Studies on the relation between BD nucleation and plastic activities

Amit Weiss, Ayelet Yashar, Inna Popov, Eli Engelberg
Itay Nachshon, Yinon Ashkenazy

Racah Institute of Physics,

Hebrew University, Jerusalem, Israel

Walter Wuensch, Sergio Calatroni, Tomoko Muranaka,
Iaroslava profatilova, Robin Rajamaki,
Ana Teresa Perez Fontenla, Enrique Rodriguez Castro….

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

Dislocation mediated – self organized criticality

Plasticity of Micrometer-Scale Single Crystals in Compression

Michael D. Uchic,[1] Paul A. Shade,[2] and Dennis M. Dimiduk[1]
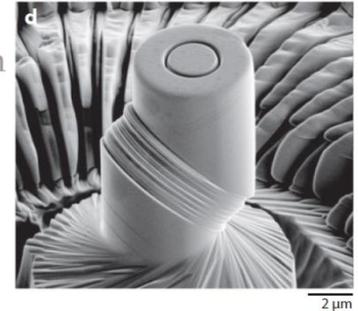
Single crystal micro-pillar compression:

Dislocation mediated intermittent flow - size effects, hardening.

Dislocation density inside a plane as a controlling parameter.

Intermittency characterized by a universal Power law burst PDF

Acoustic emissions: Similar + space and time coupling between events

(Weiss & Marsan, Scjence 2003)

Earthquakes show similar PDF and spatio-temporal correlation

(Kagan, Geopgysical J. (2007)
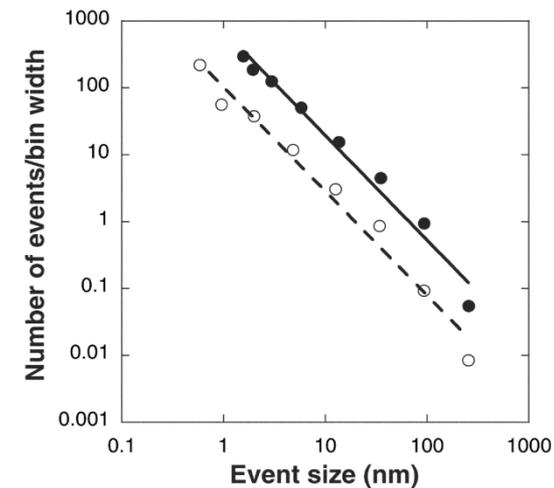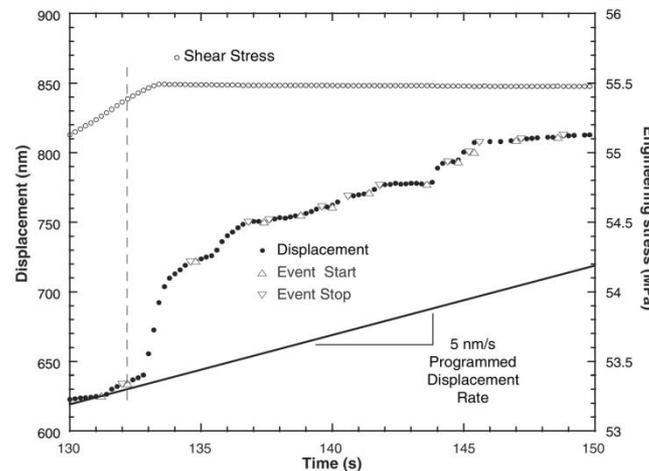
Uchic, Shade & Dimiduk, Annual Review of Materials Research (2009).

Dimiduk, Woodward, LeSar & Uchic: "Scale-Free Intermittent Flow in Crystal Plasticity." Science (2006) 1188.
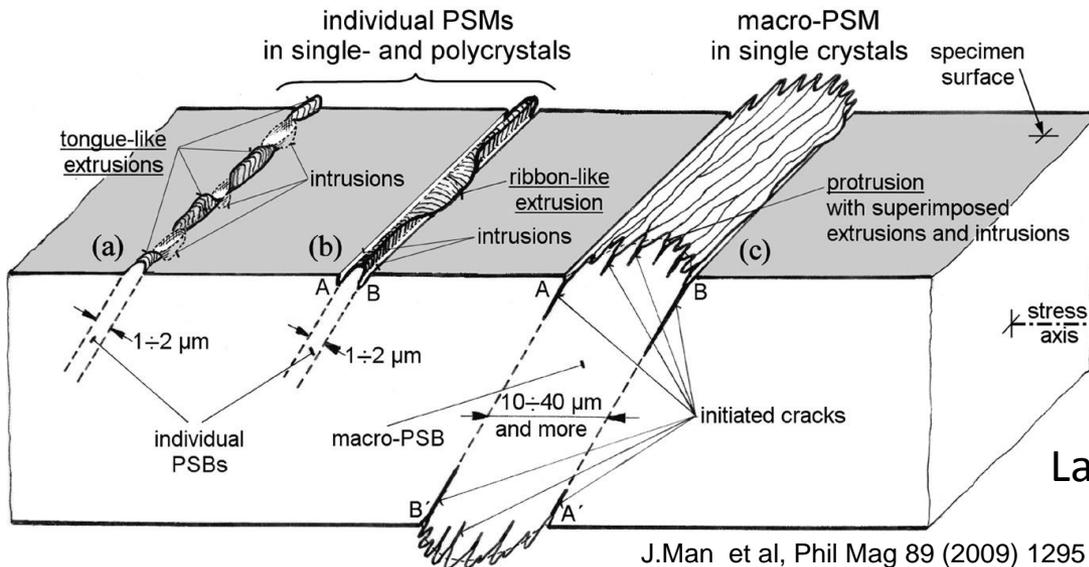
PSB -> protrusions

- Previously observed in fatigued surfaces.

- Significant sub-surface PSB leading to these surface features.

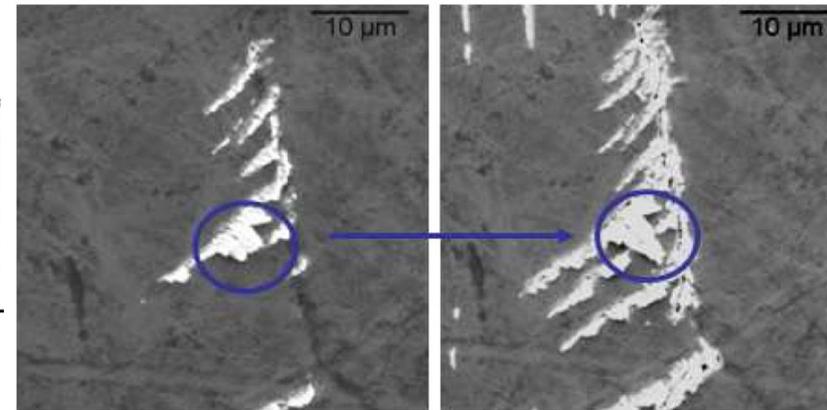- Stochastic response at sub-yield stresses.

Shear direction of the final pressing
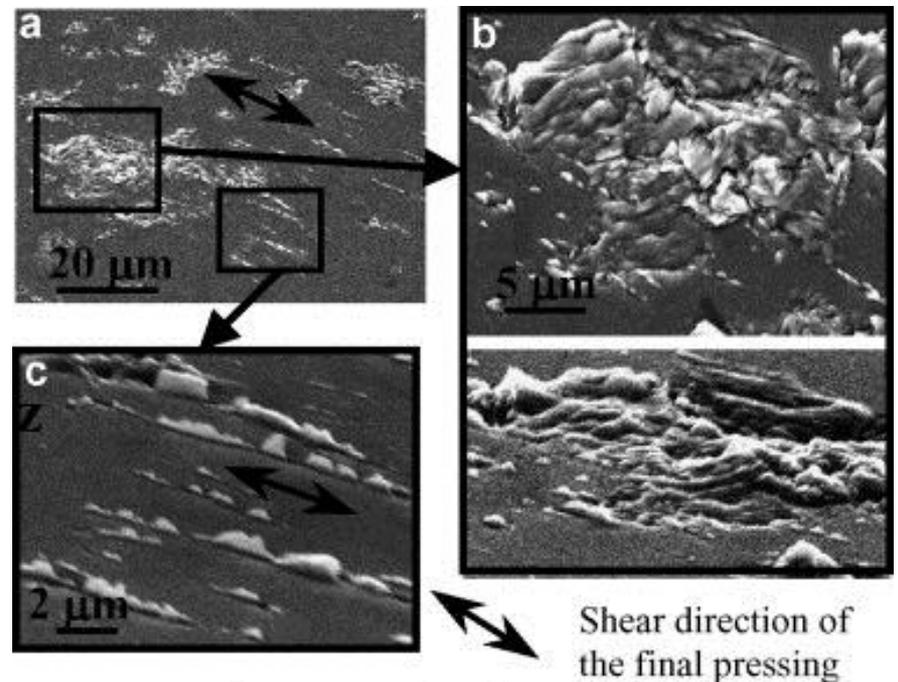
Fatigue strength and formation behavior of surface damage in ultrafine grained copper with different non-equilibrium microstructures

