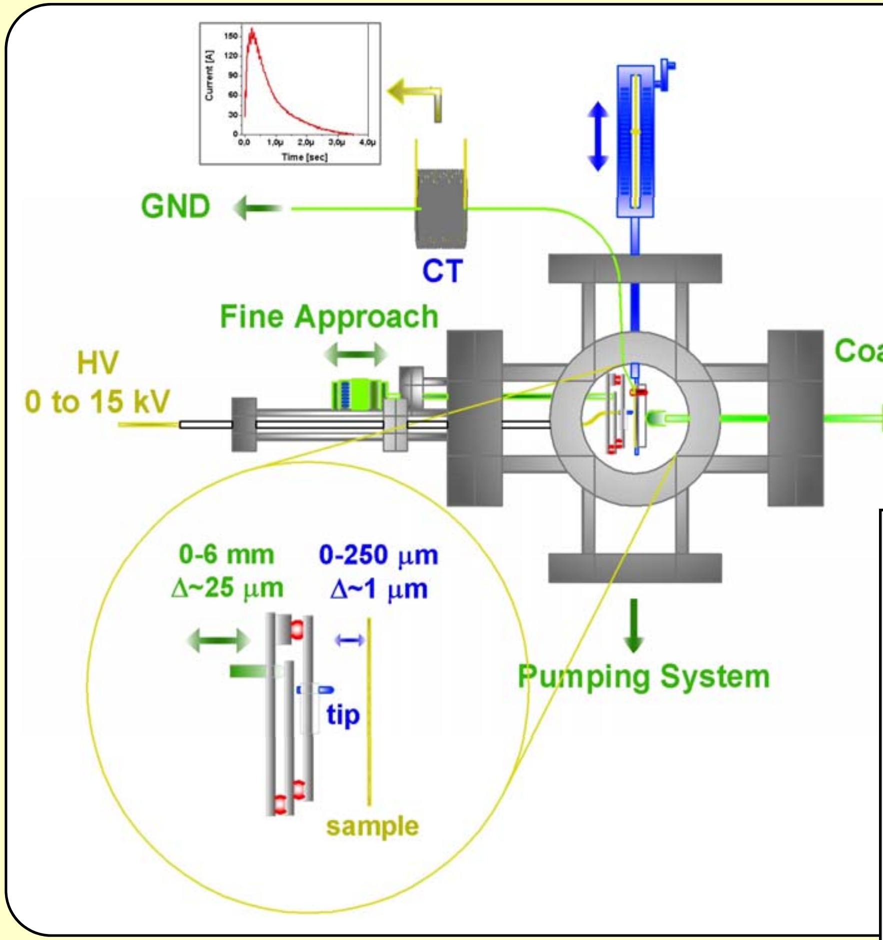
Structure Preparation Techniques and New Materials

- DC breakdown testing
  - Test of new materials
  - Test of in situ and ex-situ heating, plasma treatments, e-beam bombardment
  - Effect of machining and chemical surface treatments
  - Breakdown rate
  - Modelling of the results

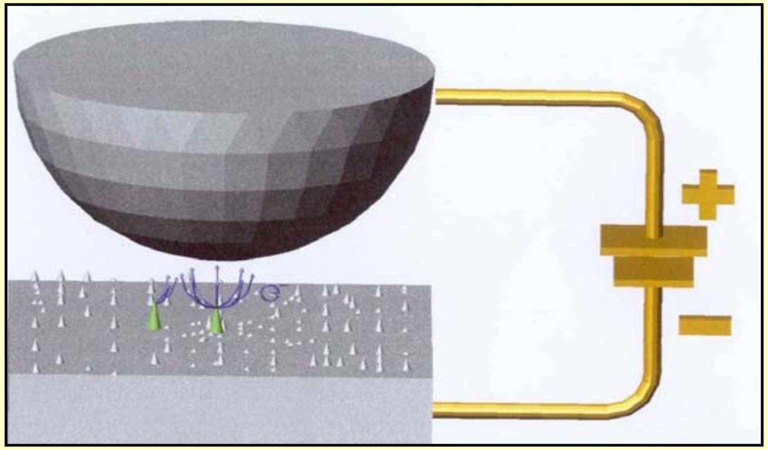
- Laser + ultrasound fatigue testing
  - Test of different materials and material states
  - Connection with manufacturing techniques
  - Benchmarking with RF testing

- (SEM, XPS, hardness, roughness, mechanical testing, vacuum properties…)

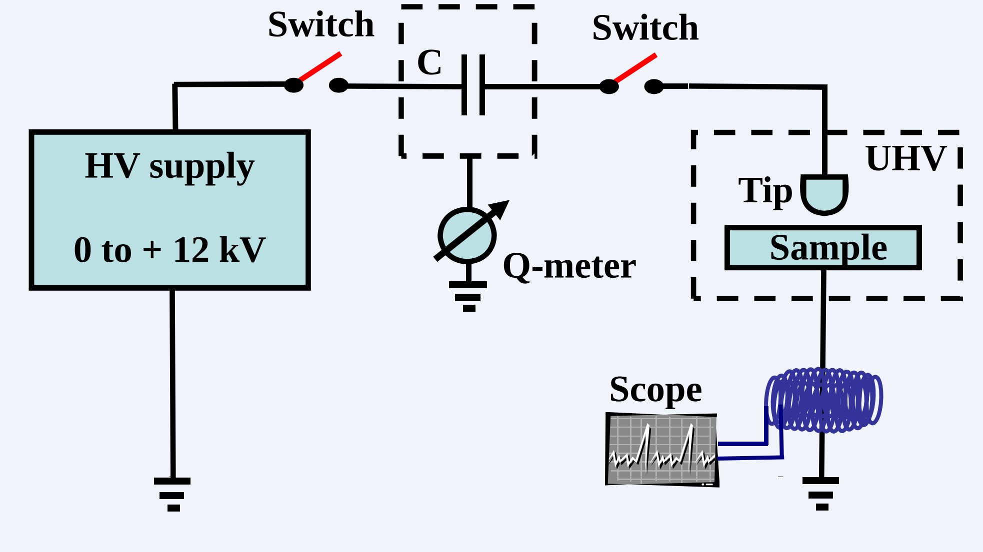
DC spark testing experimental setup



Sphere / Plane geometry



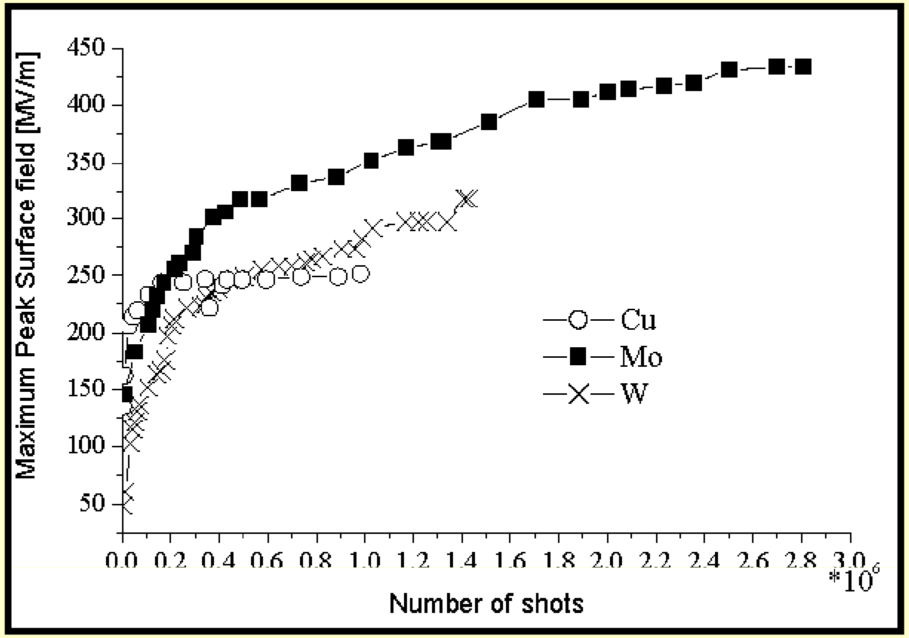
Breakdown Measurements



A second DC spark test station is being built, operating at 35 kV

From: T. Ramsvik

Comparison DC - RF



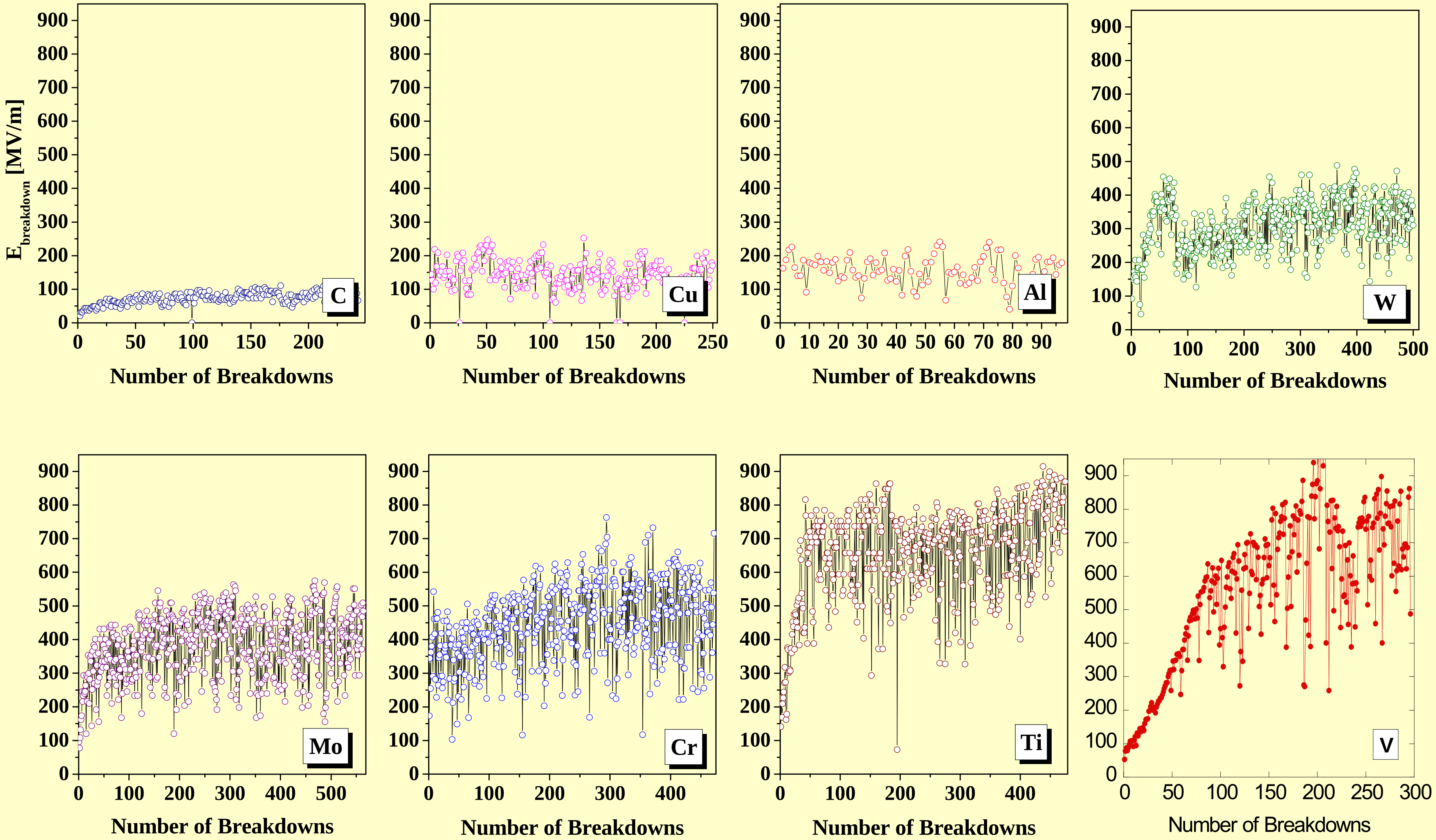
	E_{breakd}^{sat} (DC) [MV/m]	Max. surface field in RF [MV/m]
Cu	164±30	260
W	313±47	340
Mo	438±32	420

