CLIC accelerating structure R&D

A case study of a key technology development for high energy physics
and a very interesting set of applied physics problems

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

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5th Particle Physics workshop
25 November 2006

We would like to build a 2-3 TeV linear collider which produces luminosity efficiently.

What do we need?

An accelerating gradient of at least 100Mv/m and low emittance beams.

One of the key elements to achieve these performances are the

ACCELERATING STRUCTURES

Accelerating gradient is obviously up to the accelerating structures

But they contribute to emittance growth along the linac

We need to design for these two objectives, which it turns out, are profoundly interrelated.

I would like to present to you,

An overview of the structures

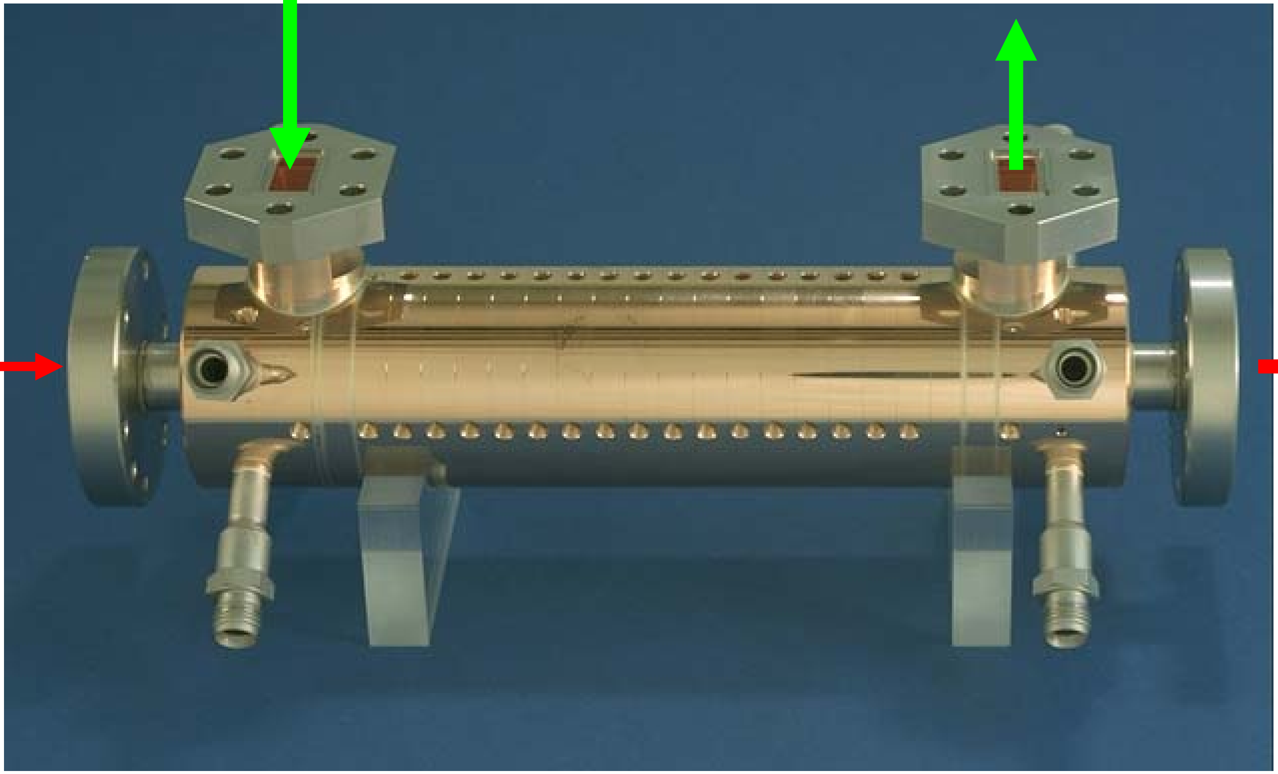
mixed with

An overview of the research and development program we undertaking

Traveling wave accelerating structure basics

Electric field

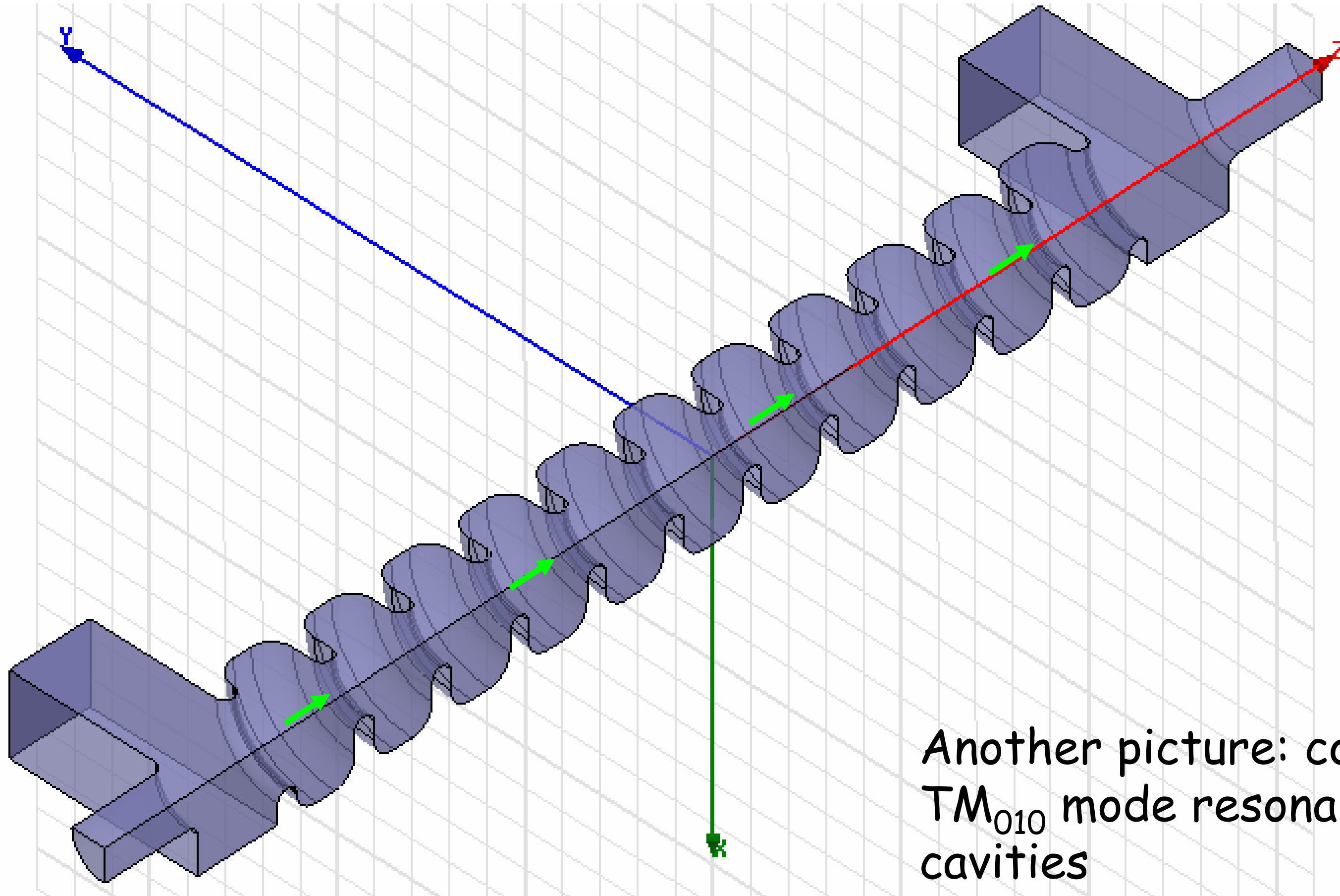
High power microwaves in



Higher energy beam out

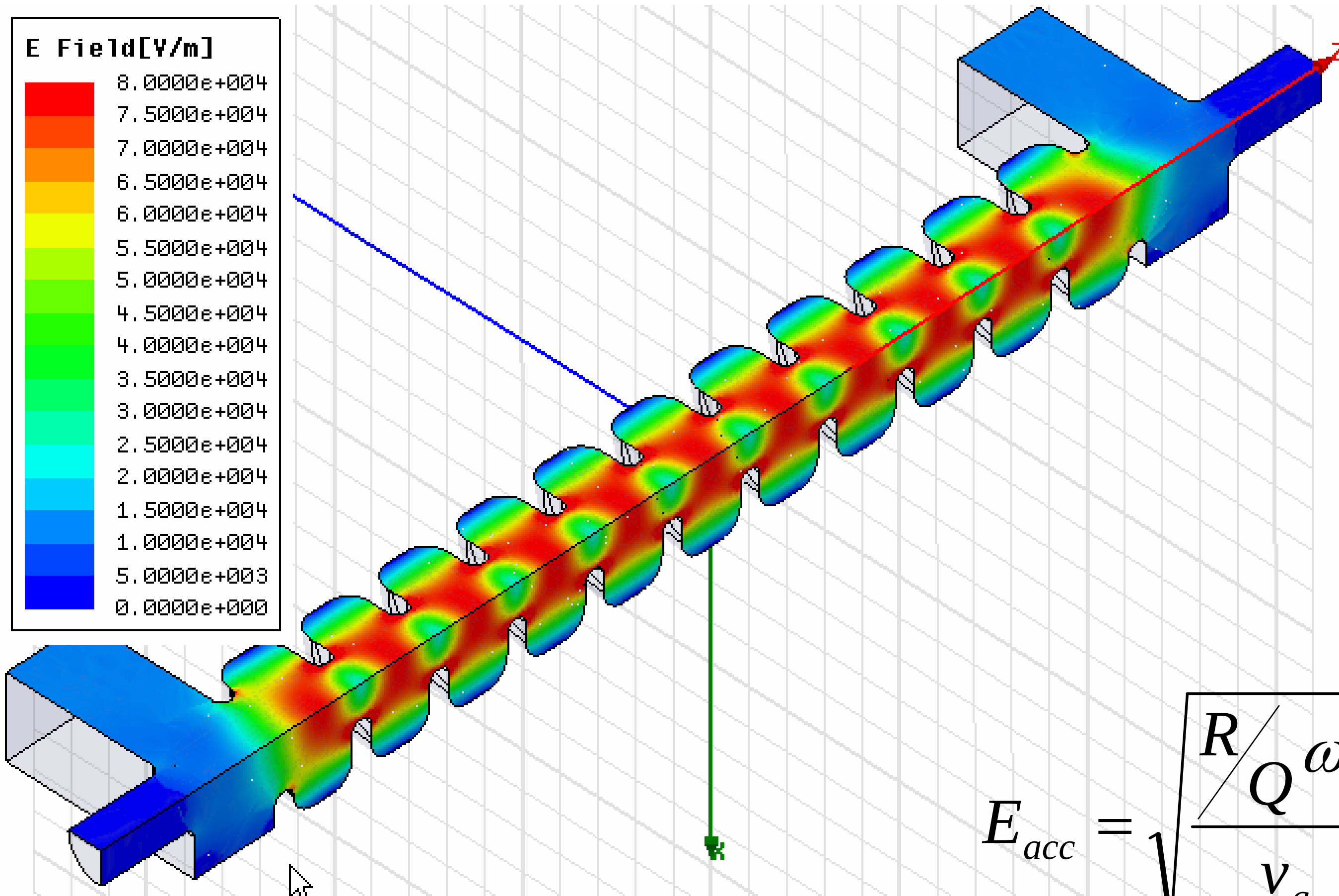
Accelerating structure basics

'Slow wave' structure to provide synchronism between rf wave and beam. Solutions to periodic boundary conditions much like solid state physics, pass/stop bands, Brillouin diagrams etc.



Another picture: coupled TM_{010} mode resonant cavities

Accelerating structure fundamental mode field pattern.



$$E_{acc} = \sqrt{\frac{R/Q\,\omega P}{v_g}}$$

Physical limits to accelerating gradient

n.b. superconducting cavities are limited to a maximum gradient of about 50 MV/m given by useable cavity shape and theoretical maximum surface magnetic field. We need over 100 MV/m so from here on out we speak about,

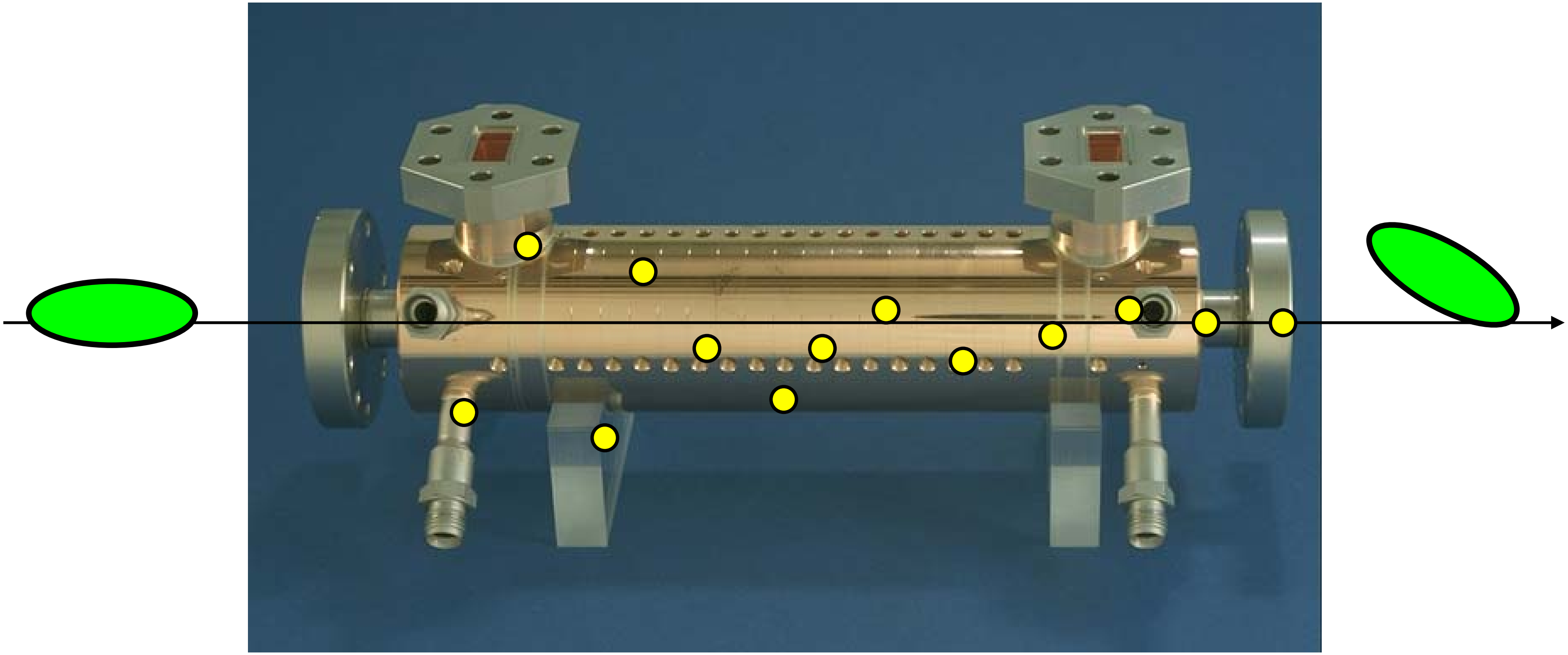
Normal conducting cavities

• rf breakdown: sparking, or technically vacuum discharge, induced by surface electric field, interrupts rf pulse, exhibits maximum threshold, eventually causes damage.