M. Goto et al. Int J of Fatigue. Vol 30 (2008) 1333

individual PSMs in single- and polycrystals

macro-PSM in single crystals

specimen surface

tongue-like extrusions

intrusions

ribbon-like extrusion

intrusions

protrusion with superimposed extrusions and intrusions

stress axis

1÷2 µm

1÷2 µm

10÷40 µm and more

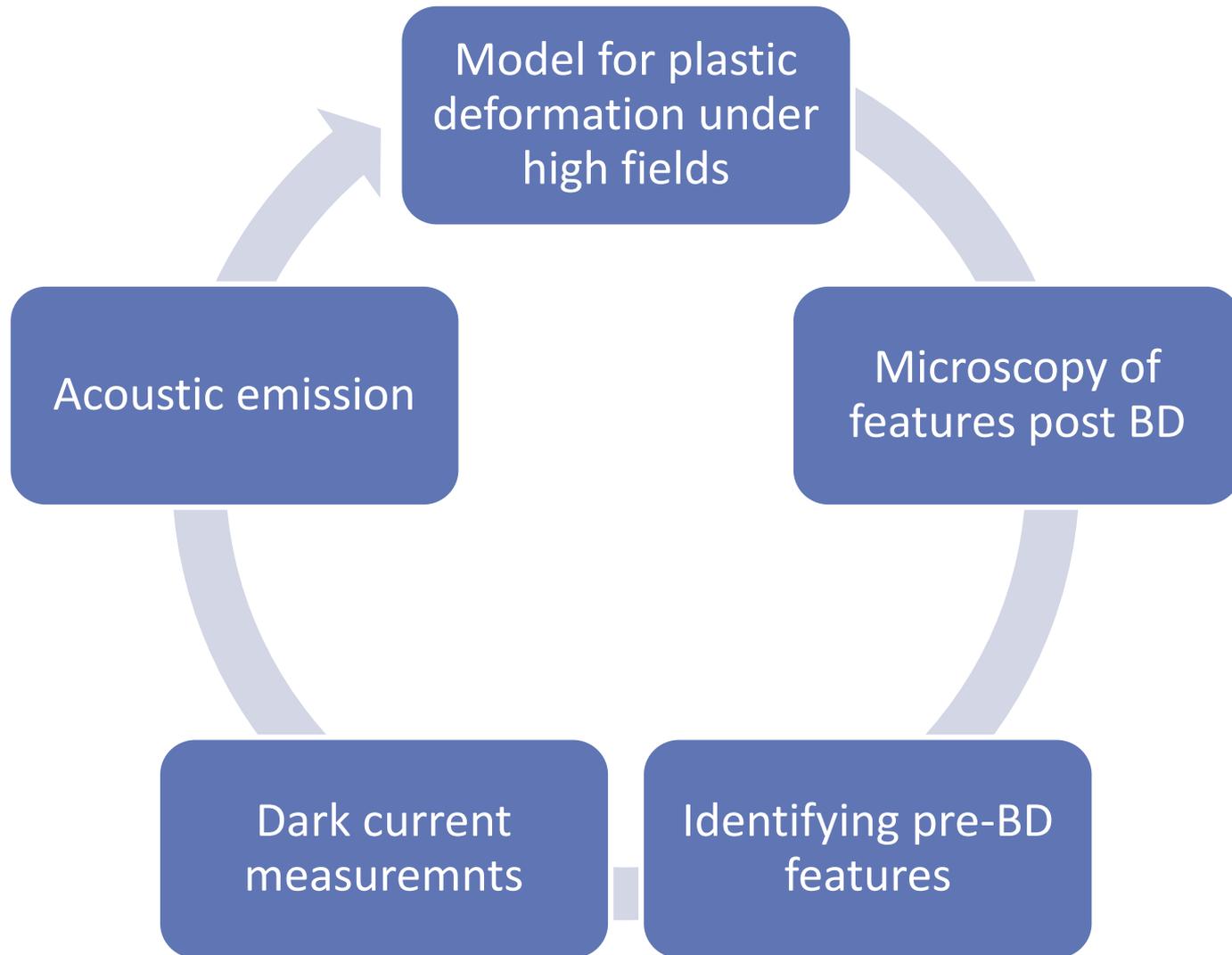initiated cracks

individual PSBs

macro-PSB

J.Man et al, Phil Mag 89 (2009) 1295

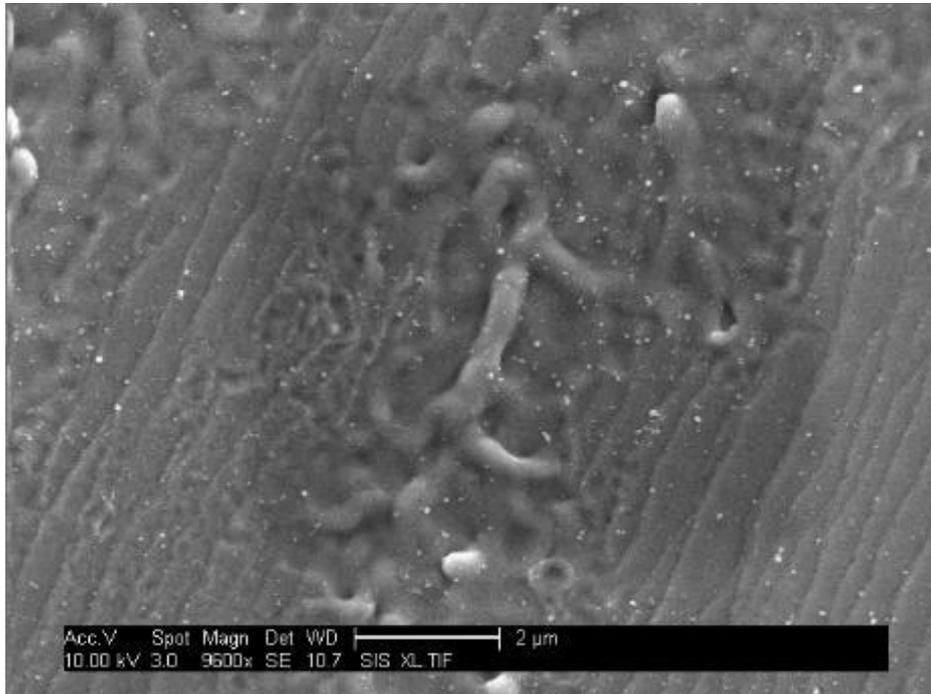Laurent et.al. Phys Rev STAB 14 (2011) 41001
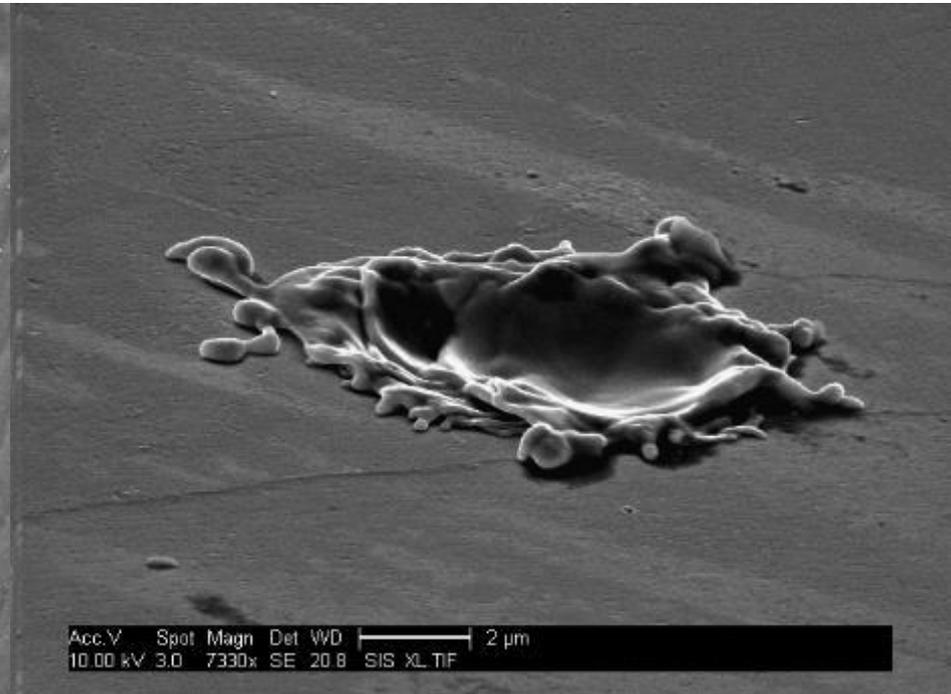
Trying to validate and calibrate a model

Surface structure
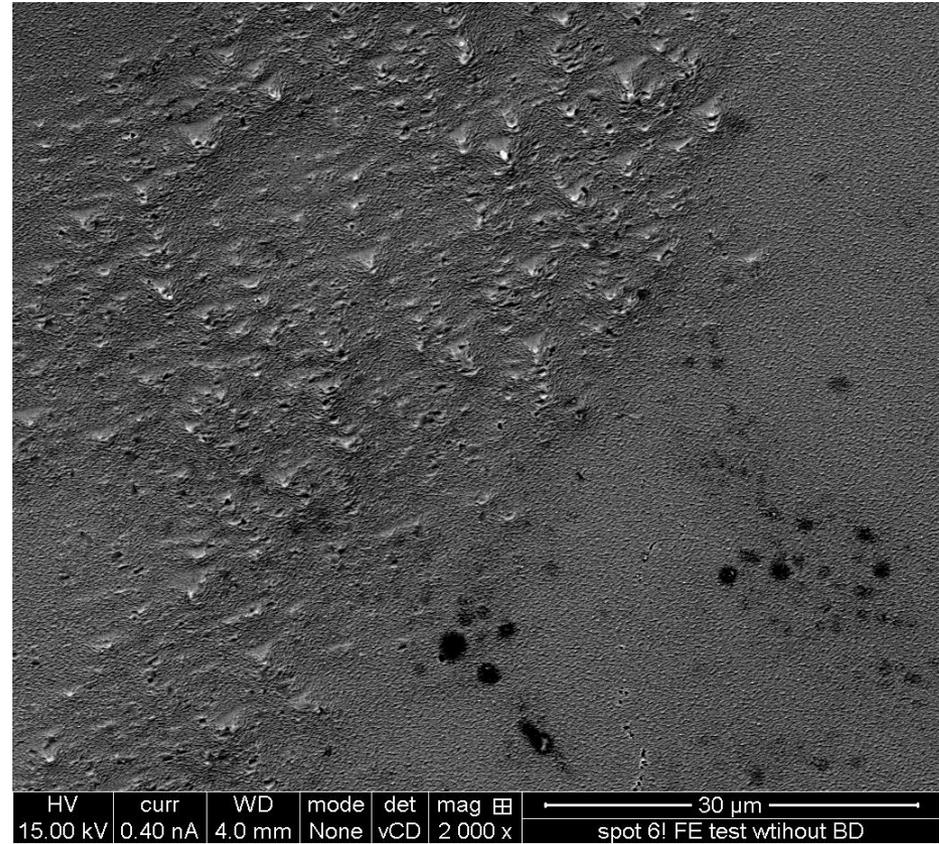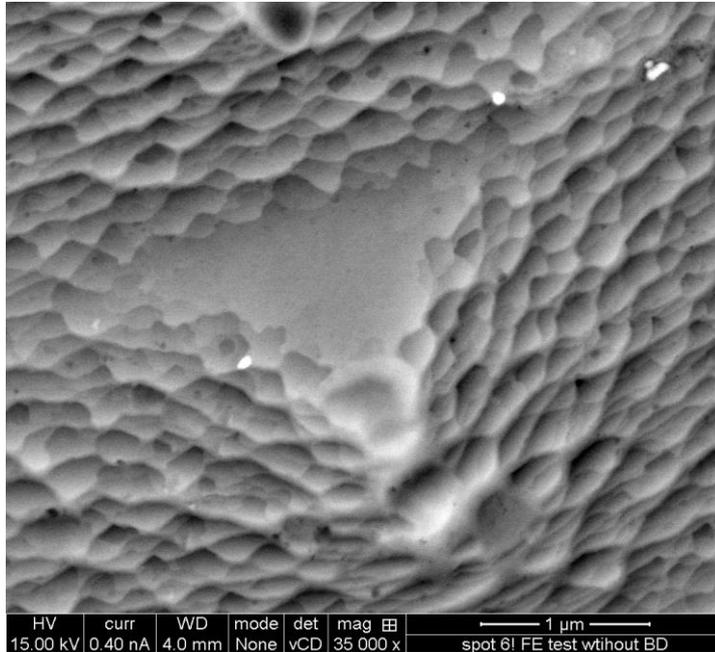
No observable features using SEM

RF post mortem – complex deposition structures … otherwise - Flat surface.

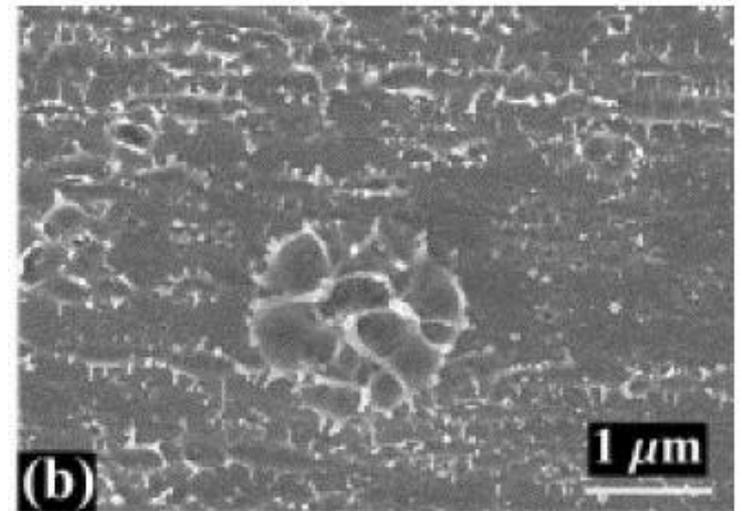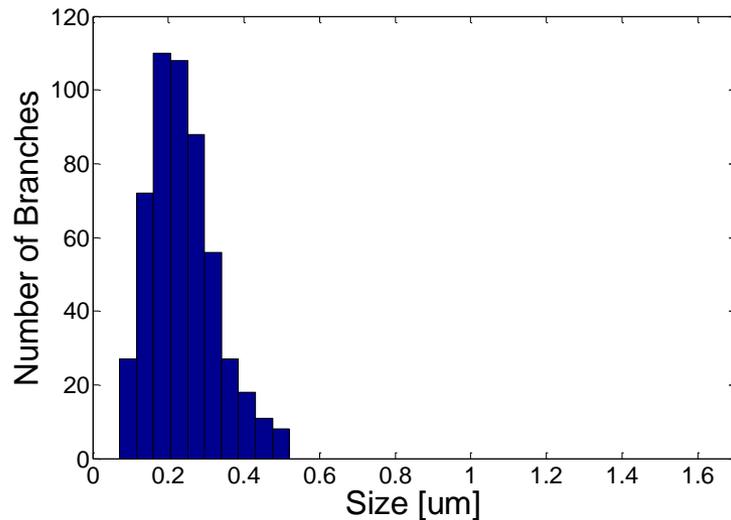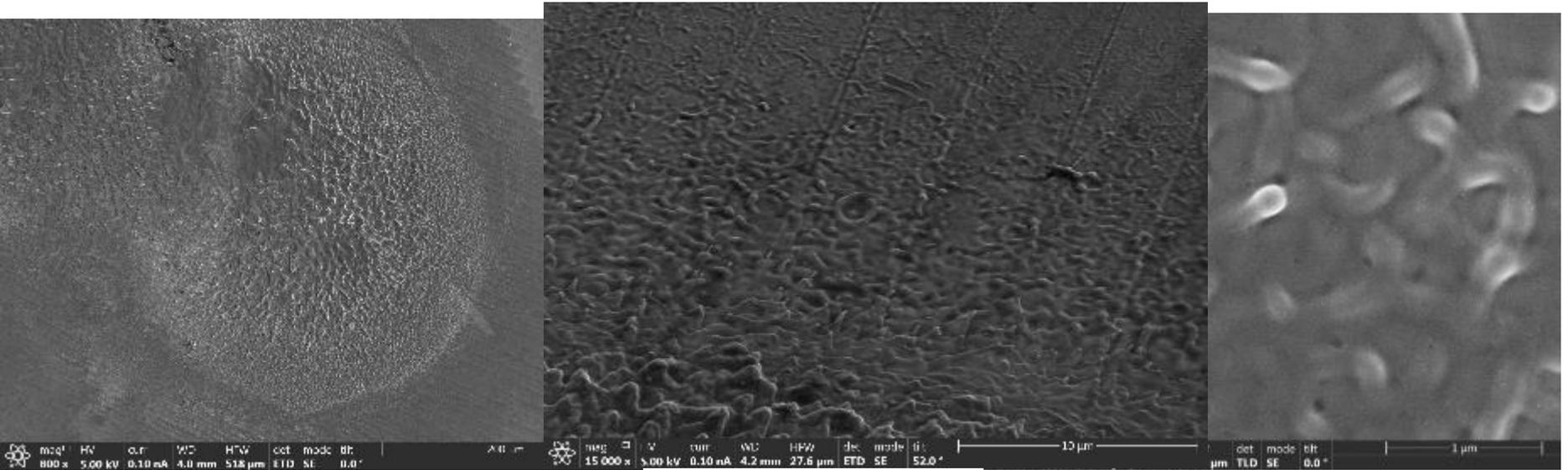DC post mortem – aside of splashed copper … Flat surface.

