Ultimate Field Gradient in Metal Structures

Walter Wuensch, CERN

Ultimate Field Gradient Limitation in Metal Structures

IPAC2017, 15 May 2017

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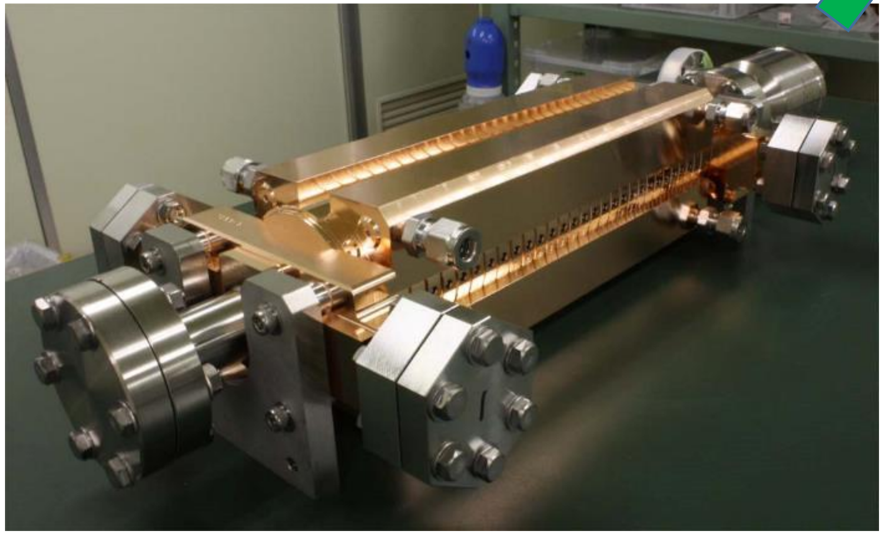
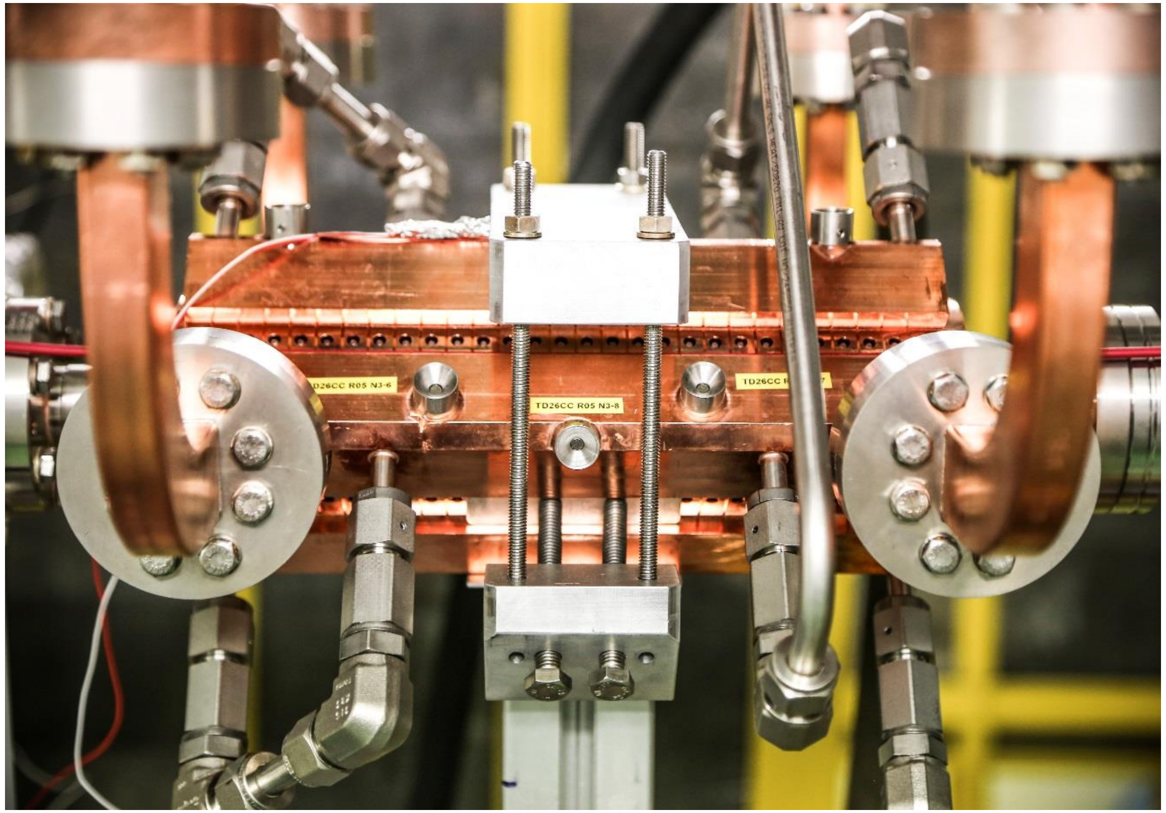
Background



In order to reach multi-TeV e^+e^- collision energies the CLIC collaboration has invested significant effort to develop 100 MV/m gradient accelerating structures.

CLIC accelerating structures

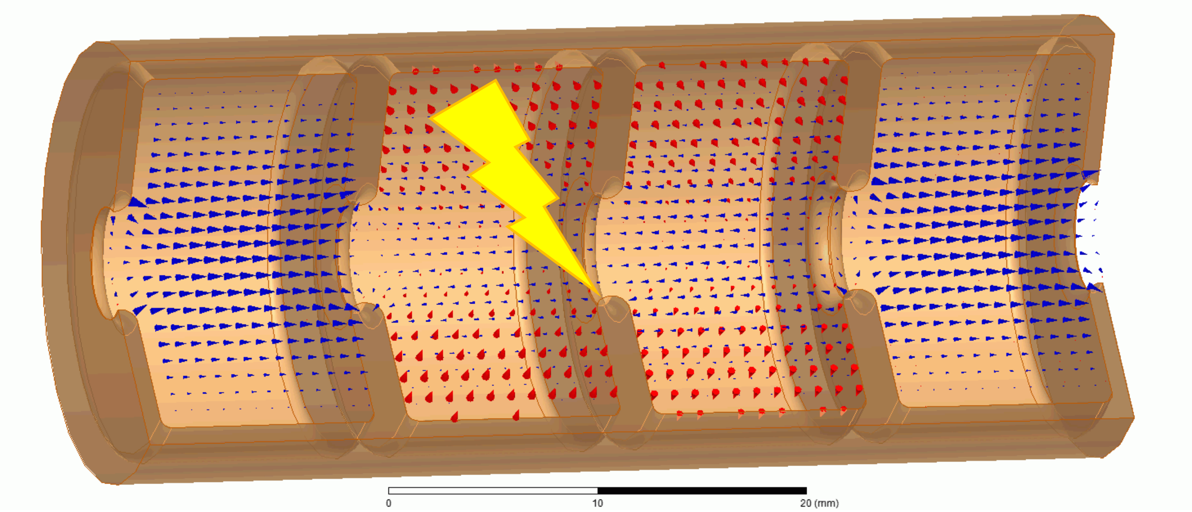


25 cm

- 11.994 GHz, X-band
- OFE copper, hydrogen bonded 1040 °C
- 100 MV/m accelerating gradient
- Input power ≈50 MW
- Pulse length ≈200 ns
- Repetition rate 50-400 Hz

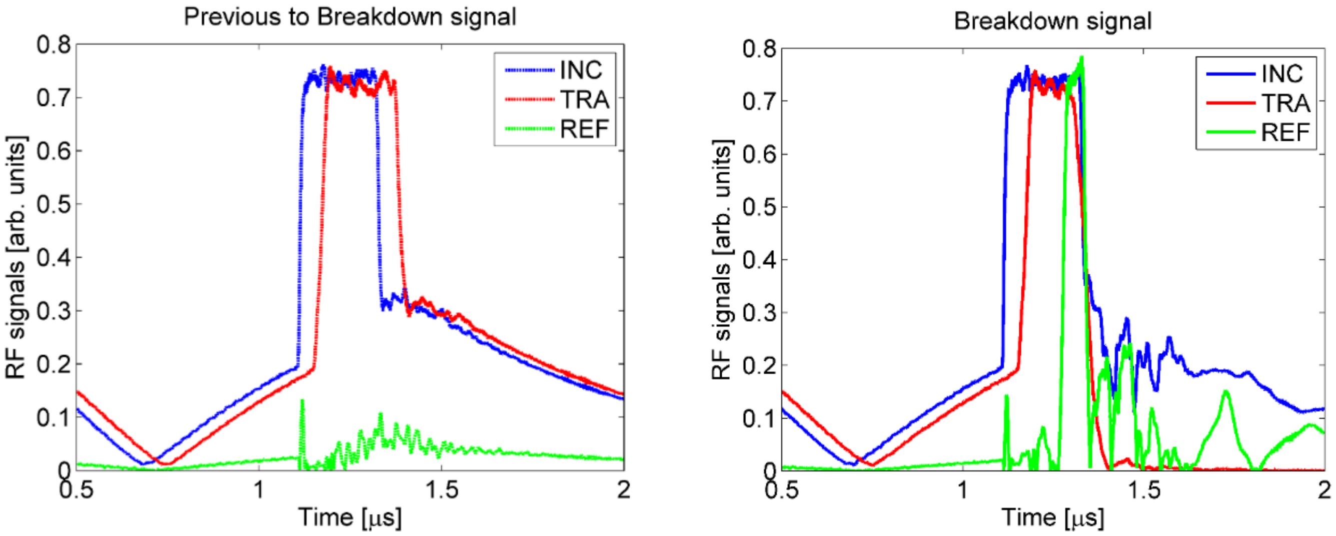
Micron–precision disk

Vacuum arcing

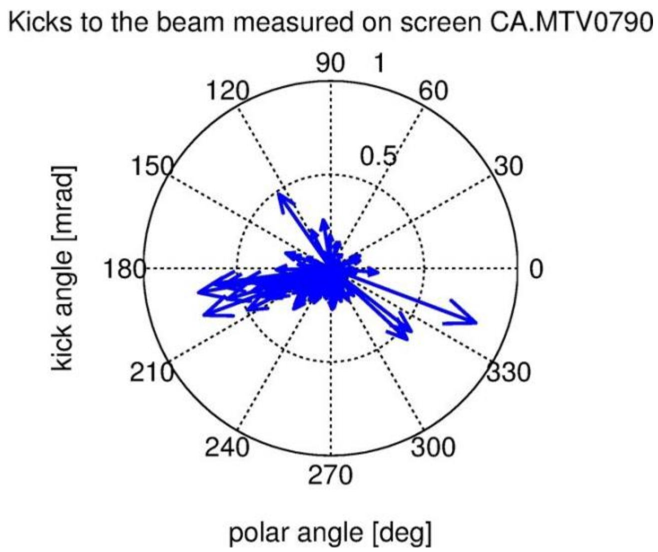


One of the main limitations we have is vacuum arcing, aka breakdown,

- Supresses power flow reducing acceleration
- Gives beam transverse kick



Effect on rf



Transverse effect on beam measured in CTF3, A. Palaia

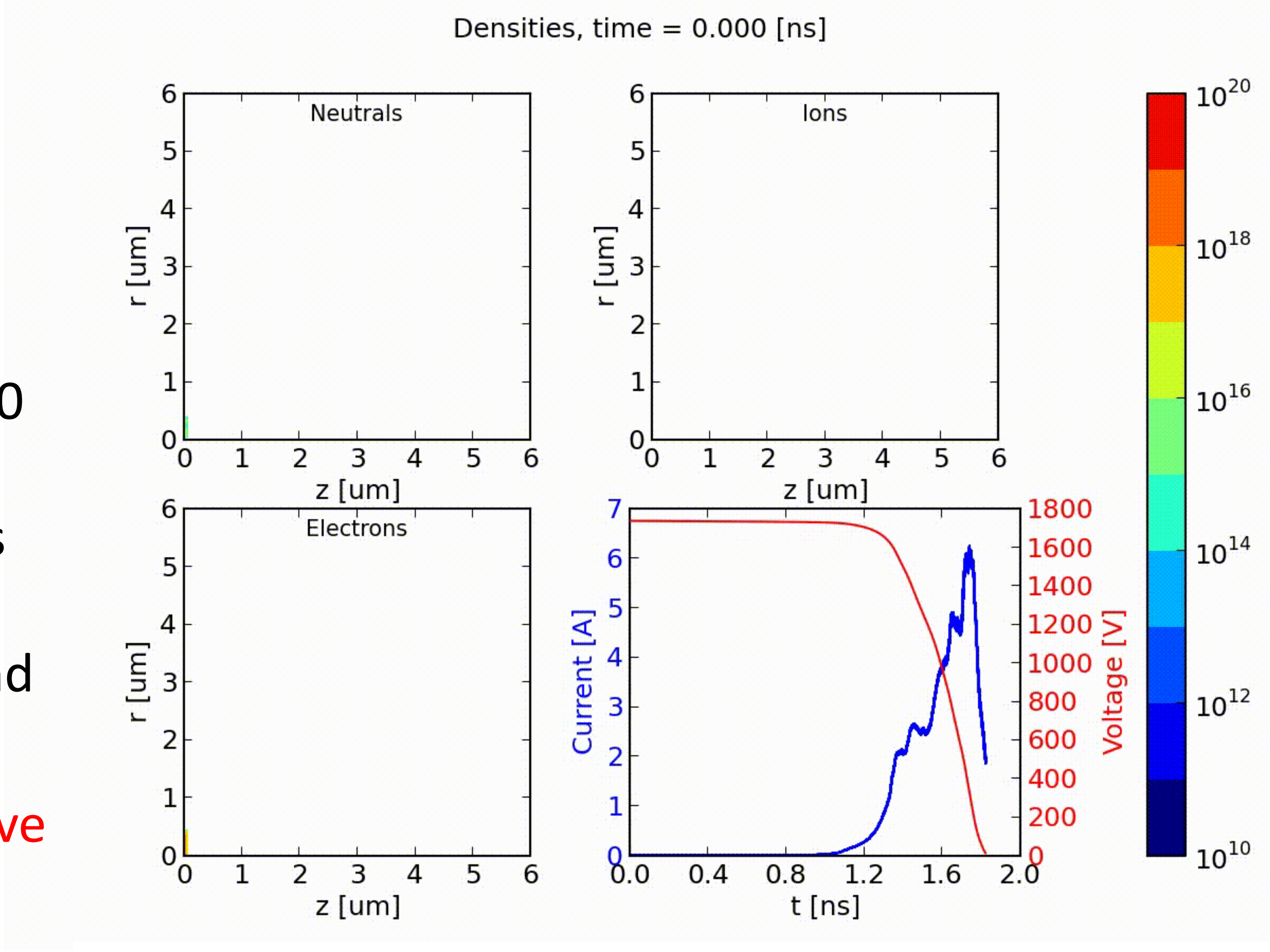
Very high-field vacuum arcs

Vacuum arcs – the formation of plasma accompanied by large electron currents - occur in many devices and applications.