• pulsed surface heating: Very short pulses, 10s to 100s of ns, and heating from rf losses from currents in skin depth result in significant thermal stresses. Repetitive cycling, 100 to 200 Hz, over long running periods, 20 years, results in fatigue cracking and surface breakup.

Luminosity - wakefield basics

Long-range transverse wakefields: Misalignments, beam and structures, induce higher-order modes which kick subsequent bunches which kick the following ones even more. Effect shown in yellow.



Short-range transverse wakefields: Misalignments, beam and structures, induce diffraction of field following relativistic bunch which acts back on itself causing it to grow in phase space (very, very higher-order modes) Effect shown in green.

Now we will revisit these effects,
- Limits to gradient
- induced emittance growth
in greater detail…

rf breakdown

At one point as you try to raise the power/gradient in the structures, sparking begins. Gradient still goes up for a while, conditioning, then saturates.

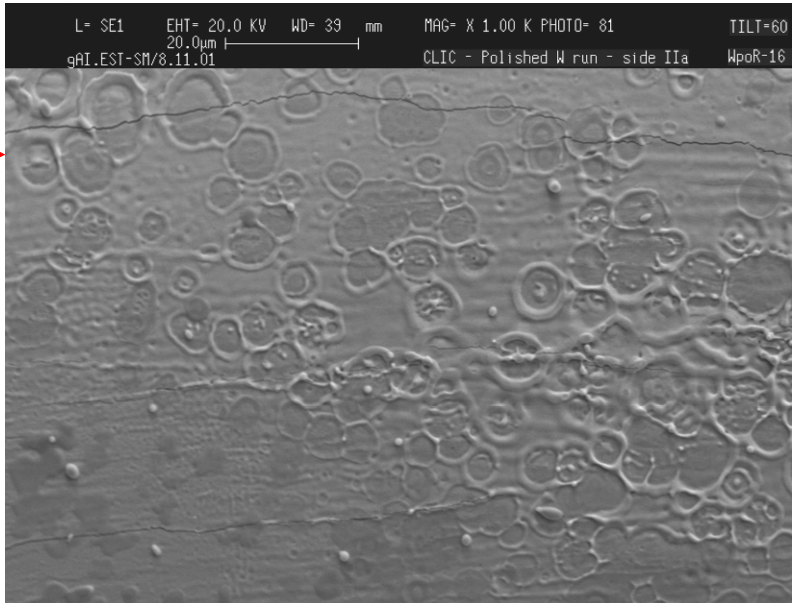
Related to dc vacuum breakdown but the theory is not complete. Two steps,

Trigger mechanism: Surface electric field initiates localized field emission and tensile force causing catastrophic failure of microscopic sized surface. This initiates arc.

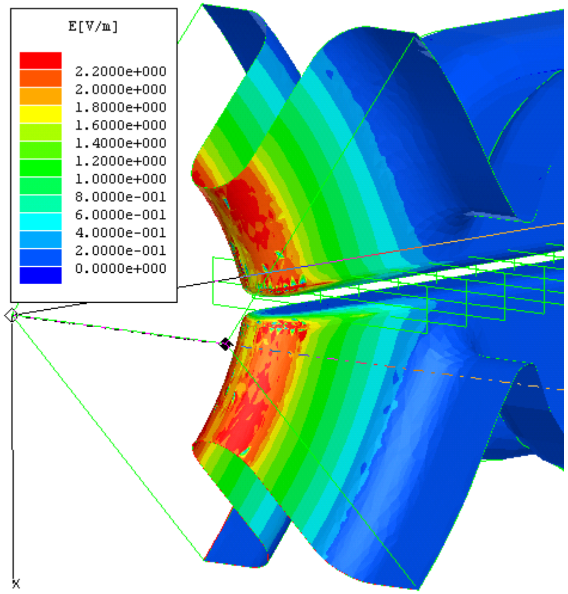
rf/arc interaction: Power from rf is absorbed by electrons in arc causing heating, melting, evaporation, ionization, plasma…

rf breakdown continued

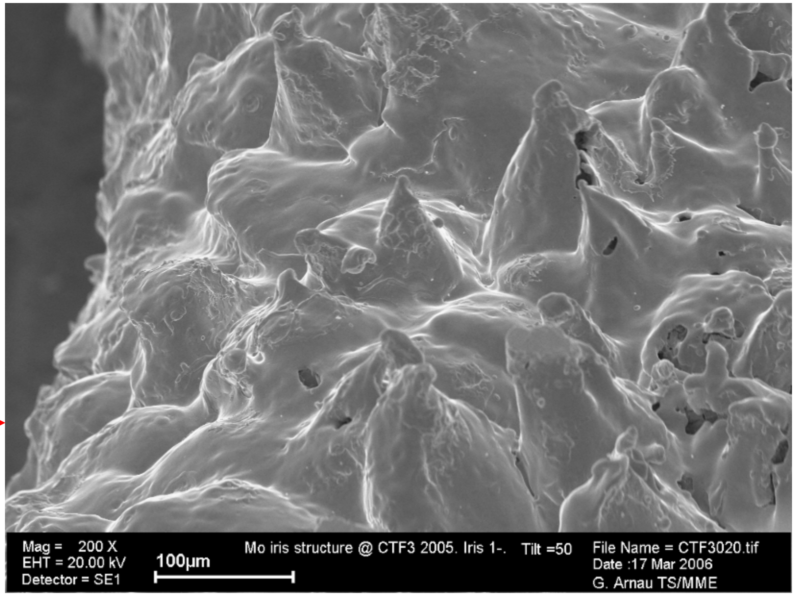
typical surface after sparks



Surface electric field



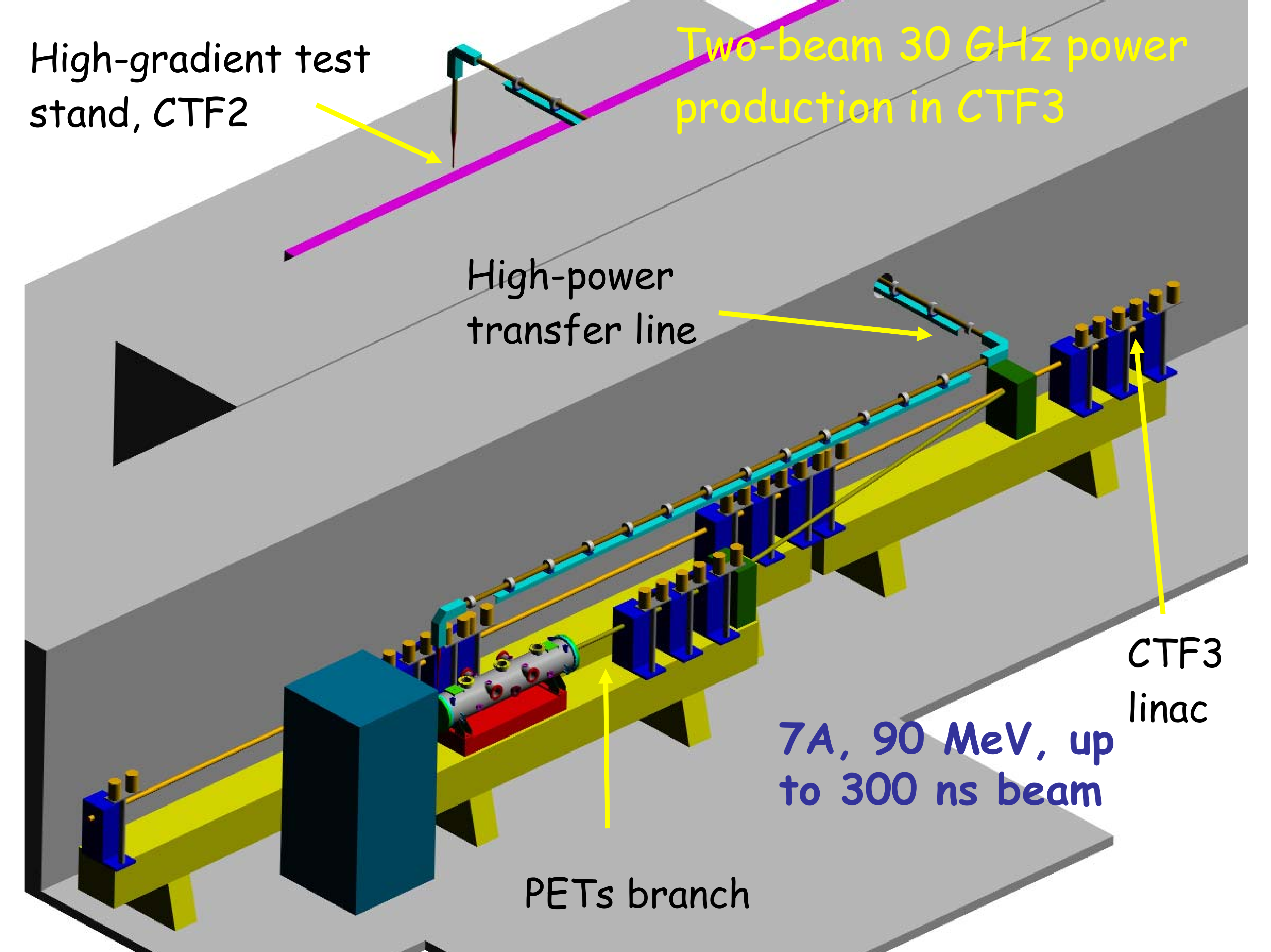
extreme example



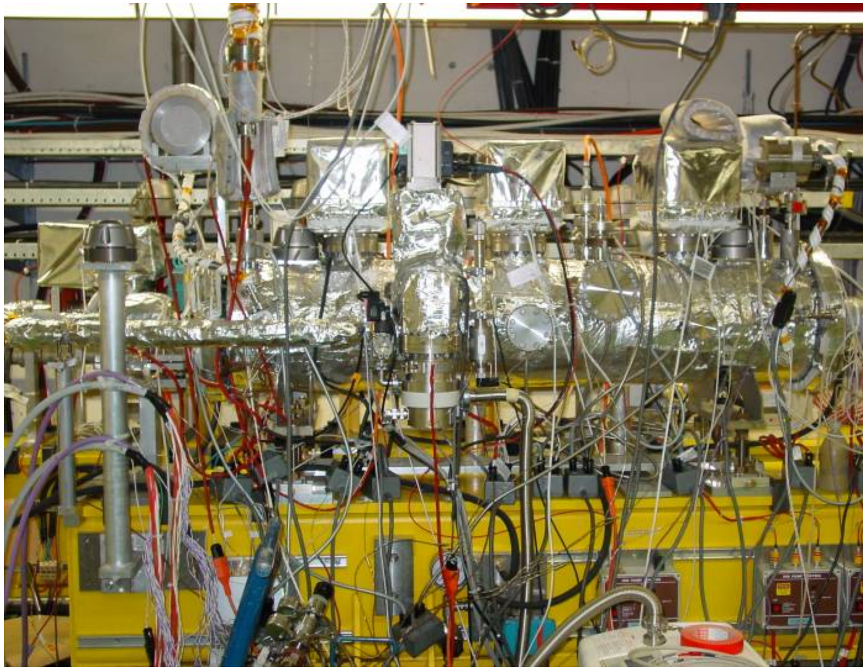
What can we do about rf breakdown?