Found once

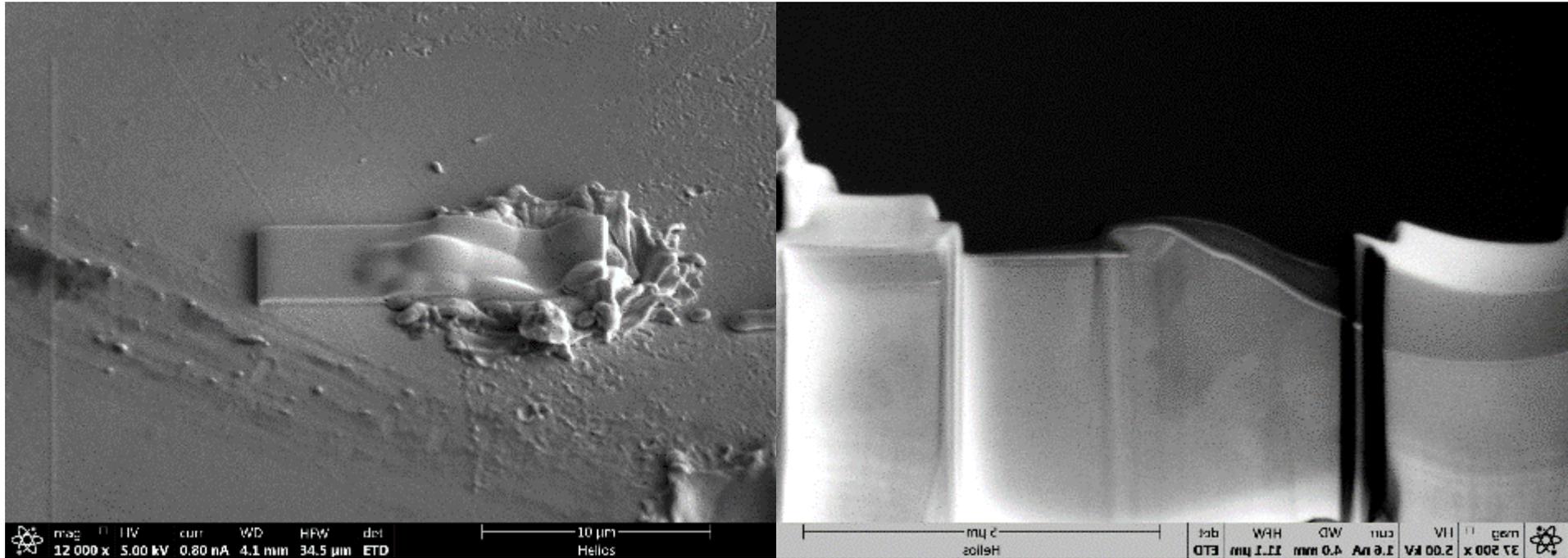- Dc samples, field emission site – assumed to be protrusion… probably not

Melt + de-wetting effects

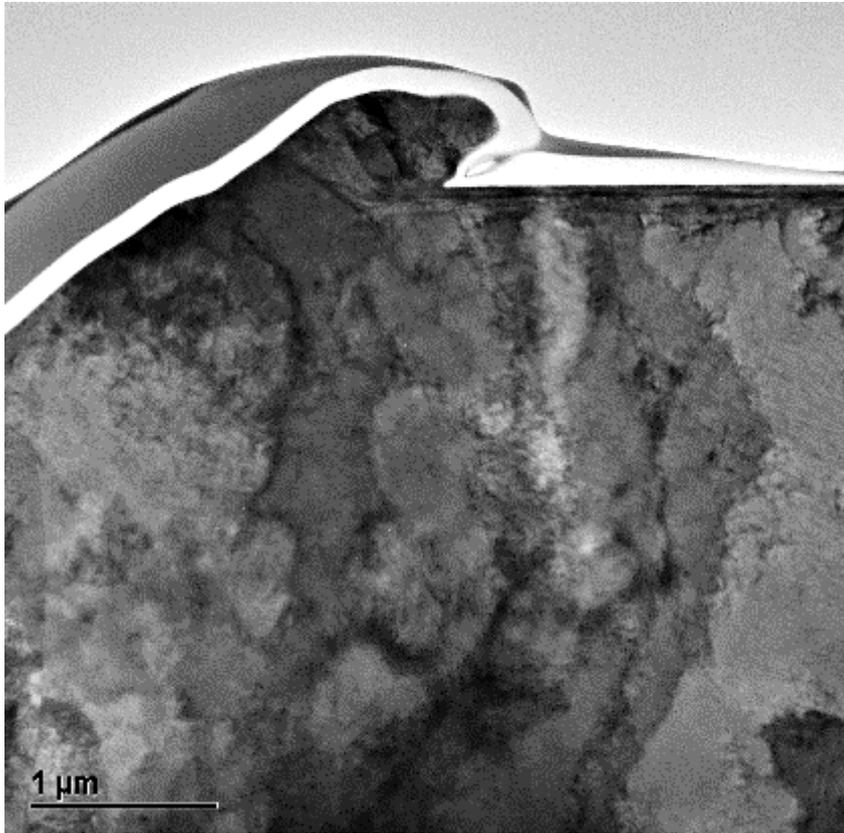A.Y. Vorobyev, Chunlei Guo, "Femtosecond laser nanostructuring of metals," Opt. Express **14**, 2164-2169 (2006);
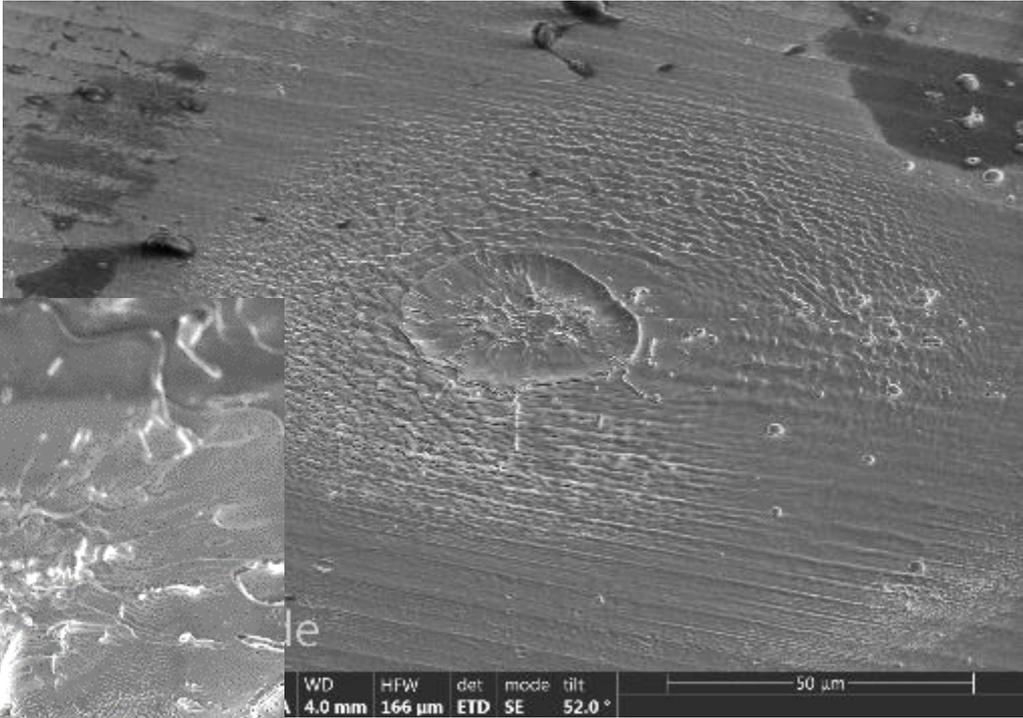
TEM sample

Dislocations in splash effected regions
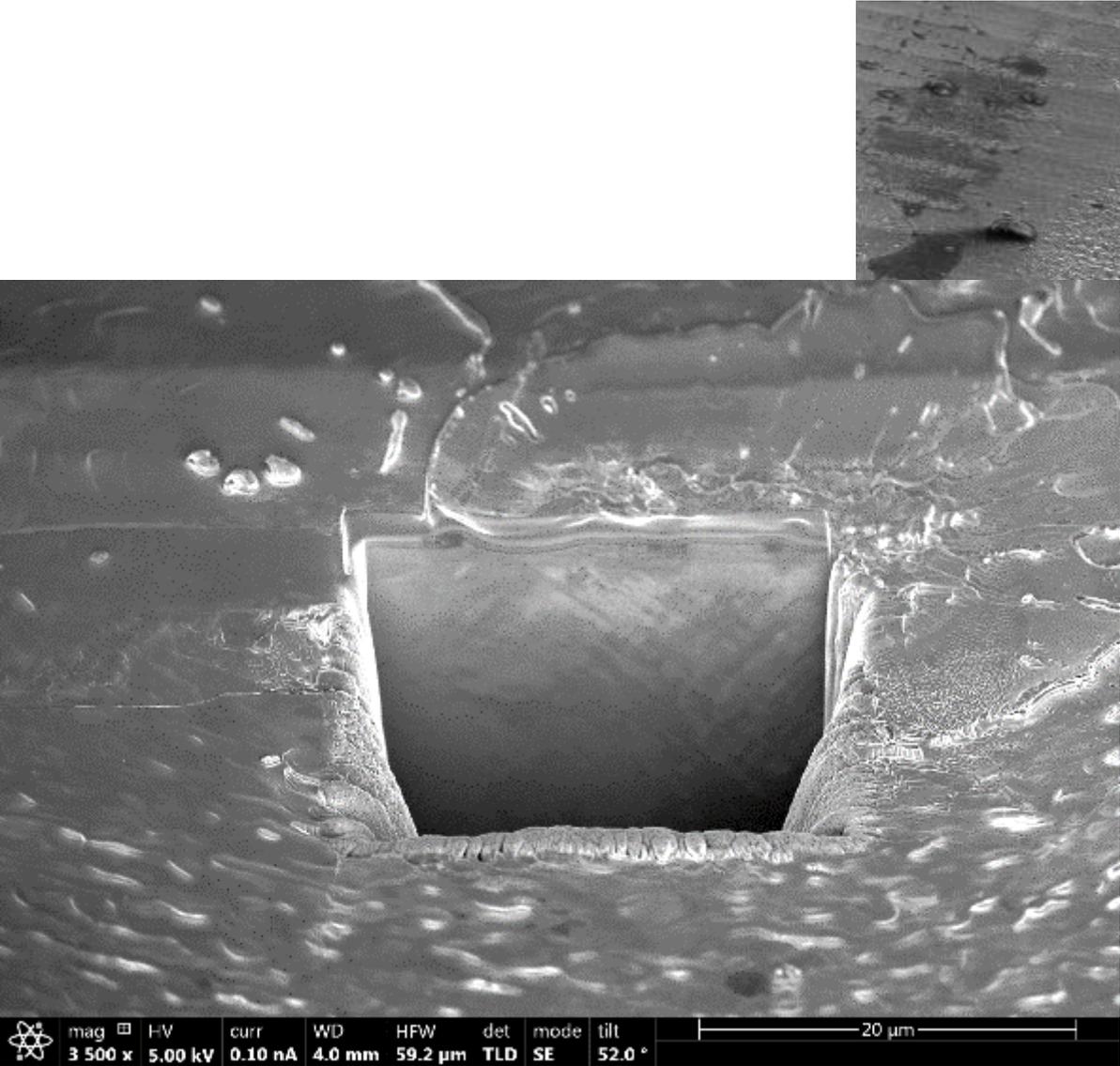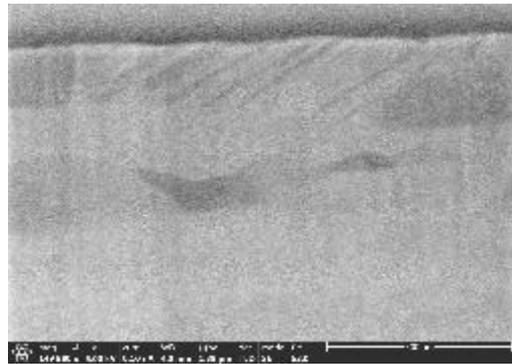

Recrystallization at edges of splash

Multiple dislocations pile ups

Melt+splash

Effects beyond the edge of the spot
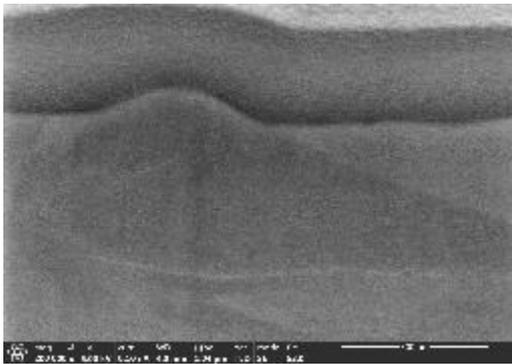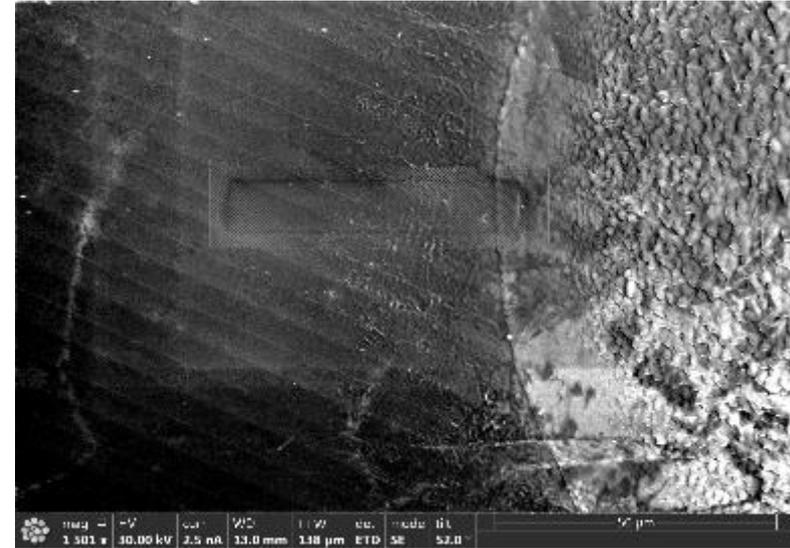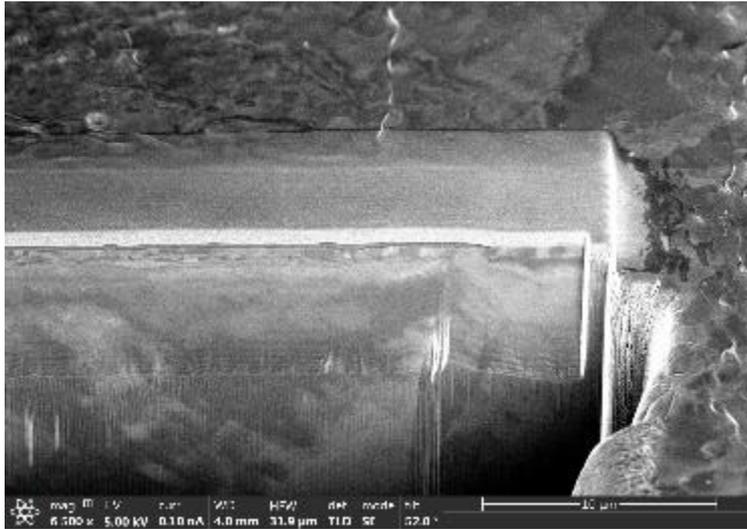
Still no clear differentiation between diamond machining effect and recrystallization
Clear top layer modifications including region with twins,, slip bands localized reliefs…

Observations until now...

