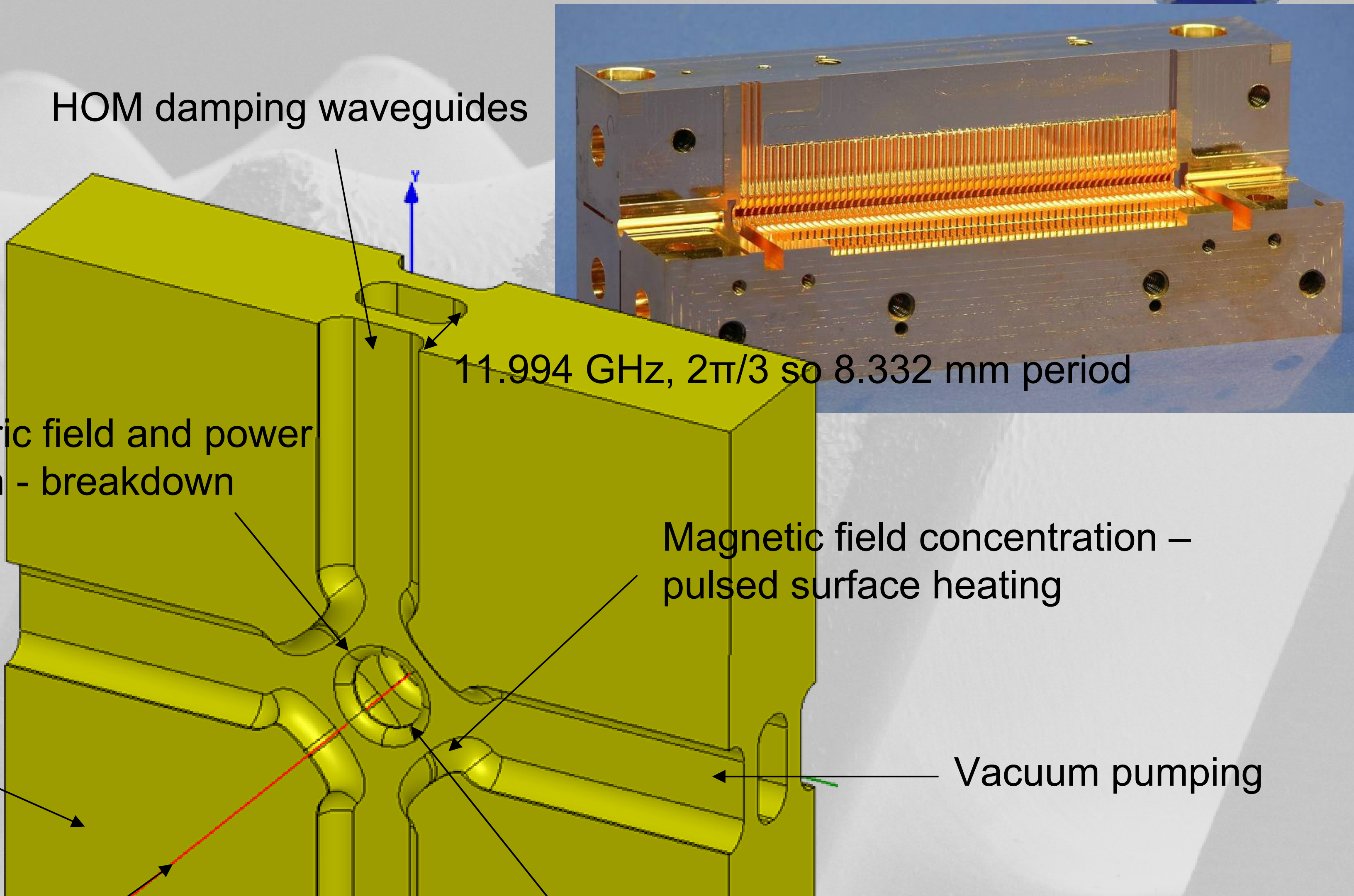
Overall objectives and issues

Design, prototypes, high-power tests and subsystem development of CLIC (Compact Linear Collider) 12 GHz accelerating structures.

- **High-gradient, 100 MV/m** – Quantitative investigation of high-power effects like breakdown and pulsed surface heating. Technologies for high gradients like materials and surface preparation. High-power rf testing
- **Beam dynamics** – Demanding short and long range transverse wakefield specifications. Strong higher-order-mode suppression. Micron alignment tolerances. Integrated optimization.
- **Technical issues** – Vacuum, cooling, manufacture and system integration.

<u>and it's all heavily coupled</u>

Basic features



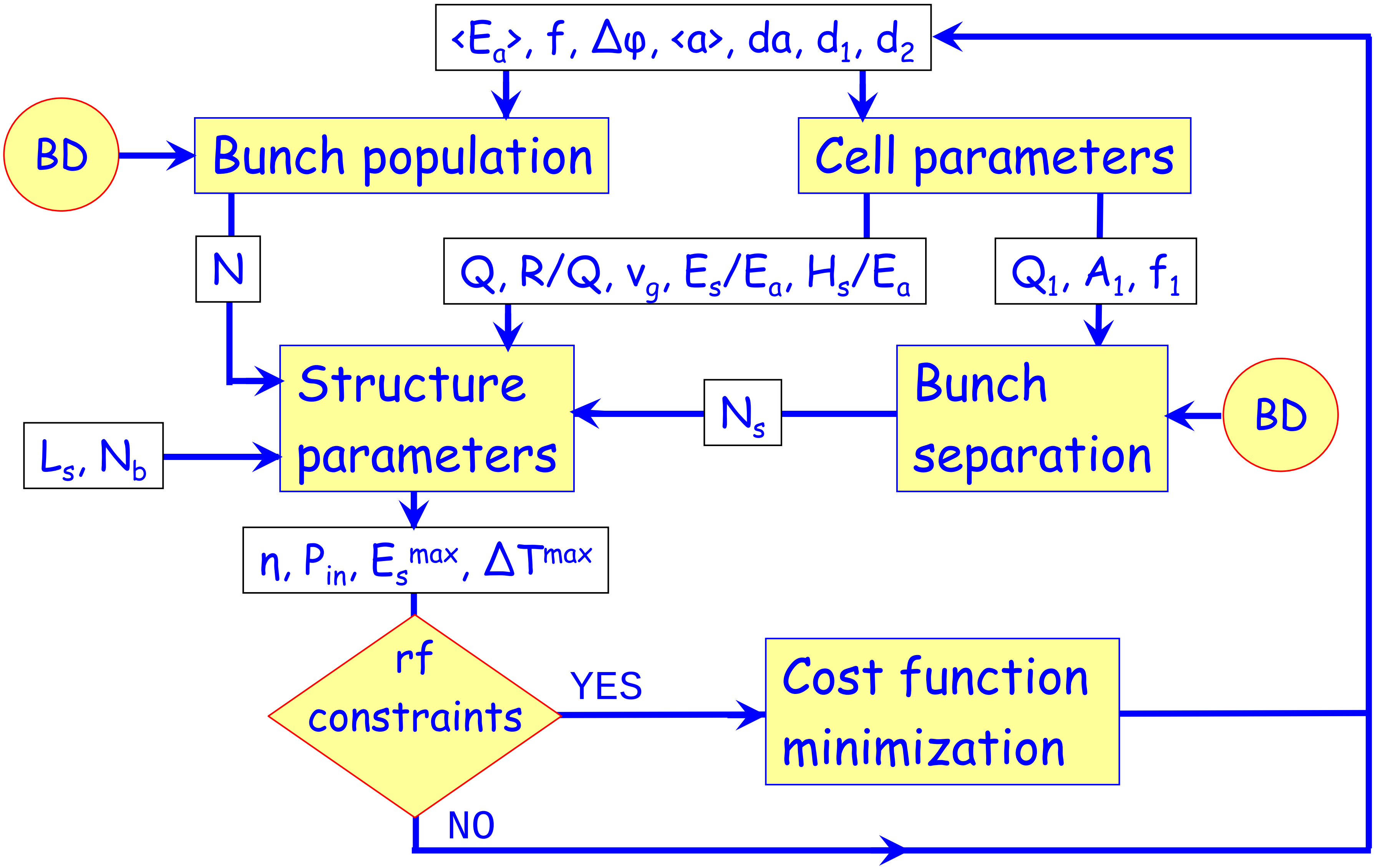
Design process

Strong interrelation between high-gradient performance and beam dynamics performance through the geometry of the structure.

Example – a structure with a smaller iris aperture will give a higher gradient but also stronger short-range transverse wakefields and thus a higher emittance growth.