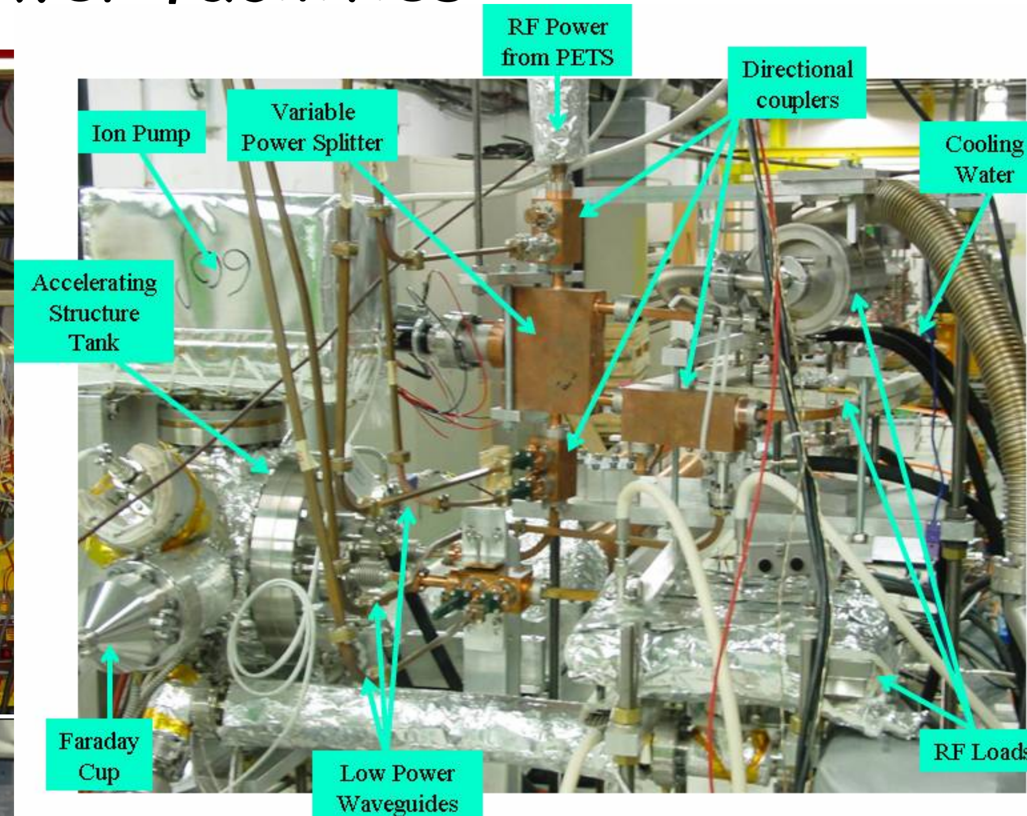
- rf design for low surface electric field and low pulse energy structures
- rf design for short pulses
- New materials

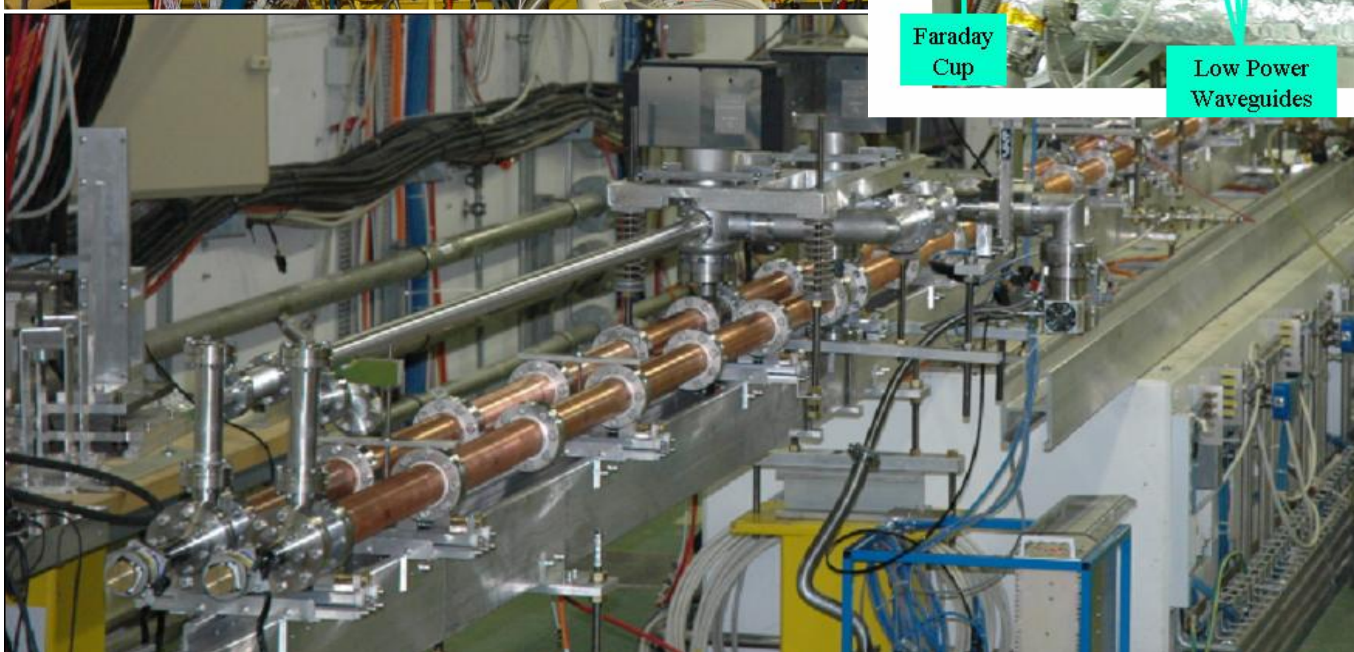
Which we study in 30 GHz and 11 GHz rf structures, and a dc spark set-up.


High-gradient test stand, CTF2
Two-beam 30 GHz power production in CTF3
High-power transfer line
CTF3 linac
7A, 90 MeV, up to 300 ns beam
PETs branch

30 GHz rf power facilities







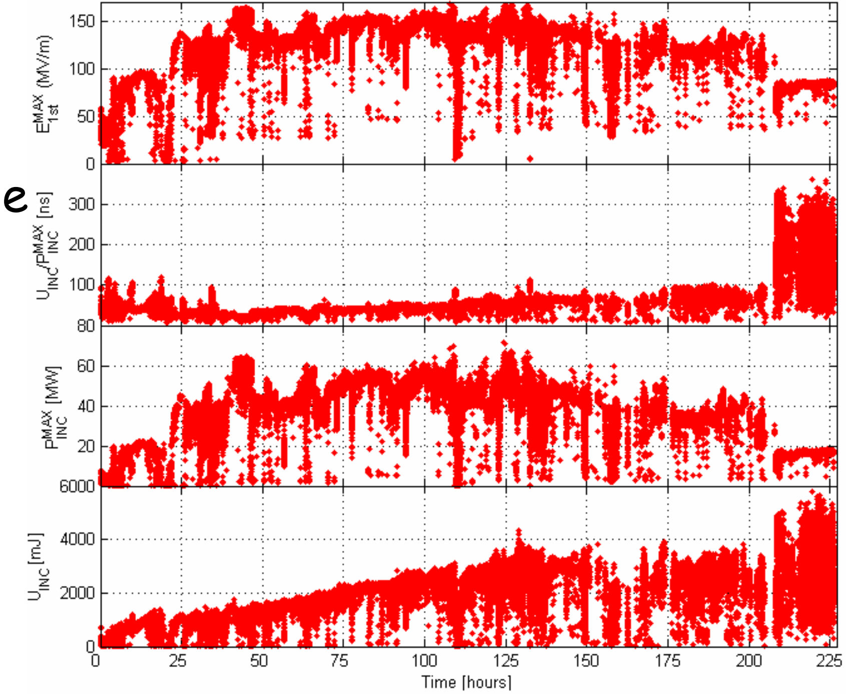
100 MW produced,
65 MW delivered
30 GHz power
10 (50) Hz
repetition rate
6 months per year