- DC and RF indications of pre-breakdown increase in dark current variance

File No. 1

DC data –
Iaroslava Profatilova
Tomoko Muranaka

RF data - Alberto Degiovanni
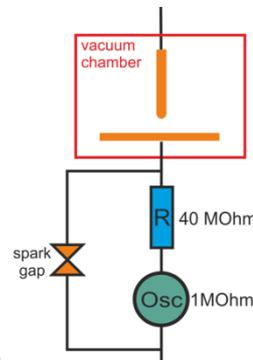
What are we looking for?

- Suggest a model which will reproduce critical protrusion formation due to plastic response in the substrate?
- Criticality due to interaction between dislocations and field emitter.

Consistency with observable characteristics:
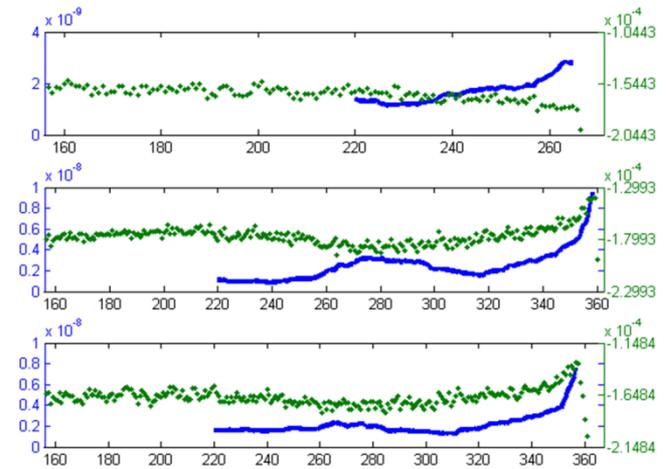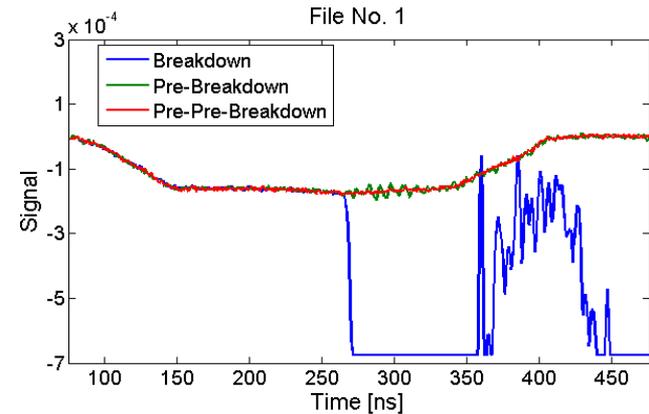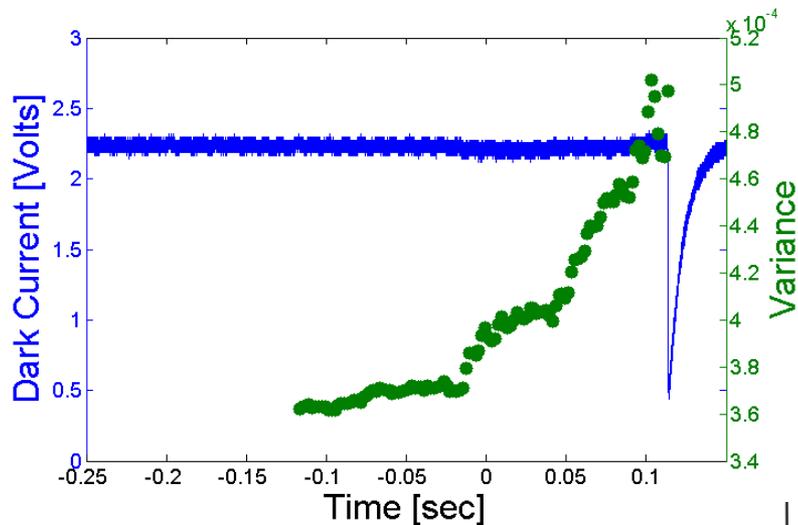- Protrusions dynamics must allow for them to disappear:
  - No strong memory effect.
  - No observable PSB or PSM
- BD rates of similar order of magnitude as observed

- BD rate field dependency: $\qquad \text{BDR} \propto E^{30} t^5$

Hope to achieve:

Critical experimental scenarios,

predictions of observable features (microscopy)

Possible outcomes – conditioning schemes, surface modifications, understand statistics…

-

0d mean field mobile dislocations model

Mean field - Single slip plane.
Define the "in-plane" mobile dislocations density (1/nm).

Protrusions forming on surface due to dislocations arriving to surface

Elastic interaction between dislocations

Field enhancement due to protrusion leads to increase in localized stress

Simulating up to creation of a runaway process which will lead to eventual tip evaporation

Not yet in...

Surface evolution – leads to hardening due to cellular structure interaction between sites
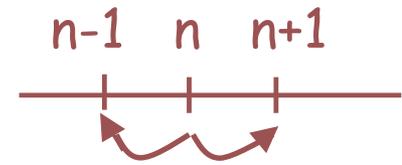
General gain-loss type Markovian processes

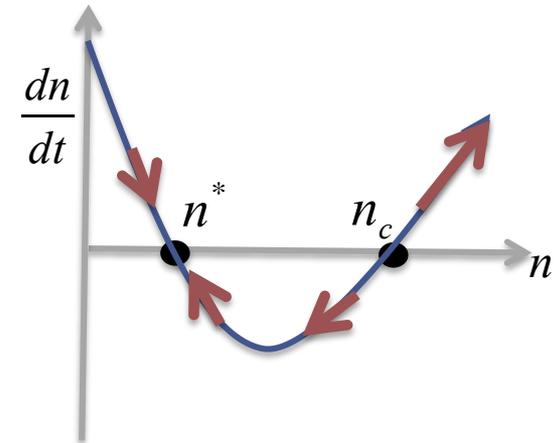Rates for transition between states

$$\rho_n^+$$
$$n \to n+1$$

$$\rho_n^-$$
$$n \to n-1$$

n-1   n   n+1

The master equation

$$\dot{P}_n = r_{n-1}^+ P_{n-1} + r_{n+1}^- P_{n+1} - \left(r_n^+ + r_n^- \right) P_n$$

can lead to bifurcation:
a metastable state and a critical one.

$$\frac{dn}{dt}$$

n^* n_c n

We look for the quasi-stationary probability distribution function
And the probability to cross the critical point (reach extinction)

Approximate solution based on WKB theory with 1/N being the small parameter.

$$\dot{P} = 0 \quad \triangleright \quad P(n) \circ P(rN) \sim e^{-N[S(r) + O(1/N)]}$$

Model basics

- Mobile dislocation multiply:
  - Activate sources
  - Release sessile dislocations at pile-ups
  - Protrusion effect on stress and temperature

- Mobile dislocations depletion
  - Collision - obstacles, other moving dislcaoitns, surface

- Protrusion form due to accumulation of dislocations but relax through diffusion (a kinetic factor)

- The problem – multi physics + multi parameters
  - First trials – use what we have
  - Better trials- learn what we need

Applied field effect
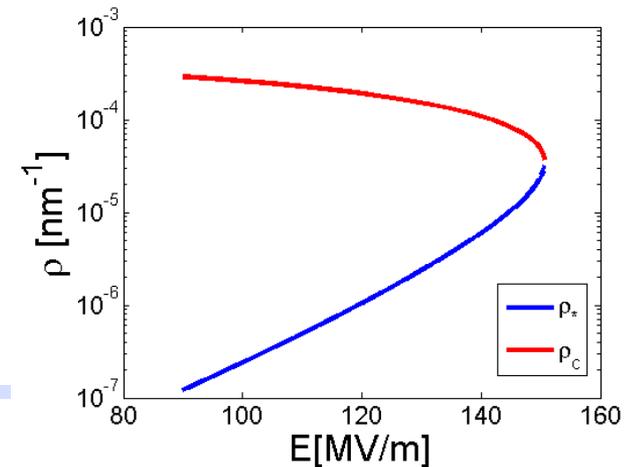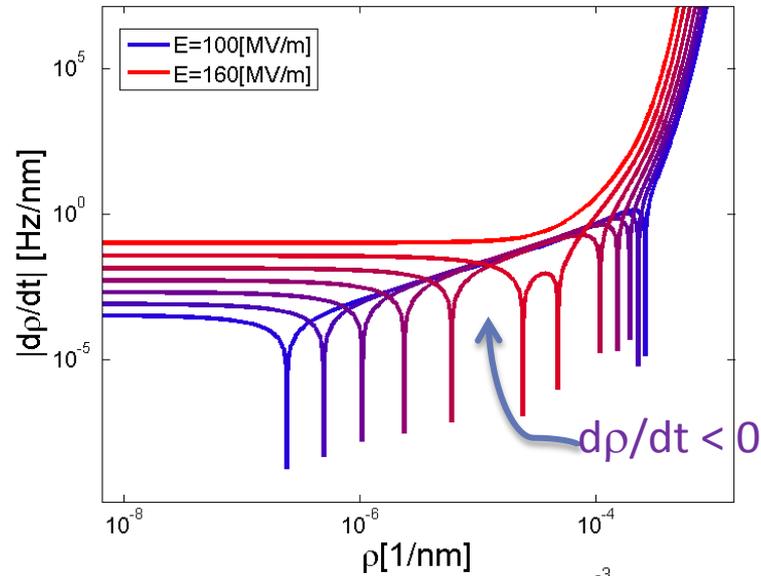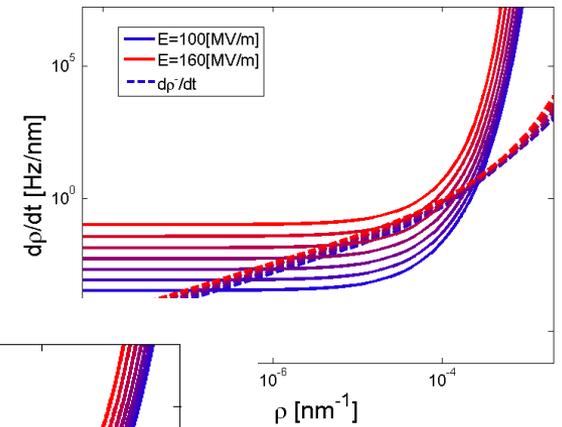
Low fields:
Mobile dislocation density remains at Metastable region. Dynamic barrier decreases with increasing fields.

Up to a critical stress – bifurcation to two solutions. Above it - no meta-stable state solution.

$d\rho/dt < 0$

Parametrization

- The model contains various competing mechanisms which can not be readily estimated.
- We scan the parameter space to see if a combination of such parameters does allow for observable behavior
- If such a region in parameter space does exist we can then check whether such a combination is indeed physically viable.

- Two main observables are used for that
- Experimental BD rates: 10^{-7} [bpp/m]
    - Estimating the number of active regions per m :

    $$N\left(\frac{1}{m}\right) = \frac{(\frac{N_{iris}}{m})\cdot(S_{iris})}{dR_{active\ regions}{}^2} \approx \frac{100\cdot2\pi\cdot2.35(mm)\cdot1(mm)}{(10^{-2}mm)^2} = 10^7$$

    - Since the pulses are of 230 nsec we get :

    $$\tau(BD)_{per\ area\ unit} = dt_p/(P(bpp/m)/N) = \frac{230nsec}{\frac{10^{-7}}{10^7}} \approx 10^7(\frac{sec}{zone})$$