There are many more such interrelations so an integrated design procedure has been developed,

Optimization procedure



Inputs to the design

Beam dynamics

High-power constraints

Beam dynamics input

$$FoM = L_{bx}/N \cdot \eta$$

BD → L_{bx}/N

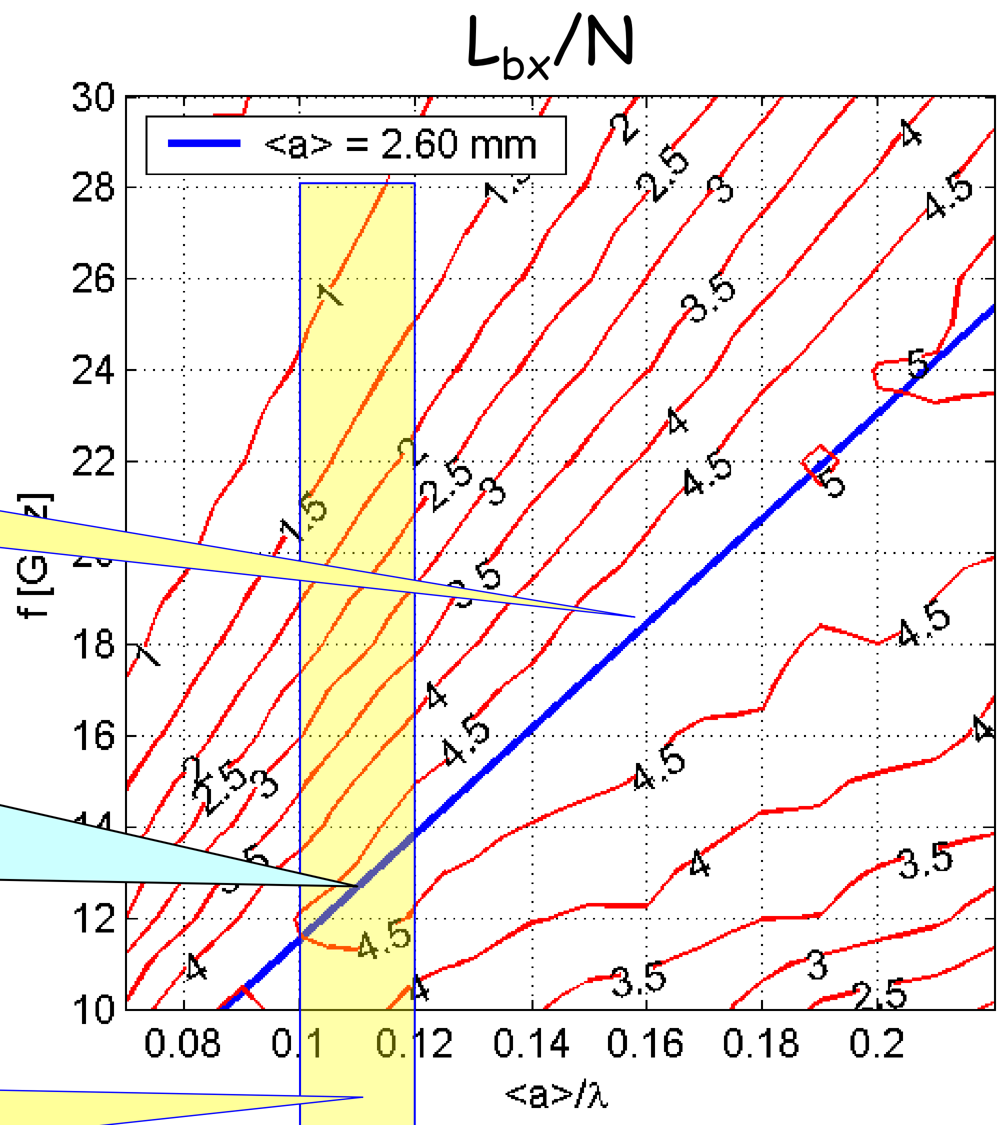
RF → η

BD optimum aperture:
<a> = 2.6 mm

Why X-band ?

Crossing gives optimum frequency

High-power RF optimum aperture: <a>/λ = 0.1 ÷ 0.12



High-power rf constraints

We face two main effects, rf breakdown and pulsed surface heating.

• rf breakdown – Need to determine gradient as a function of geometry. Local fields appear to give most of the answer but some hints of global effects.

• Pulsed surface heating – We know functional dependence but need basic material input data.

Next some latest ideas of the rf breakdown limit, then latest data on pulsed surface heating.

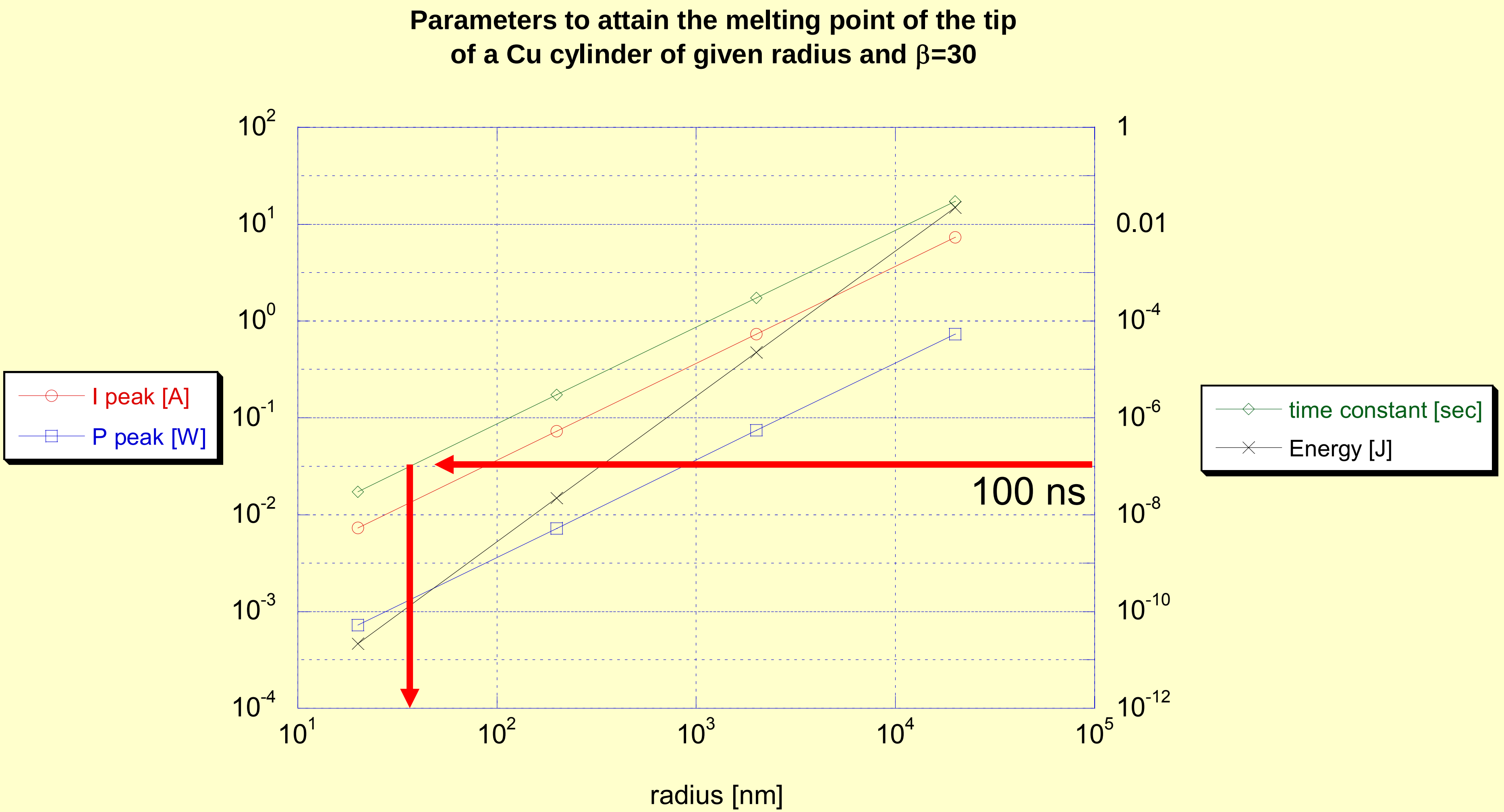
Quantifying rf breakdown

We are going to look at the breakdown trigger from the point of view of power flow.

First by applying the classical Fowler-Nordheim field-emission equations.

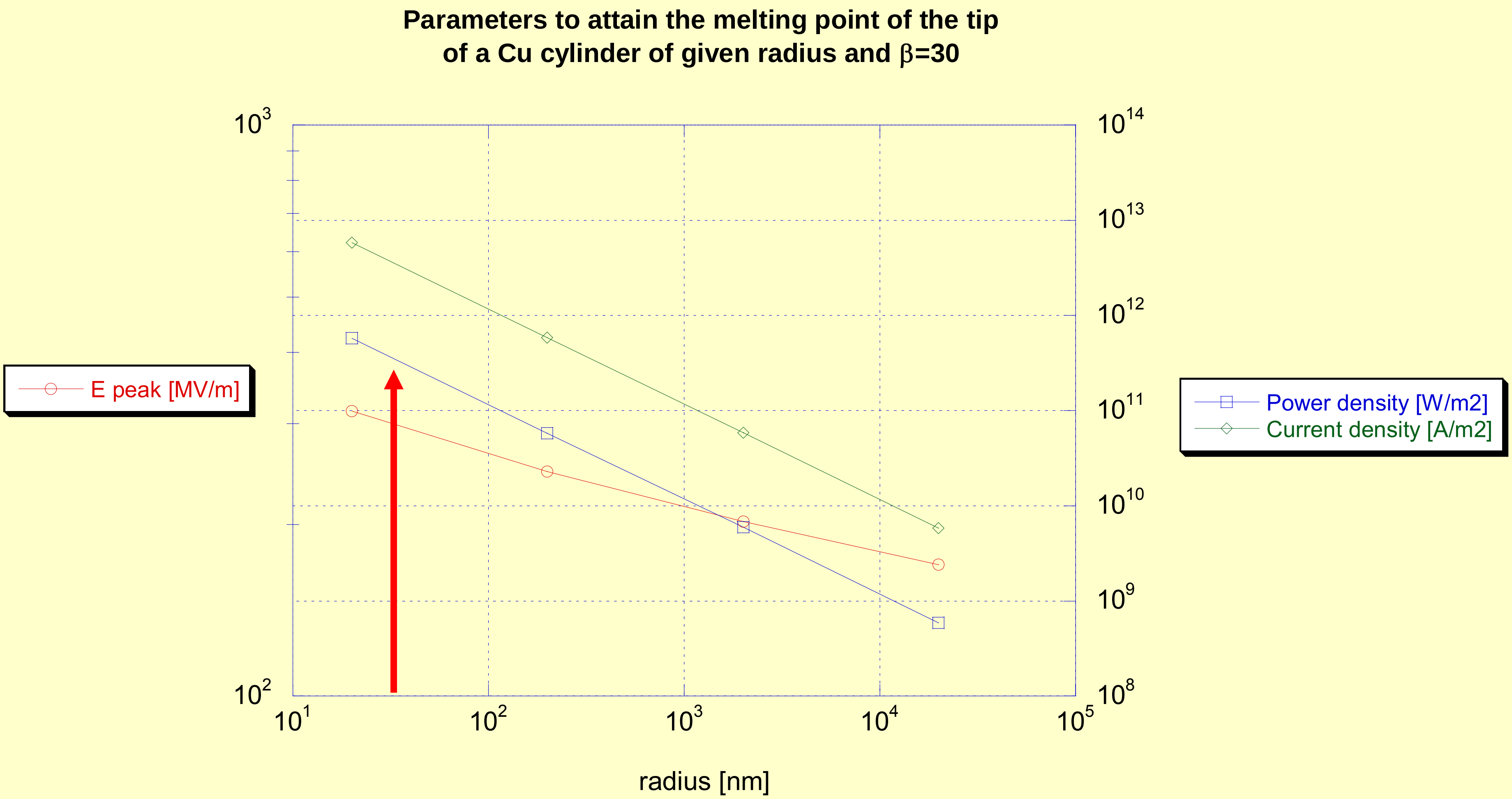
Then we will look at the coupling of rf power to field emission sites.