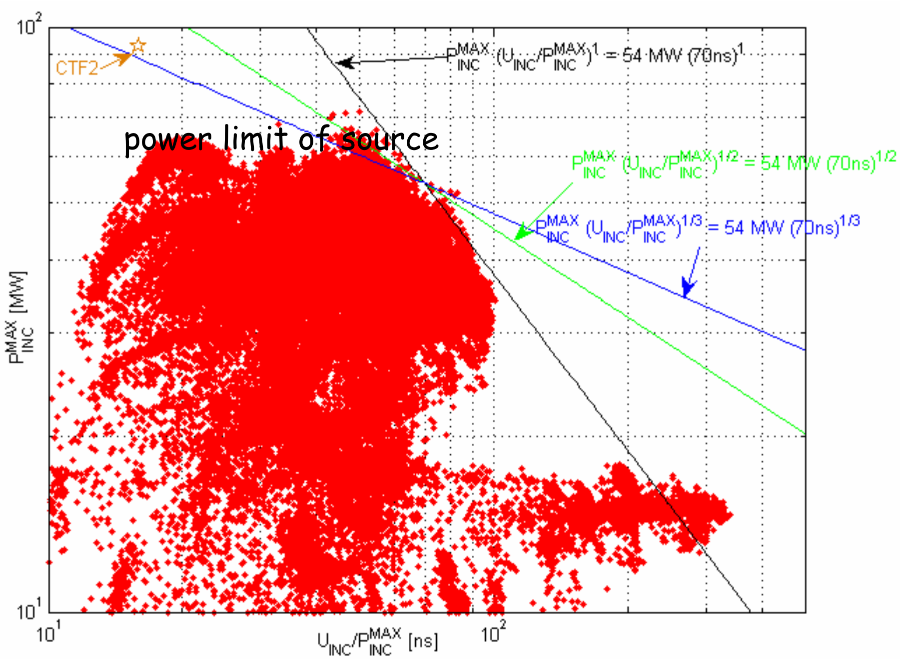
30 GHz Mo-iris structure

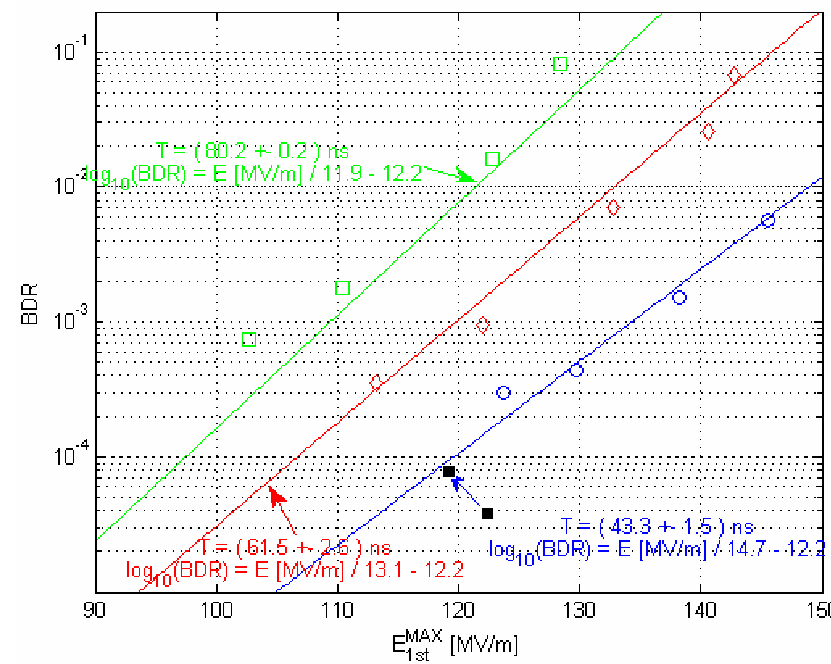
Conditioned to 140 MV/m, 70 ns, 52 MW

Breakdown probability slope 12 MV/m/decade

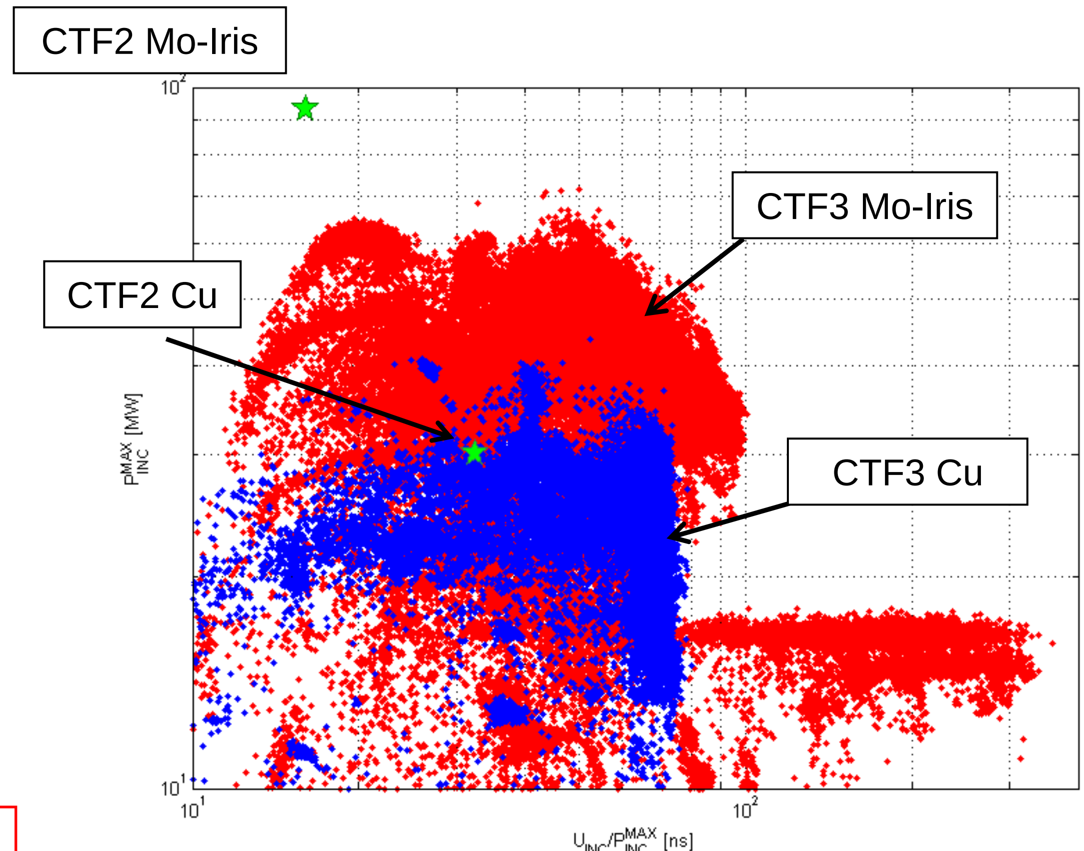
Presented at EPAC





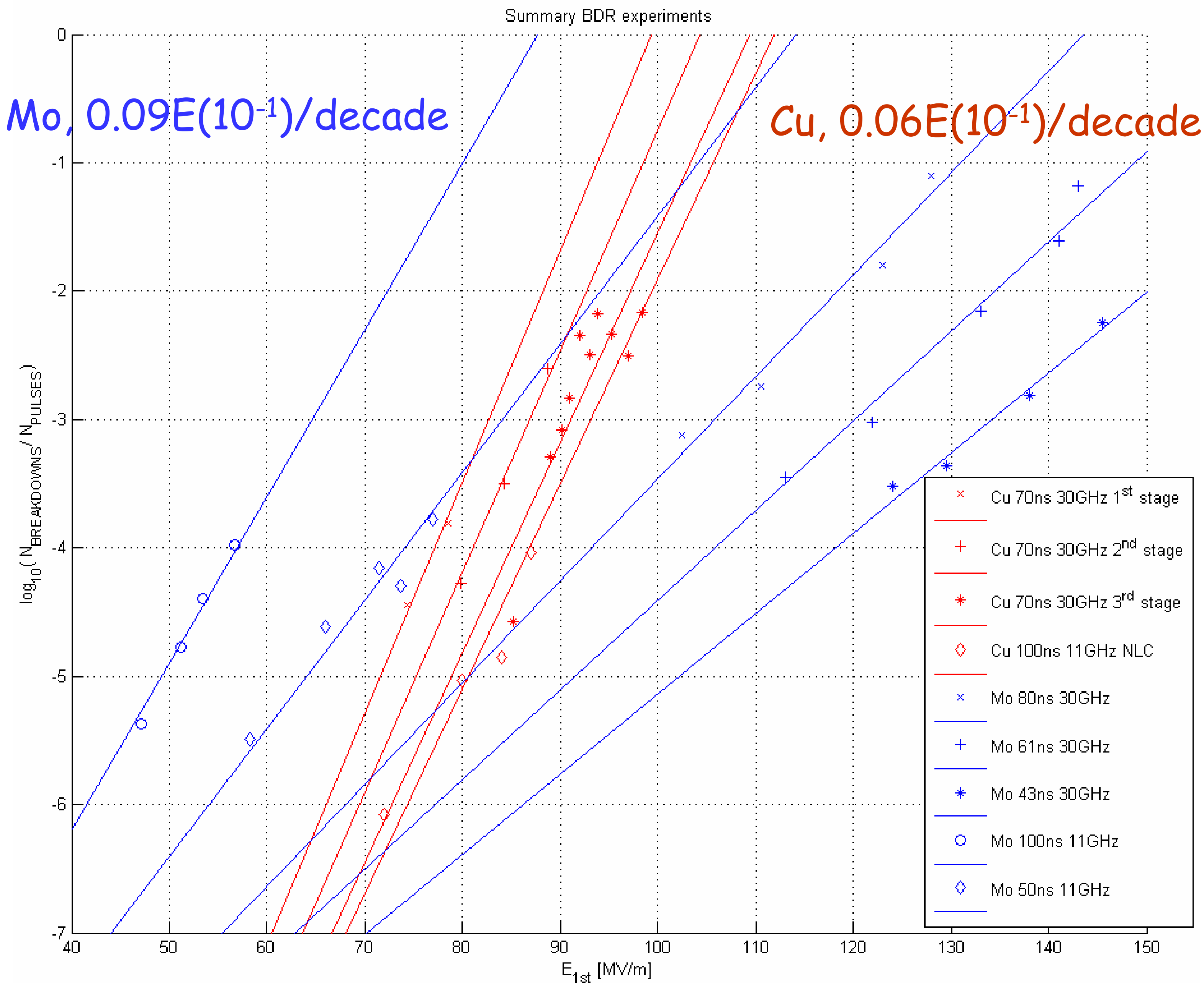


30 GHz copper 2π/3 structure



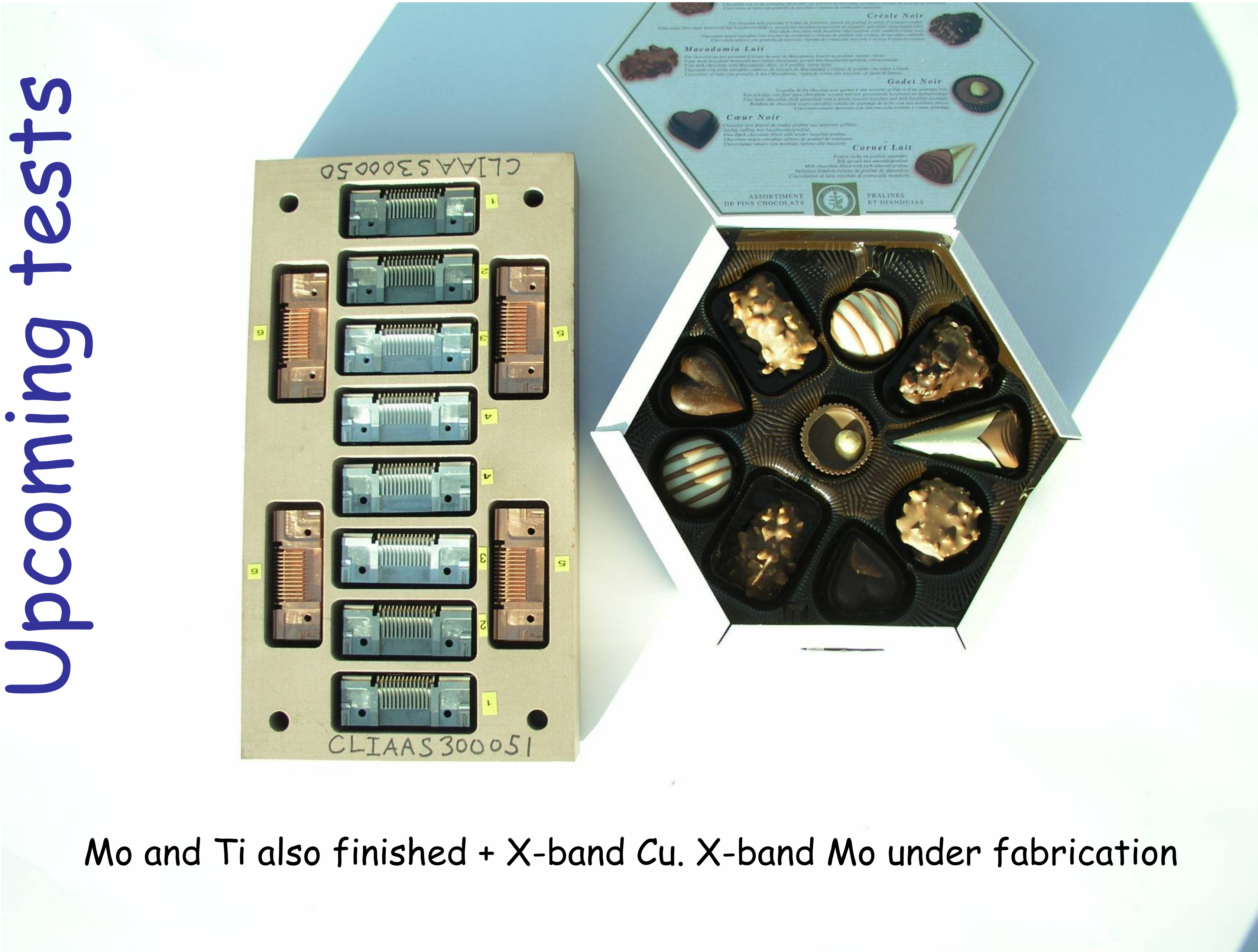
Peak gradient 110 MV/m, 70 ns

Breakdown probability – material dependence



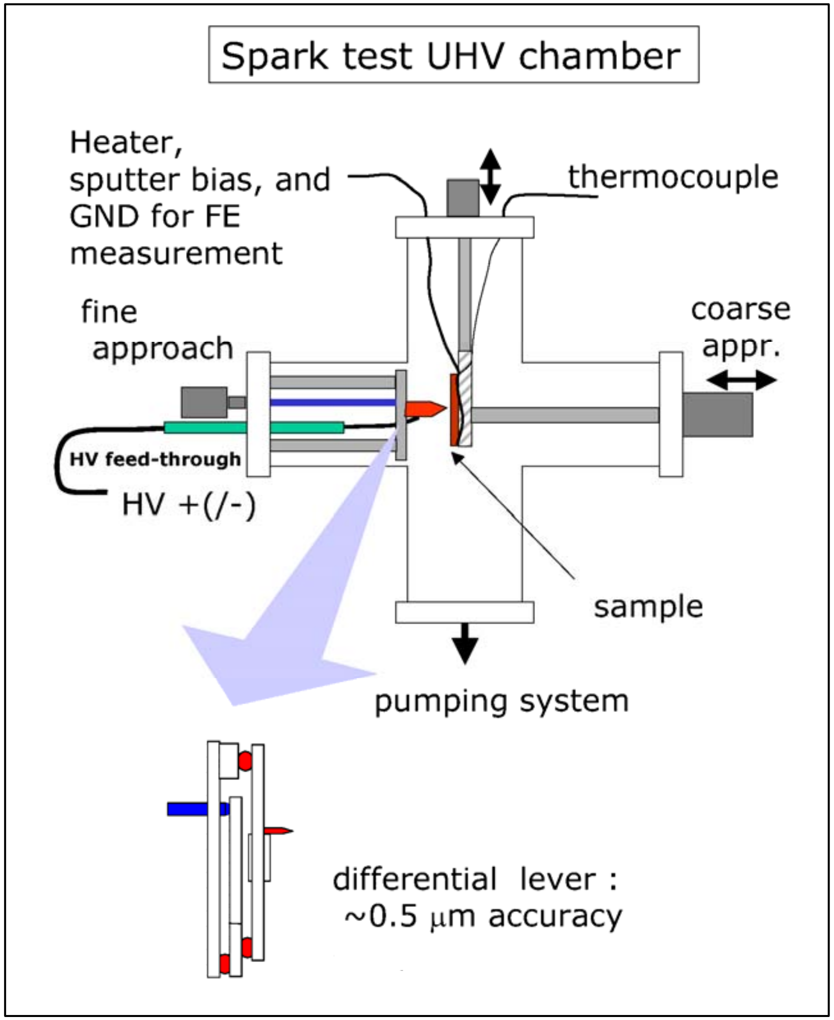
Upcoming tests

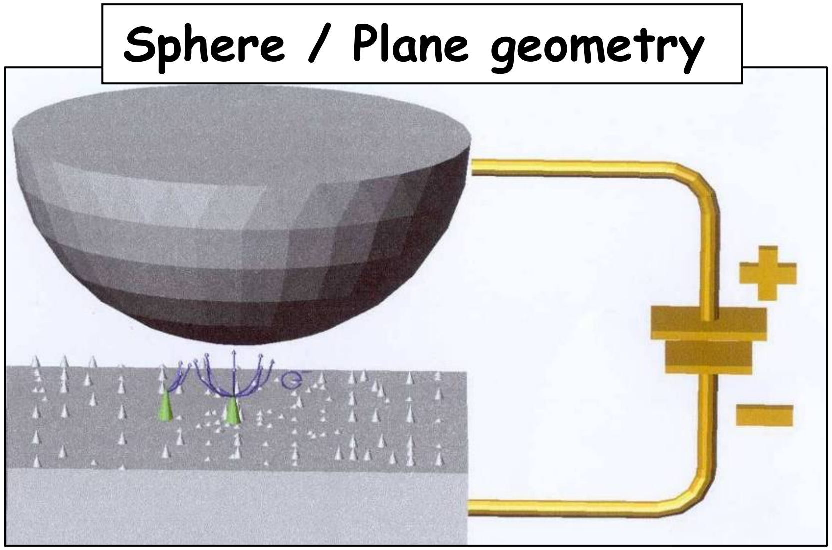
Cu, Al, stainless steel 30 GHz test structures