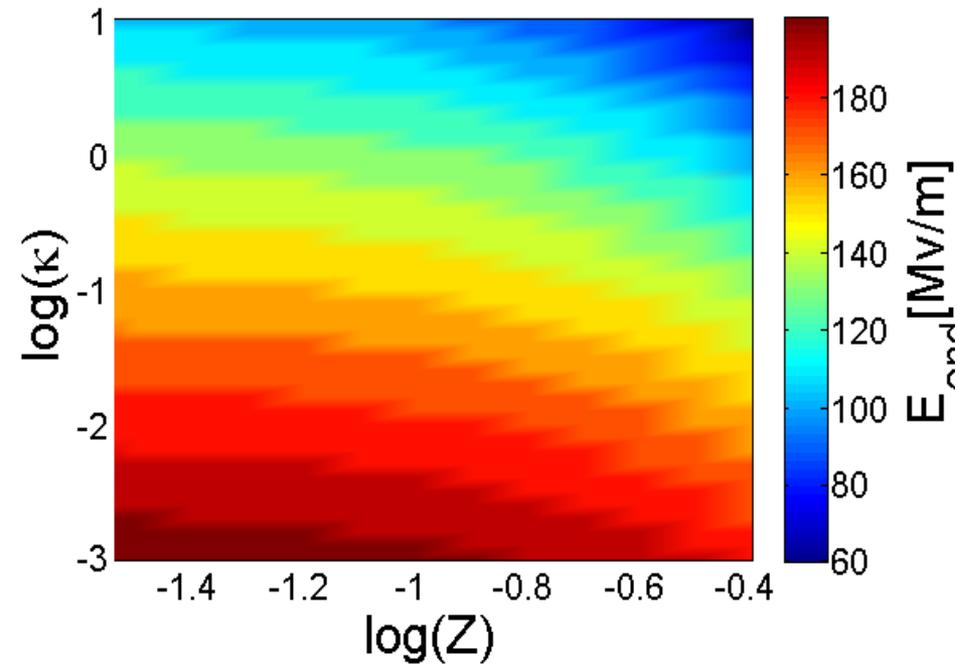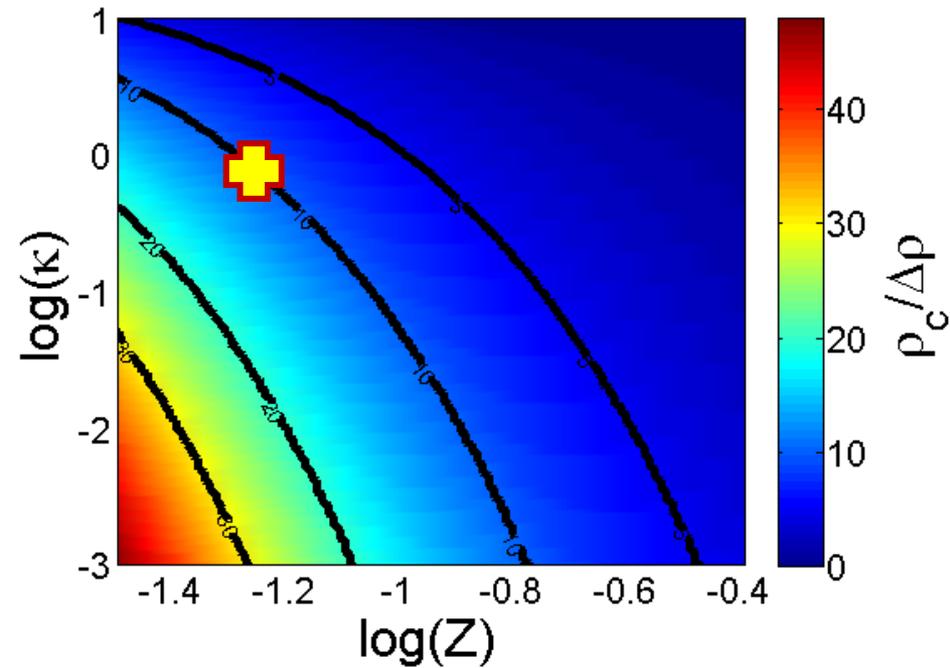- Field dependency of the breakdown rate (estimated as E^{30}) .
  So we define the localized (10%) exponent : $n = \log_{1.1}(\frac{\tau(E)}{\tau(1.1\cdot E)}) \approx 30$
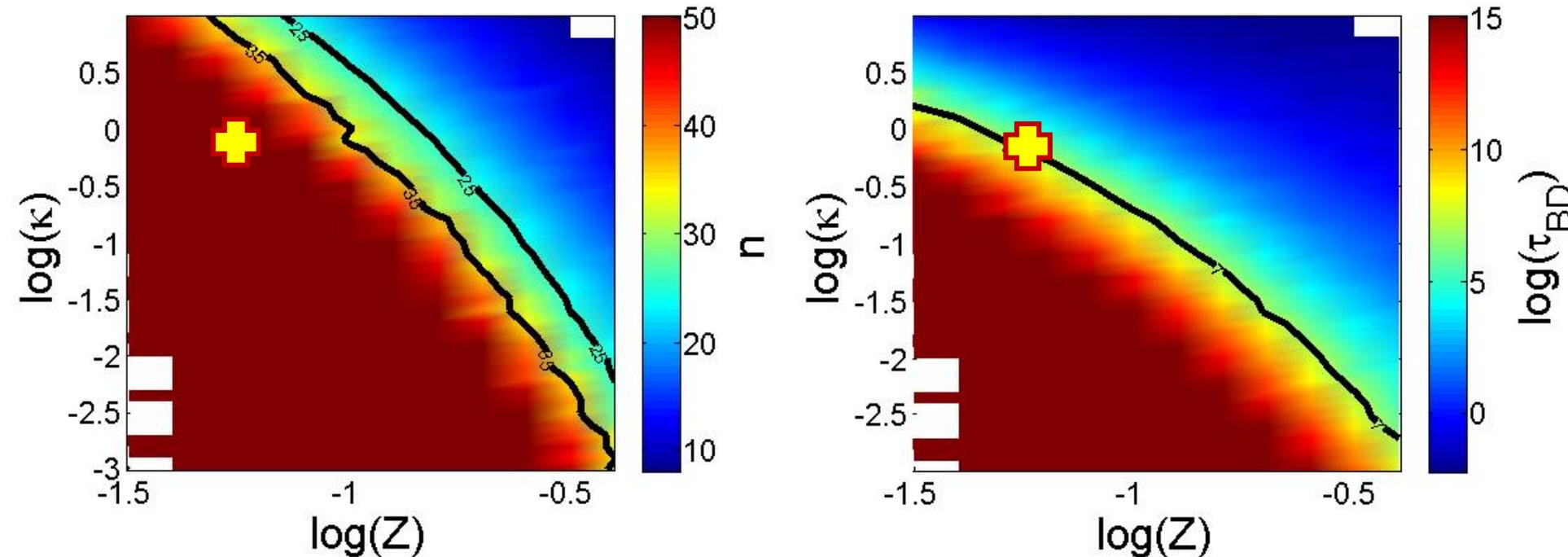
Parameter space – kmc simulations

- full model validity range – using kmc

Parameter space – kmc simulations
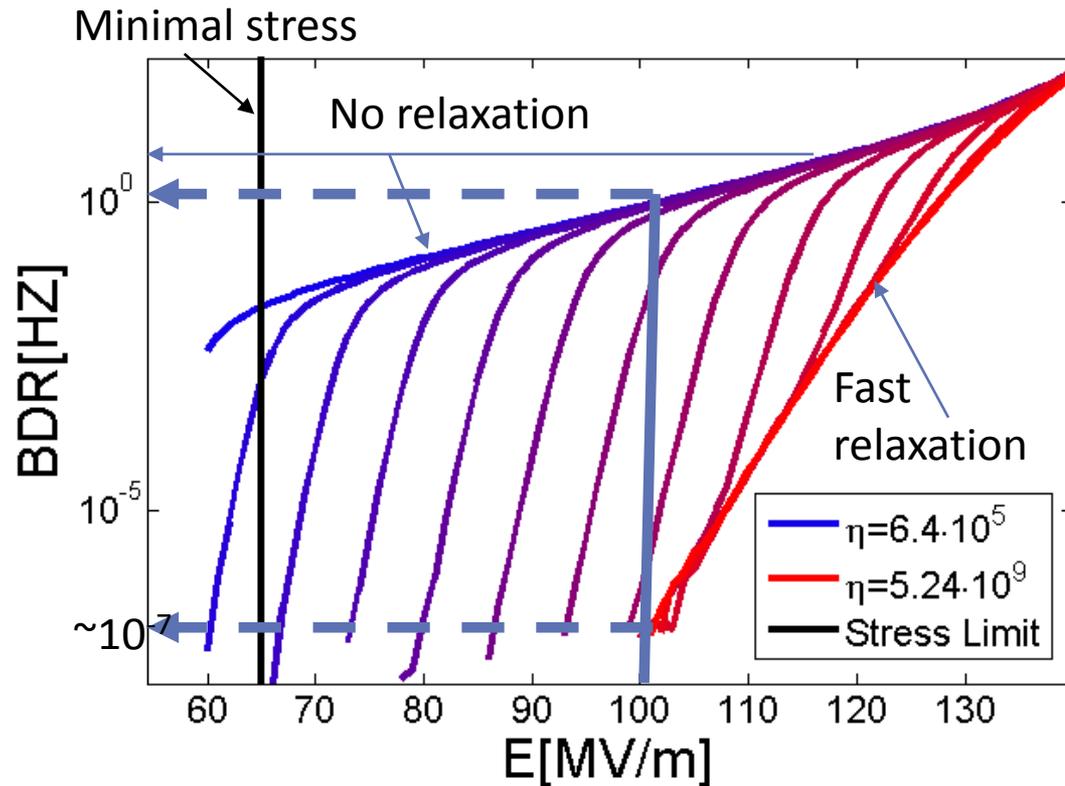
- full model validity range – using kmc

- Observable values:

$$\tau_{bd} \approx 10^7 \, sec \; , \; n = ln(\frac{\tau(E)}{\tau(rE)})/\ln(r) \approx 30$$

- Significant coincidence region:

Effect of kinetic relaxation parameter

Relaxation kinetics (surface diffusion) defines two limits:
a. Fast– surface topography follows mobile dislocations content.
b. Slow– surface builds up even at metastable state of mobile dislocations .

Evolution trajectories

- Dynamics of surface protrusions shows relation between surface protrusions and mobile dislocations.
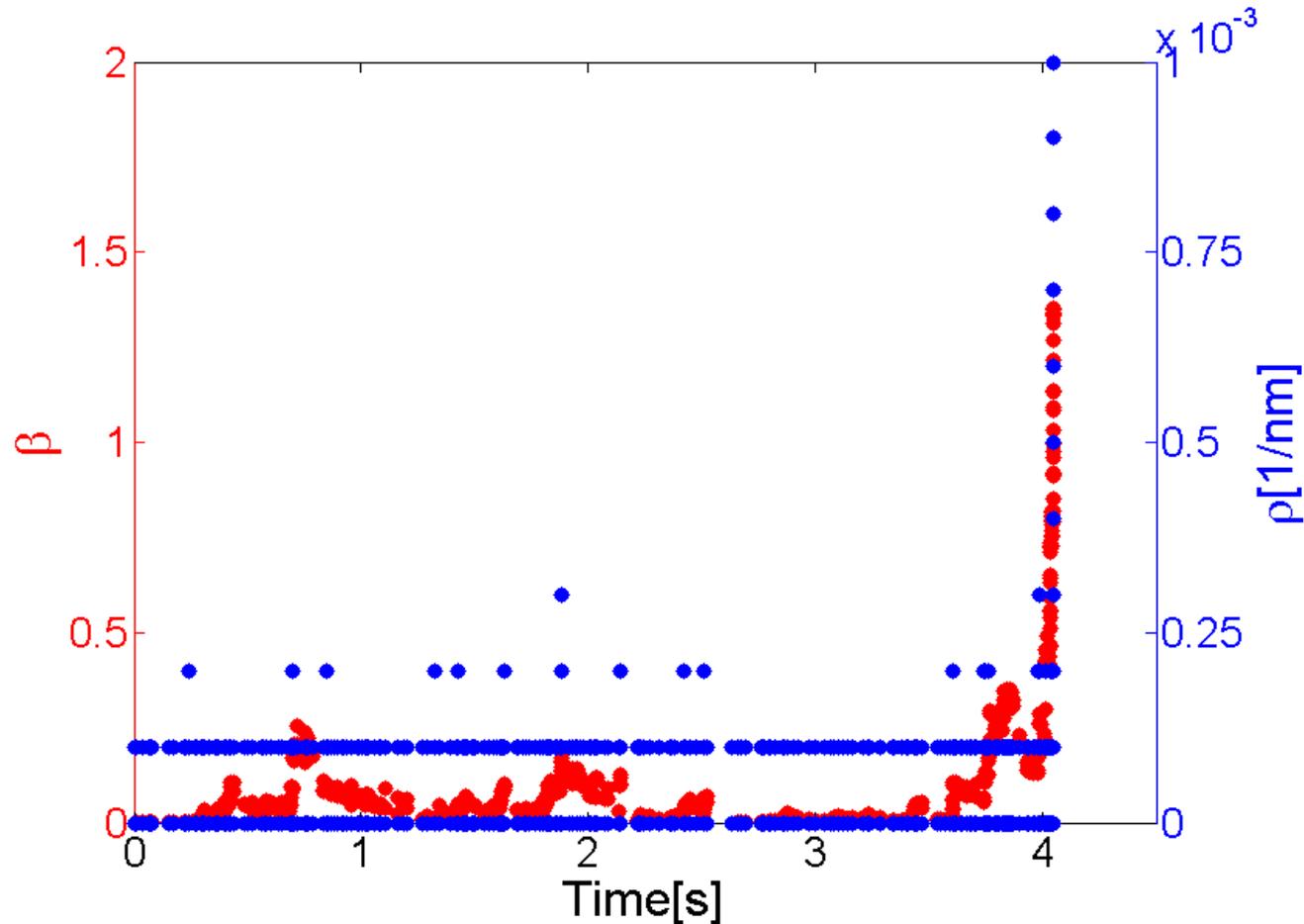
Signs of criticality

- Adiabatically moving between quasi-stationary PDF:
  Change in pdf moments with field
    -> identify threshold

- At specific conditions, probe time dependencies of the QS pdf:
  Identify large fluctuations time dependency
    -> identify time constants
    -> mechanism

$$P_c\left(s,r,t\right) = \int_0^t P\left(s,r\grave{}>r,t\grave{}\right)dt\grave{}$$
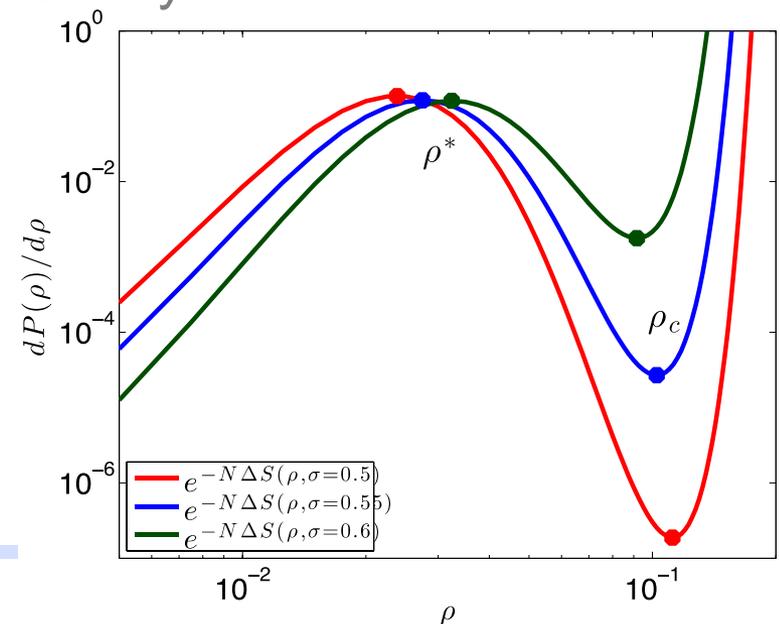
PRE-BD signals

- As the system approaches the critical point. Fluctuation diverge.

