The Harvey M. Krueger Family Center for Nanoscience and Nanotechnology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

BD nucleation as a critical transition in dislocation population

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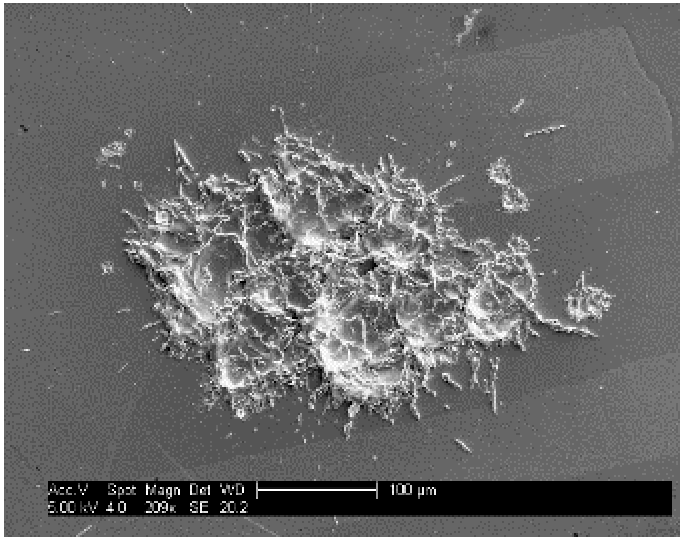
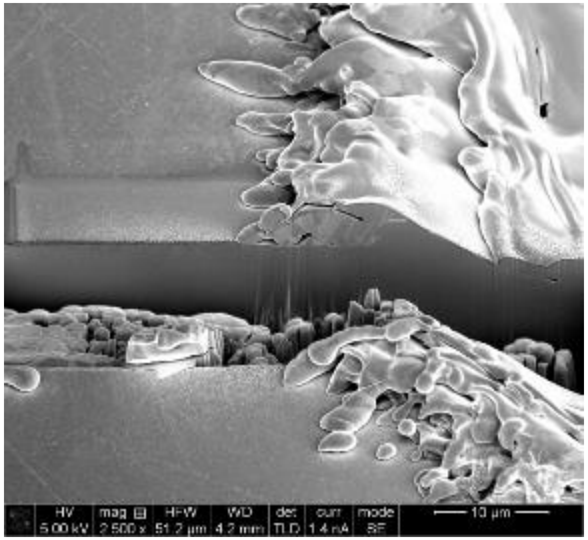
What nucleates a BD?

High E → nucleation → Protrusions? Local effect? → Cu plasma → breakdown (arc formation)