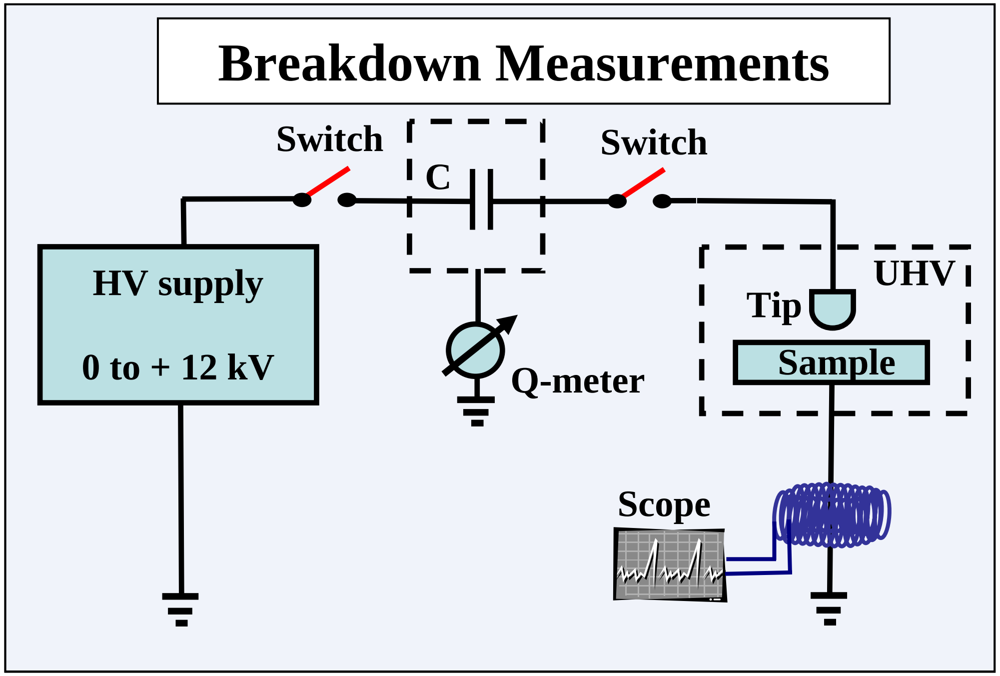


Mo and Ti also finished + X-band Cu. X-band Mo under fabrication

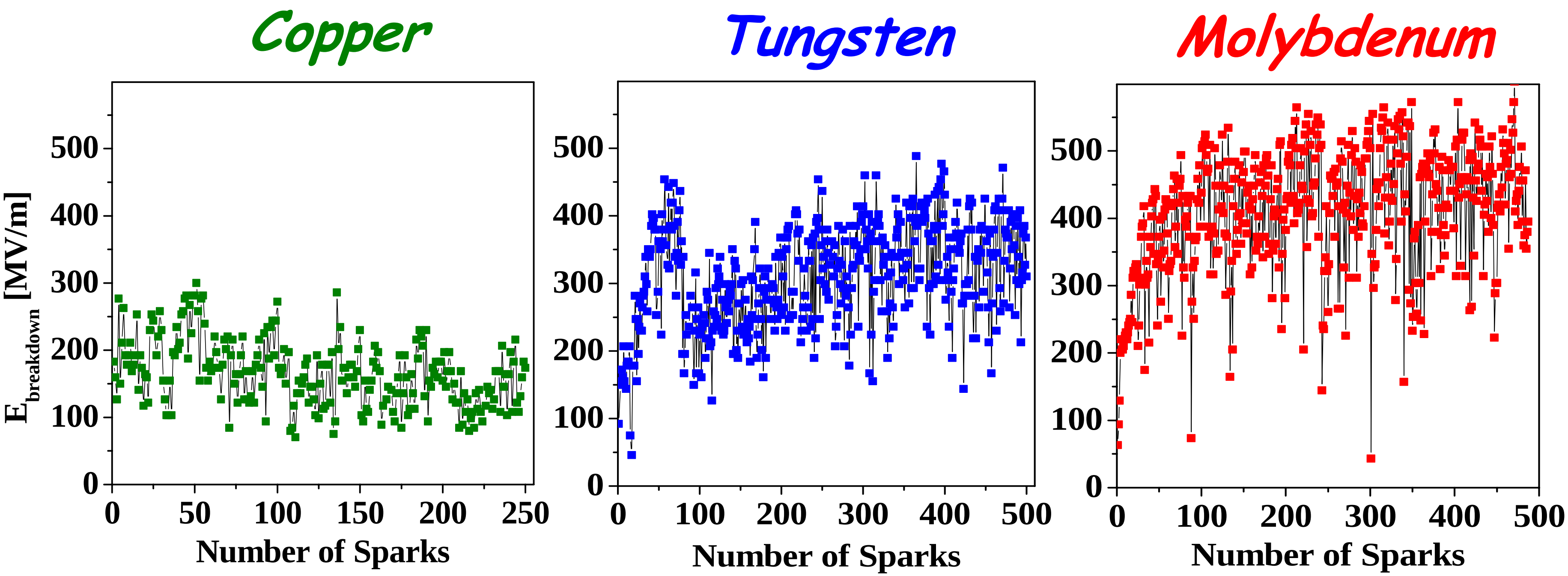
Experimental Setup







Comparison Cu – W - Mo



Cu: $E_{breakdown}^{sat} \cong (159 \pm 3)$ MV/m at $\sim 7 \times 10^{-10}$ mbar

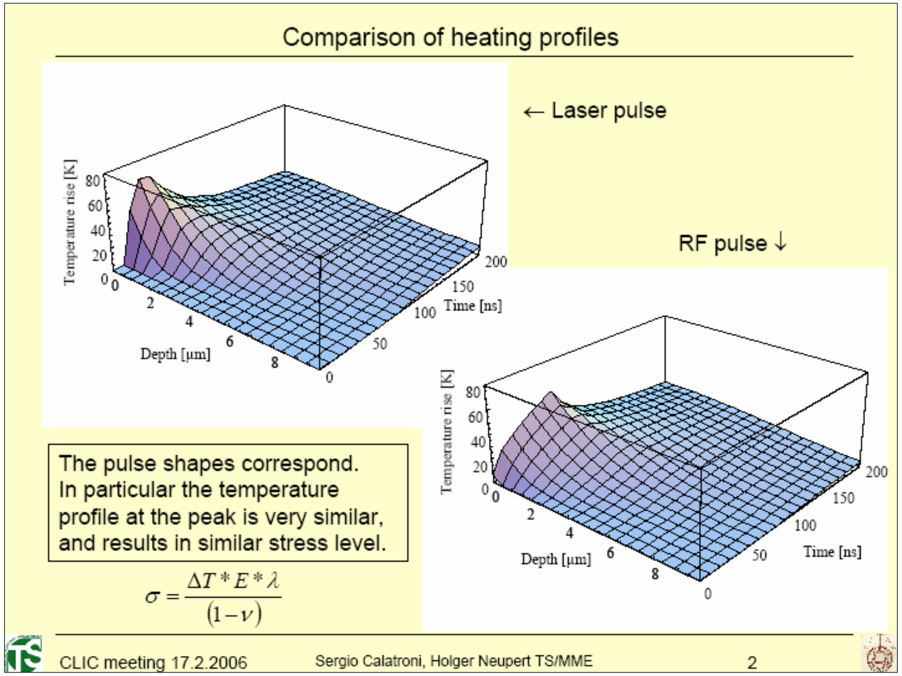
W: $E_{breakdown}^{sat} \cong (349 \pm 6)$ MV/m at $\sim 2 \times 10^{-08}$ mbar

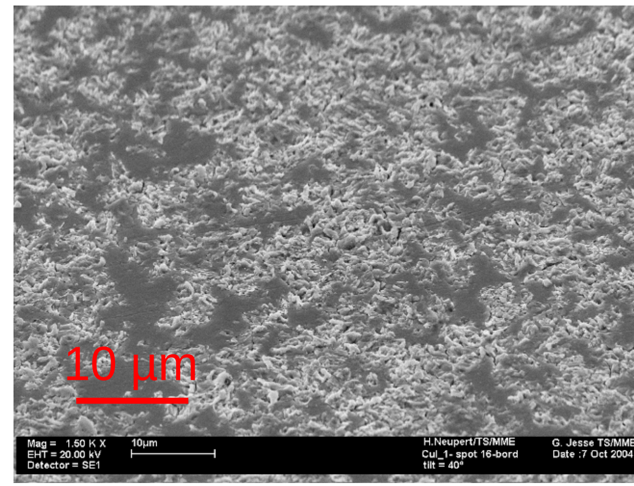
Mo: $E_{breakdown}^{sat} \cong (431 \pm 7)$ MV/m at $\sim 2 \times 10^{-09}$ mbar

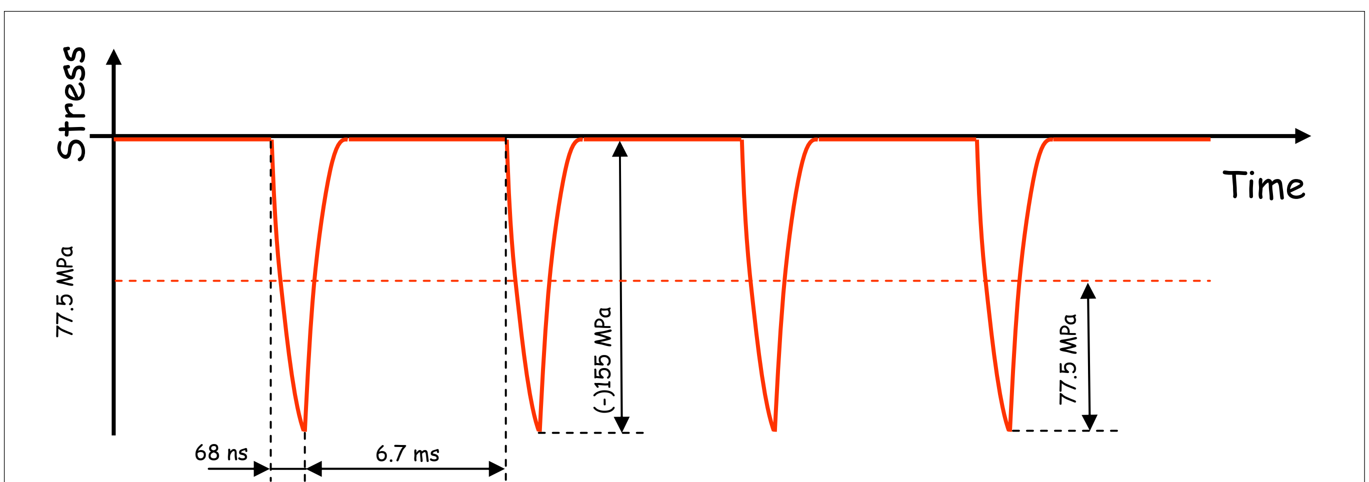
Pulsed surface heating

Pulsed surface heating

Temperature rise in thin layer during short pulse causes cyclical compressive stress leading to fatigue cracking.

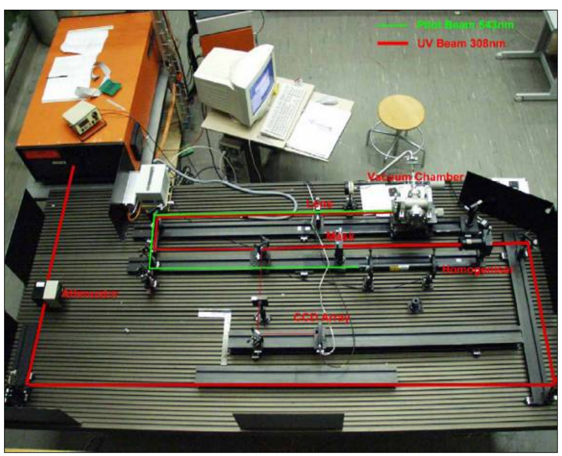




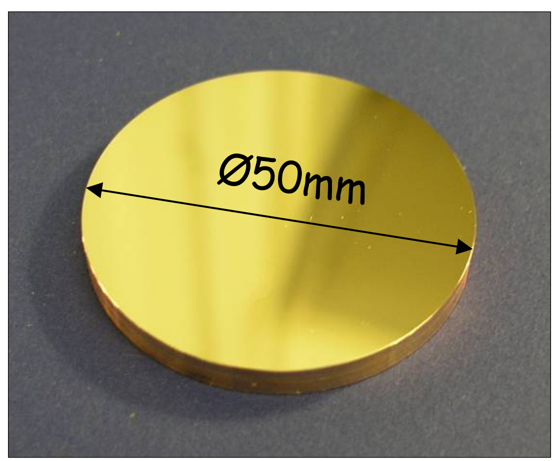


Pulsed Laser Fatigue Tests

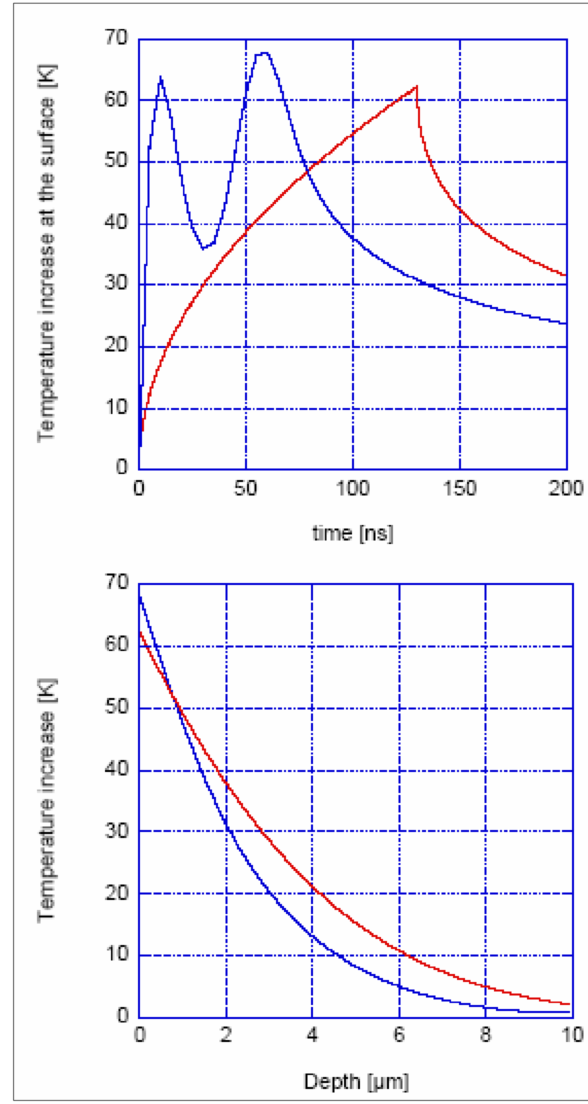
- Surface of test sample is heated with pulsed laser. Between the pulses the heat will be conducted into the bulk.
- The Laser fatigue phenomenon is close to RF fatigue.
- The operating frequency of the pulsed laser is 20 Hz -> low cycle tests.
- Observation of surface damage with electron microscope and by measuring the change in surface roughness.
- Tests for CuZr & GlidCop in different states under way.