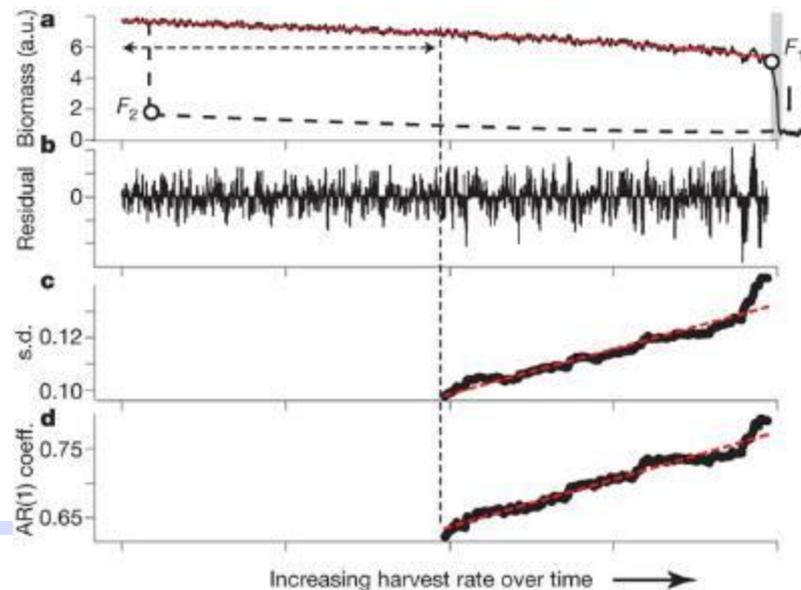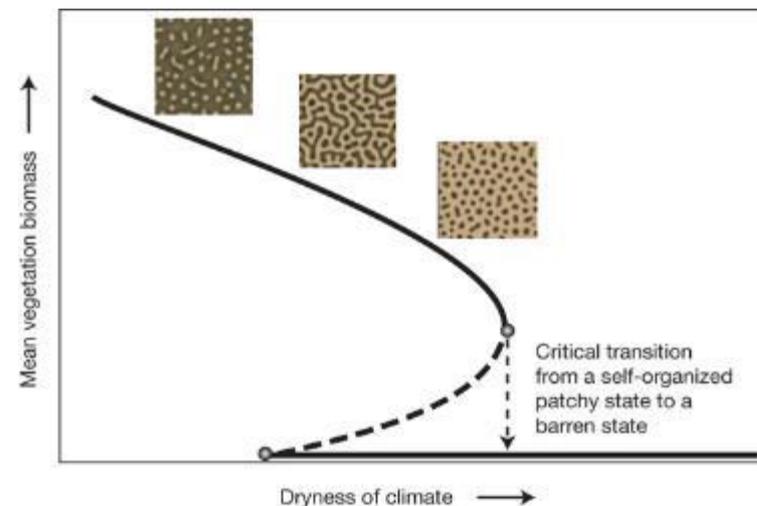- Observable through standard deviation of the time correlation

$$SD(t) = \frac{\int_{t-D}^{t+D} \left(I(t) - <I>\right)^2 dt}{\left(<I>\right)^2}$$

- Or, more generally, autocorrelation in the signal

$$R(k) = \frac{\int_0^{t-k} \left(I(t) - <I>\right)\left(I(t+k) - <I>\right) dt}{\int_0^{t-k} \left(I(t) - <I>\right)^2 dt}$$
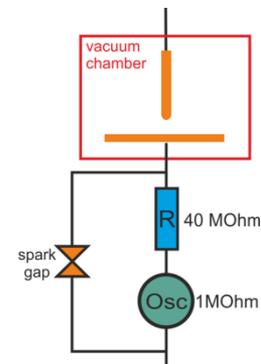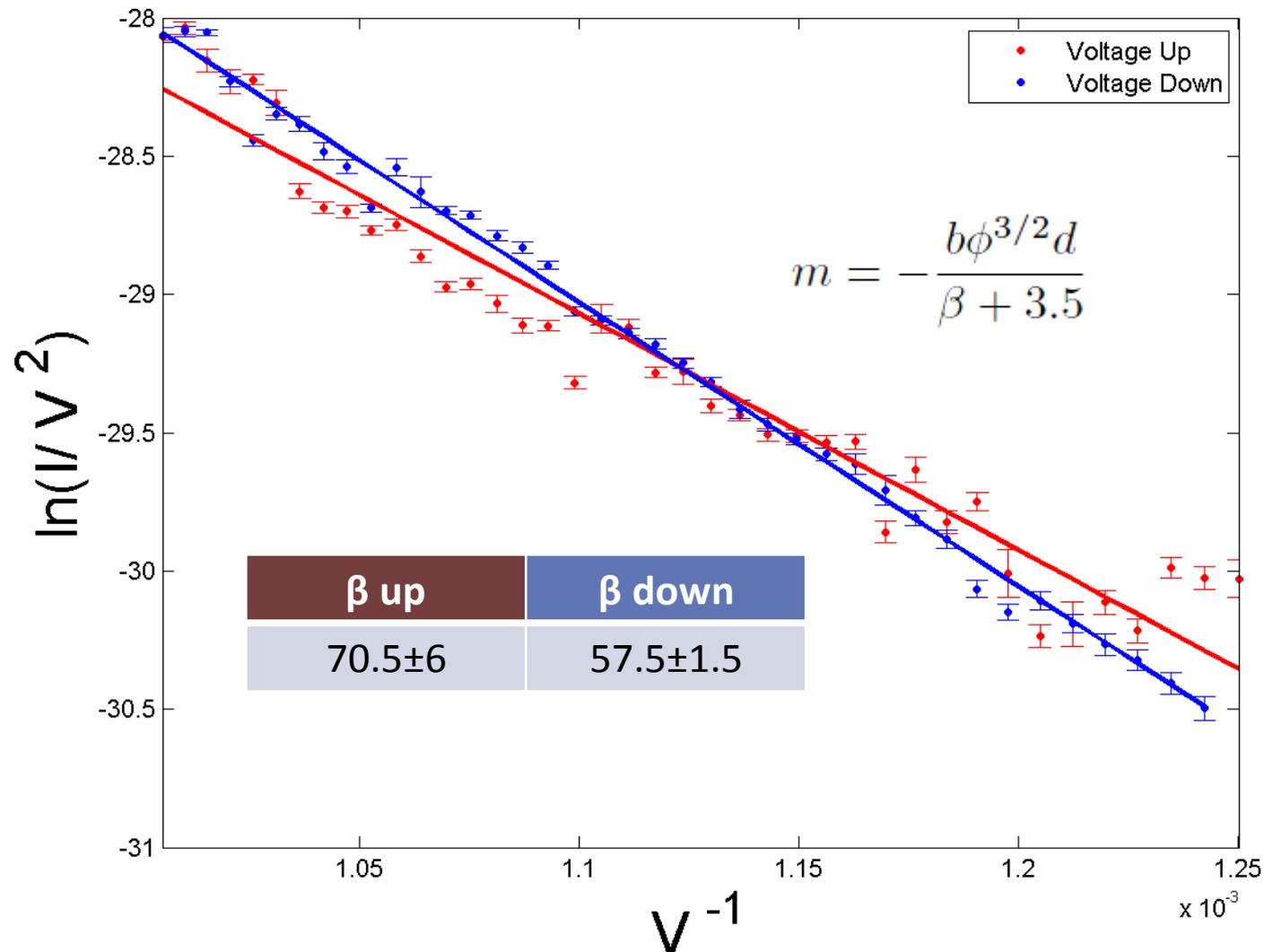
-

Early-warning signals for critical transitions

Marten Scheffer[1], Jordi Bascompte[2], William A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1], Hermann Held[6], Egbert H. van Nes[1], Max Rietkerk[7] & George Sugihara[8]

Critical transition from a self-organized patchy state to a barren state

Mean vegetation biomass

Dryness of climate

Residual Biomass (a.u.)

s.d.

AR(1) coeff.

Increasing harvest rate over time

DC measurements

Set 1

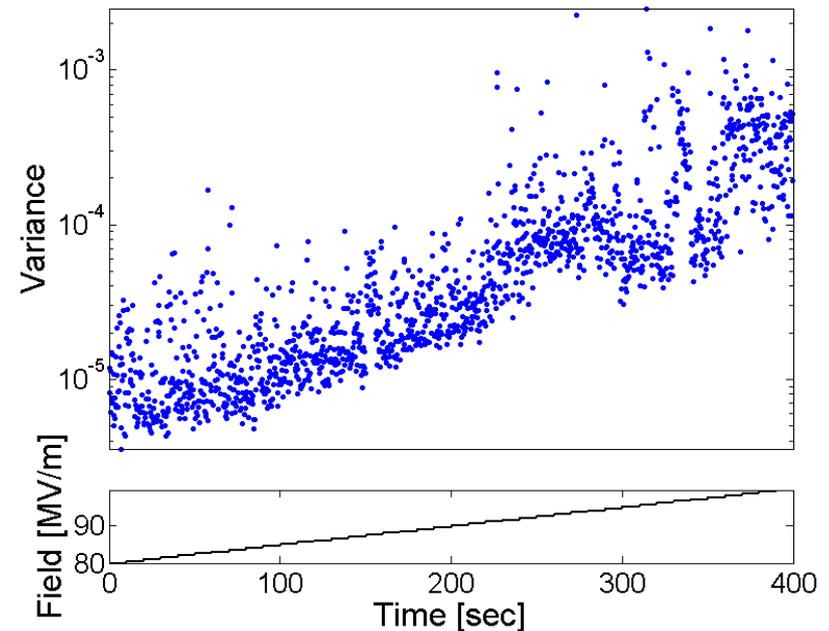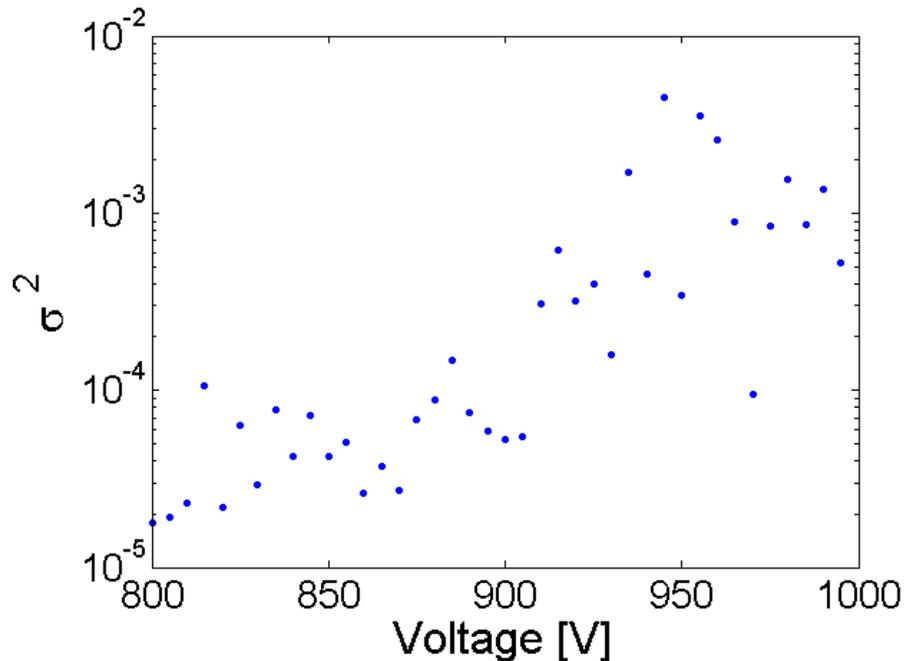$$m = -\frac{b\phi^{3/2}d}{\beta + 3.5}$$

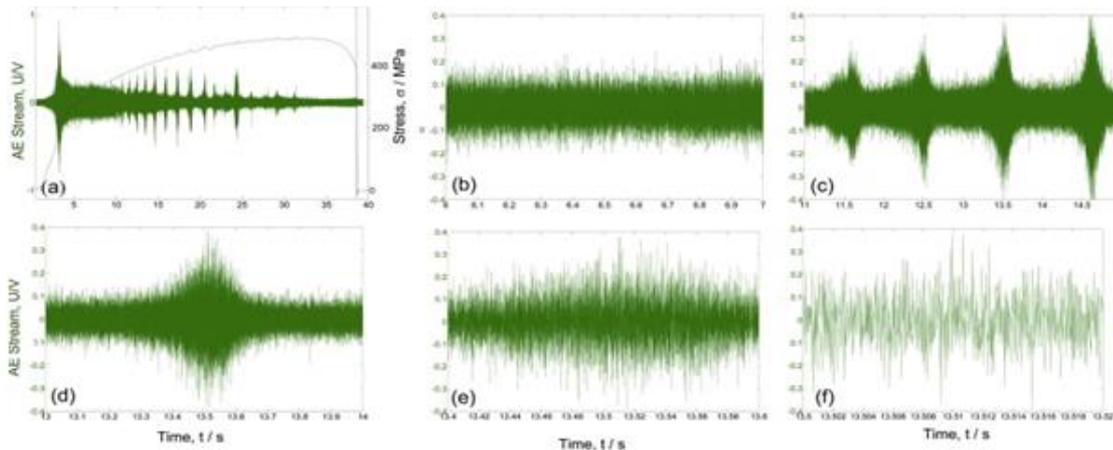| β up	β down
70.5±6	57.5±1.5

Field dependent fluctuations

- Monitoring FN allows direct access to the protrusion population, and therefor show pre BD increase.

- Time scale of fluctuations - indicative to the dynamic timescale.