Post BD: "liquid pool" - craters, pre BD - Flat surface

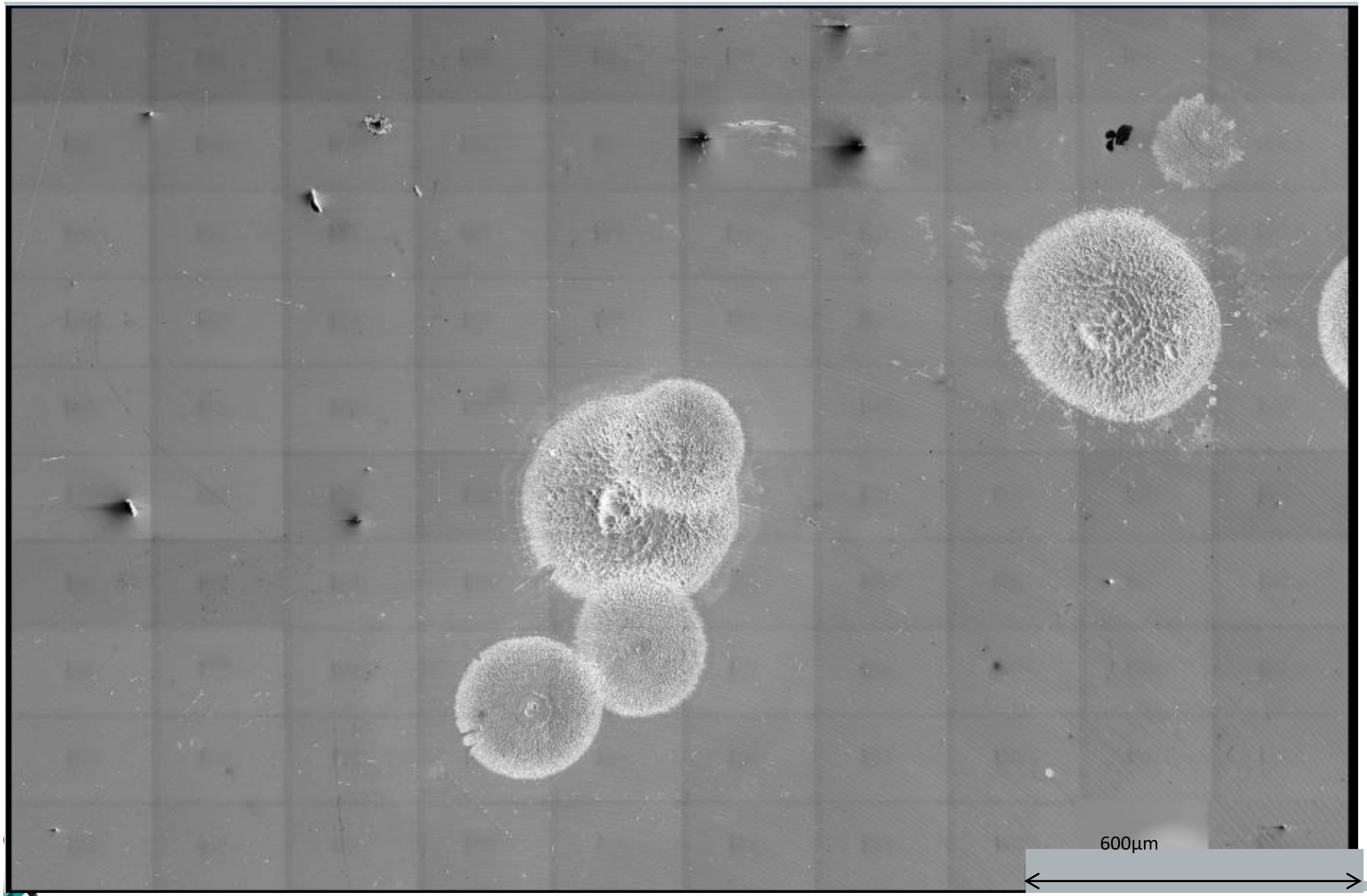




Well established since 70's

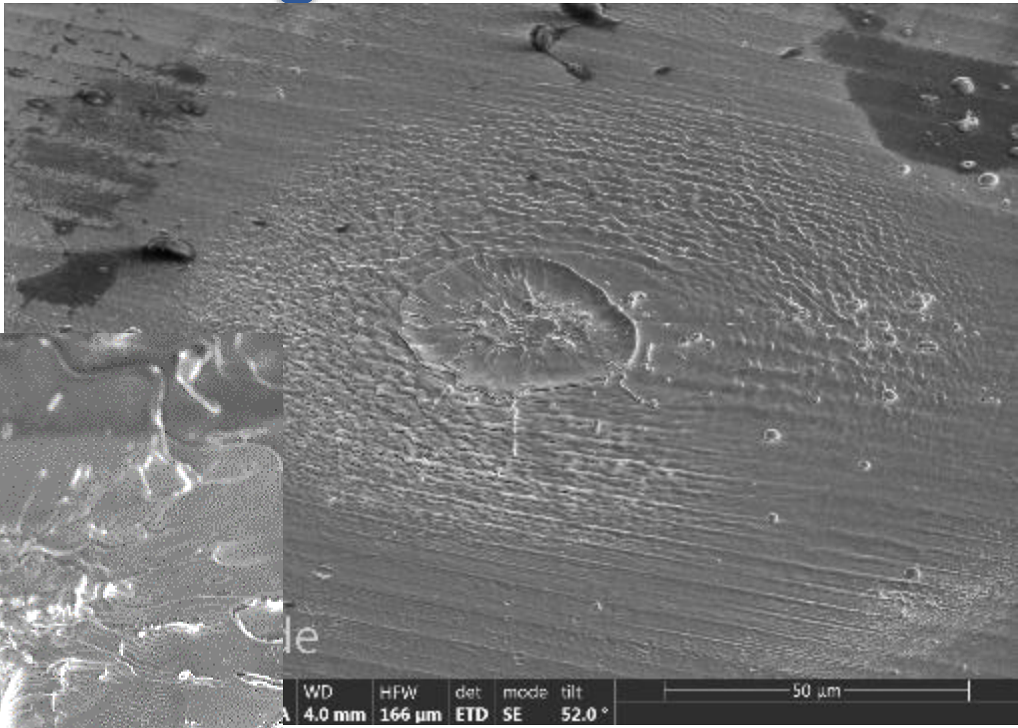
But…. Missing a nucleation mechanism

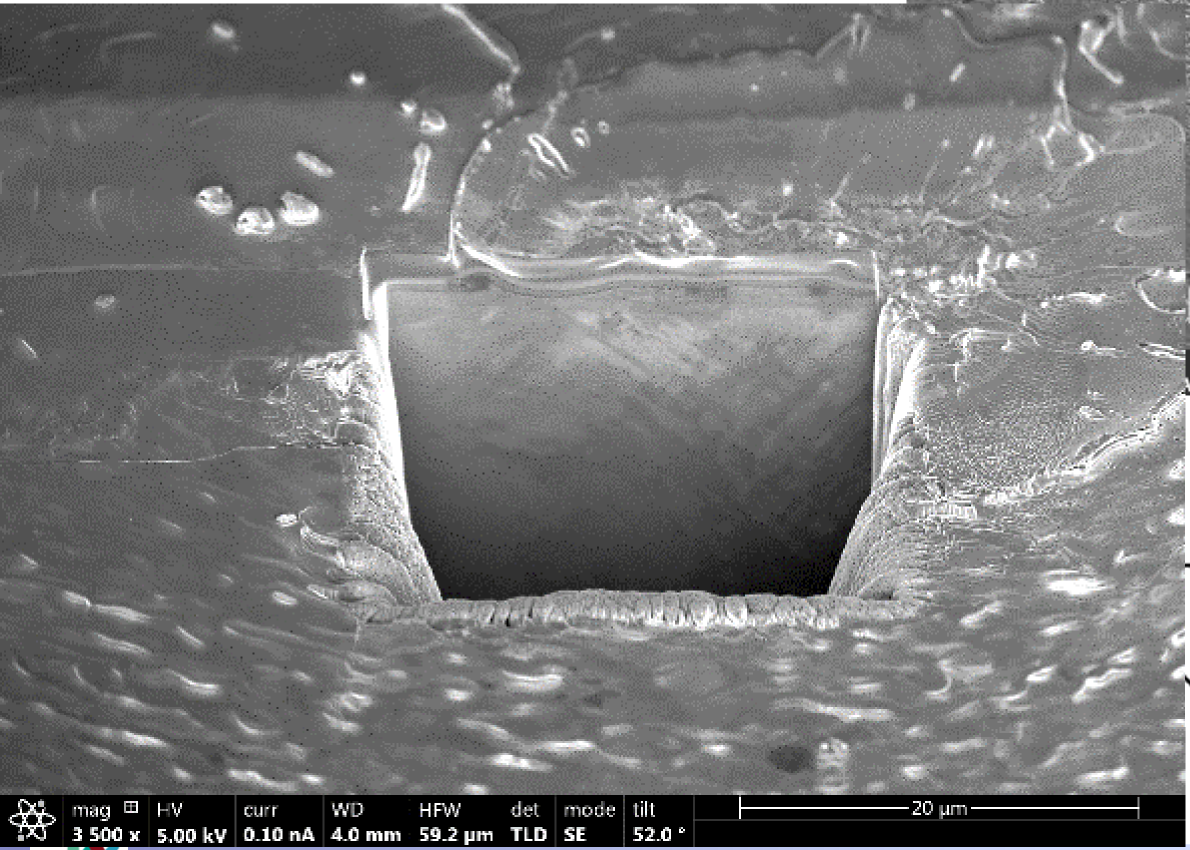
Post BD - Scattered cathodic spots

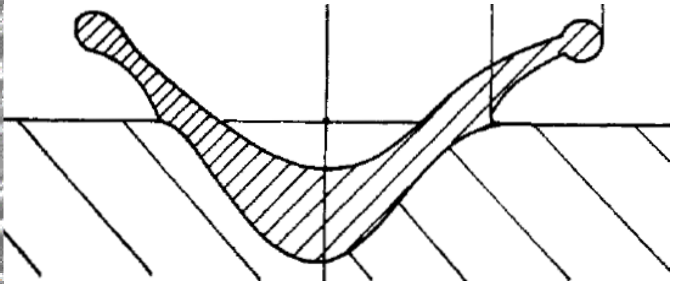


Spot melting

- Ion melting of thin (<0.1μm) layer. Melt expelled by discharge pressure.