Laser test setup

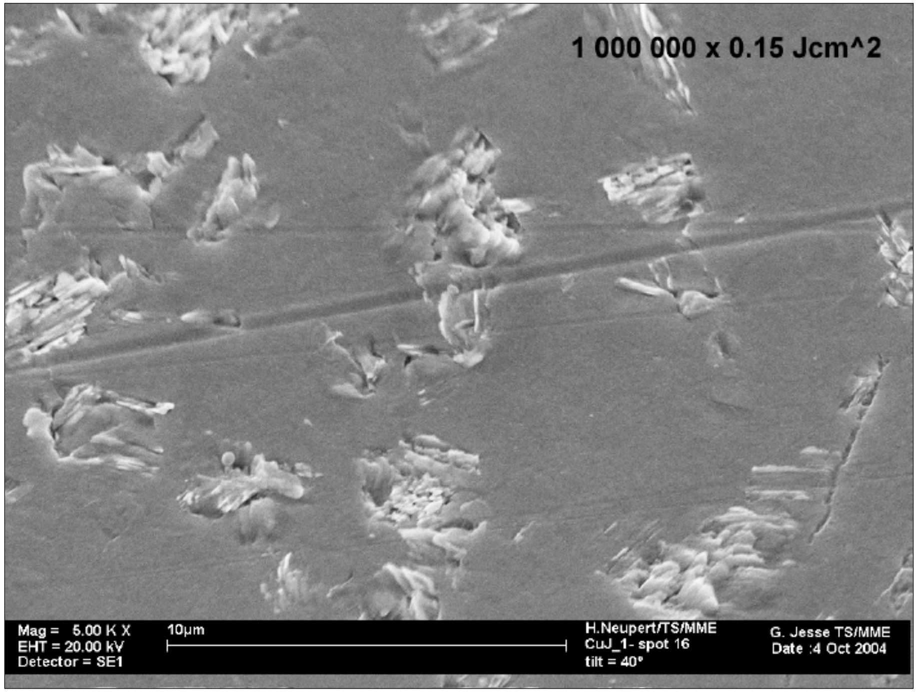


Diamond turned test sample, Ra 0.025μm

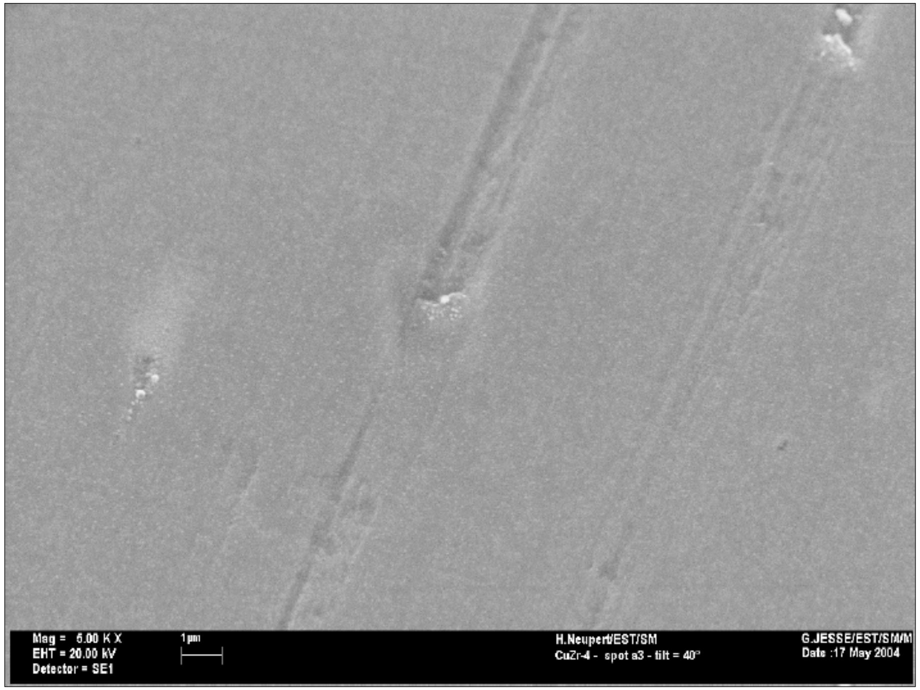


Red curve – CLIC RF pulse
Blue curve – Laser pulse

Pulsed Laser Fatigue Tests



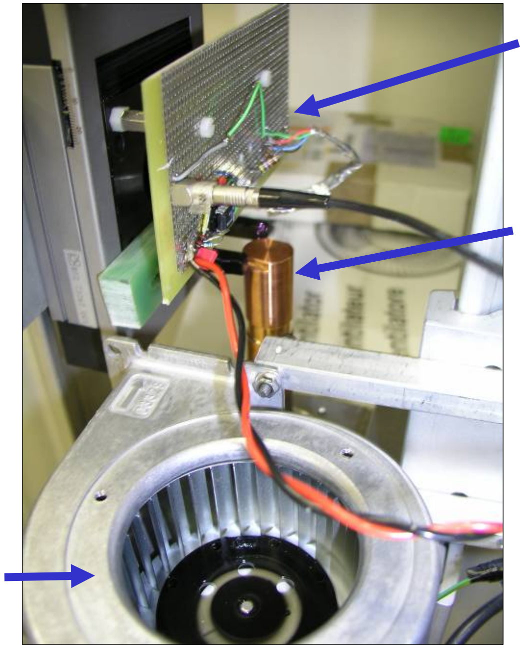
Cu-OFE at 10^6 cycles, ΔT=90°C
Fatigued surface



CuZr at 10^6 cycles, ΔT=90°C
No fatigue.

Ultrasonic fatigue experiment

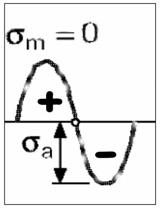
- **Cyclic mechanical stressing of material at frequency of 24 kHz.**
- **High cycle fatigue data within a reasonable testing time. CLIC lifetime 7×10^{10} cycles in 30 days.**
- **Will be used to extend the laser fatigue data up to high cycle region.**
- **Tests for Cu-OFE, CuZr, CuCr1Zr & GlidCop Al-15 under way.**



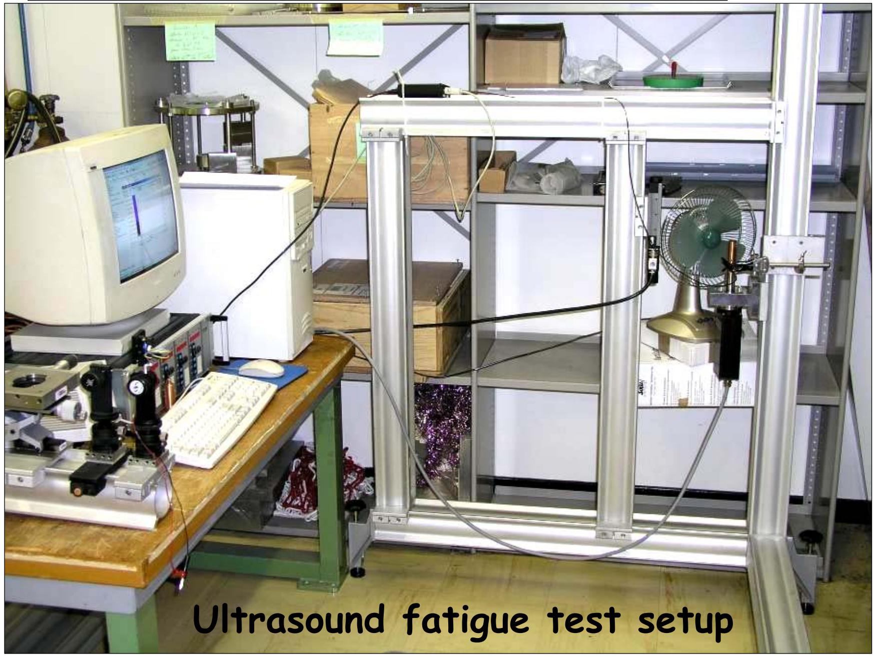
Calibration card measures the displacement amplitude of the specimen's tip

