HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

HIP

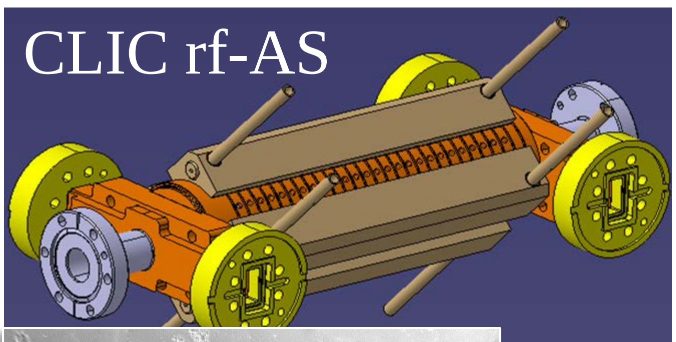
Multiphysics simulations of onset of vacuum electrical breakdowns

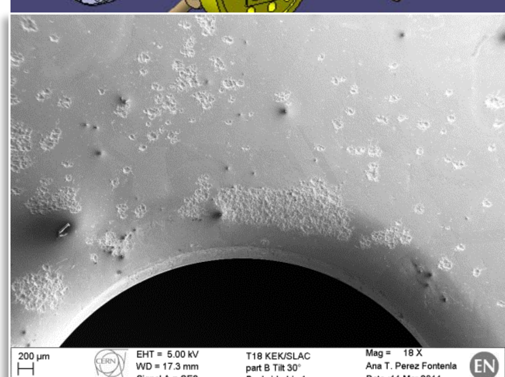
Flyura Djurabekova

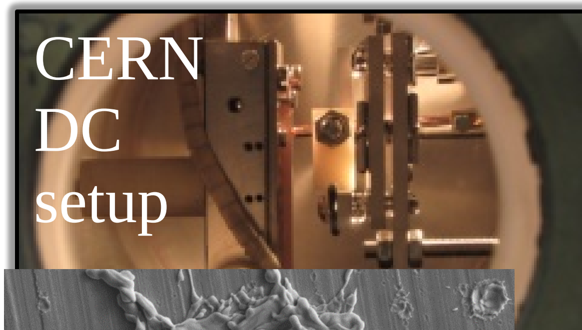
Helsinki Institute of Physics and Department of Physics
University of Helsinki
Finland

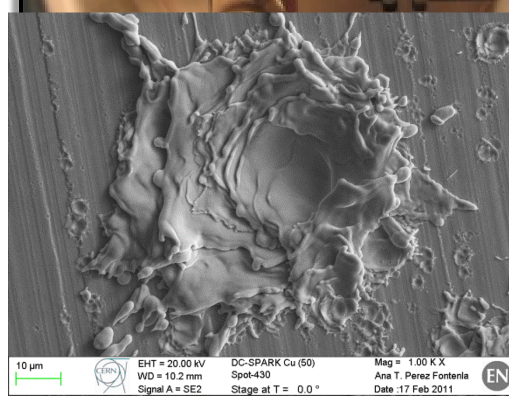
Breakdowns in ultra high vacuum

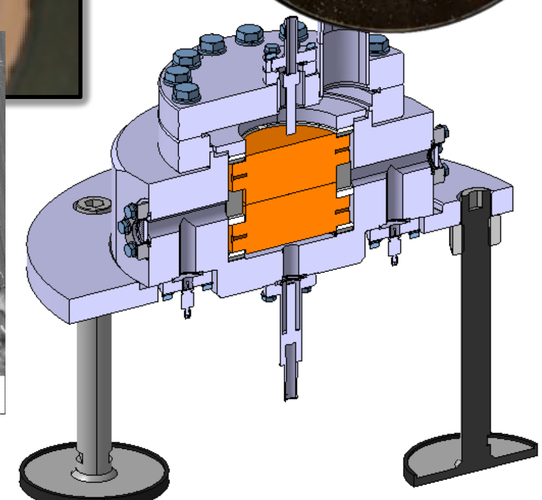
- We are developing the model, which will be able to describe the processes involved in the processes of electrical breakdowns in rf and dc-fields.