What's so special about us?

- Very high surface electric fields, over 200 MV/m
- Opportunity to test over 20 rf structures and over 40 pulsed dc electrodes combined with significant theoretical and simulation effort.

We believe that we see processes which give fundamental field limits for copper.

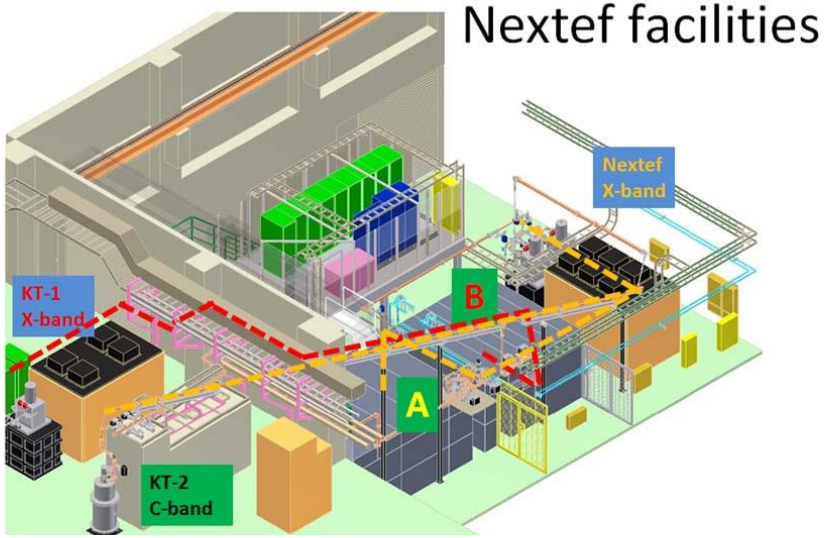


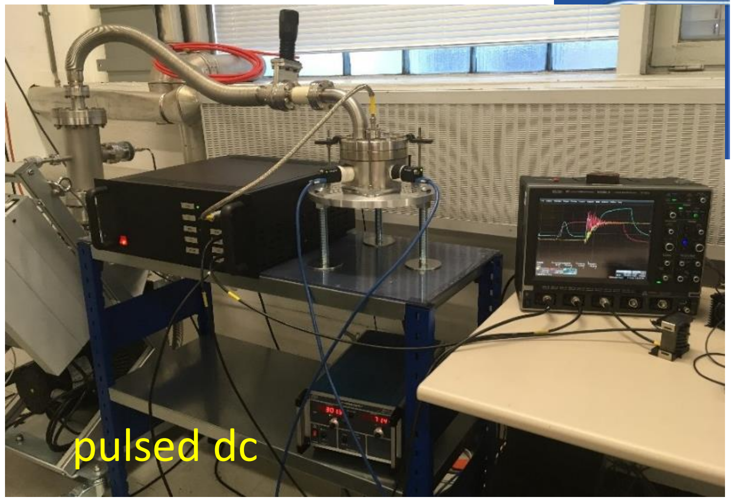
Onset of a vacuum arc simulated by ArcPIC, K. Sjobaek

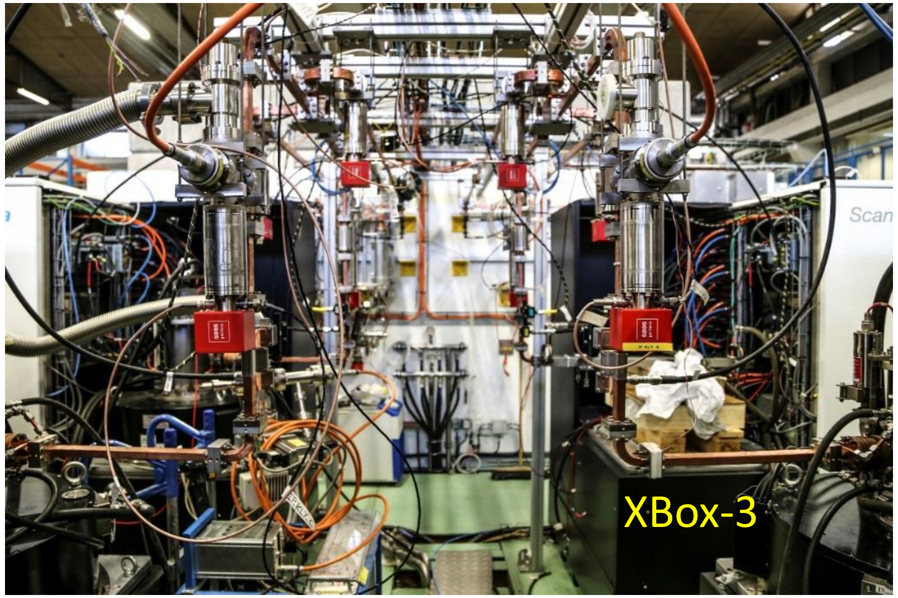
Where we do our experiments

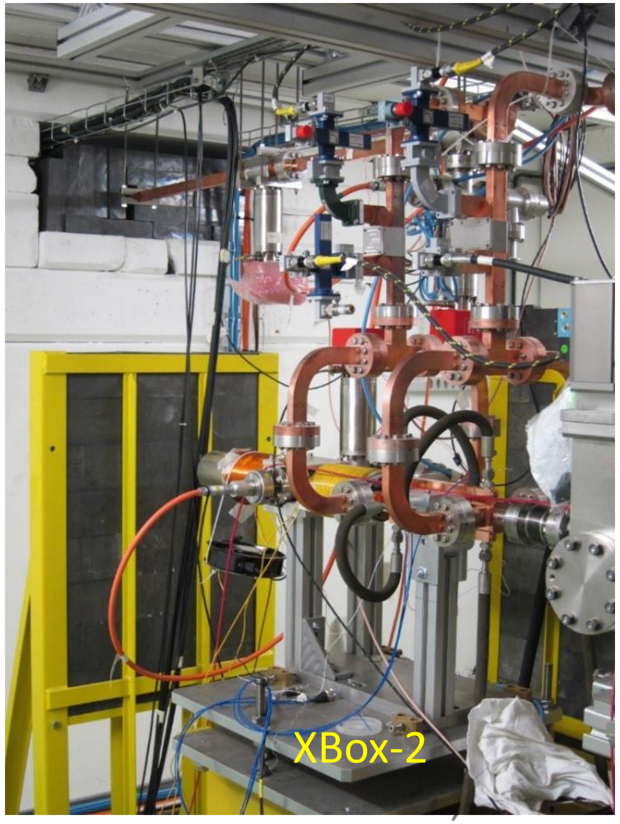
Klystron-based test stands at CERN:

- XBox1 to 3
- NEXTEF at KEK
- Two pulsed-dc systems.

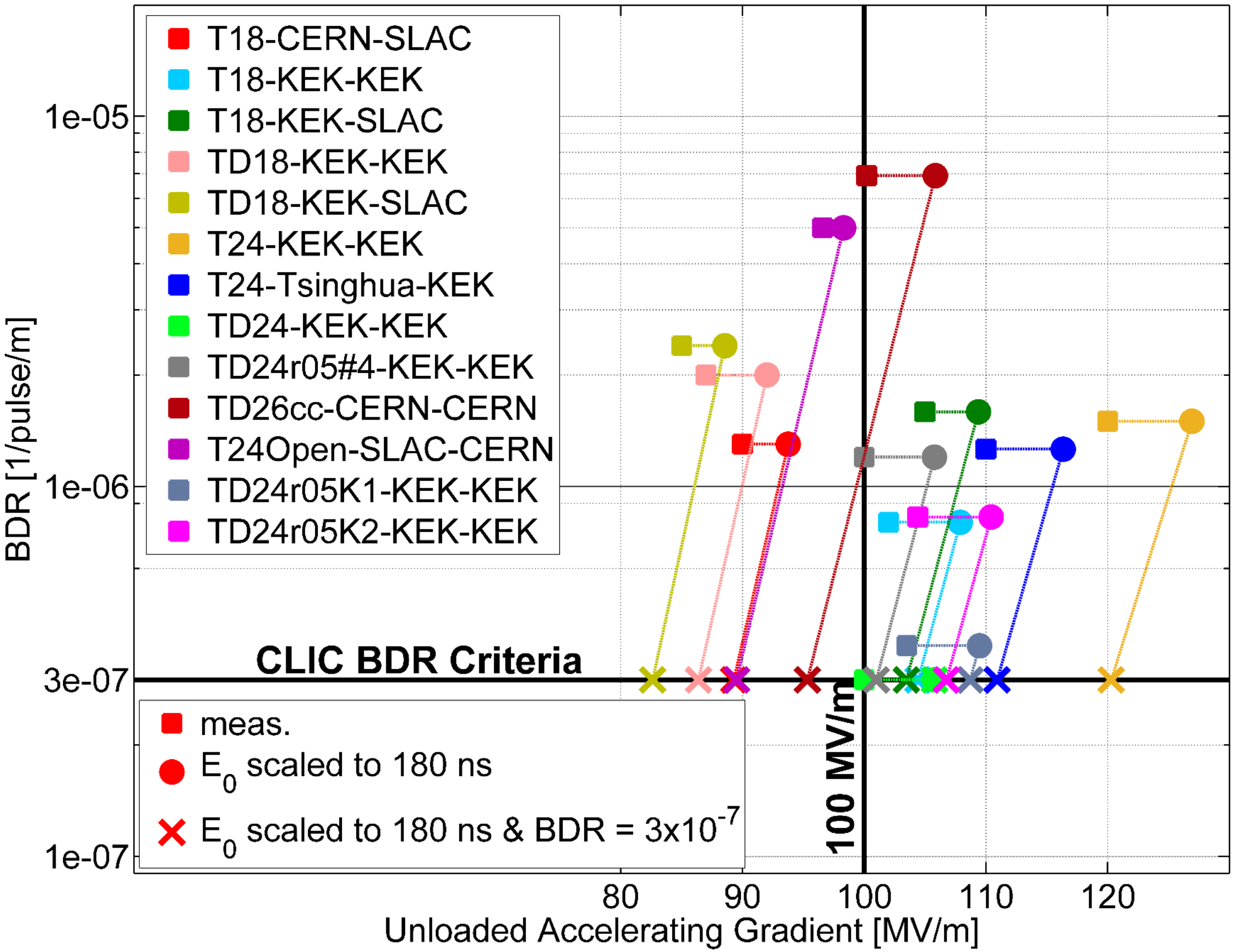








CLIC accelerating structures - performance summary



Currently under test:

XBox1 – TD26CC N2

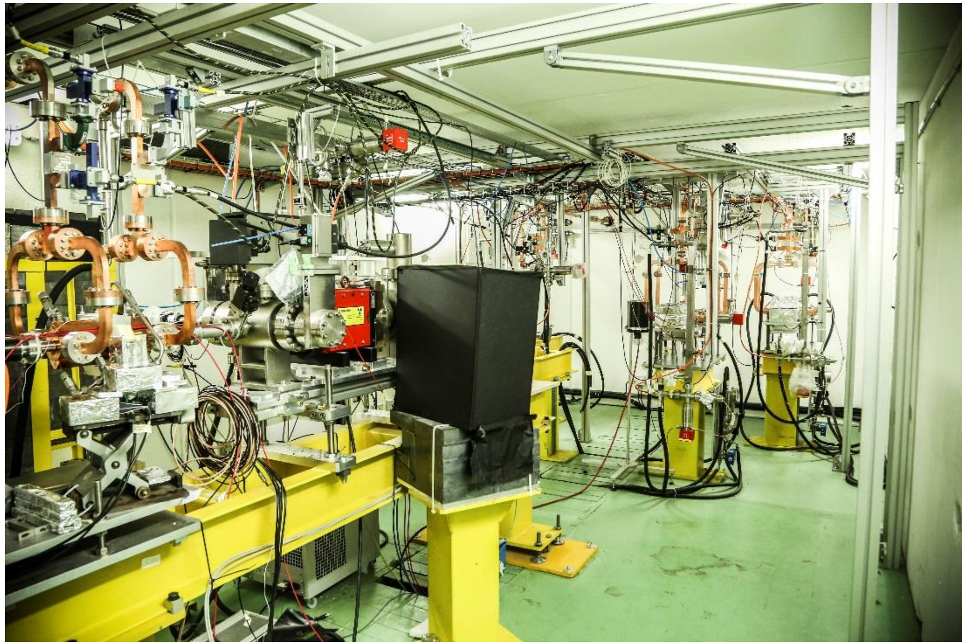
XBox2 – TD26CC N3

XBox3 – TD24CC SiC

T24 PSI

SBox - 3 GHz BTW

NEXTEF (KEK) – TD24 R05



Very high-field vacuum arcs, in more detail

Consider the vacuum arc trigger.