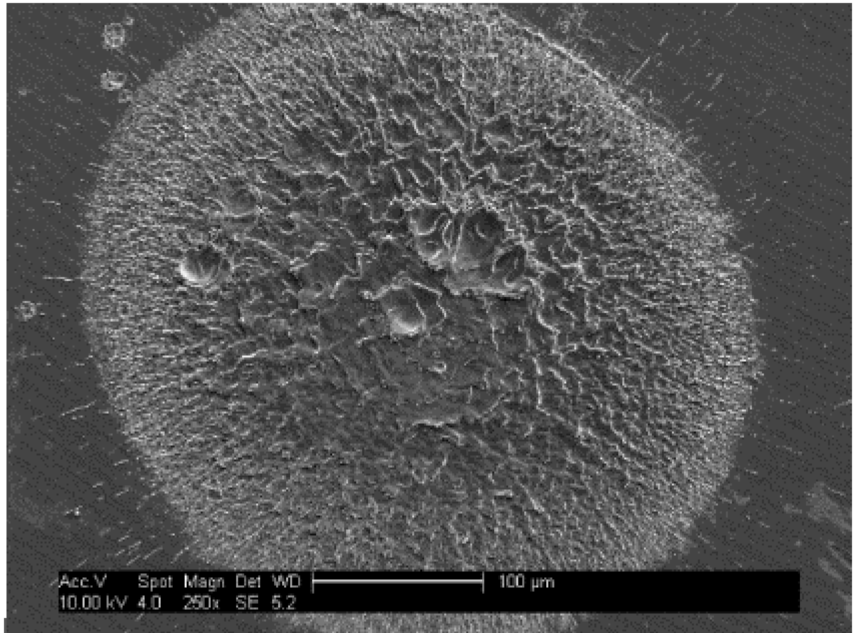


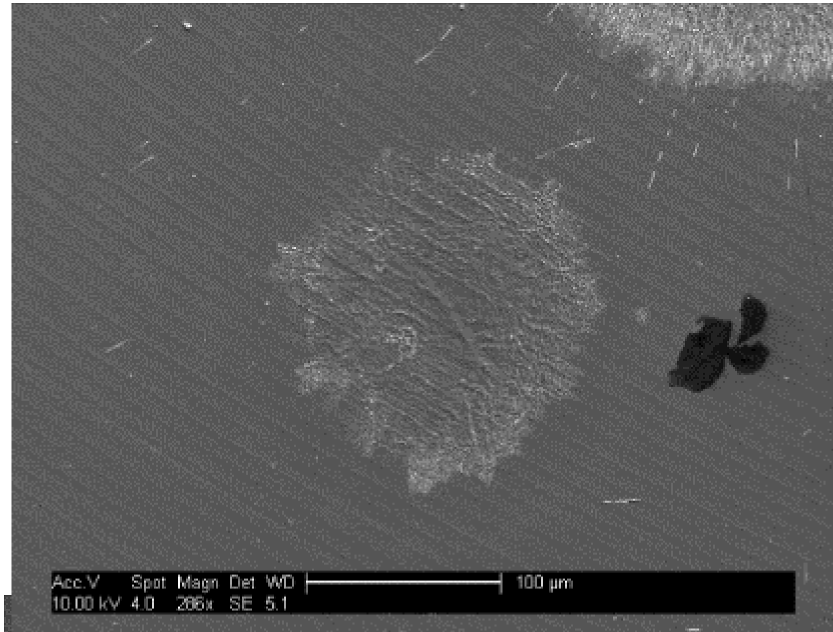




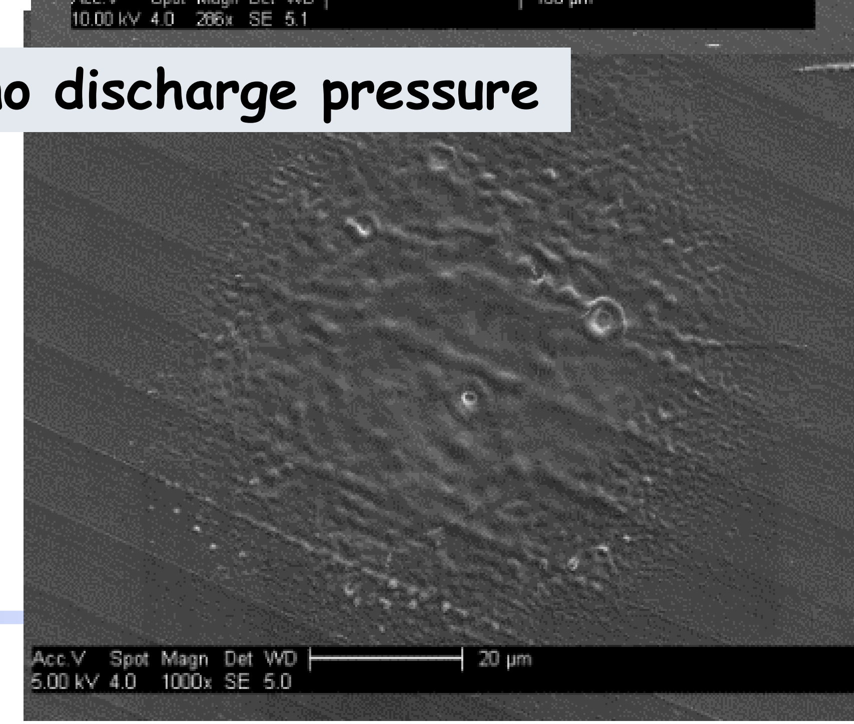
Juttner (1981), formation time and heating mechanism…
Also Daalder (1978)

BD to sub BD



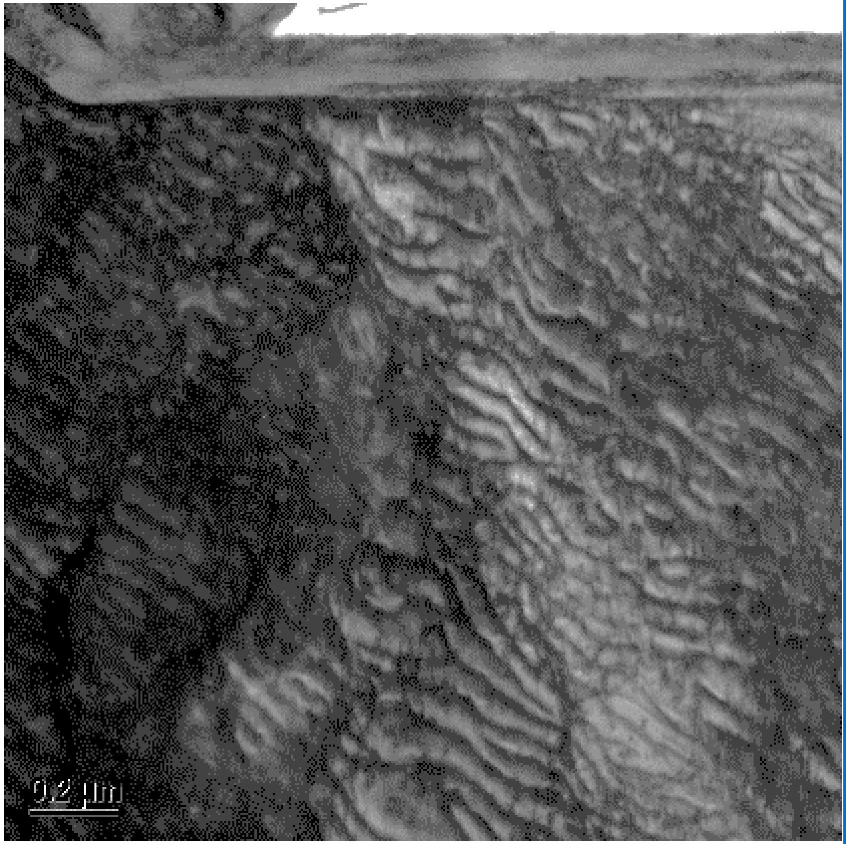


Melt formation – but no discharge pressure

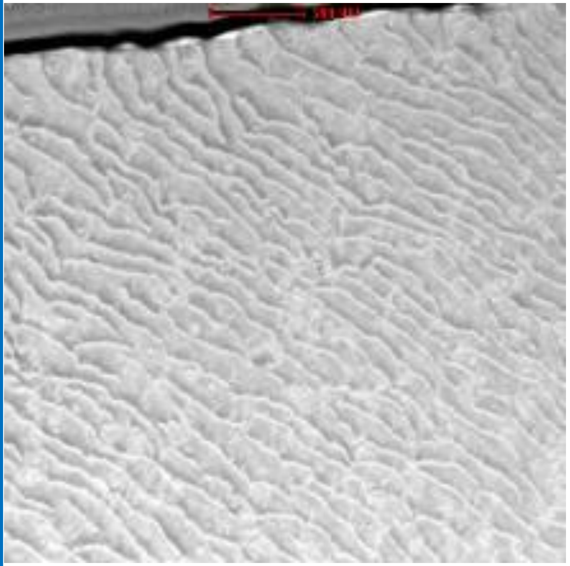


Uniform Dislocation Distribution

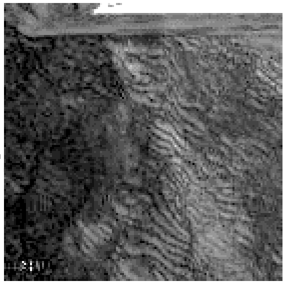
Crater



2mm to the side



Up to now - Plasticity and BD



Localized plastic deformation at BD spot (Post BD)

Uniform Dislocation distribution at the top layer of the electr

- DC – RF similarity - not a skin-effect controlled process
- Previously (Flyura) – Maximal field correlates with crystalline phase
- Yesterday (Jay) - Correlation between alloy structure and
- Monday (Walter) - Conditioning as a function of number of pulses and not BD events.
- No observable pre-BD signature, but sub BD events do exist

All consistent with conditioning by a surface hardening mechanism.