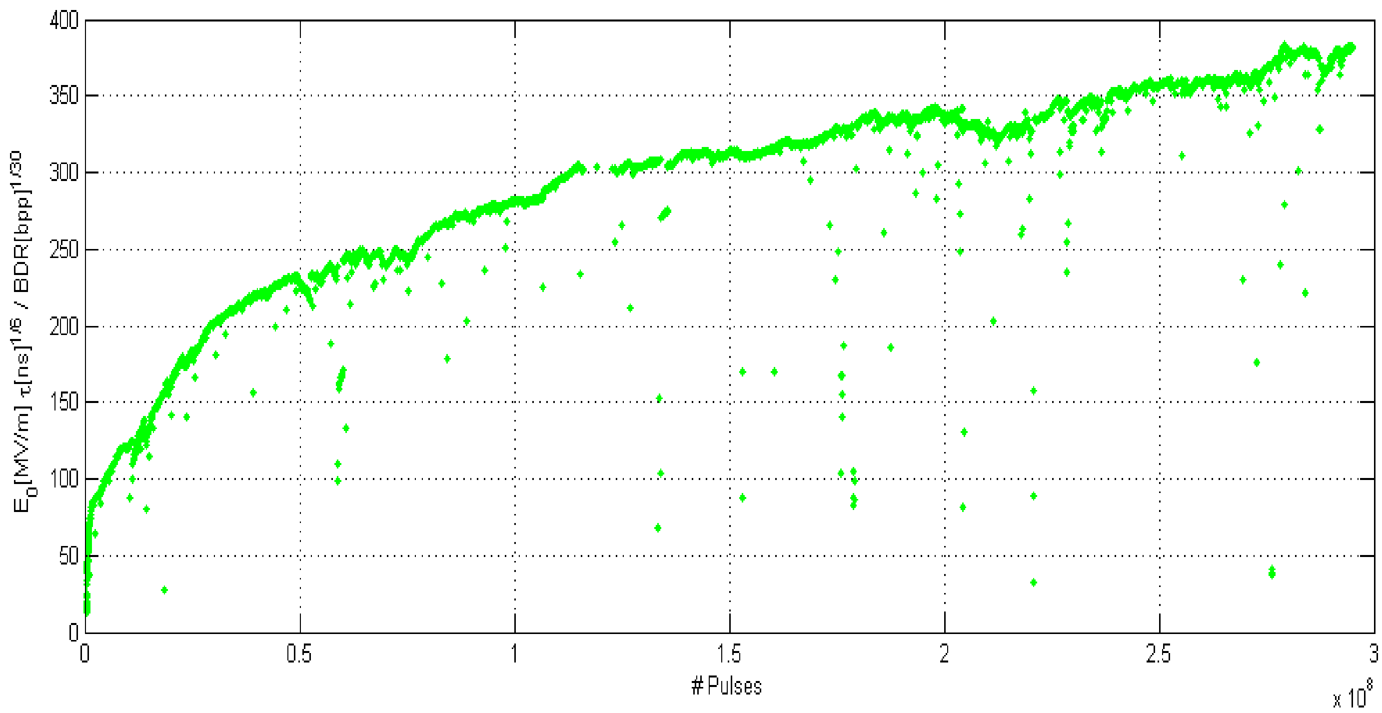




Conditioning history of AS at CERN

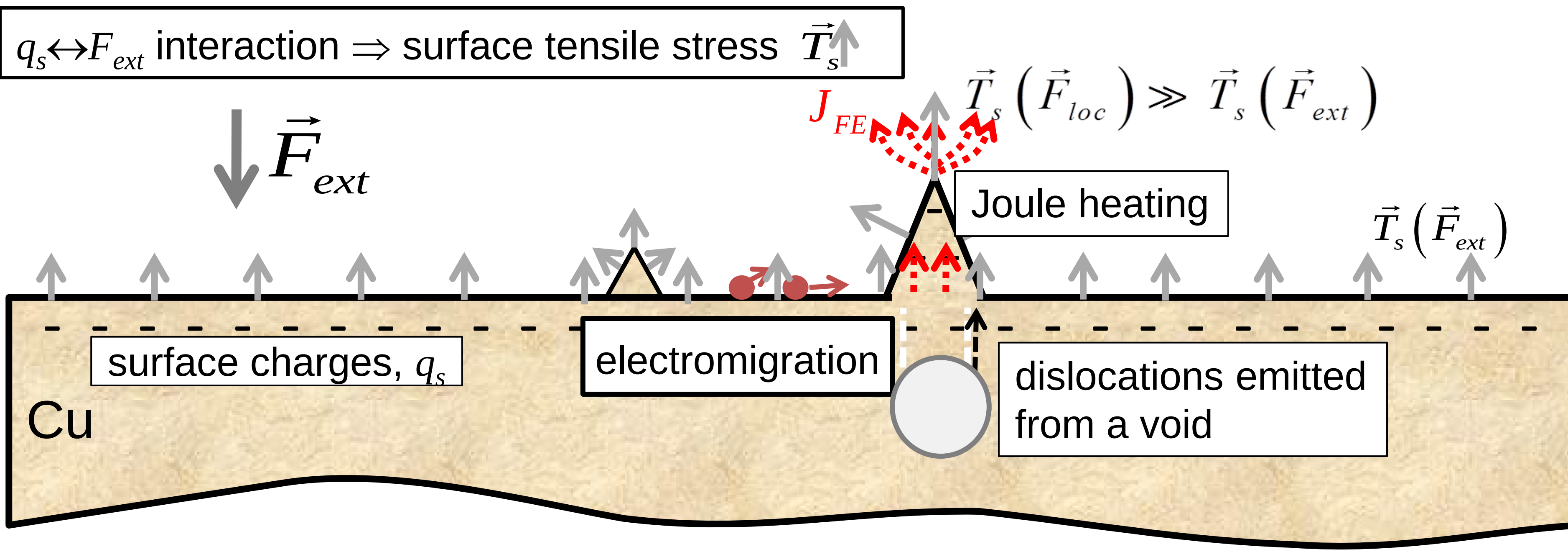
11168 BDs

- CERN TD26R05CC conditioning history plot



The conditioning behaviour of a CLIC prototype accelerating structure. The time corresponds to over four months of operation at 50 Hz. The vertical scale is the accelerating gradient normalized for pulse length and breakdown rate.

Mechanisms on and under the surface in the presence of electric fields

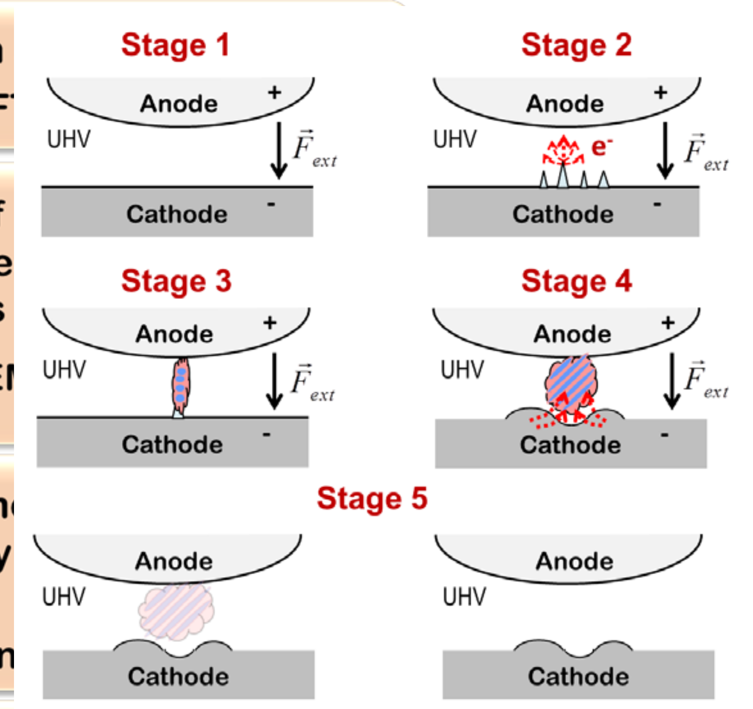


ultiphysics model

Stage 1 Charge on
Method: SIESTA (DF

Stage 2a Onset of
Dislocation-mediate
surface protrusions
Method: Comsol (FE
helmod