Time constant to reach the copper melting point (cylinders, β=30)



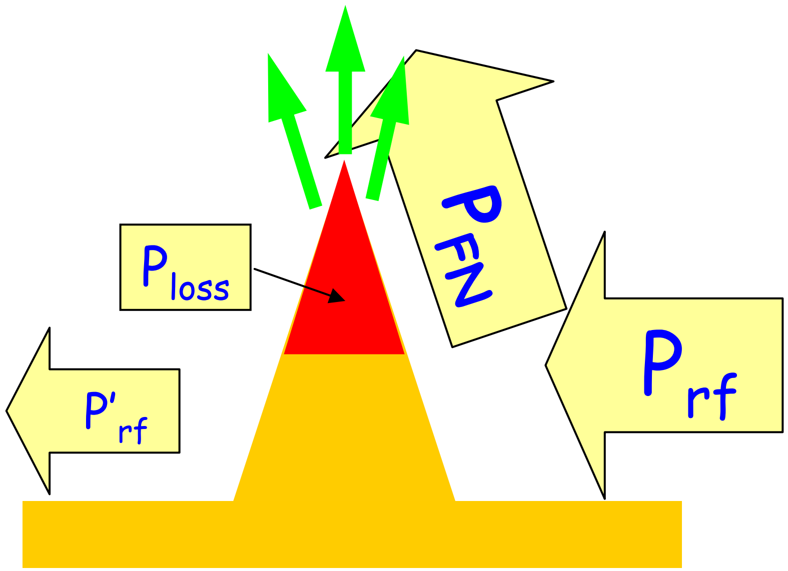
The tips which are of interest for us are extremely tiny, <100 nm (i.e. almost invisible even with an electron microscope)

Power density at the copper melting point (cylinders, β=30)



Power density of about 0.5 W/μm²

Field emission and rf power flow



$$\Delta T \sim P_{loss} \ll P_{FN} \leq P_{rf}$$

$$P_{loss} = \int_V J_{FN}^2 \rho \, dv$$

$$P_{FN} = \oint_S E \times H_{FN} \, ds \sim E \cdot I_{FN}$$

$$P_{rf} = \oint_S E \times H \, ds$$

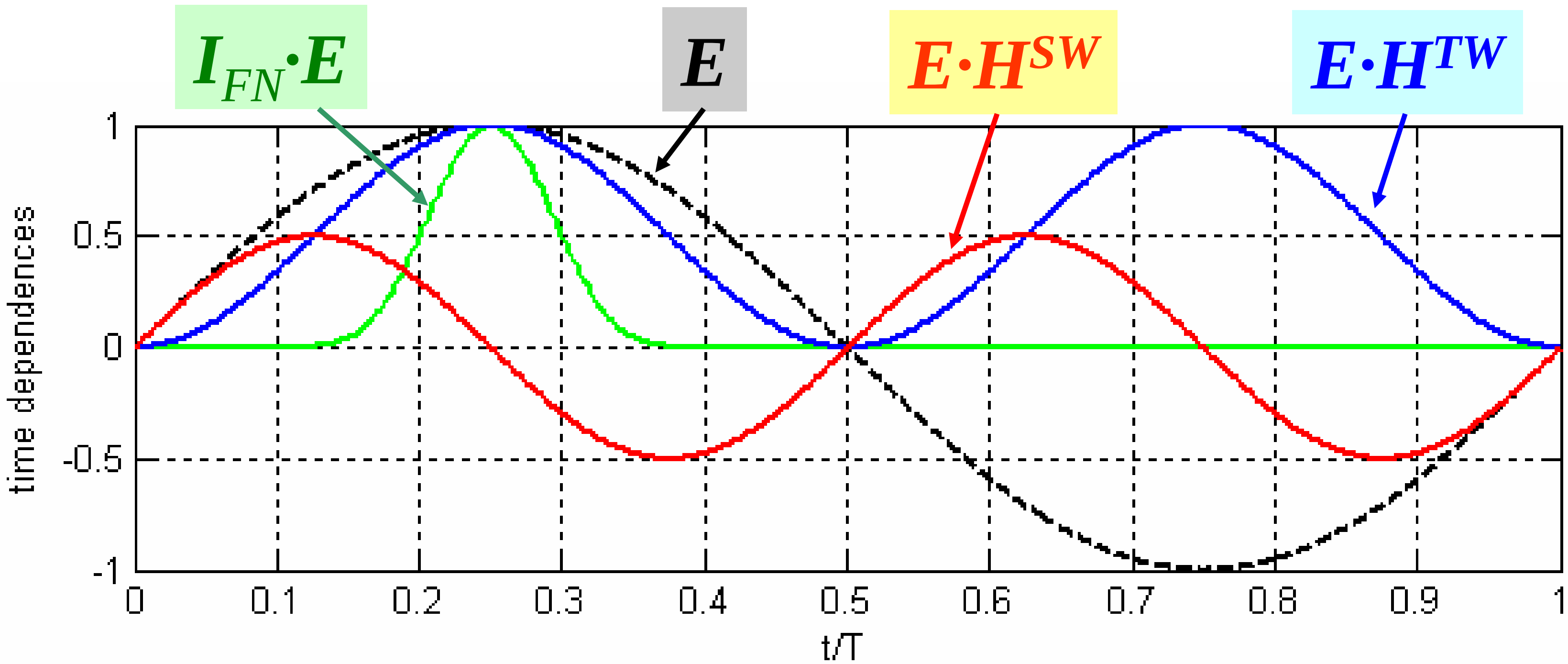
There are two regimes depending on the level of rf power flow

1. If the rf power flow dominates, the electric field remains unperturbed by the field emission currents and heating is limited by the rf power flow (We are in this regime)
2. If power flow associated with field emission current P_{FN} dominates, the electric field is reduced due to "beam loading" thus limiting field emission and heating

Field emission and power flow

$$E \times H = E_0 \cdot H_0^{TW} \sin^2 \omega t + E_0 \cdot H_0^{SW} \sin \omega t \cos \omega t$$

$$I_{FN} \cdot E = A E_0^3 \sin^3 \omega t \cdot \exp\left(\frac{-62\, GV/m}{\beta E_0 \sin \omega t} \right)$$



What matters for the breakdown is the amount of rf power coupled to the field emission power flow.

$$P_{coup} = \int_0^{T/4} P_{rf} \cdot P_{FN} dt \bigg/ \left(\int_0^{T/4} P_{FN} dt \cdot \int_0^{T/4} P_{rf} dt \right)$$

$$= C^{TW} E_0 H_0^{TW} + C^{SW} E_0 H_0^{SW}$$

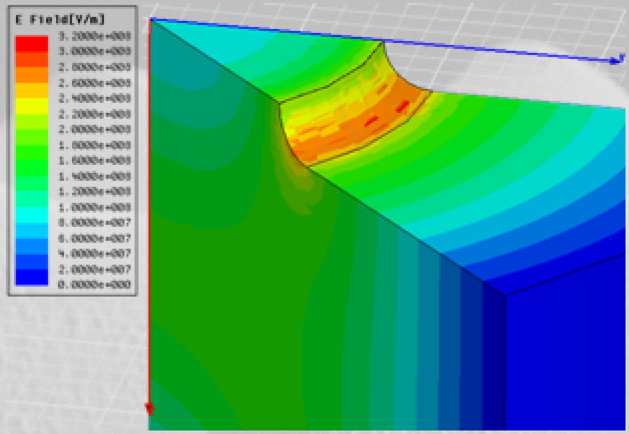
Assuming that all breakdown sites have the same geometrical parameters the breakdown limit can be expressed in terms of modified Poynting vector S_c.

$$S_c = E_0 H_0^{TW} + \frac{C^{SW}}{C^{TW}} E_0 H_0^{SW} = \mathrm{Re}\{\mathbf{S}\} + g_c \cdot \mathrm{Im}\{\mathbf{S}\}$$

Our new design constraint. Must be less than 6 W/μm^2 at 100 ns.