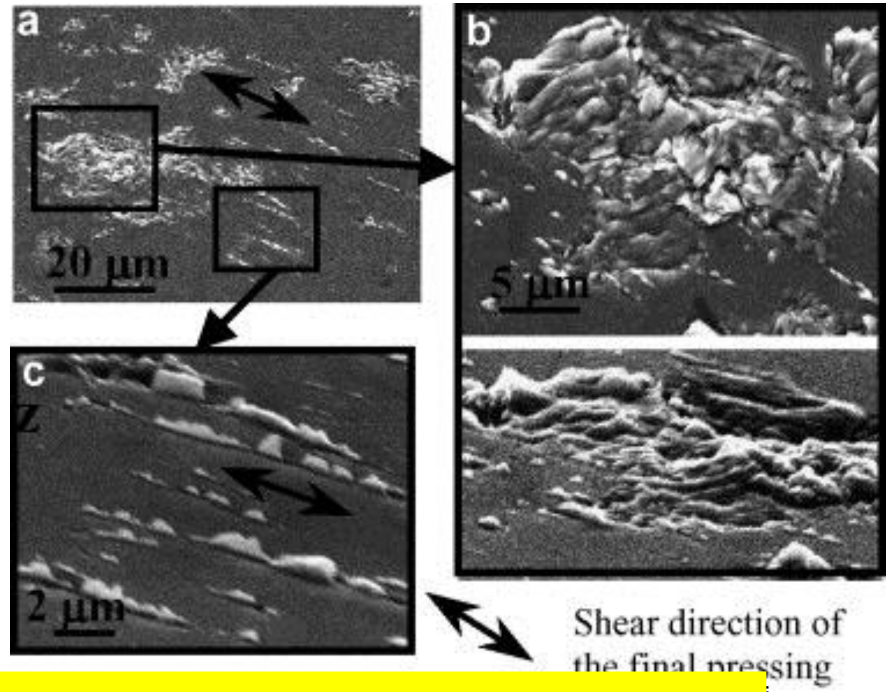
Suggesting that BD nucleation – related to surface plastic activity

leading to localized critical increase in field emission current.

A. Descoeudres, CLIC-Note 875, 1 (2010).

features

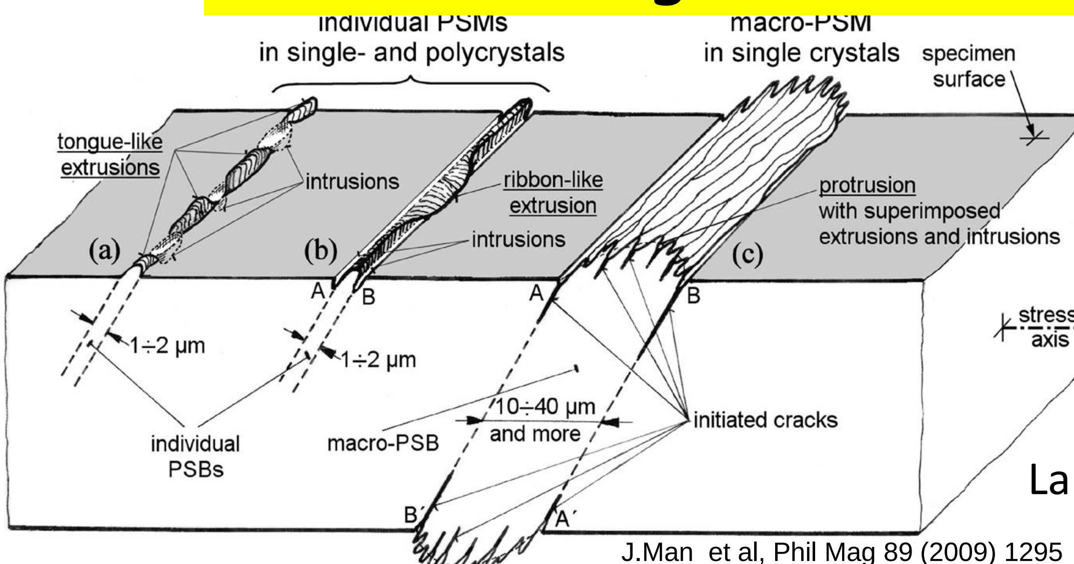
- Previously observed in <u>fatigued</u> surfaces.
- Significant sub-surface PSB leading to surface features.
- Stochastic response at **sub-yield stresses.**
- Easily observed via SEM



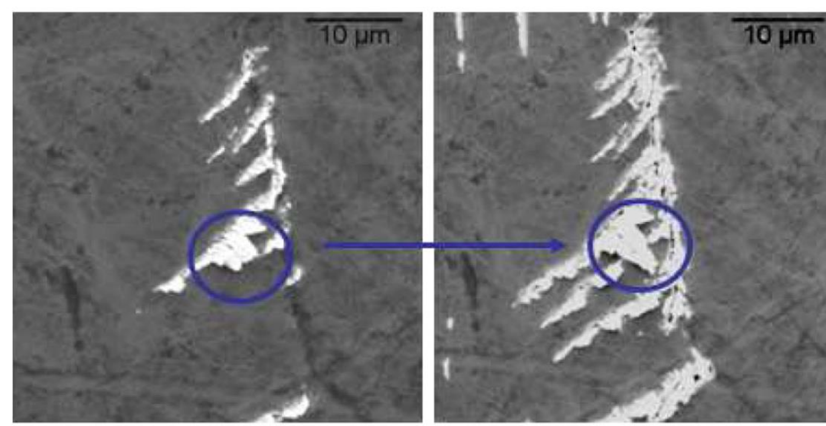
with

333

Dislocations activity at sub-yield stresses leads to significant surface modifications



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

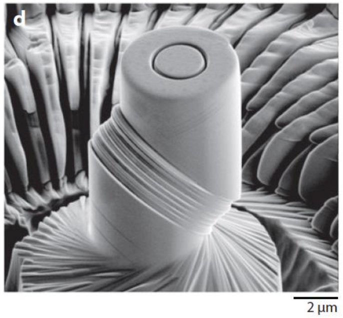


Laurent et.al. Phys Rev STAB 14 (2011) 41001

Dislocation mediated – self organized criticality

Dislocation interactions are known to demonstrate critical behavior in slip planes even at nm scale.

Criticality driven by interaction between moving dislocations within the slip plane and with the surfaces



Plasticity of Micrometer-Scale Single Crystals in Compression

Michael D. Uchic,[1] Paul A. Shade,[2] and Dennis M. Dimiduk[1]

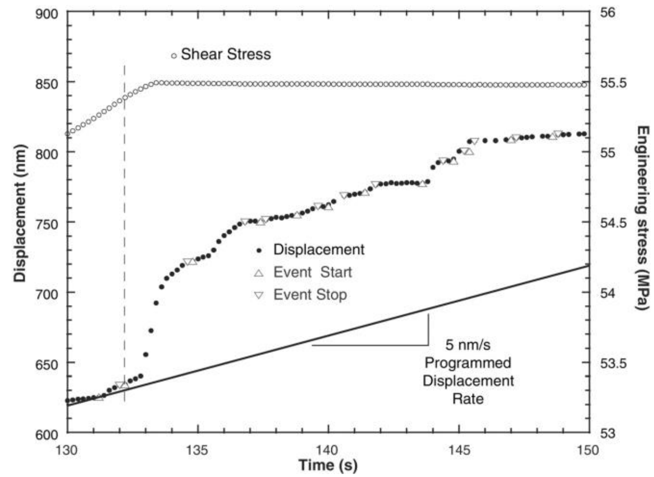
Intermittency characterized by a universal Power law burst PDF

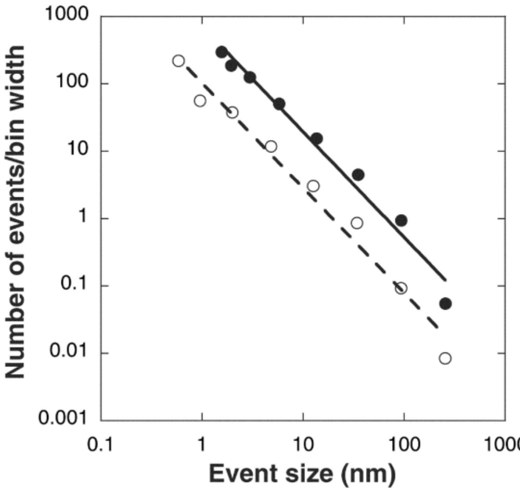
Acoustic emissions: Similar + space and time coupling between events

(Weiss & Marsan, Scjence 2003)

This type of response is universal (Earthquakes show similar PDF and spatio-temporal correlation

(Kagan, Geopgysical J. (2007))





Uchic, Dimiduk at. Al., Annual Review of Materials Research (2009).