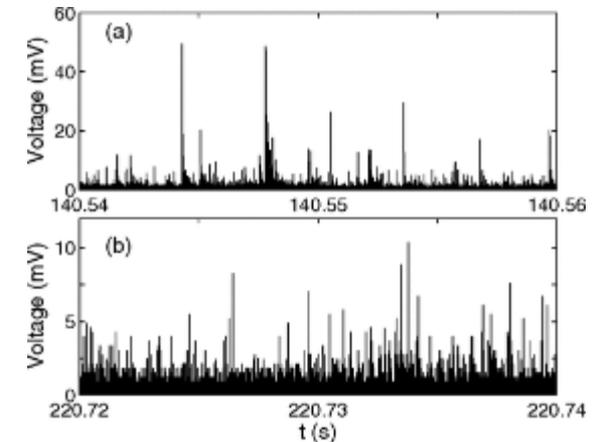# Acoustic emission - the mean to identify mobile dislocation popoulaiton

A. Vinogradov, A. Lazarev

Continuous acoustic emission during intermittent plastic flow in α-brass

Scripta Materialia, Volume 66, Issue 10, 2012, 745 - 748

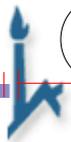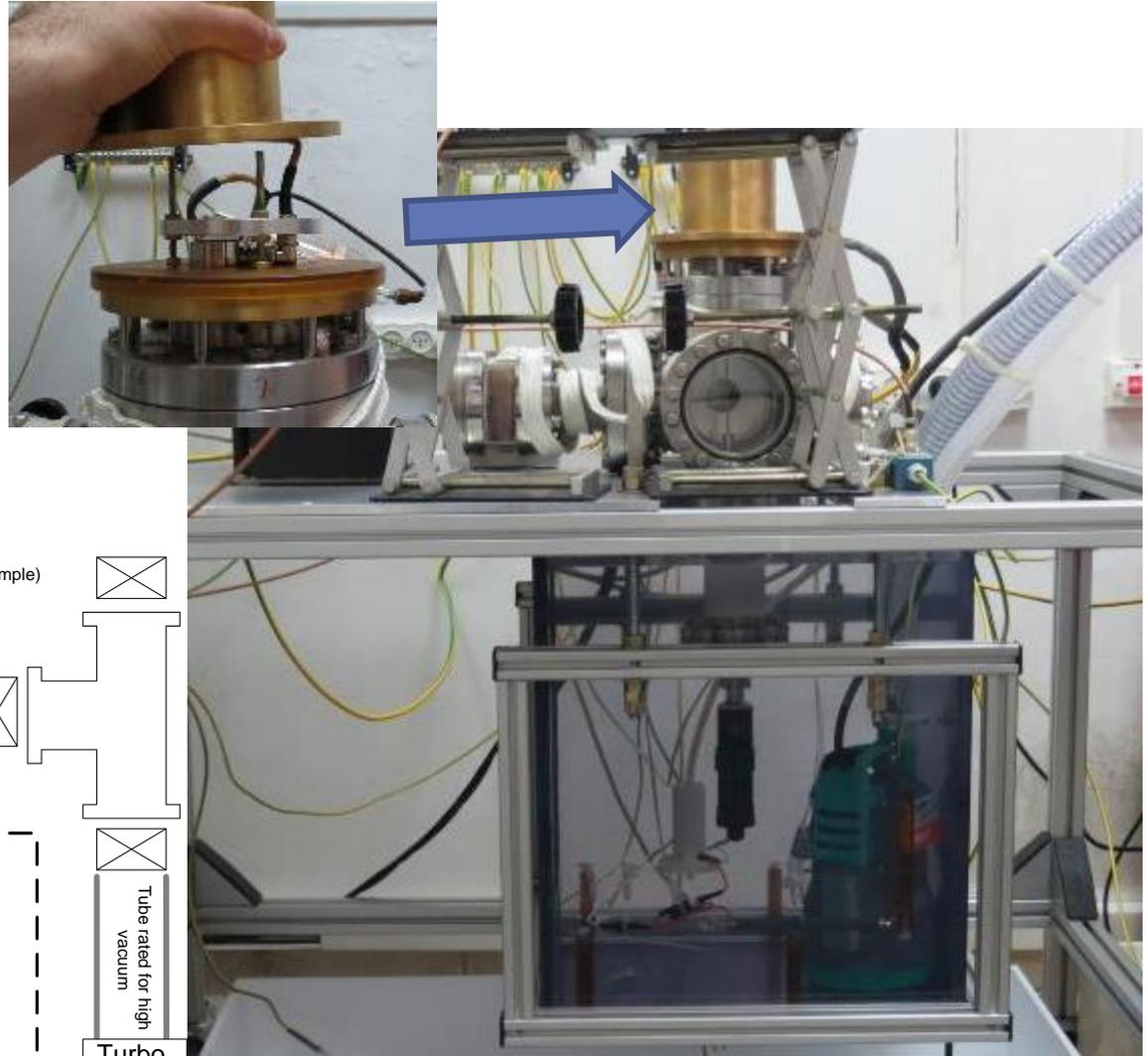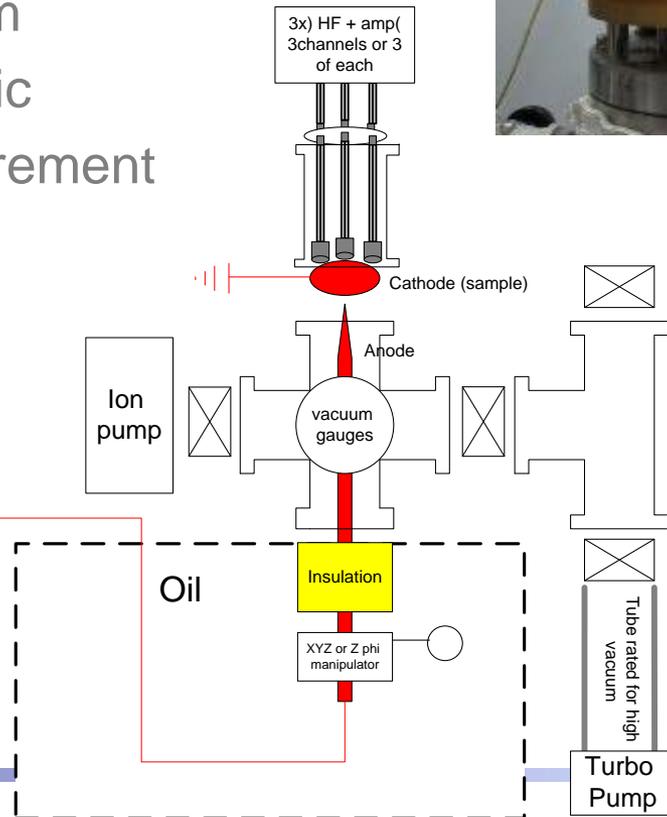http://dx.doi.org/10.1016/j.scriptamat.2012.01.053

Lebyodkin, M. A. et al. Role of superposition of dislocation avalanches in the statistics of acoustic emission during plastic deformation. Phys. Rev. E 88, 042402 (2013)
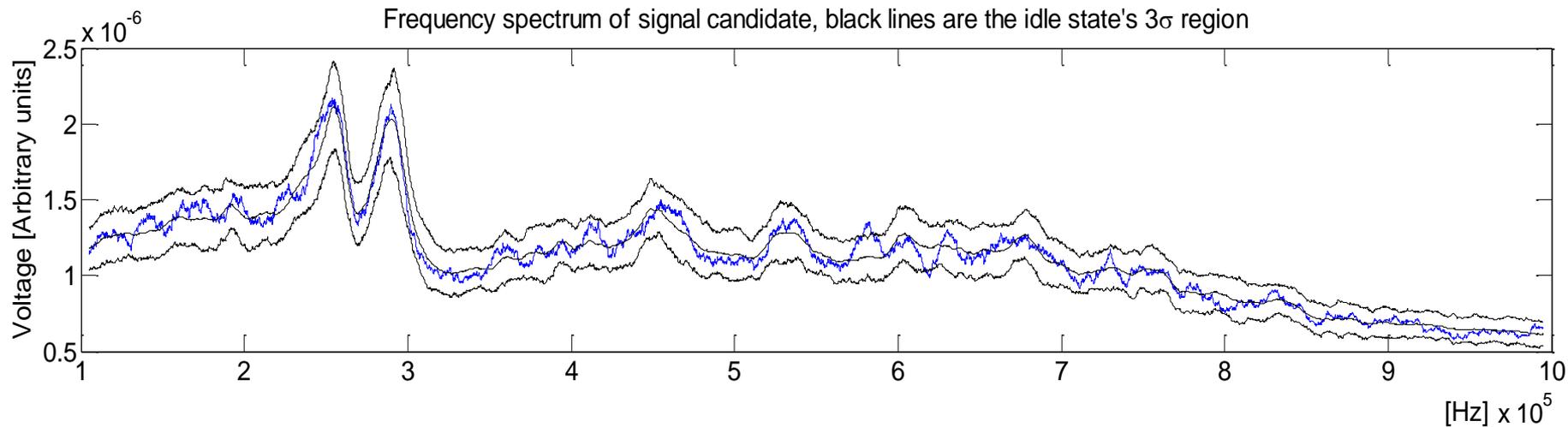
High voltage acoustic emission system

System designed For:
- High voltage
- Vacuum
- Acoustic
  measurement

3x) HF + amp(
3channels or 3
of each

Cathode (sample)

Anode

Ion
pump

vacuum
gauges

Insulation

Oil

XYZ or Z phi
manipulator

Tube rated for high
vacuum

Turbo
Pump

+
DC
supply
-

Preliminary results (AI)

pre-breakdown, I ≈ 30 [μA]

Frequency spectrum of signal candidate, black lines are the idle state's 3σ region

Tension between signal candidate and idle sample mean, The black lines are the idle sample's 3σ region
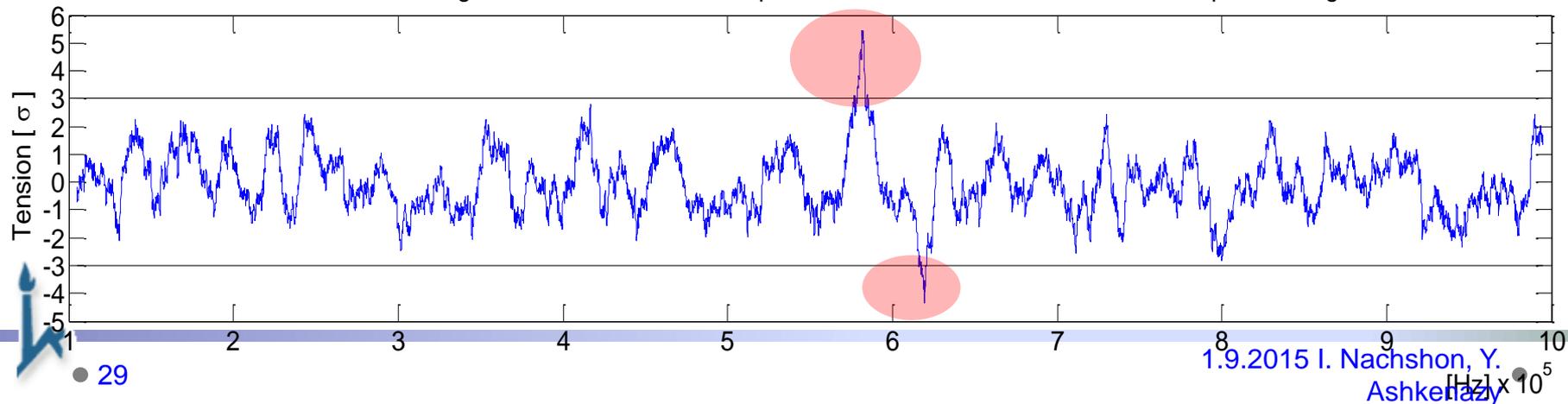
Vacuum initiation due to pre-BD plastic activity

- Assuming a plastic process leads to protrusion formation which have large aspect ratio - field enhancement and locally reduced work function
- Trying to calibrate a full stochastic model for surface evolution prior to breakdown formation – leading to the actual BD event.
- It is suggested that dark current fluctuations due to surface topography evolution is indicative of imminent breakdown
- Population of mobile dislocations kinetics is described using a stochastic model.
- The model shows a metastable region with a critical transition in a range of fields..
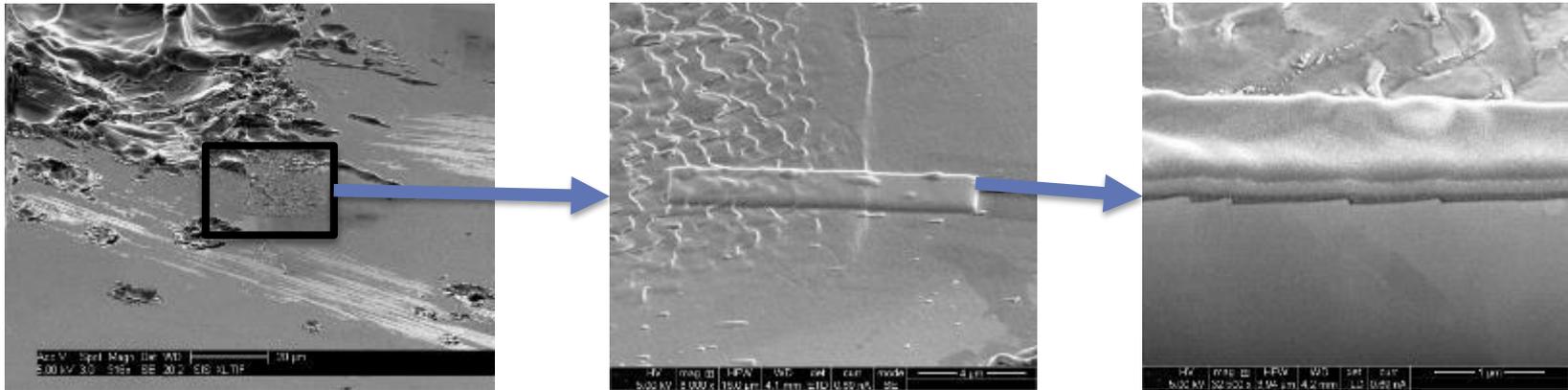- Current efforts focused parameterization.