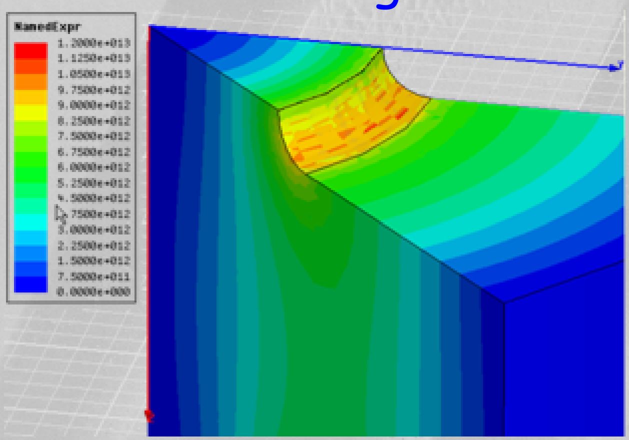
Surface field distributions

E_s



T53vg3

S_c



Looks similar to Es but varies correctly for high and low vg

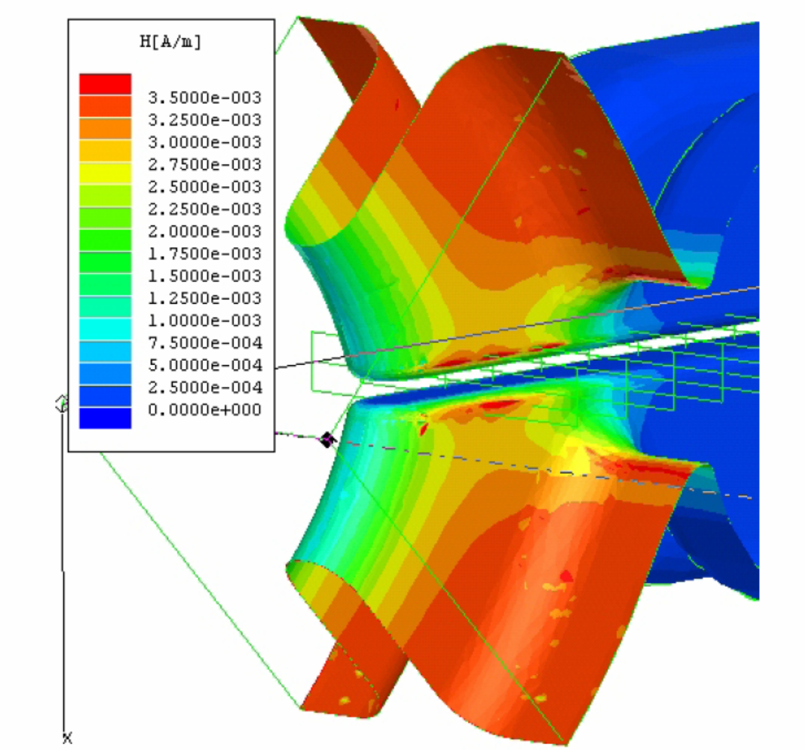


Figure 2.10: Magnetic field distribution on the cell walls of an HDS CLIC prototype structure. The magnetic field distribution in the figure (H [A/m]) is given for 1 MV/m accelerating gradient. For fixed geometry the magnetic field is proportional to gradient, so for 100 MV/m H need to be multiplied by 100. ©Alexej Grudiev, CERN

Now pulsed surface heating

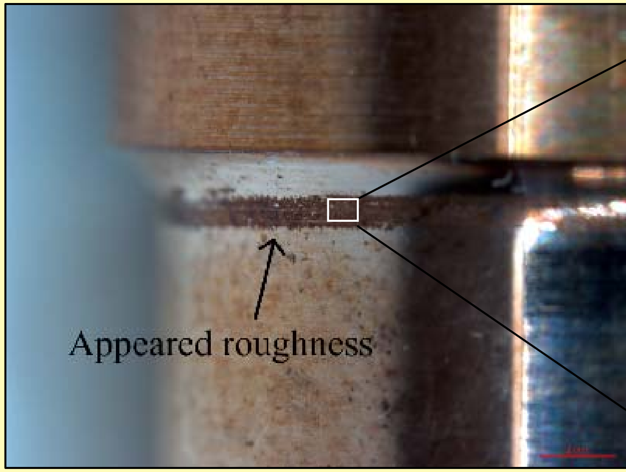
Pulsed surface heating

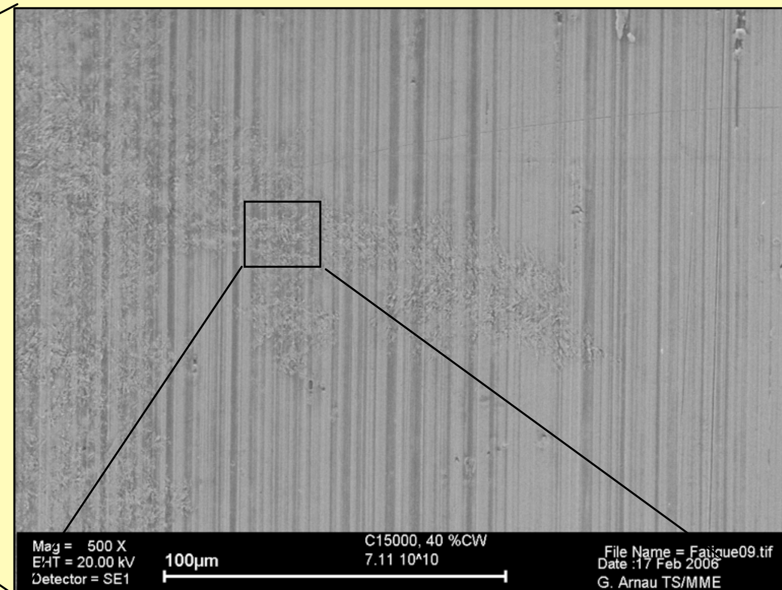
Each rf pulse induces a temperature rise, typically 50 ºC, in the cavity walls creating a cyclic compressive stress which results eventually in fatigue damage. The stress level is easily calculated but material property data in the time and distance scales, the number of cycles for CLIC is not available.

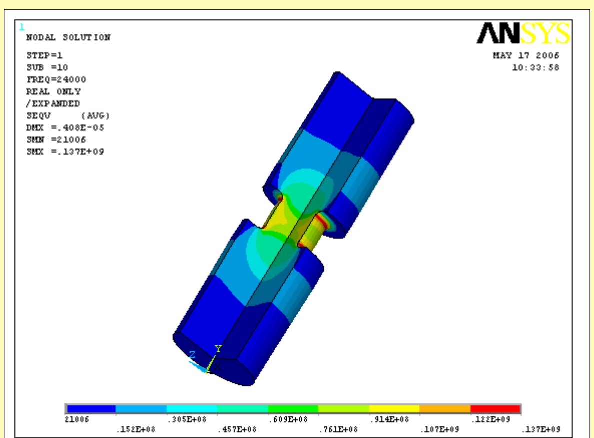
We have made a trio of experiments to obtain this data.

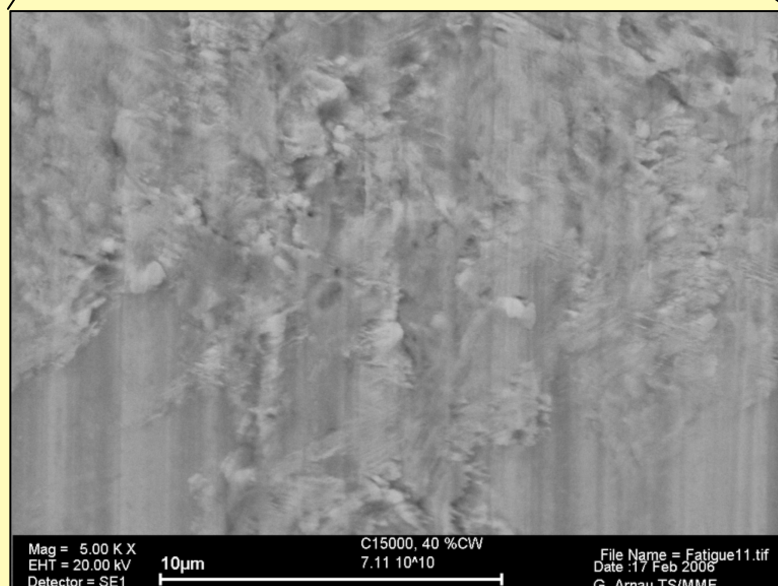
- Ultrasonic – Correct number of cycles, many samples, cheap (but bulk stress, failure criterion different)
- Laser – Correct pulse characteristics, thermally induced, available at CERN (few cycles, failure criterion different)
- rf tests – What we really need (limited number of cycles, limited number of tests (and facilities), expensive)