“Scale-Free Intermittent Flow in Crystal Plasticity.” Science (2006) 1188.

Critical plastic response leading to BD

- **We suggest a similar critical process which is initiated by dislocations reaching the surface.**
- These may lead to local protrusion, oxide modifications and more.
- Criticality due to interaction between dislocations.

- Plastic response is critical with no significant pre-BD activity (no roughening of the surface)
- Time scale for surface evolution ~ nano-seconds
- "Memory" through dislocation pileups
- Increased BDR with pulse length
  (2nd order effects - such as interactions between dislocation systems)

<u>Hope to achieve:</u>

Critical experimental scenarios,

predictions of observable features (microscopy)

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

Master equations

- Gain-loss Markovian process

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

- Mobile dislocations multiplication
  - Activate FR type sources
  - Release sessile dislocations at pile-ups

$$\dot{\rho}^+ = \frac{25\kappa C_t}{G^2 b}(\rho + c)\sigma^2 e^{-\frac{E_a - \Omega\sigma}{k_B T}}$$

- Mobile dislocations depletion
  - Collision: obstacles, other moving dislocations

$$\dot{\rho}^- = \frac{50\xi C_t}{G}\sigma\rho(c + \rho)$$

Parametrization

- The model contains various competing mechanisms which can not be readily estimated.

We use Cu known parameters + Two main observables used:

- Experimental BD rates: 10^{-7} [bpp/m]
  - Estimating the number of active regions per m :

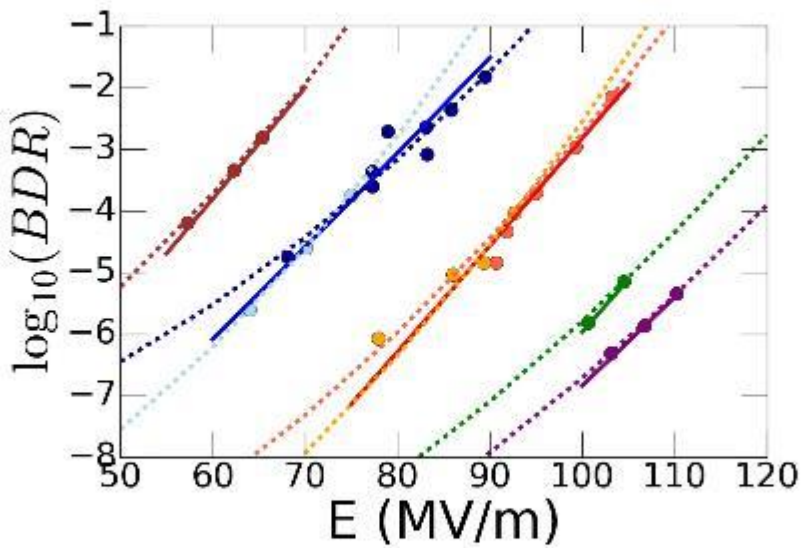
$$N\left(\frac{1}{m}\right) = \frac{(\frac{N_{iris}}{m})\cdot(S_{iris})}{dR_{active\ regions}{}^{2}} \approx \frac{100\cdot 2\pi\cdot 2.35(mm)\cdot 1(mm)}{(10^{-2}mm)^2} = 10^7$$

  - Since the pulses are of 230 nsec we get :
  - $\tau(BD)_{per\ area\ unit} = dt_p/(P(bpp/m)/N) = \frac{230nsec}{\frac{10^{-7}}{10^{7}}} \approx \boxed{10^7(\frac{sec}{zone})}$

Rare event (per active cell)

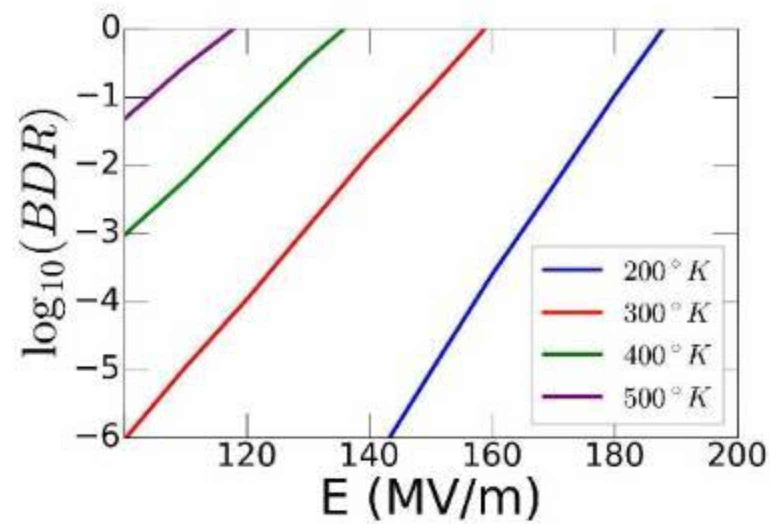
- Field dependency of the breakdown rate (estimated as E^{30}) .
  Fitting a localized (10%E) exponent : $n = \log_{1.1}(\frac{\tau(E)}{\tau(1.1\cdot E)}) \approx 30$

Results



$$BDR \propto E^{25} \;\ldots E^{35}$$

Successfully reproduce apparent power law dependence



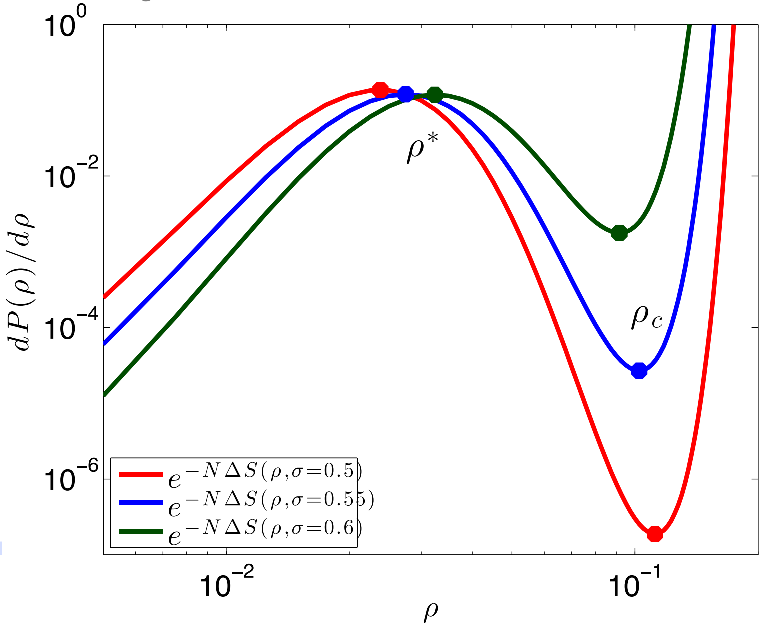
Strong multiplication dependence on T, leads to a significant shift in fields where active dynamics is observed.