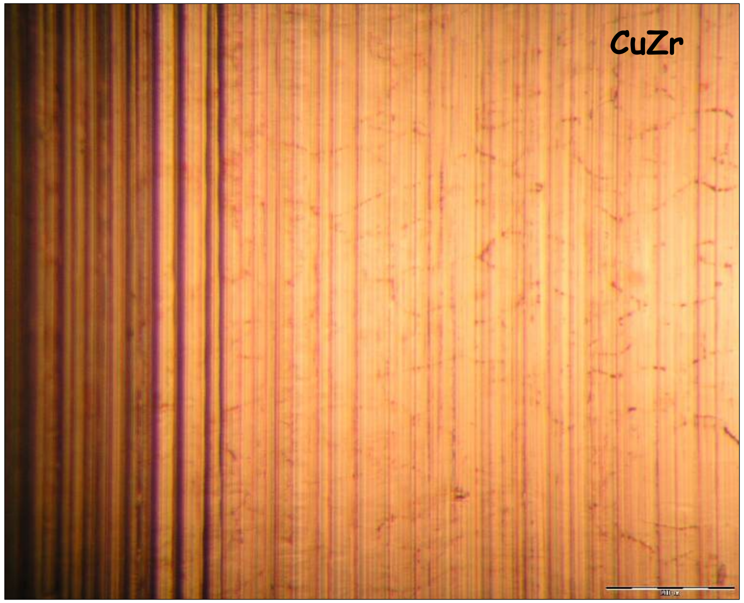
Fatigue test specimen

Air Cooling

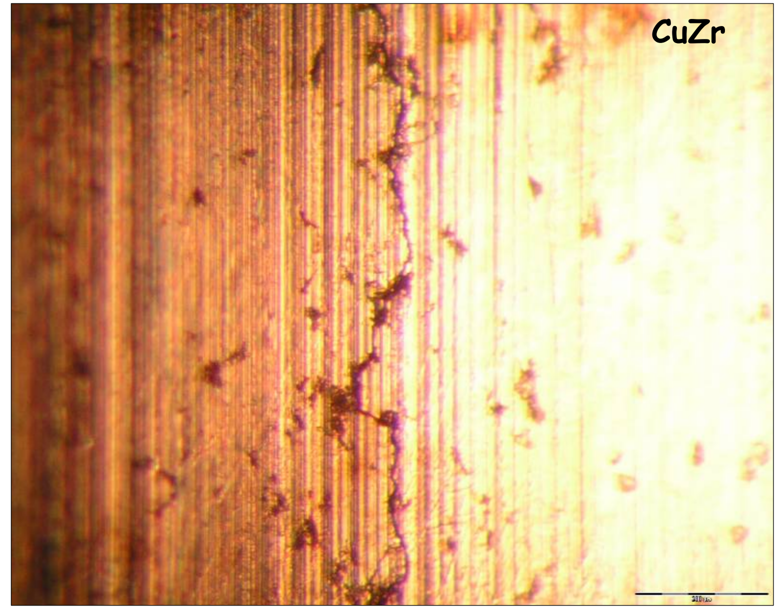


Reversed stress condition

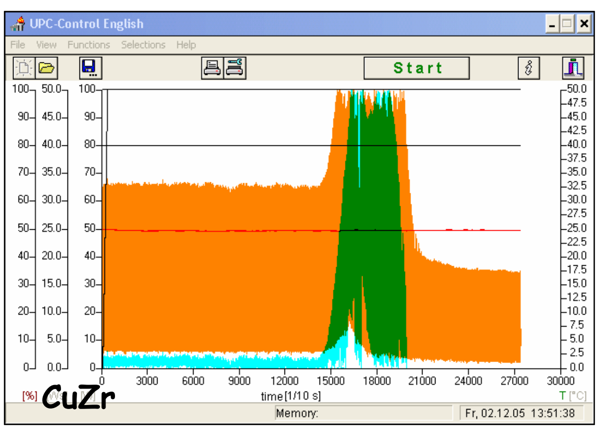


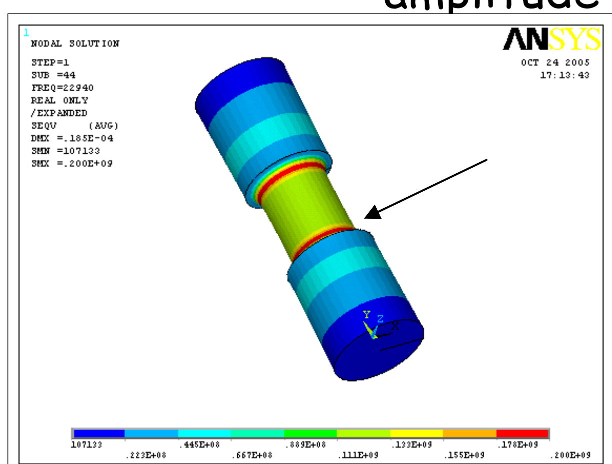


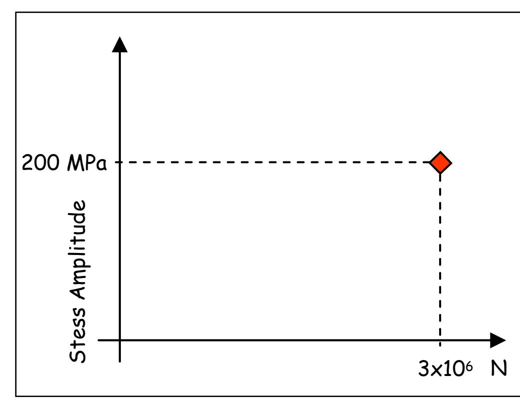
Diamond turned specimen before



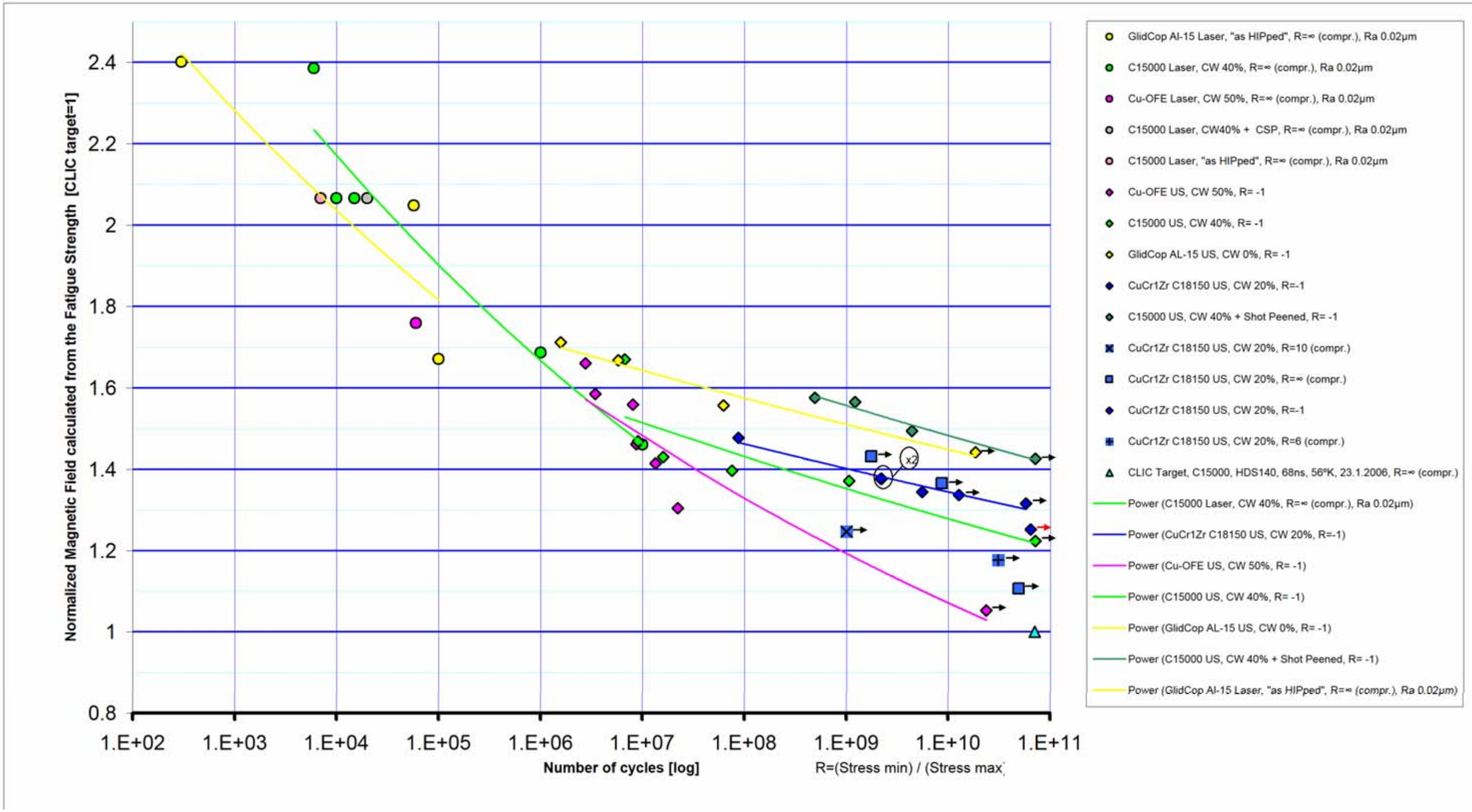
After $3*10^6$ cycles at stress amplitude 200 MPa





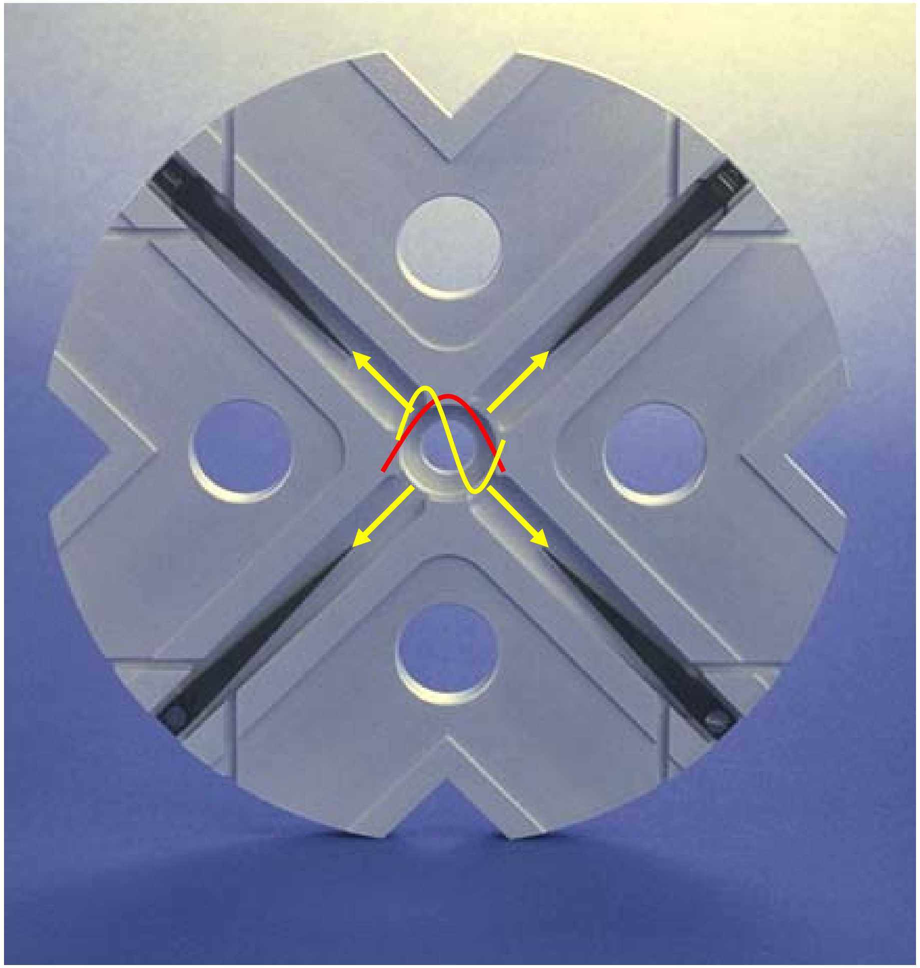


Laser and ultrasonic fatigue results summary



30 GHz and X-band rf benchmark experiments under preparation.
Low cycle 34 GHz experiment under way at Dubna.

Higher order mode damping basics



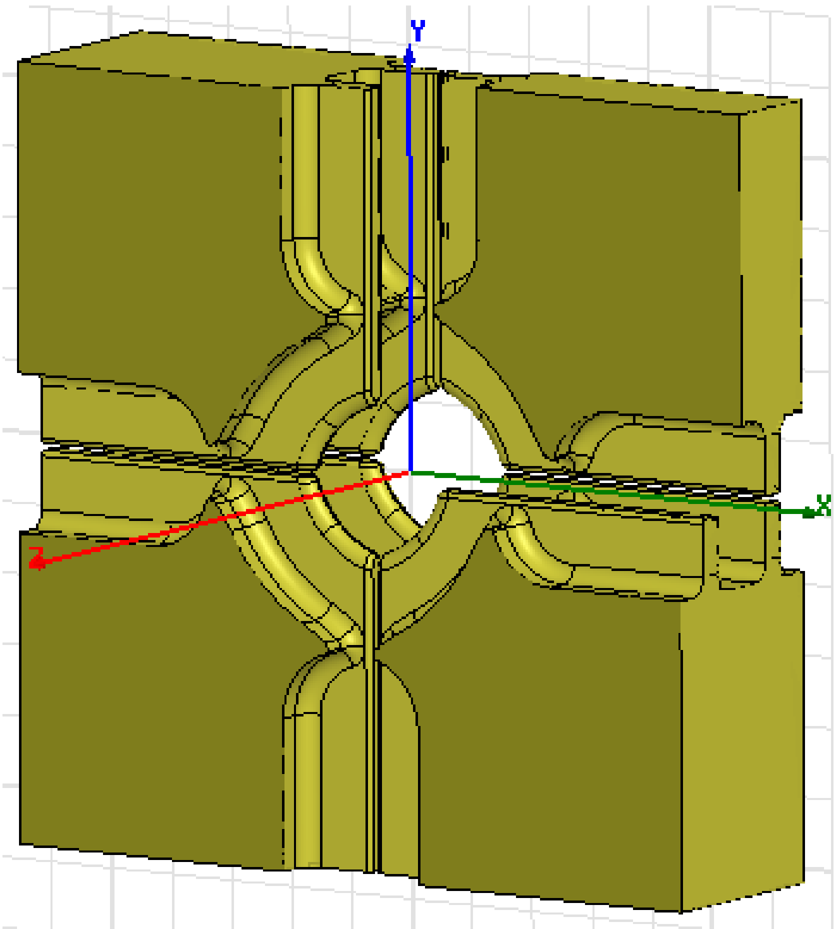
Fundamental mode, red, stays inside cavity because *f* below cut-off of waveguides.

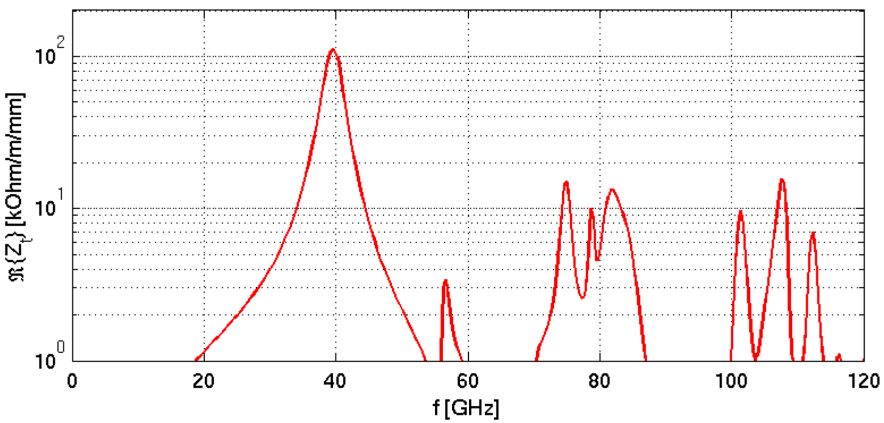
All other modes, lowest dipole shown in yellow, can propagate in waveguides.

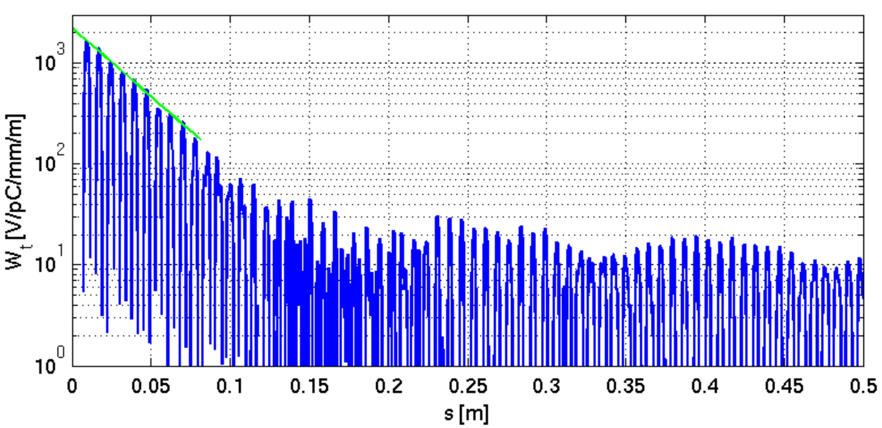
They are then absorbed in loads, the black pointed objects.