Fatigue by ultrasonic experiments

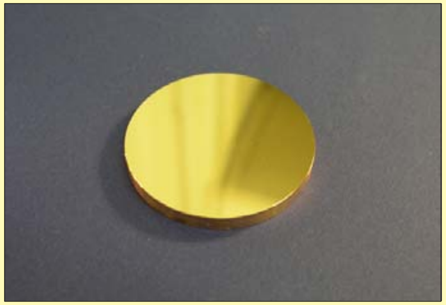


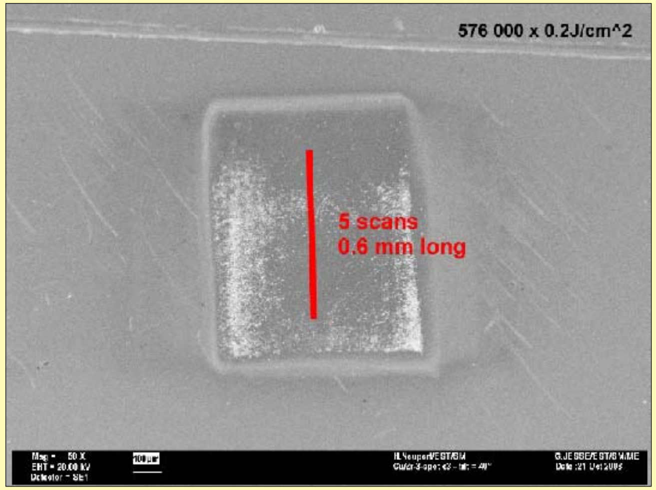


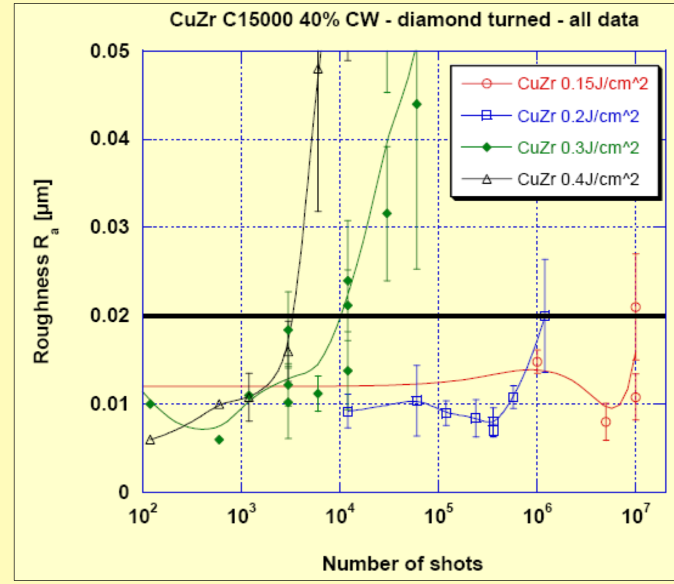


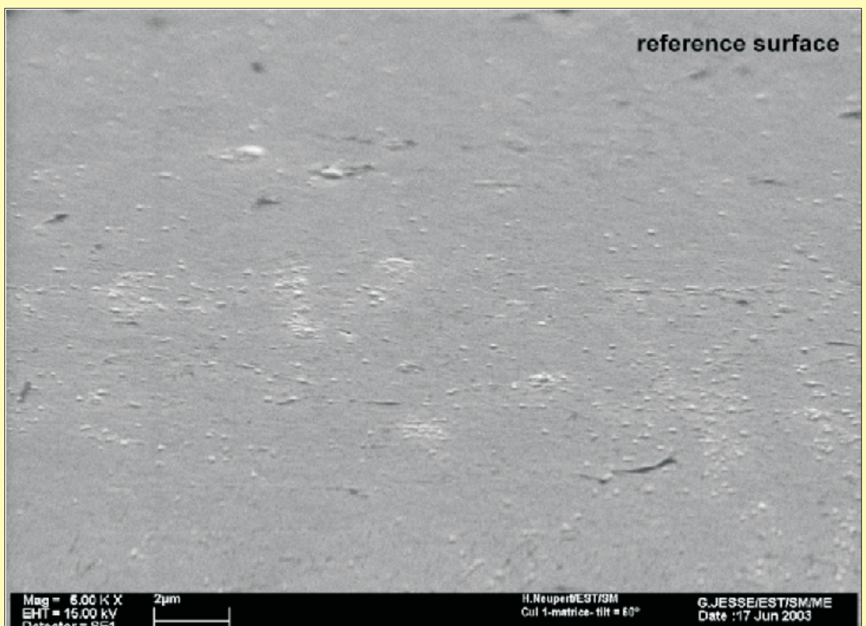


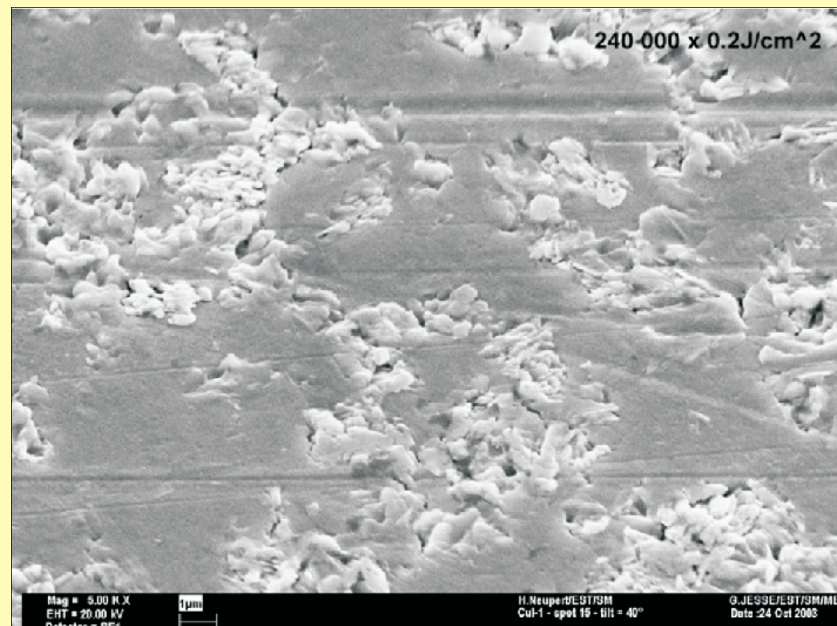
Fatigue by laser experiments







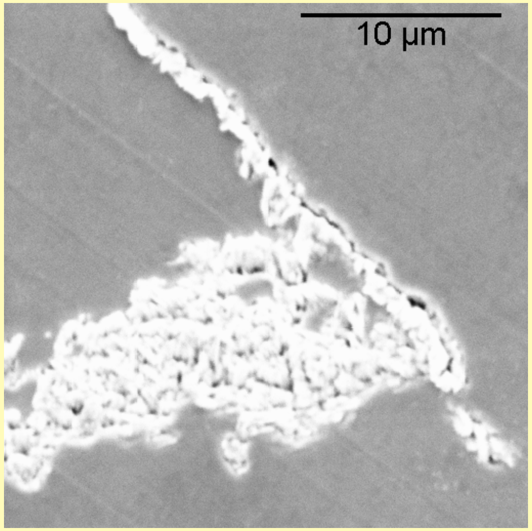


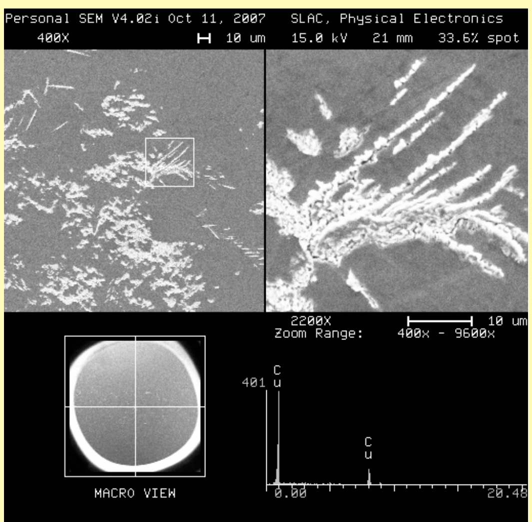


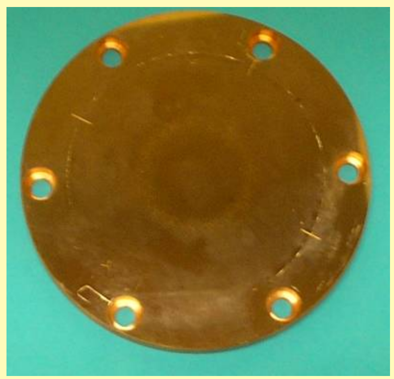
Fatigue by RF experiments at SLAC

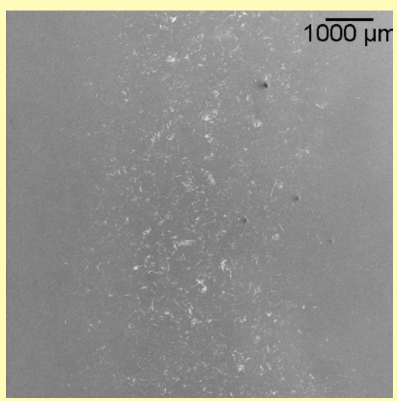
CLIC

Cu-OFE_1 (ΔT ~ 70ºC) after N=2*10^6

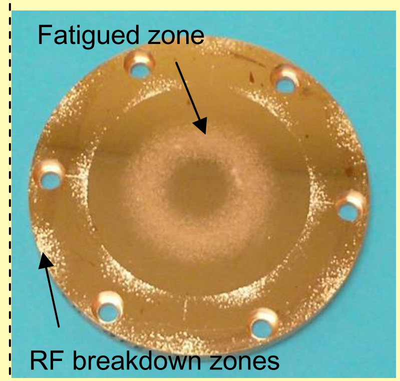


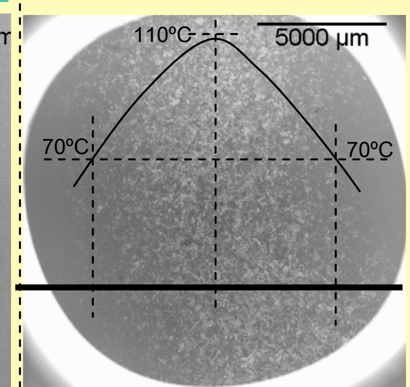