Data + dashed from Nordlund & Djurabekova PRSTAB **15** 071002 (2012)

Signs of criticality

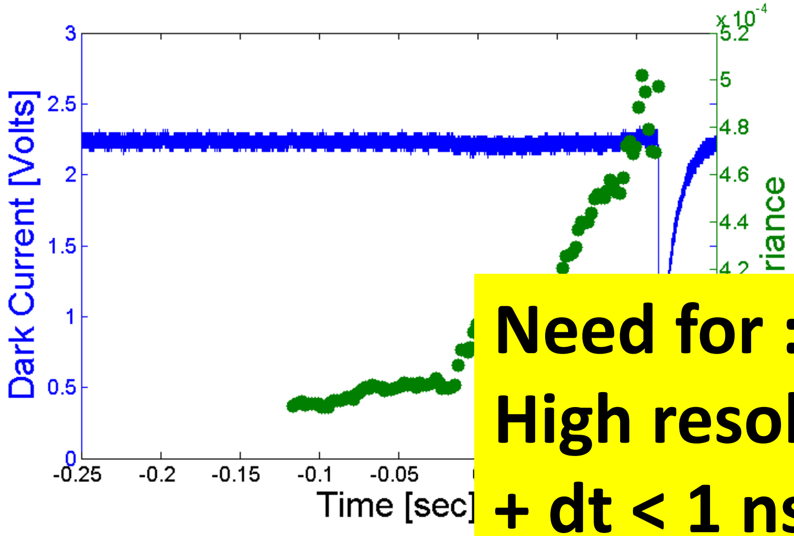
- Adiabatically moving between quasi-stationary PDF:
  Change in pdf moments while ramping field
  - -> identify threshold

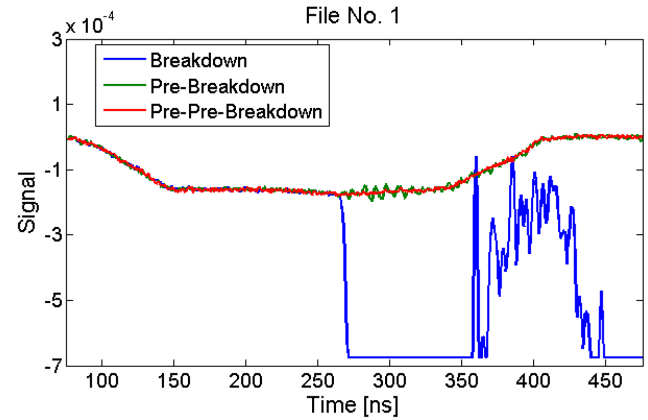
- At specific conditions, probe time dependencies of the QS pdf:
  Identify large fluctuations time dependency
  - -> identify time constants
  - -> mechanism



Early warning signals?

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

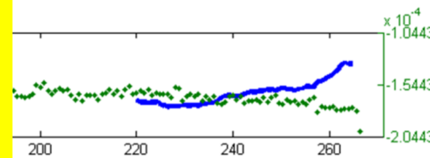


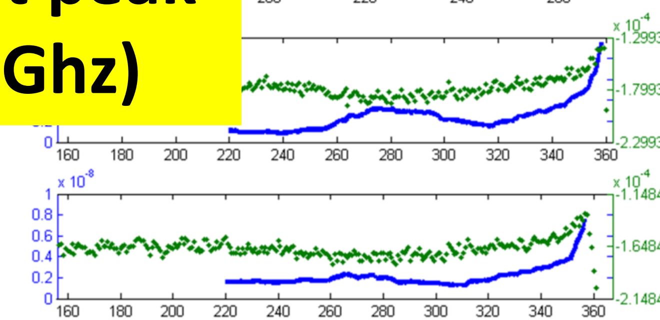


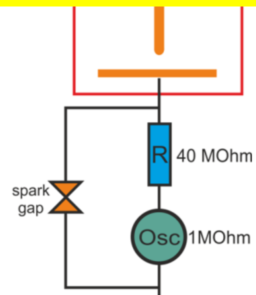
Need for :

High resolution at peak

+ dt < 1 nsec (f>2Ghz)





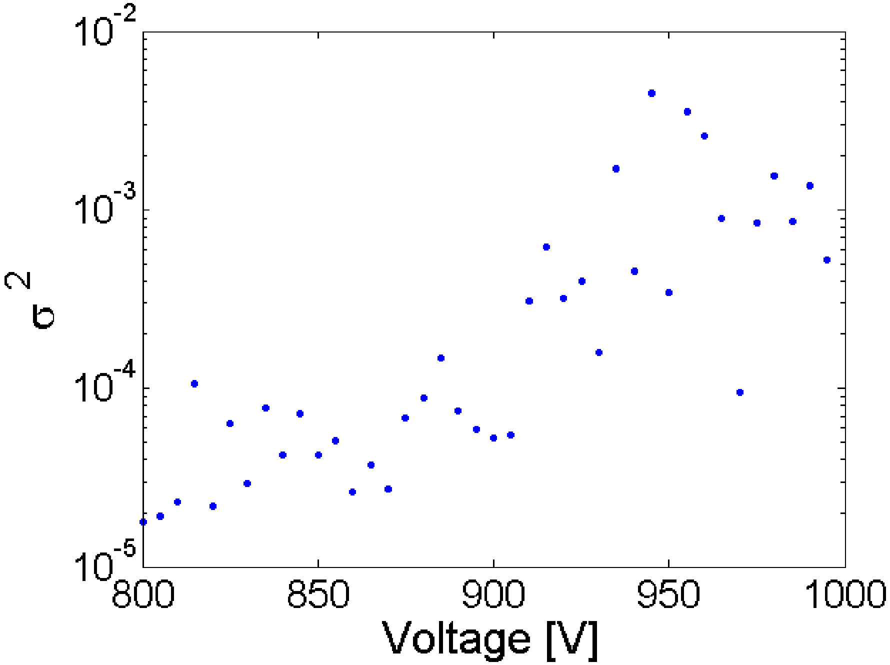


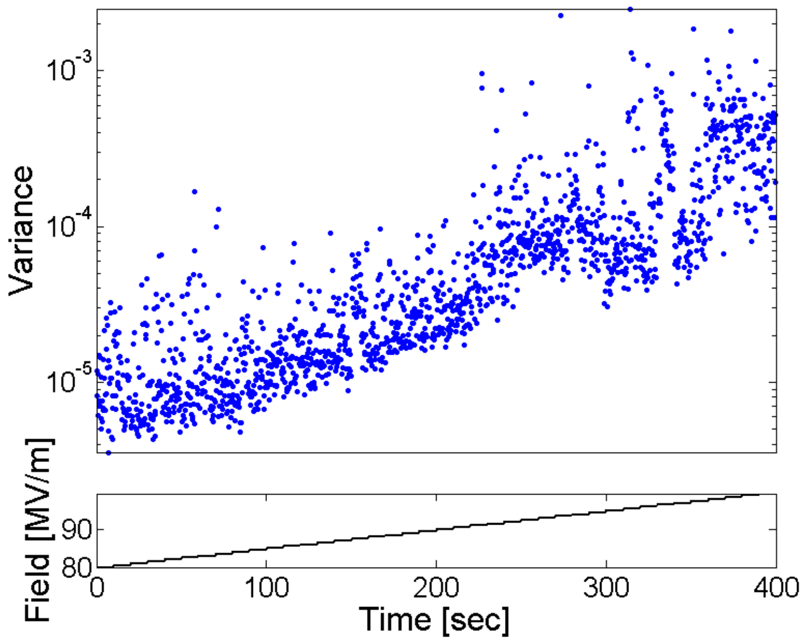
DC data –
Iaroslava Profatilova
Tomoko Muranaka

RF data - Alberto Degiovanni

Field dependent fluctuations

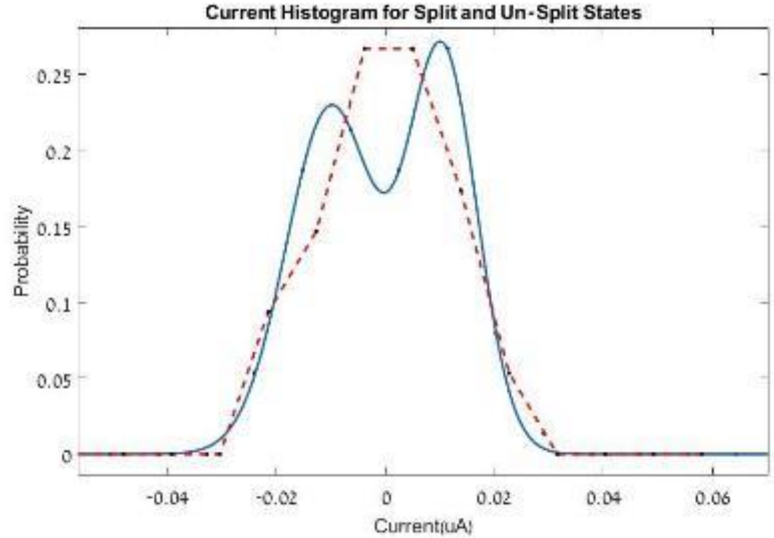
- Increase in FN fluctuations with field is consistent with increase in surface related plastic activity
- Time scale of fluctuations - indicative to the dynamic timescale.