Need a site which produces enhanced electron field emission and neutral atom emission.

What is the nature of such a site?

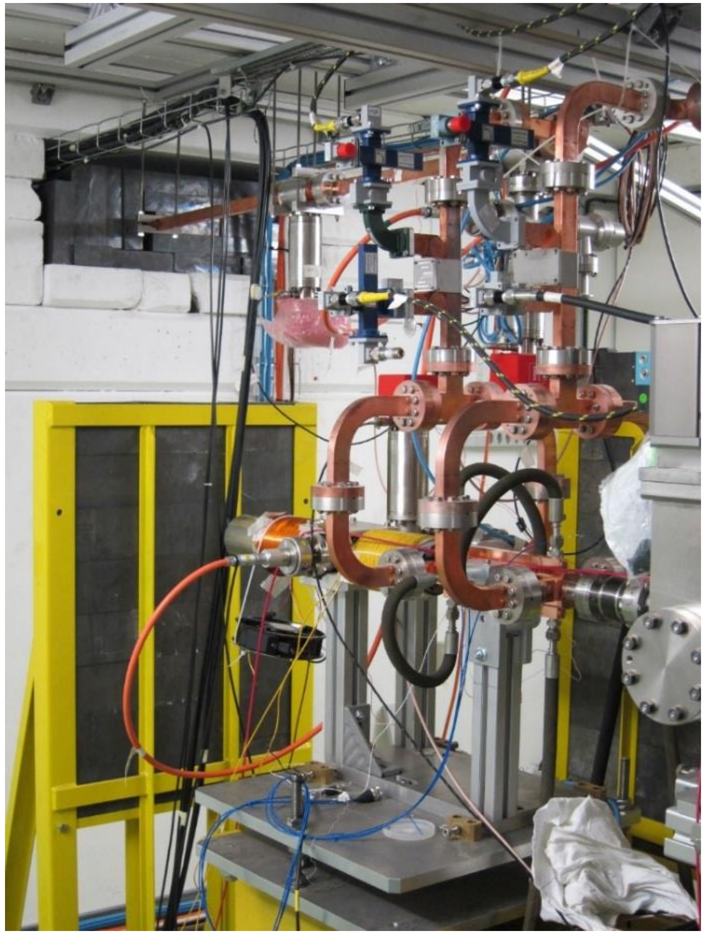
For most applications these are contaminants: dust, particles, oxides etc.

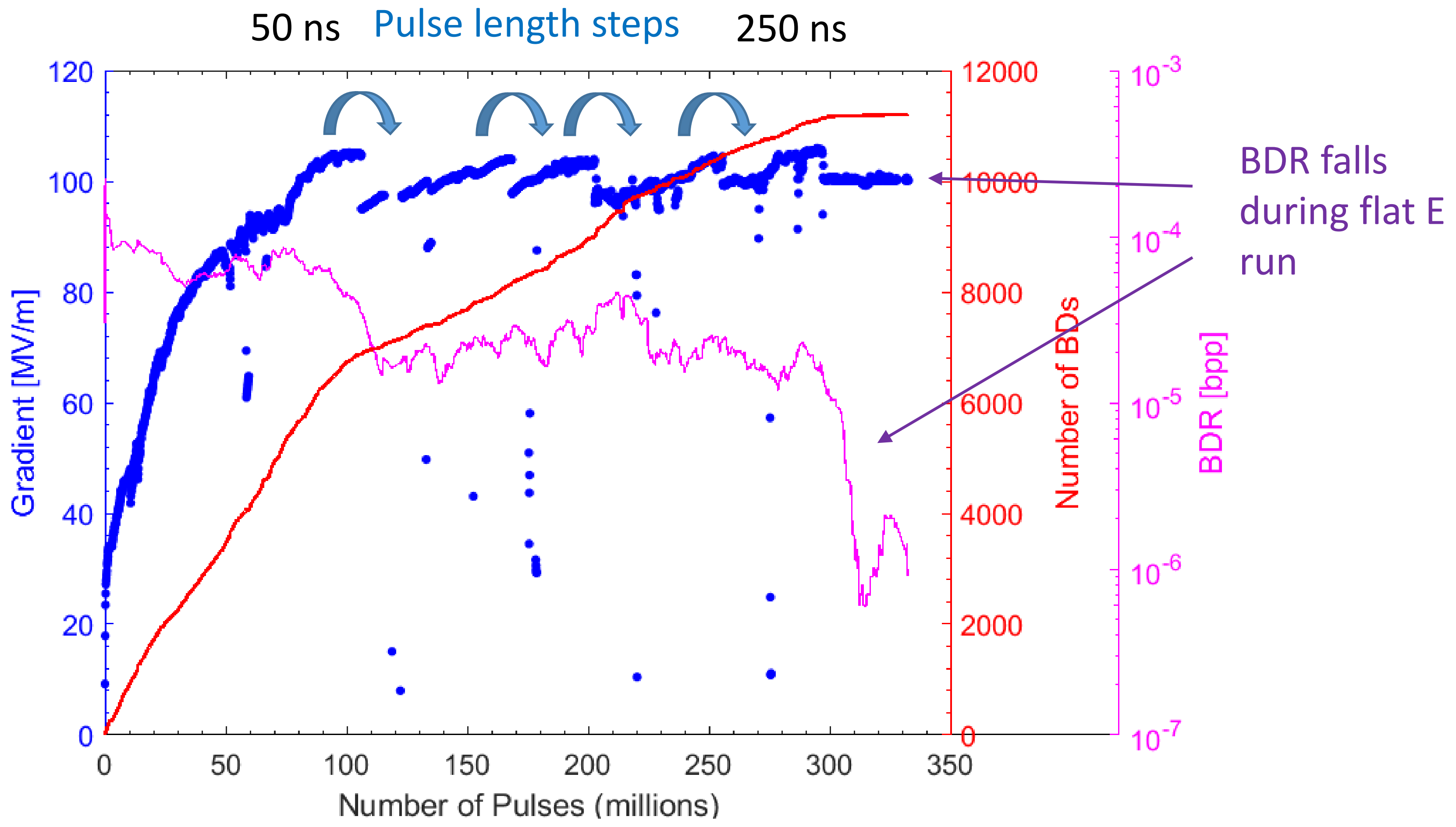
But at high fields, > 100 MV/m surface electric field, we see clear evidence of field-generated features – that give the ultimate field limit.

These features seem to form below the surface and are generated by dislocation dynamics.

Conditioning

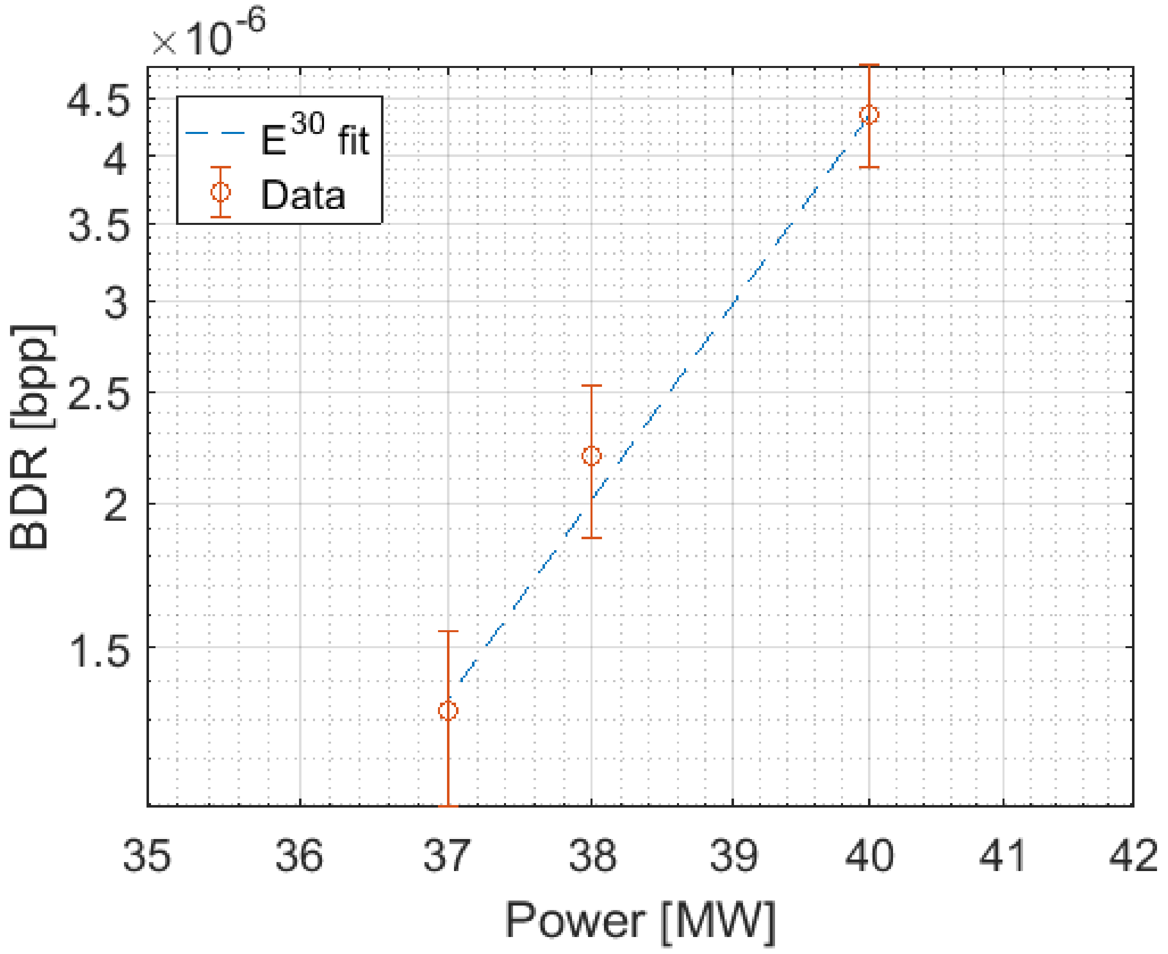
Accelerating structures do not run right away at full specification – pulse length and gradient need to be gradually increased while pulsing. Typical behaviour looks like this:





4 million pulses per day at 50 Hz

BDR dependence



Data taken in XBox-2 with TD26CC structure, T. Lucas

Regularly observed dependence:

$$BDR \propto E^{30}\tau^{5}$$

Physical model based on defect formation

$$BDR \propto e^{\frac{-E^{f}+\varepsilon_0 E^2 \Delta V}{k_b T}}$$

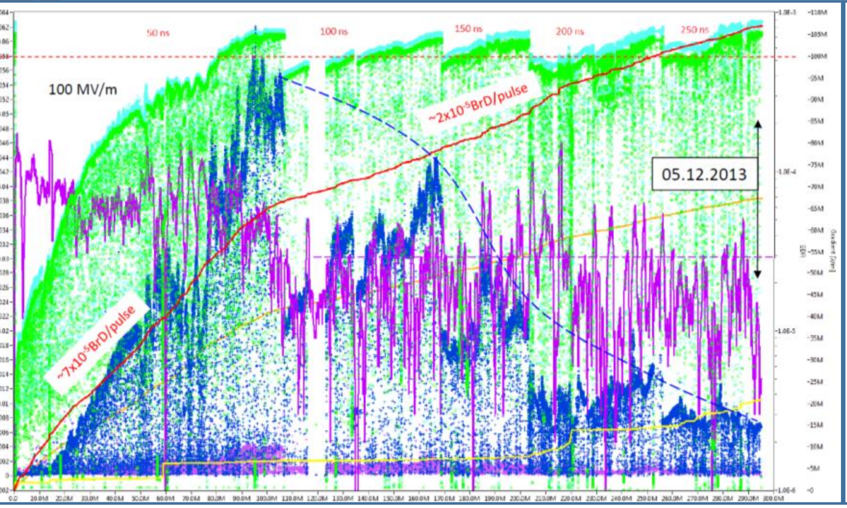
$$E^{f} = 0.8\ eV$$

$$\Delta V = 0.8 \times 10^{-24} m^3$$

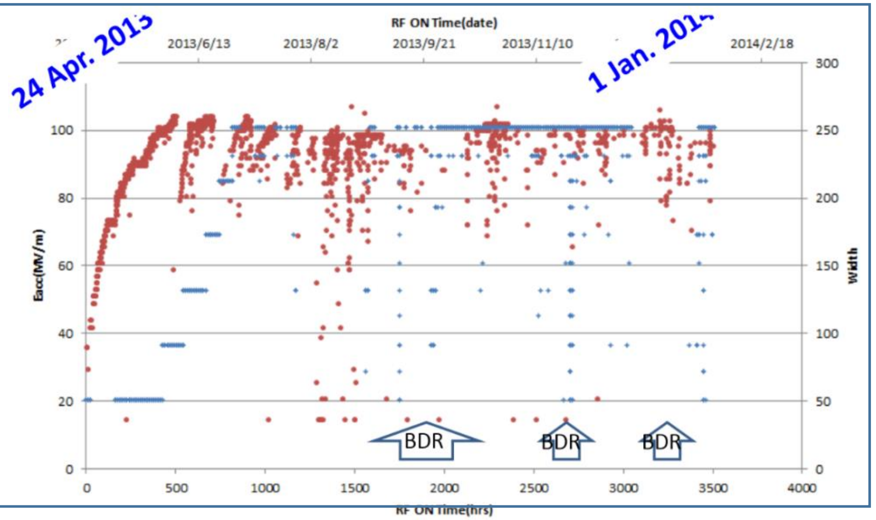
K. Nordlund, F. Djurabekova, *Defect model for the dependence of breakdown rate on external electric fields*, Phys. Rev. ST Accel. Beams 15, 071002 (2012)