- ***DC and RF breakdown measurements give similar breakdown fields (PRST-AB 10, 042001 (2007))***

- ***Superior behavior of both Mo and W with respect to Cu.***

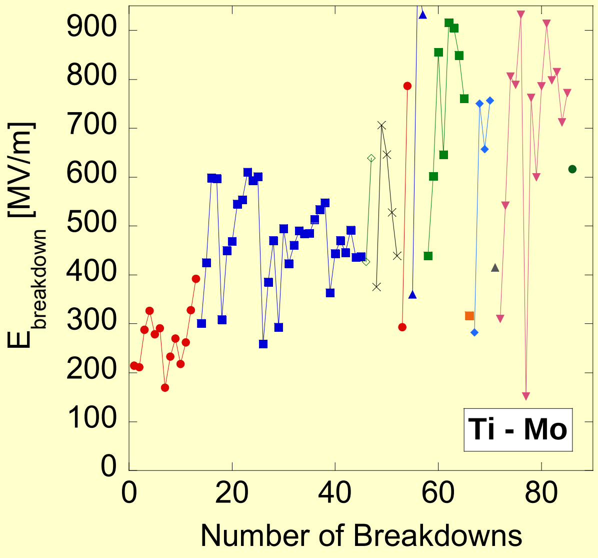
From: T. Ramsvik

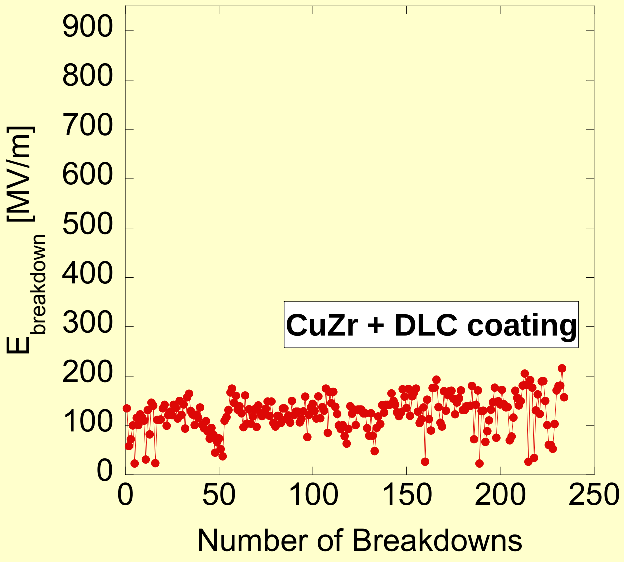
Typical conditioning curves – pure metals

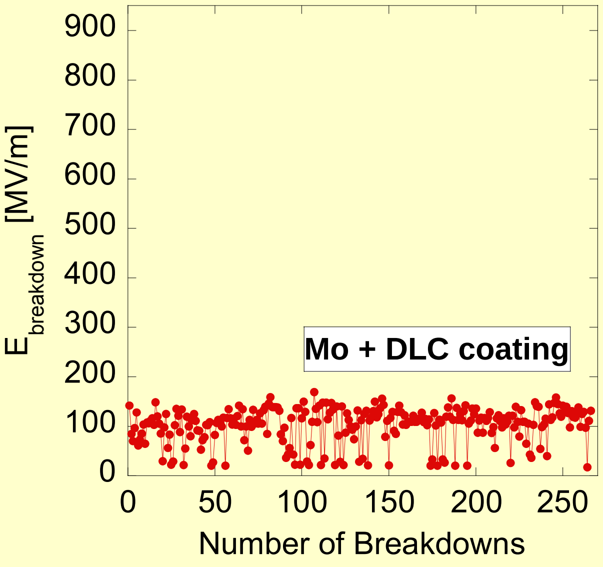


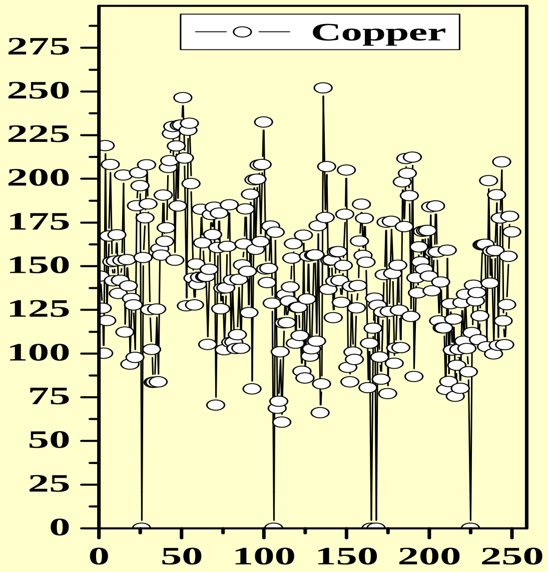
From: T. Ramsvik, A. Descoeudres

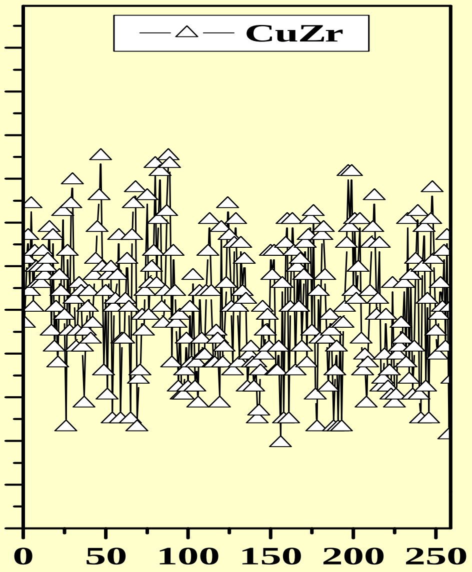
Typical conditioning curves – more exotic

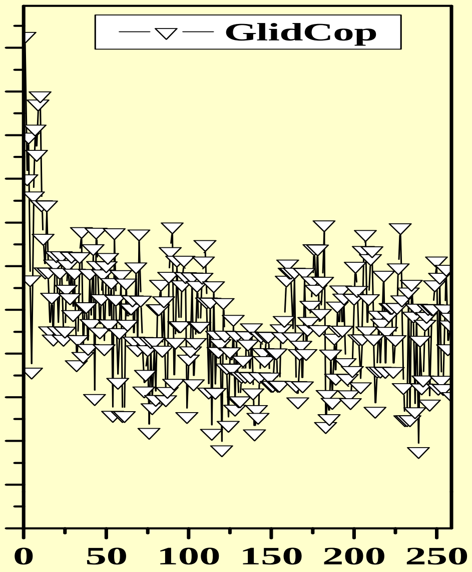












From: T. Ramsvik, A. Descoeudres

New materials

The guidelines that have led to the choice of refractory metals as new candidate materials for the high-field regions are the high melting point, the low vapour pressure (other ideas exist, cf. Perry Wilson)

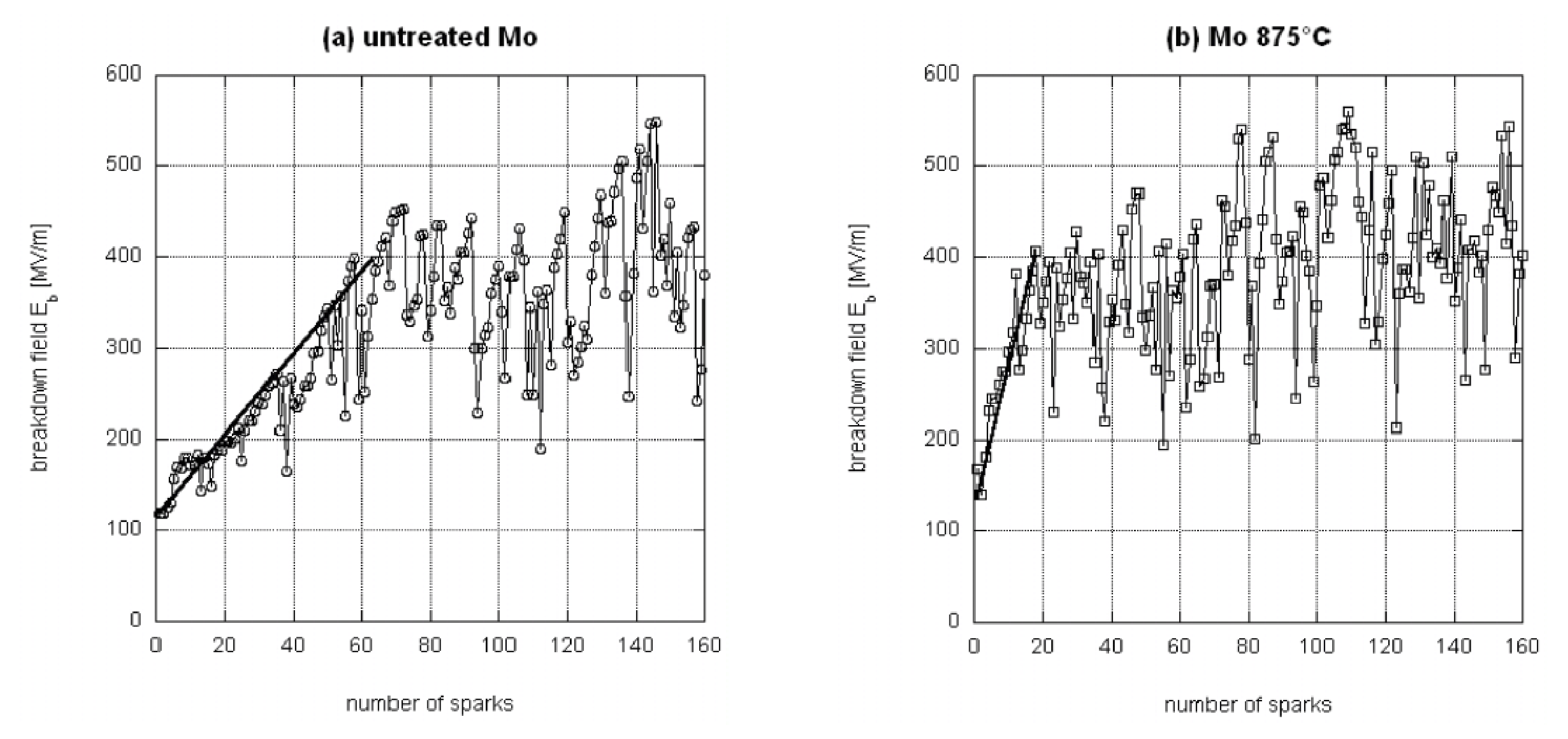
- Experimental evidence (either in DC or RF) indicates that these criteria are not enough. For example:
  - Mechanical fragility hinders the performance of W
  - The surface oxide plays a strong role in the conditioning behaviour of Mo
  - The machining process affects the performance of Cu alloys
  - ??? makes that the performance of Ti is very good but highly unstable

- **More extensive experimental testing both in DC and in RF will help in refining our guidelines.**

- New materials alone are useless without a strategy for bimetal fabrication.
- Current best candidate is Mo-CuZr (discussed by M. Taborelli).
- There are ides for bimetallic structure fabrication by plating technology. This will be first tested with chromium and validated in DC.

Example: heating of Mo

- We have strong evidence that heating is beneficial for the conditioning rate of molybdenum, and that it is the result of the reduction of surface oxides.
- Mo can be exposed to air only for a limited amount of time after heat treatment (<8h), otherwise oxides build up again
- This will soon be tested in HDS structures

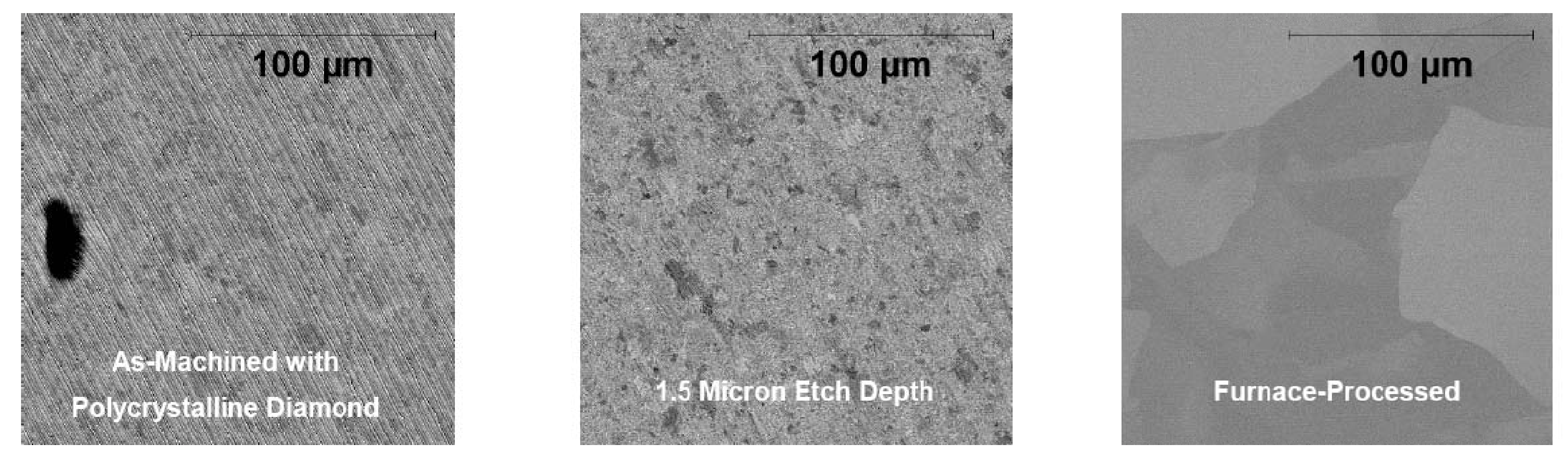


From: A. Descoeudres

Heating – further studies

- High-temperature heating is difficult to apply to a bimetallic structure
- -> Need for a different but equally effective surface treatment
- Ideas tested (partially) at CERN:
  - plasma treatment for oxide removal (could it be done in-situ in RF structures?)
  - e-beam heating (ex-situ local heating, then storage in appropriate conditions)

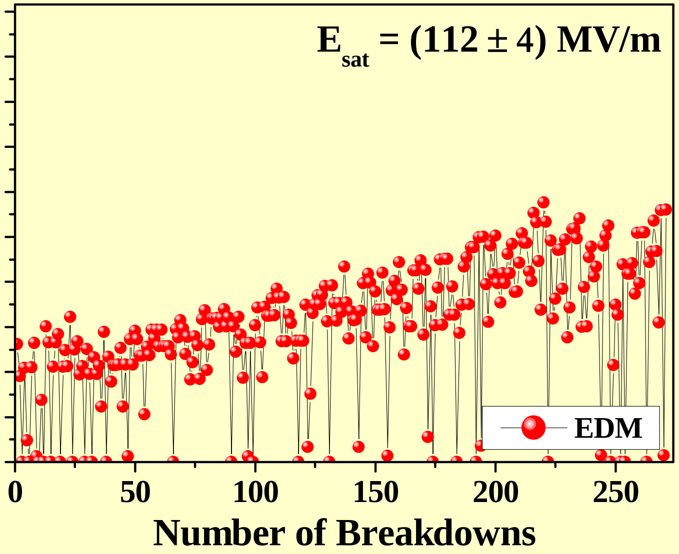
- High-temperature heating (and surface etching) has been consistently applied to copper structures at SLAC and KEK. There are indications (both DC – KEK and RF – SLAC) of an advantage in the breakdown limit.
- Is this due to changes to the oxide, to the outgassing, to topography, to cleanliness, or combined?

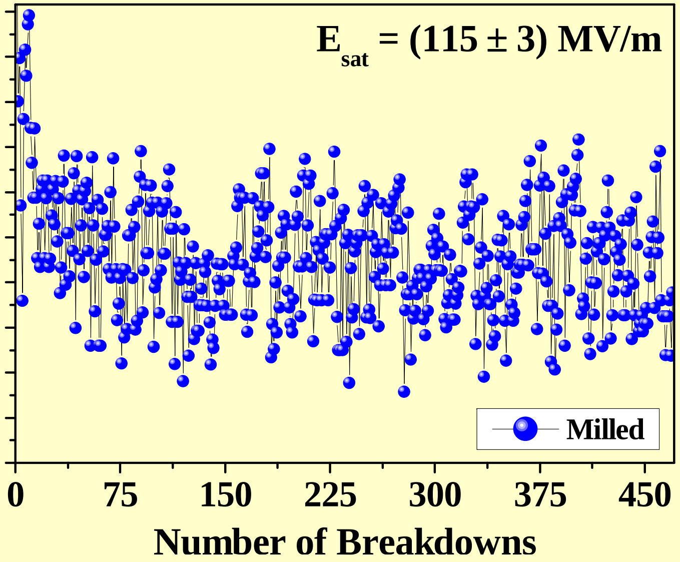


Surface treatments

- All DC spark testing has been carried out on rolled metal sheets (with a few exceptions).
- All RF testing has been done on turned or milled structures
- SLAC structures underwent surface treatments which were dependent on the machining procedure
- The effect of machining and chemical surface treatments on the conditioning rate and breakdown limit have been studied in RF at SLAC. More data are however needed in particular on breakdown probability

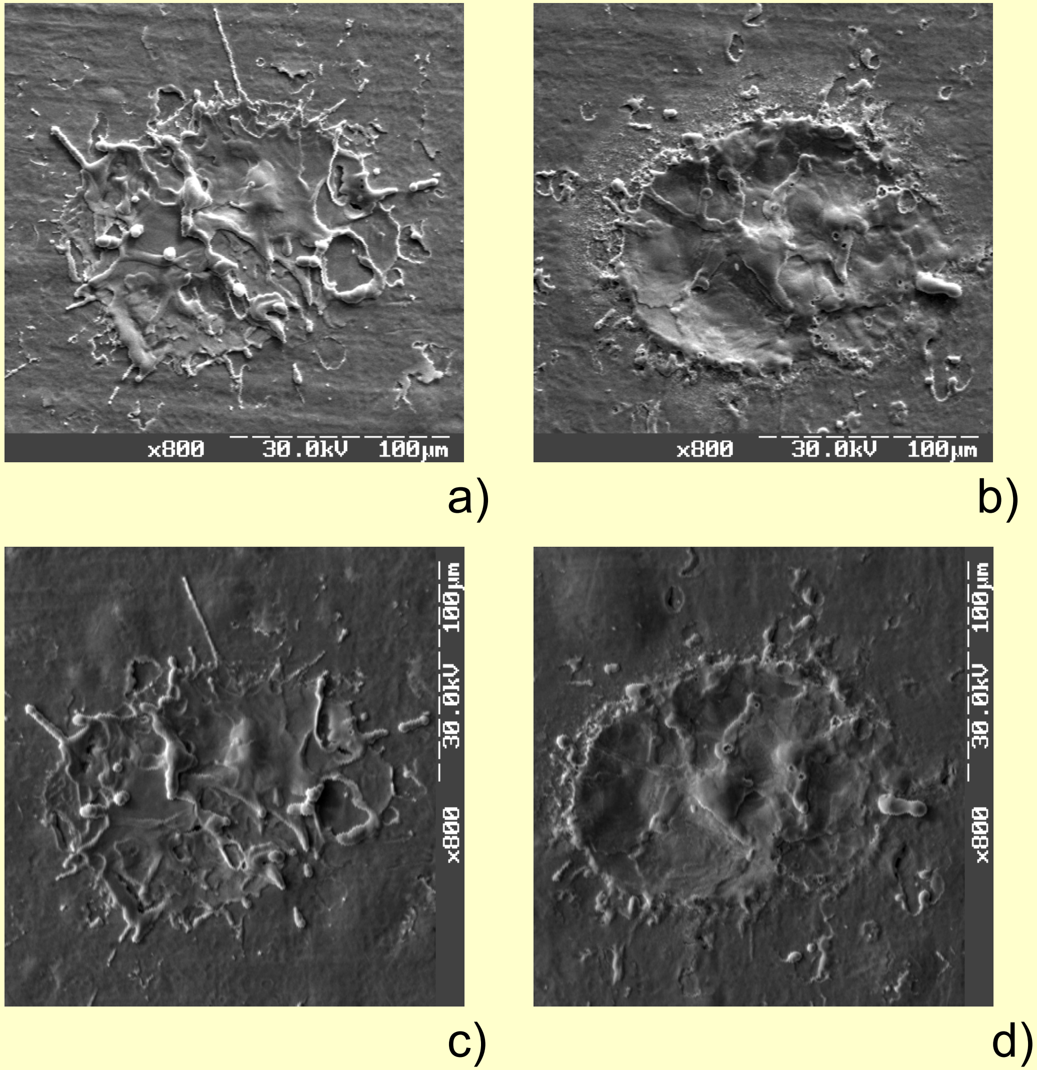
- One example of the effect of machining from our DC spark testing: Glidcop





Surface treatments: helicon plasma?

Modeling of laser-ablation damage of Mo sample and cleaning of the micro tips by H + He helicon discharge



a) Image of Mo sample after 1 laser pulse (energy 20 mJ, time of pulse 50 ns)

b) Image of Mo sample after 10 laser pulse (energy 20 mJ, time of pulse 50 ns)

c) Image of Mo sample (1 laser pulse) after cleaning by helicon discharge (Prf=200 W, p=20 mTorr)

d) Image of Mo sample (10 laser pulse) after cleaning by helicon discharge (Prf=200 W, p=20 mTorr)

Time of discharge only 2 hours (hydrogen) and 1 hour (helium)

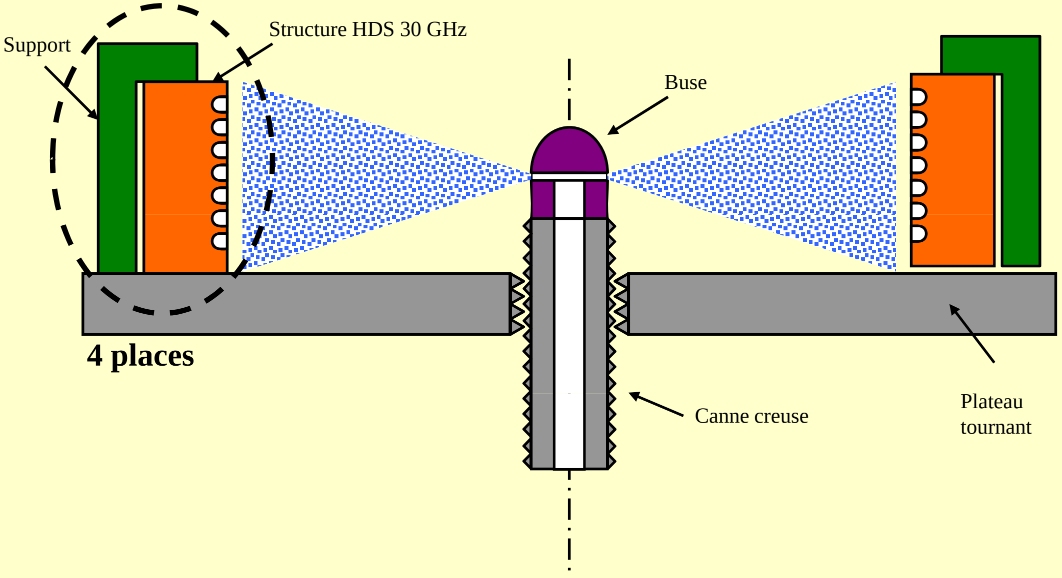
Conclusion:

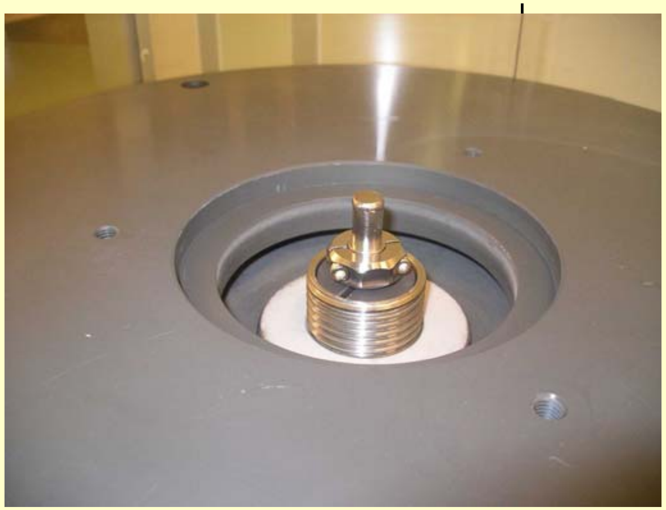
1) RF structure need cleaning before installation by glow or helicon discharge

2) There is possibilities of repairing rf structure by low pressure (10 -100 mTorr) helicon discharge

From: S. Mordyk, SUMY

Surface treatments: HPWR and SC-cavity like treatments?

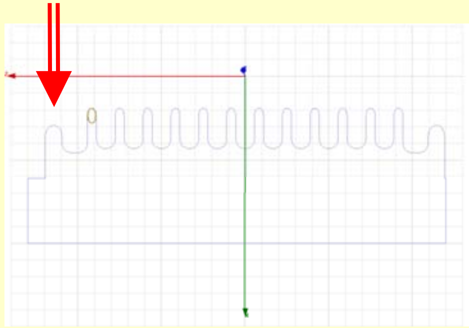


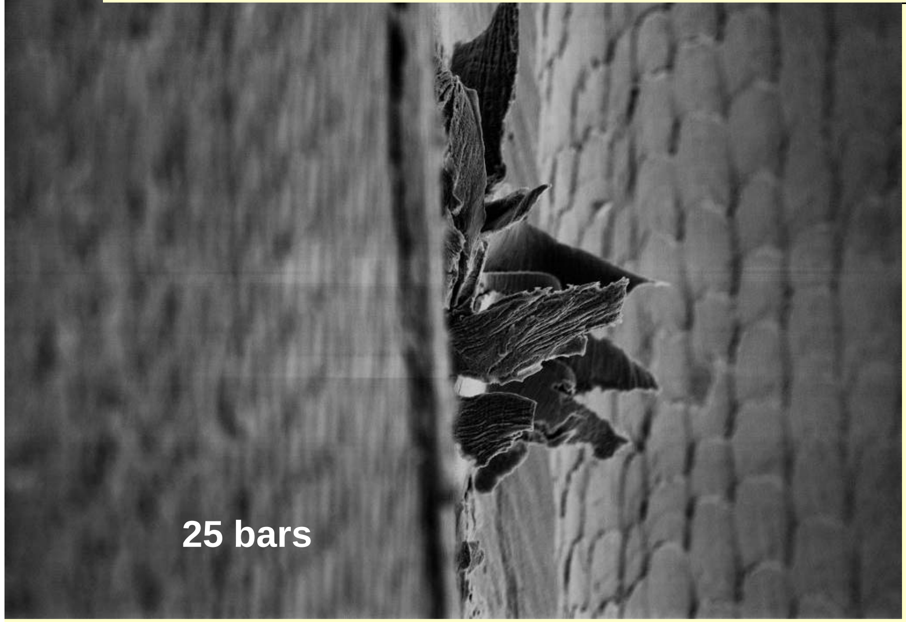


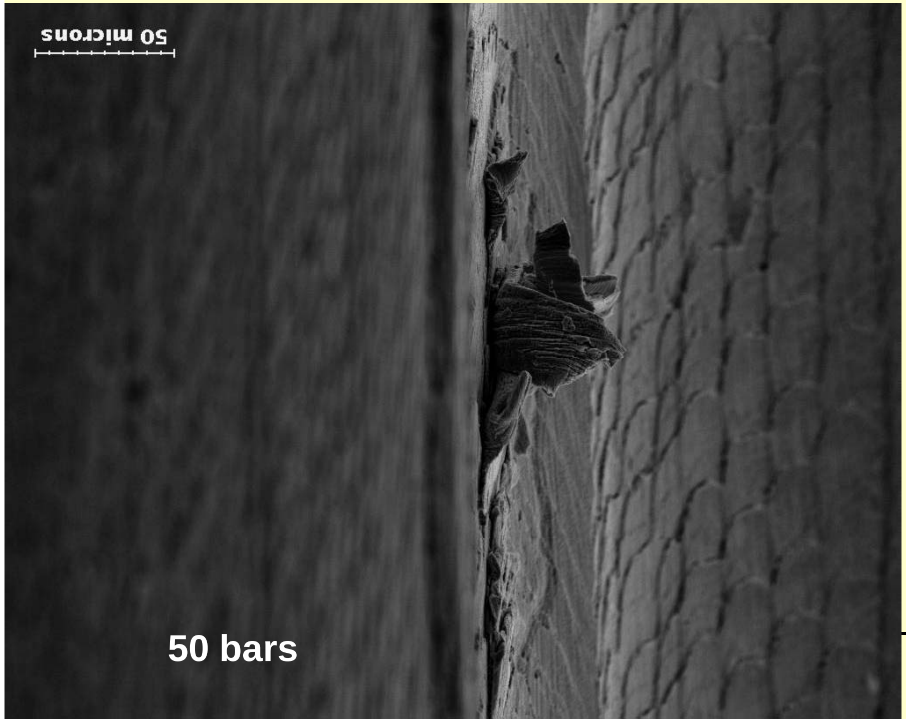
High Pressure Water rinsing and Clean Room operations are standard practice in the world of superconducting cavities

From: F. Peauger, CEA

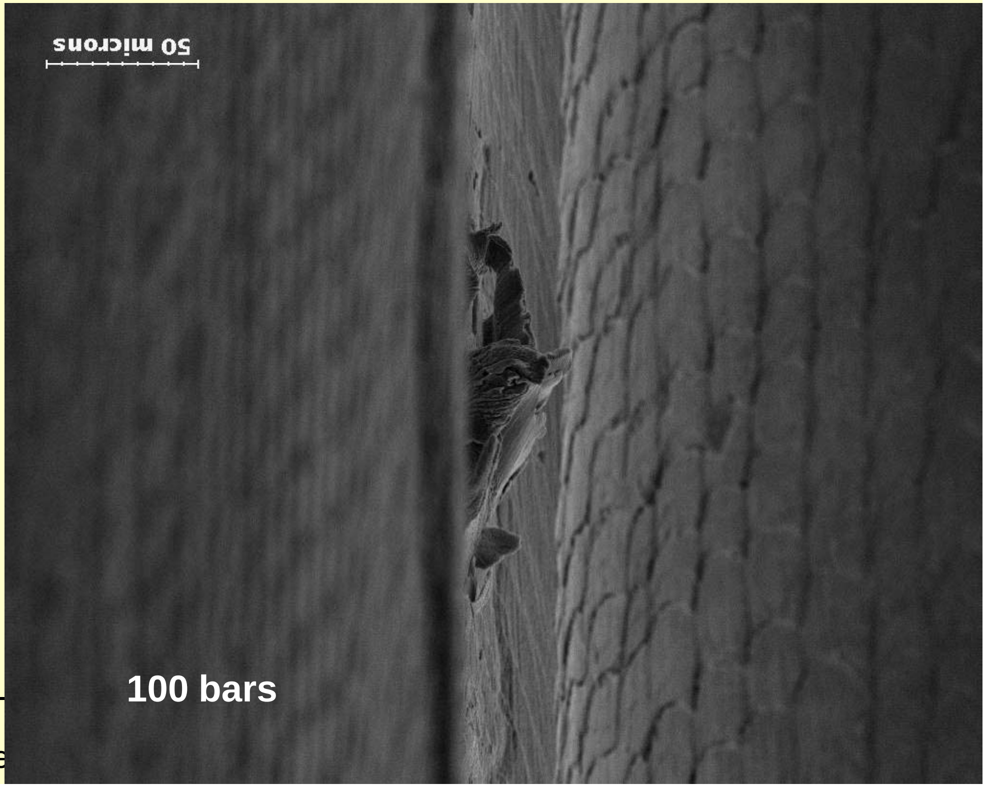
Defects in milling revealed – and then maybe reduced




25 bars



50 bars



100 bars

Se

Breakdown rate

- We will try to produce statistical breakdown data, by applying DC pulses of HV to test specimens, in our test stand
- However:
  - These will be second-long pulses, and we have first to verify that the results are meaningful compared to RF data (as was done for the breakdown limit)
  - It is also time-consuming, and will probably use or new test system 100%

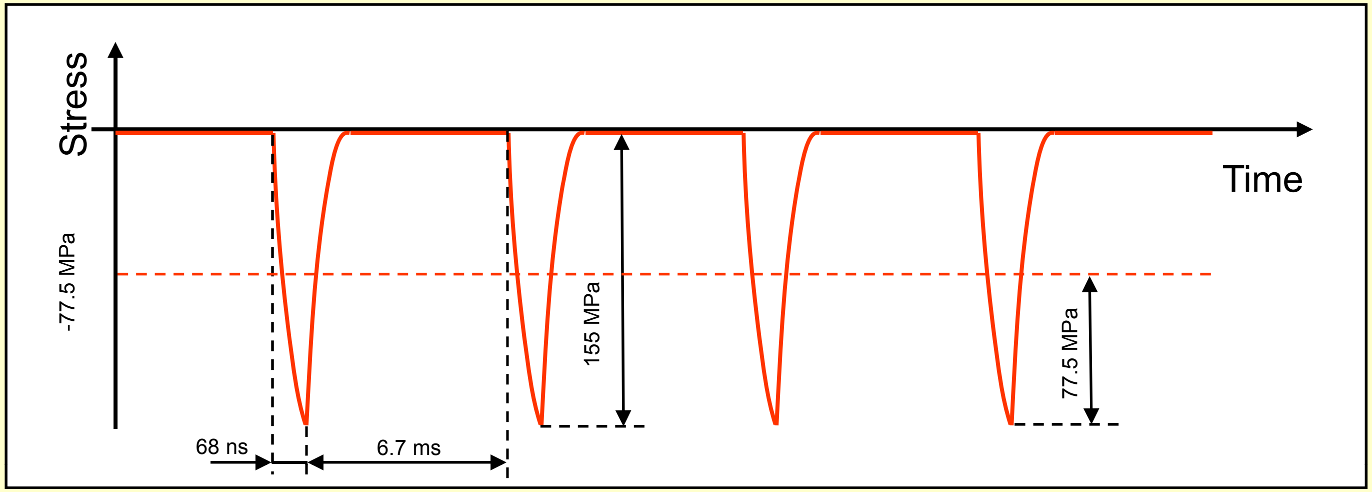
- Some theoretical modelling of the breakdown rate phenomenon is under way. A couple of solid hypothesis have been laid, and we have some encouraging quantitative results. Still, the validity must be checked
- Missing experimental information: is there any influence of the surface treatment? (It is speculated that even the structure assembly technique might play a role)

- **Additional RF data would be greatly helpful**

The problem of fatigue

CLIC number of cycles (old parameters):

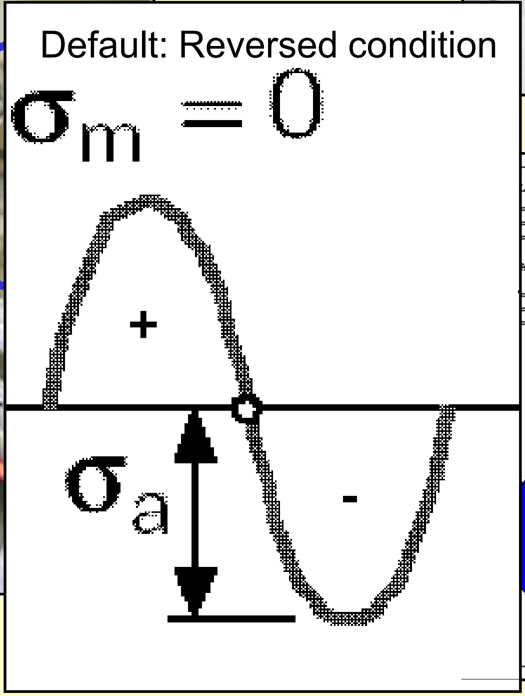
Repetition rate	**150 Hz**
Estimated lifetime	**20 years**
	9 months / year
	7 days / week
	24 hours / day
Total N	**7 x 10^{10}**



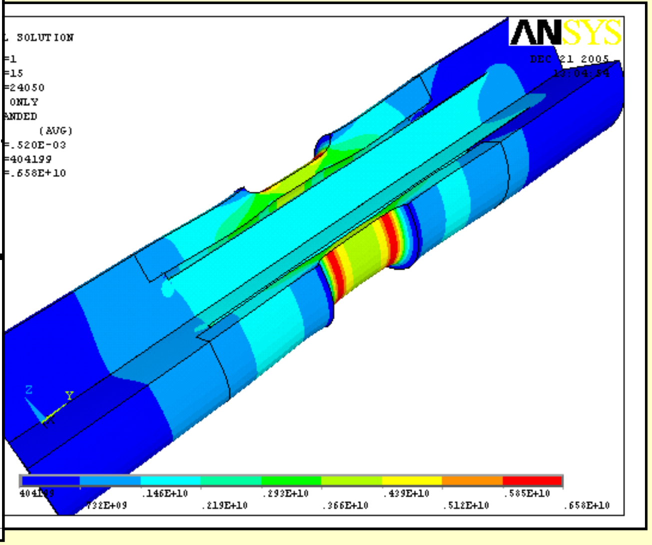
From: S. Heikkinen

Ultrasonic fatigue testing

- **Cyclic mechanical stressing of material at frequency of 24 kHz.**
- **Scope: High cycle regime, 10^7 - 10^{11} cycles**
- **High cycle fatigue data within a reasonable testing time. CLIC lifetime 7×10^{10} cycles in 30 days.**

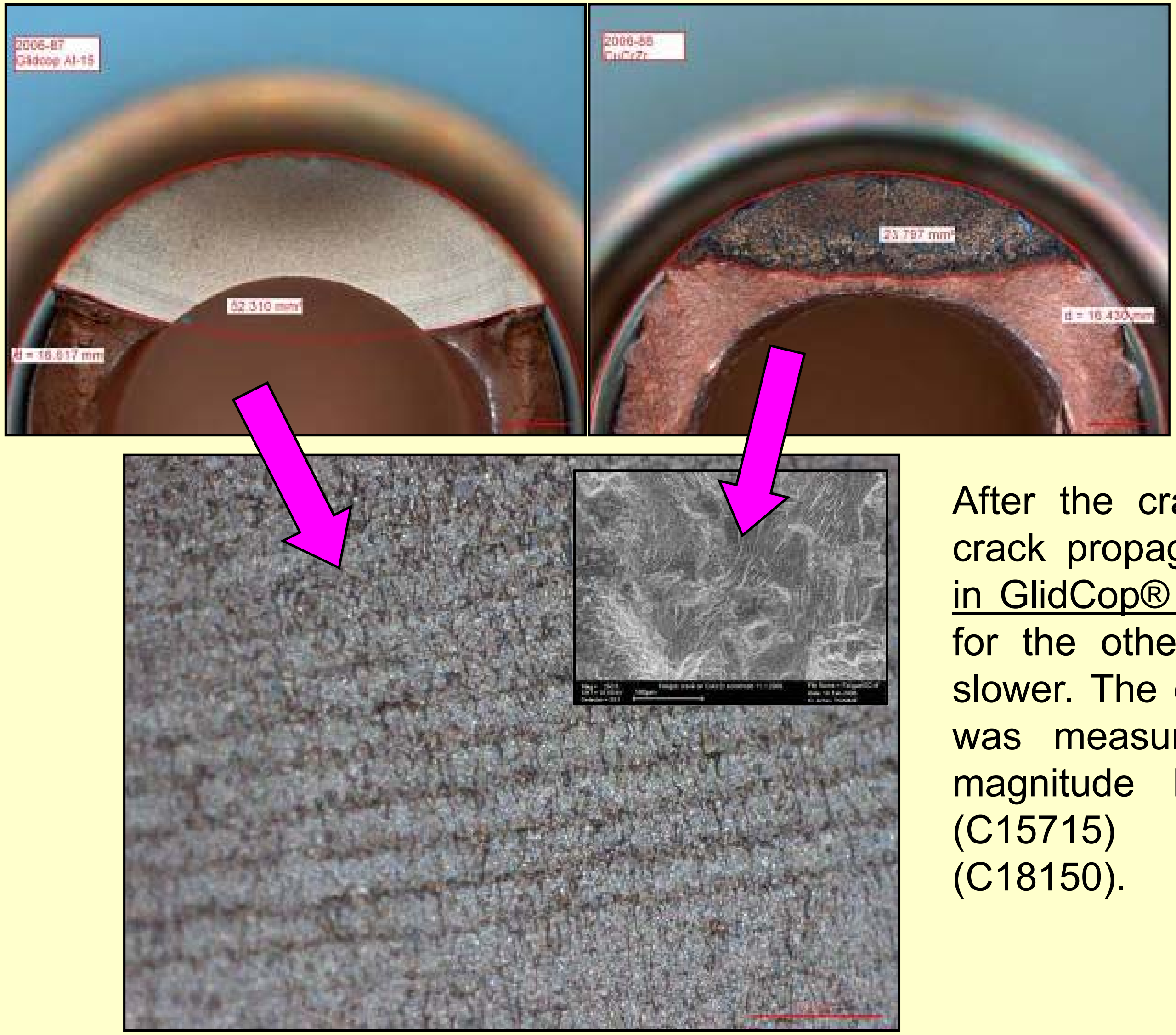



Diamond turned test samples



From: S. Heikkinen

Crack propagation in US testing

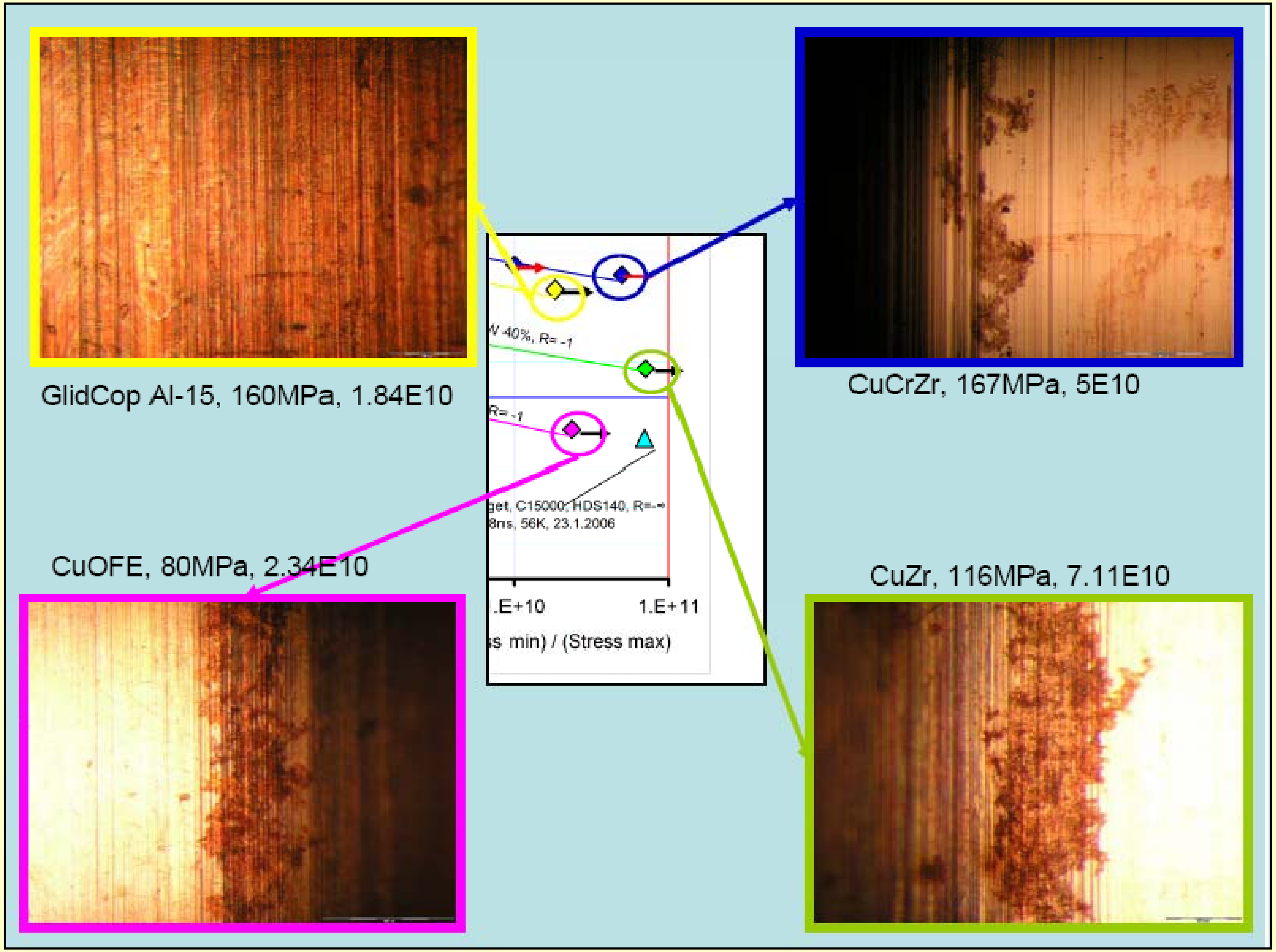


G. Arnau Izquierdo TS/MME

After the crack was initiated, the crack propagation was the fastest in GlidCop® Al-15 (C15715), while for the others it was significantly slower. The crack propagation rate was measured to be orders of magnitude higher for GlidCop® (C15715) than for CuCrZr (C18150).

From: S. Heikkinen

Surface roughening in US testing



GlidCop Al-15, 160MPa, 1.84E10

CuCrZr, 167MPa, 5E10

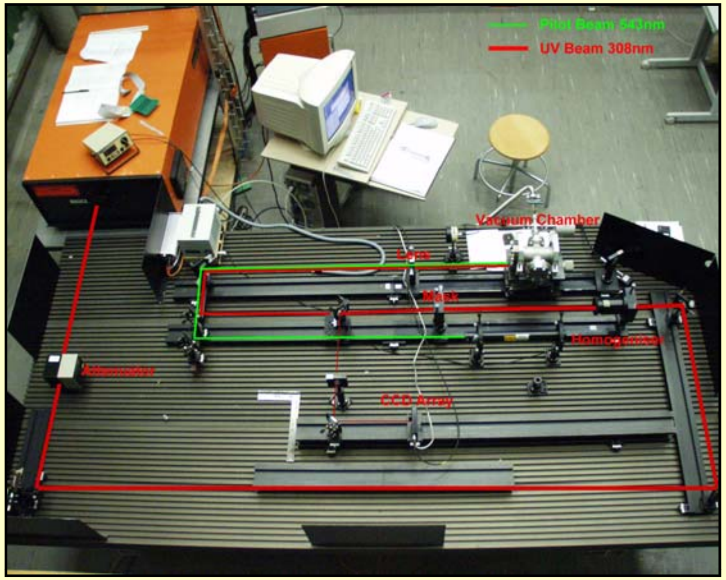
CuOFE, 80MPa, 2.34E10

CuZr, 116MPa, 7.11E10

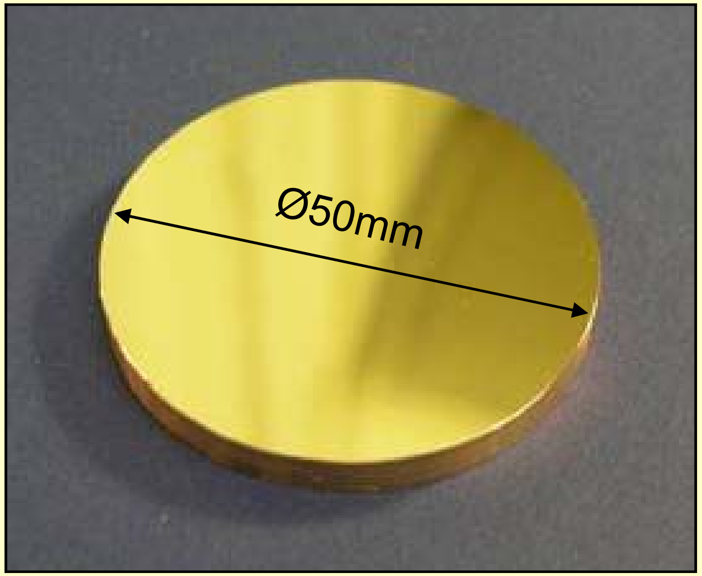
From: S. Heikkinen

Laser fatigue testing

- Surface of test sample is heated with pulsed laser. Between the pulses the heat is evacuated into the bulk.
- The laser fatigue is assumed to be close to RF fatigue.
- The operating frequencies of the apparatus available are 20 and 200 Hz.
- Scope: Low cycle regime, up to 10^7.
- Observation of surface damage with electron microscope.
- The surface damage is characterized by SEM observations and roughness measurements.

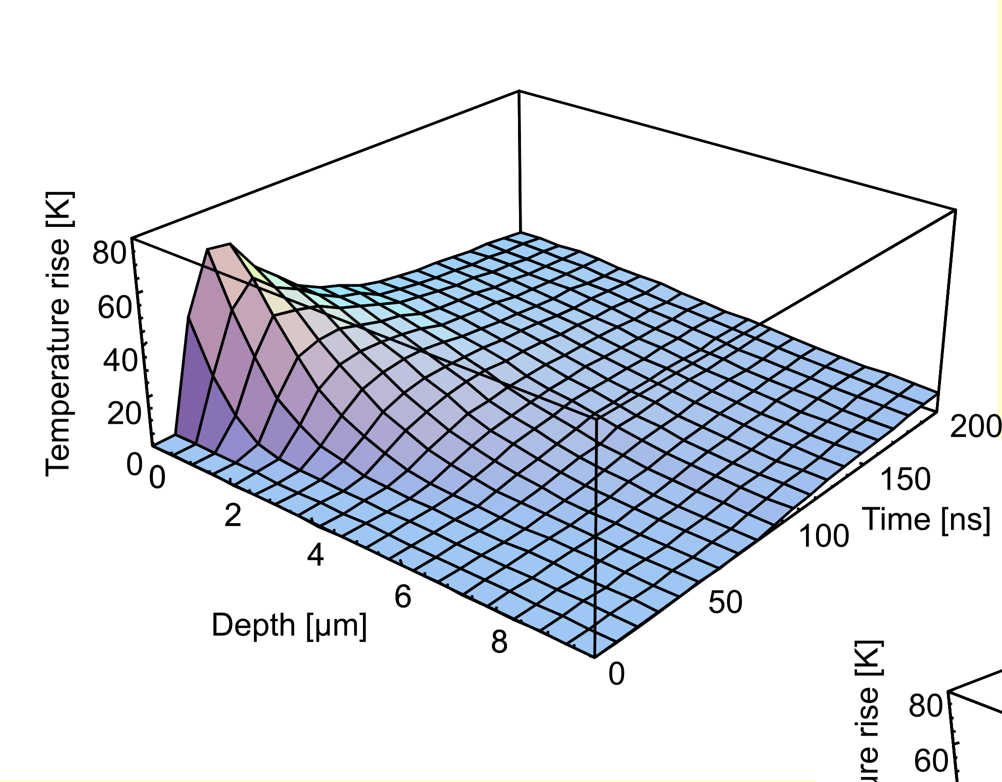


Laser test setup



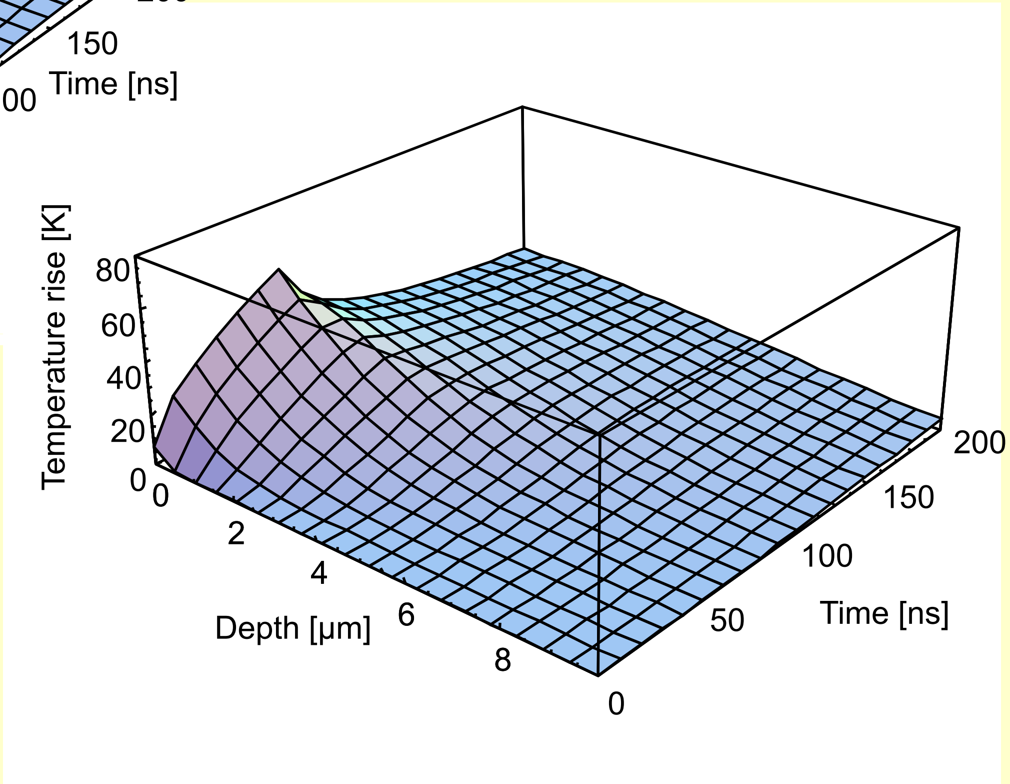
Diamond turned test sample

Comparison of heating profiles



← Laser pulse

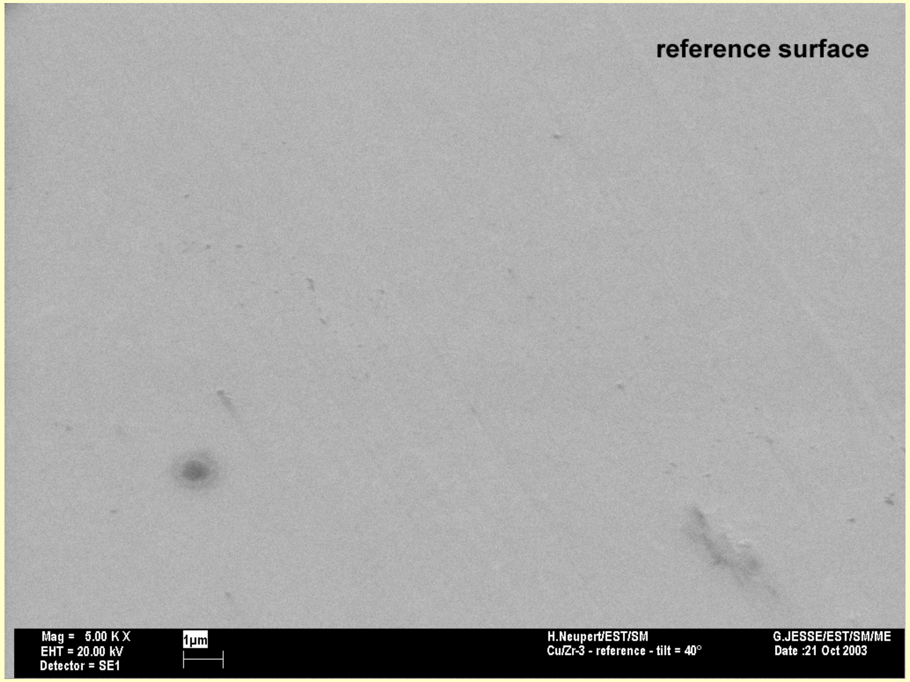
RF pulse ↓



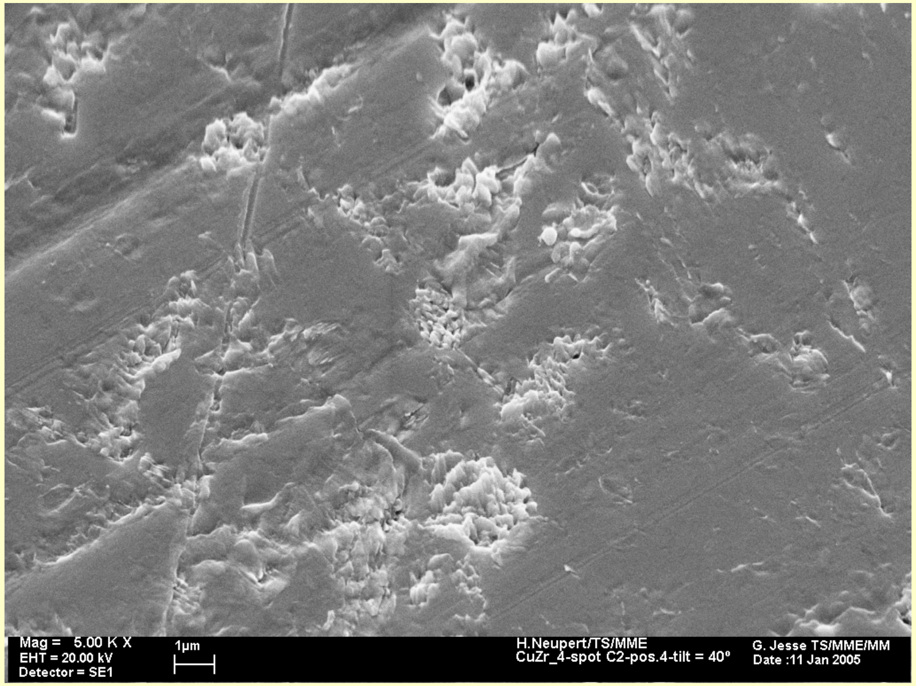
The pulse shapes correspond.
In particular the temperature profile at the peak is very similar, and results in similar stress level.

$$\sigma = \frac{\Delta T * E * \lambda}{(1-\nu)}$$

Laser surface damage



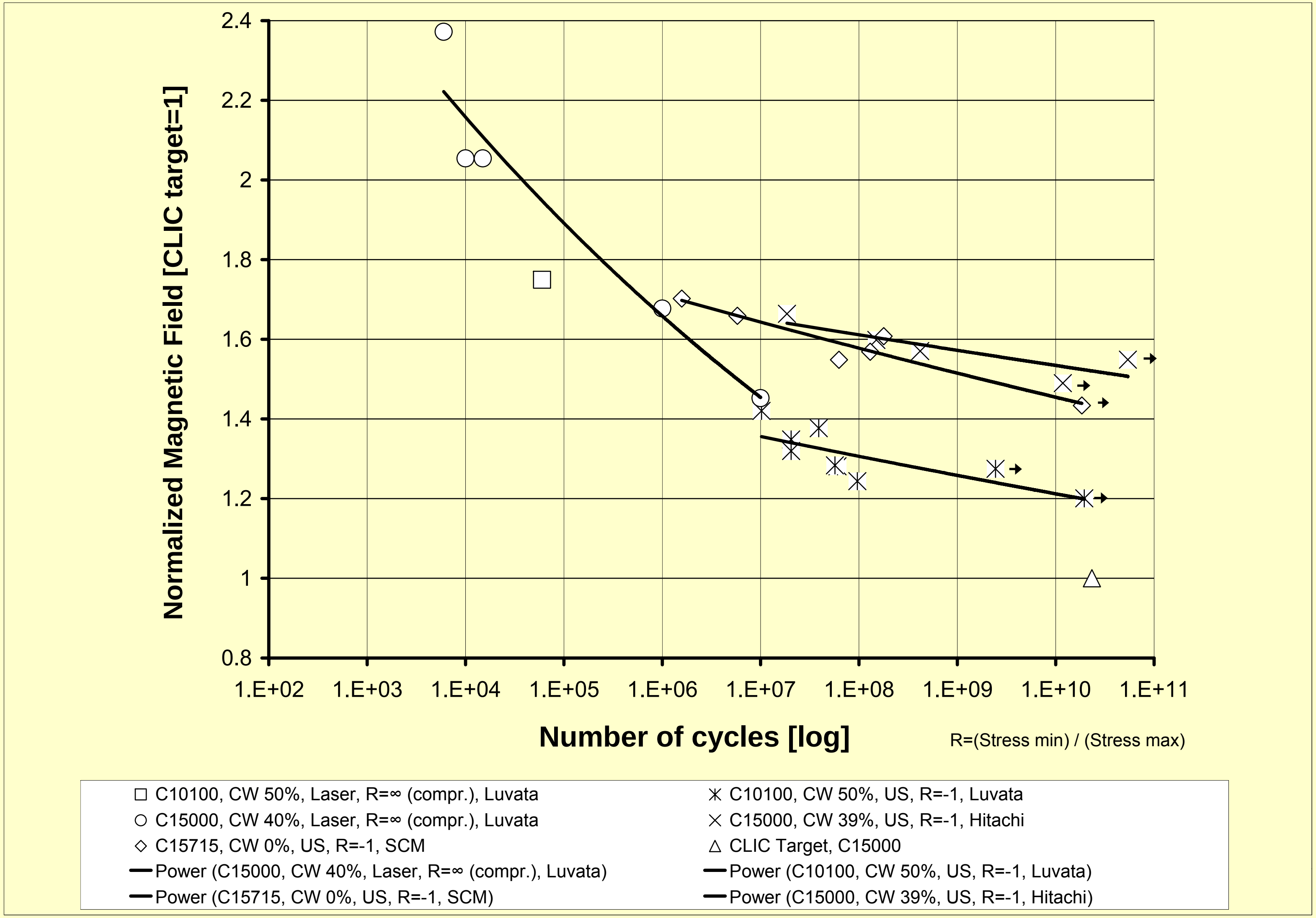
CuZr reference



CuZr, 10 Mshots, 0.15 J/cm^2,
ΔT = 120 K, σ = 170 MPa,
under high vacuum (turbopump)

From: G. Arnau Izquierdo

US and laser data



More fatigue ?

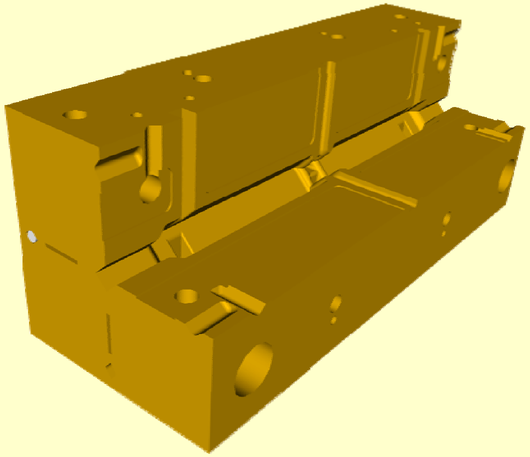
- Fatigue is a statistical phenomenon. Statistical information is still missing in our study on samples, in particular for the laser data.
- The technological choice for fabrication has strong influence on fatigue resistance (for example a thermal treatments zeroes most of the advantage of CuZr, or the benefits from cold working)

- **It would be of extreme importance to have a clear RF benchmark of fatigue data.**

- The old SLAC data (D.P. Pritzkau and R.H. Siemann, PRST-AB 5, 112002 (2002)) are too few, and moreover don‘t give information on the „appearance“ of fatigue damage, which is thought being the most critical issue for RF cavities
- (a PhD student has just started working on the material science aspect of this topic)

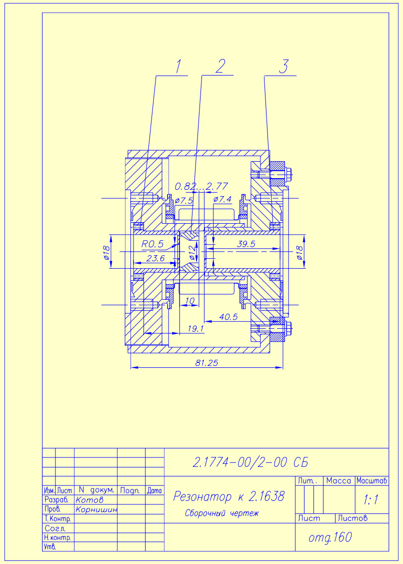
RF fatigue studies - planned

30 GHz pulsed heating cavity, CERN



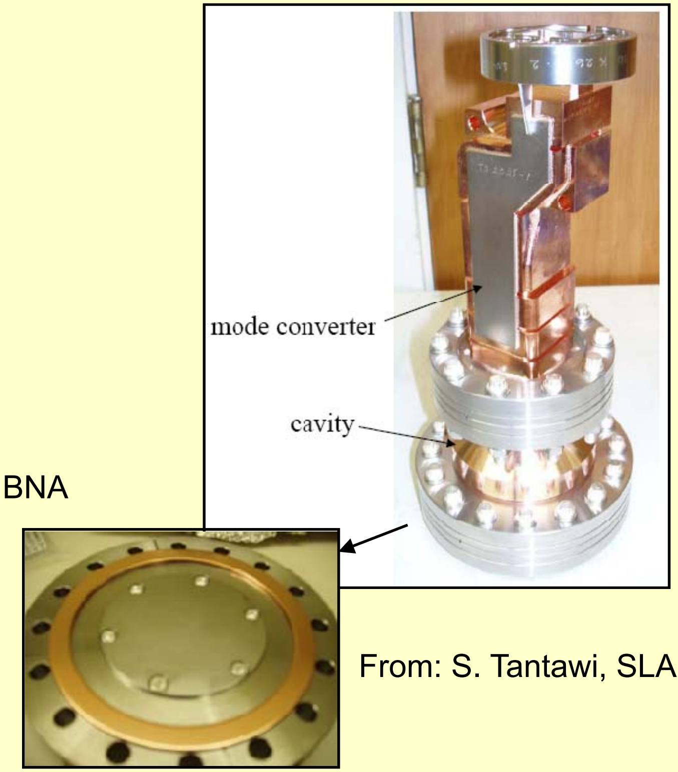
From: A. Grudiev, S. Heikkinen

30 GHz pulsed heating cavity, Dubna



From: A. Kaminsky, M. Petelin, DUBNA

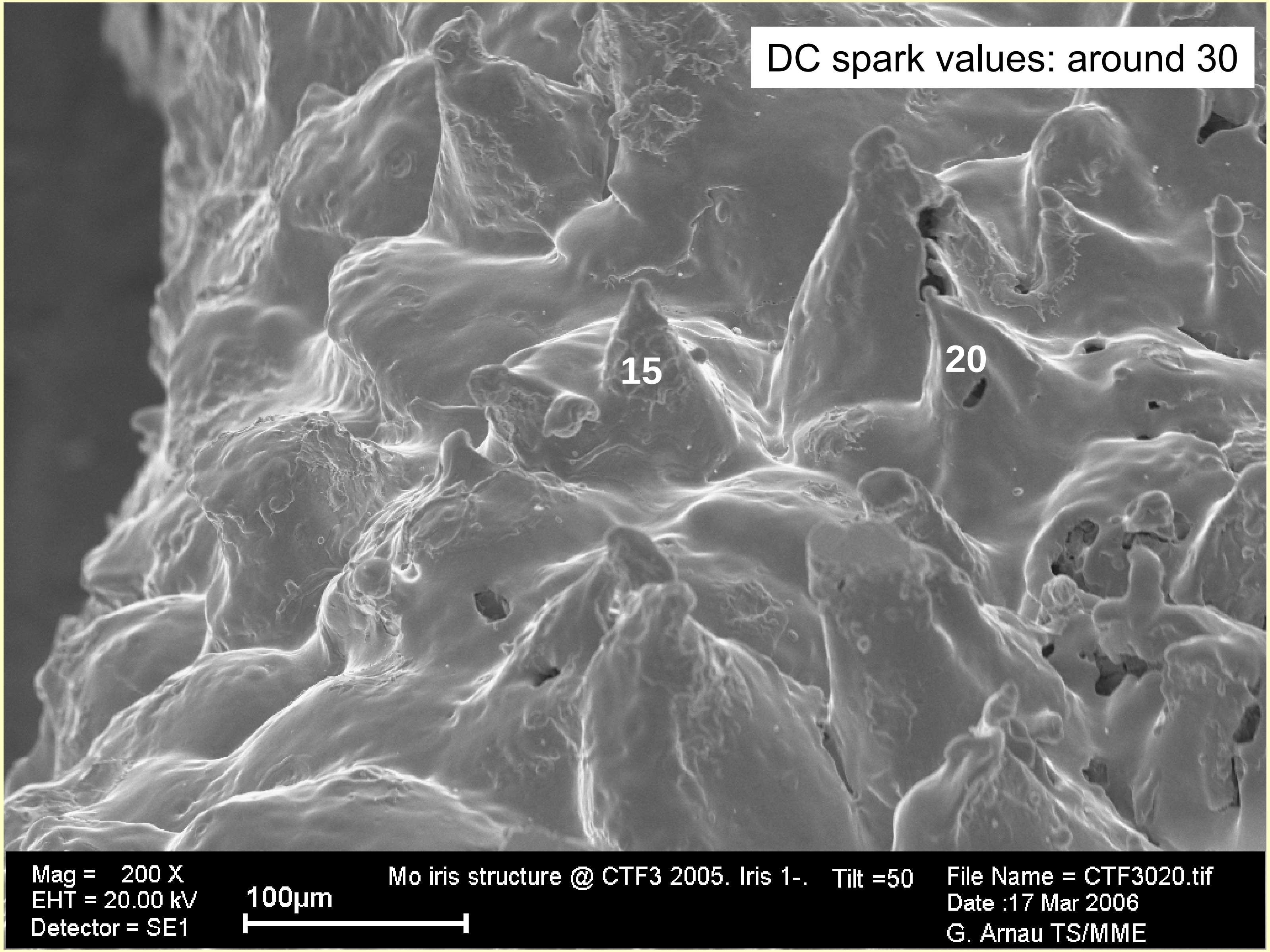
11.4 GHz pulsed heating cavity, SLAC



From: S. Tantawi, SLAC

The end

Beta calculations from SEM observation - Mo


DC spark values: around 30

Comparison with breakdown rate measurements?

- The electron current is given by the standard Fowler-Nordheim equation:

$$I_{electrons} = FN(\beta E)$$
$$FN(\beta E) = Const * (\beta E)^2 \exp(-B/\beta E)$$

- The constant includes the emitter area

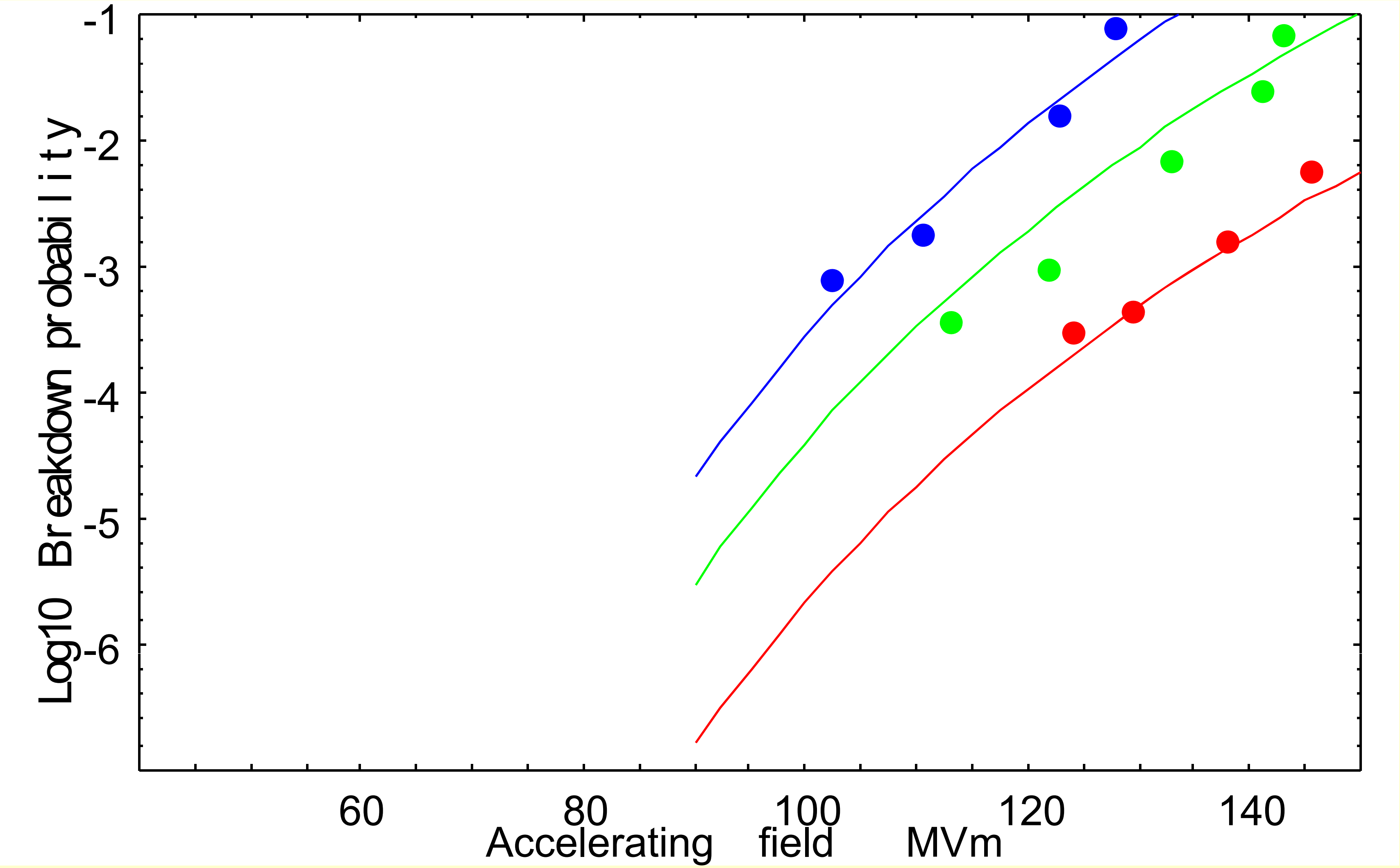
- The gas molecules that get ionised (and allow me this far-fetched assumption!) are indeed the metal vapours created at the tip of the emitters, because of Joule heating by the F-N current.
- It is very difficult to use the full heating model seen before. I made the very crude assumption that the temperature grows with $(\text{time})^{0.5}$ and scales inversely with the $(\text{thermal conductivity})^{0.5}$.
- The vapour pressure is then given by:

$$p = p_0 \exp(\frac{-H_0}{RT})$$

- Where H_0 is the heat of vaporisation and R the gas constant. p_0 is a normalisation factor, there is a ratio of approximately $10^{\wedge 2.5}$ between Mo and Cu

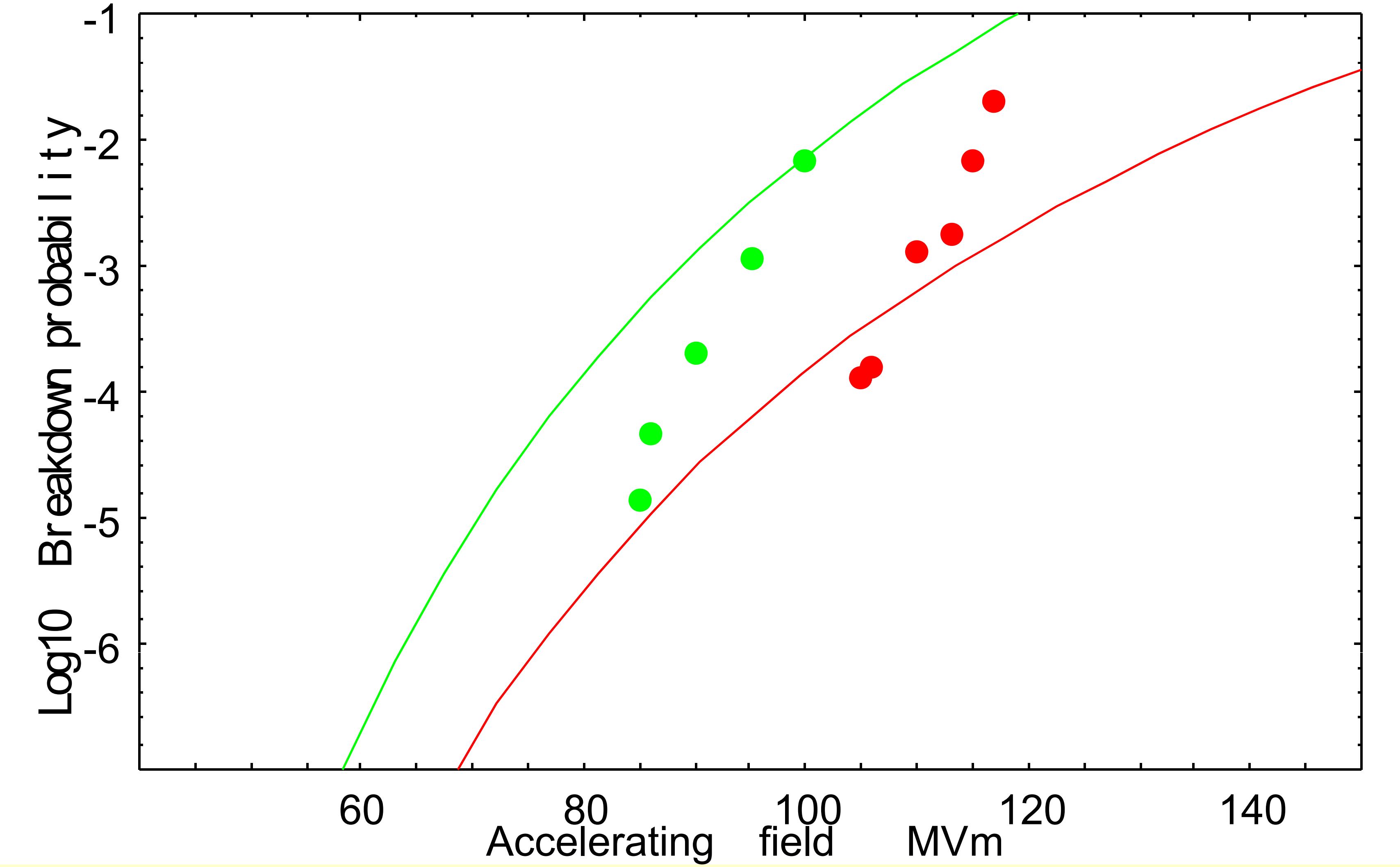
Fit to Mo data, 30 GHz circular iris

- β = 30, k = 138 $\mathrm{Wm^{-1}K^{-1}}$, p_0 = 10^{14.5} mbar, H_0 = 598 kJ/mol

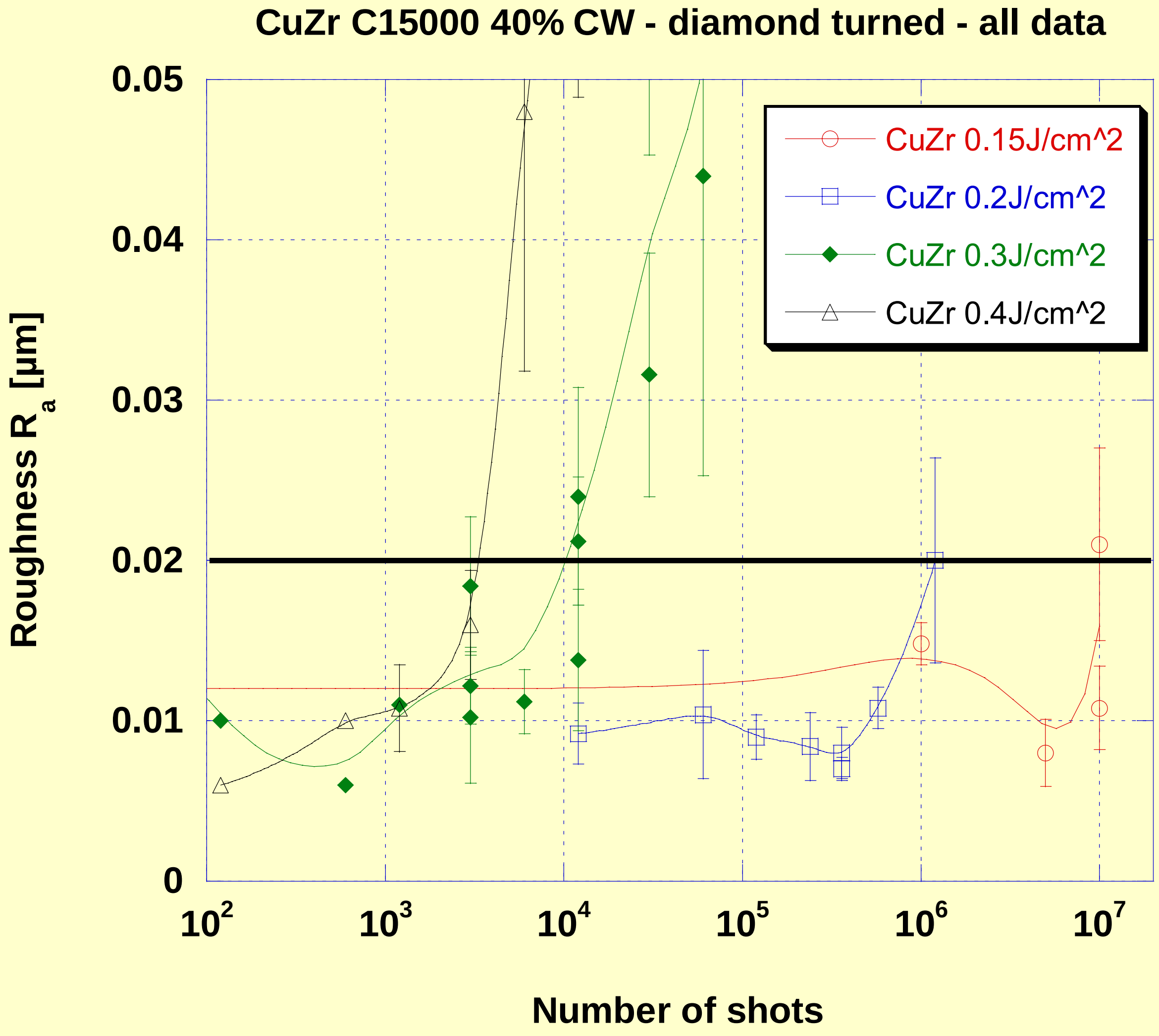


Keeping the same fit parameters and comparing to Cu data, 30 GHz

- $\beta = 45$, k = 400 $Wm^{-1}K^{-1}$, $p_0 = 10^{12}$ mbar, H_0 = 300 kJ/mol.



CuZr – illustration of laser data



The value of 0.02 µm has been chosen as the first measurable departure from the reference surface (flat, diamond turned).

This is thought being the most important phenomenon. The further increase of roughness is only crack propagation.

All fatigue data