



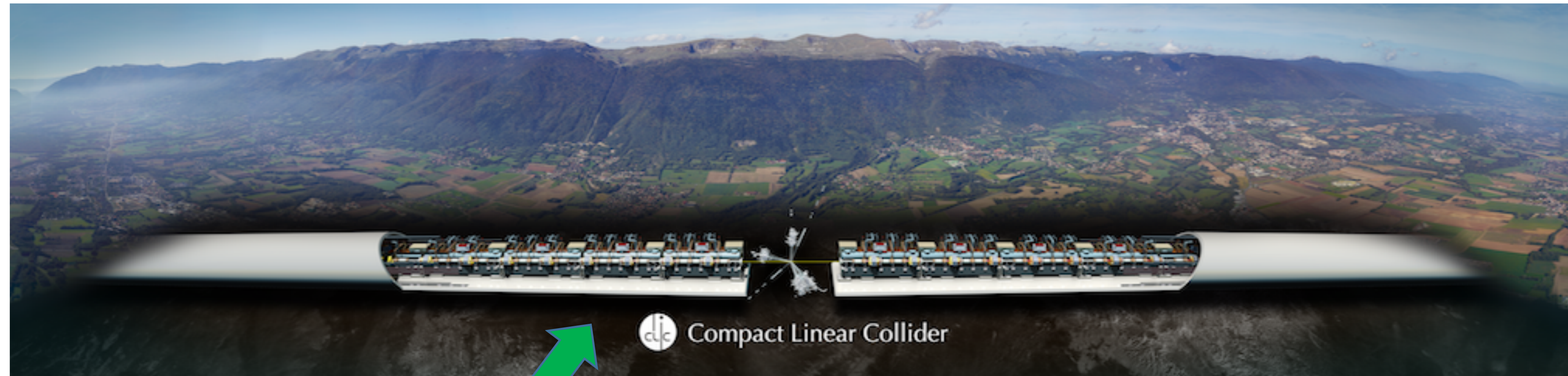
Ultimate Field Gradient in Metal Structures



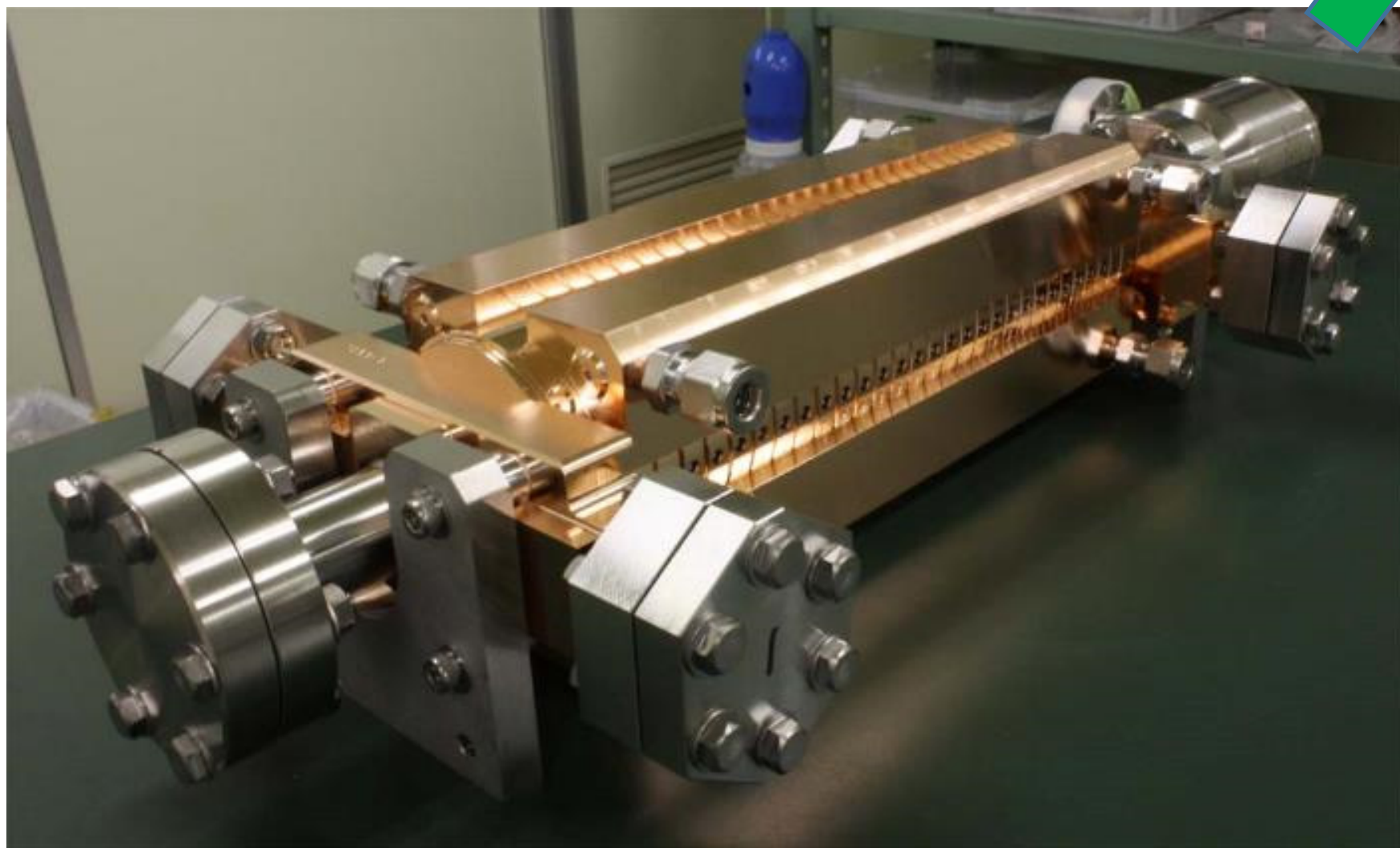
Ultimate Field Gradient **Limitation** in Metal Structures

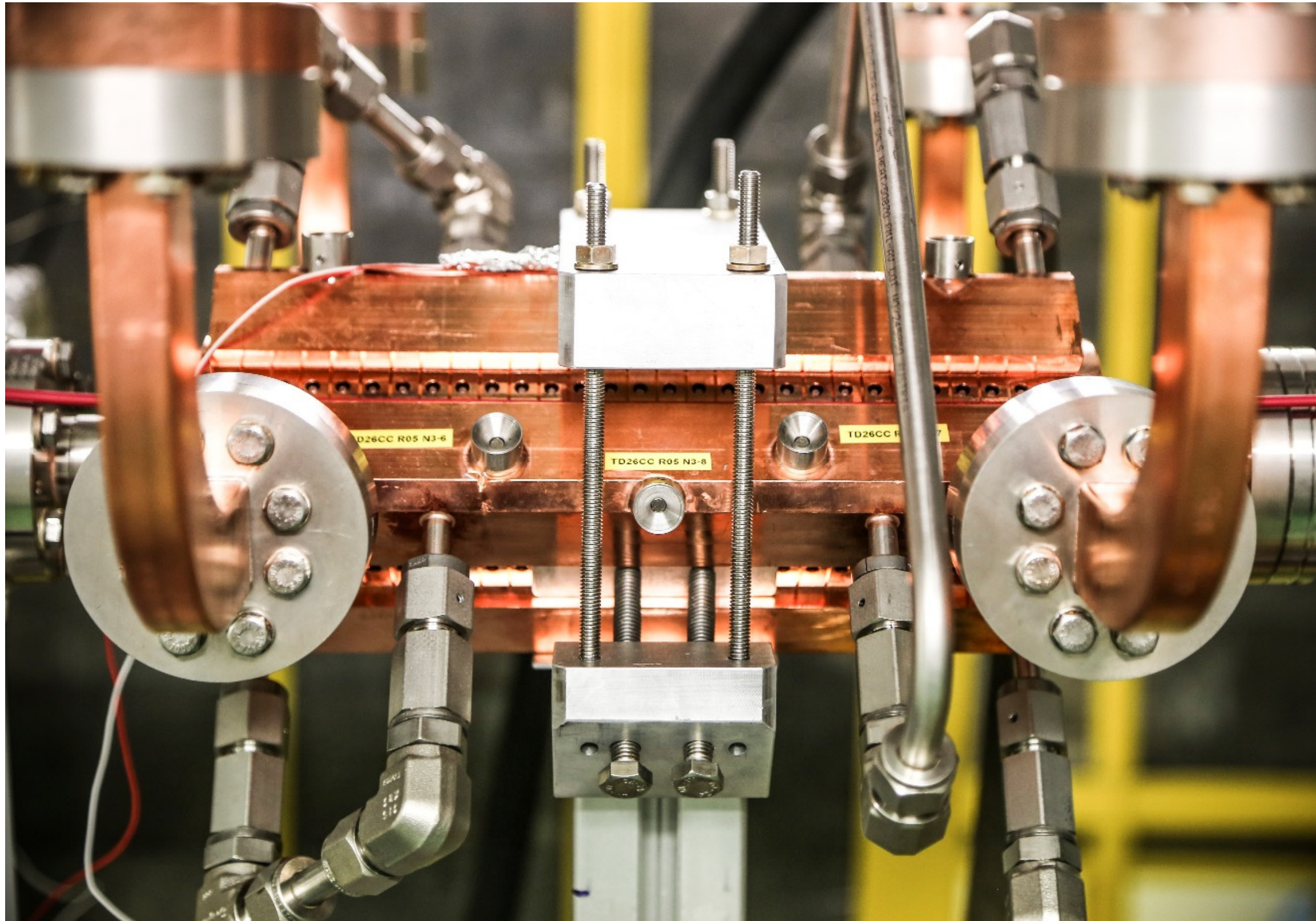


Background



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.





← 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

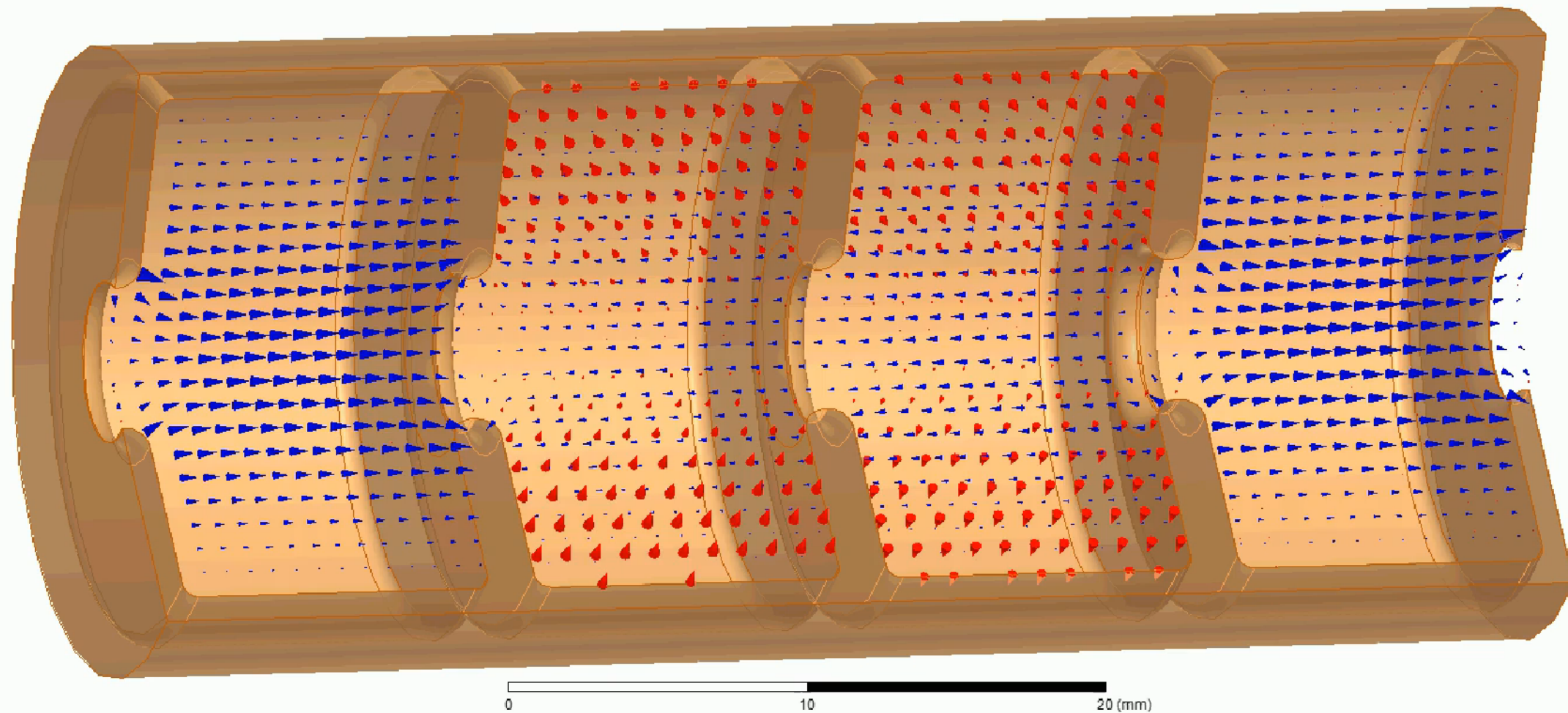


Micron-precision disk

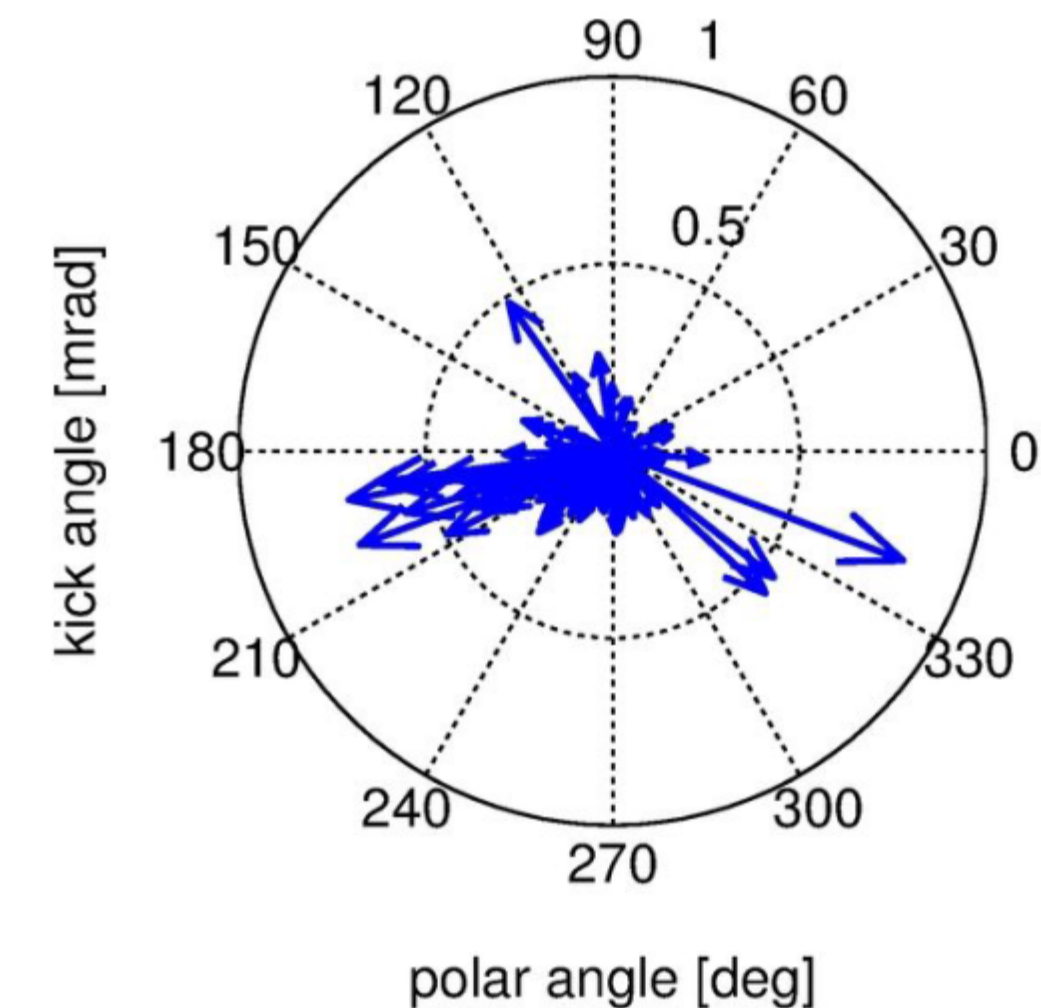
Vacuum arcing

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

- Suppresses power flow reducing acceleration
- Gives beam transverse kick

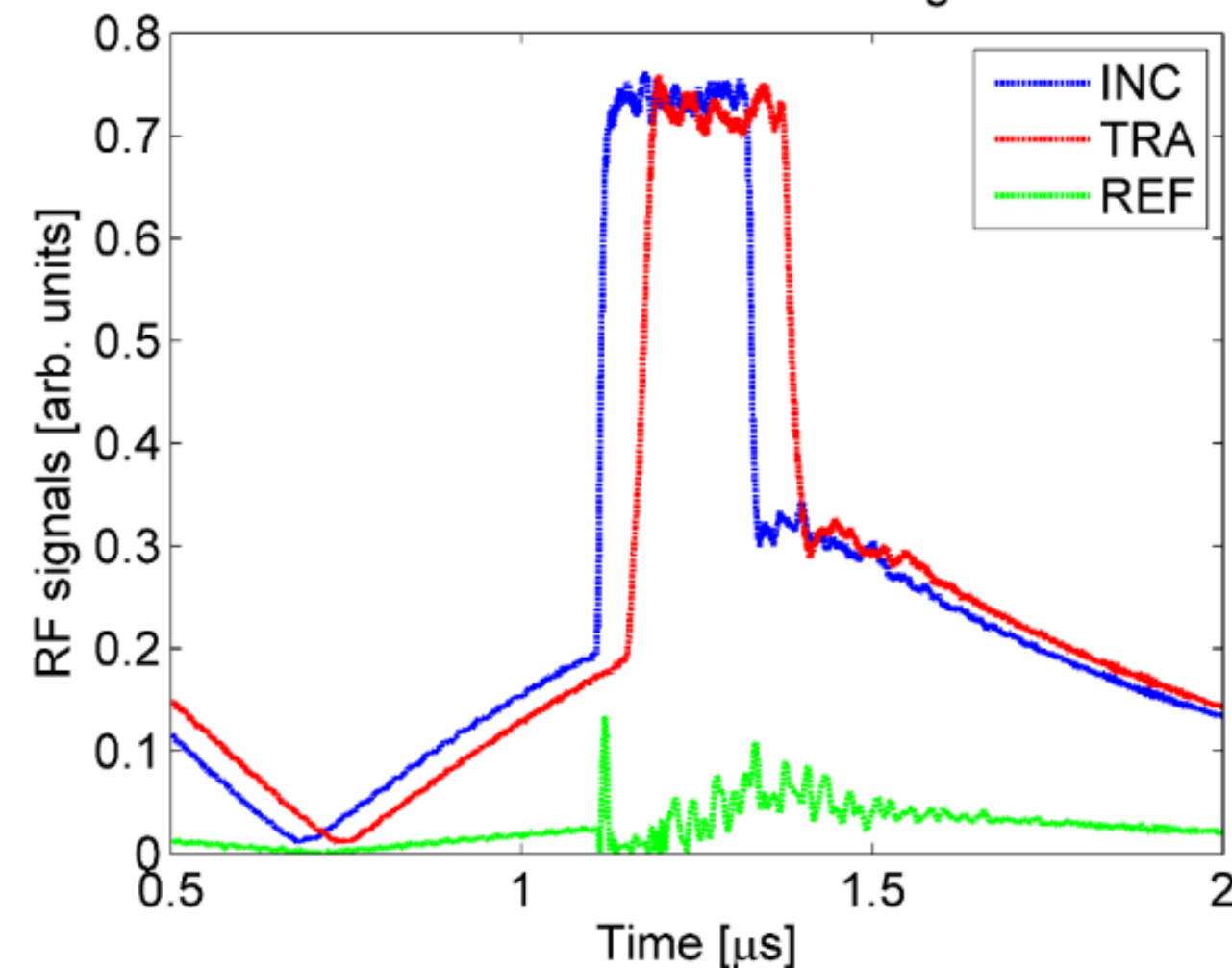


Kicks to the beam measured on screen CA.MTV0790

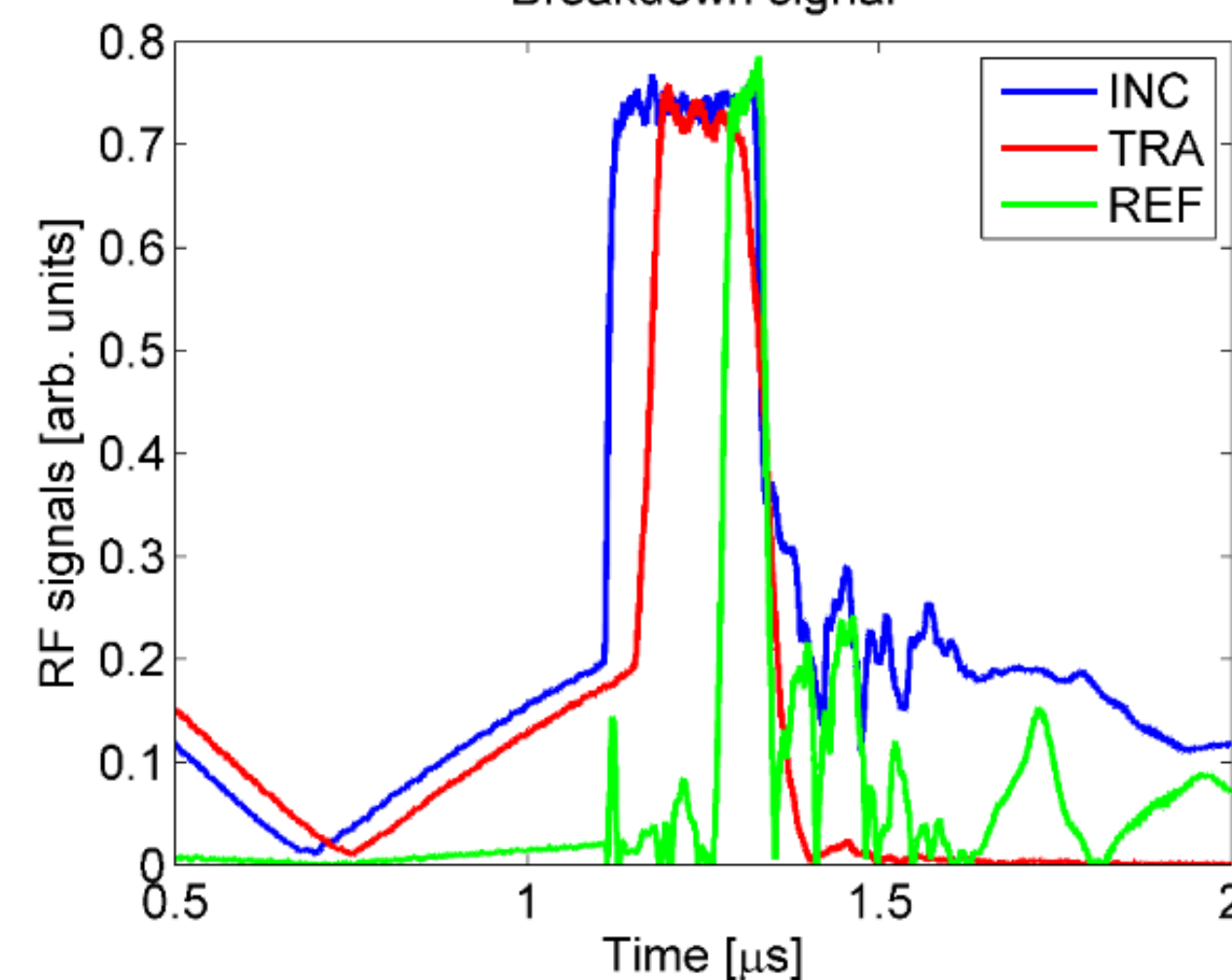


Transverse effect on beam measured in CTF3, A. Palaia

Previous to Breakdown signal



Breakdown signal



Effect on rf



Very high-field vacuum arcs

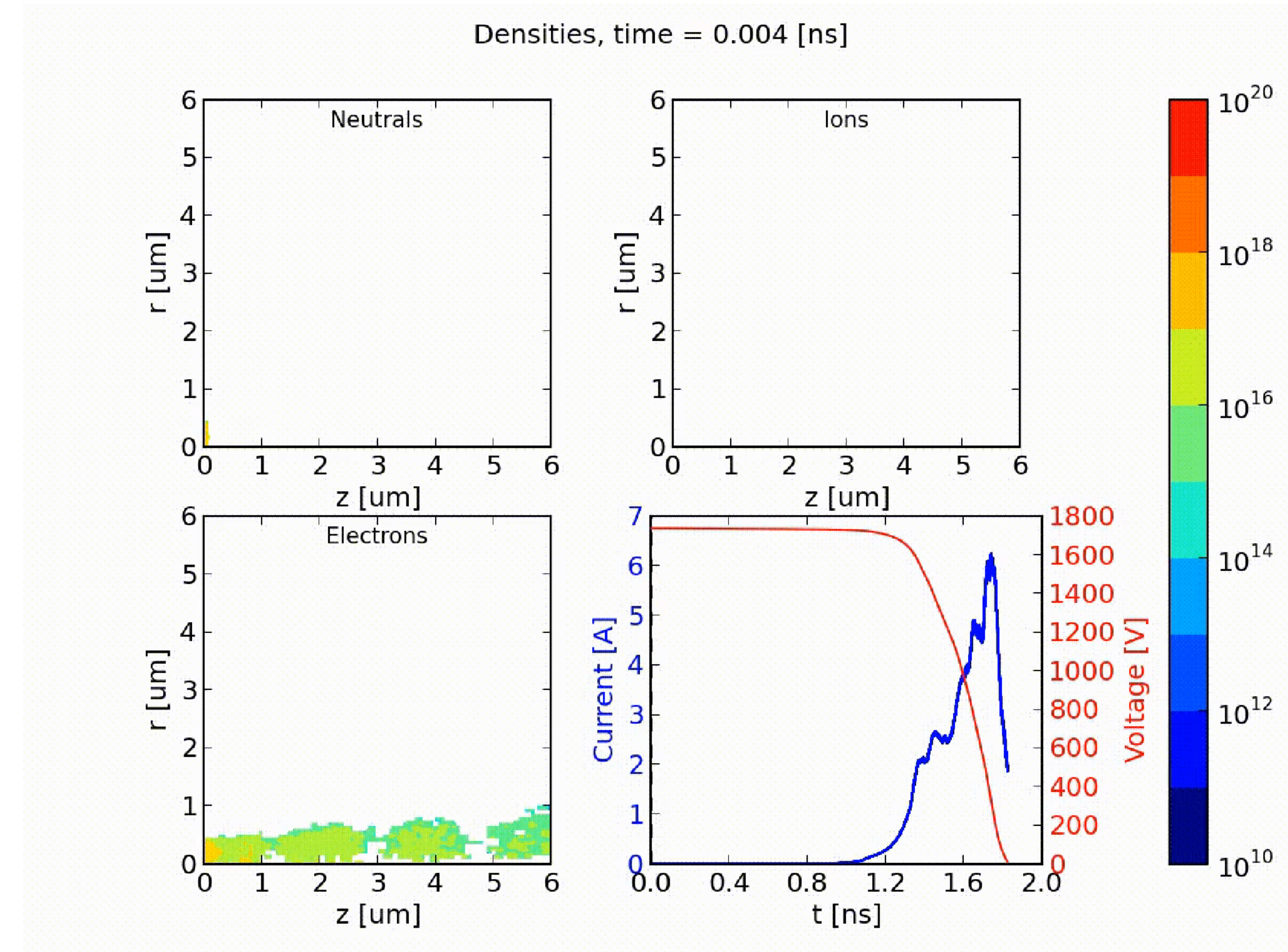


Vacuum arcs – the formation of plasma accompanied by large electron currents - occur in many devices and applications.

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.



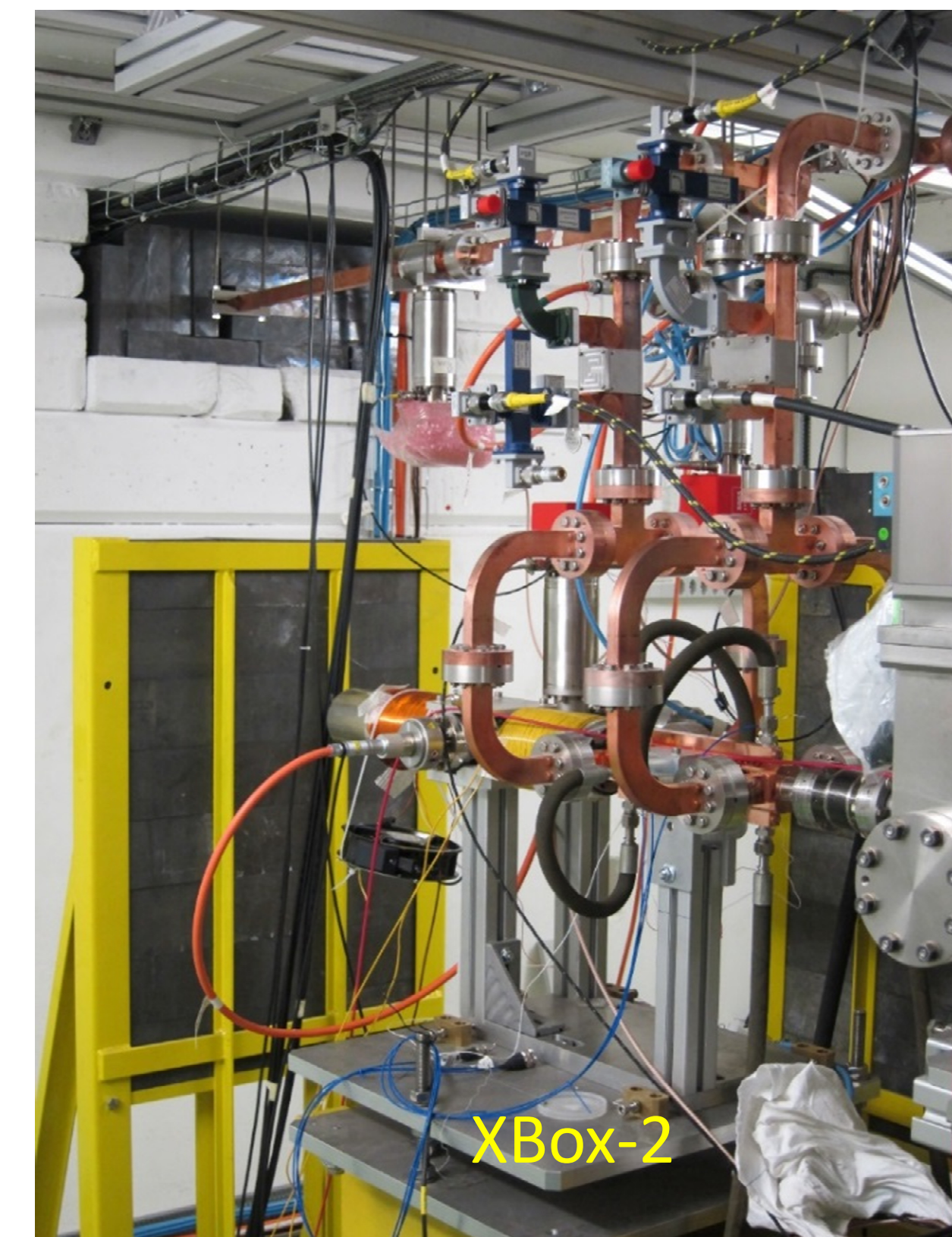
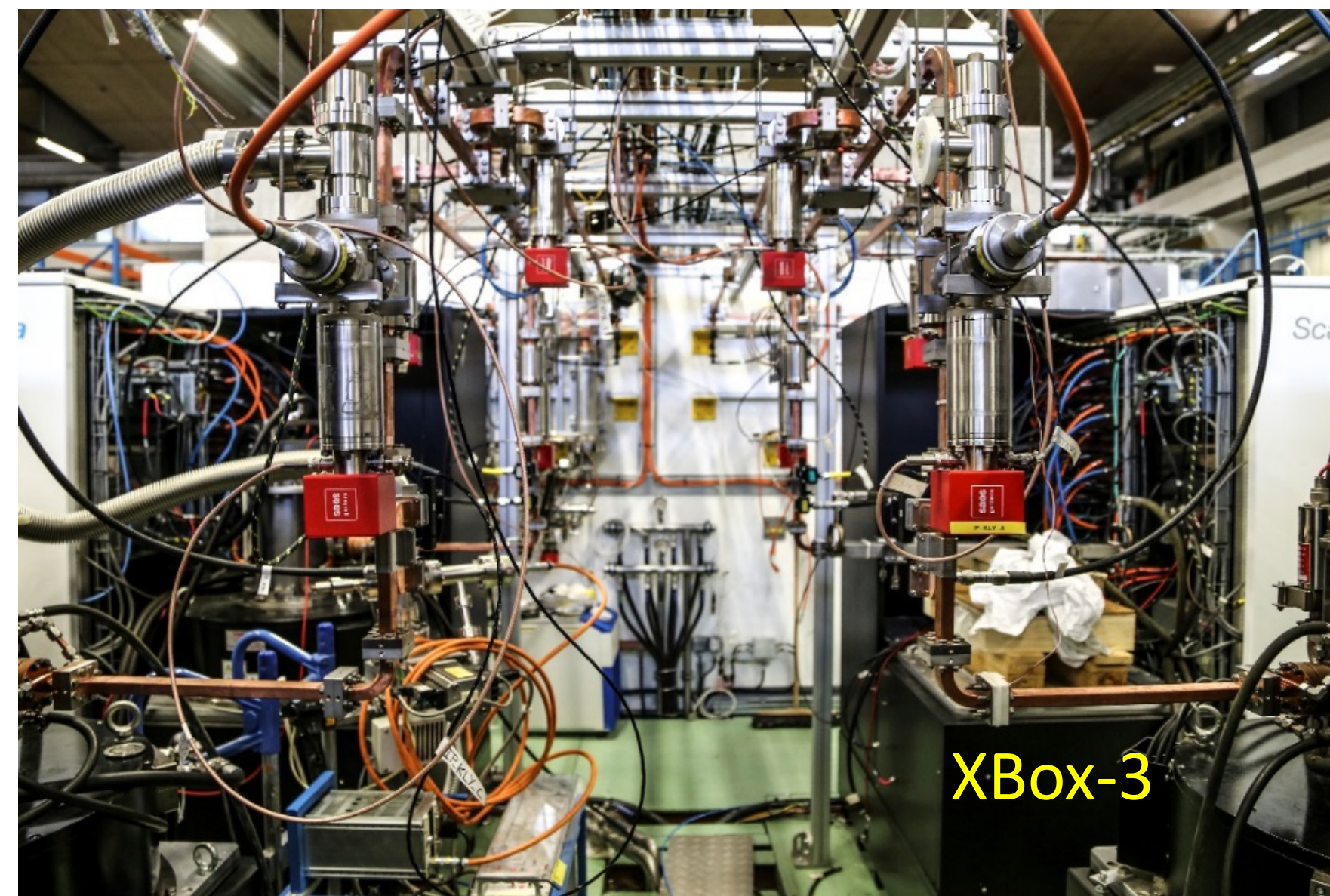
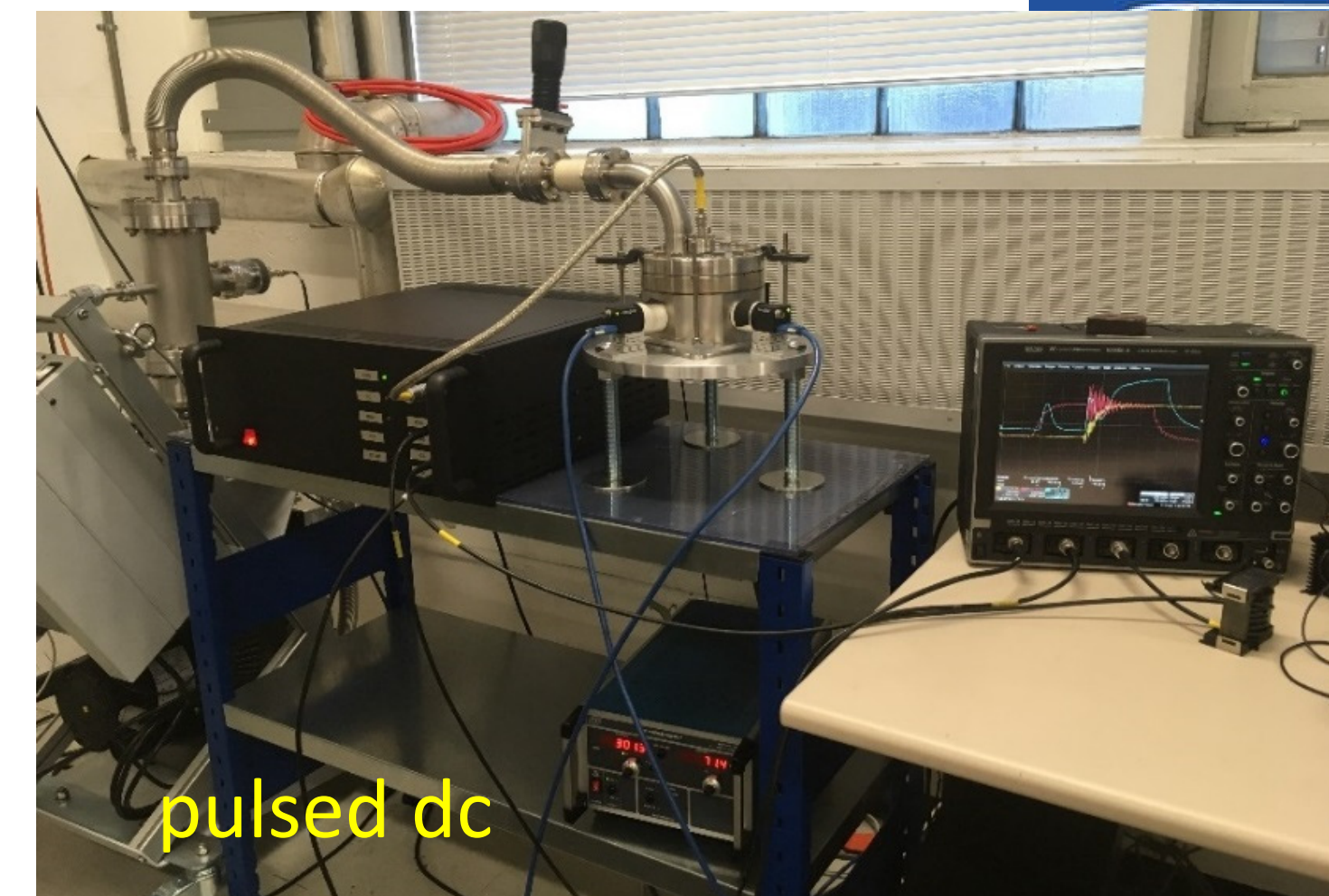
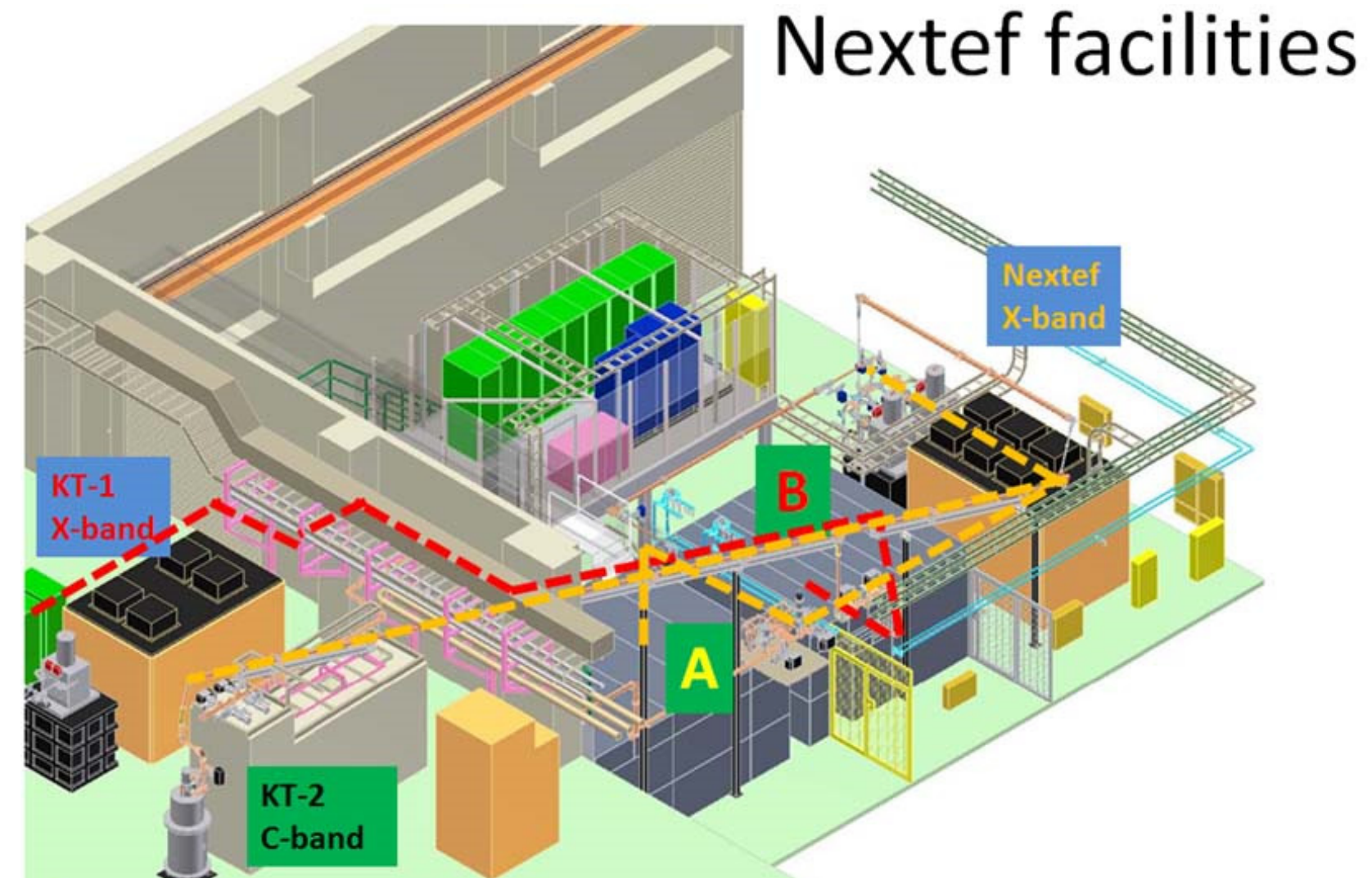
Onset of a vacuum arc simulated by ArcPIC, K. Sjobaek

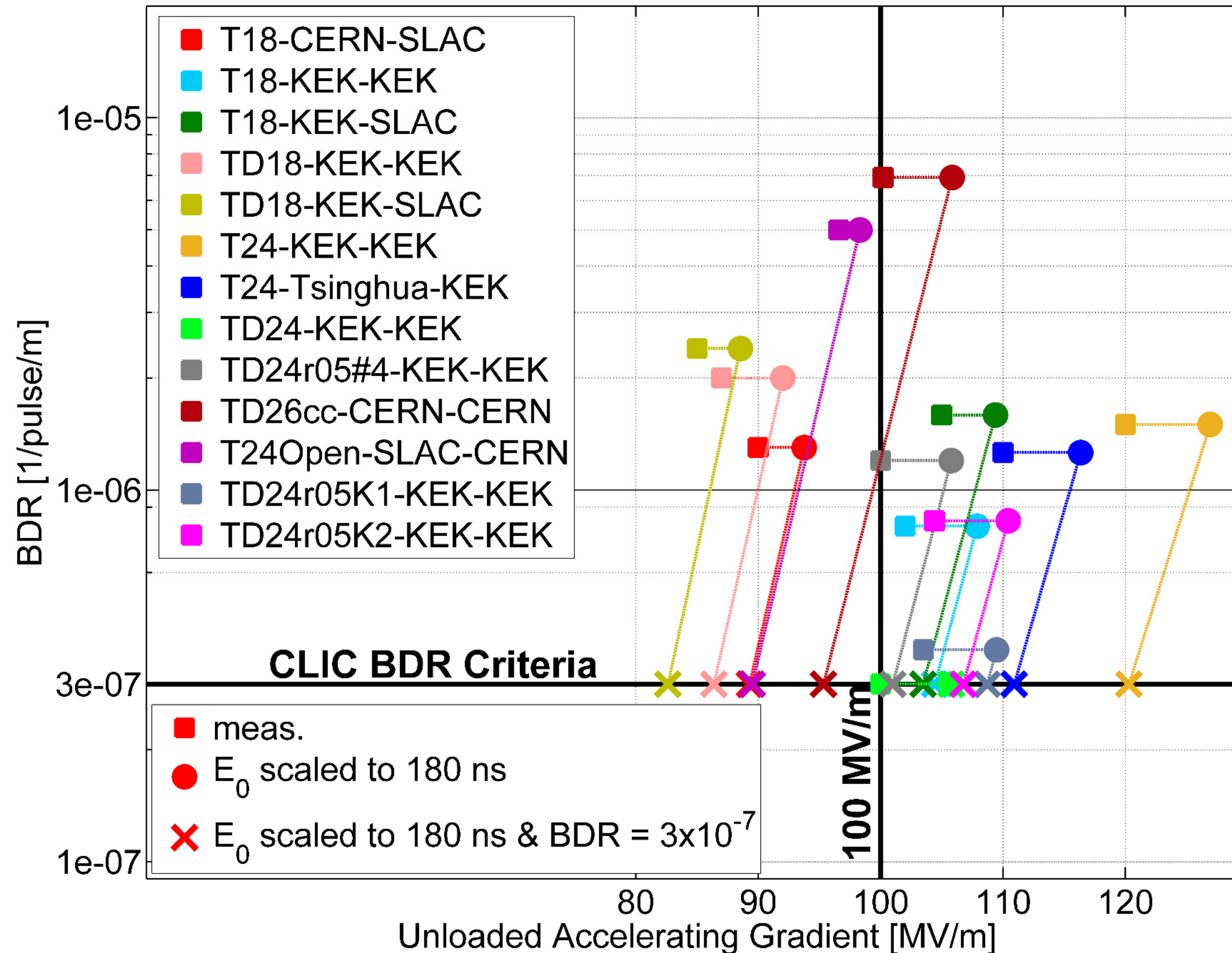


Where we do our experiments

Klystron-based test stands at CERN:

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





Currently under test:

XBox1 – TD26CC N2

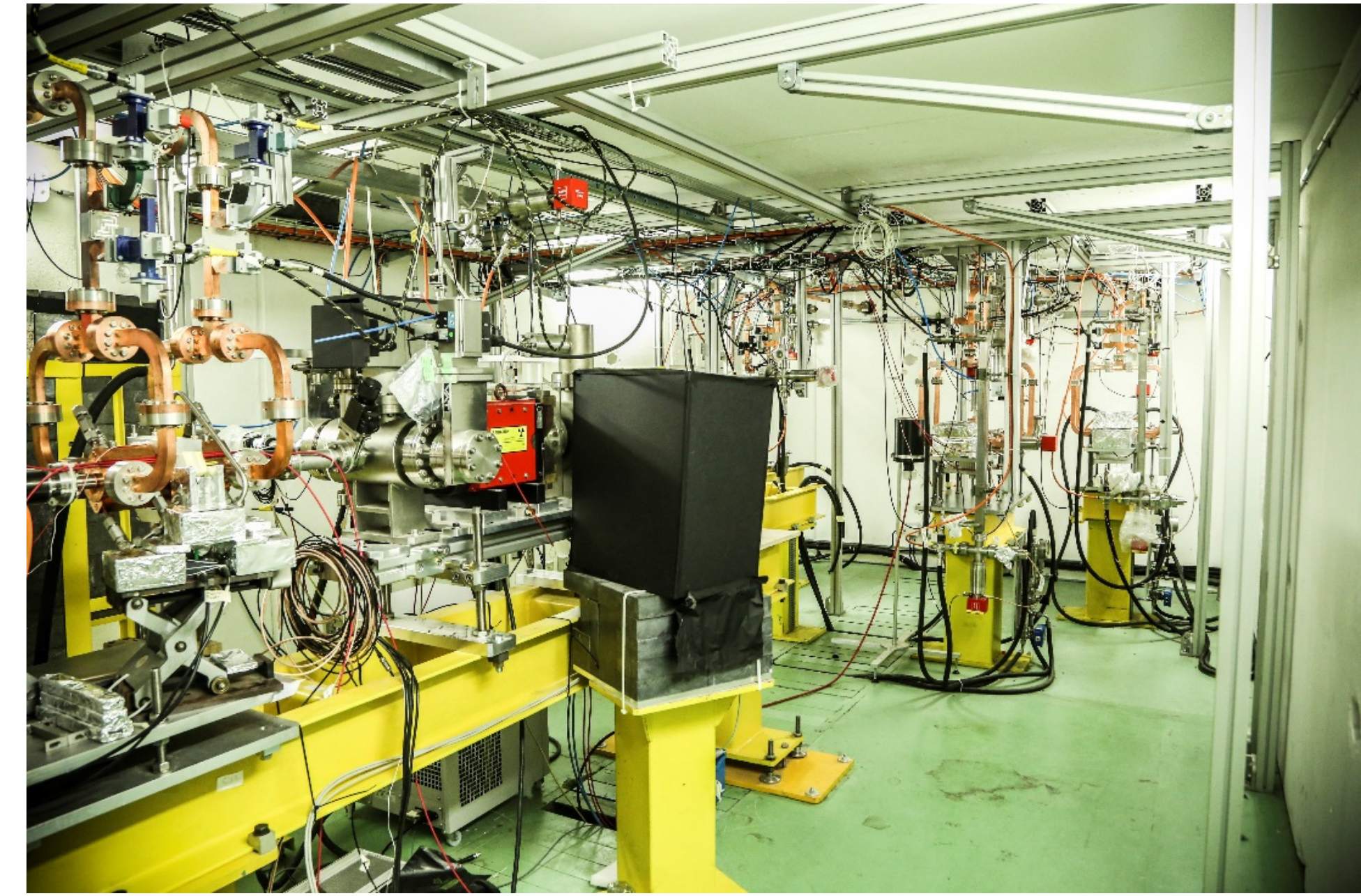
XBox2 – TD26CC N3

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?

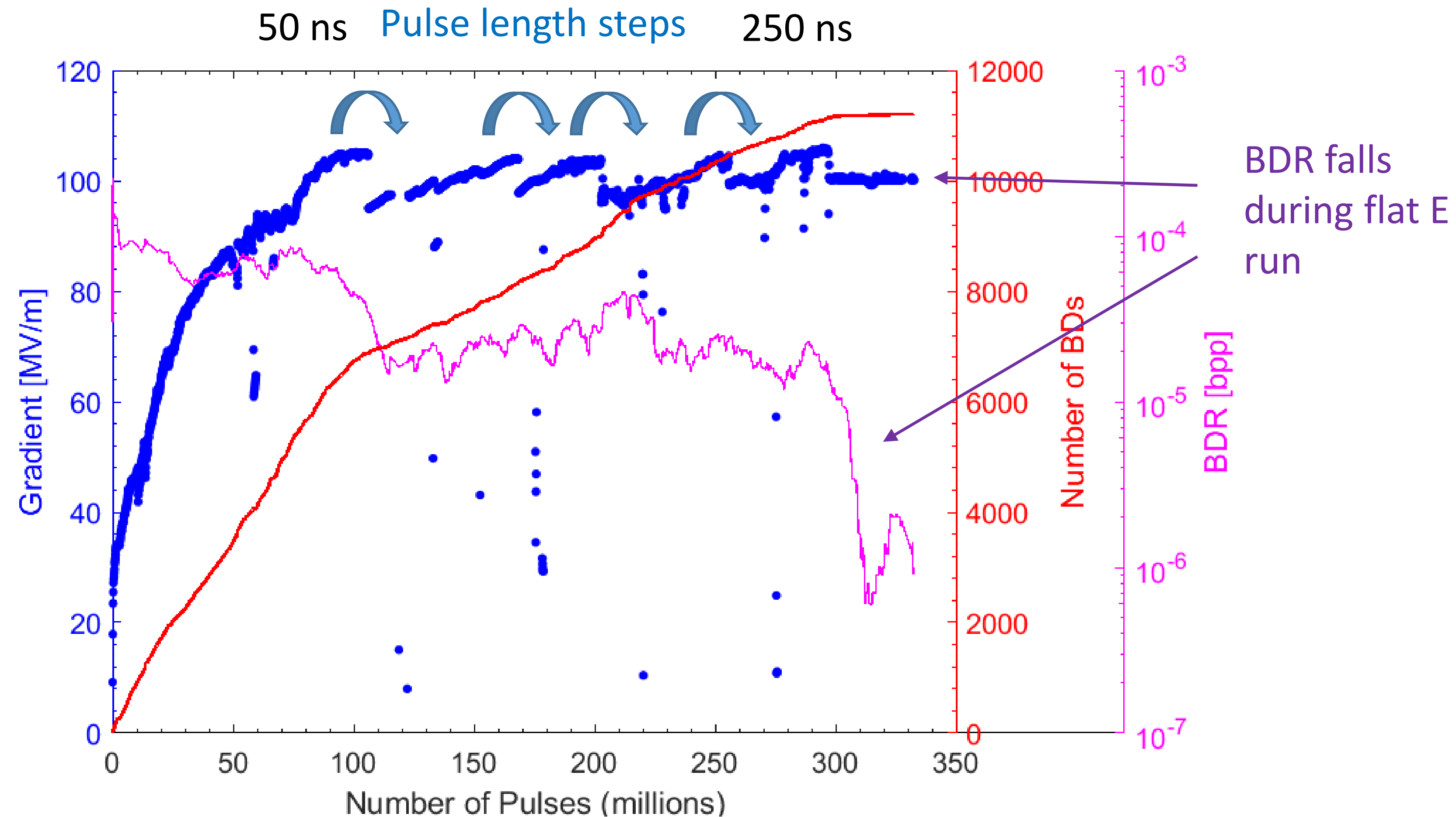
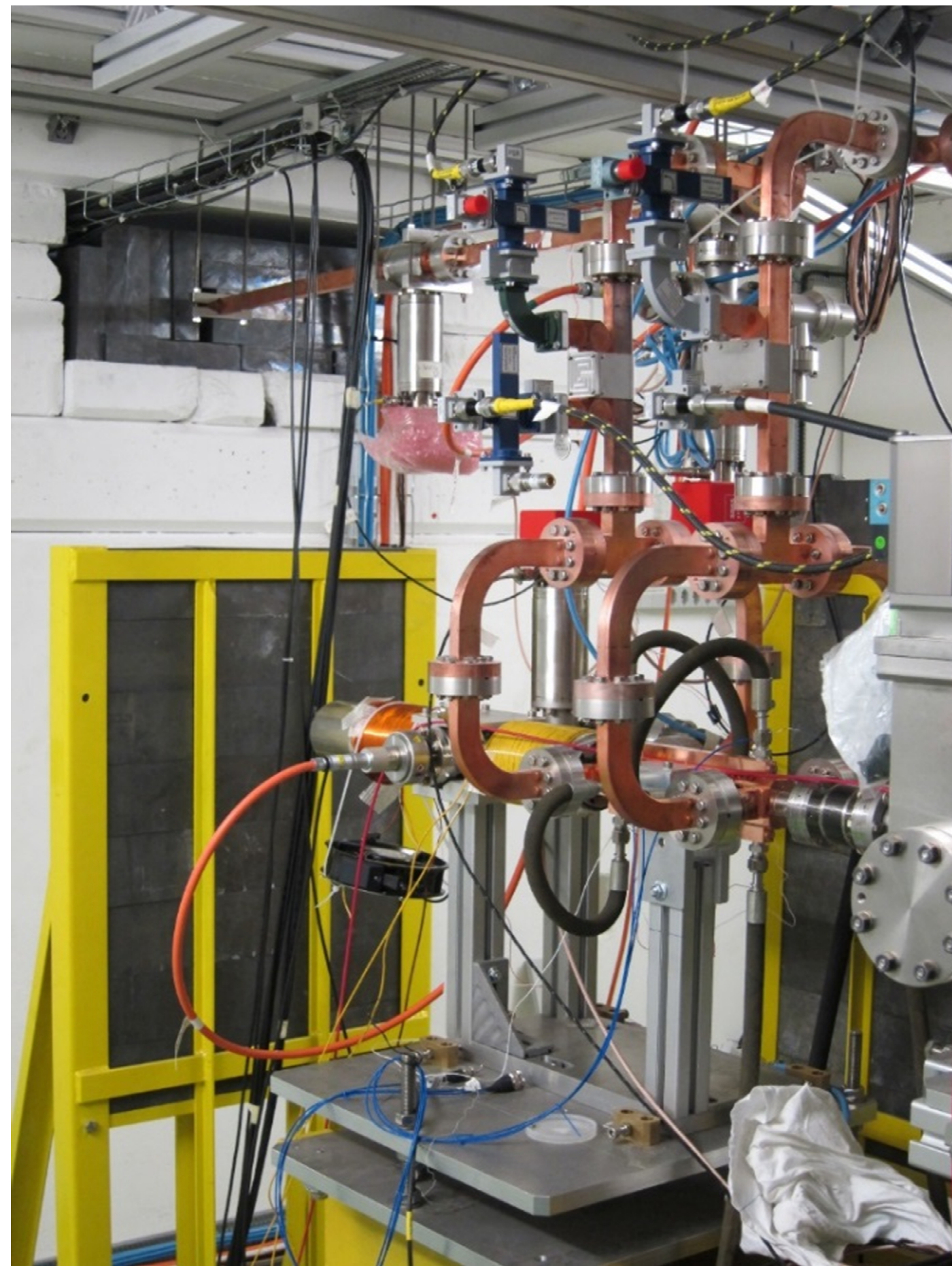
For most applications these are contaminants: dust, particles, oxides etc.

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

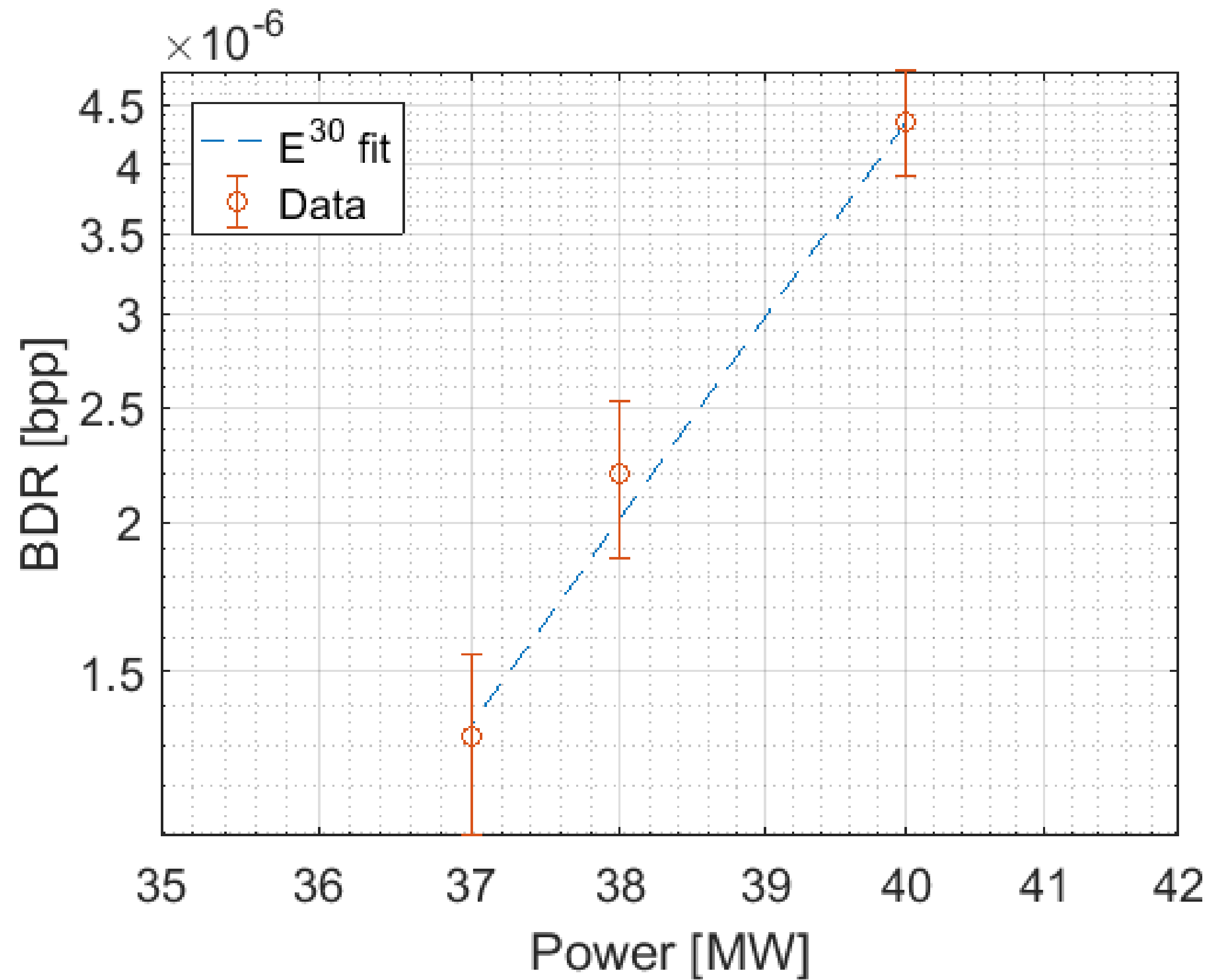
These features seem to form **below the surface** and are generated by **dislocation dynamics**.

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:



BDR dependence

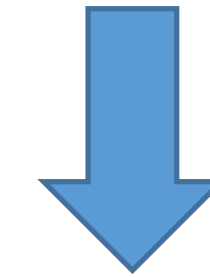


Data taken in XBox-2 with TD26CC structure, T. Lucas

Regularly observed dependence:

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

Physical model based on defect formation



$$BDR \propto e^{\frac{-E^f + \epsilon_0 E^2 \Delta V}{k_b T}}$$

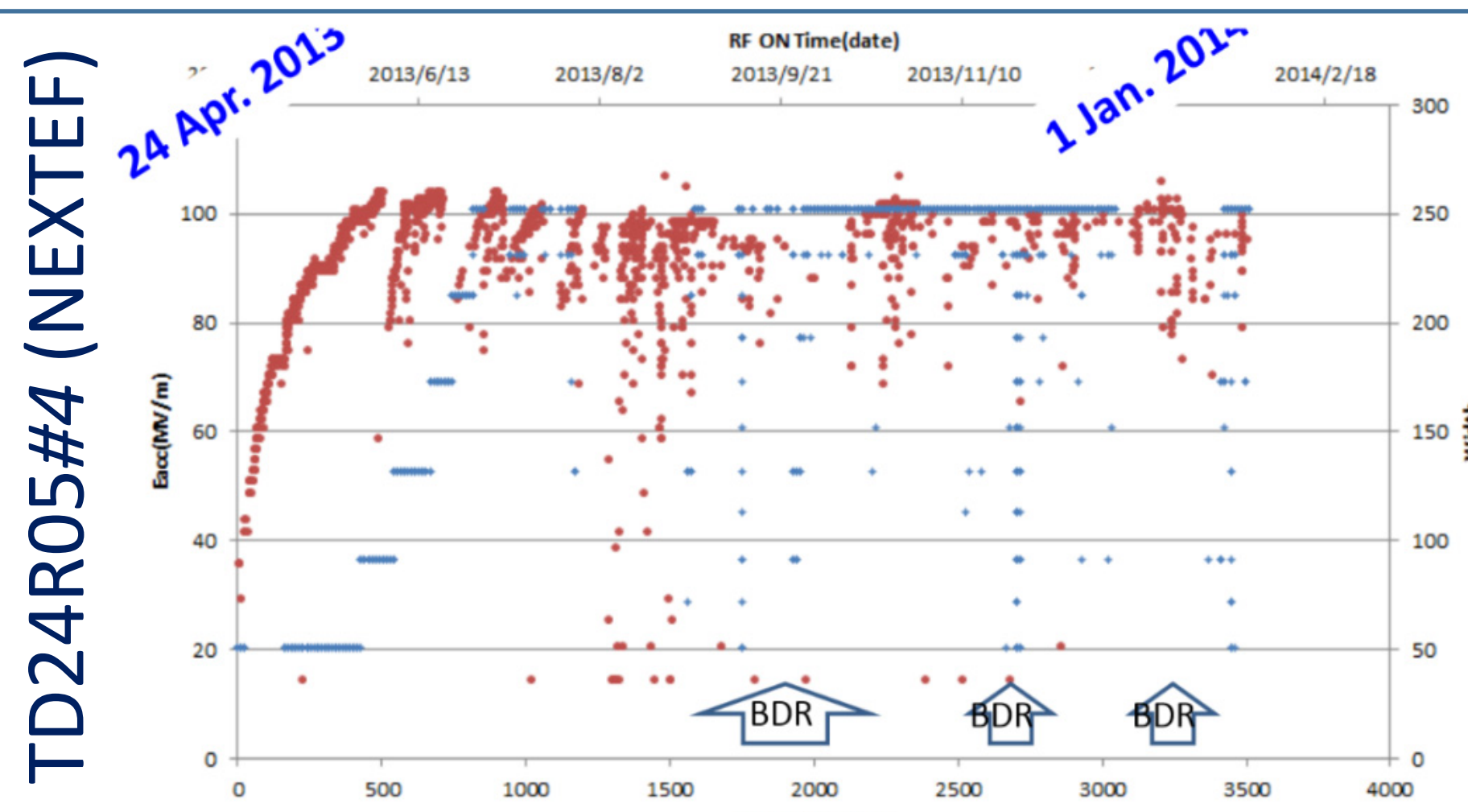
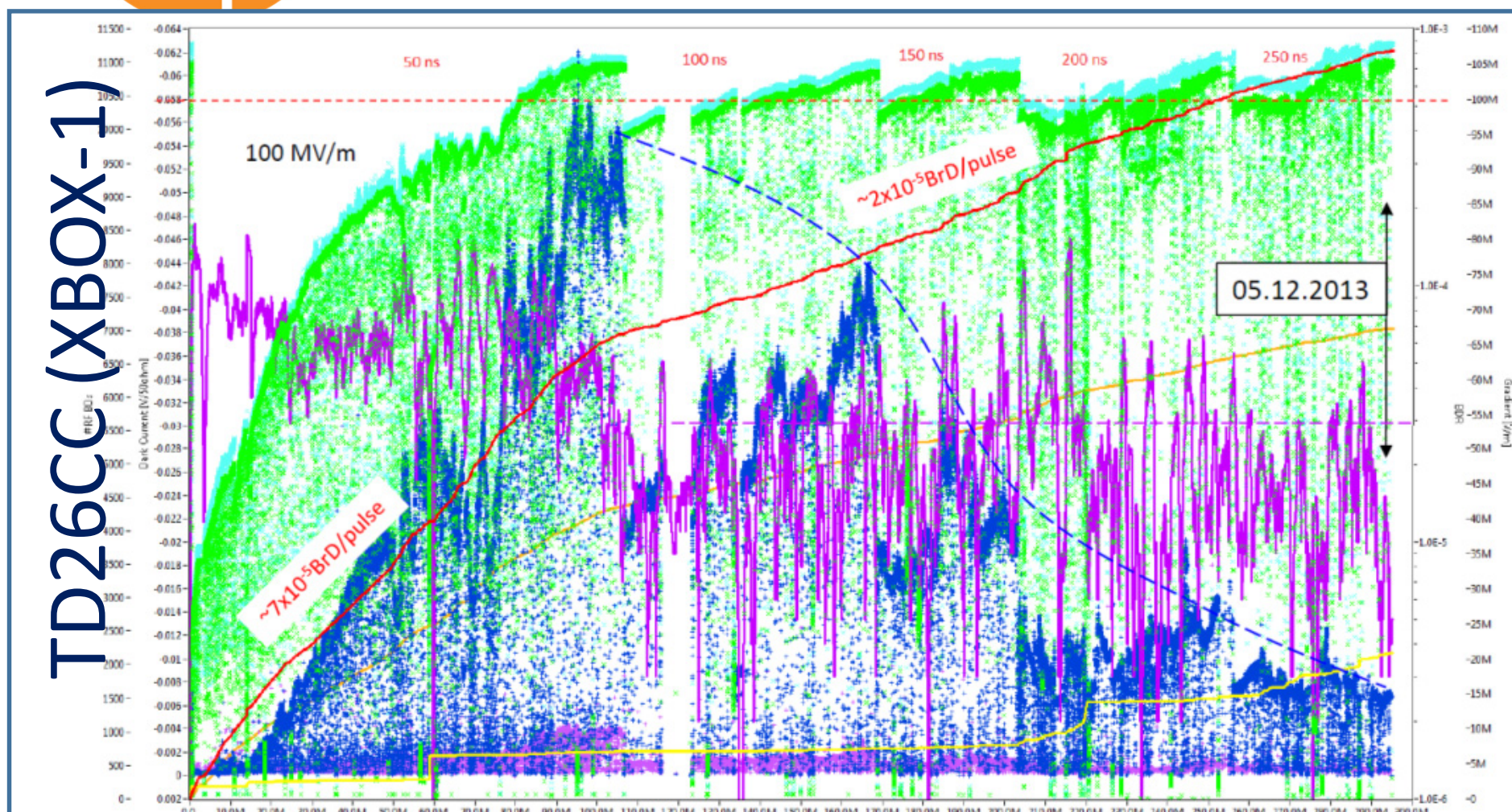
$$E^f = 0.8 \text{ eV}$$

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

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



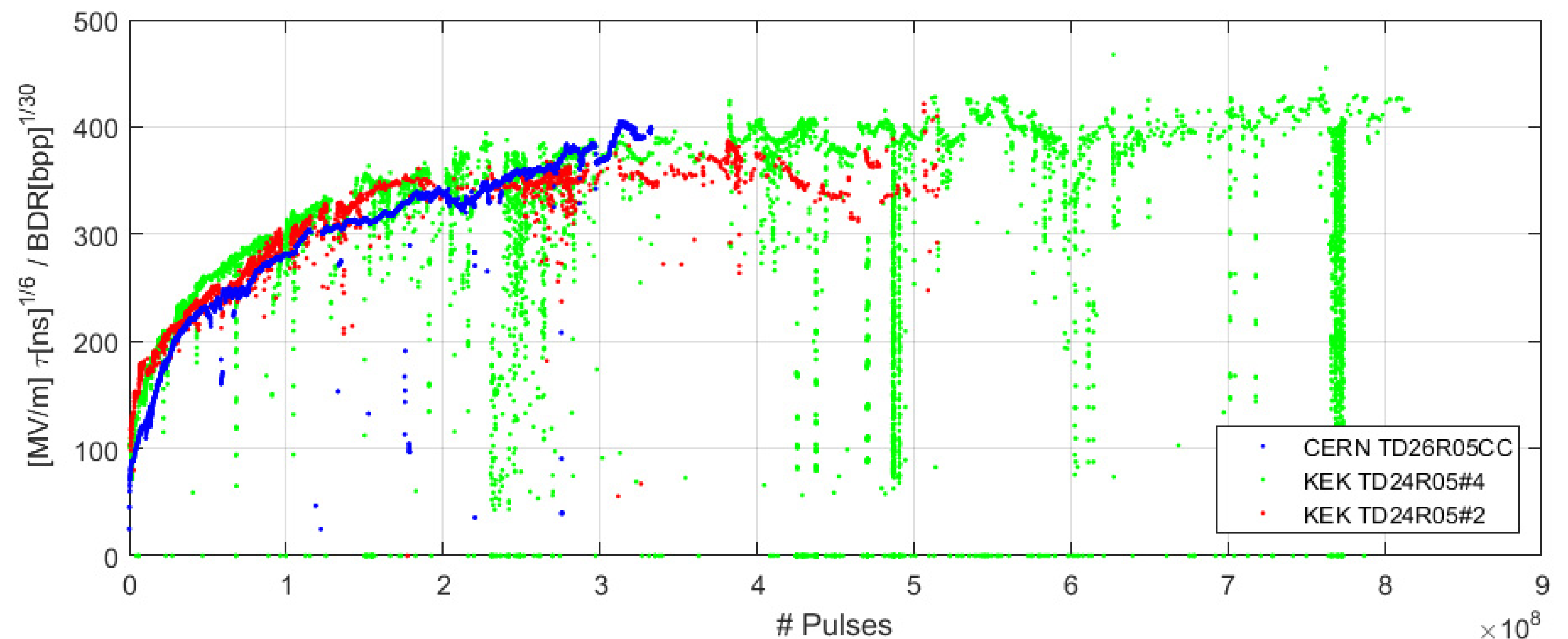
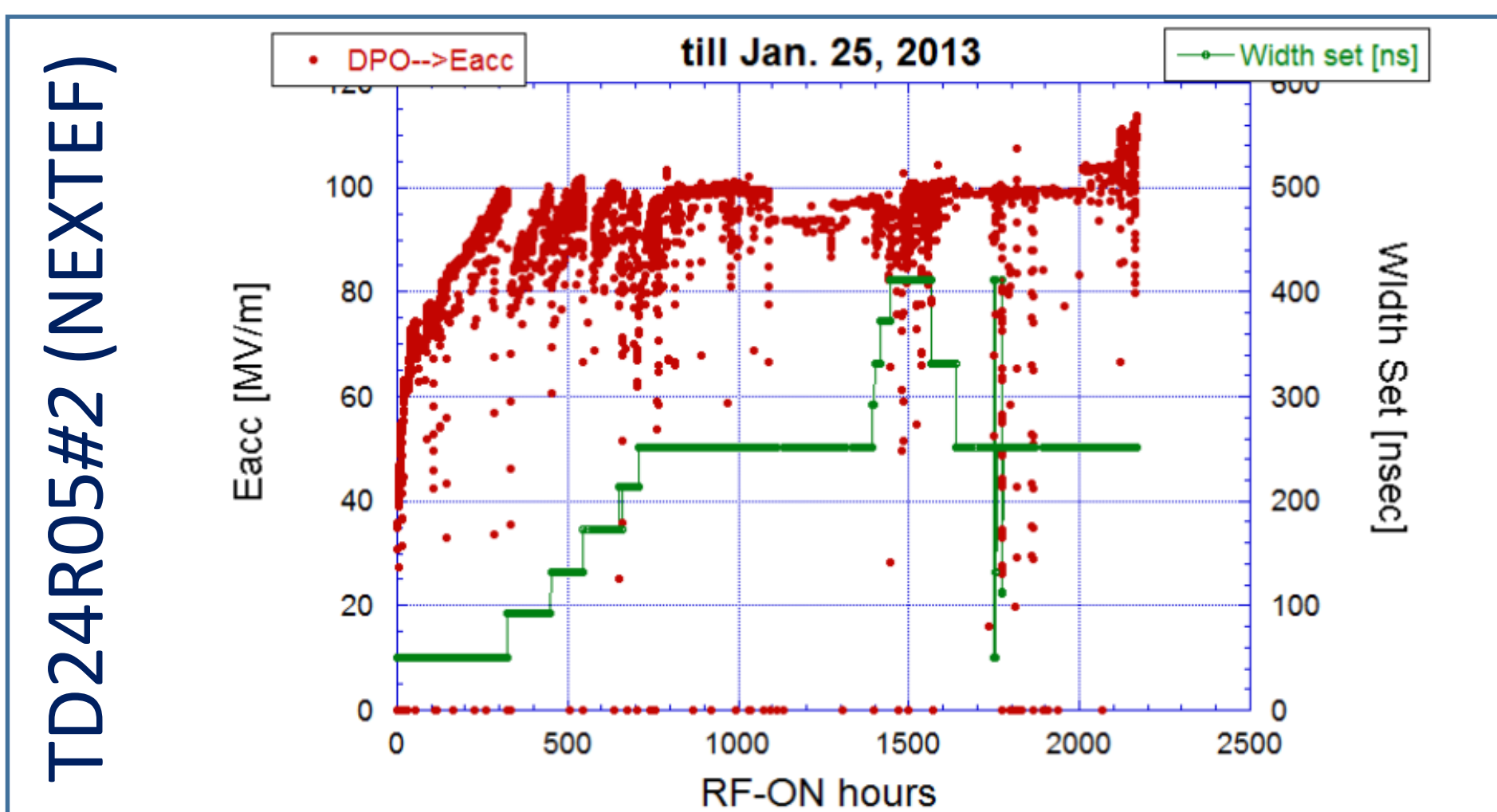
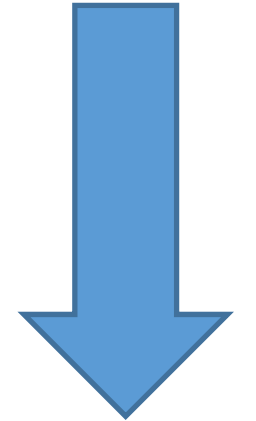
Comparison of three similar structures



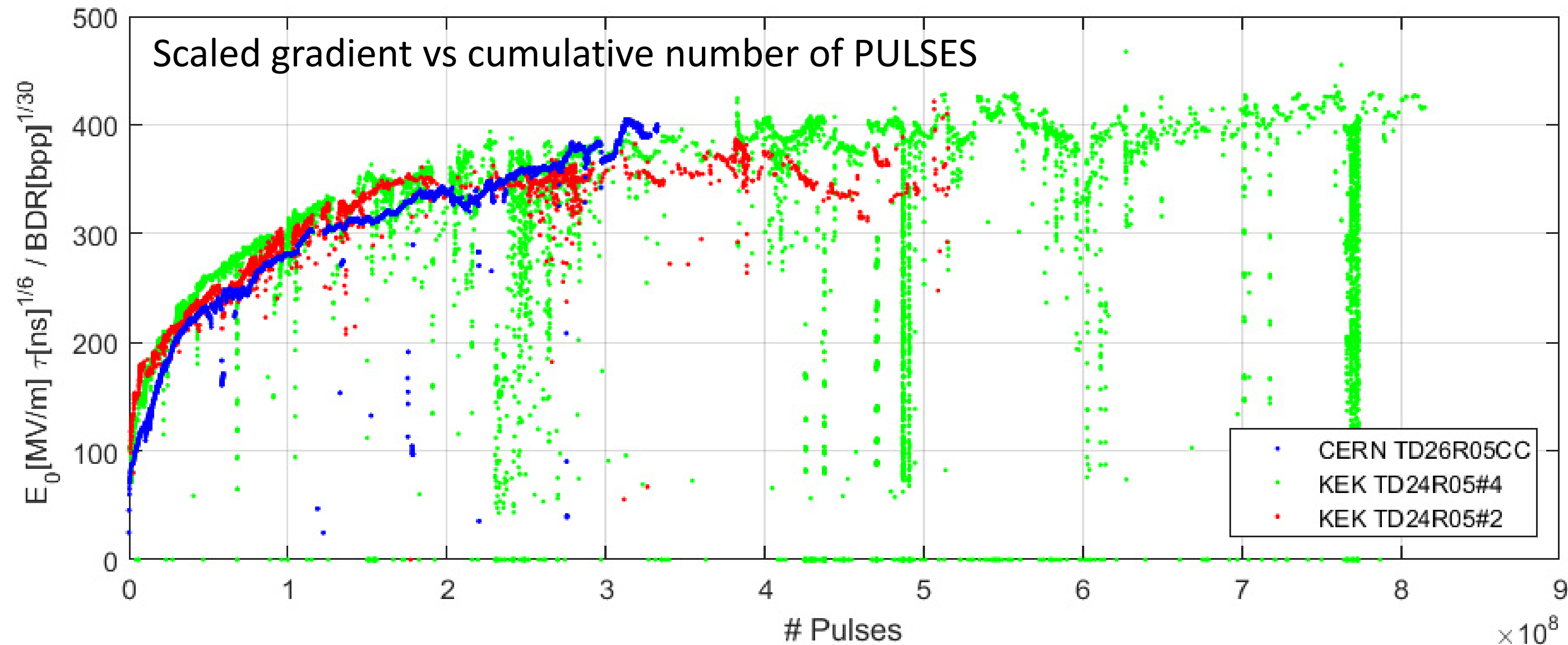
We normalize by:

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

And get

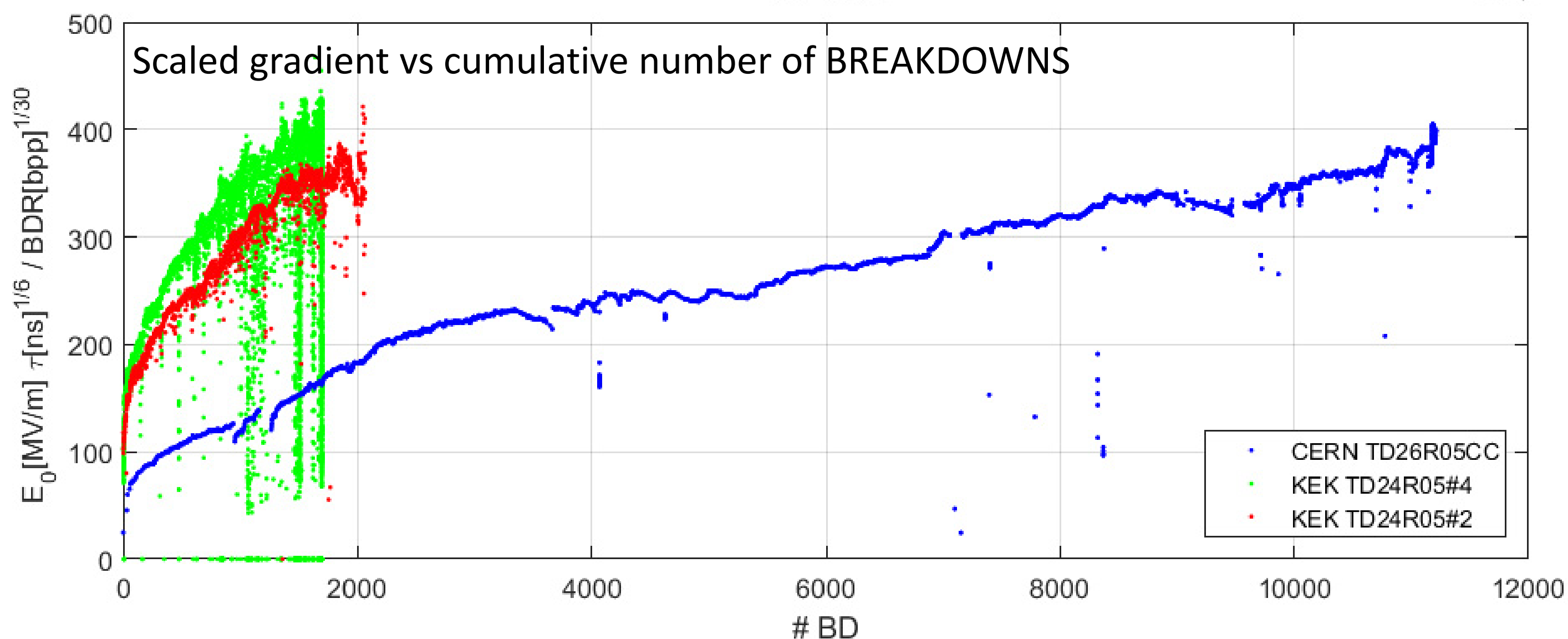


Interpretation: Conditioning is a reproducible process which implies a well defined physical mechanism.



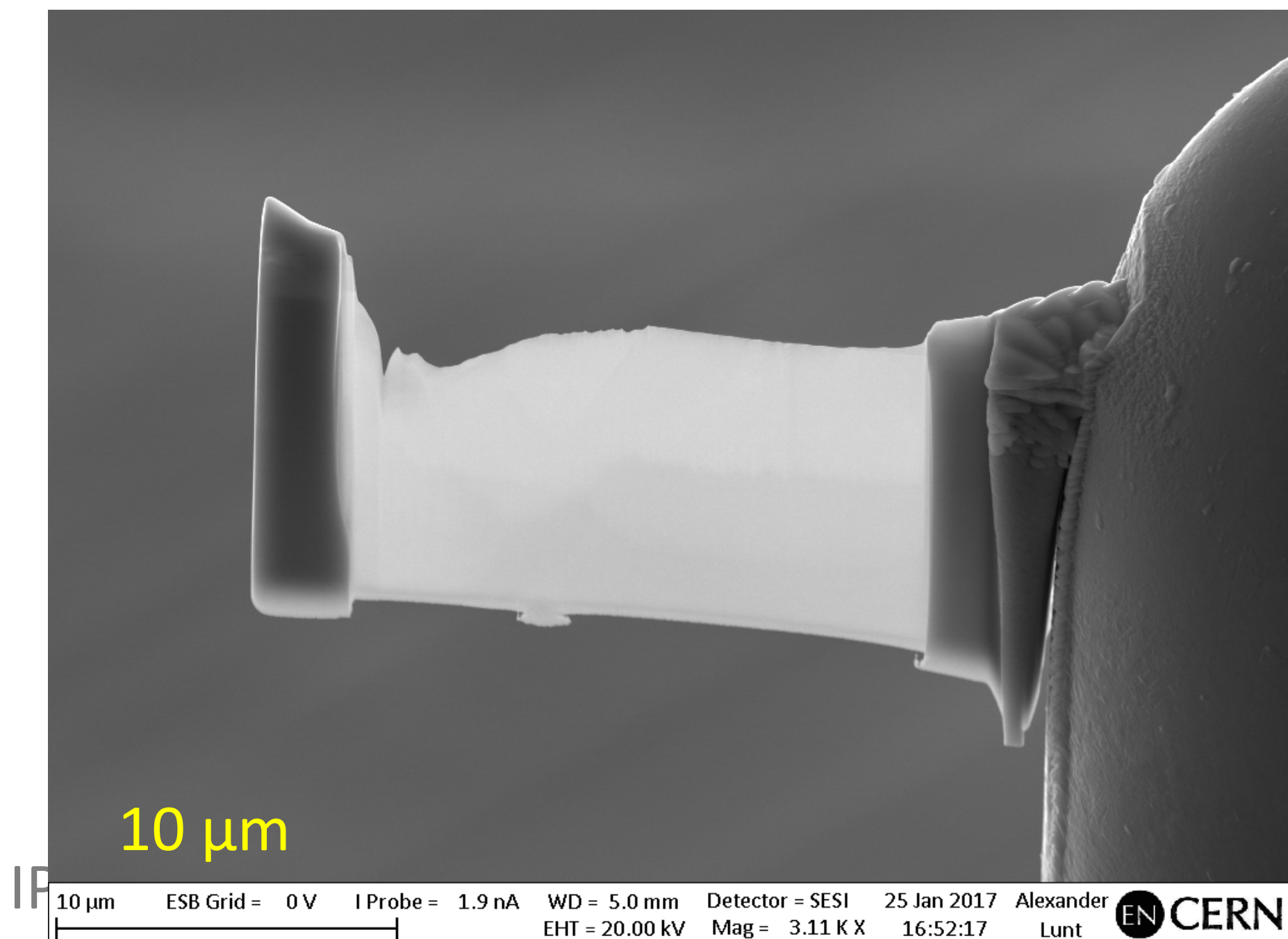
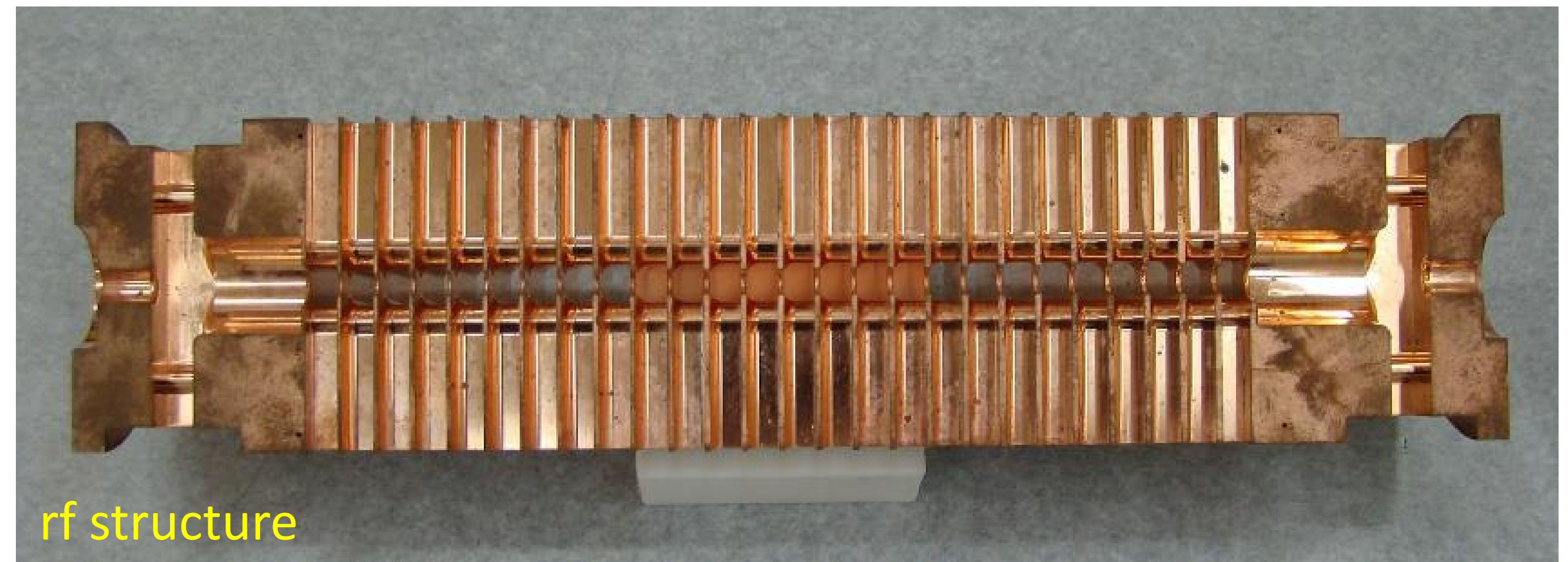
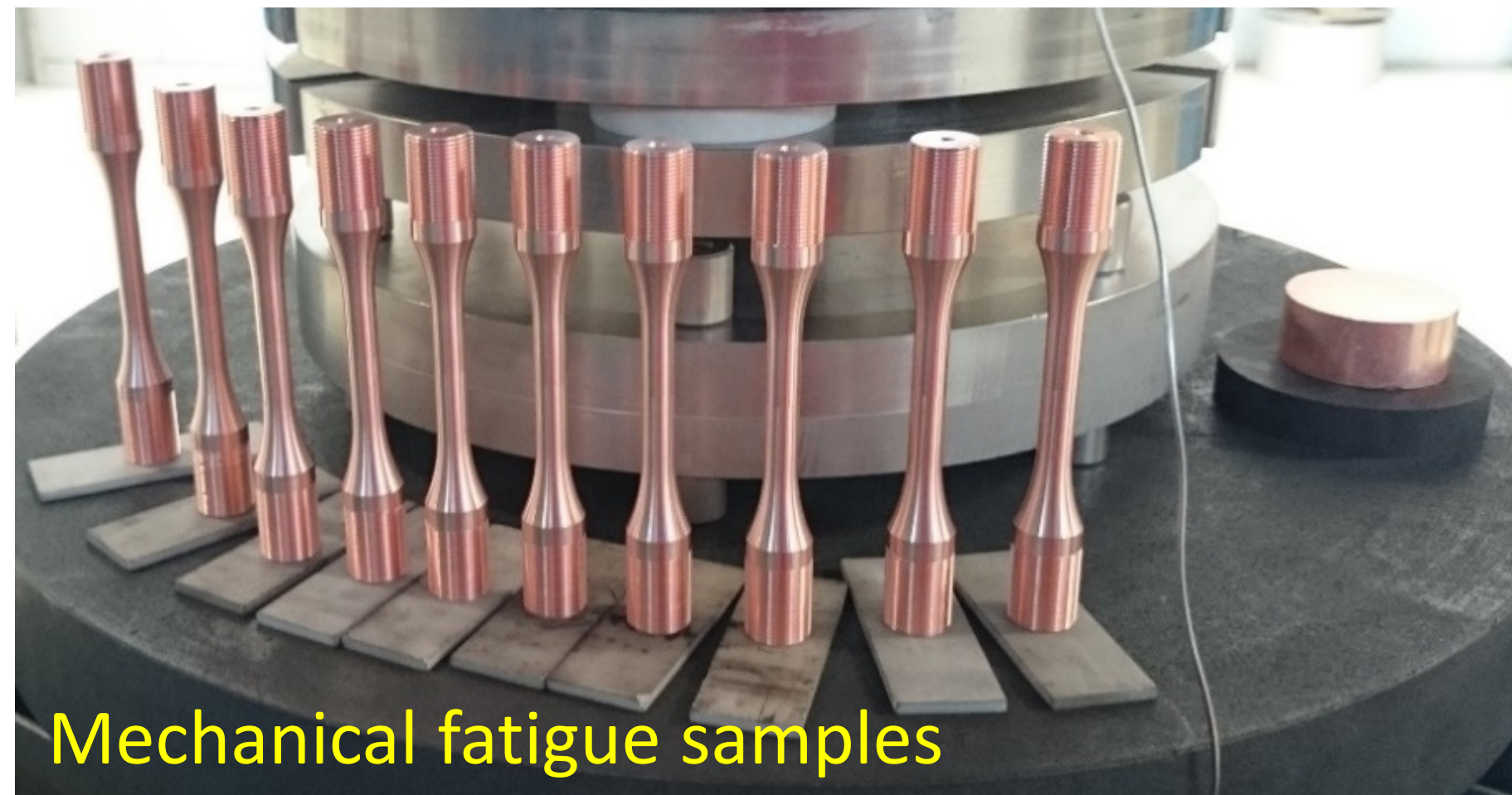
vs. number of pulses

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



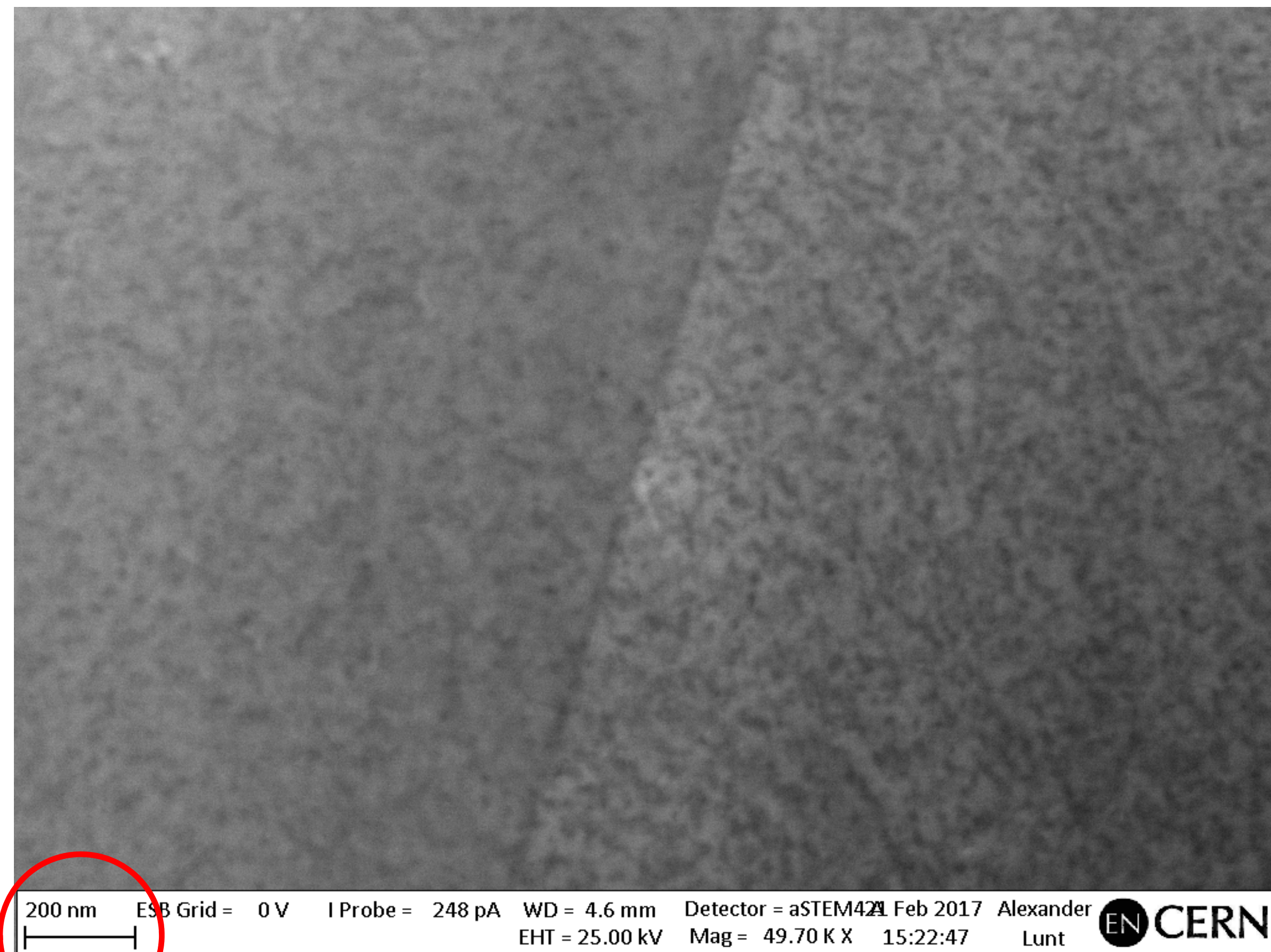
vs. number of Breakdowns

Comparison of mechanical and rf samples

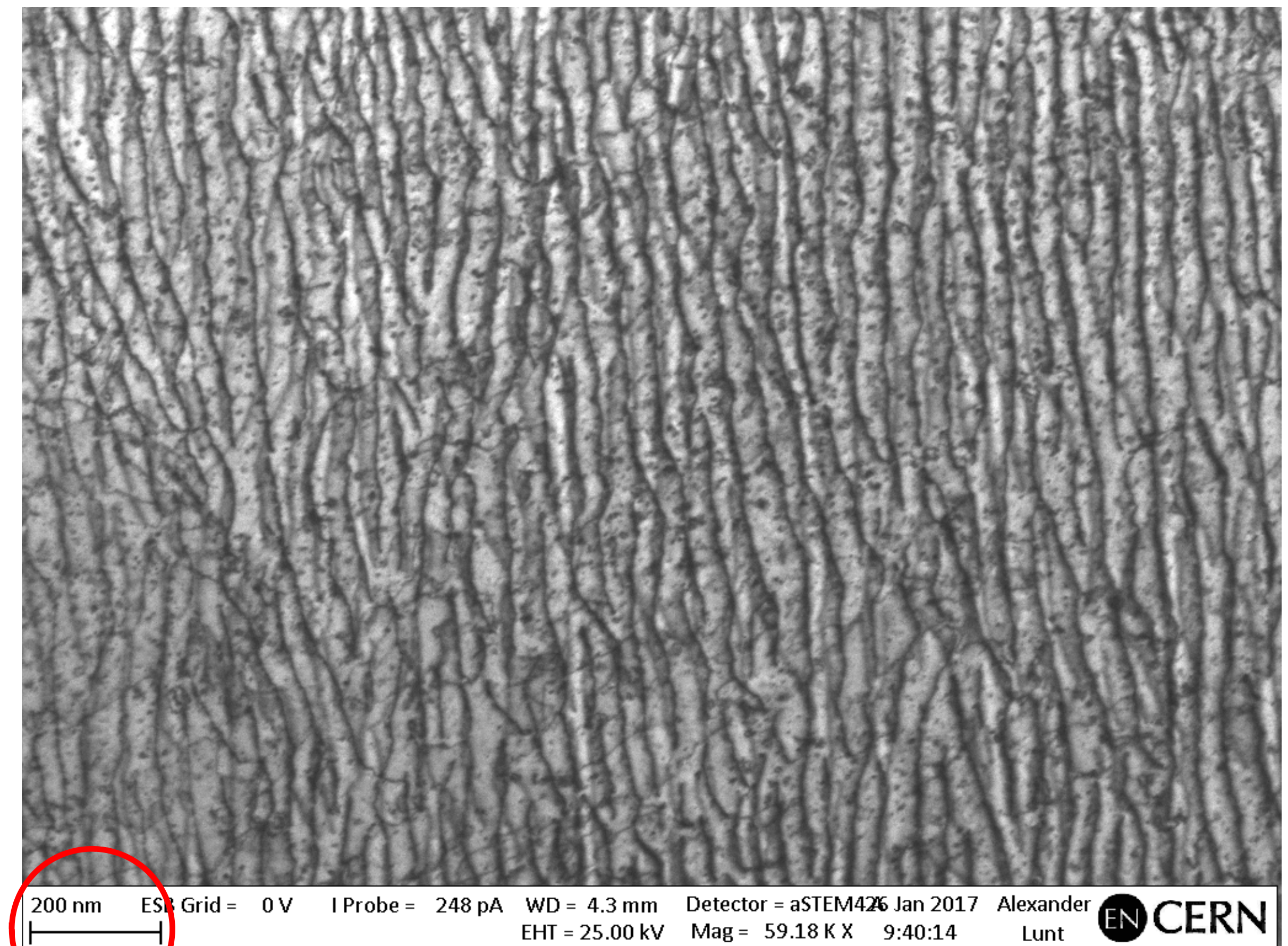


Experiment:

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.



After heat treatment



200 nm After mechanical fatigue

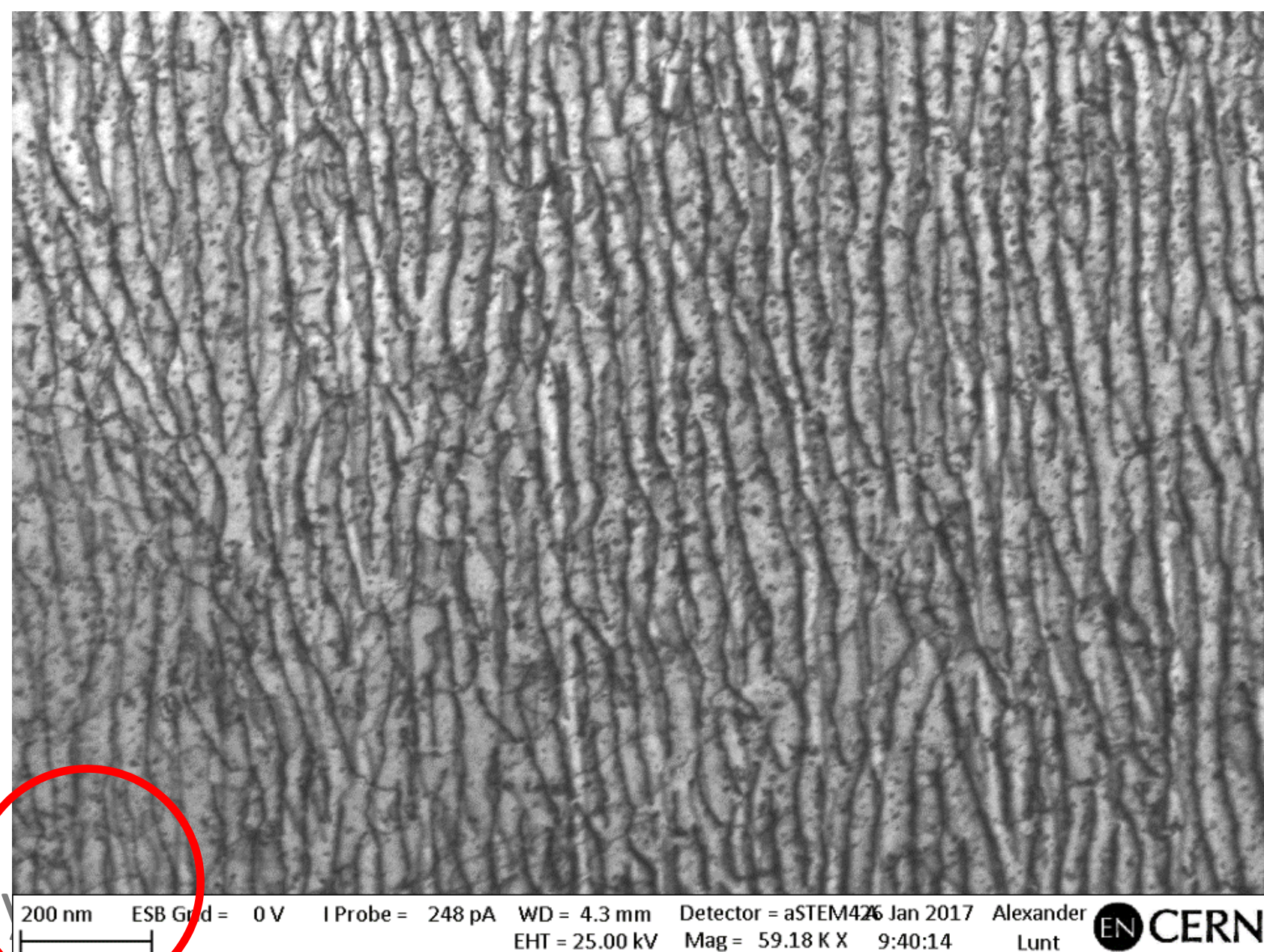
Formation of dislocation patterns characteristic of hardening.



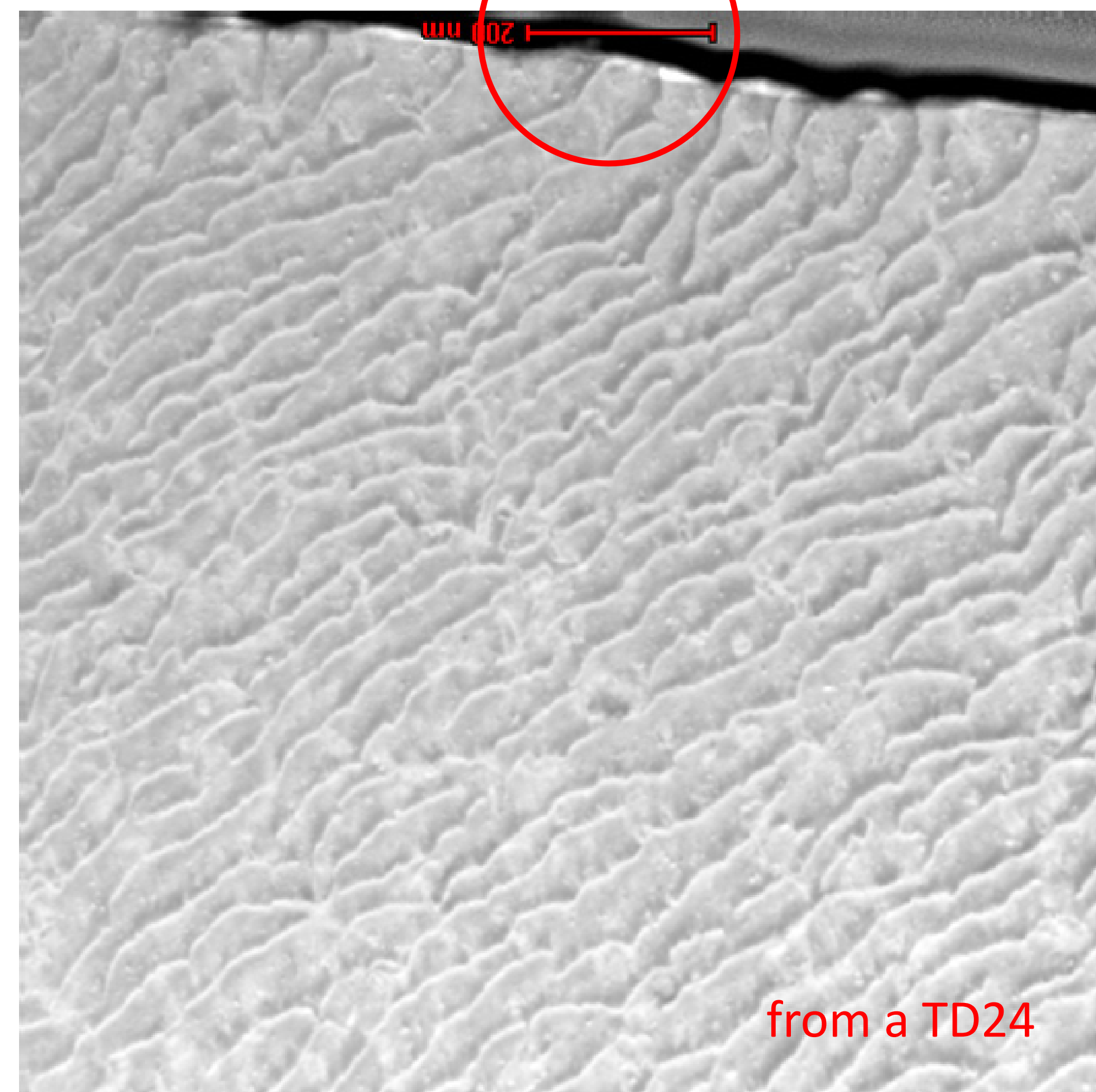
Comparison of mechanical and rf samples



200 nm



IPAC2017, 15 May



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:

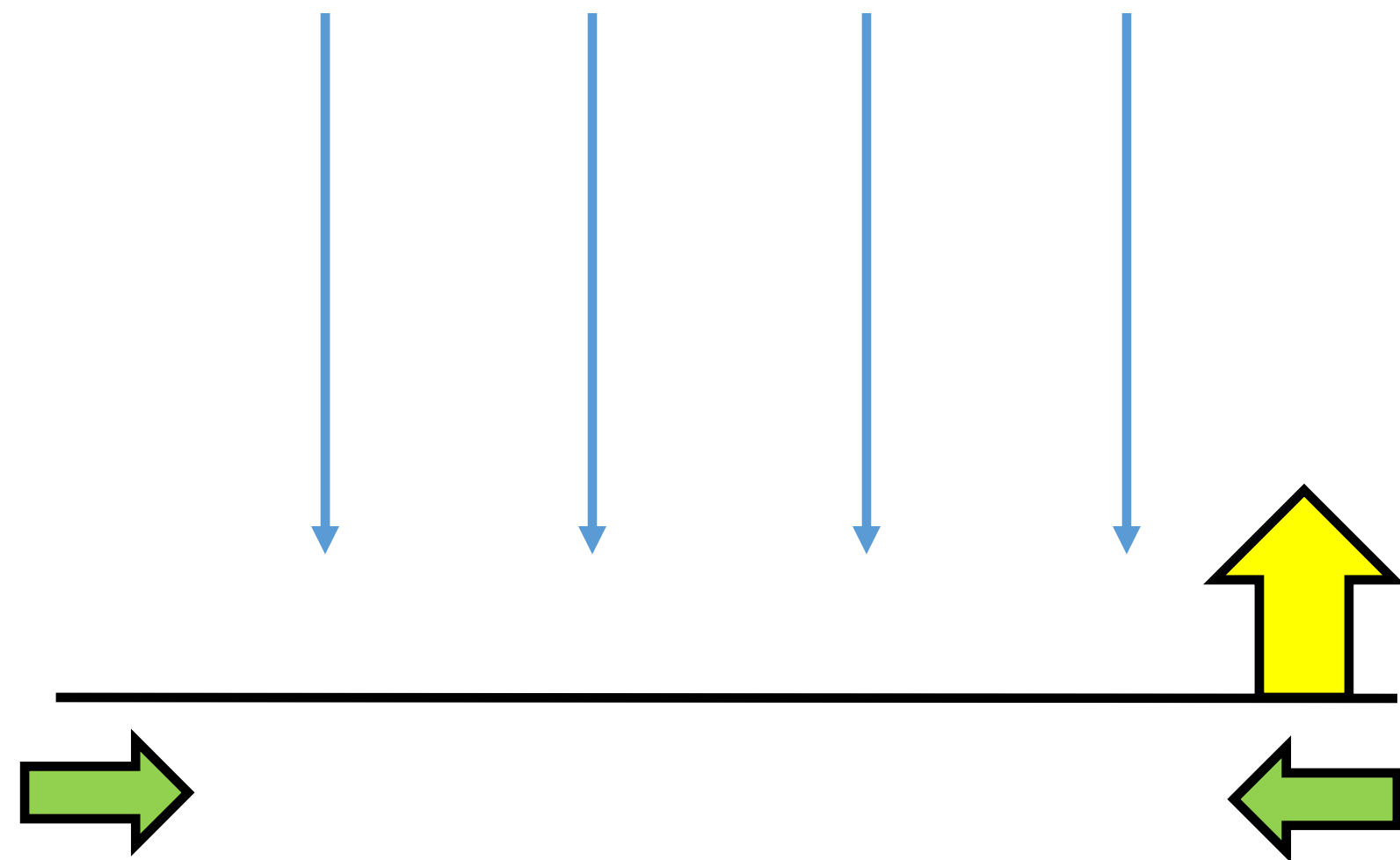
- A hardening process occurs during conditioning,
- Dislocation dynamics, formation and movement, are central to high-gradient behaviour.

Some numbers:

- Electric field stress is $\sigma = \frac{1}{2} \epsilon_0 E^2$ 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

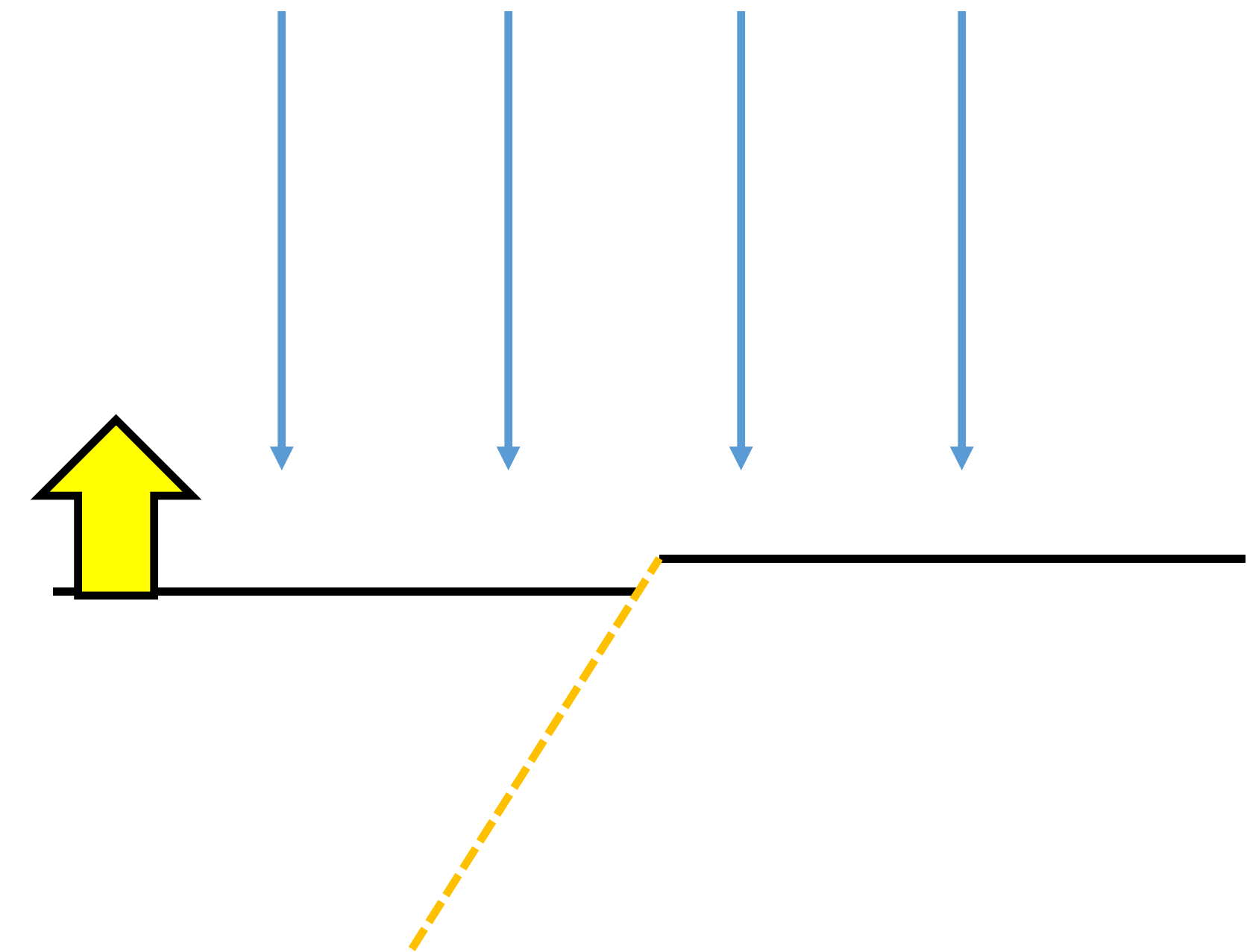
Applied external electric field



Vacuum

Tensile force

Copper

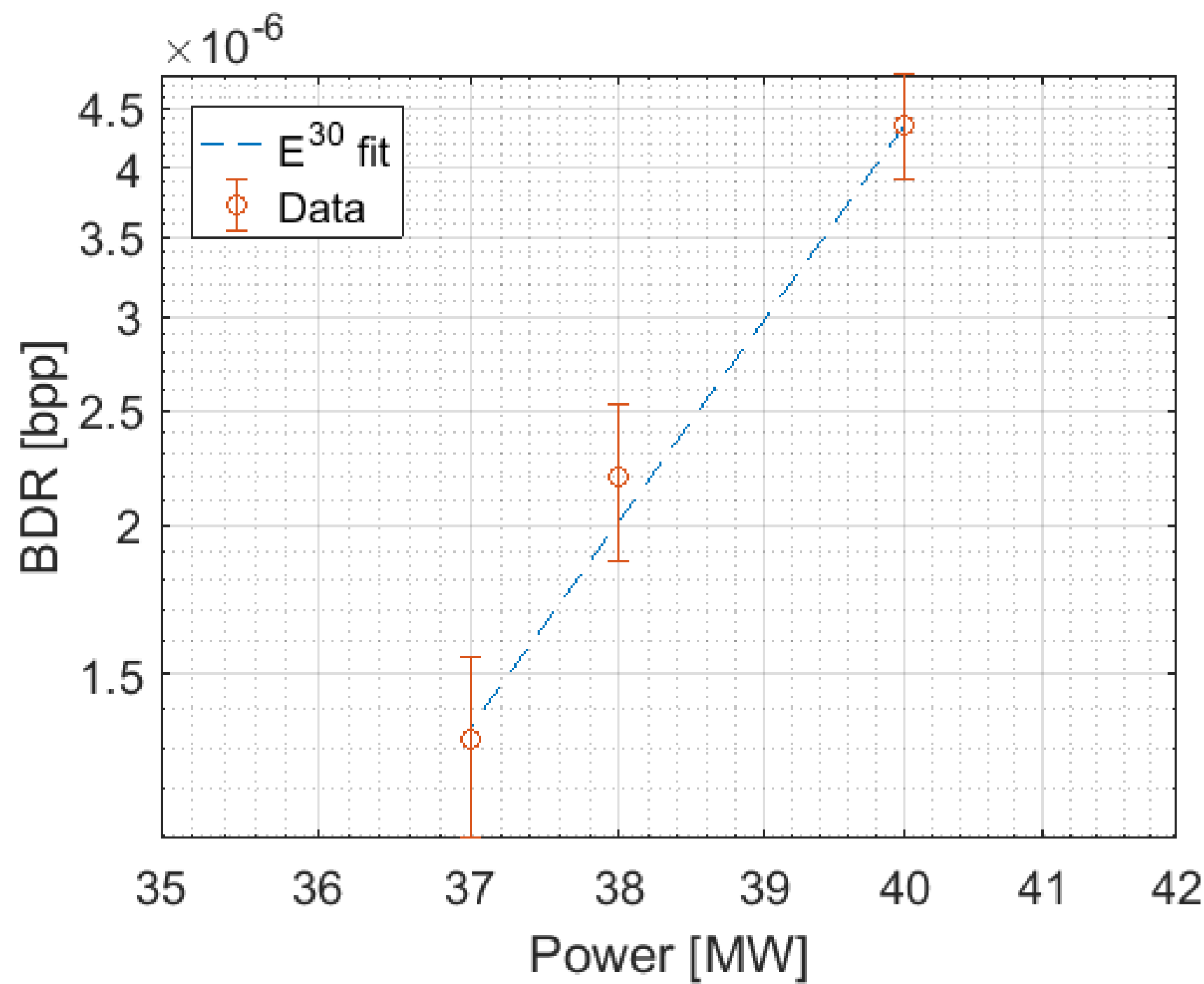
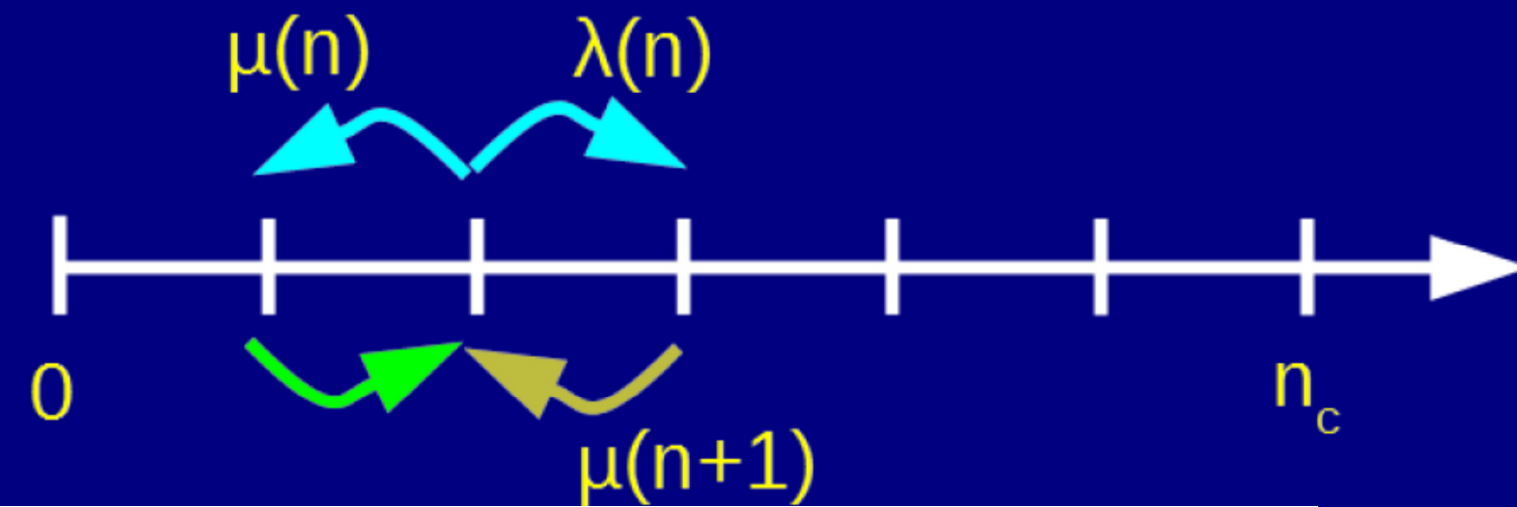


(Pulsed surface heating – not subject for today)

- 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)

Exact Solution: Master Equation

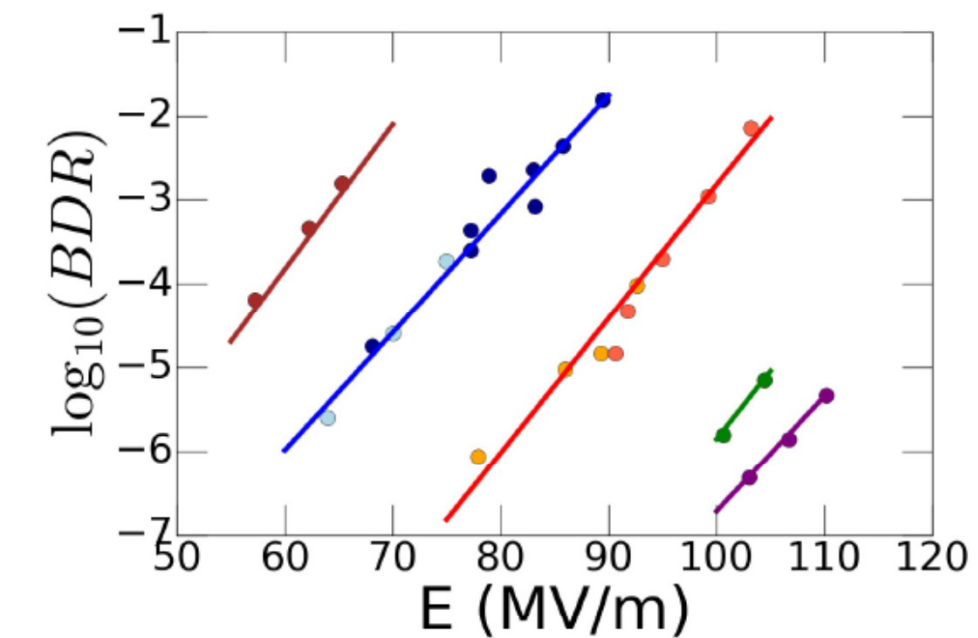
$$\frac{dP(n, t)}{dt} = \lambda(n-1)P(n-1, t) + \mu(n+1)P(n+1, t) - [\lambda(n) + \mu(n)]P(n, t)$$



E. Engelberg

BDR dependence - II

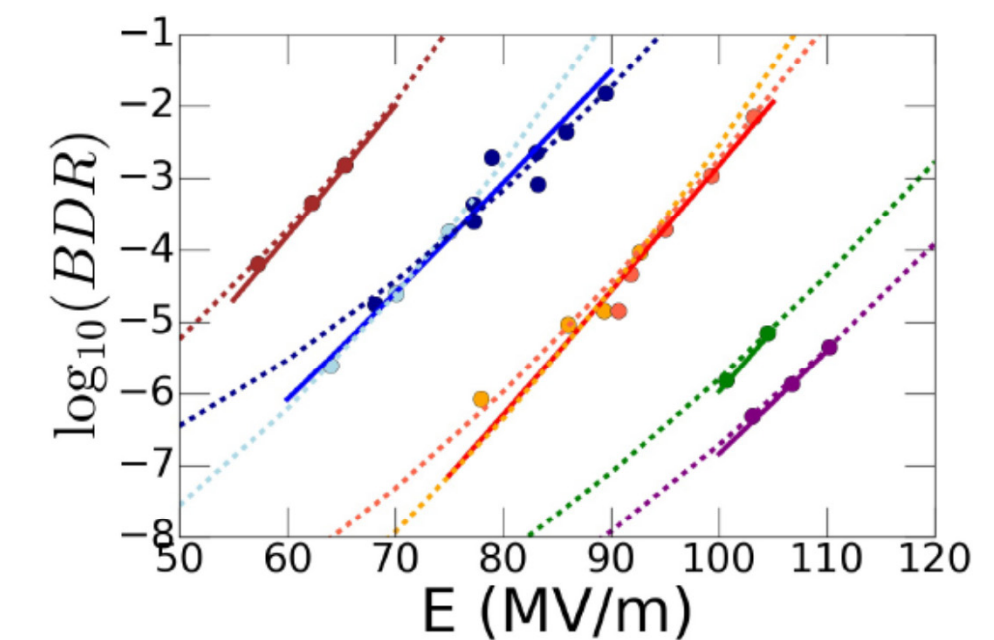
Experiment: Dependence on Field



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.

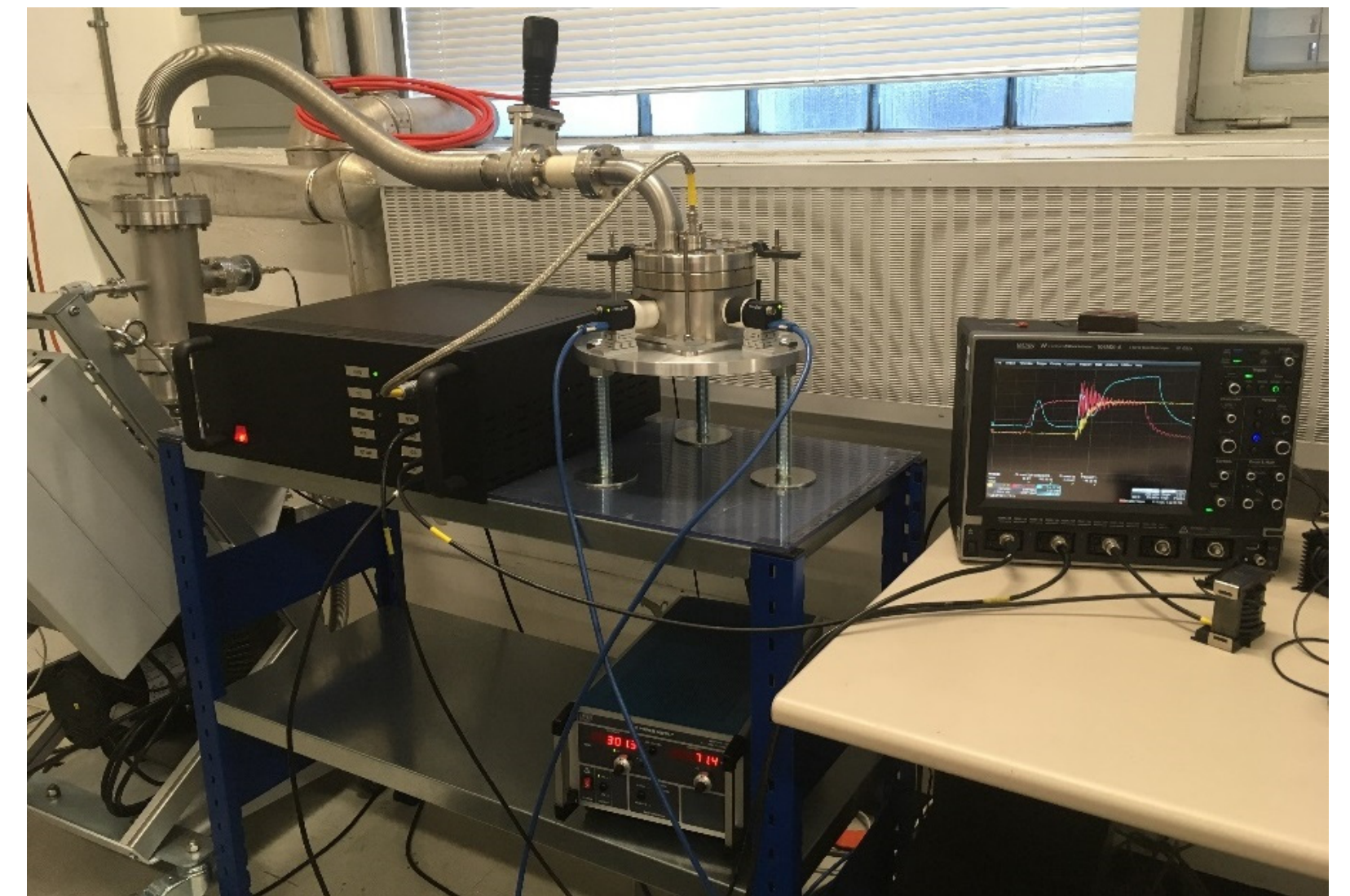
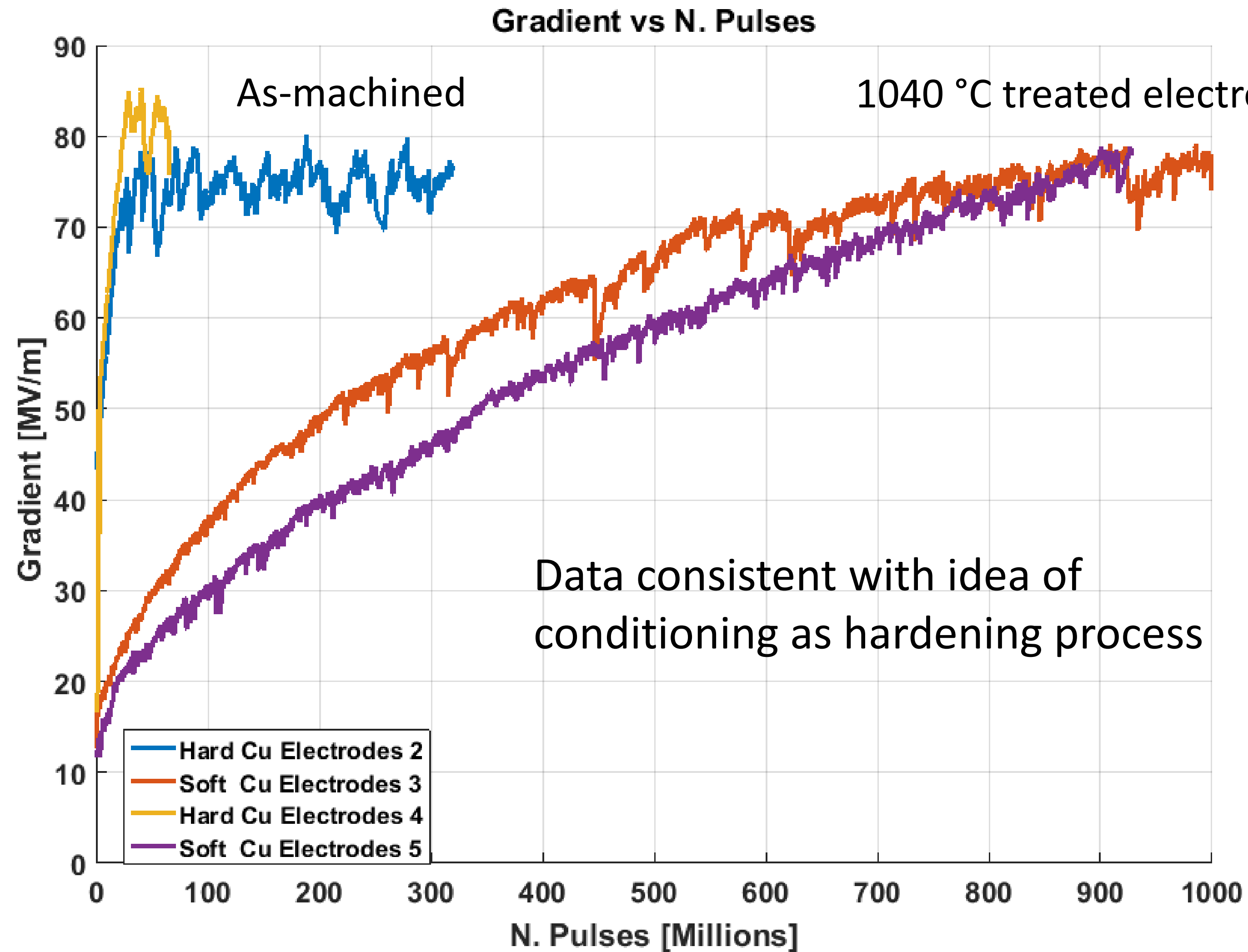
This interplay is what lies behind field dependence, conditioning and gives ultimate gradient.

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

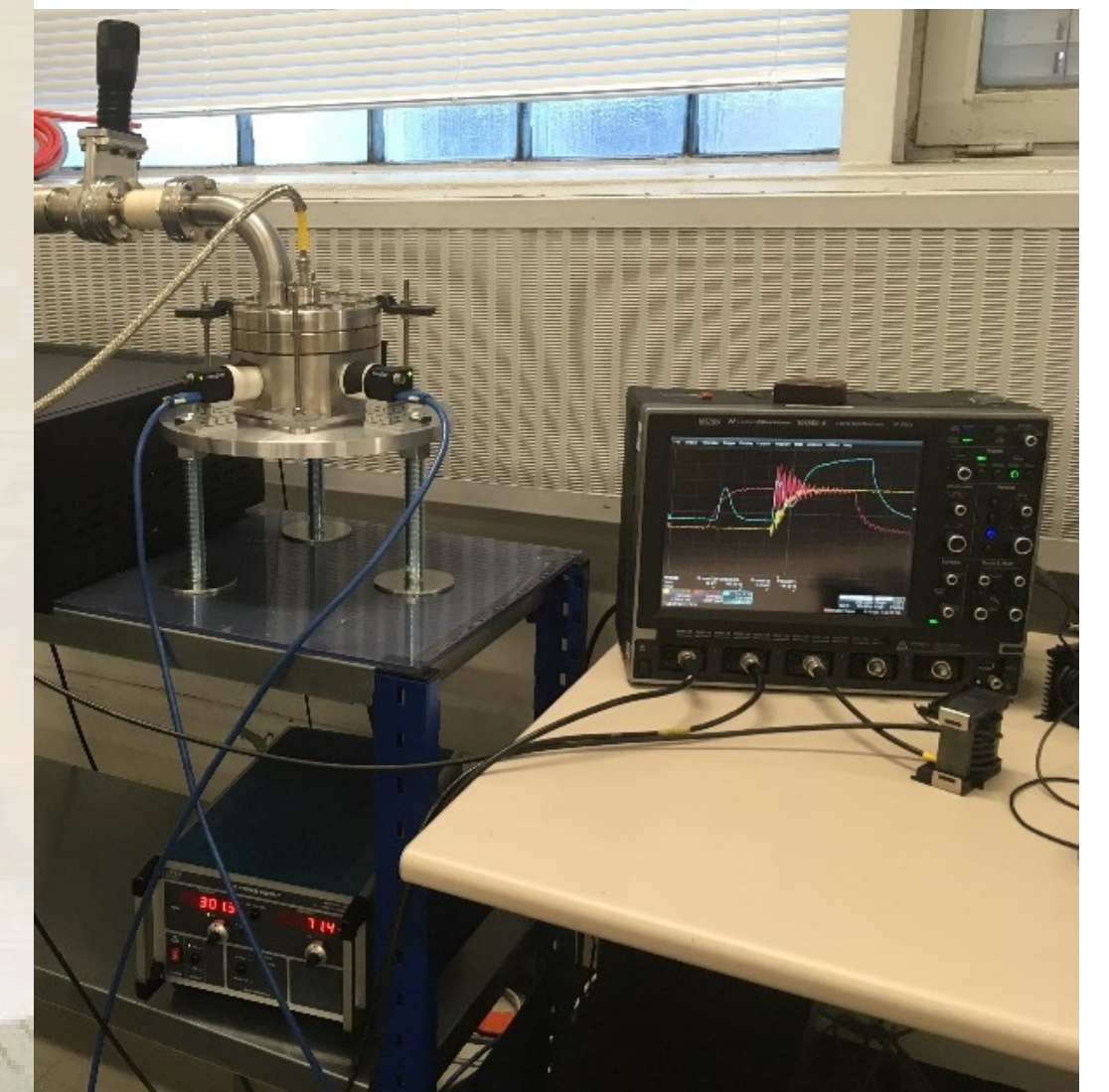
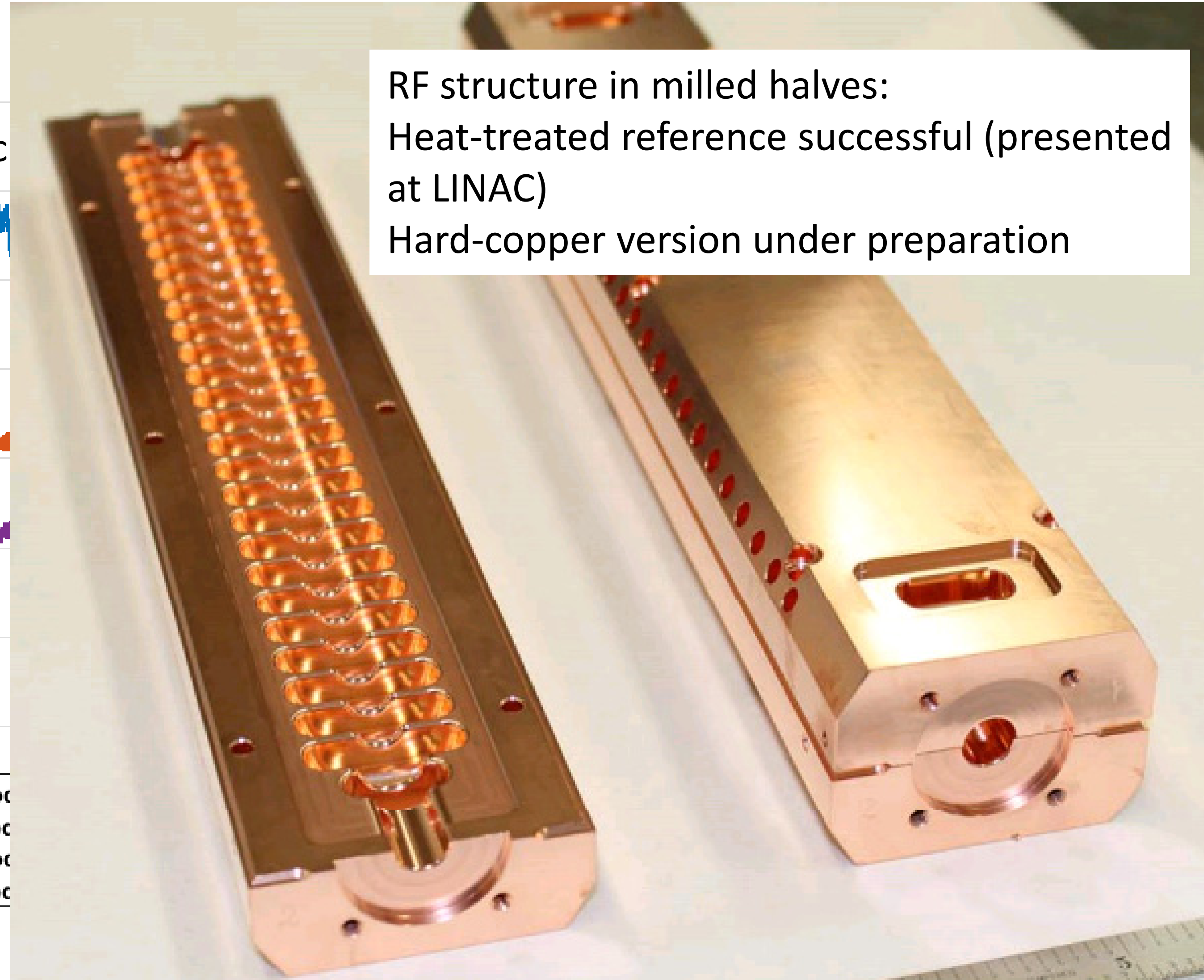
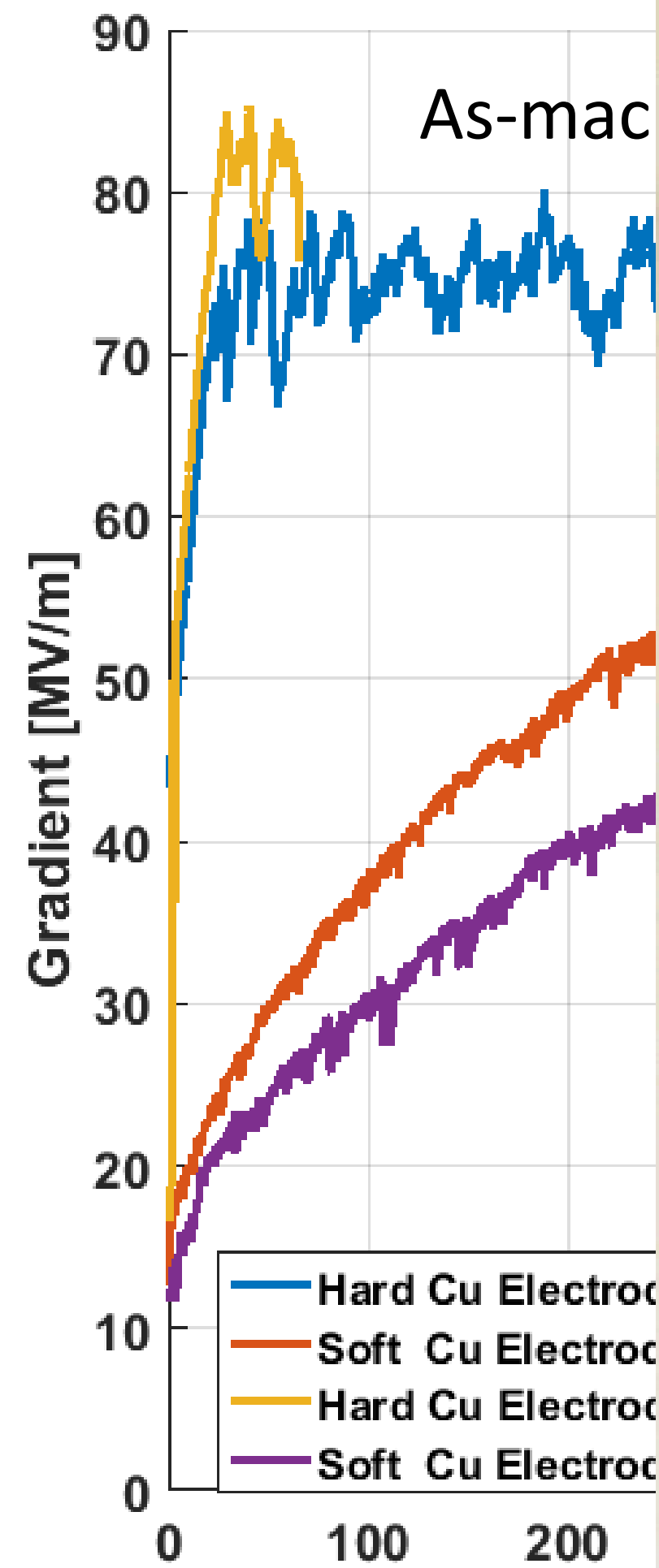
Stochastic Model of Breakdown Nucleation under Intense Electric Fields, E. Engelberg

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





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.

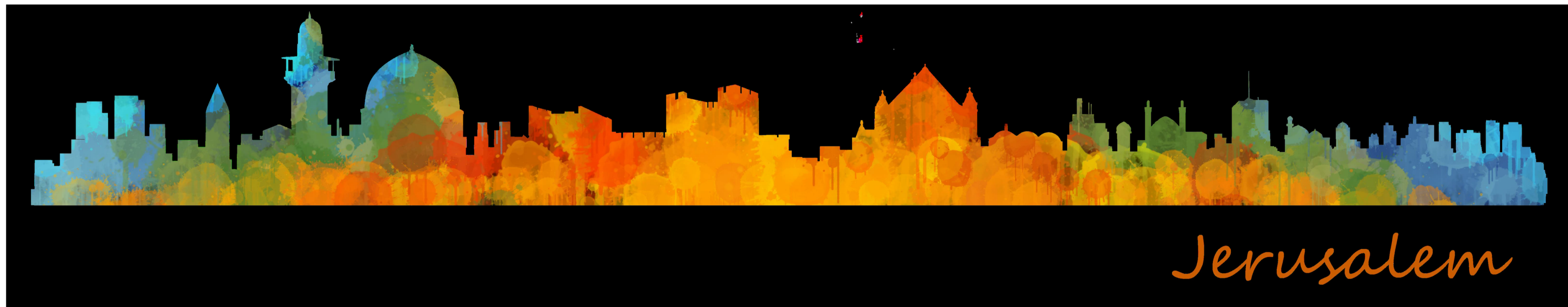
A crucial stage of the action is below the surface!



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>