Comparison of three similar structures

TD26CC (XBOX-1)



TD24R05#4 (NEXTEF)

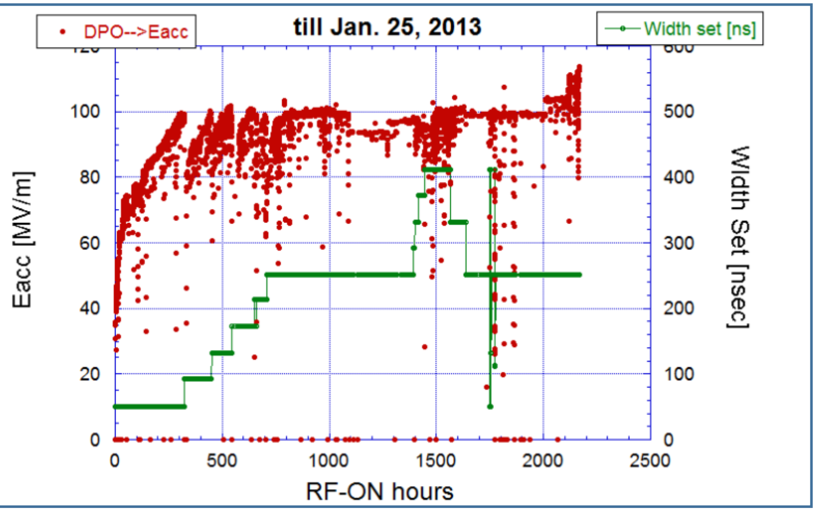


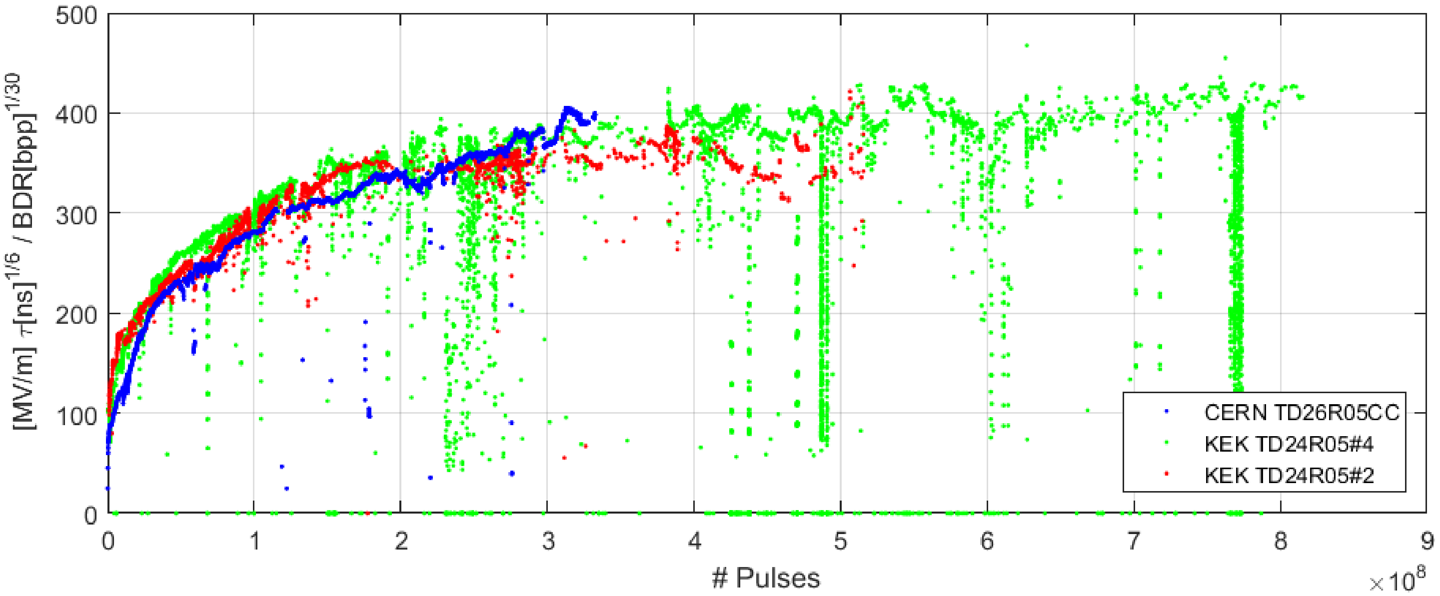
We normalize by:

$$BDR \propto E^{30}\tau^{5}$$

And get

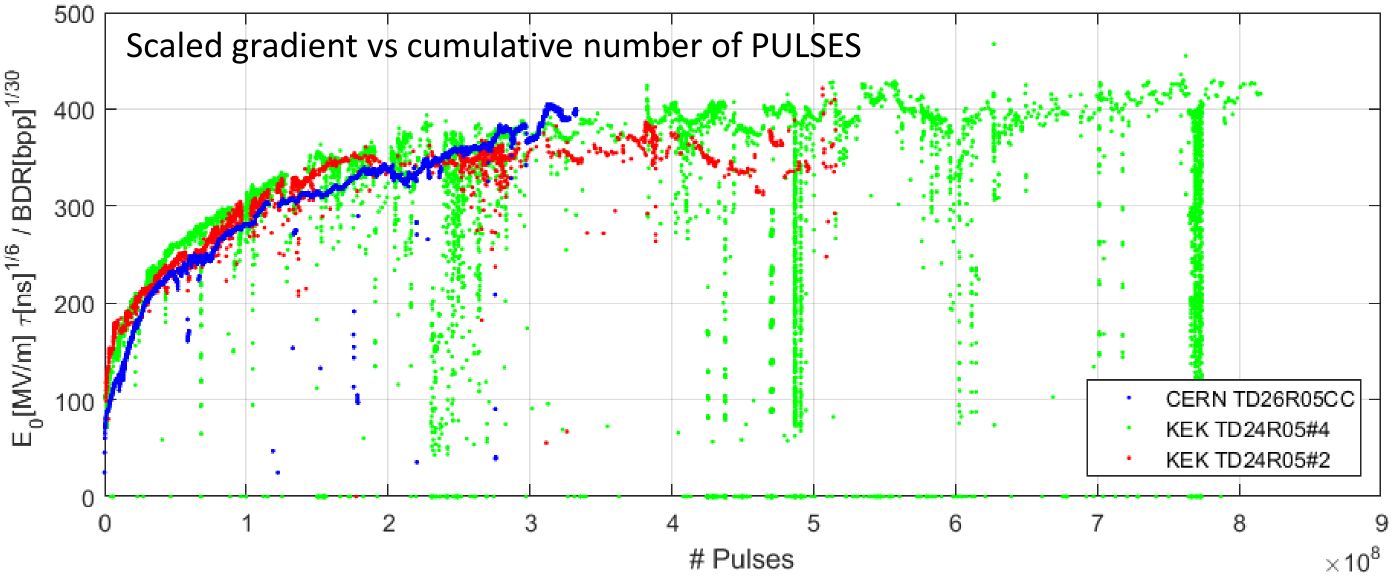
TD24R05#2 (NEXTEF)

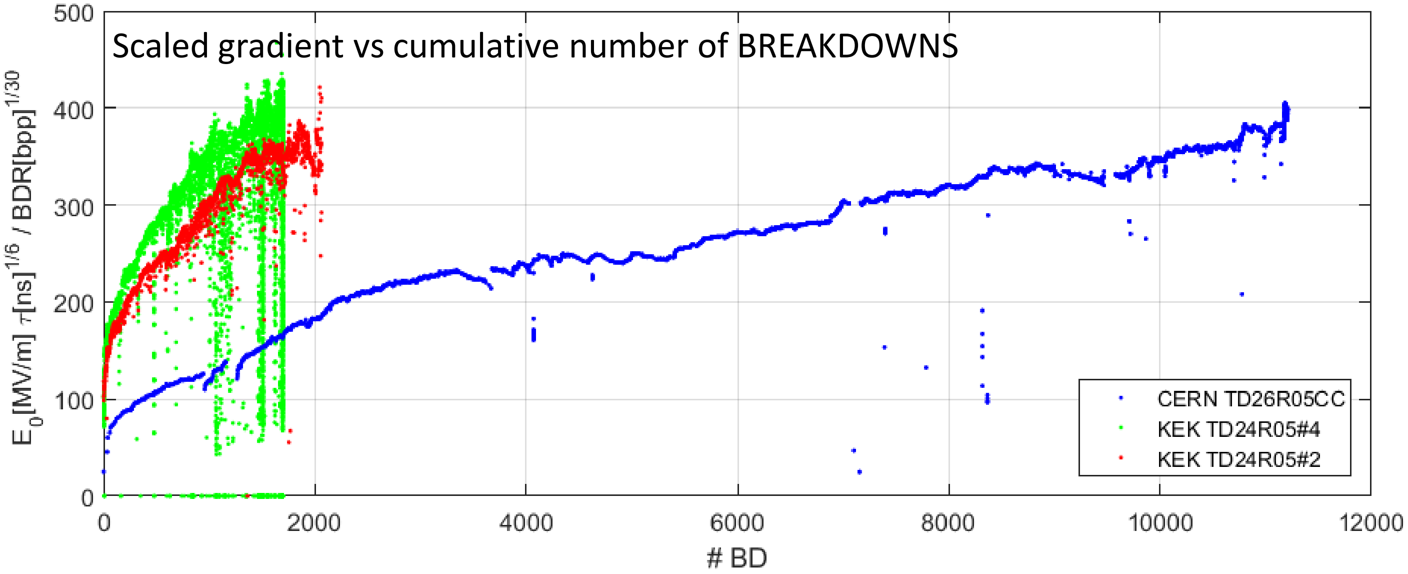




Interpretation: Conditioning is a reproducible process which implies a well defined physical mechanism.

Comparing conditioning





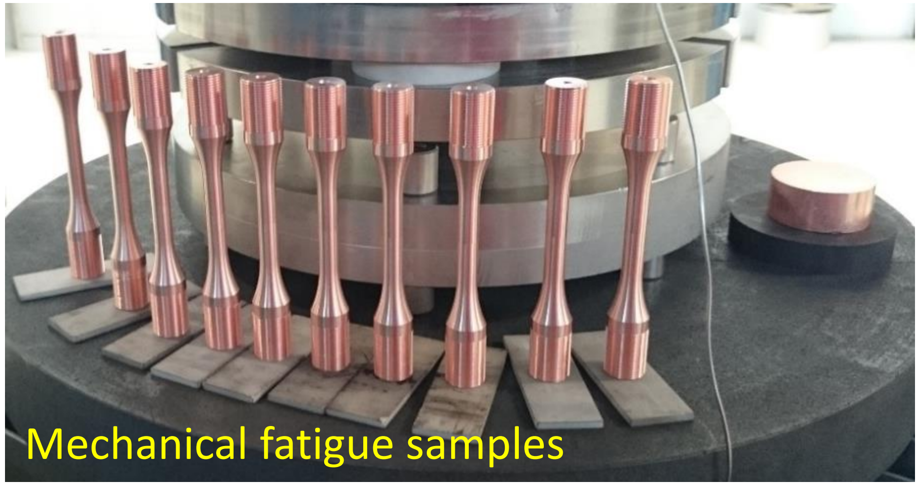
vs. number of pulses

Interpretation – conditioning proceeds as the number of pulses *not* the number of breakdowns. This implies a steady modification of the structure for each pulse.