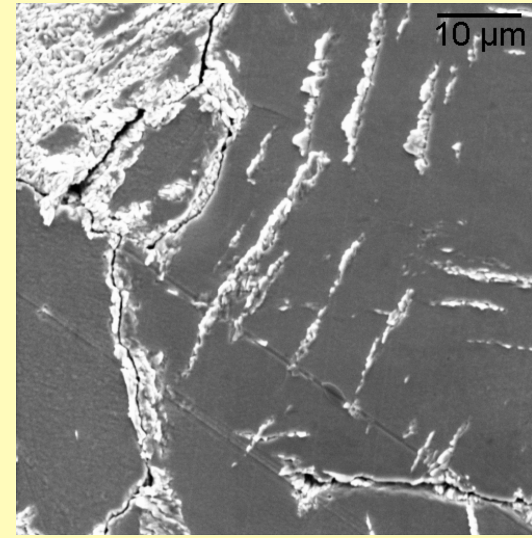


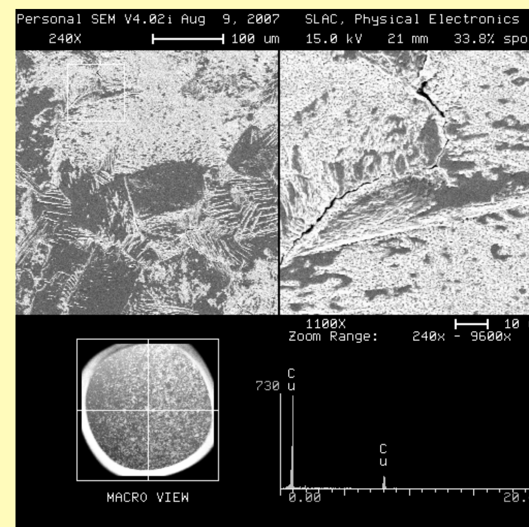


Cu-OFE_2 (ΔT ~ 110ºC) after N=2*10^6









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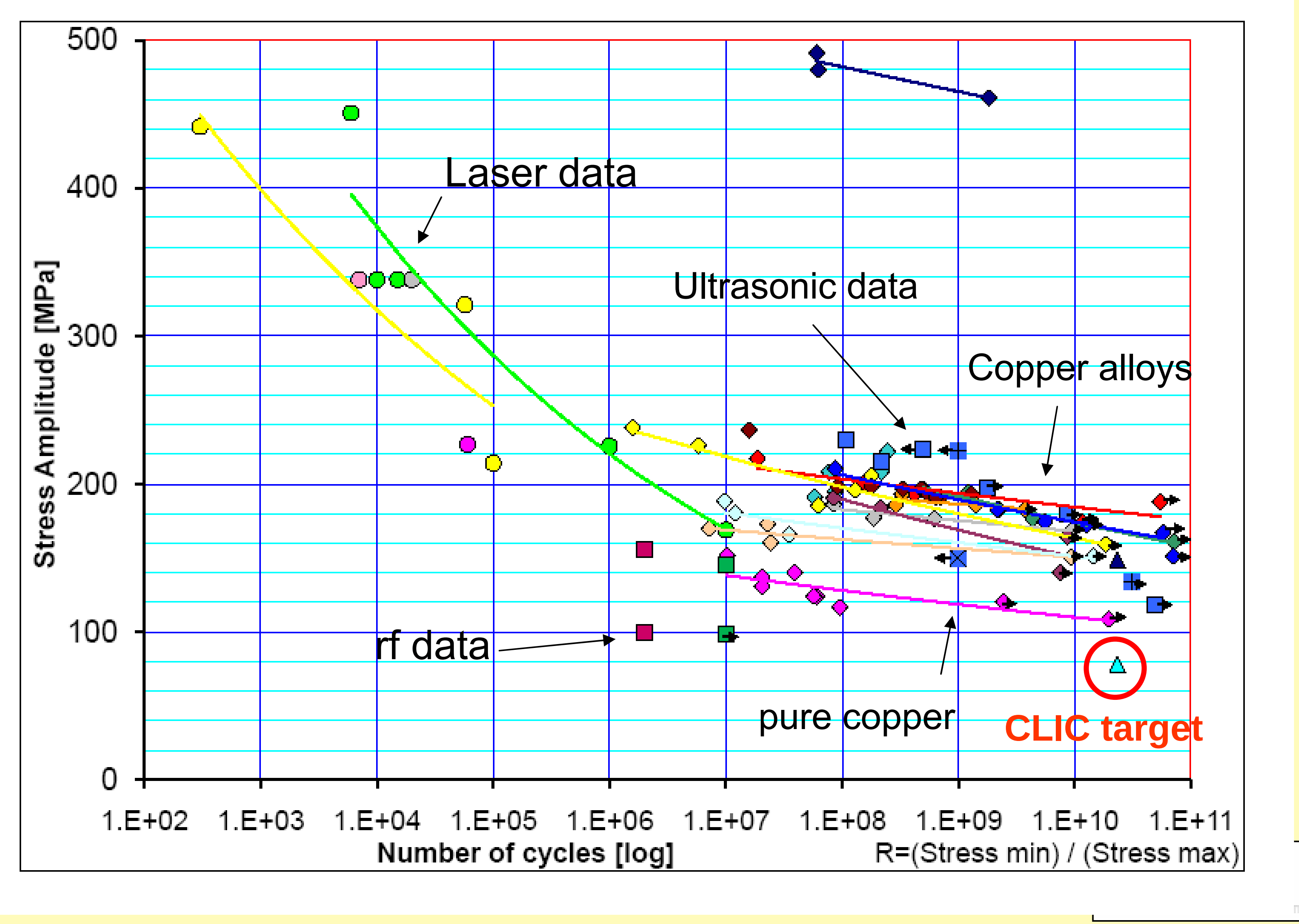
Wöhler curves of the test results (Stress vs. N)

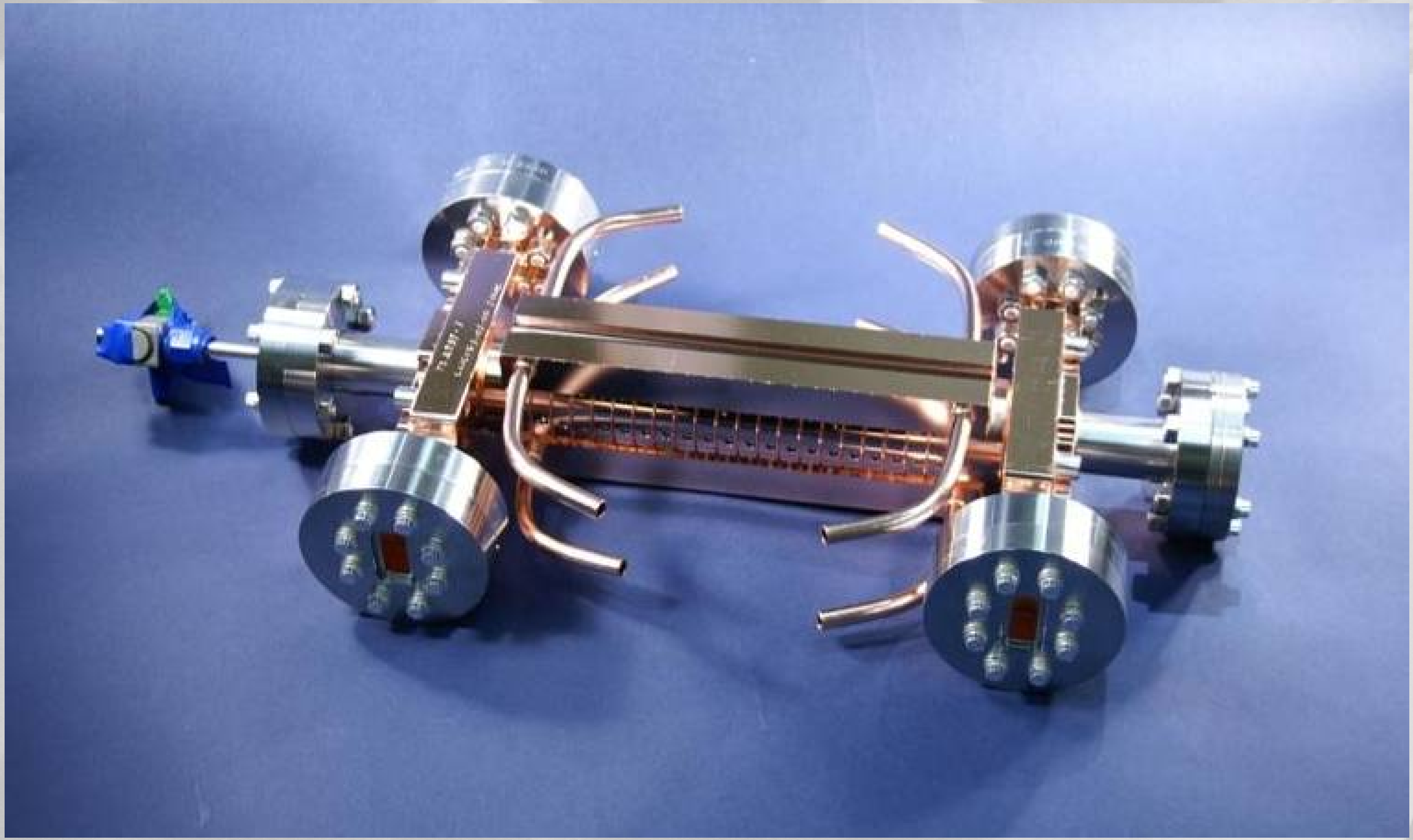


High-power rf testing

Now we need to put our theory to test!

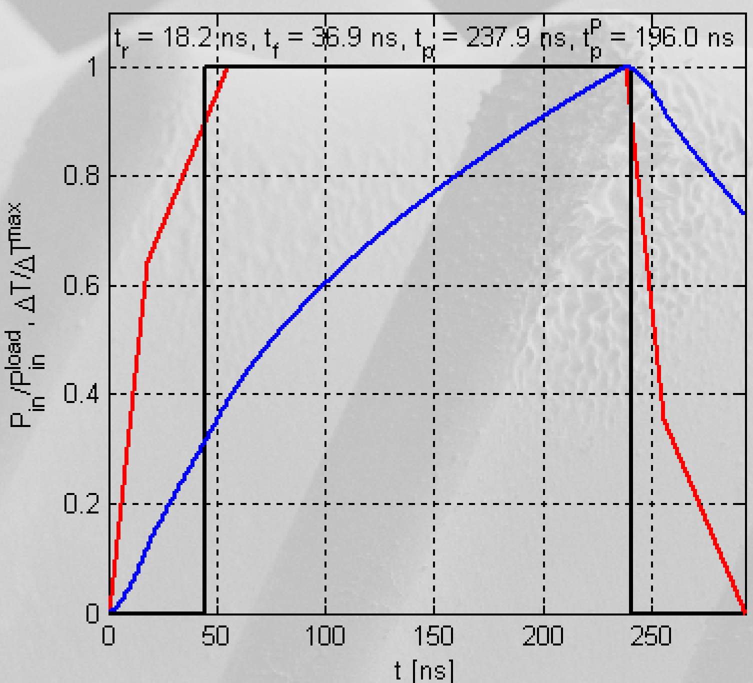
The work I will describe now is part of an extremely active and productive collaboration between KEK, SLAC and CERN.

T18 – The collaboration structure.

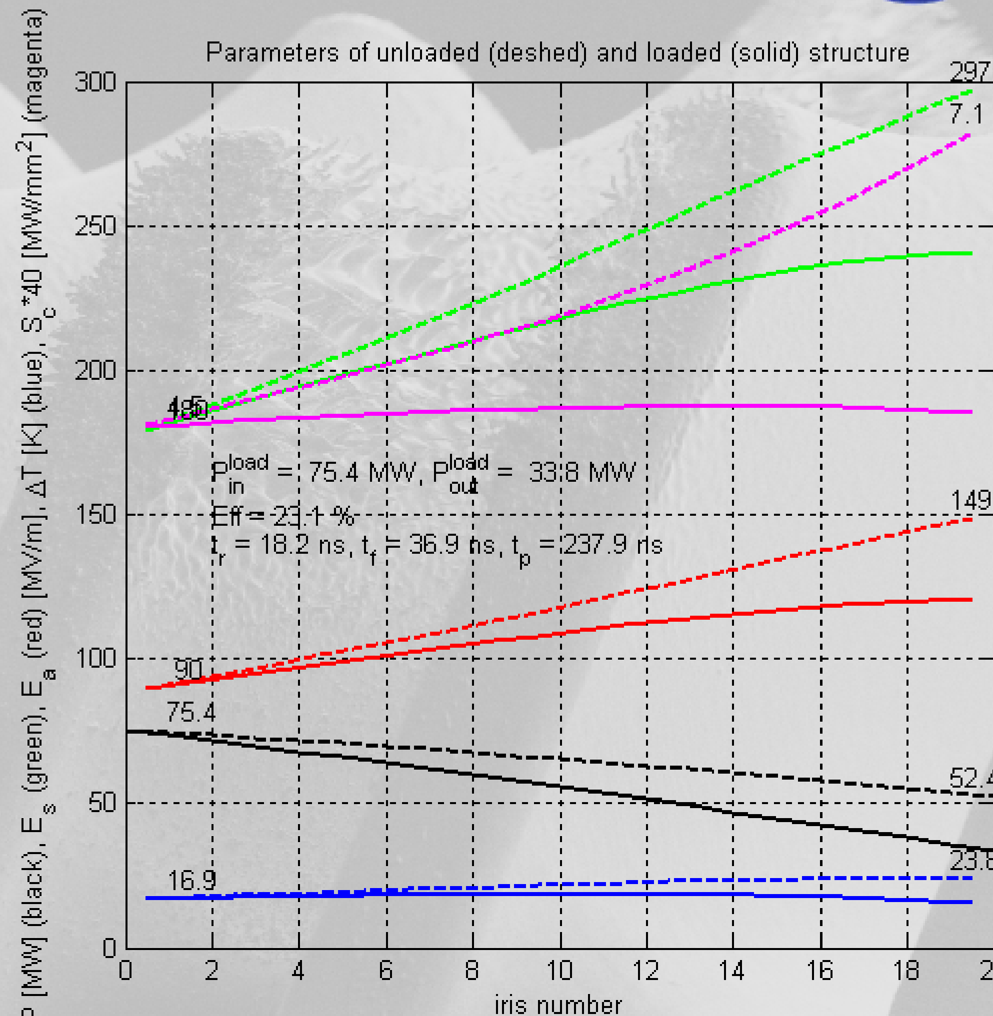


High-power rf test design

Test structure pulse



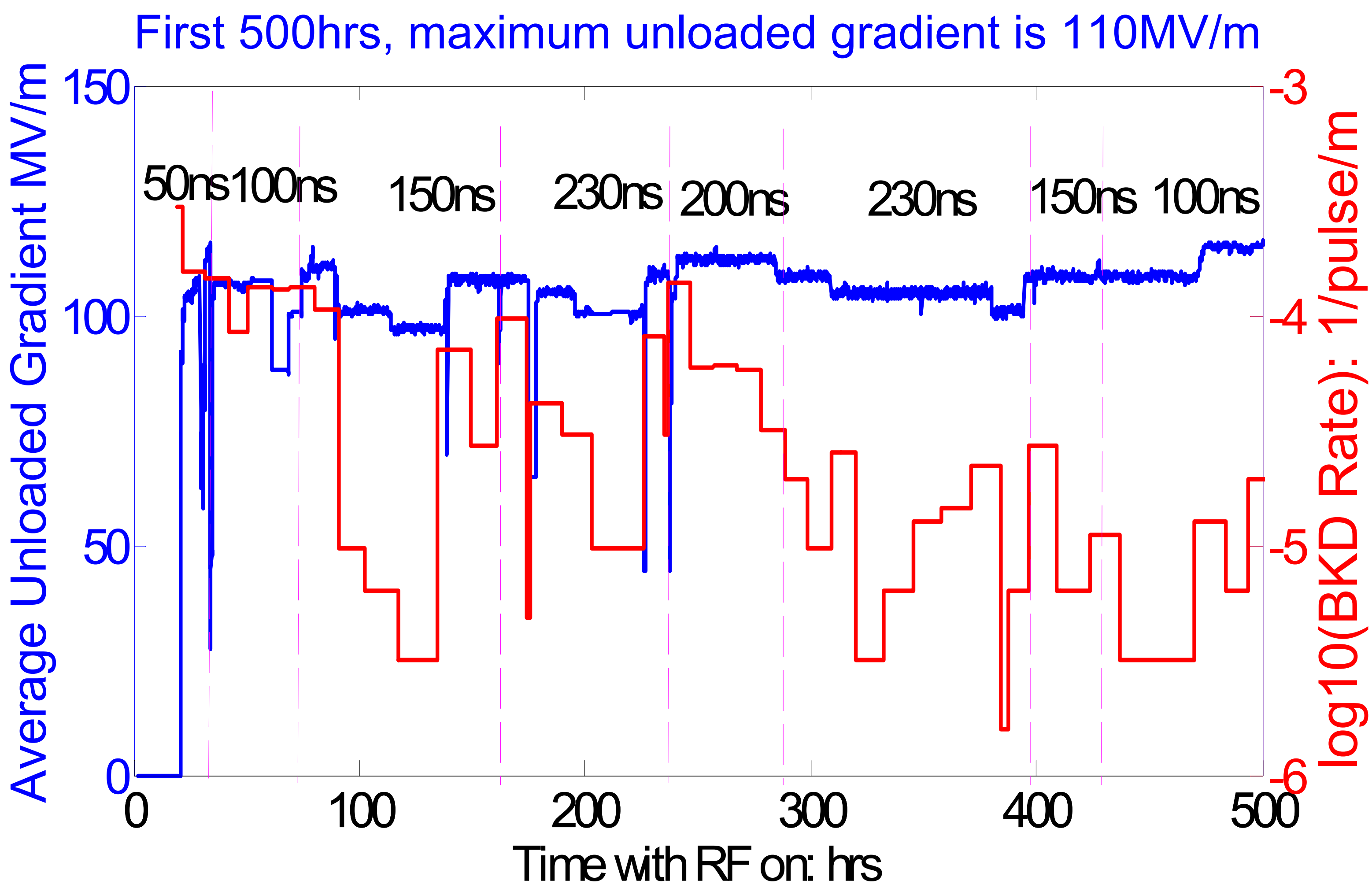
n.b. no HOM damping in this test structure!



Fields and powers along structure

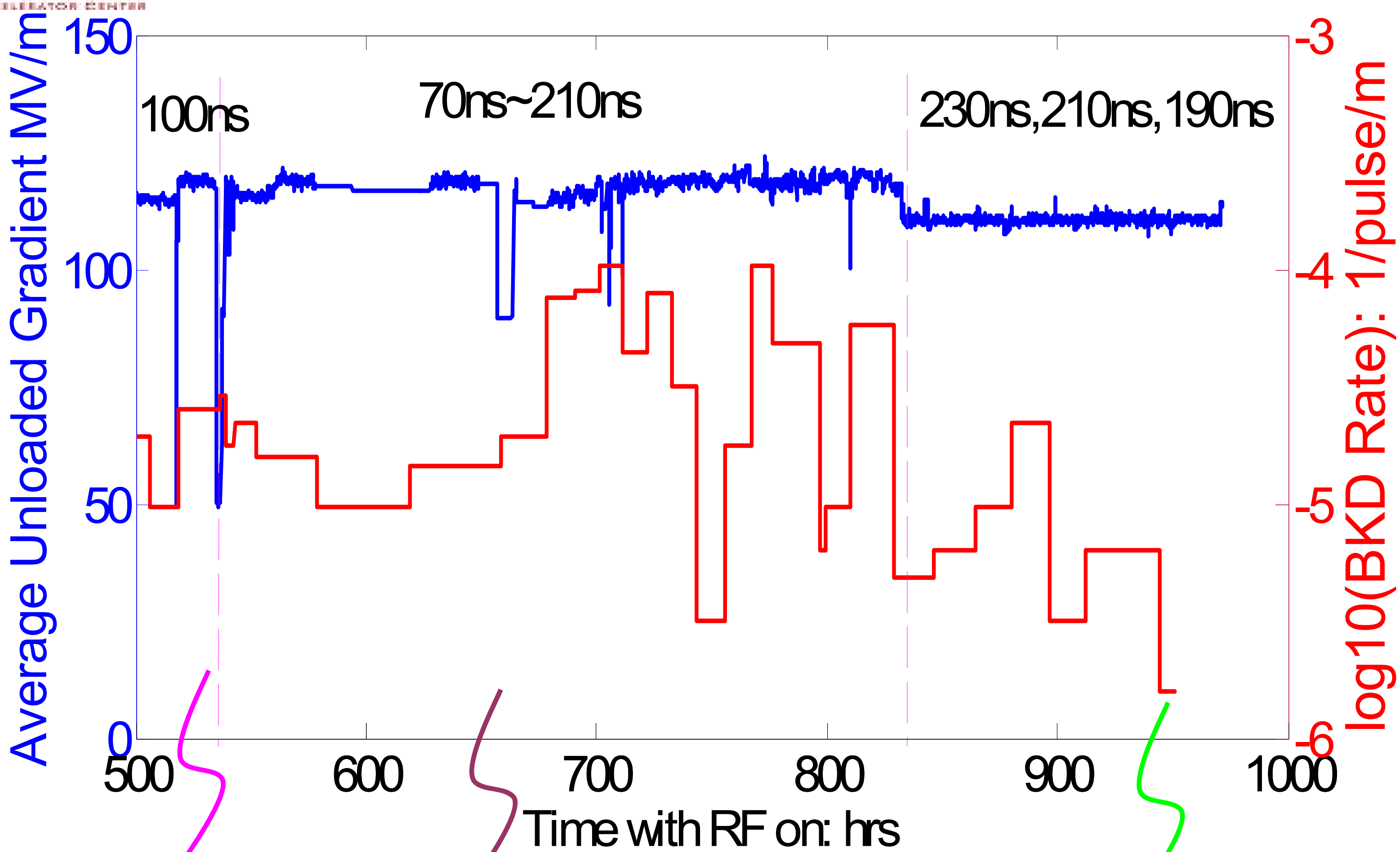
T18VG2.4_Disk structure RF process profile begin at Apr.14 2008

The gradient is the average unloaded gradient for the full structure.