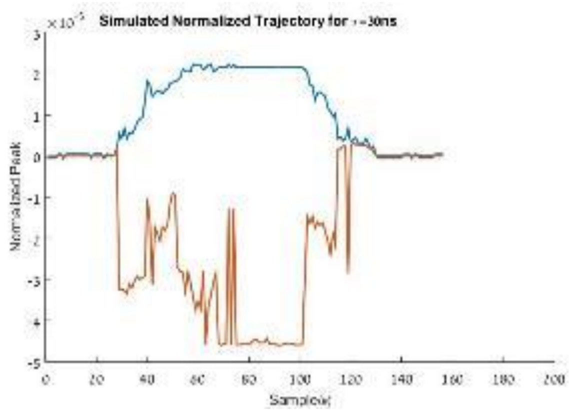




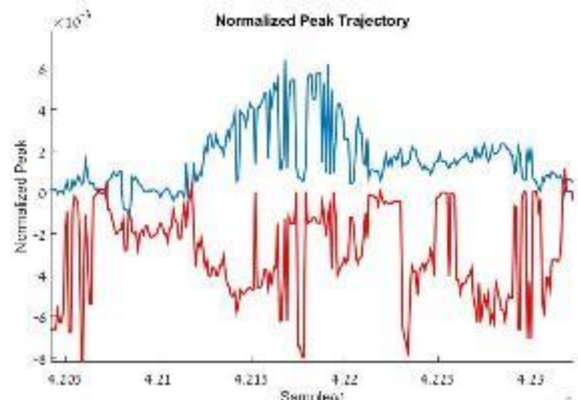
Dark current distribution

- Dark currents are expected to have a Gaussian distribution.
- High frequency (GHz) data sets demonstrate “splitting” to two Gaussians.
- “life time” of ~10-50 nsec





Simulated signal



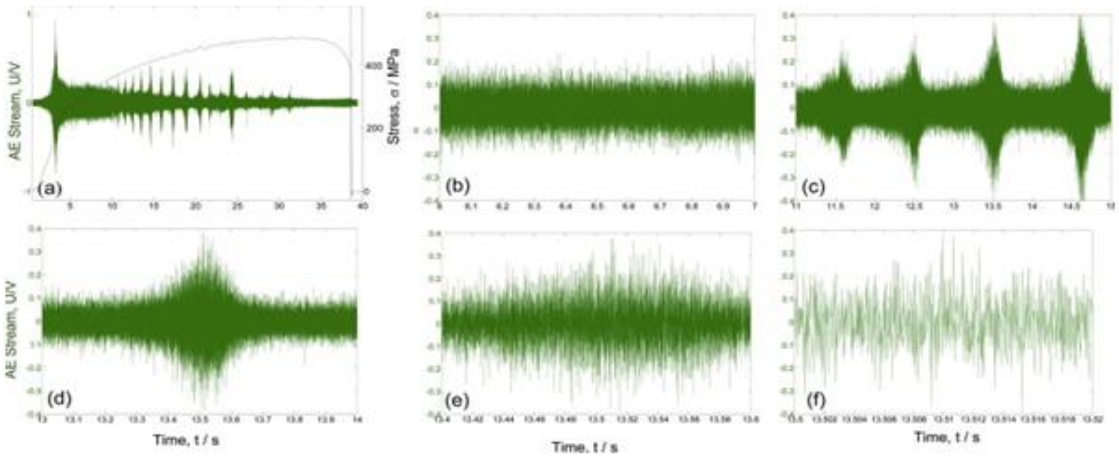
Measured signal

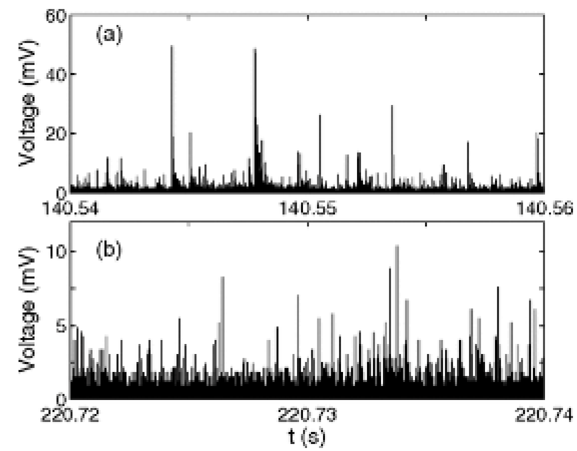
Sagi Lahman
Tomoko Muranaka

Need MUCH more GHz data!

Identifying pre-BD dislocations activity?

Dislocation avalanches were identified using AE





A. Vinogradov , A. Lazarev

Continuous acoustic emission during intermittent plastic flow in α-brass

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

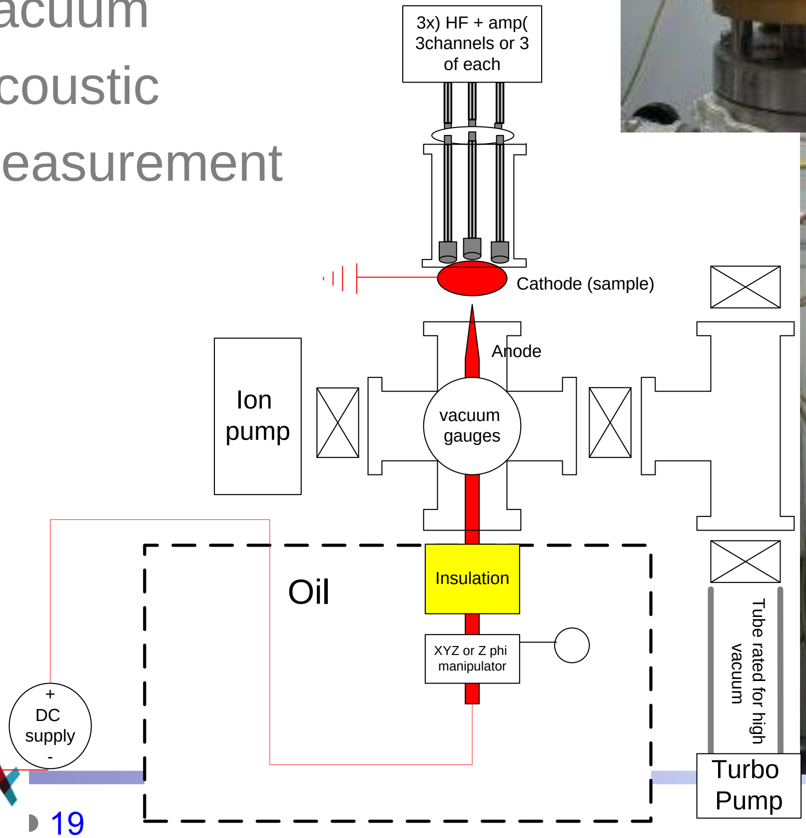
http://dx.doi.org/10.1016/j.scriptamat.2012.01.053

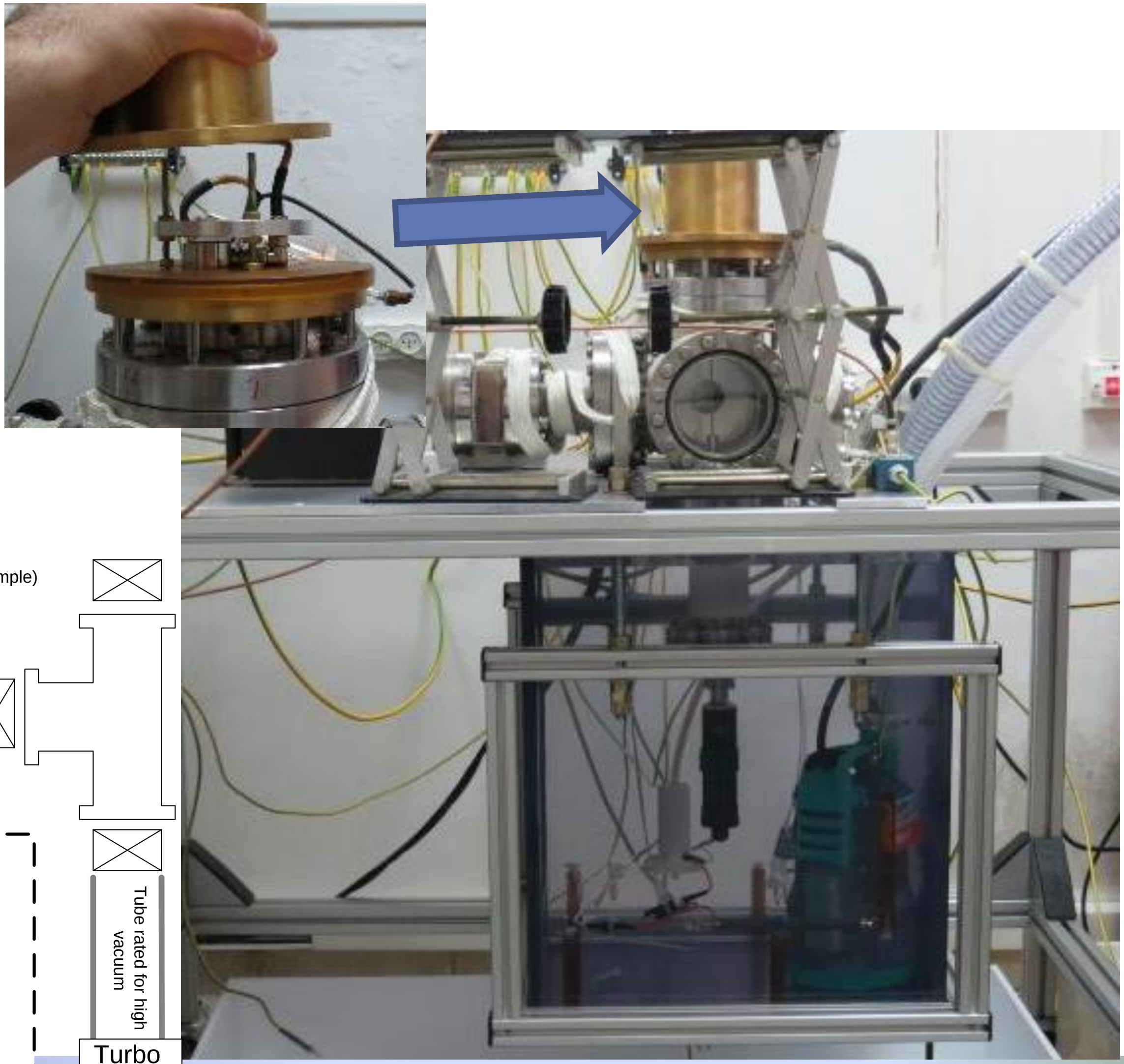
Lebyodkin, M. A. et al. Role of superposition of dislocation avalanches in the statistics of acoustic emission during plastic deformation. Phys. Rev. E 88, 042402 (2013)

High voltage acoustic emission system

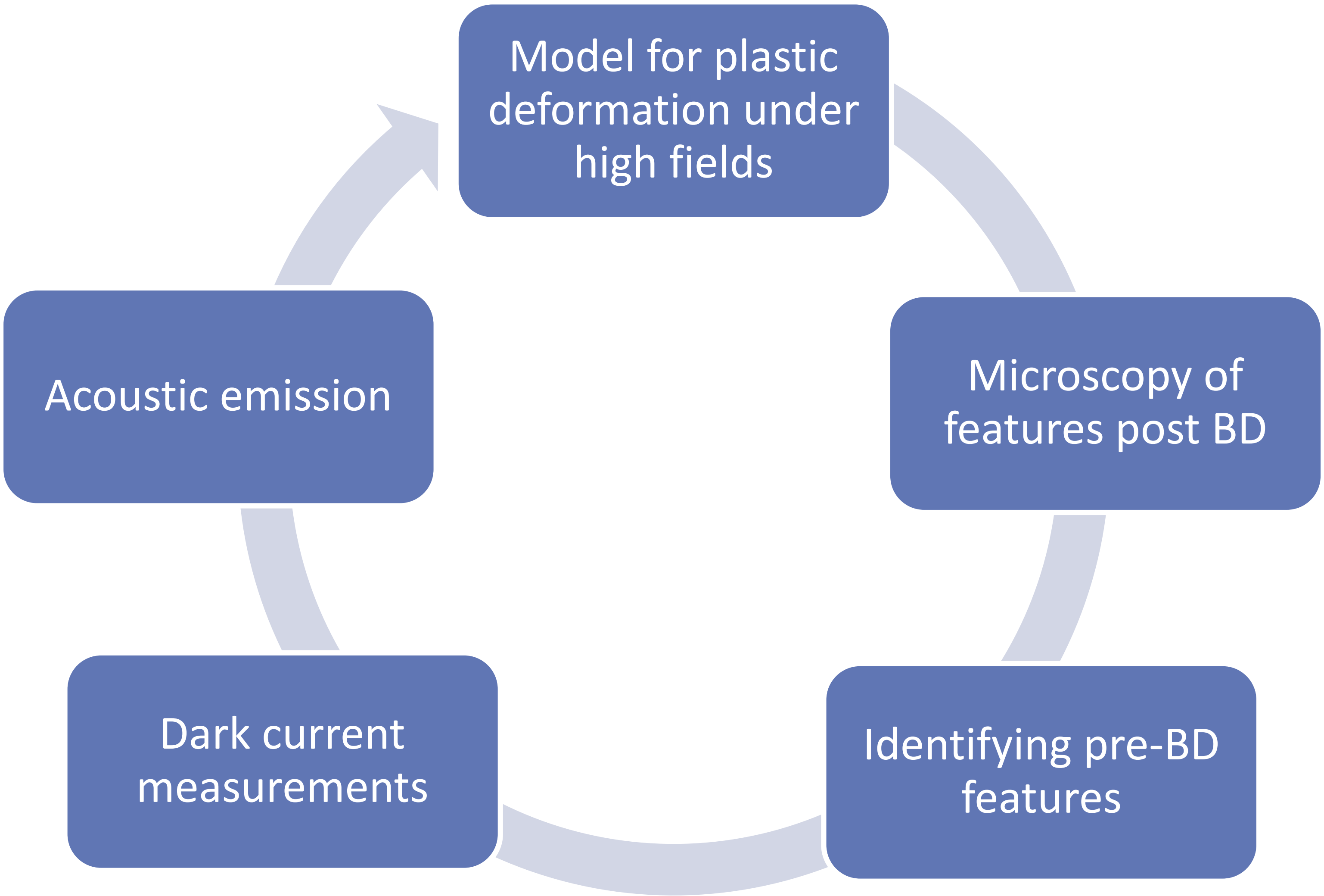
Itay Nachshon

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





Modelling and validation



Summary

- BD and sub BD events leads to liquid cathodic spot – Not preceded by observable features or significant changes in dislocation network.
- Distinct dislocation structures in Cu exposed to high E.

BD nucleation through mobile dislocations interaction - leading to critical sub yield surface effect:

- Instantaneous + Only remains are sessile networks

Mean field naïve model - (simulation + analytic)
Validation:

- Rates + exponents fitting experiments.
- Fluctuations in dark current – early warning signals
- Acoustic emission – unique to dislocations - under development

Applications:

- “external” efficient conditioning.
- BD prediction.

Future plans:

- Verify Field – Network link
- AE – measurements + model.
- Extend theory - time, 2nd order