Hybrid Damped Structure (HDS)

Combination of slotted iris and radial waveguide (hybrid) damping results in low Q-factor of the first dipole mode: ~ **10**

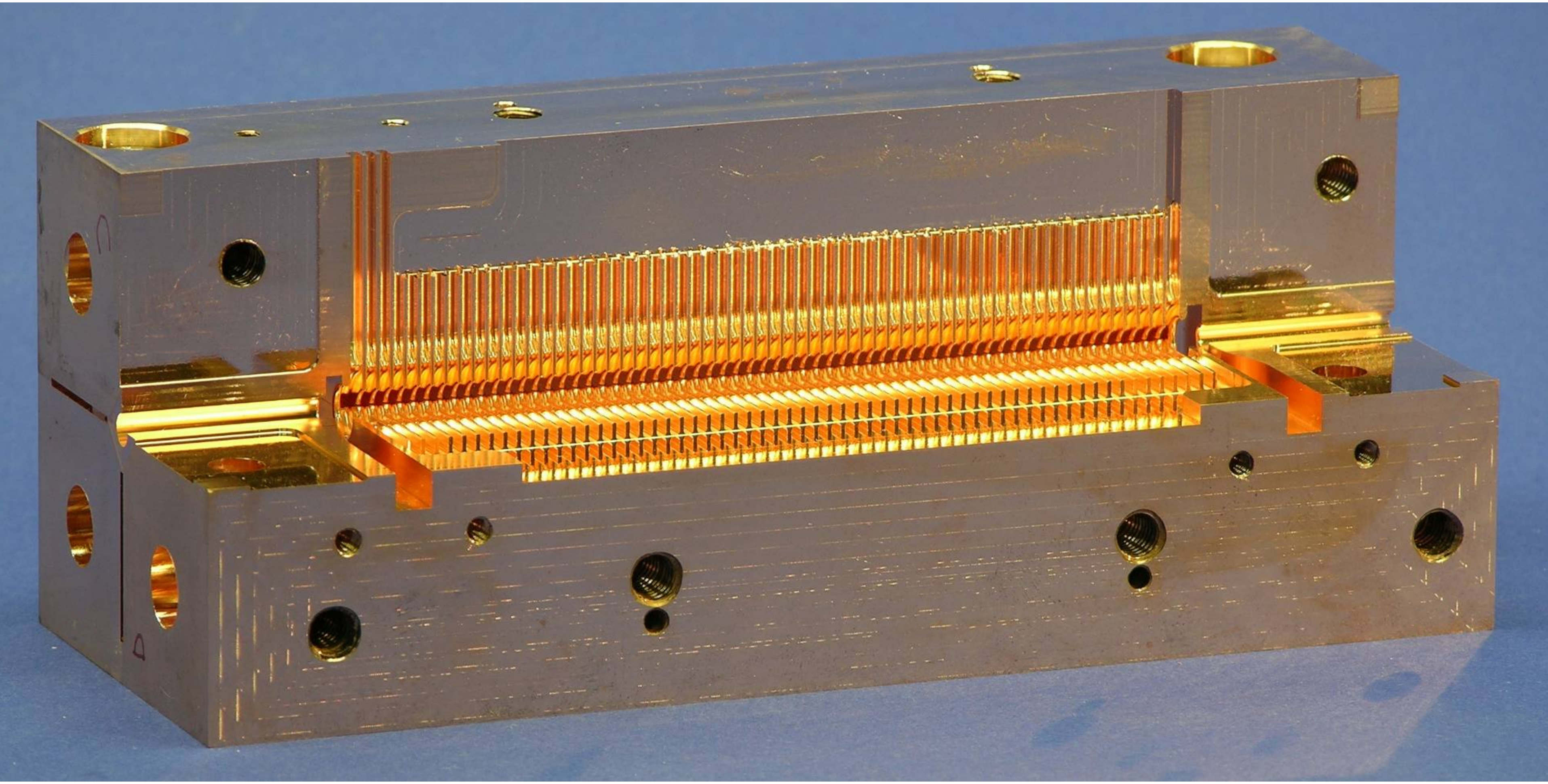






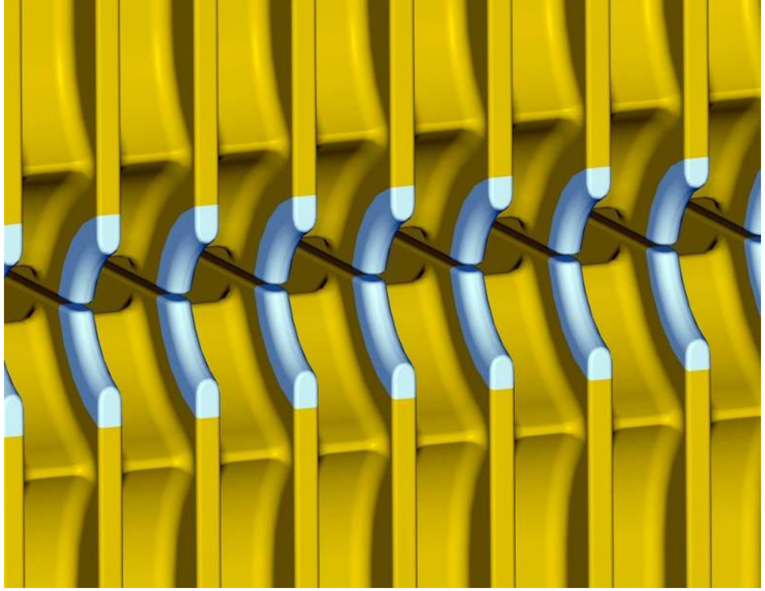
HDS 60-cells Cu prototype

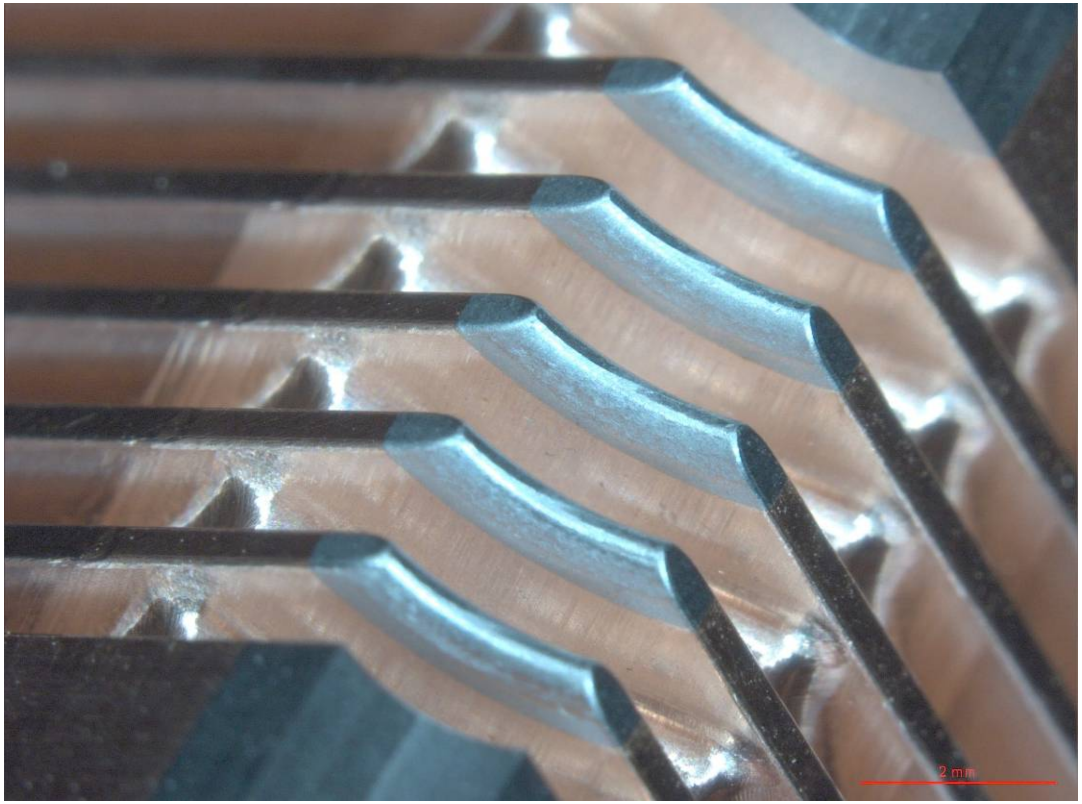
High speed 3D-milling with 10 μm precision



Putting it together technologically

Bimetallic structures
Hot isostatic pressing and high-speed milling of CuZr/Mo





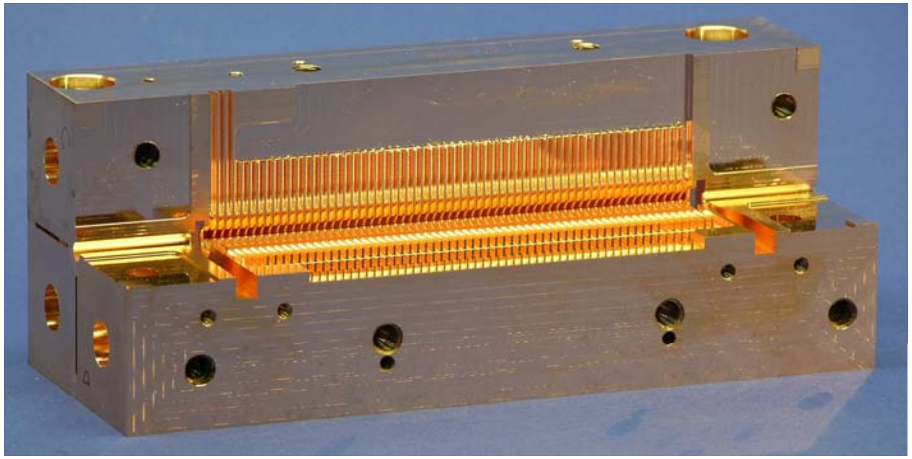
Now try to reconcile the two effects for a linear collider design,

High gradient – small aperture structures which gives low surface electric field and power flow, short rf pulses, short structure length, exotic breakdown resistant and fatigue resistant materials with lower electrical conductivity

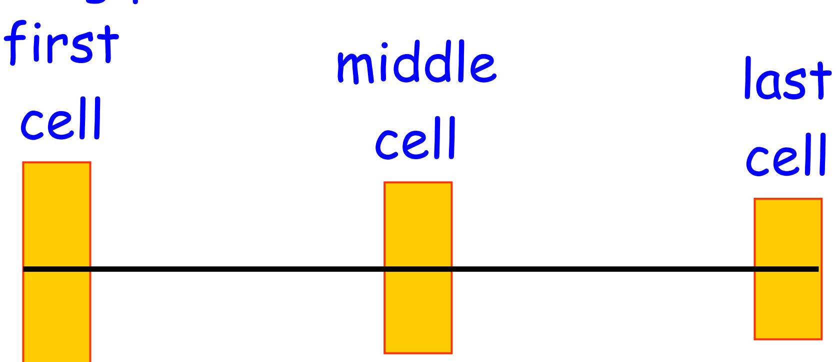
High luminosity/efficiency – large aperture structures for low transverse wakefields, long rf pulses, long rf structures, as much copper as possible

For this we have developed a highly refined optimization procedure.

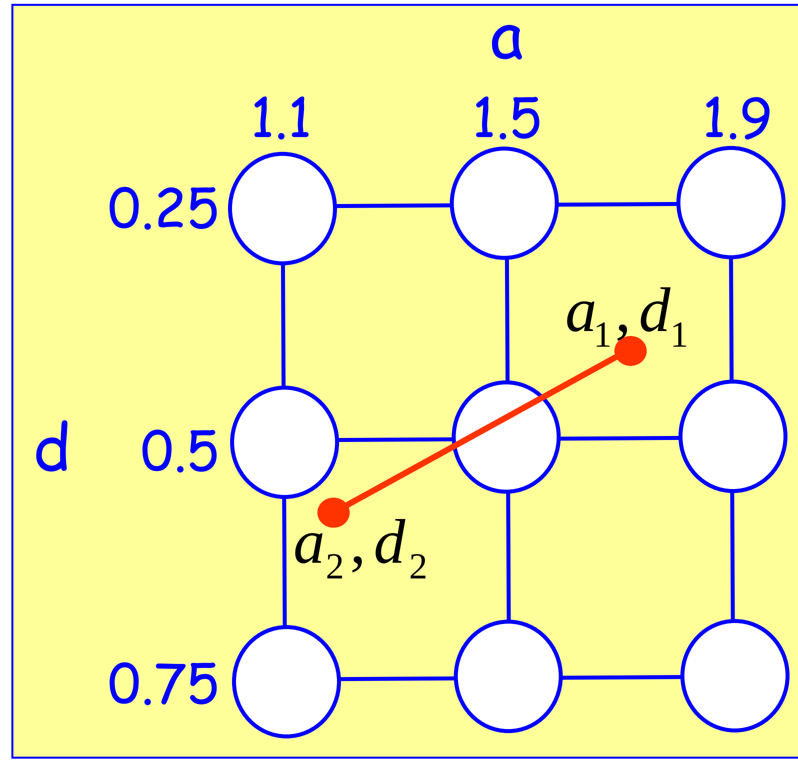
Optimization procedure



Structure parameters are calculated using parameters of the three cells:



Single cell parameter interpolation



Presented at EPAC

Optimization constraints

Beam dynamics constraints:

N depends on <a>/λ, Δa/<a>, f and $<E_{acc}>$ because of short-range wake

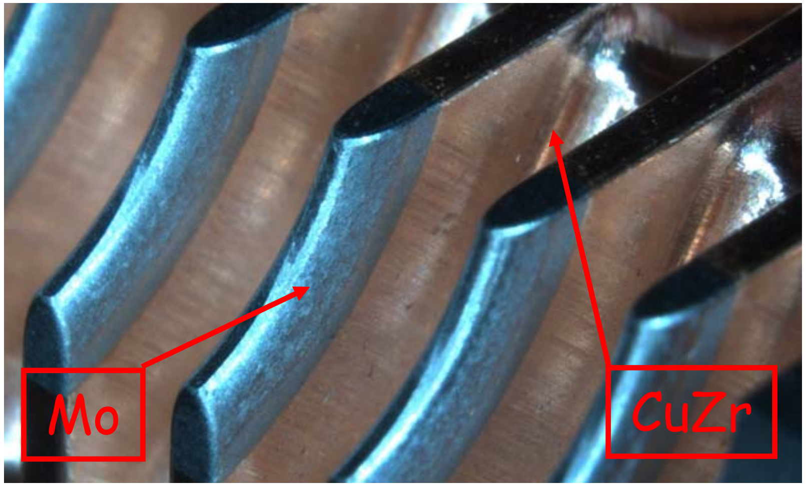
N_s is determined by condition: $W_{t,2}$ = 10 V/pC/mm/m for N = $4x10^9$

rf breakdown and pulsed surface heating (rf) constraints:

$E_{surf}^{max} < 380MV/m$ & $P_{in}t_p^{1/2}/C < 24\ MWns^{1/2}/mm$ & $\Delta T^{max} < 56K$

30 GHz, Mo | X-band, Cu <-> 30 GHz, Mo | CuZr

Bi-metallic HDS



Posters: MOPLS128; MOPLS103

N.B. Applying the same constraints to different structures implies that the structures are equally challenging

Optimization figure of merit

Luminosity per linac input power:

$$\frac{L}{P_l} = \frac{L_{b\times} N_b f_{rep}}{\dfrac{eE_c N N_b f_{rep}}{\eta}} = \frac{1}{eE_c} \bullet \frac{L_{b\times}}{N} \eta$$

Collision energy is constant

Figure of merit

Optimization results