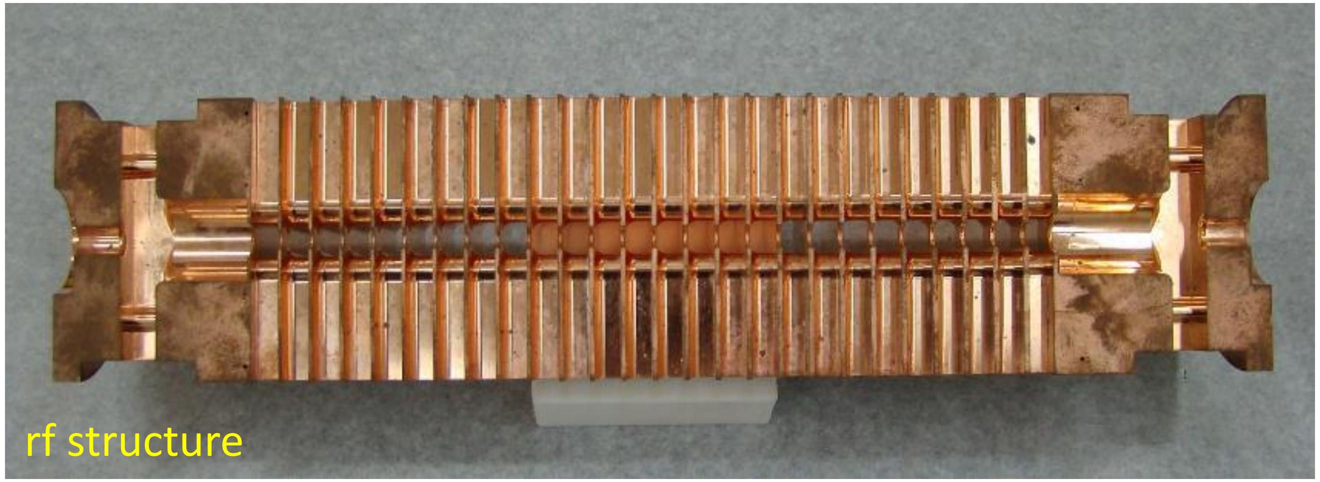
vs. number of Breakdowns

Alberto Degiovanni, Walter Wuensch, and Jorge Giner Navarro, *Comparison of the conditioning of high gradient accelerating structures*, Phys. Rev. Accel. Beams 19, 032001 (2016)

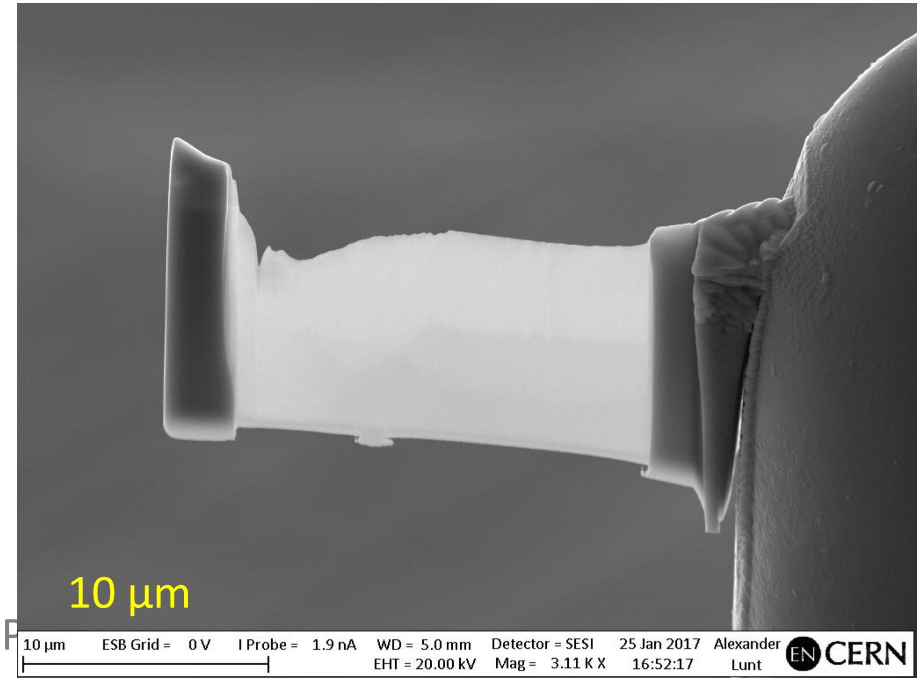
Comparison of mechanical and rf samples



Mechanical fatigue samples



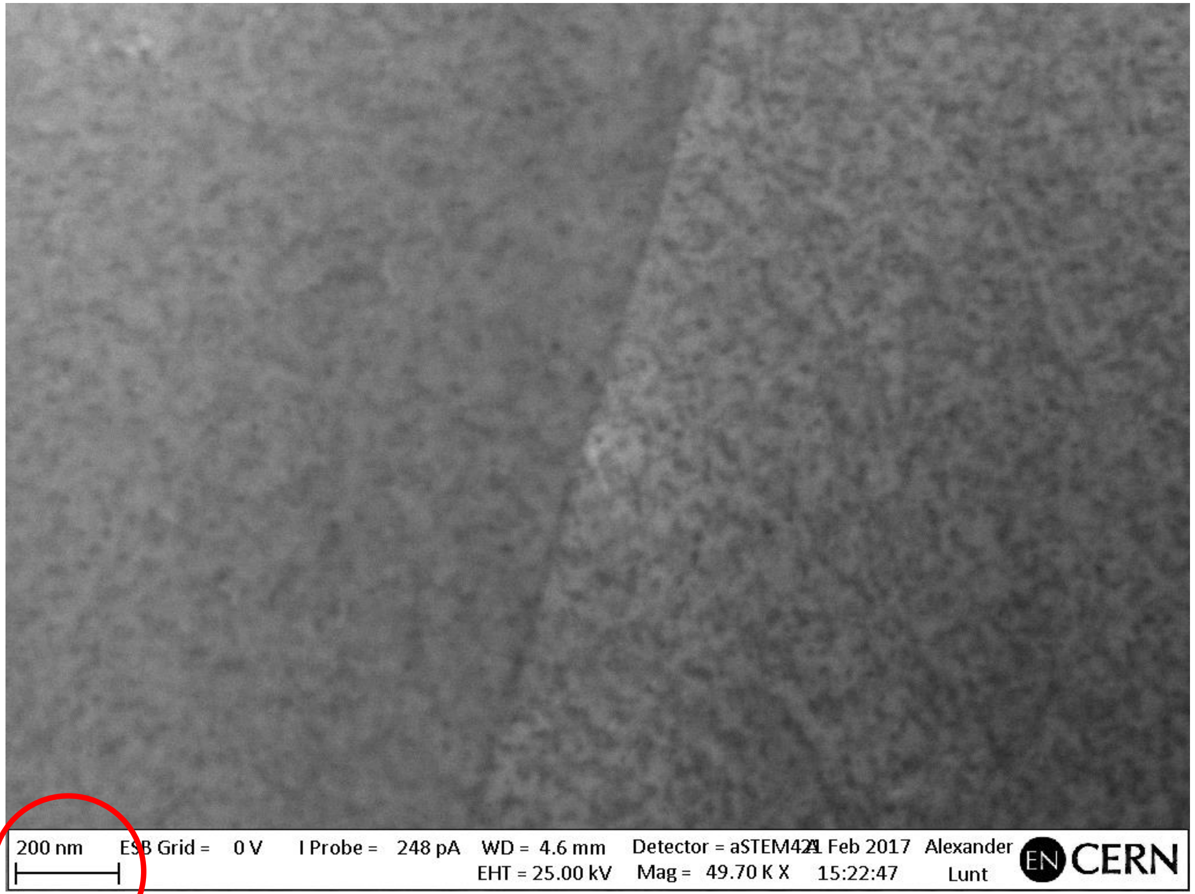
rf structure



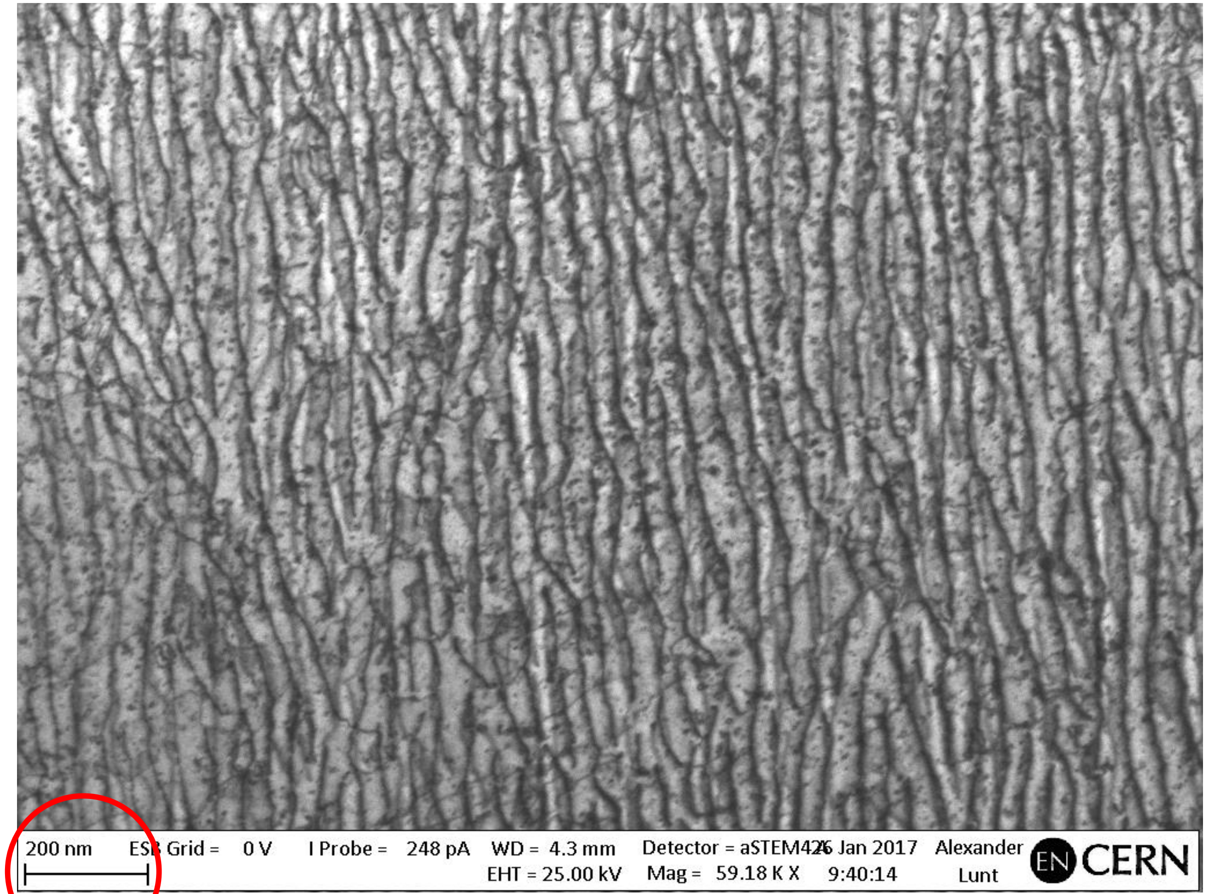
Experiment:

1. Build rf structure, standard procedure with 1040 °C bonding, and mechanical sample with same heat treatment.
2. Condition rf structure and fatigue mechanical sample.
3. Compare material state before/after/between using advanced microscopy techniques: FIB cutting lamella and image using STEM and TEM.

Mechanical fatigue – STEM images



After heat treatment



200 nm

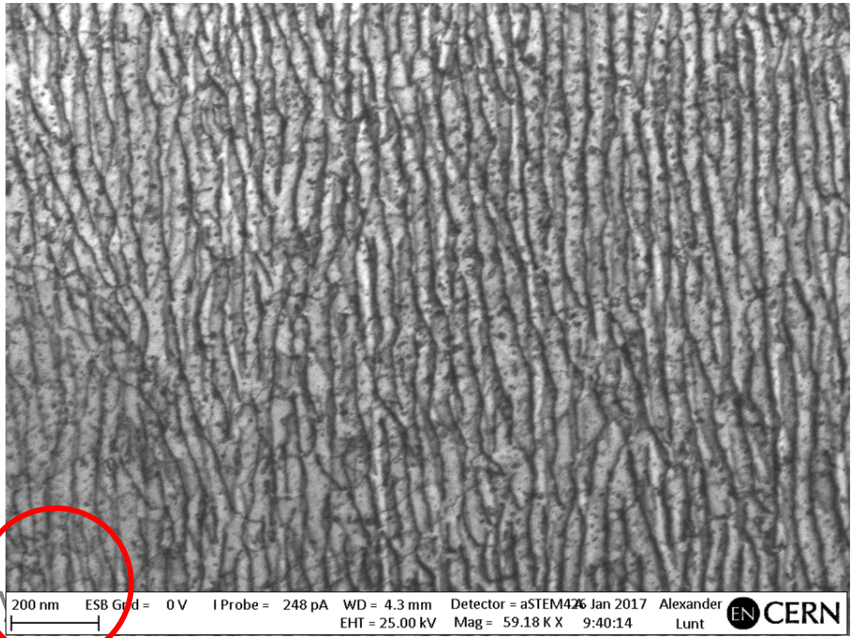
After mechanical fatigue

Formation of dislocation patterns characteristic of hardening.

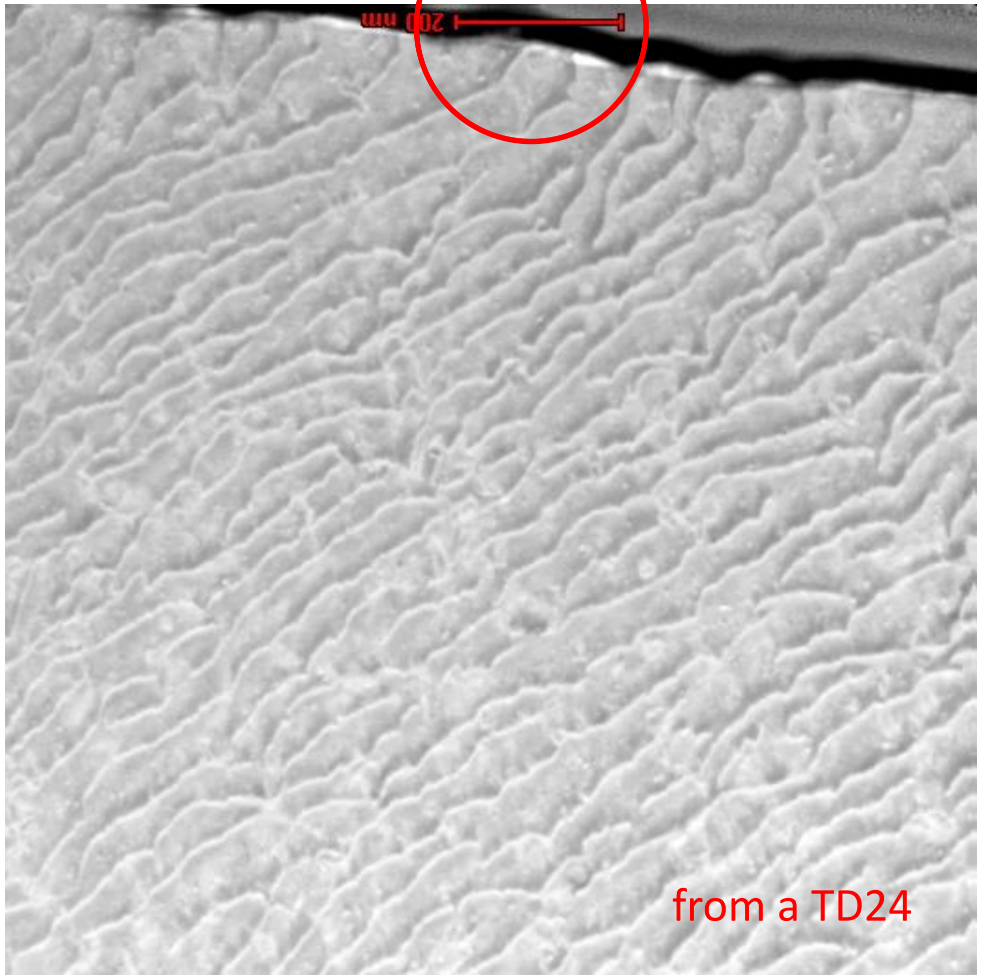
E. Rodriguez Castro

Comparison of mechanical and rf samples

200 nm



200 nm



After rf conditioning, high E field region – TEM image

A. Yashar, I. Popov

Interpretation

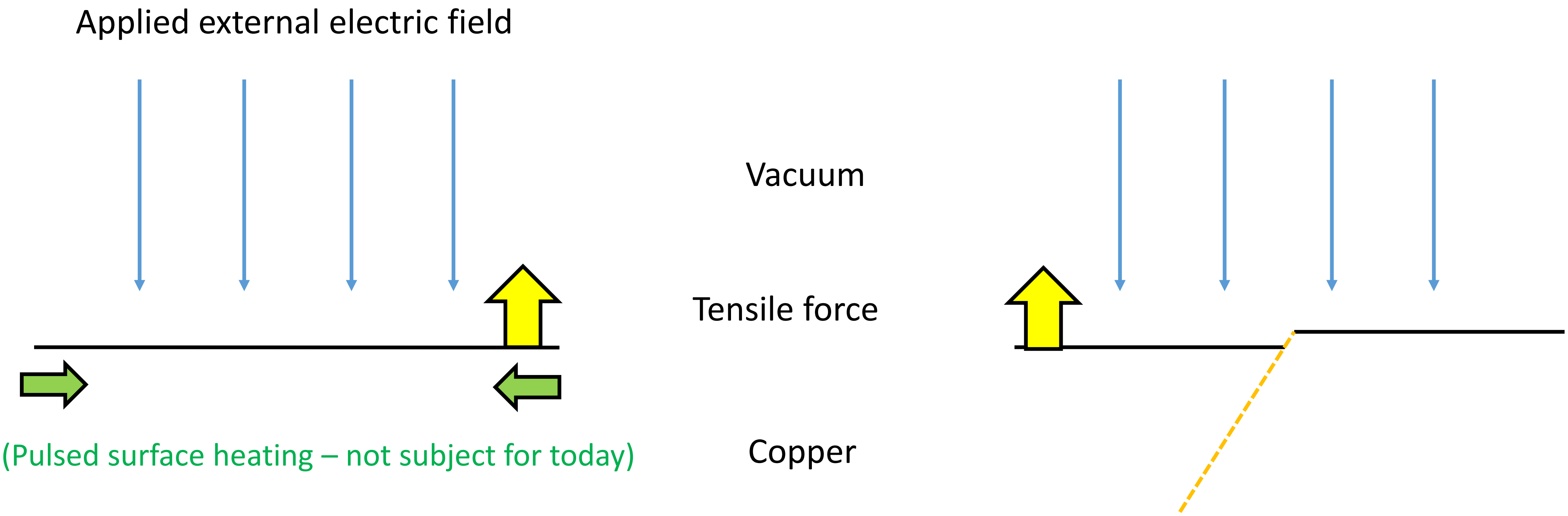
RF operation at high fields produces dislocation patterns similar to fatigue implying:

- A hardening process occurs during conditioning,
- Dislocation dynamics, formation and movement, are central to high-gradient behaviour.

Some numbers:

- Electric field stress is $\sigma = \frac{1}{2}\varepsilon_0 E^2$ so for 250 MV/m surface field, 270 kPa – for perfect flat surface.
- The onset of plastic behaviour in Cu is of the order of kPa, so well above already at 100 MV/m surface field.
- Speed of sound in copper is .38 mm/100 ns, so bulk phenomenon.

Simplified picture

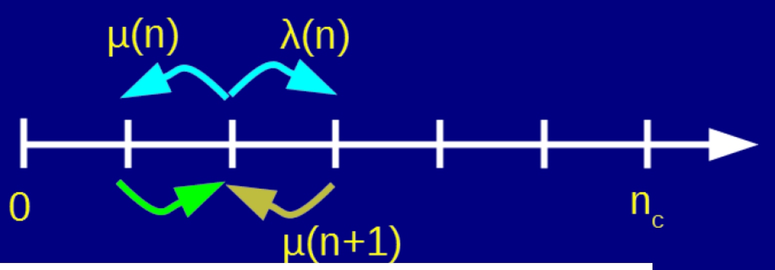


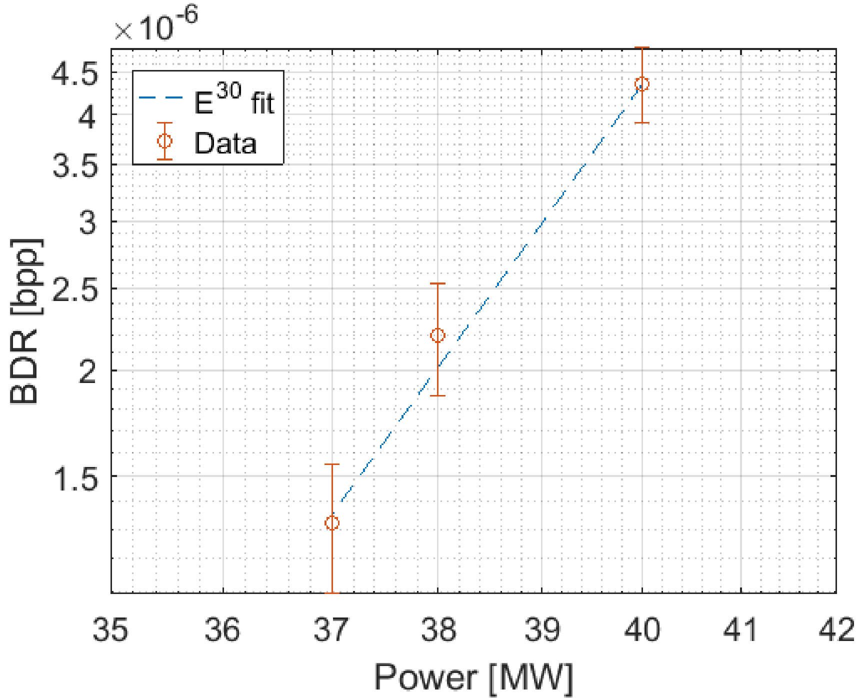
- Tensile stress induces plastic behaviour, i.e. creates dislocations.
- Dislocations move to surface to reduce energy.
- Projection of dislocation on surface in nucleation point for continuation of breakdown process (too little time today for rest of story)

BDR dependence - II

Exact Solution: Master Equation

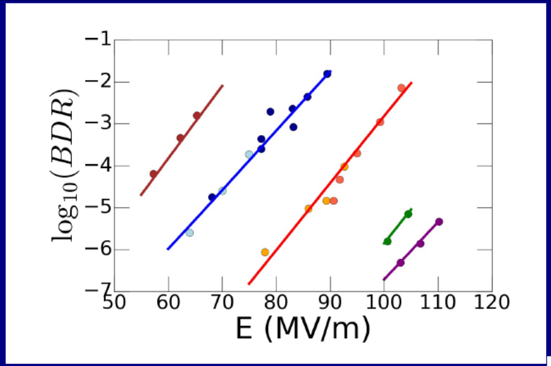
$$\frac{dP(n,t)}{dt} = \lambda(n-1)P(n-1,t) + \mu(n+1)P(n+1,t) - [\lambda(n)+\mu(n)]P(n,t)$$





E. Engelberg

Experiment: Dependence on Field

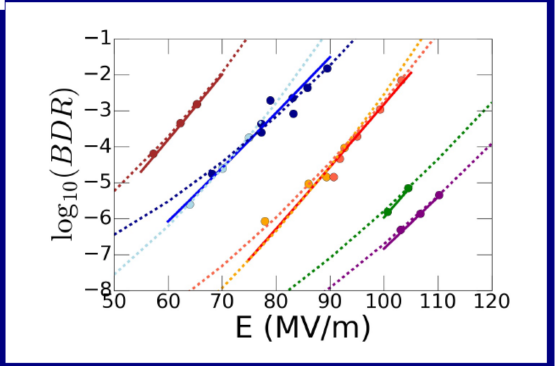


A. Grudiev, S. Calatroni, and W. Wuensch, PRST-AB 12, 102001 (2009)

K. Nordlund and F. Djurabekova, PRST-AB 15, 071002 (2012)

Good fits, consistent with the previously proposed power law!

$$\tau \sim E^{\nu}, \quad 25 < \nu < 30$$



An explanation of high-field conditioning

Copper in its annealed state always has some, but very mobile, dislocations.

Stresses from rf pulses create and move dislocations, which migrate towards surface creating surface features which nucleate breakdown sites.

This dynamic gives us breakdown rate.

Movement of dislocations also form interlocking “sessile” patterns, which reduce movement of later-formed dislocations.

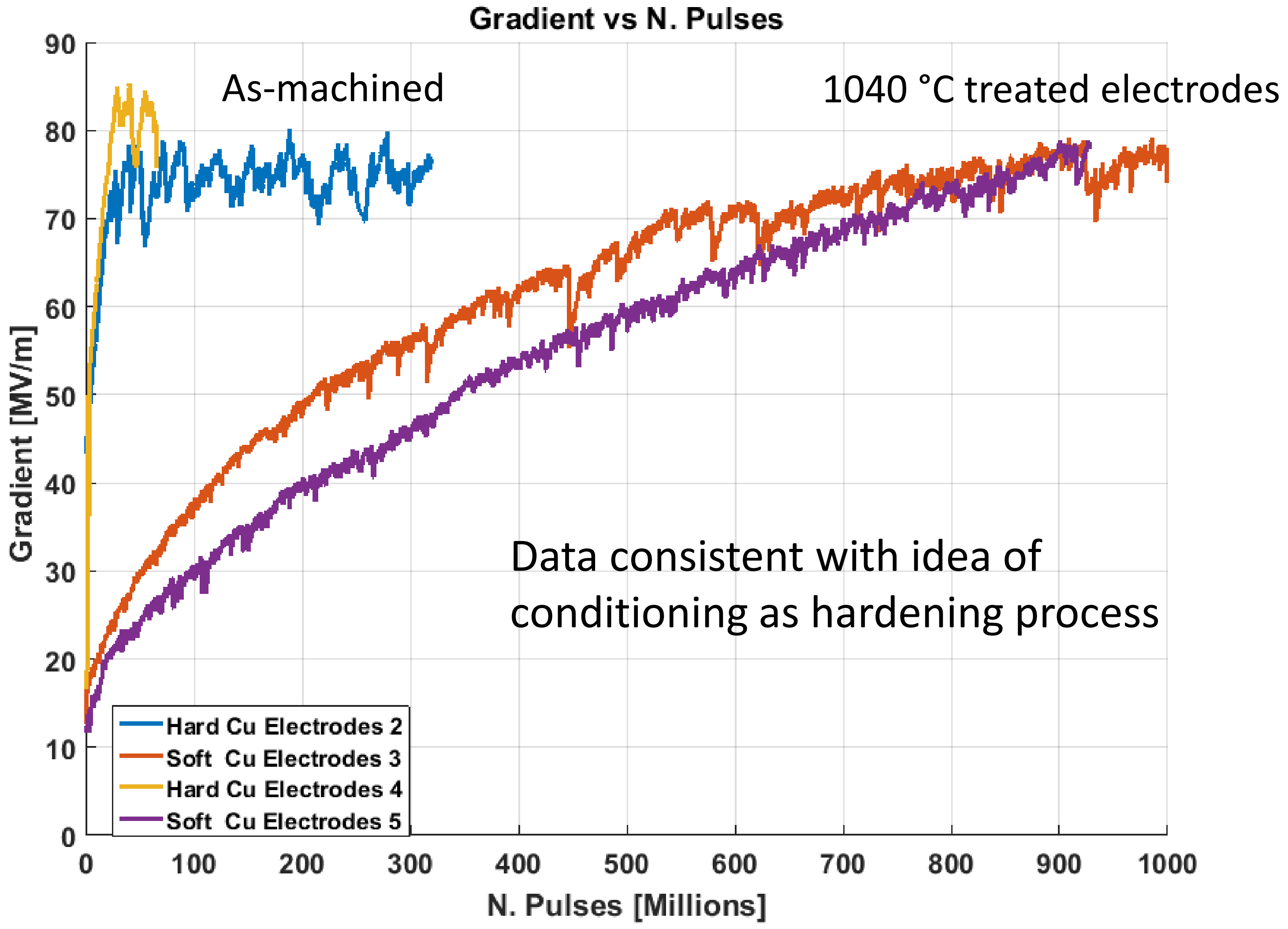
This interplay is what lies behind field dependence, conditioning and gives ultimate gradient.

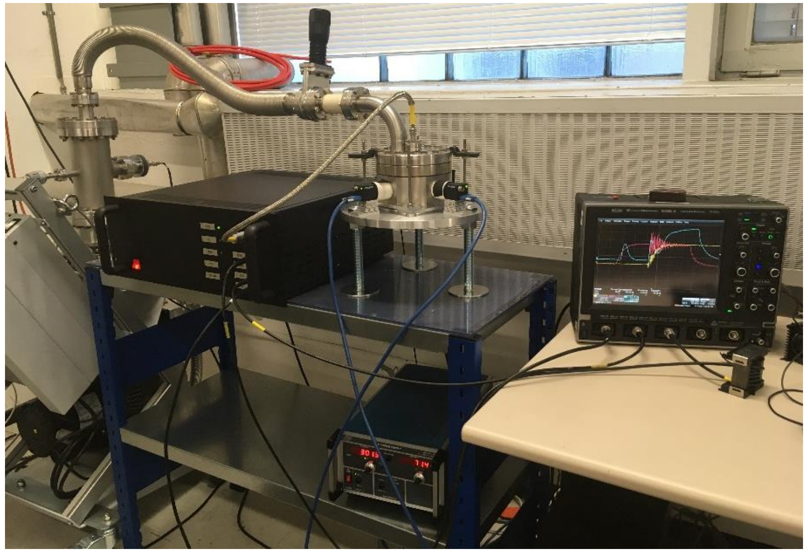
BD nucleation as a critical transition in dislocation population, Y. Ashkenazy

Stochastic Model of Breakdown Nucleation under Intense Electric Fields, E. Engelberg

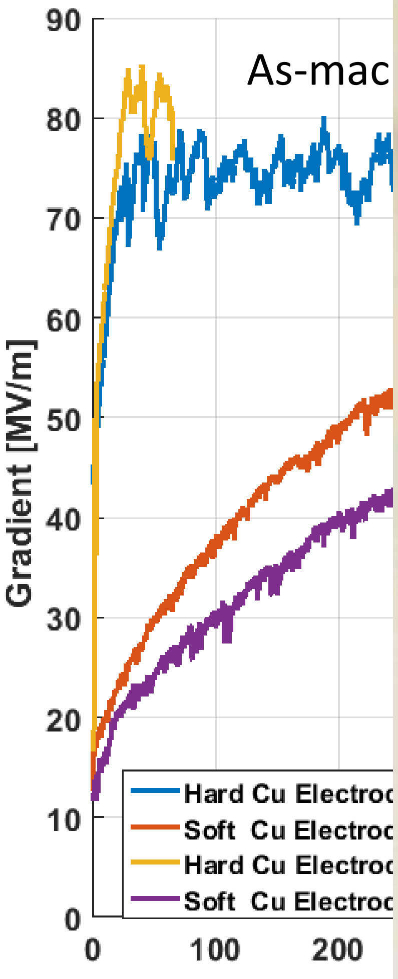
both at MeVArc2017 https://indico.cern.ch/event/521667/

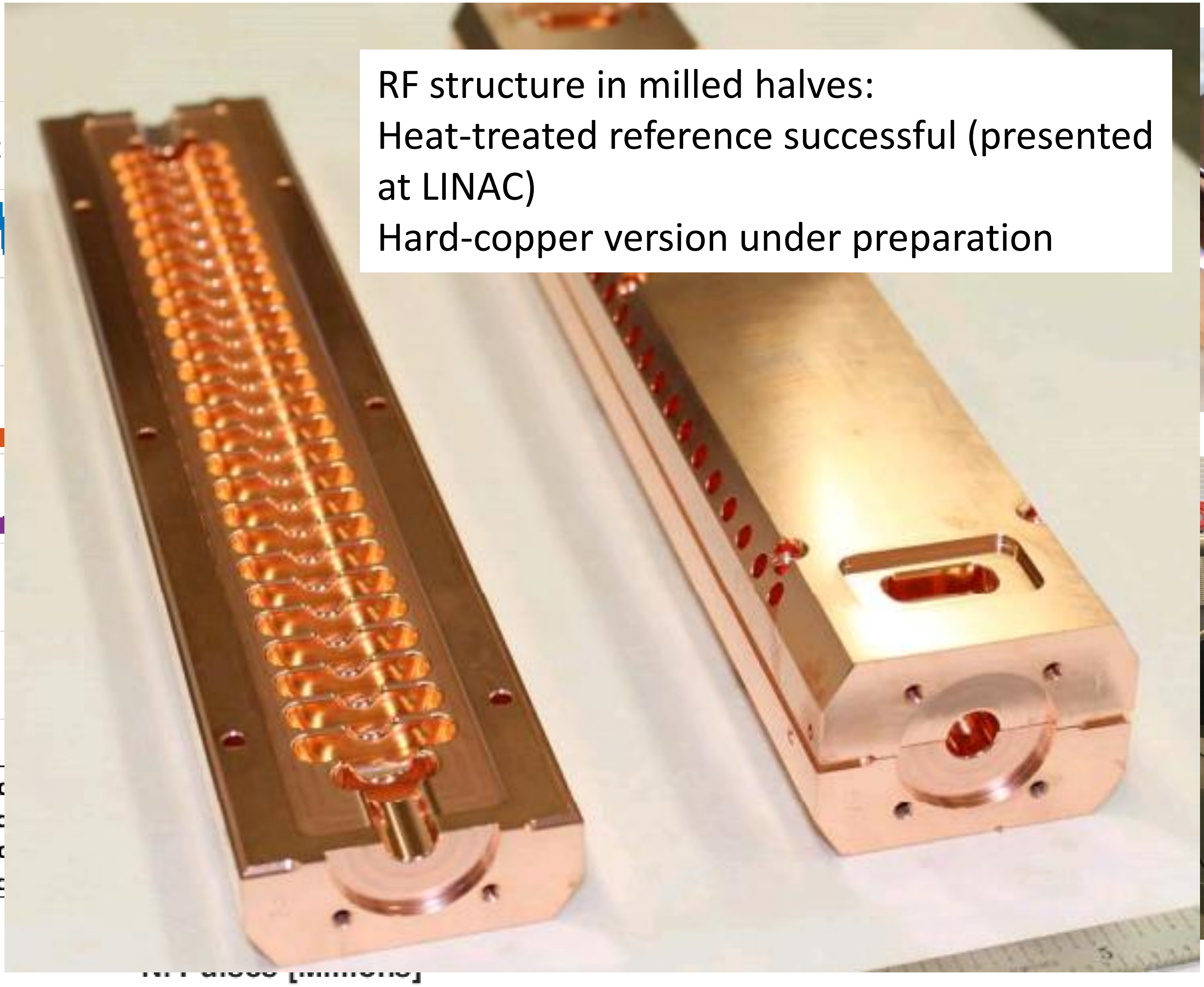
Hard vs. soft copper in pulsed dc system



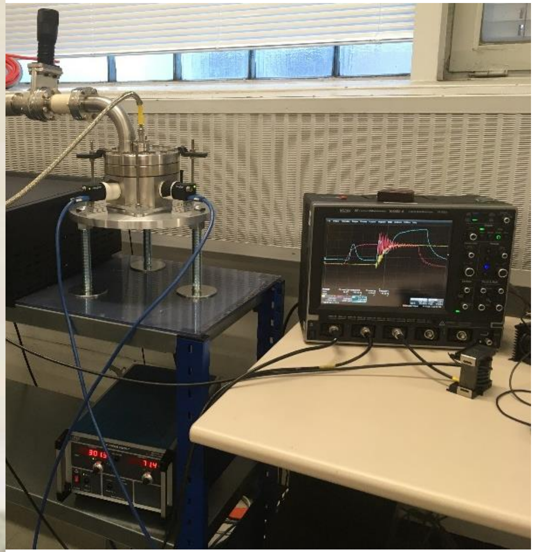


Hard vs. soft copper in pulsed dc system





RF structure in milled halves:
Heat-treated reference successful (presented at LINAC)
Hard-copper version under preparation



Summary

- Breakdown rate vs gradient,
- Conditioning vs number of pulses,
- Material state before and after conditioning,

All point to the importance of dislocation dynamics in determining behaviour and Ultimate Gradient in high-gradient normal conducting rf structures.

A crucial stage of the action is below the surface!

Acknowledgements

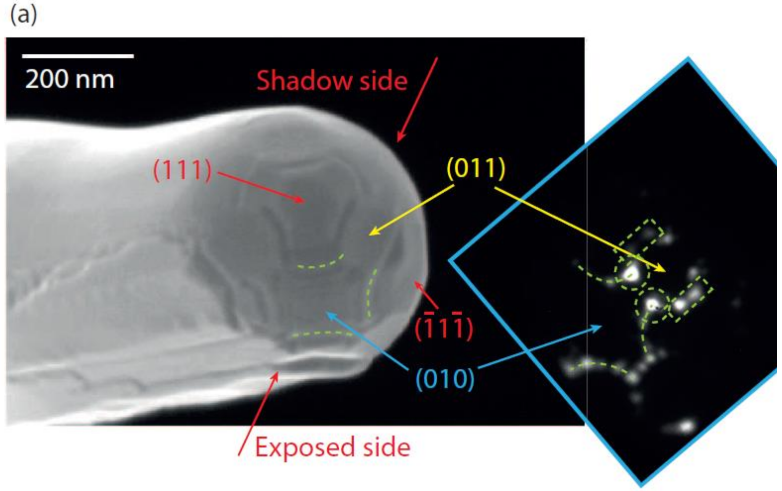
The results presented are the fruit of an extensive effort of many colleagues over many years. I would like to sincerely acknowledge, and thank:

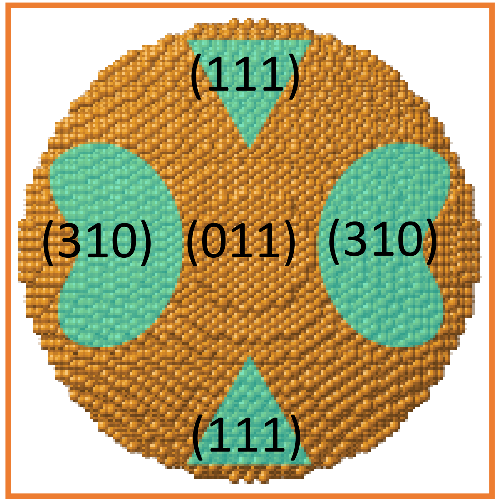
- Flyura Djurabekova and her team at the University of Helsinki
- Yinon Ashkenazy and his team at the University of Jerusalem
- Vahur Zhadin and his team at the University of Tartu
- My high-gradient CLIC colleagues at CERN

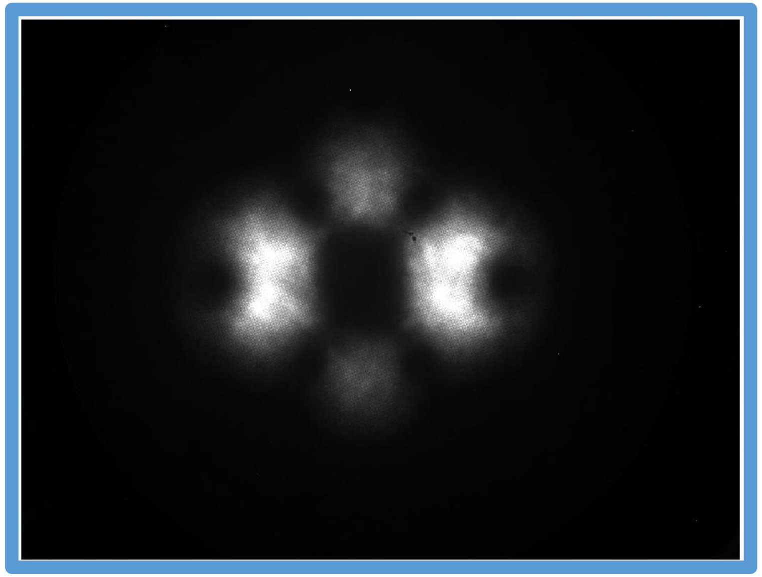
Much more at Mechanisms of Vacuum Arcs, MeVArc2017
https://indico.cern.ch/event/521667/overview

Extra slides
(next step in breakdown)

Example of growth of nano-sized field emitter







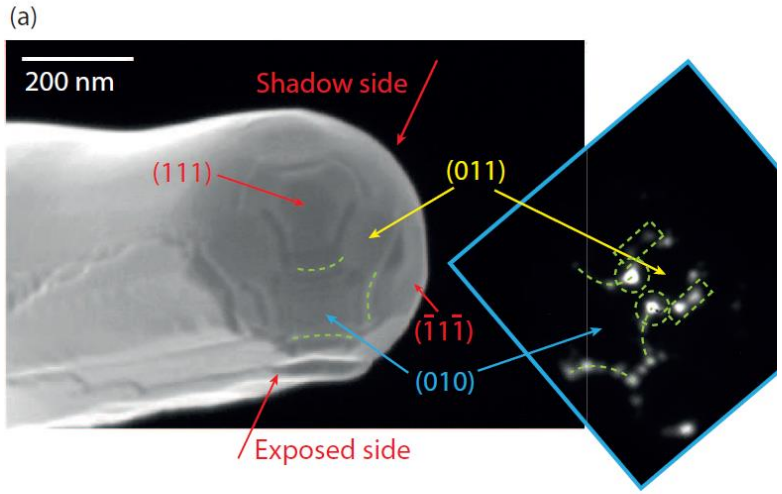
Tungsten tip used in ultra-fast electron diffraction.

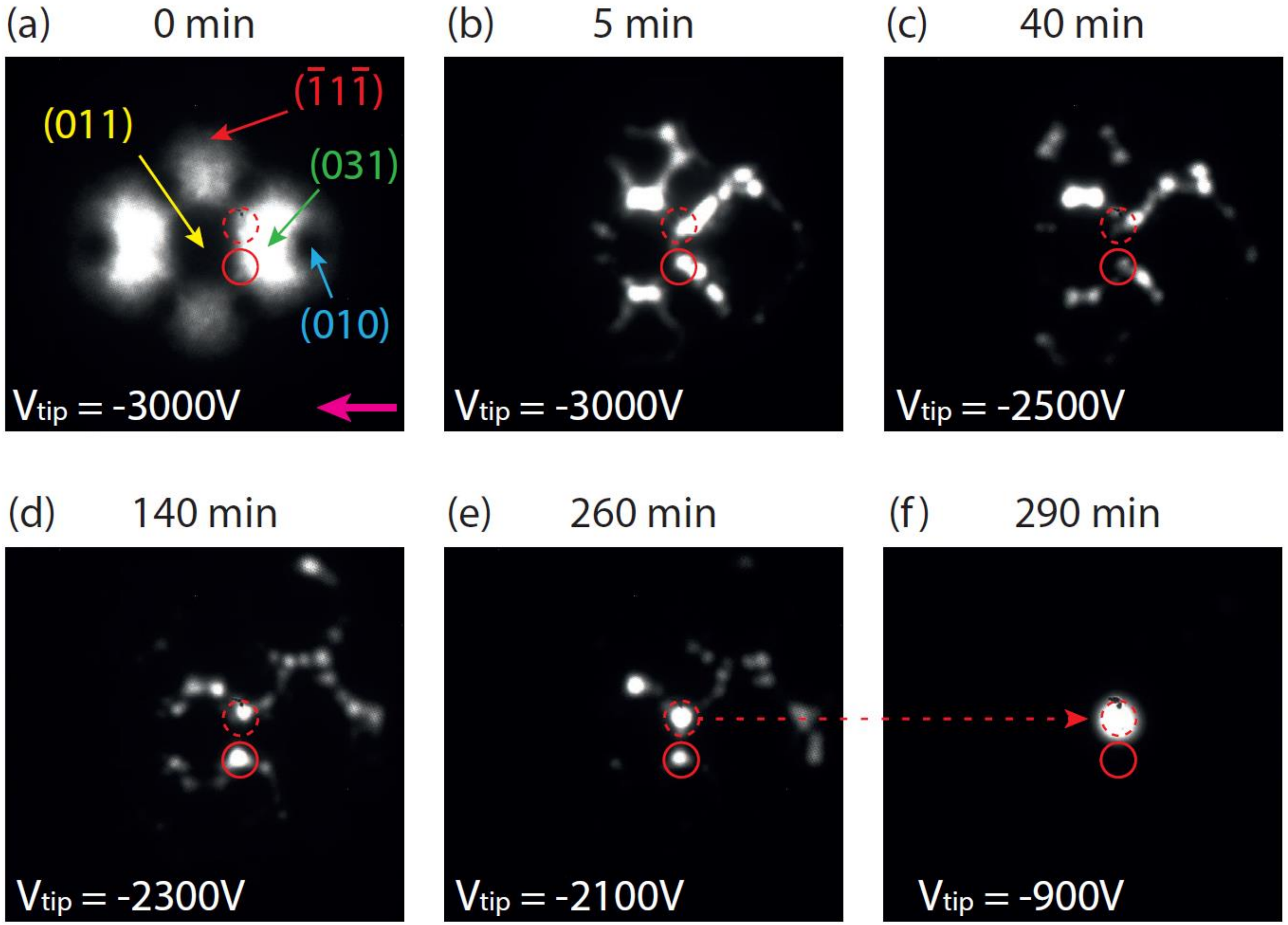
Tips deteriorate under laser pulsing but:

- Small area to uniquely identify characteristics of field emission sites
- Intense femtosecond fields opportunity to benchmark molecular dynamics and kinetic Monte Carlo codes

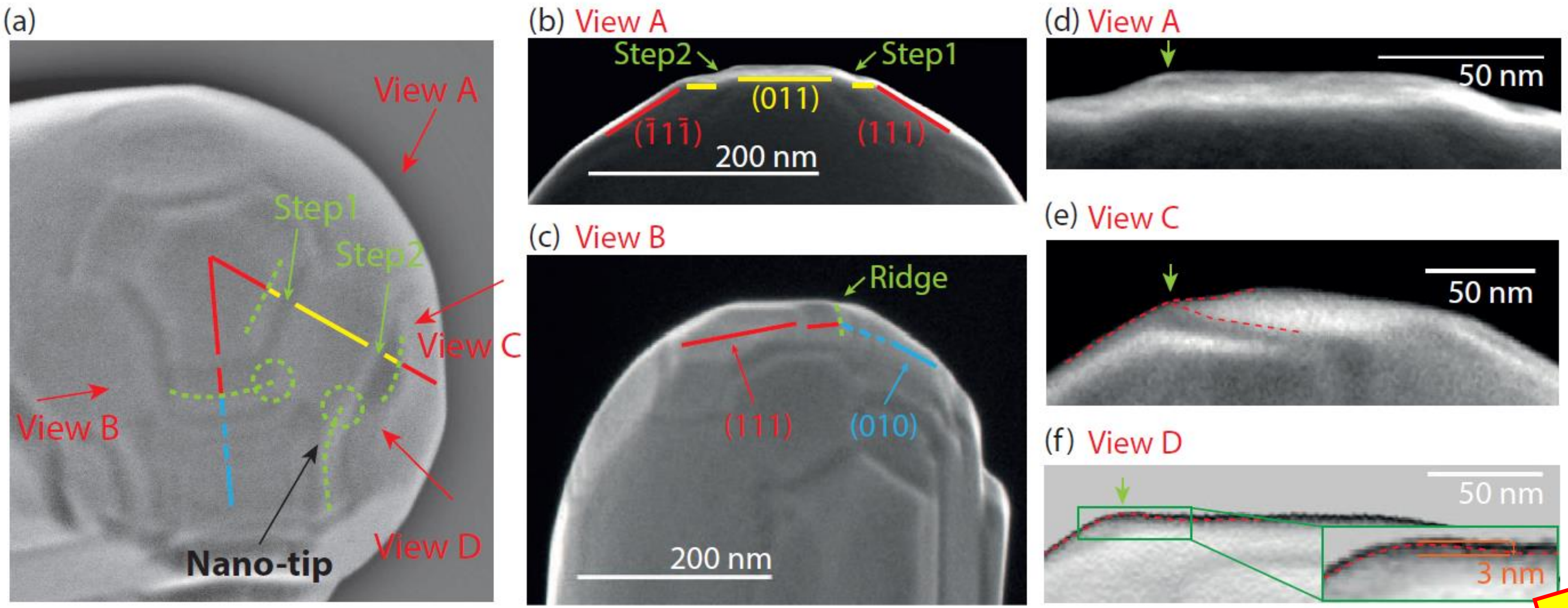
Hirofumi Yanagisawa, et. al. *Laser-induced asymmetric faceting and growth of a nano-protrusion on a tungsten tip*, APL Photonics 1, 091305 (2016); doi: 10.1063/1.4967494

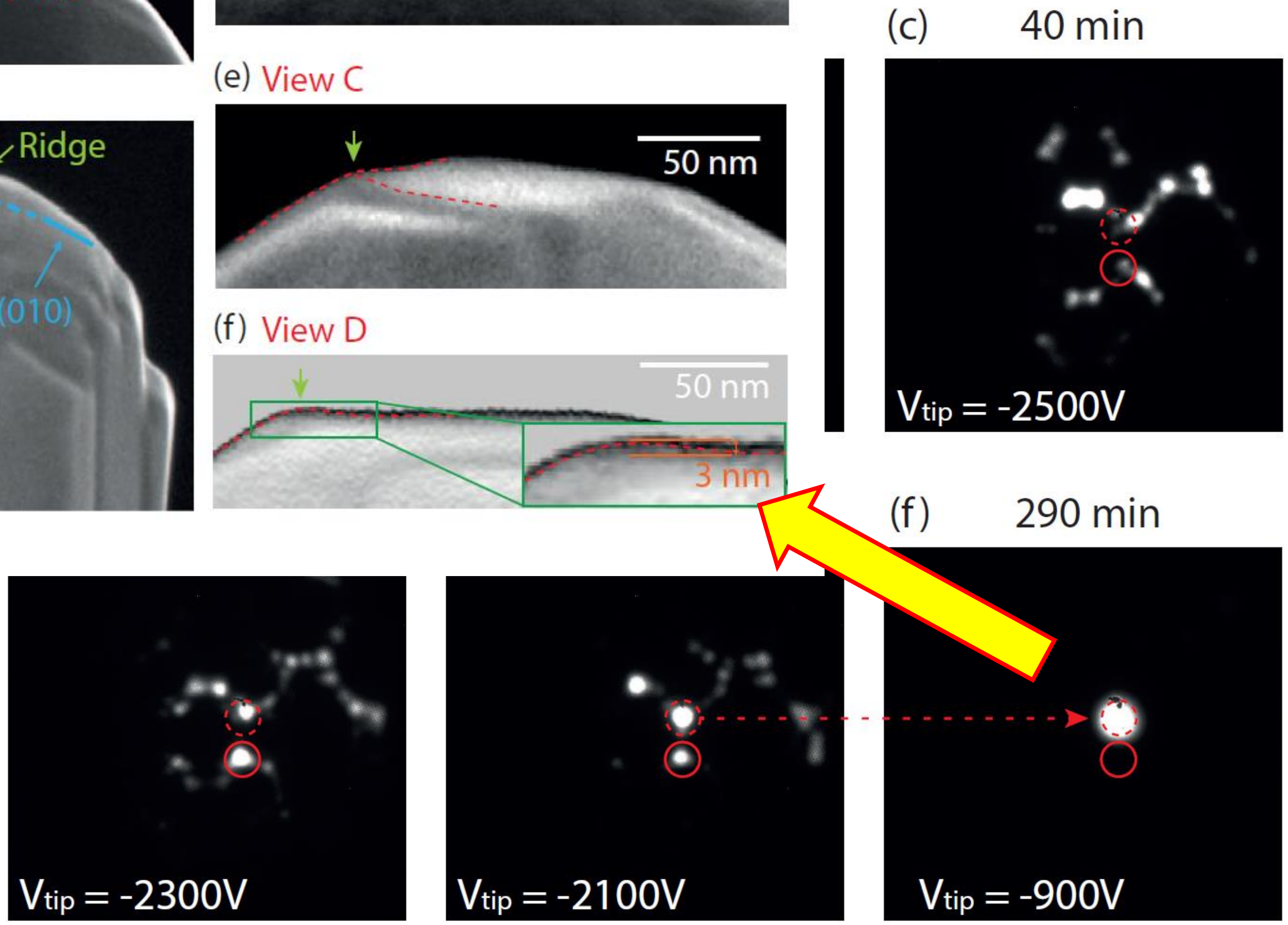
Evolution of field emission during laser pulsing





Identification of nm-sized emission site





Kinetic Monte Carlo Results