Creation and annihilation rates
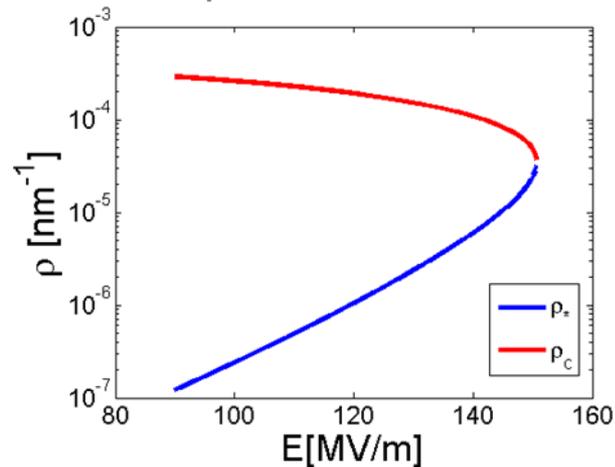
Critical (red) and metastable (clue) mobile dislcaoitons density

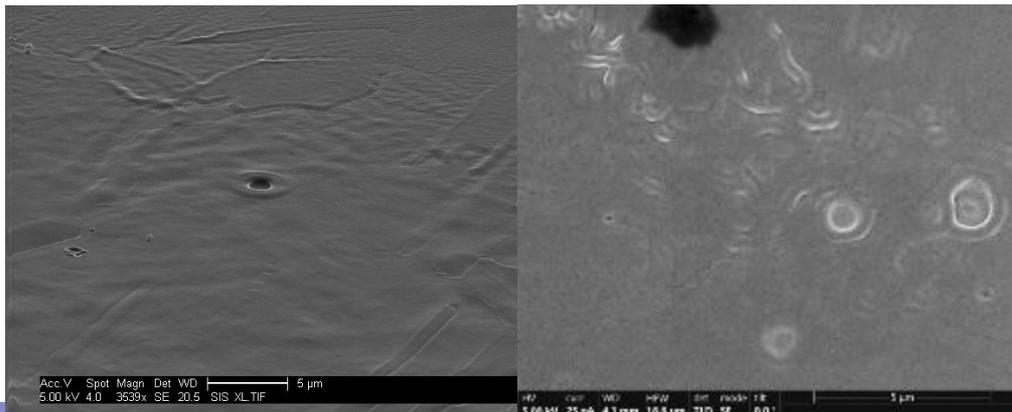- Y. Ashkenazy, Hebrew University of Jerusalem
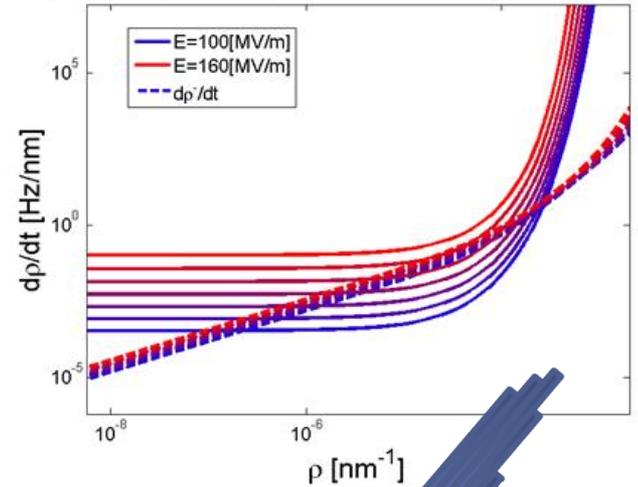
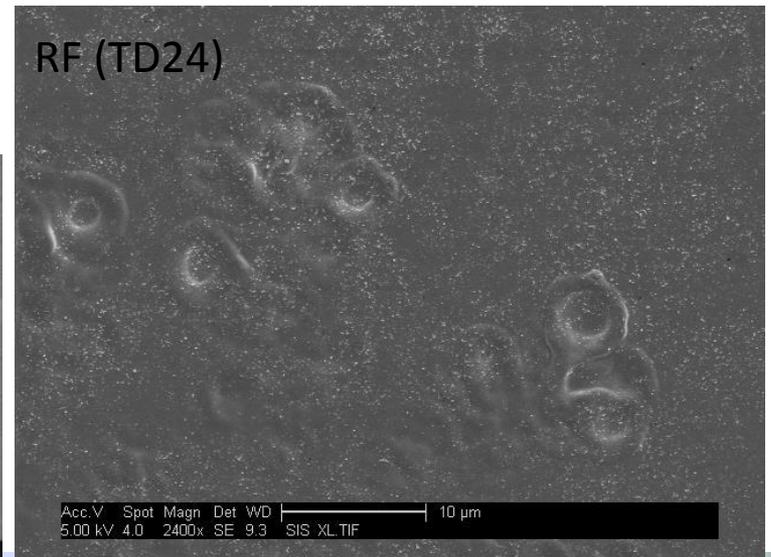# Surface modifications affecting plastic activity

- SEM+FIB - Violently modified BD "craters" are surrounded by larger (gentle) surface modified regions
- Similarity between RF and DC "far from BD" regions
- Possible source for conditioning?

DC

RF (TD24)

A. Yashar, Y. Ashkenazy, I. Popov, Hebrew University of Jerusalem

Pre-BD signals of plastic activity

- As a critical plastic process – increase in pre-transition fluctuation is expected

- Initial indications to increase in dark current fluctuations as measured in CERN DC system
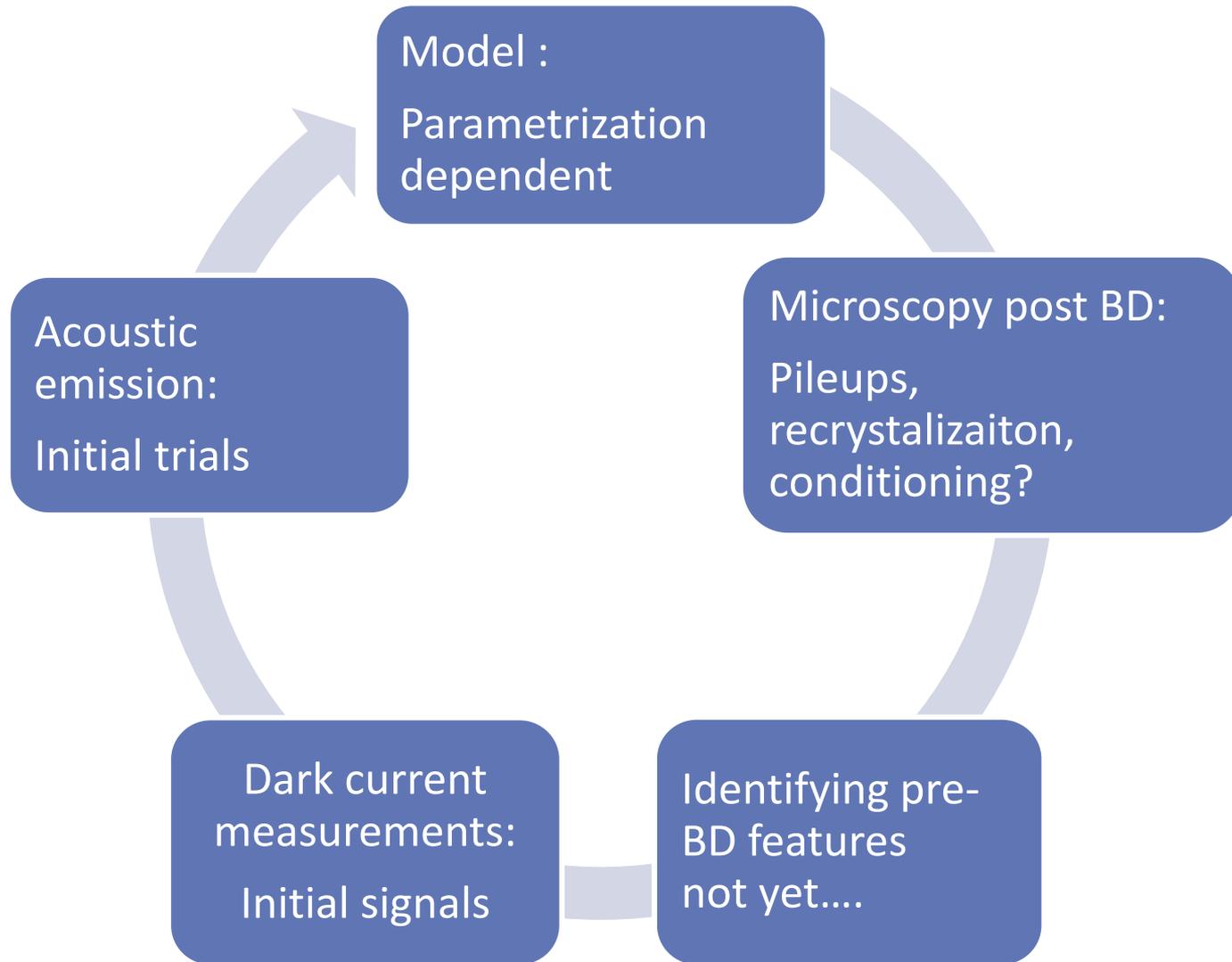
  T. Muranaka & Y. Ashkenazy

- Using a new system that monitors acoustic emission in unison with DC- high field application initial indication of pre-BD plastic activity

DC- High field vacuum cell

Acoustic Transducers
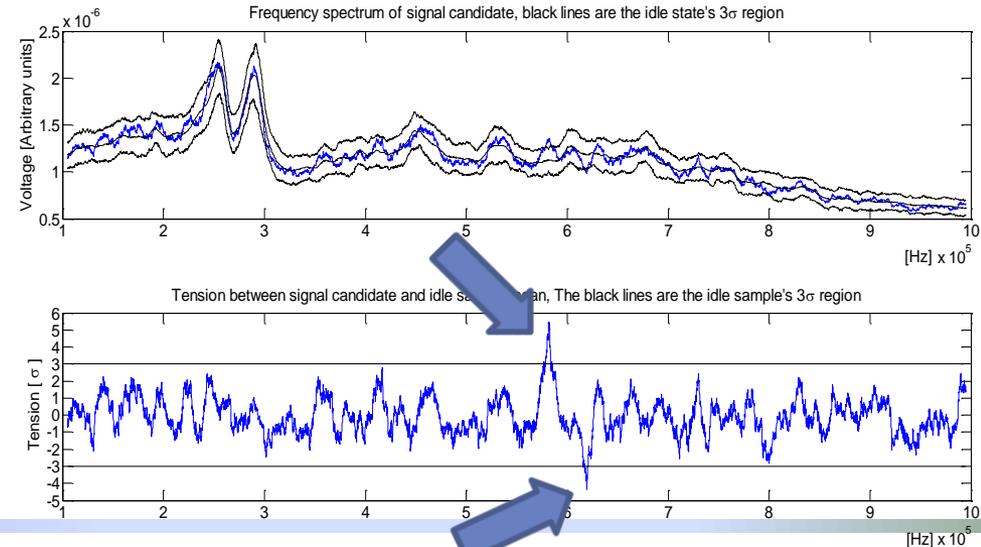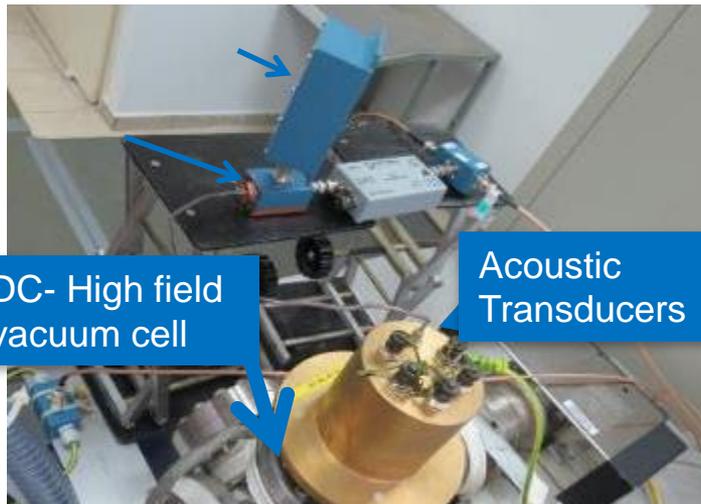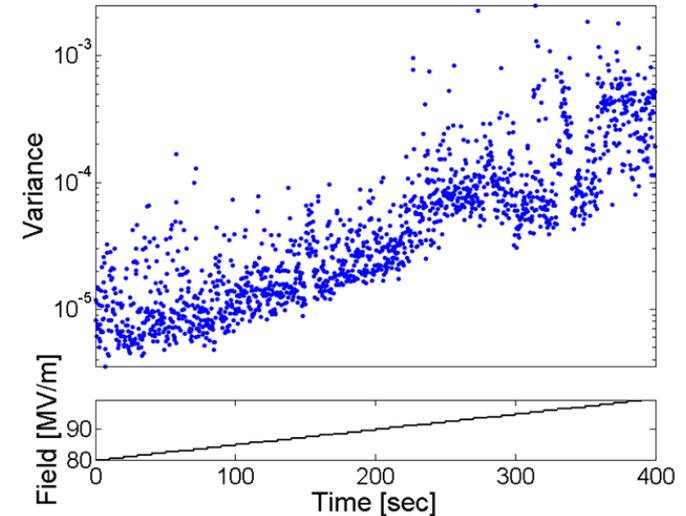
- I. Nachshon & Y. Ashkenazy, Hebrew university of Jerusalem

Trying to validate and calibrate a model

Mevarc 2017

Save the dates: 20-23 March
Jerusalem, Israel

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem