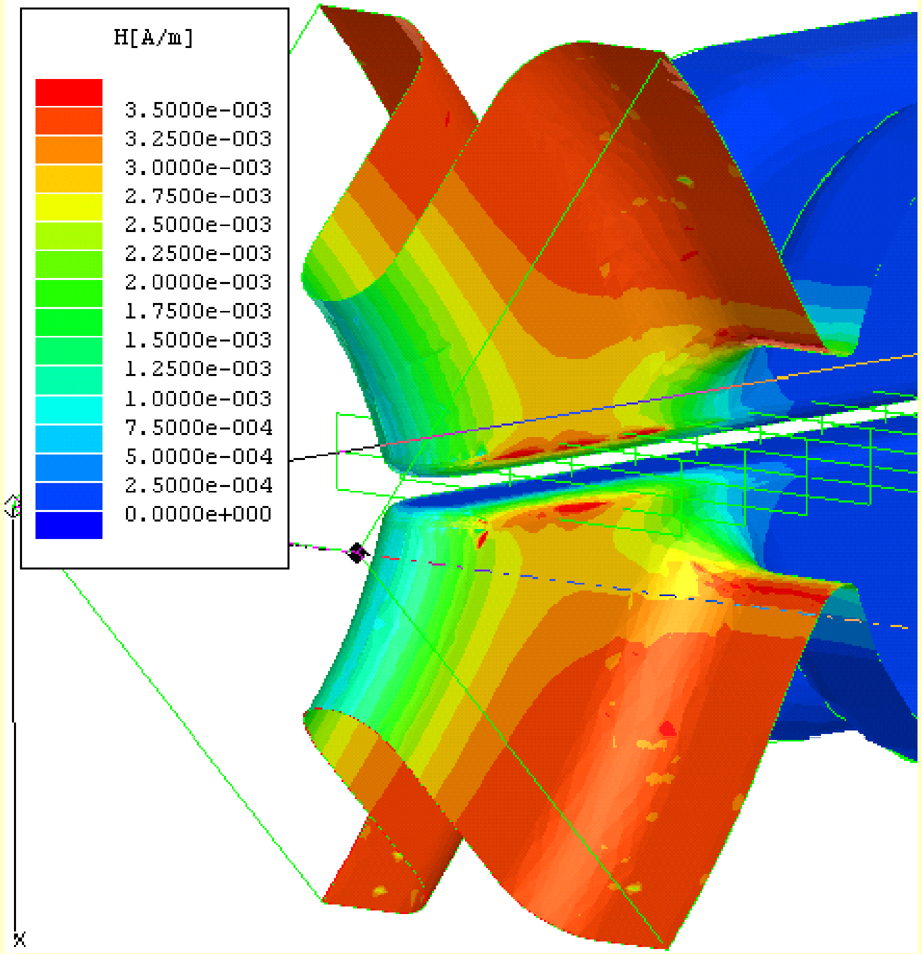
DC breakdown testing and thermal fatigue

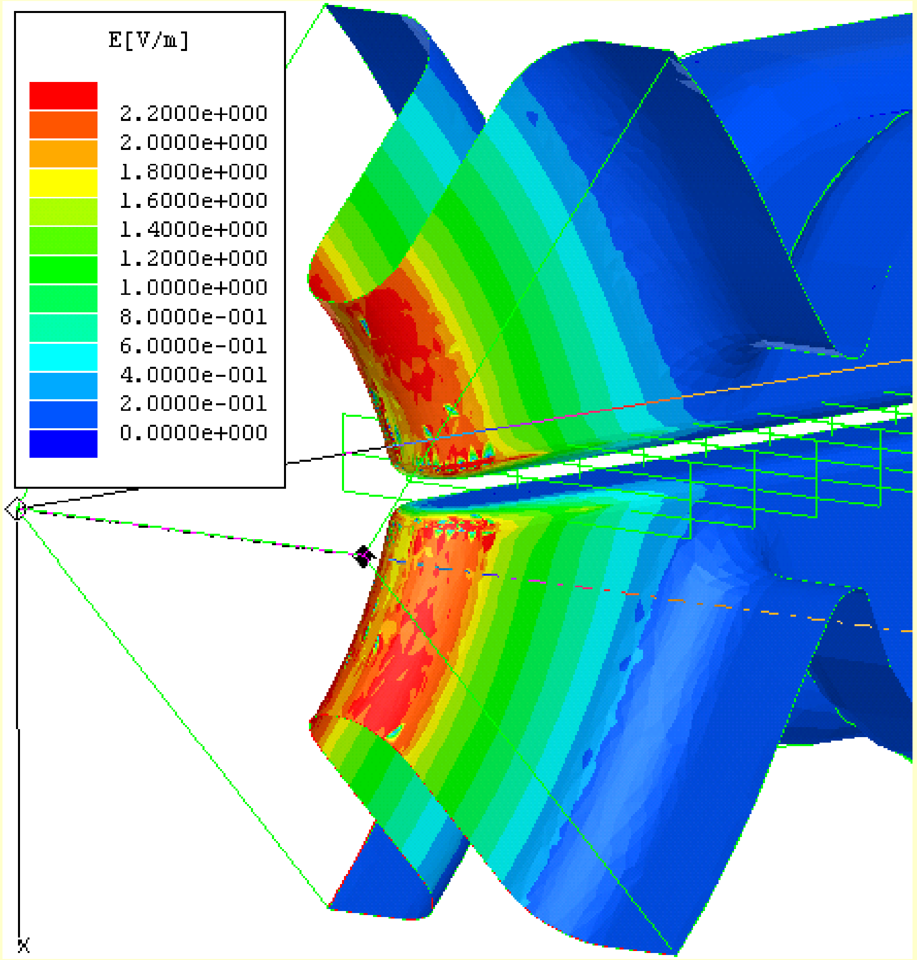
Surface treatments

HDS cell design

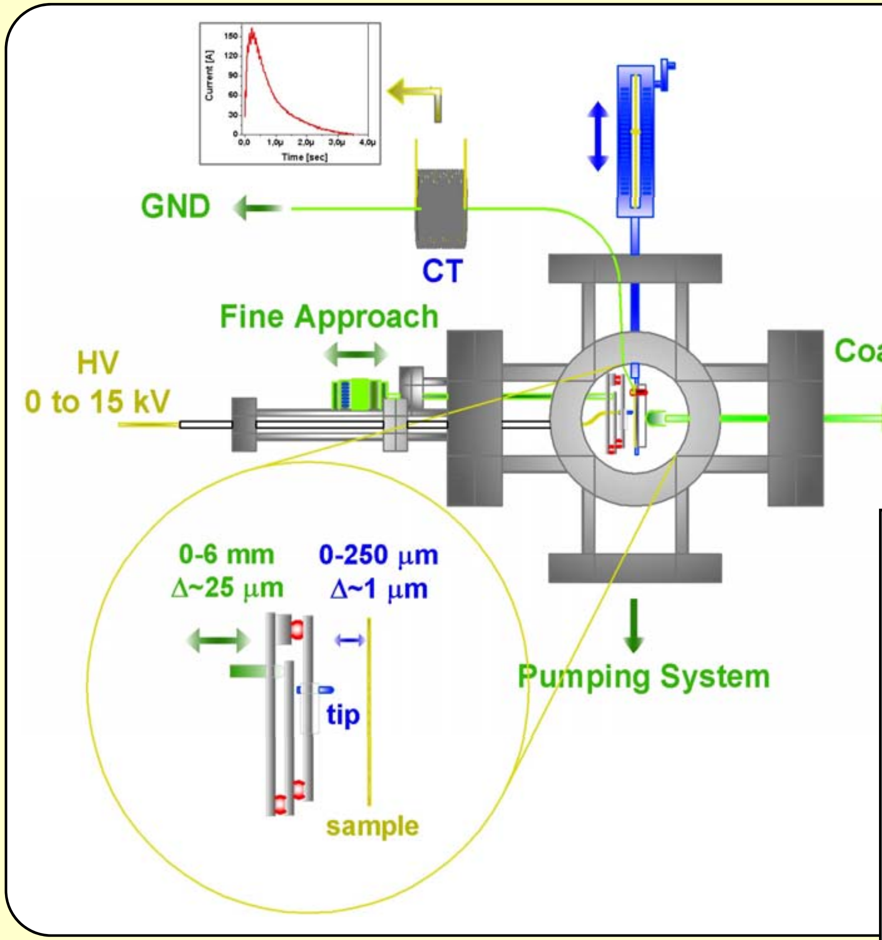
Surface magnetic field



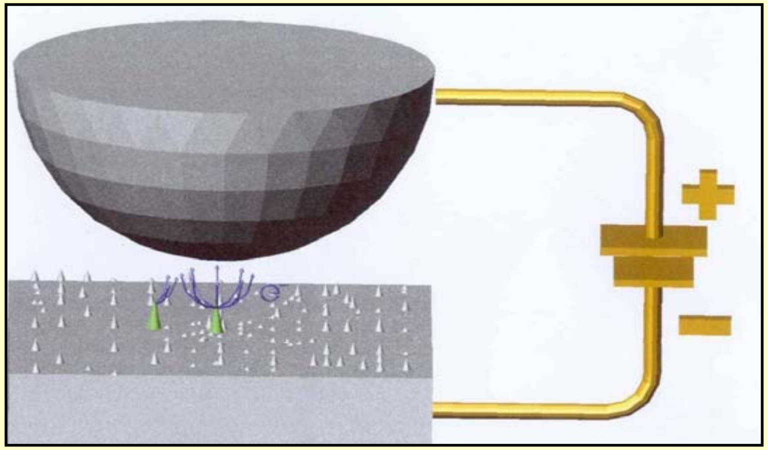
Surface electric field



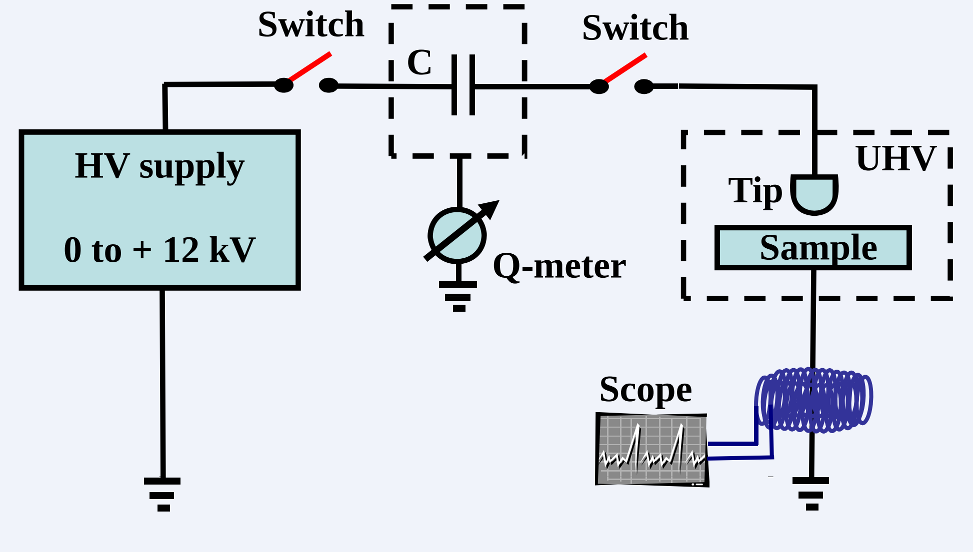
DC spark testing experimental setup



Sphere / Plane geometry

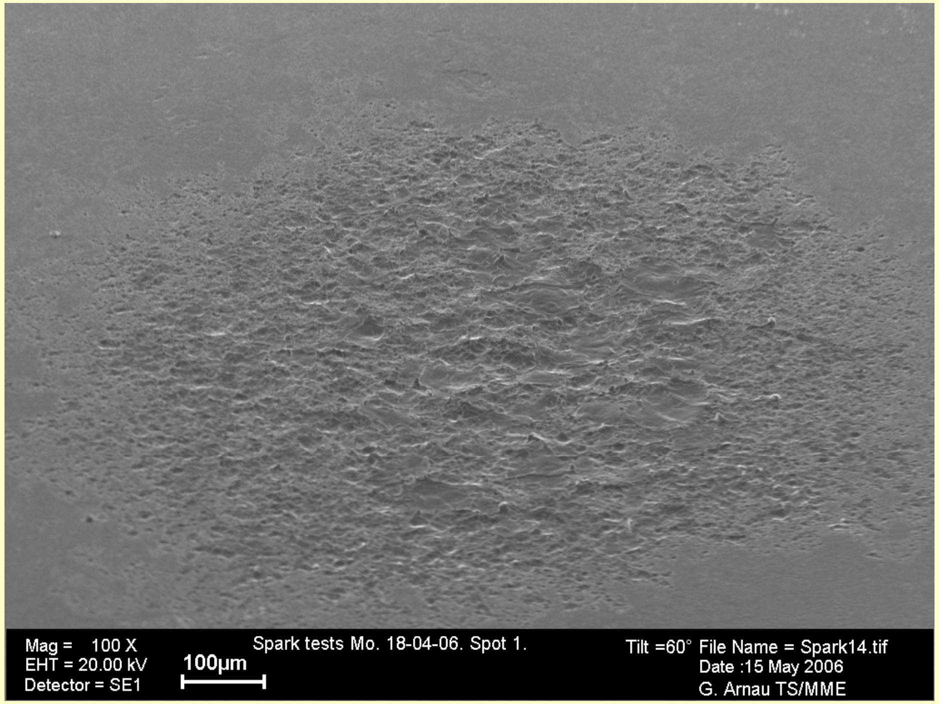


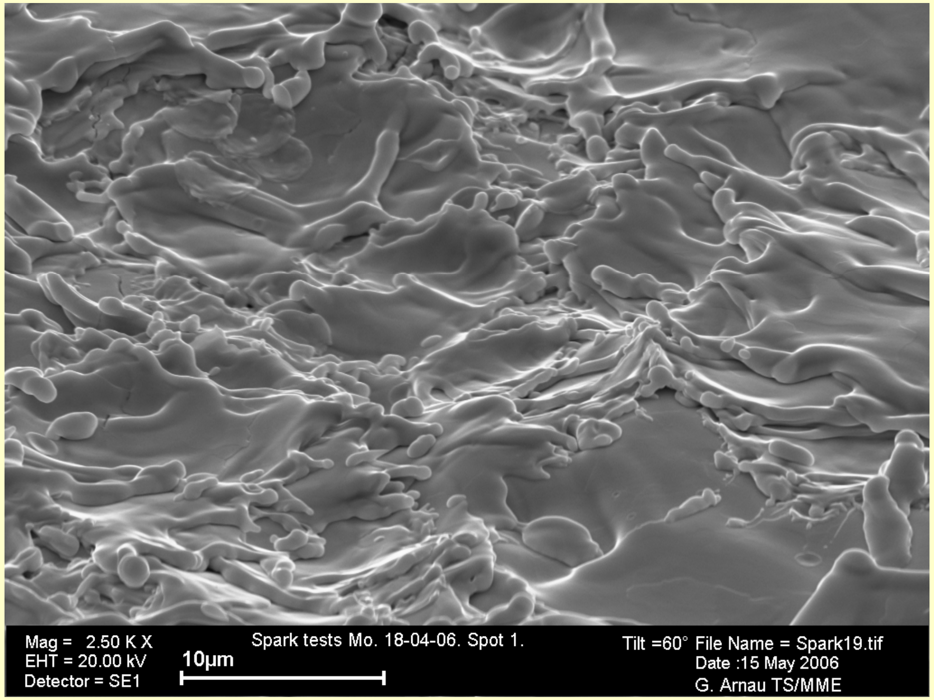
Breakdown Measurements



From: T. Ramsvik

DC spark test – surface damage





DC spark test: aims

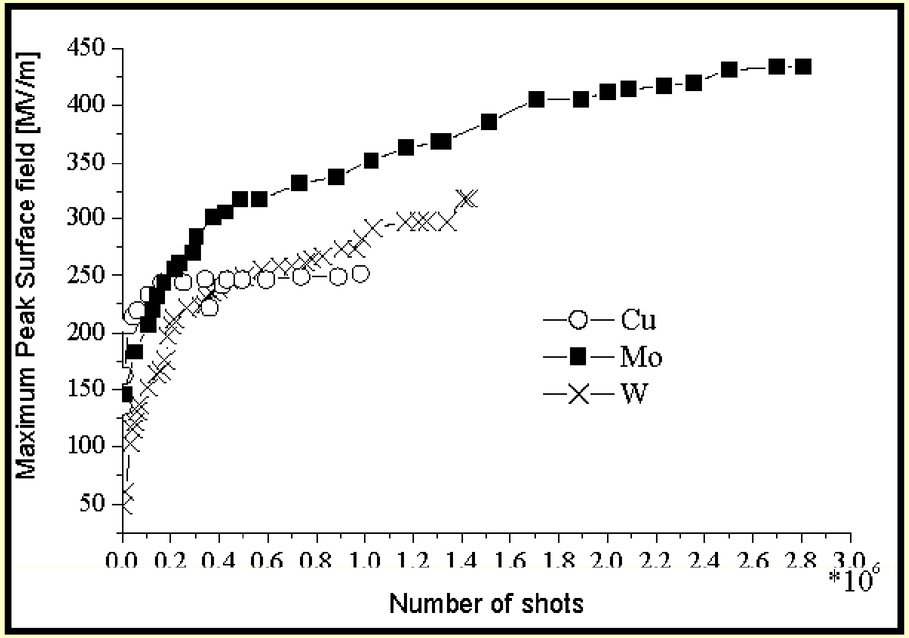
Past - looking for the highest gradient:

- (Prove that DC breakdown testing was relevant for RF application)
- Identify materials having a higher breakdown field than copper -> molybdenum
- Identify treatments to increase the conditioning rate of molybdenum -> heat treatment
- Identify vacuum conditions that allow attaining the full breakdown field -> results available

Future - looking for the lowest breakdown rate at the new CLIC parameters:

- DC breakdown rate on different materials
- Identify the necessary surface treatments depending on the chosen fabrication technology, focussing on copper (see next presentation)

Comparison DC - RF

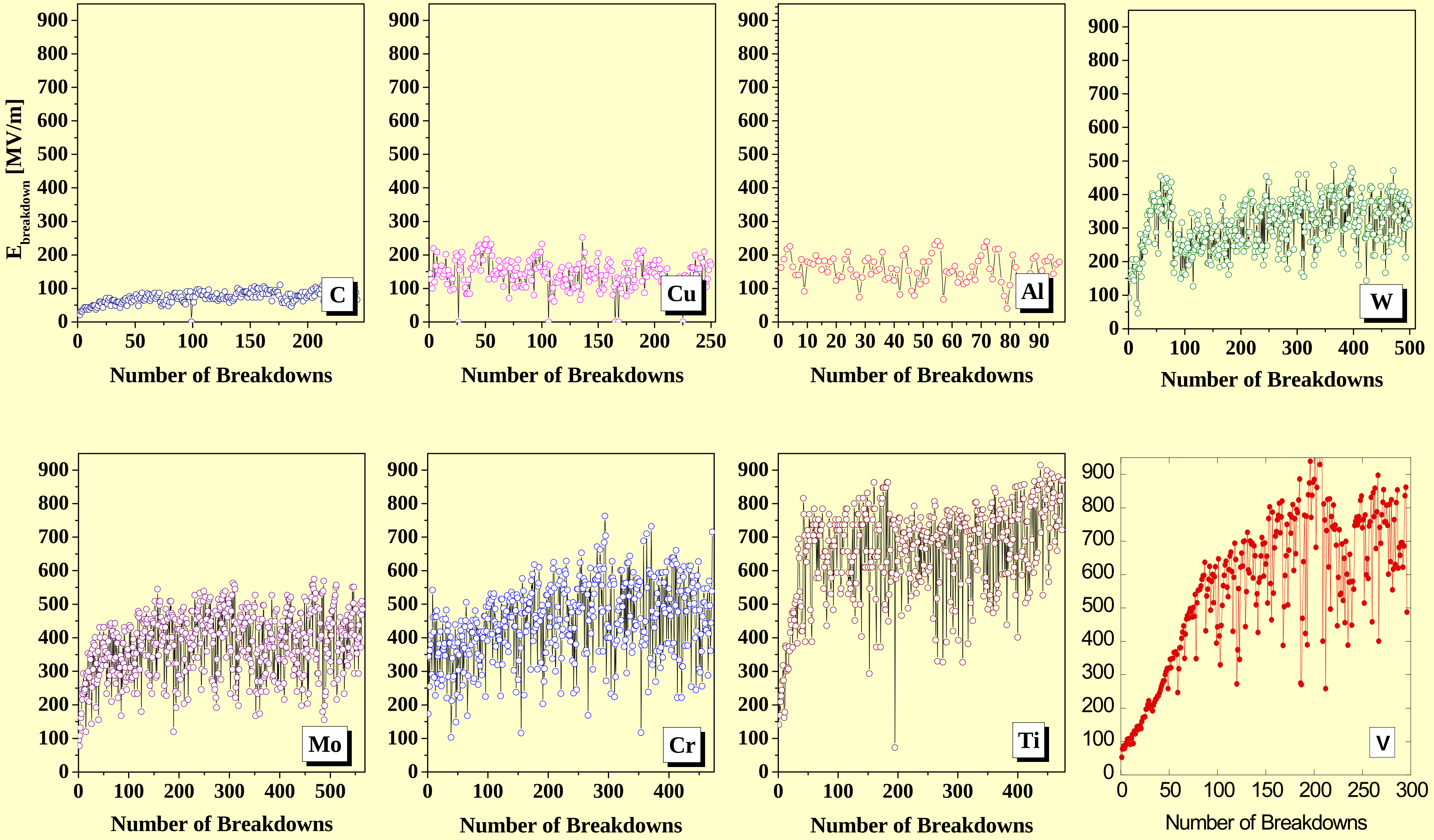


	E^{sat}_{breakd} (DC) [MV/m]	Max. surface field in RF [MV/m]
Cu	164±30	260
W	313±47	340
Mo	438±32	420

- ***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.***

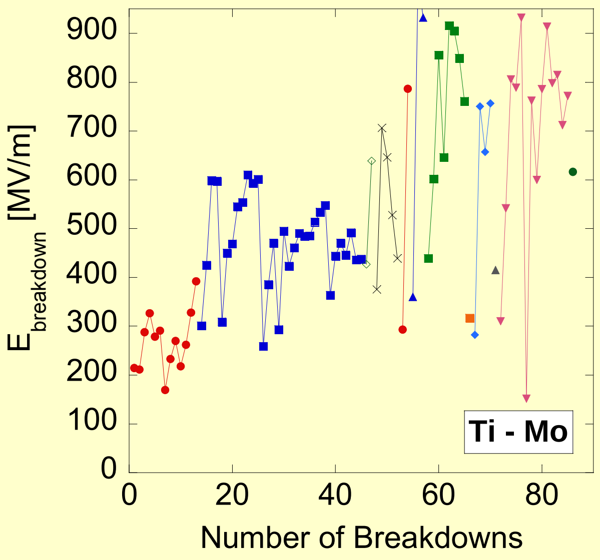
From: T. Ramsvik

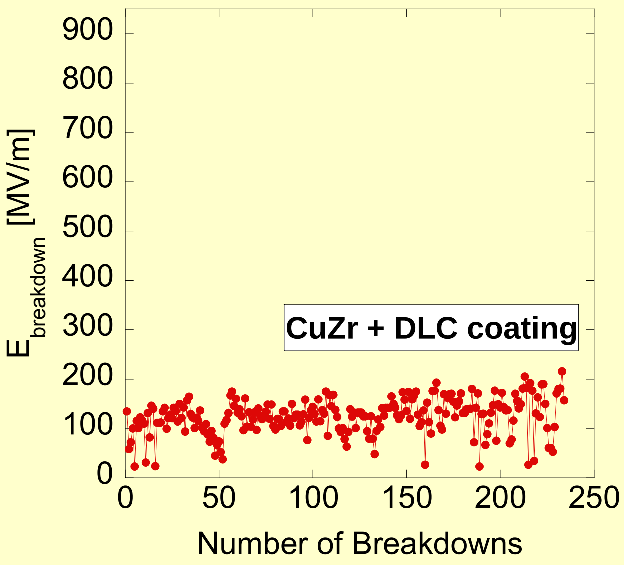
Typical conditioning curves – pure metals

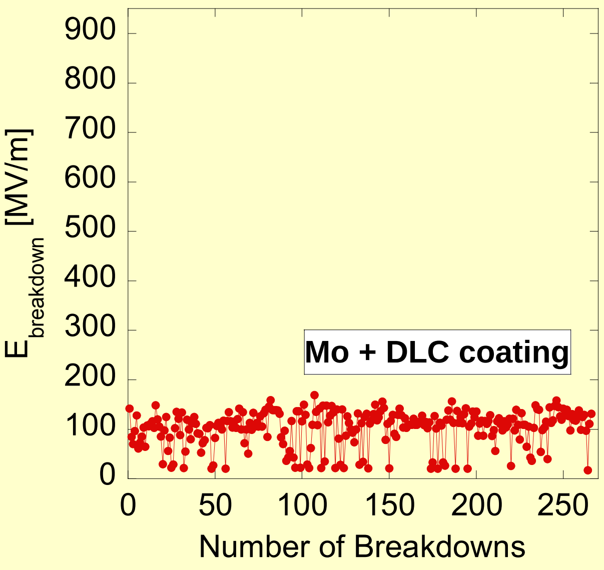


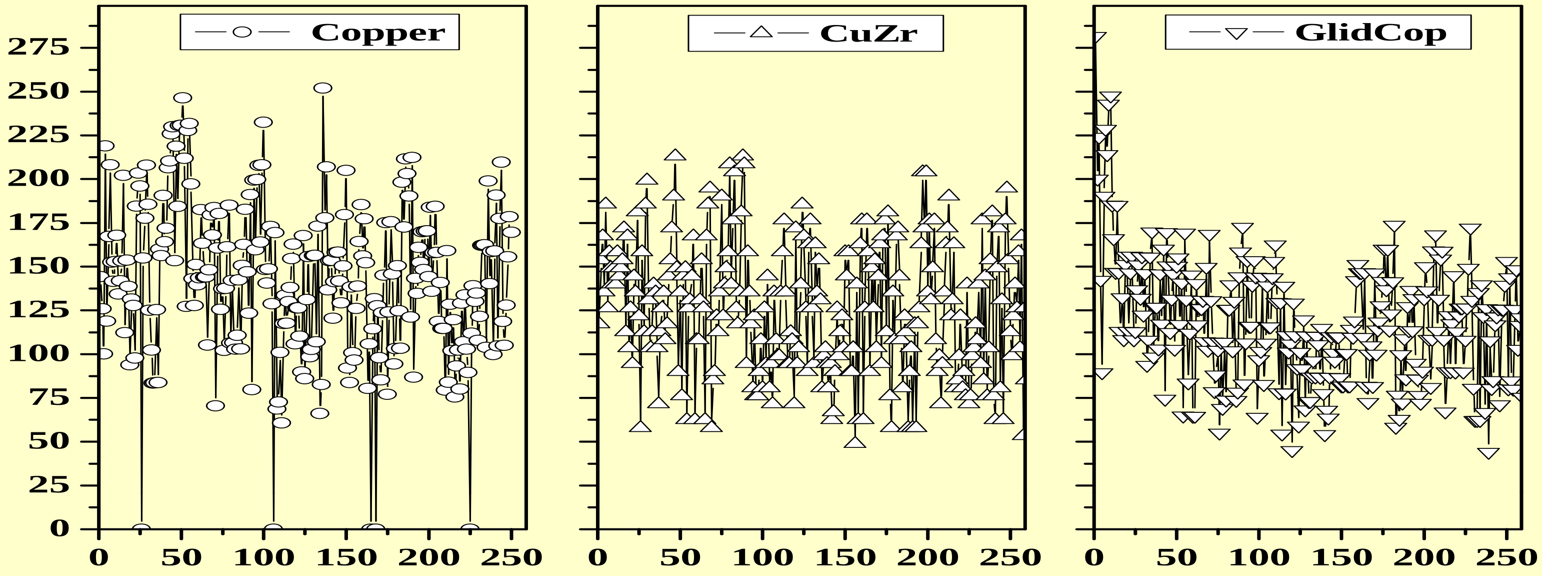
From: T. Ramsvik, A. Descoeudres

Typical conditioning curves – more exotic









From: T. Ramsvik, A. Descoeudres

New materials

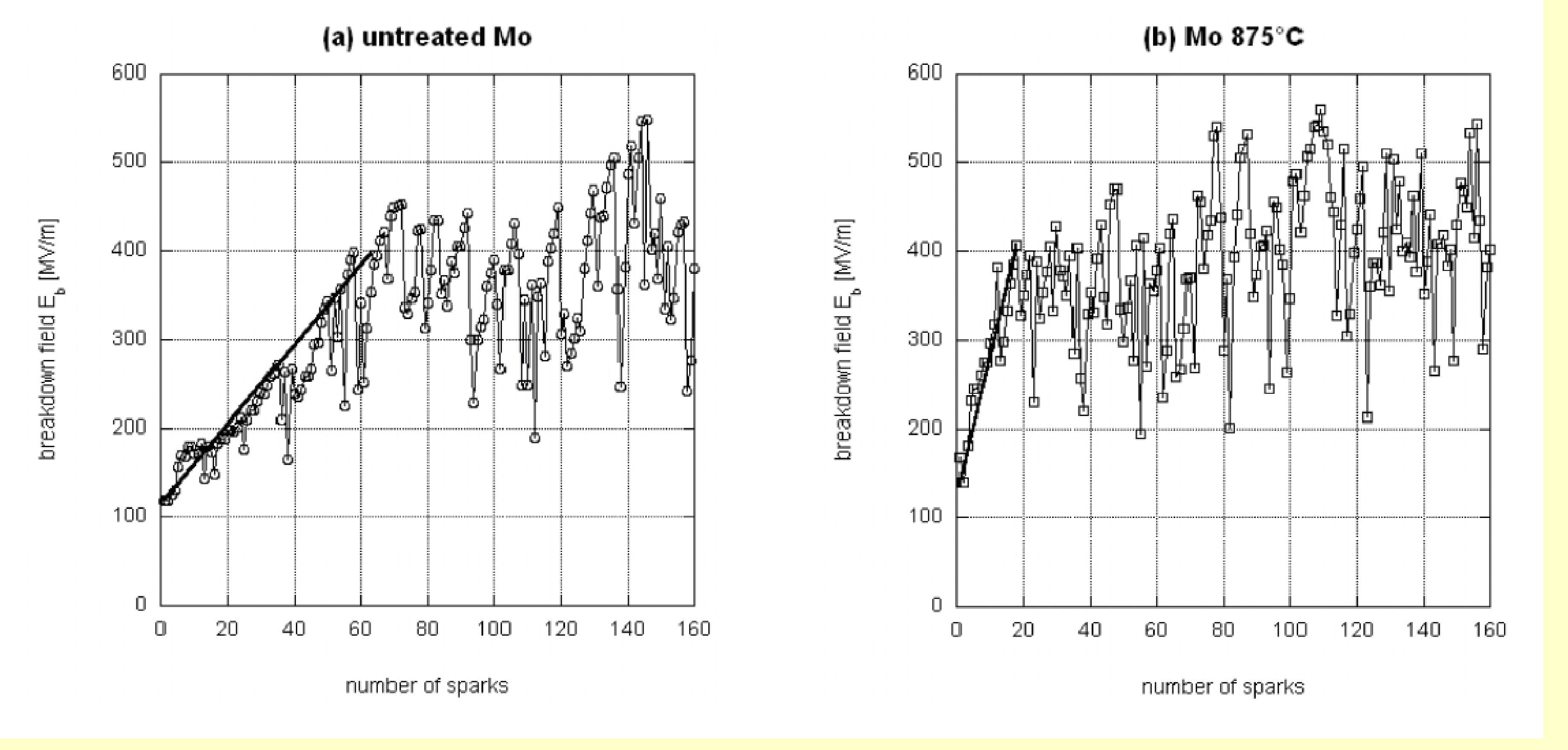
- The guidelines that have led to the choice of refractory metals as new candidate materials for the high-field regions are the high melting point, the low vapour pressure

- Experimental evidence (either in DC or RF) indicates that these criteria are not sufficient. 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

- New materials alone are useless without a strategy for bimetal fabrication.

Reducing conditioning time: heating of Mo

- We have strong evidence that heating is beneficial for the conditioning rate of molybdenum, and that this is due to the reduction of surface oxides.
- Tests showed that Mo can be re-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 molybdenum HDS structures

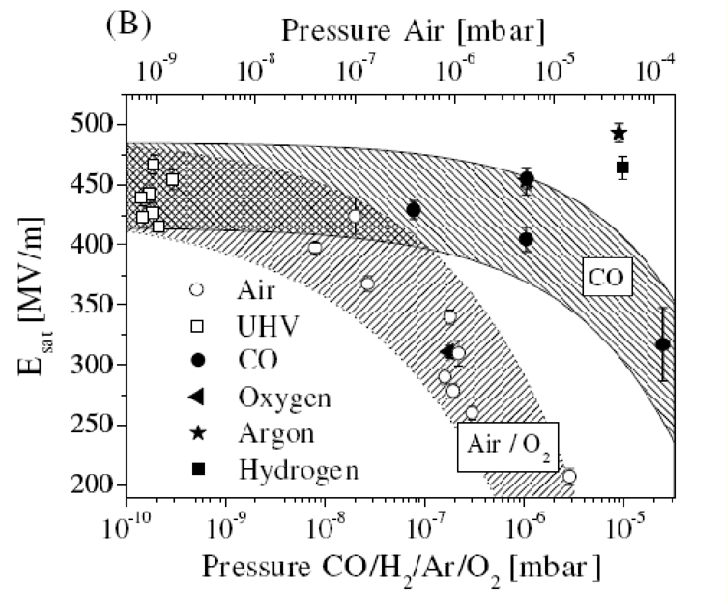


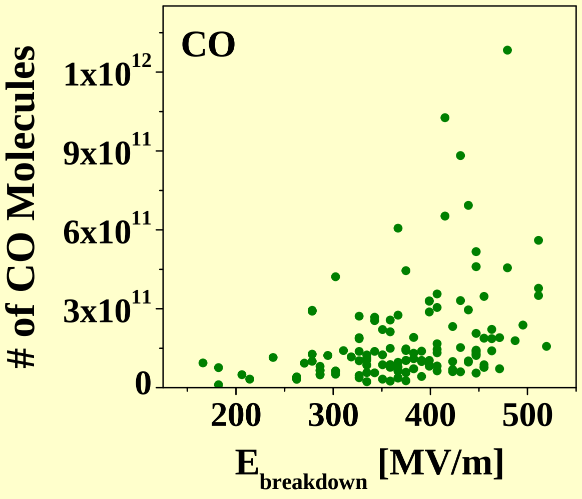
From: A. Descoeudres

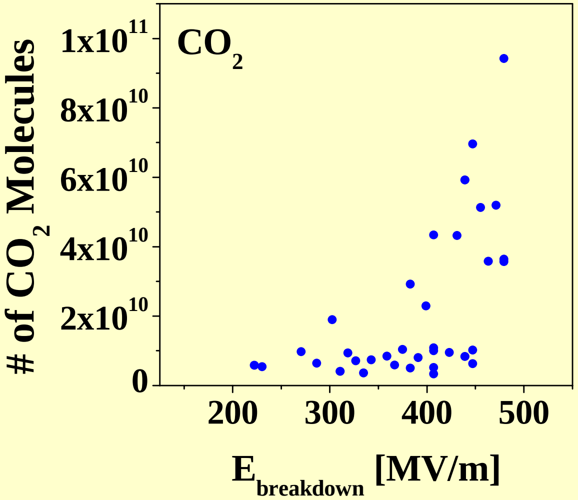
Gas release (Mo case)

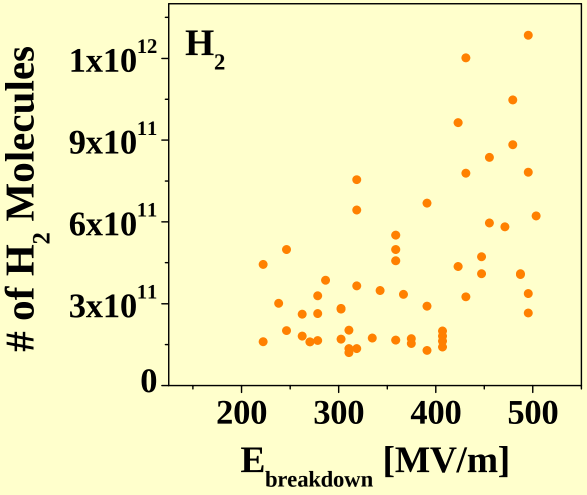
Added gases in the vacuum chamber results in reduced breakdown limit.

In CLIC structures there might be gas released from previous breakdowns and not sufficiently evacuated.
First data (in particular for Mo) are available for the calculation of the vacuum system

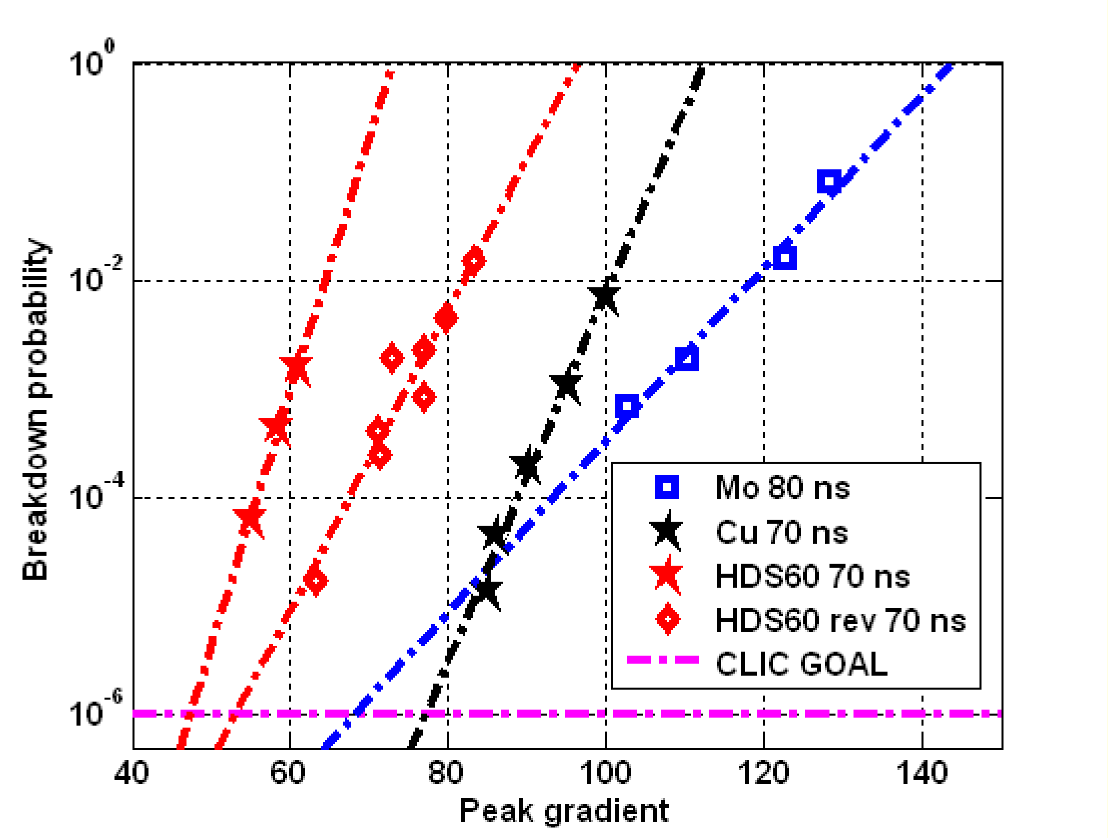




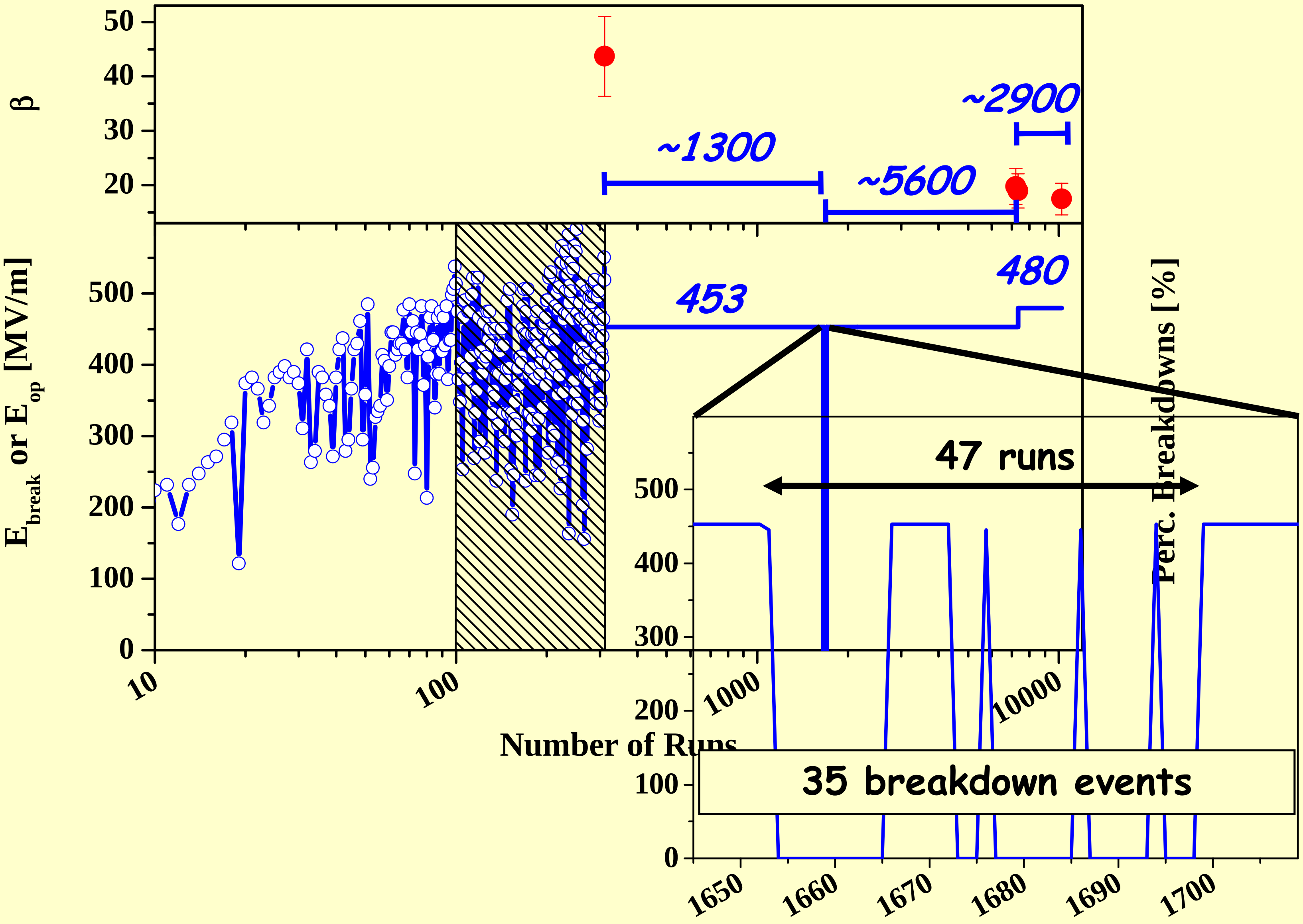




Breakdown rate: RF



Breakdown rate: DC



Breakdown rate: future

- A new DC spark system is being built (~2 months)
- First experiments will be aimed at proving that the results in DC are relevant for the RF breakdown rate studies (~3 months):
  - Log(p) dependence on applied field
  - Different slopes of Cu and Mo
- Then the experiments should be aimed at studying the effect of surface preparation on breakdown rate (~2008) (see next presentation)

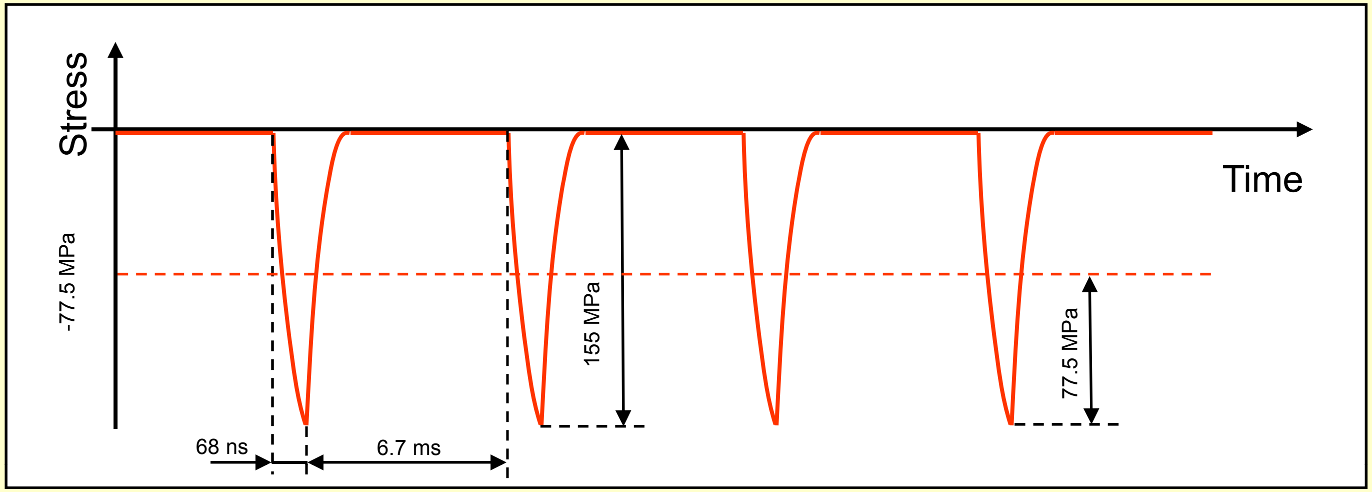
- Two theoretical models are the guidelines for the understanding:
  - Field emission + ionisation of metallic vapours produced by Joule heating
  - Fatigue related to thermal stress due to Joule heating

- Manpower:
  - 1 PostDoc Fellow (Antoine Descoeudres, started 1.1.2007)
  - 1 Technical Student (Yngve Levinsen, started 1.7.2007)

The problem of fatigue

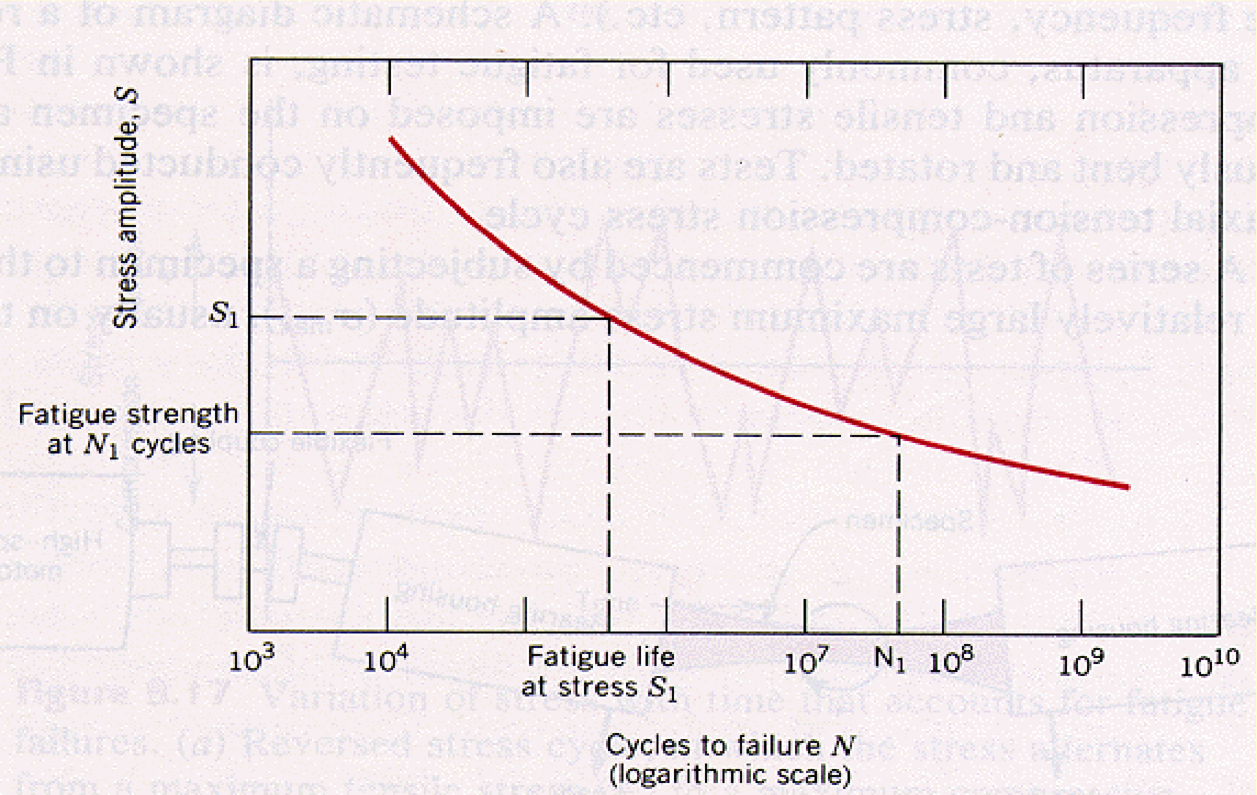
CLIC number of cycles (old parameters):

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

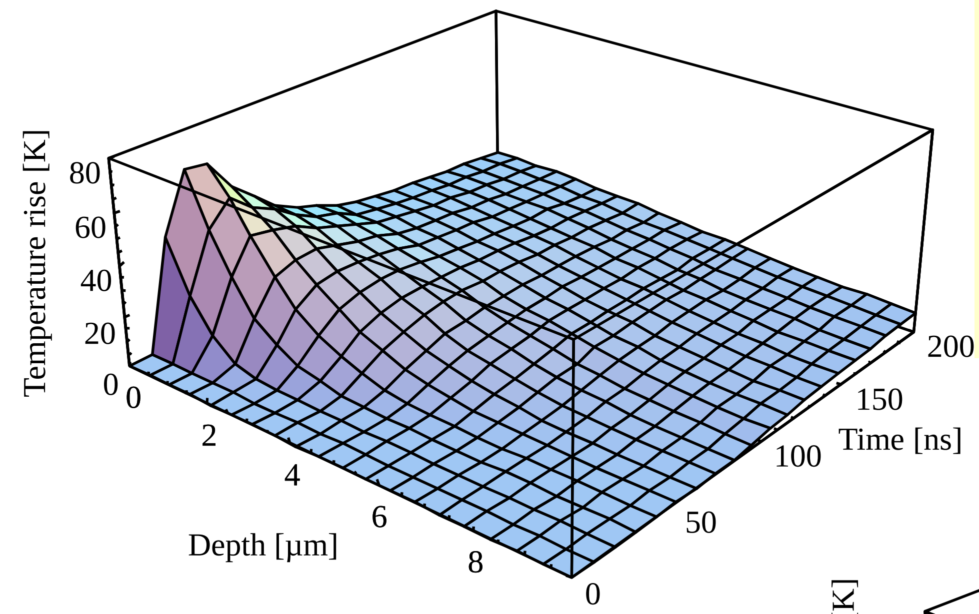


From: S. Heikkinen

Fatigue – Wohler curve

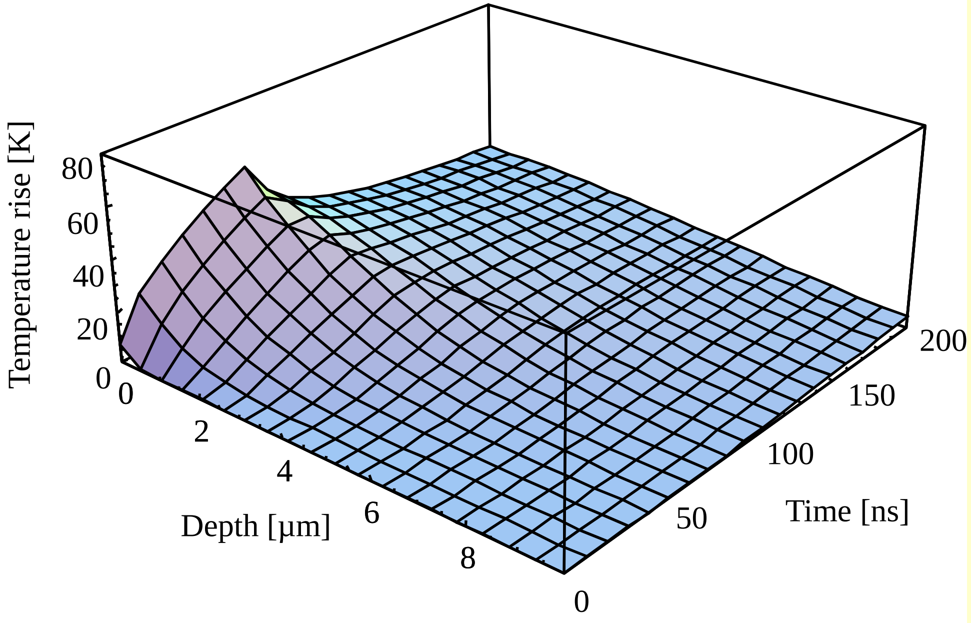


Comparison of heating profiles



← Laser pulse

RF pulse ↓

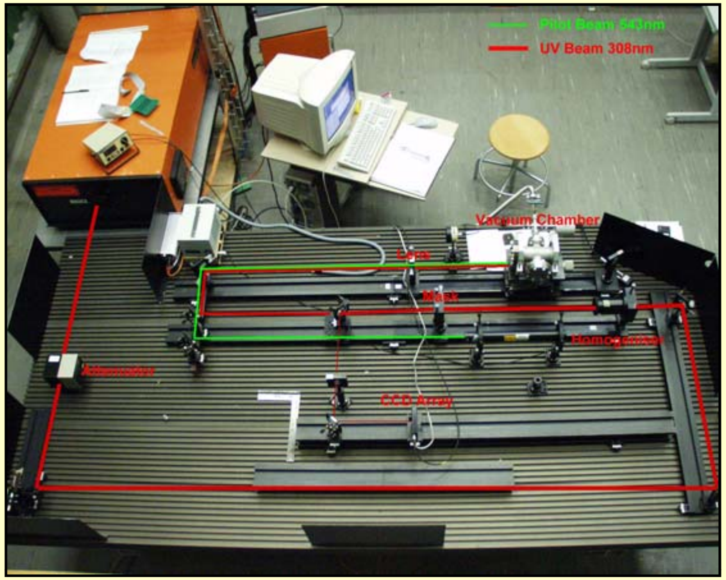


The pulse shapes correspond.
In particular the temperature profile at the peak is very similar, and results in similar stress level.

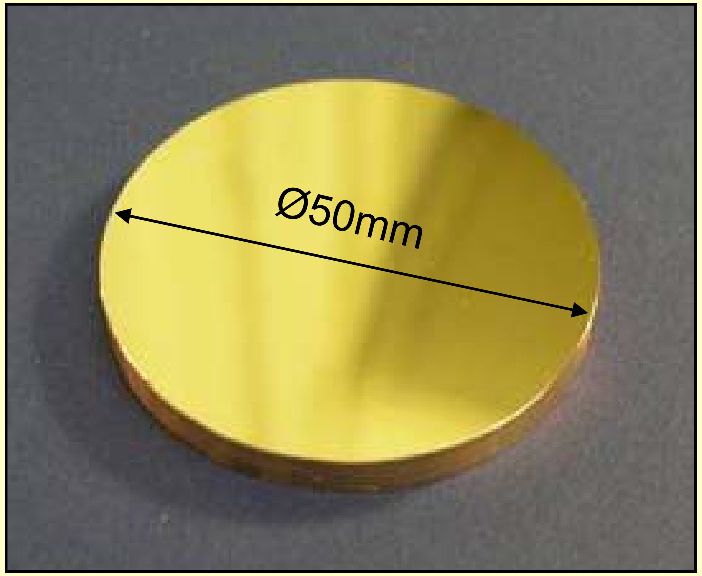
$$\sigma = \frac{\Delta T * E * \lambda}{(1-\nu)}$$

Laser 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.

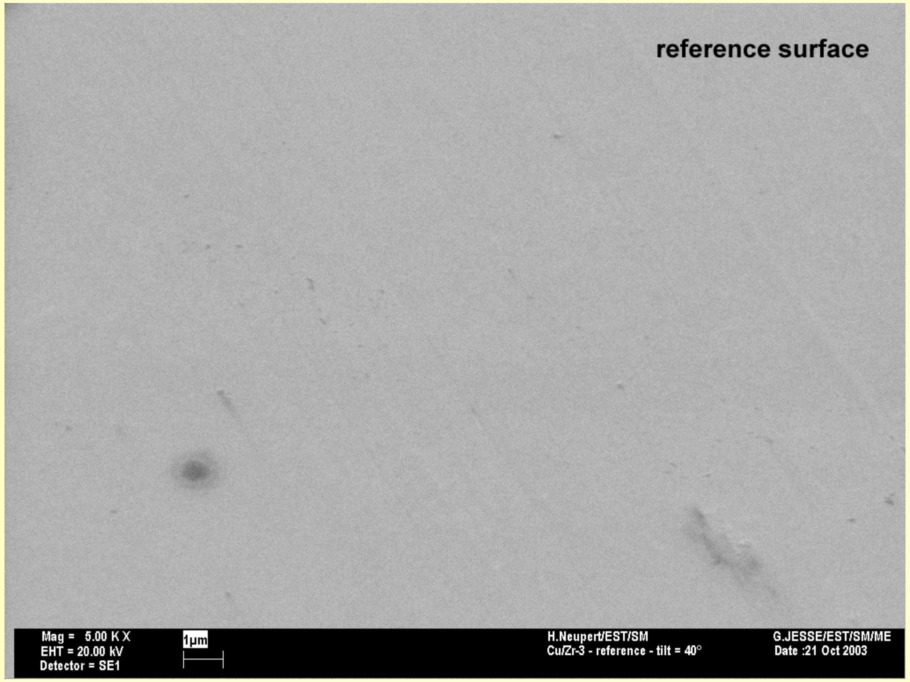


Laser test setup

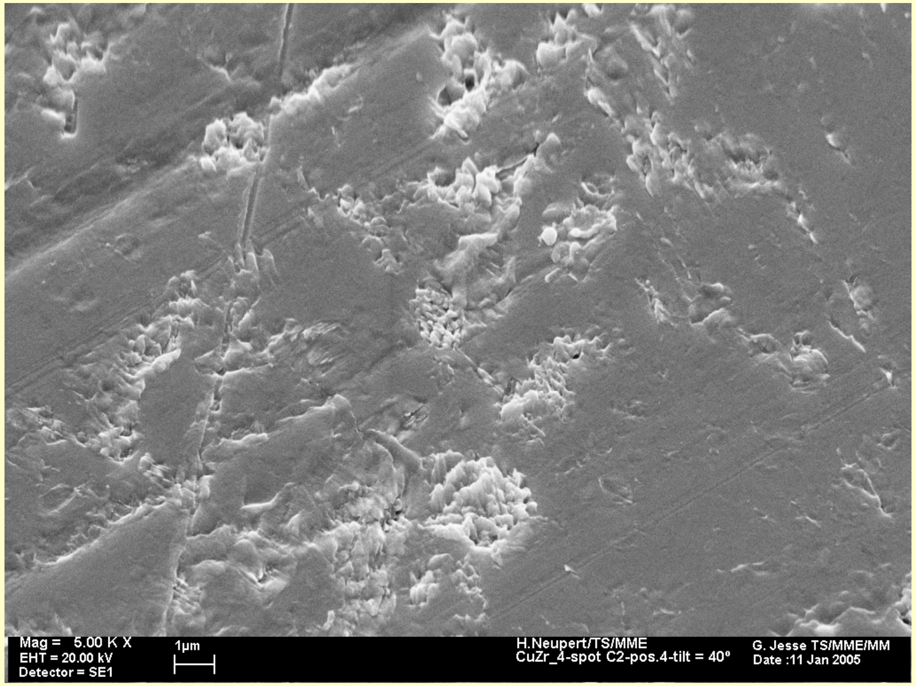


Diamond turned test sample

Laser surface damage



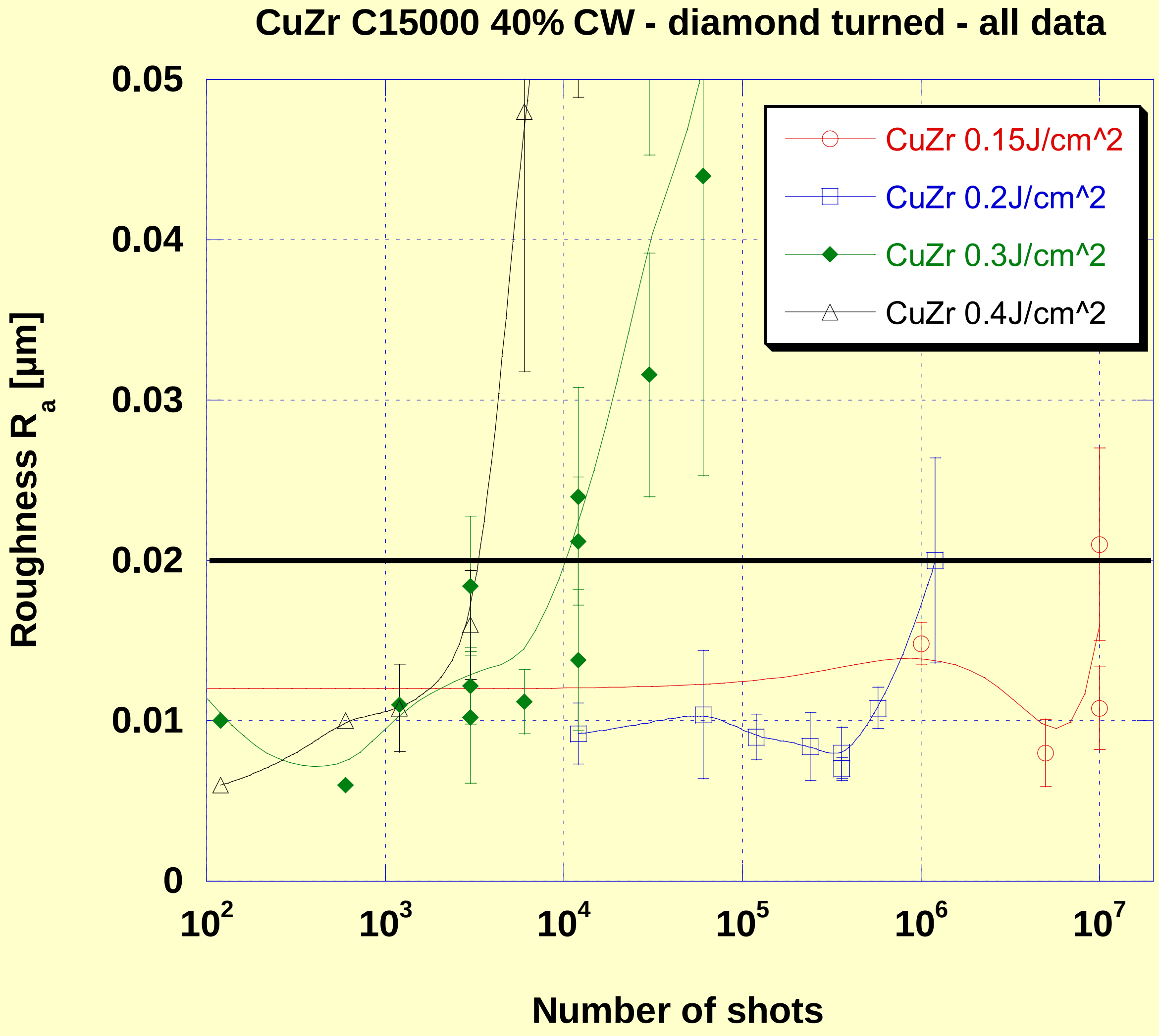
CuZr reference



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

From: G. Arnau Izquierdo

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.

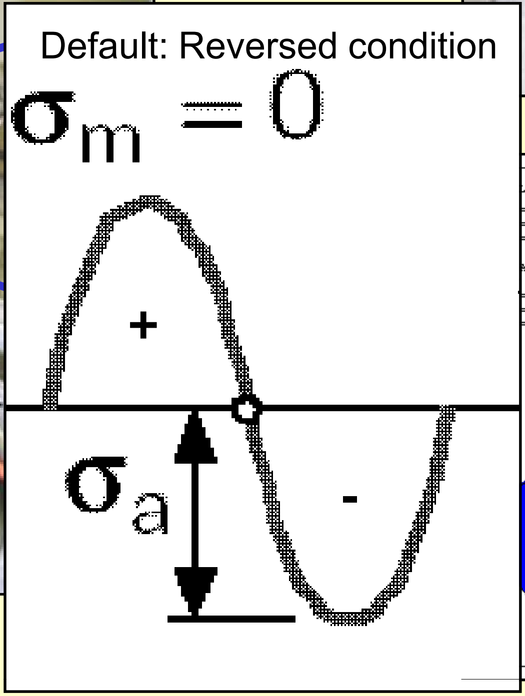
Ultrasonic fatigue testing

- **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

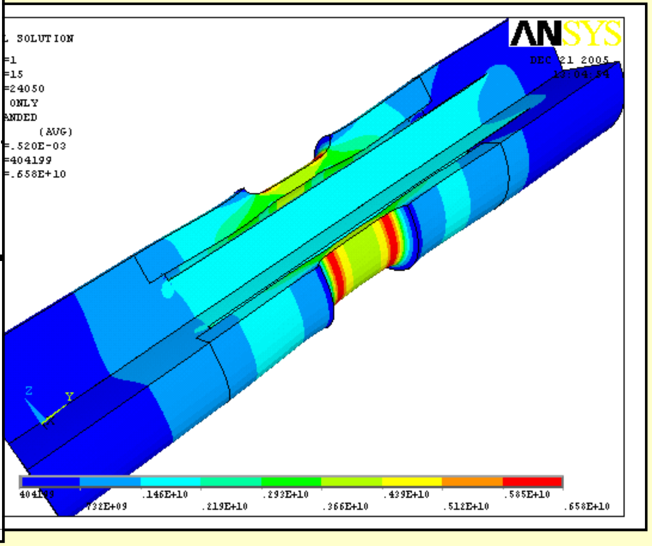
Amplitude measurement

Air Cooling



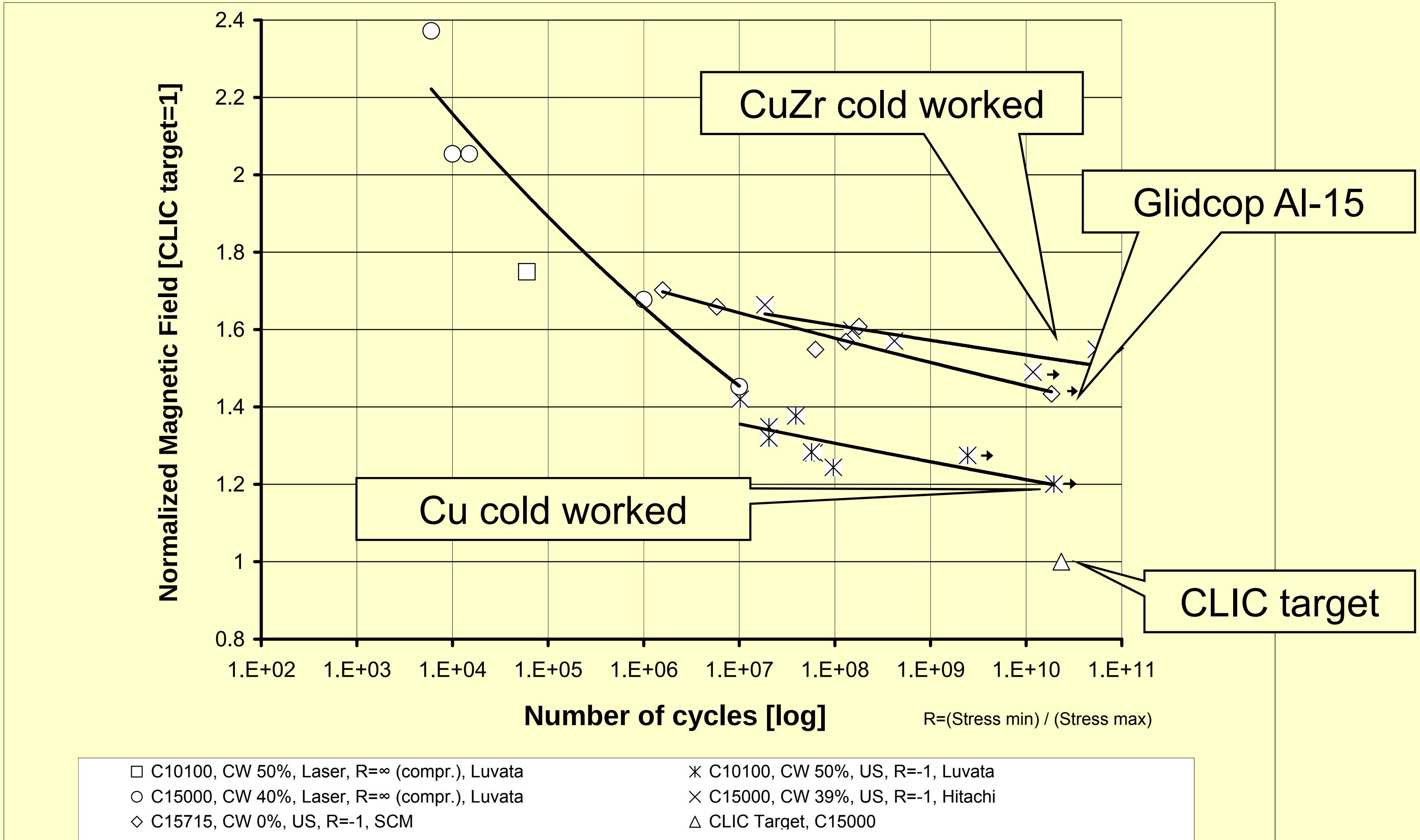
Default: Reversed condition

$\sigma_m = 0$



From: S. Heikkinen

US and laser data



CuZr cold worked

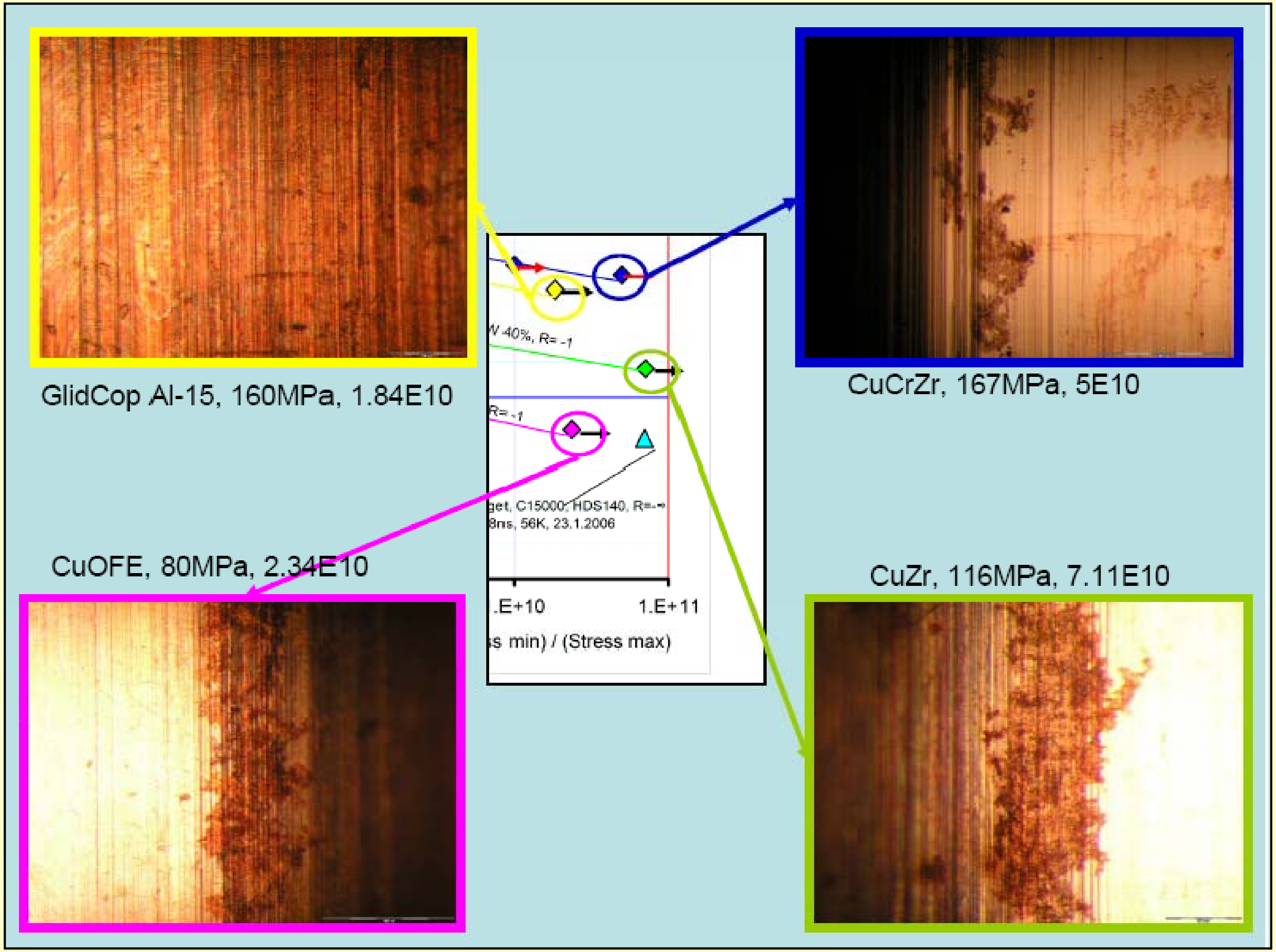
Glidcop Al-15

Cu cold worked

CLIC target

It is of extreme importance to obtain a clear RF benchmark of fatigue data

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

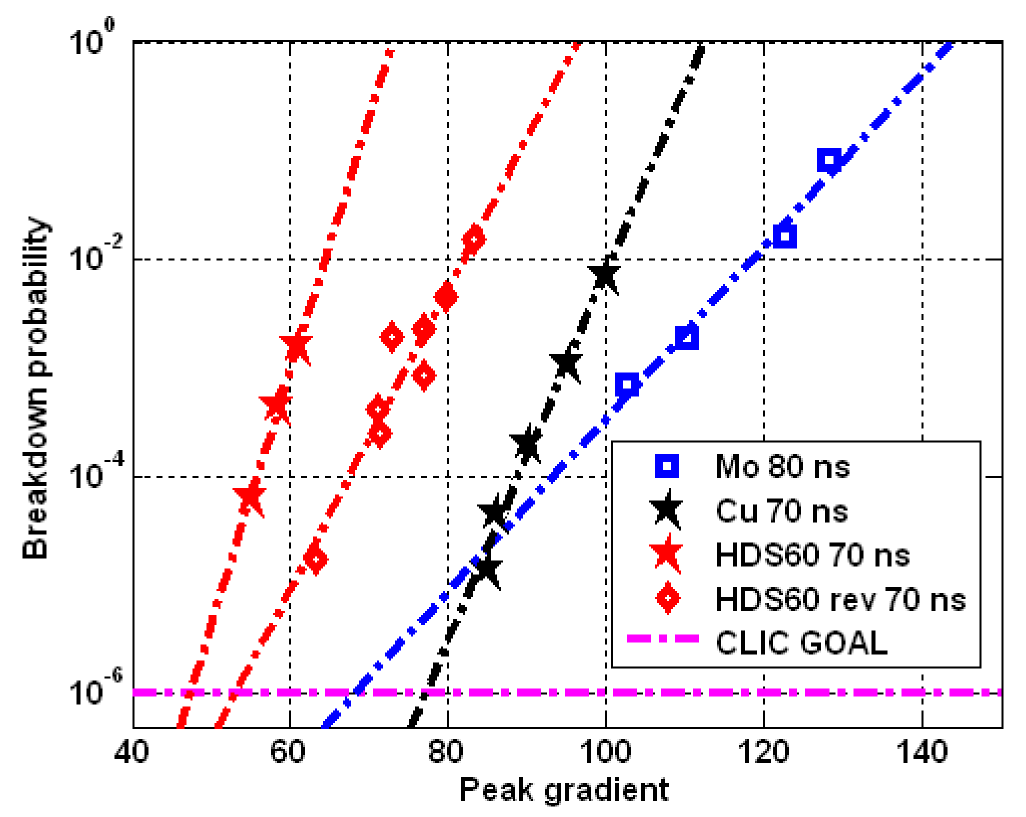
More fatigue ?

- 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:
  - A thermal treatments zeroes most of the advantage of CuZr, or the benefits from cold working
  - Surface finishing certainly has a strong influence on crack generation

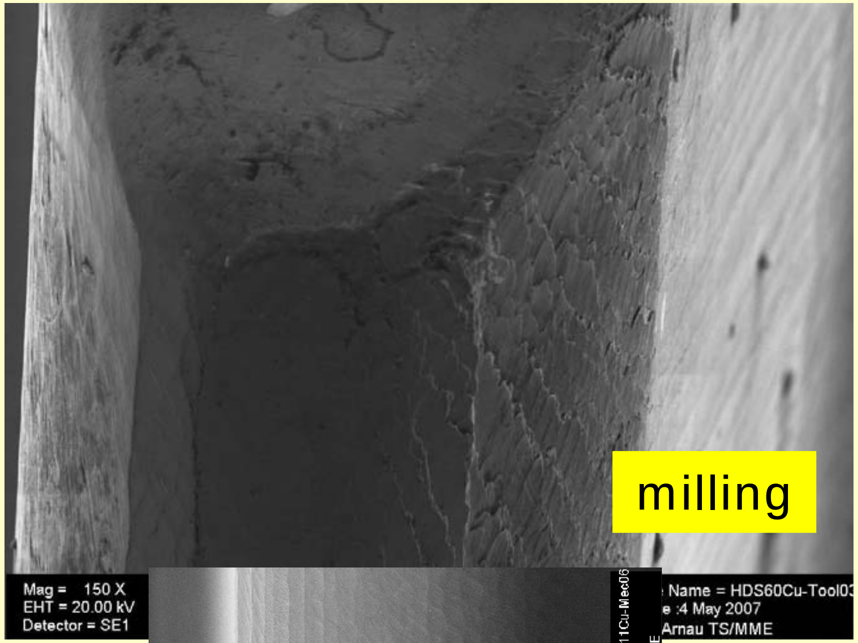
- The mechanism leading to the development of fatigue (accumulation of dislocations, formation of slip bands) is not well understood -> Stefano

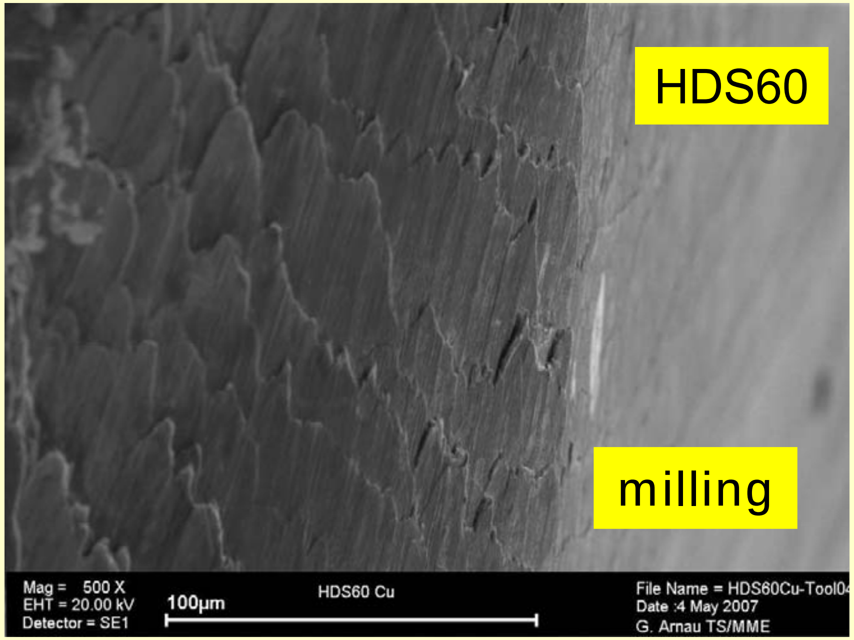
Breakdown rate: reasons for surface treatments

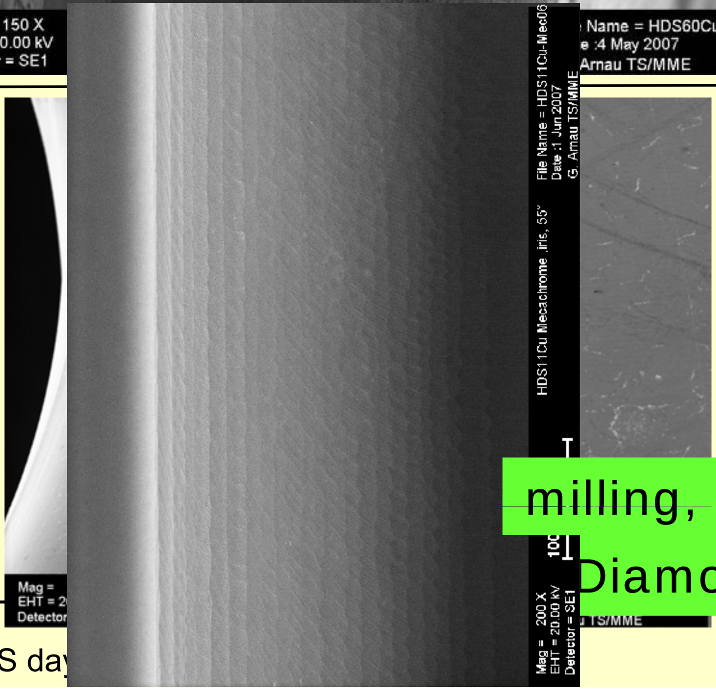


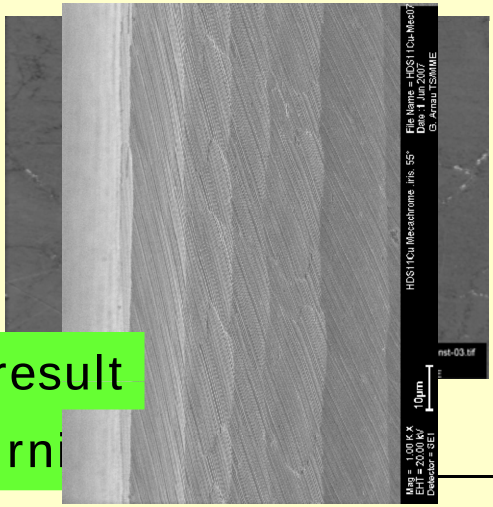
quadrant structures

Surface quality: on copper









milling, best result

Diamond turni

Possible surface treatments (mainly copper)

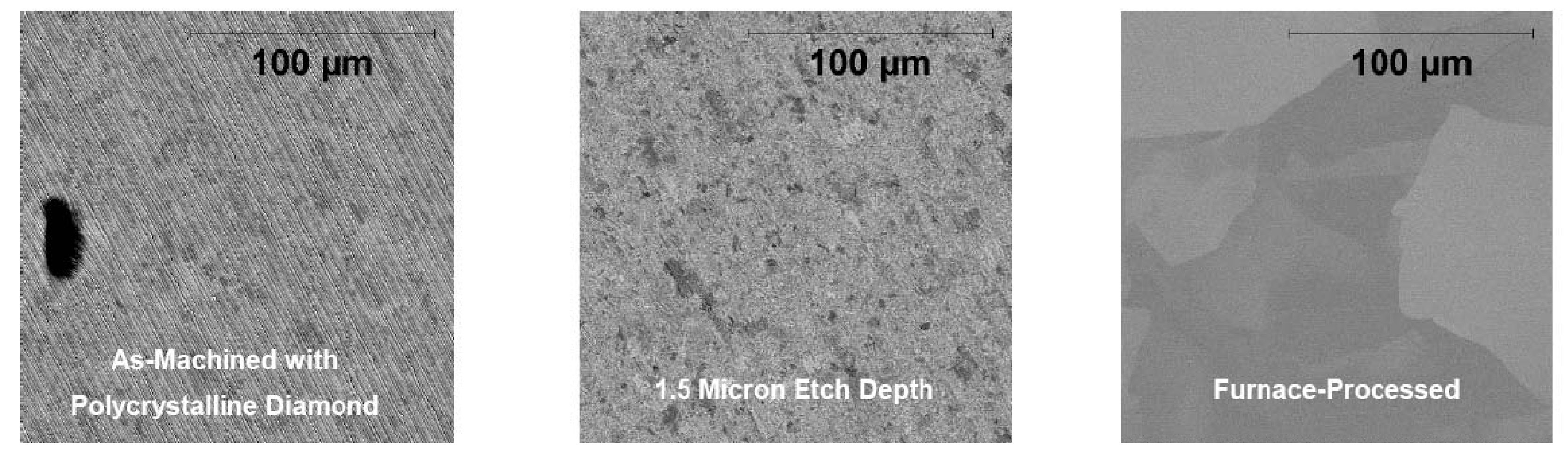
- It is necessary to identify a procedure to remove surface defects from 3D milled structures.

- SLAC applies etching + heat treatment for RF copper structures
- KEK has DC breakdown tests on heat treated copper

- At CERN we have considerable experience both in copper polishing and heat treatment.
- Suitable procedures should be identified in order to maintain the tight tolerances obtained from machining, while still improving the surface

SLAC results

- The combined 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
- It is as yet unknown whether the effects are due to changes to the oxide, to the outgassing, to topography, to cleanliness, or combined?



KEK results

KEK ->

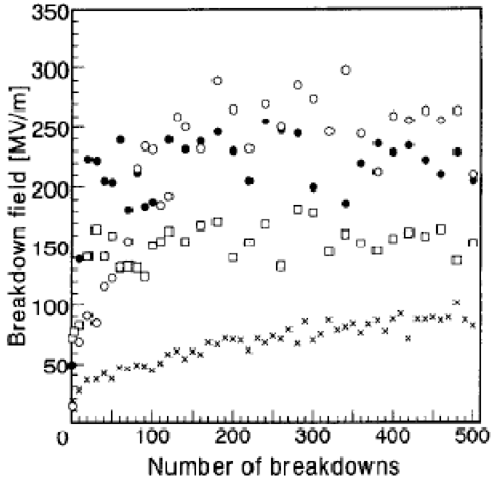


Figure 3. Breakdown properties of OFC electrodes processed by diamond turning and heat treatments. × lathing only, □ diamond turning and non-heat treatment, ● heated at 400°C, ○ heated at 700°C.

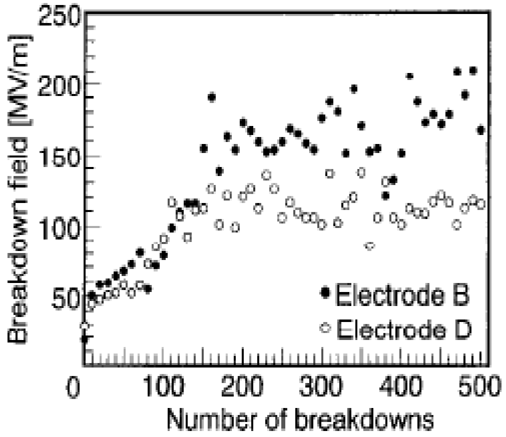
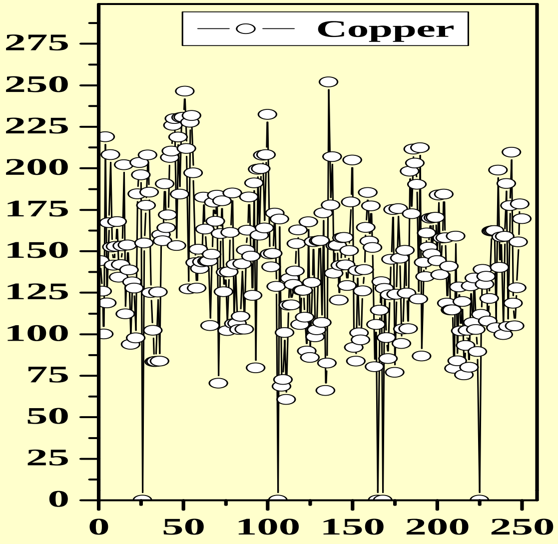
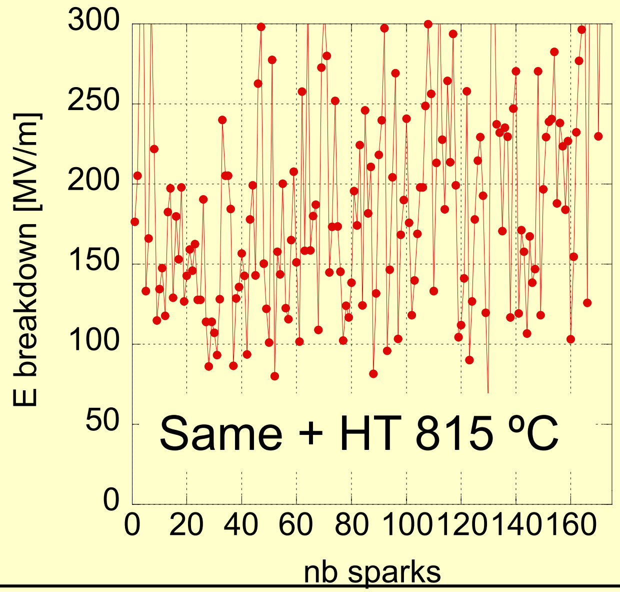


Figure 4. Breakdown properties of electrodes B (heat treated) and D (non-heat treated), which were machined from a 20% reduction material.

CERN ->





Same + HT 815 °C

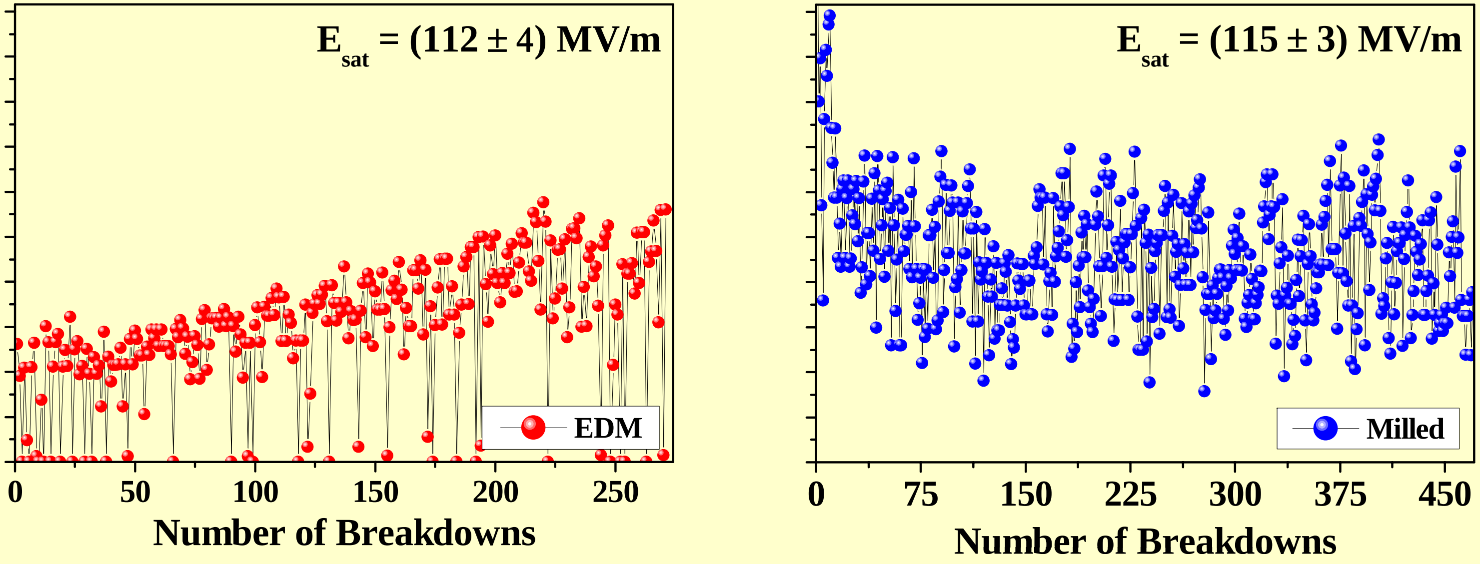
Un-verified
result
(last week!)

From: A. Descoeudres

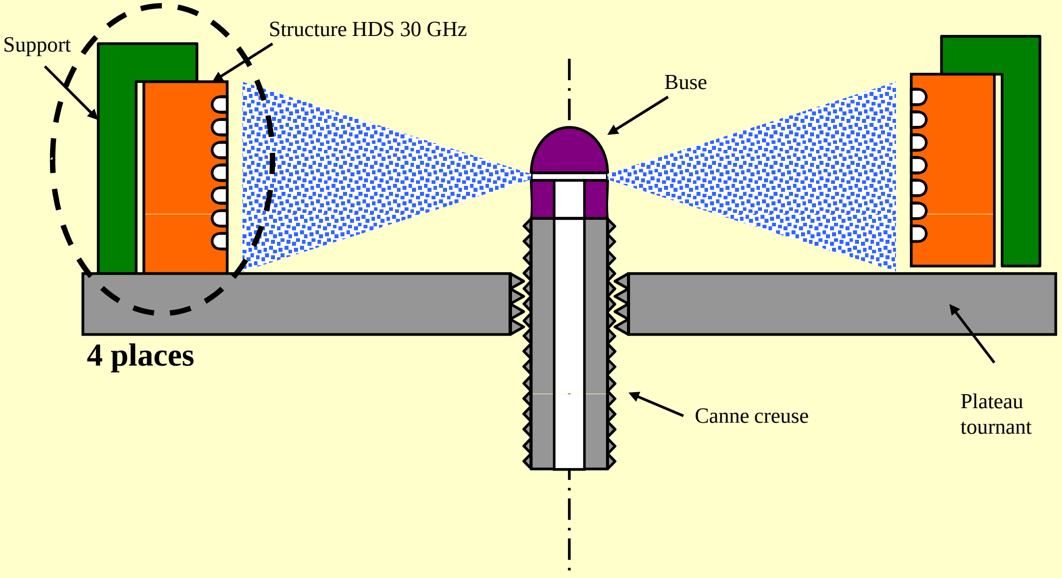
Effects of machining

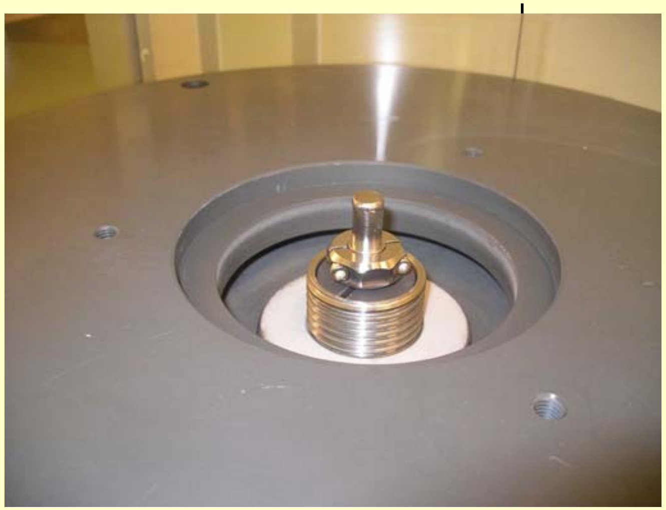
- All DC spark testing has been carried out on rolled metal sheets (with a few exceptions).
- All RF testing has been done on turned or milled structures

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



Surface treatments: HPWR and SC-cavity like treatments?

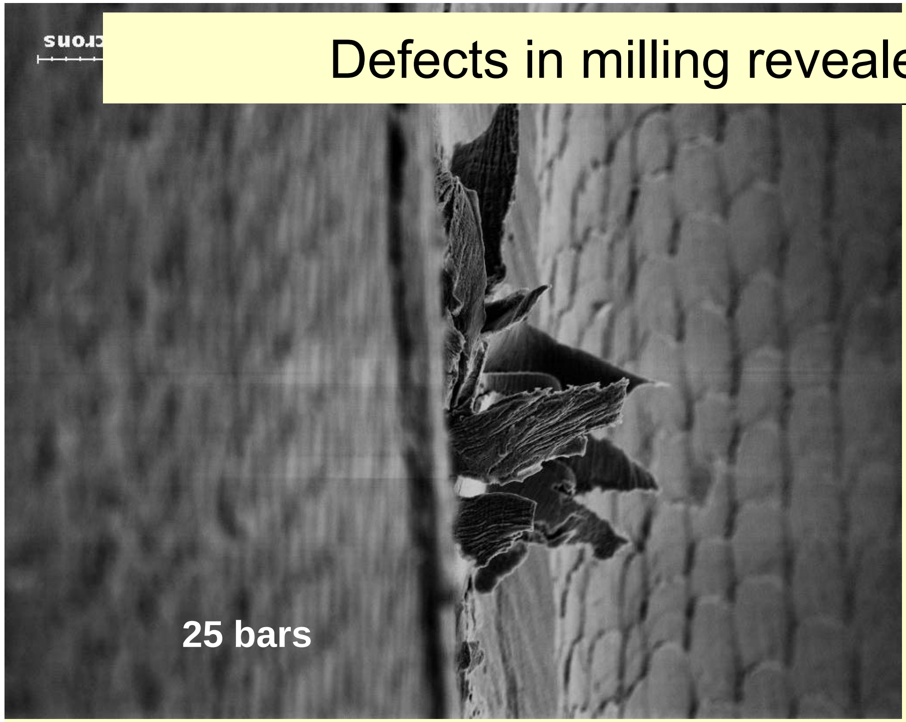




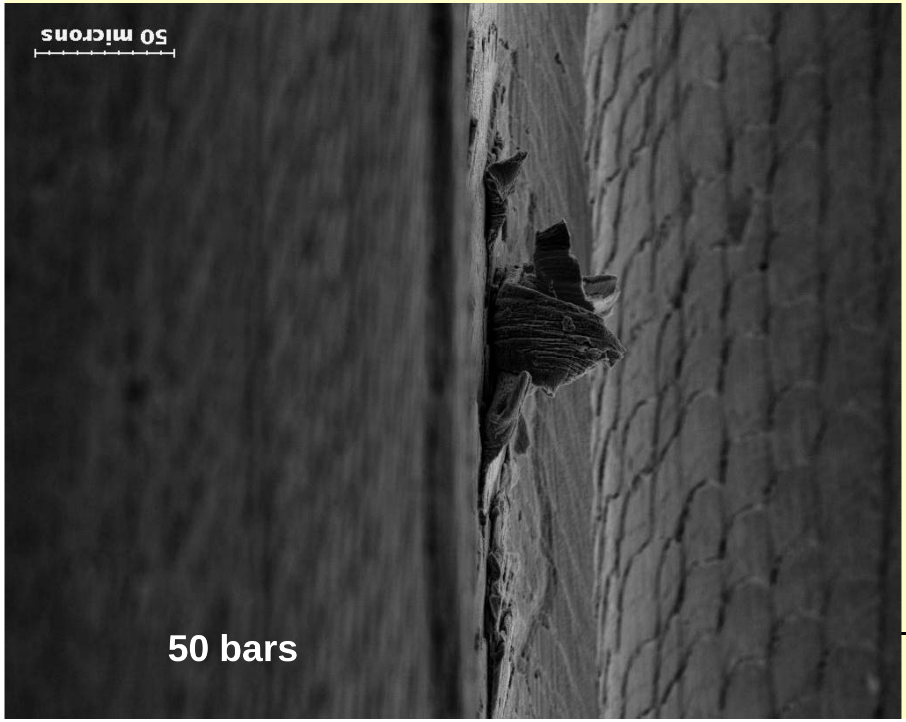
High Pressure Water rinsing and Clean Room operations are standard practice in the world of superconducting cavities

From: F. Peauger, CEA

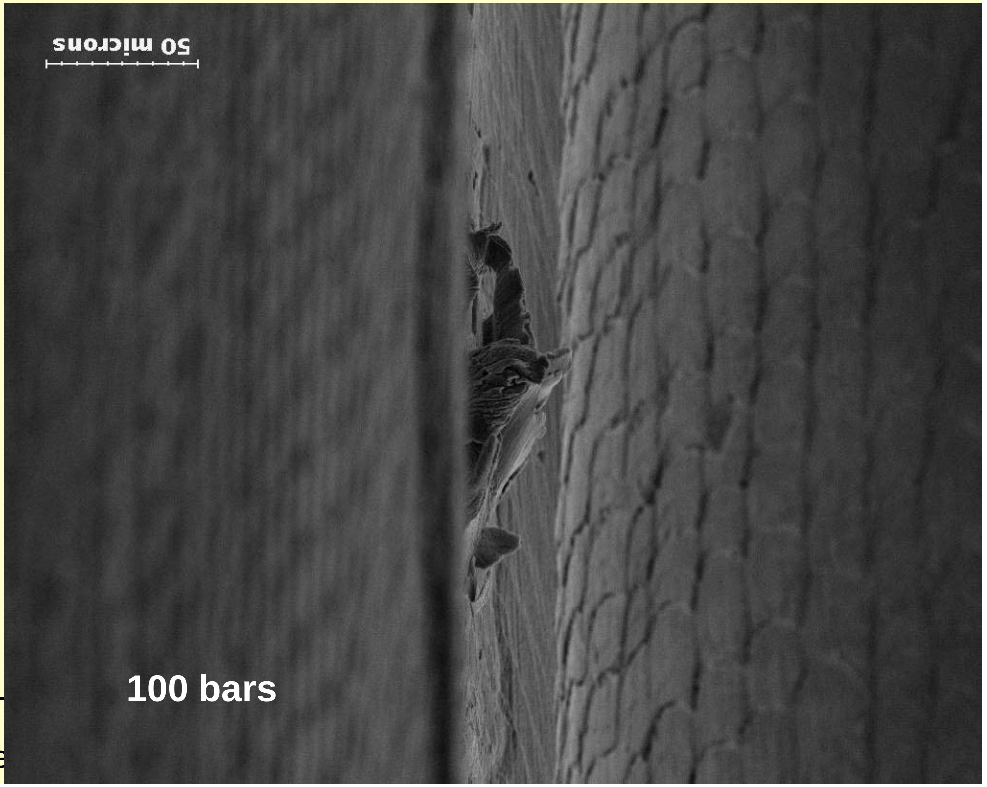
Defects in milling revealed – and then maybe reduced



25 bars



50 bars

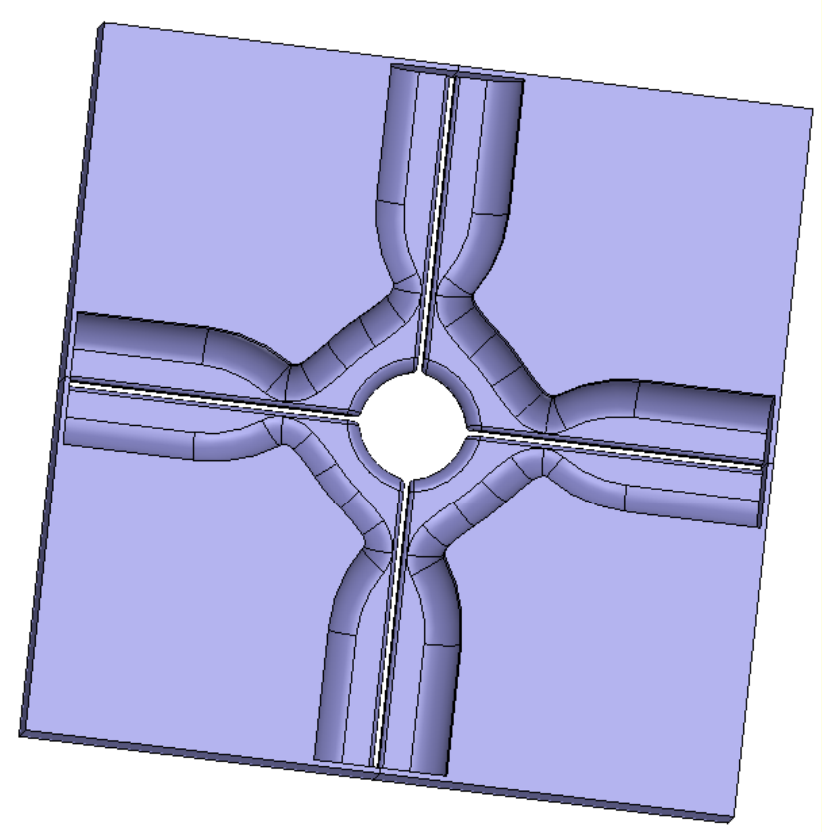


100 bars

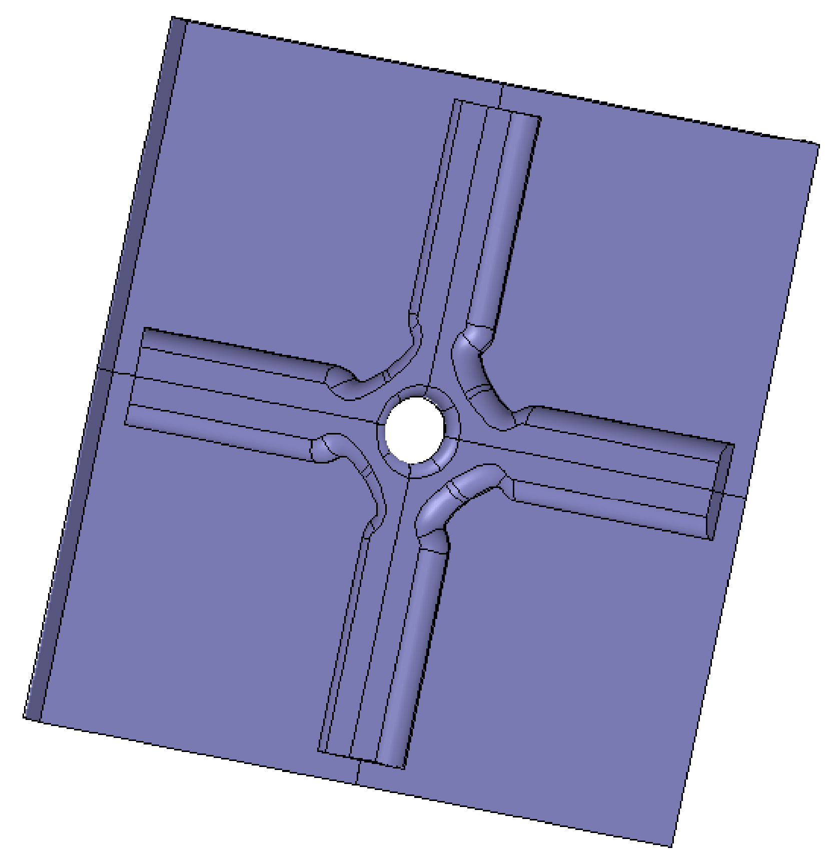
HDS and WDS

Traveling wave structure, heavy transverse mode damping, detuning

Two main types under consideration – Hybrid Damped Structure (HDS), Waveguide Damped Structure (WDS).



HDS: better for pulsed surface heating, quadrant assembly necessary



WDS: less risk of enhanced breakdown at iris, disk or quadrant assembly

From: W.Wuensch

Possible work programme

- Identify possible etching solutions, characterise etching rate, effect on roughness (~3 months)
- Test effectiveness on 3D milled structures + quality control (SEM, metrology) (~3 months)
- Heat treatments (combined with etching): study the effects on topography, outgassing (~6 months)
- DC breakdown study of the combined effects of etching and heat treatment (~2008)

- Manpower: this need has been identified only recently,

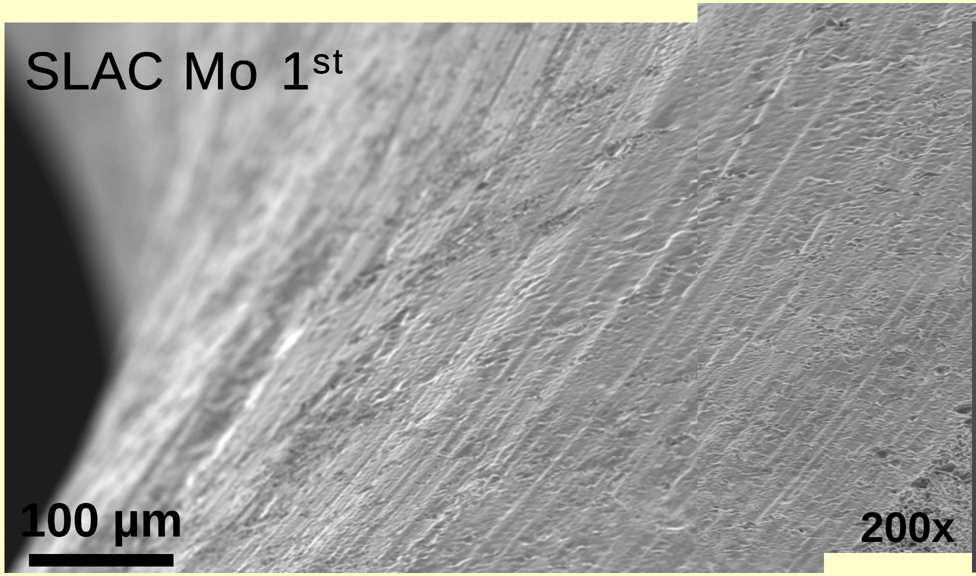
Looking further

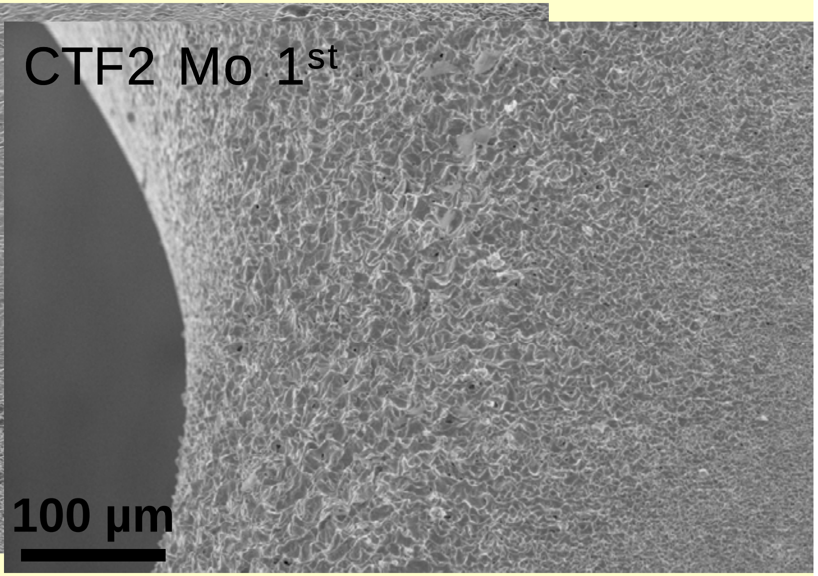
- High-temperature heating heavily affects all mechanical properties (fatigue)
- -> Need for a different but equally effective surface treatment
- Ideas tested (partially) at CERN:
  - plasma treatment for oxide removal (could it be done in-situ in RF structures?)
  - e-beam heating (ex-situ local heating),

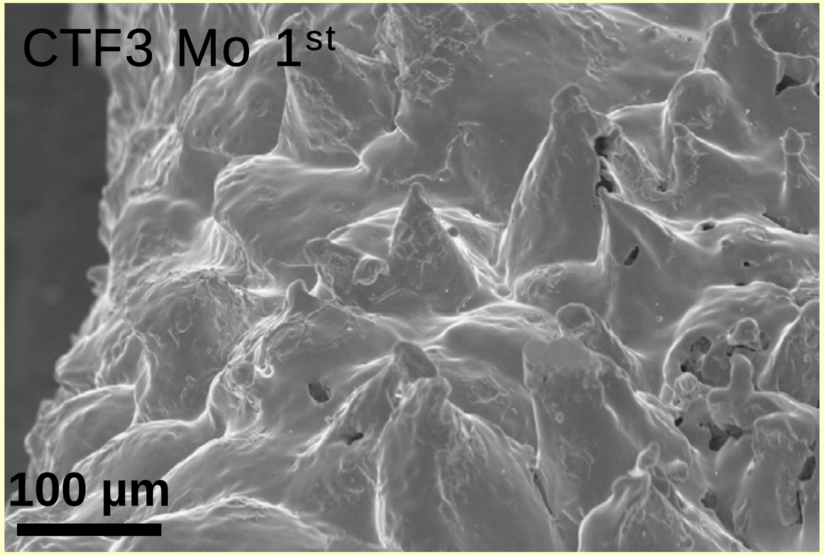
- We could also foster ideas in other domains:
  - Fabrication of complex waveguides and RF plumbing by electroplating, directly incorporating flanges.
  - Cr-Cu bi-metal fabrication by electroplating
- In both cases the work could be done by industrial contractors, with CERN guidance (expertise needed for obtaining the requested material qualities)
- Testing and qualification done at CERN

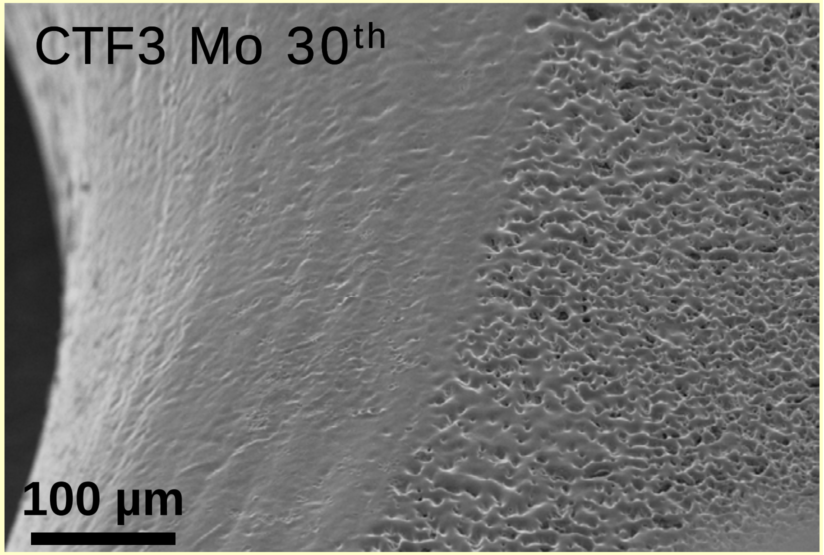
The end

Reminder of old images of disc structures.
Side tilted views x200.

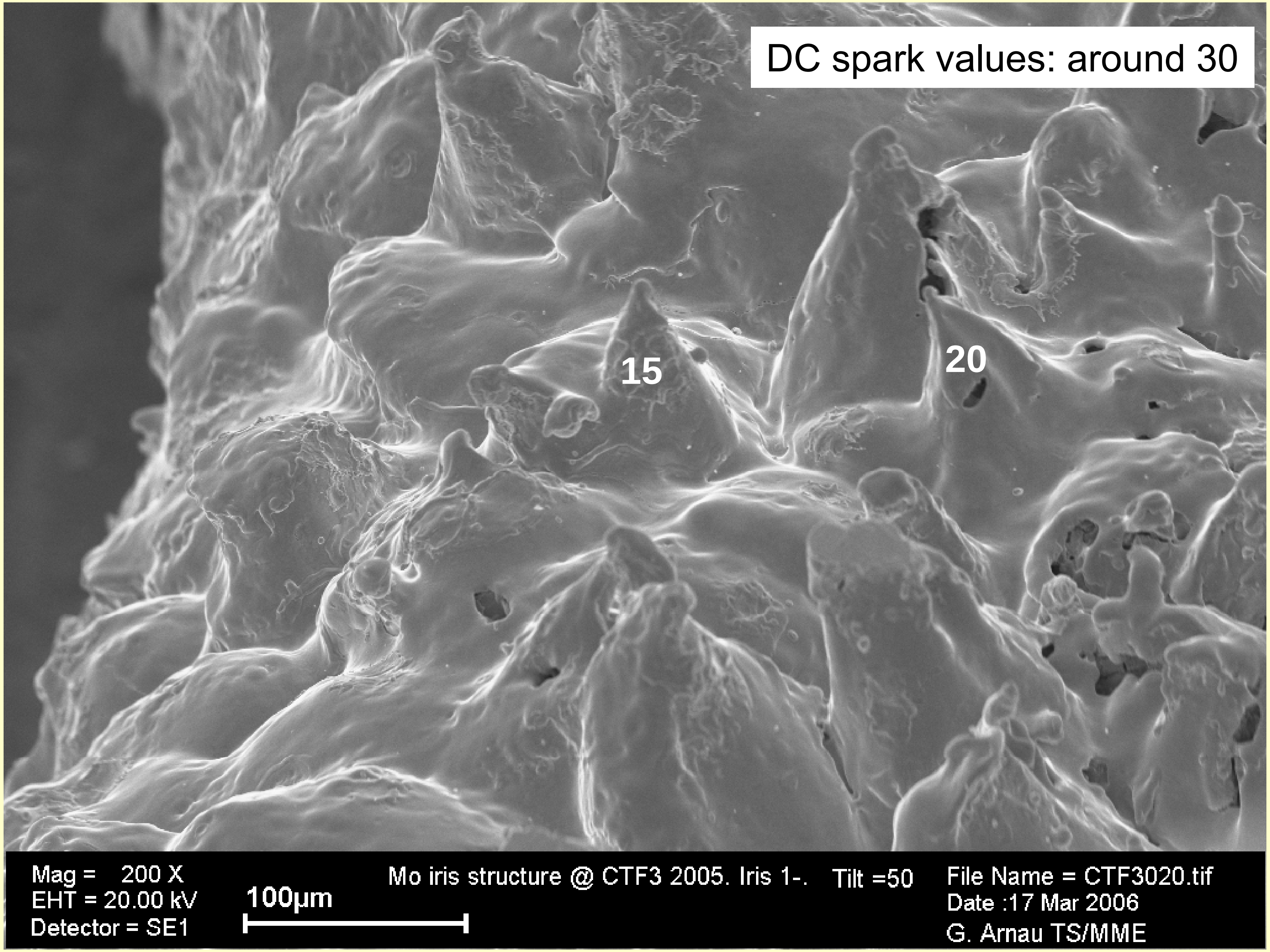

SLAC Mo 1st


CTF2 Mo 1st


CTF3 Mo 1st


CTF3 Mo 30th

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

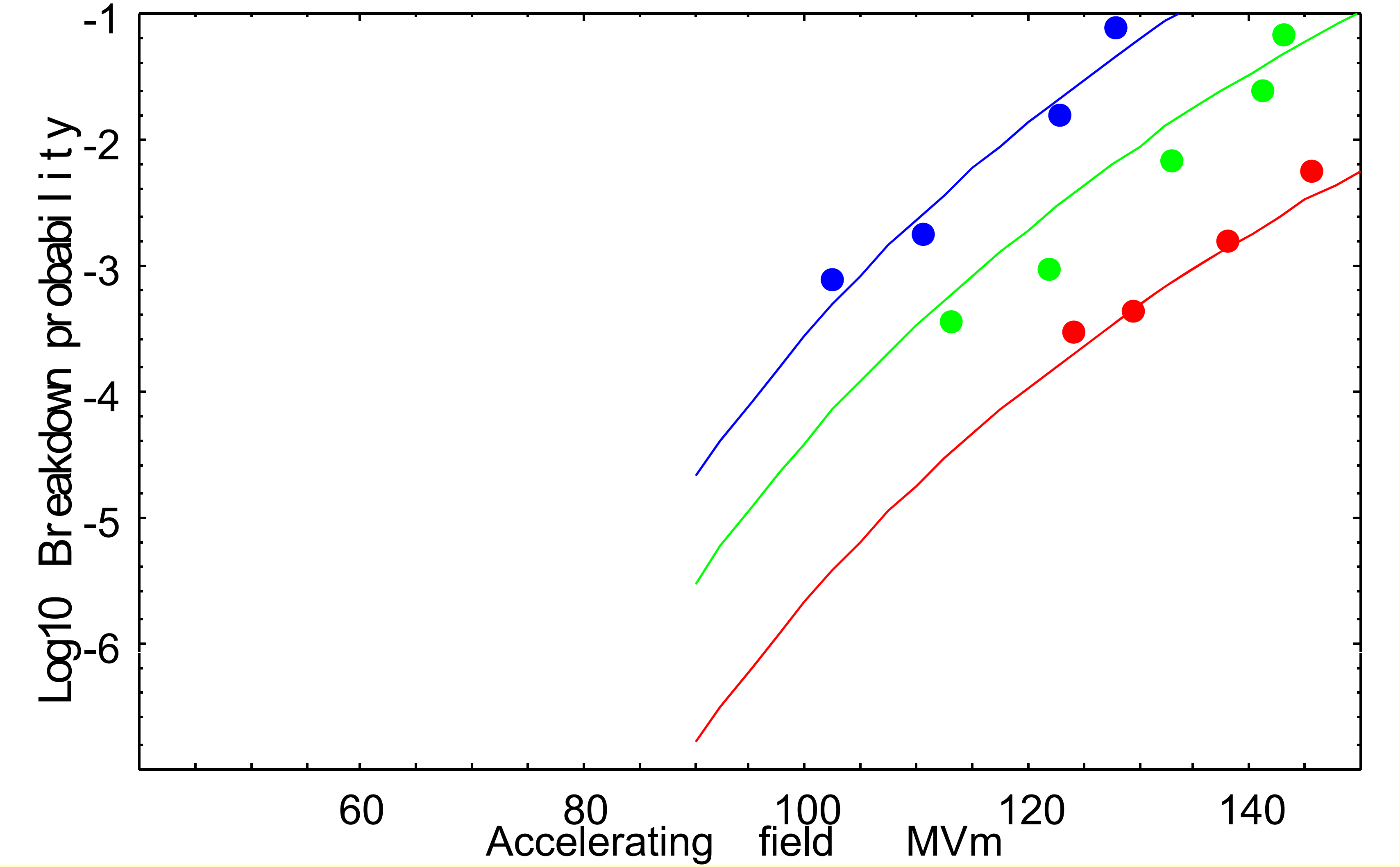
- The gas molecules that get ionised (and allow me this far-fetched assumption!) are indeed the metal vapours created at the tip of the emitters, because of Joule heating by the F-N current.
- It is very difficult to use the full heating model seen before. I made the very crude assumption that the temperature grows with (time)$^{0.5}$ and scales inversely with the (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^$^{2.5}$ between Mo and Cu

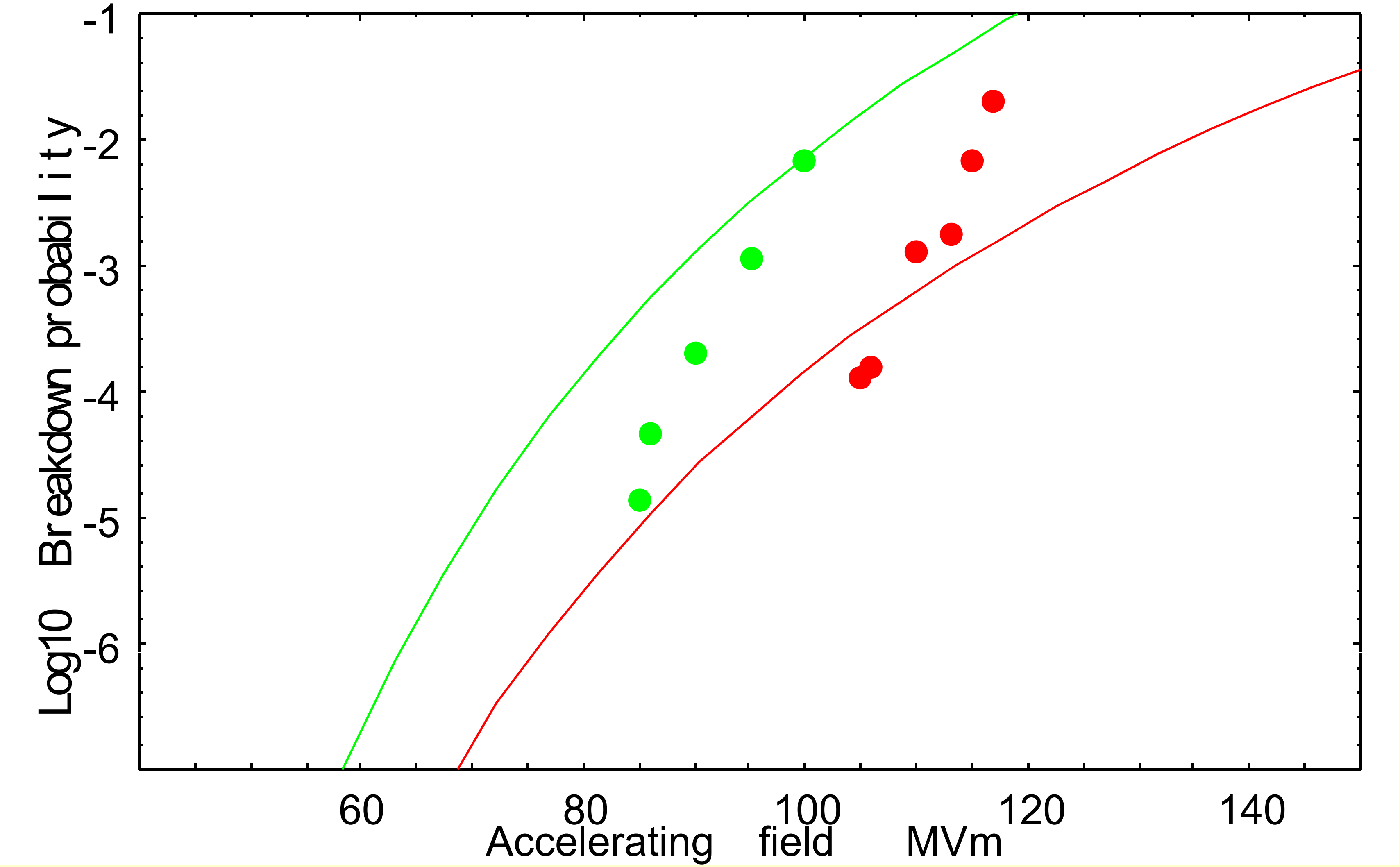
Fit to Mo data, 30 GHz circular iris

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

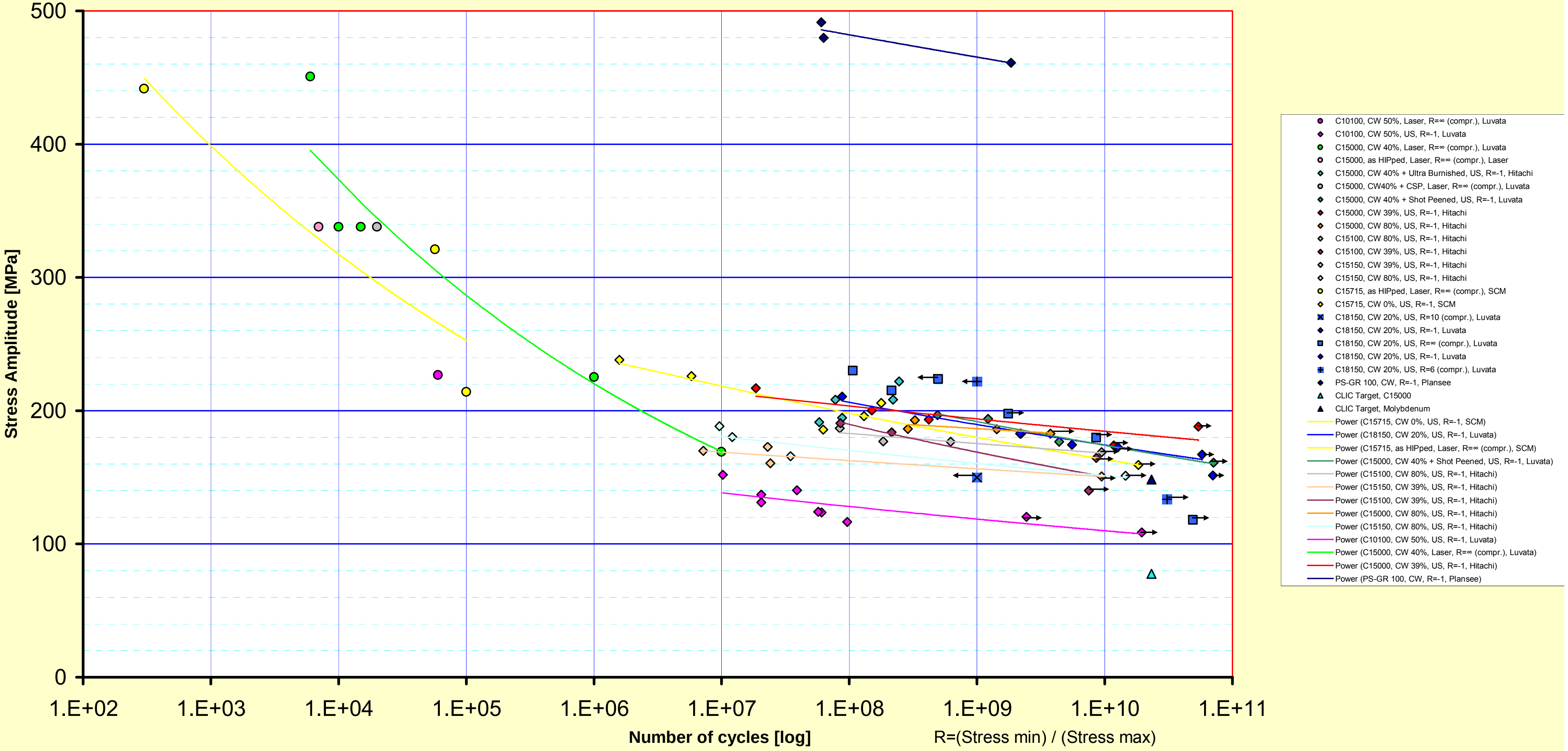


Keeping the same fit parameters and comparing to Cu data, 30 GHz

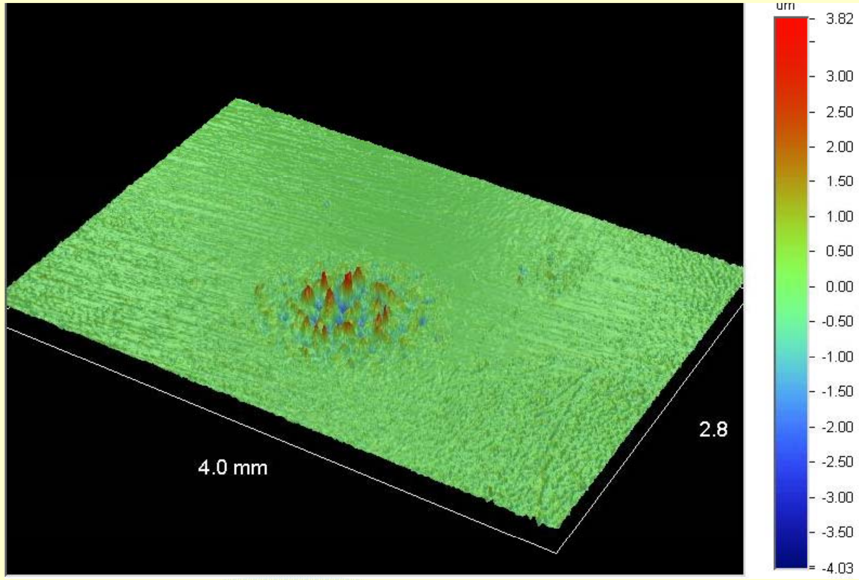
- $\beta = 45$, $k = 400$ Wm^{-1}K^{-1}, $p_0 = 10$^12 mbar, $H_0 = 300$ kJ/mol.

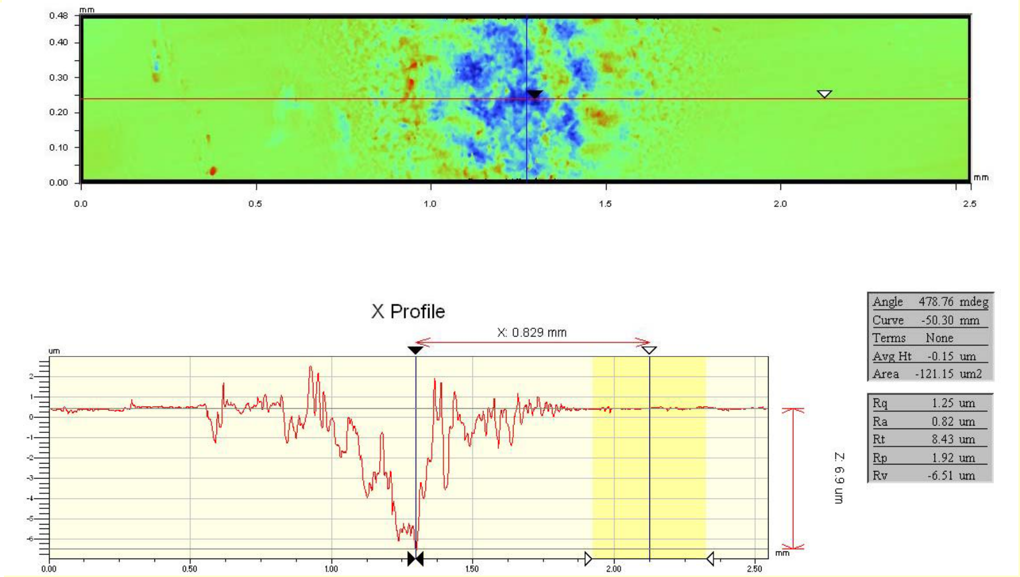


All fatigue data



Depth Profile - Mo





Angle	478.76	mdeg
Curve	-50.30	mm
Terms	None	
Avg Ht	-0.15	um
Area	-121.15	um2

Rq	1.25	um
Ra	0.82	um
Rt	8.43	um
Rp	1.92	um
Rv	-6.51	um

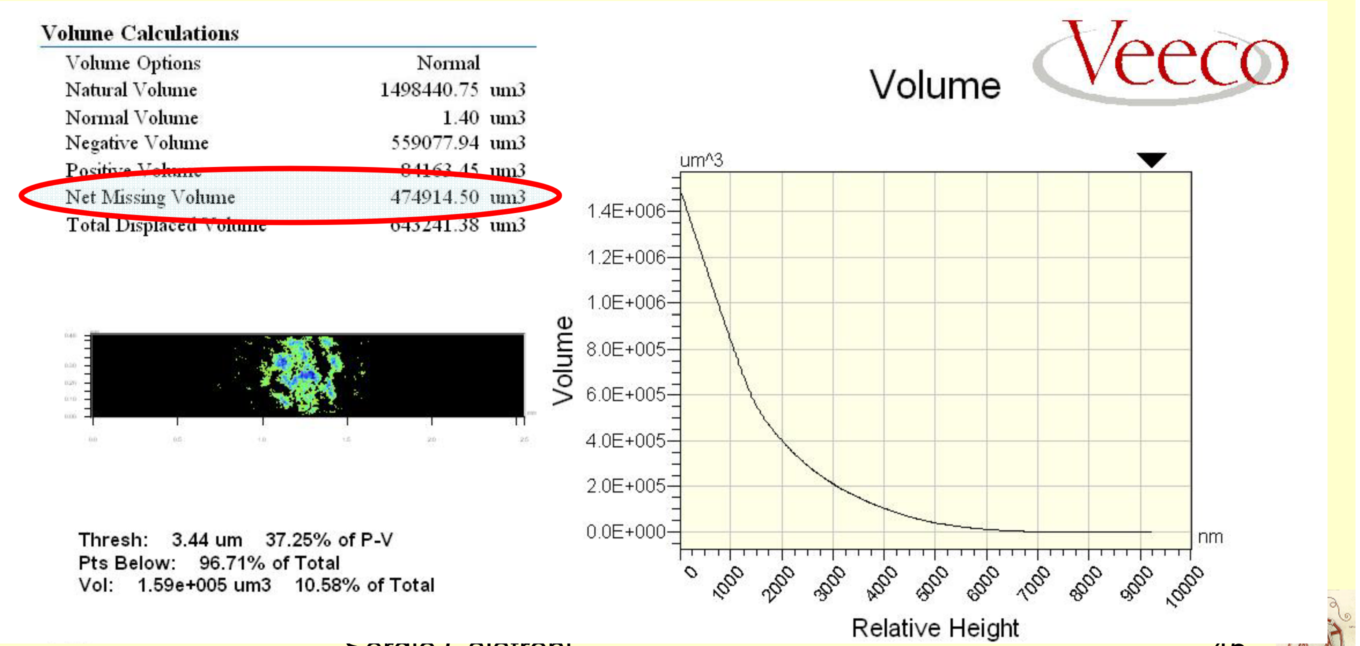
Net Missing Volume:

474914,5 μm^3

297 μm^3/spark

~3 ng/spark

@ 0.8 J/spark



Volume Calculations

Volume Options	Normal	
Natural Volume	1498440.75	um3
Normal Volume	1.40	um3
Negative Volume	559077.94	um3
Positive Volume	84163.45	um3
Net Missing Volume	474914.50	um3
Total Displaced Volume	643241.38	um3

Thresh: 3.44 um 37.25% of P-V
Pts Below: 96.71% of Total
Vol: 1.59e+005 um3 10.58% of Total