The BKD Rate is normalized to the structure length(29cm).

Second 500hrs, maximum unloaded gradient is 120MV/m



Short pulse higher gradient condition

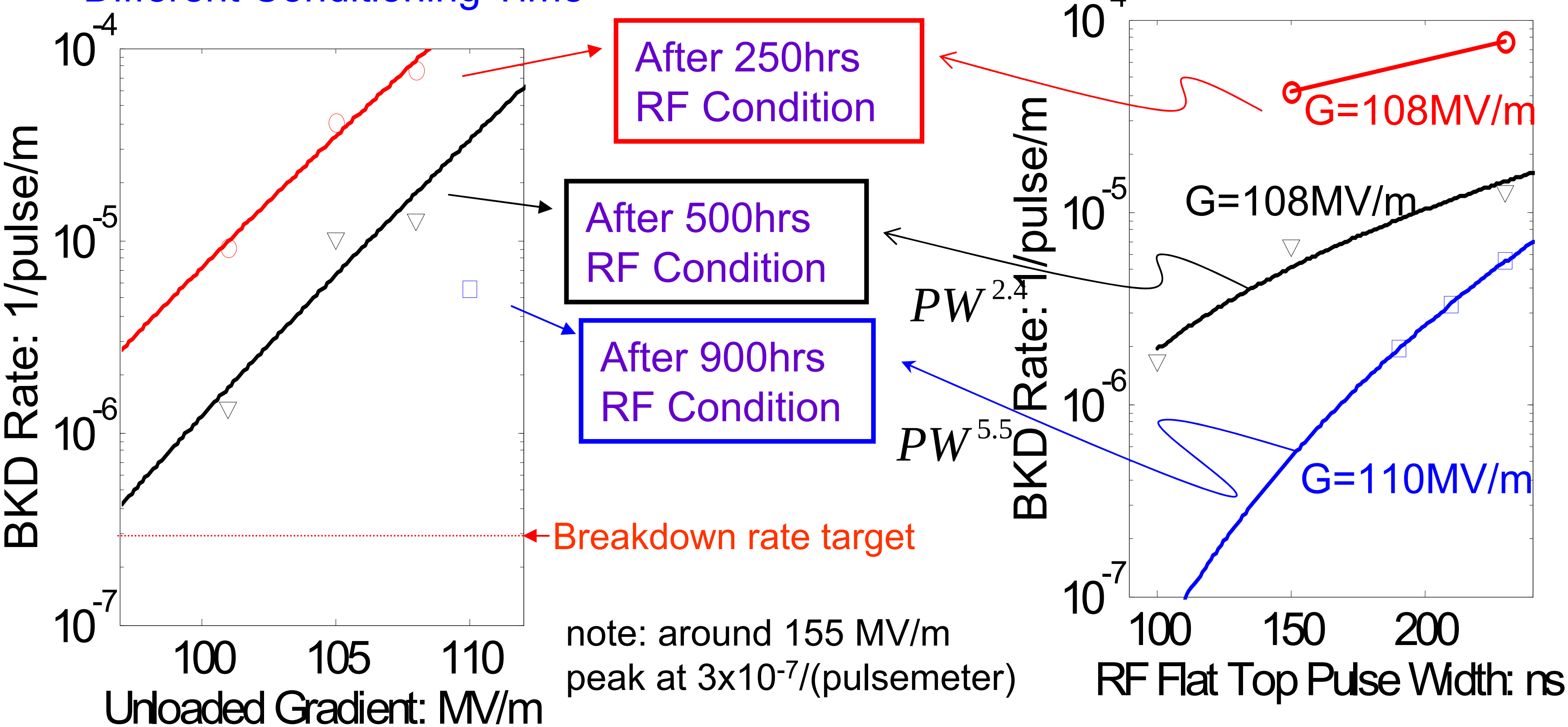
Pulse shape dependence BKD study.

At 110MV/m with pulse width around 220ns.

BKD Rate Profile at Different Conditioning Time

RF BKD Rate Gradient Dependence for 230ns Pulse at Different Conditioning Time

RF BKD Rate Pulse Width Dependence at Different Conditioning Time



After 900hrs RF condition BKD rate has a gradient dependence ~ G^{32}

and pulse width dependence ~ $PW^{5.5}$

Predictions for test structures

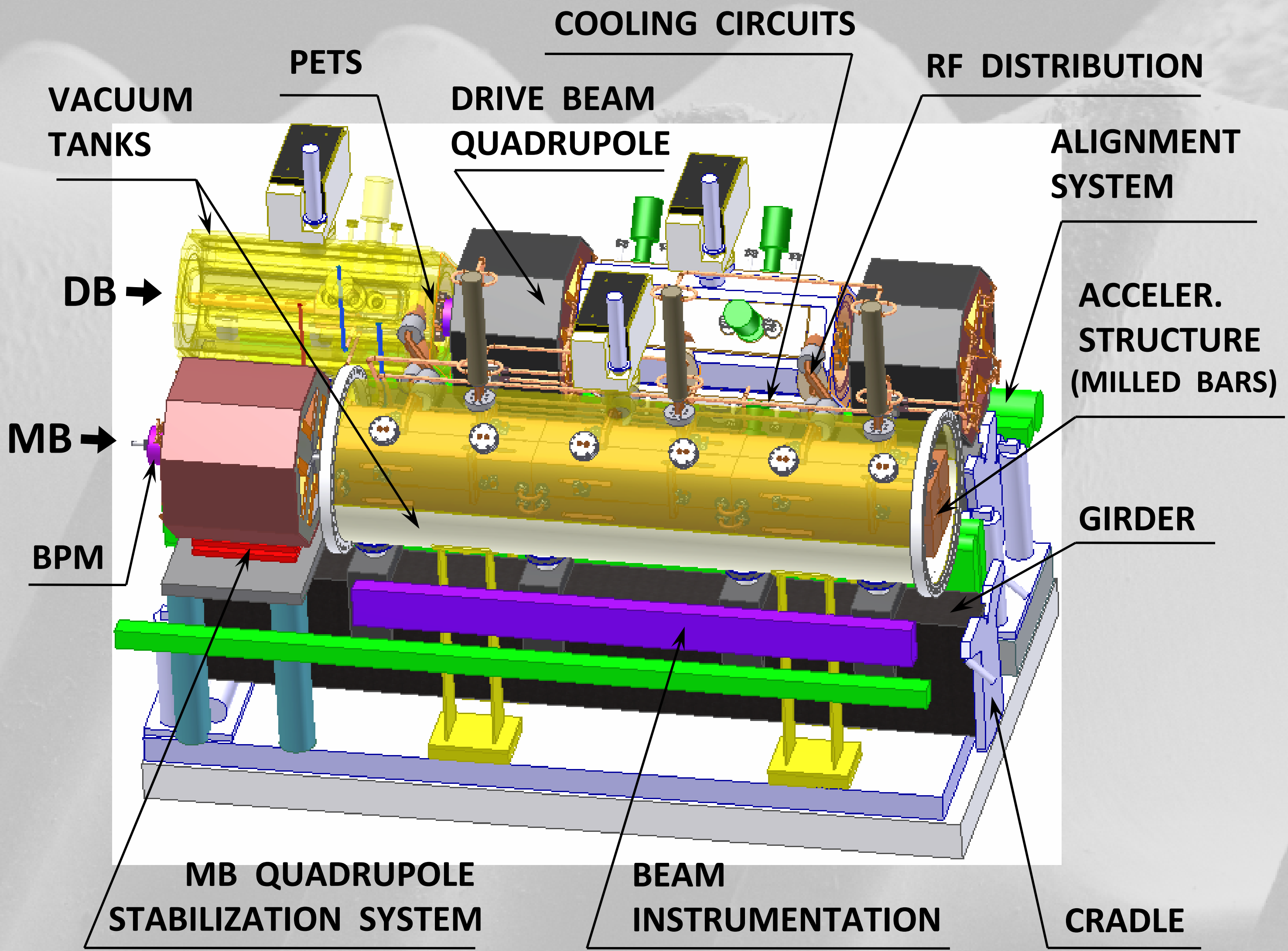
Prediction of average unloaded gradient at rect. pulse length of 100ns and BDR=1e-6 based on the results achieved in T53vg3MC: 102.3MV/m at 100ns and BDR=1e-6:

19.5Wu or $Sc=6.2MW/mm^2$@100ns.

	TD18vg2.4	T18vg2.4	T28vg3	TD28vg3	CLIC_G
$P/C*(t_p^P)^{1/3}$= 19.5Wu					
Average unloaded gradient [MV/m]	132	136	110	104	134
$S_c=6.2MW/mm^2$ @ t_p^P=100ns					
Average unloaded gradient [MV/m]	109	106	105	103	120

Observed value is 124 MV/m. Effect of strong tapering?

Technical issues



Conclusions

• A reasonably coherent and quantitative picture of the effects which limit gradient is emerging.

• The T18 has so far achieved a gradient of 100 MVM/m, which represents a significant step forward towards showing our predictions are accurate and that the gradient goal is reachable.

• A strong international collaboration has formed to develop accelerating structures.

Links:

CLIC homepage: http://clic-study.web.cern.ch/CLIC-Study/

Breakdown workshop: http://indico.cern.ch/conferenceDisplay.py?confId=33140

X-band collaboration meeting: http://indico.cern.ch/conferenceDisplay.py?confId=30911