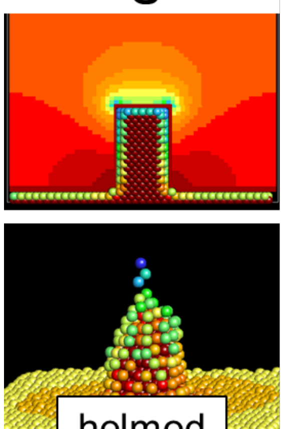
Stage 2b Long tim
surface morphology
surface charge
Method: kimocs (Kin



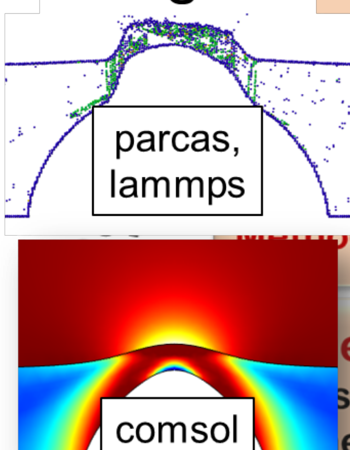
Stage 3 Field assisted evaporation of
ns & Jo ectromig
FE currents

se ion bombardment from
eating b ents
Method: Arc MD

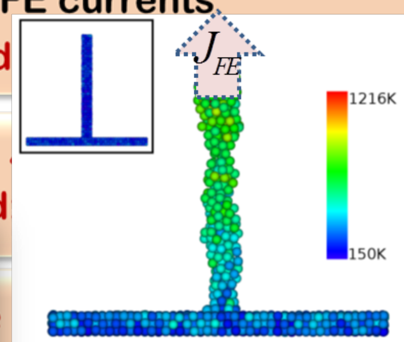
Stage 1



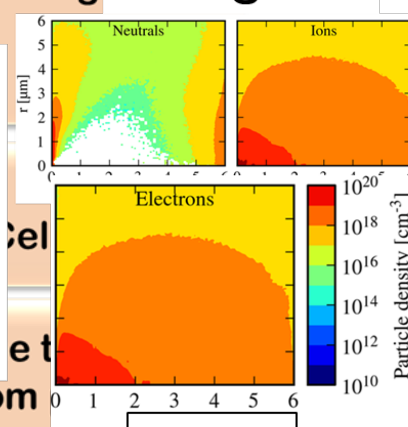
Stage 2



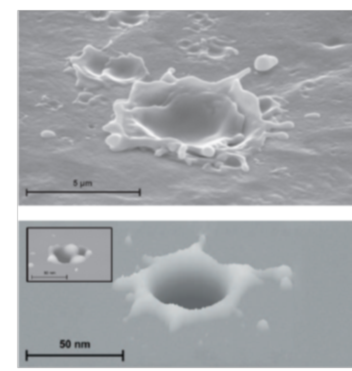
Stage 3



Stage 4

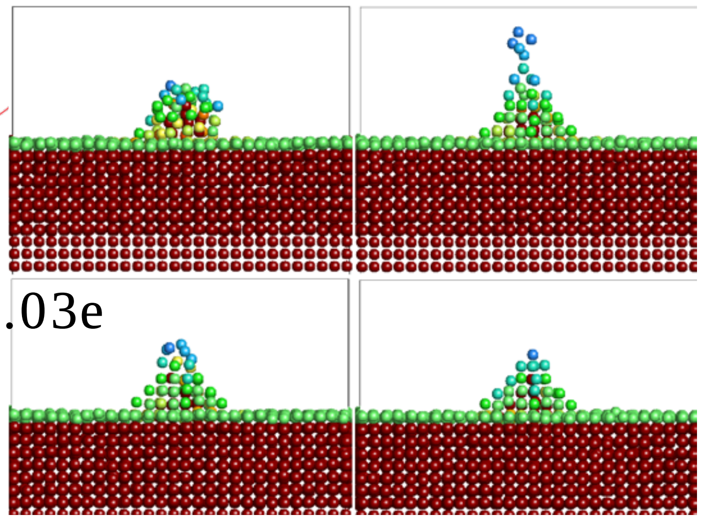


Stage 5



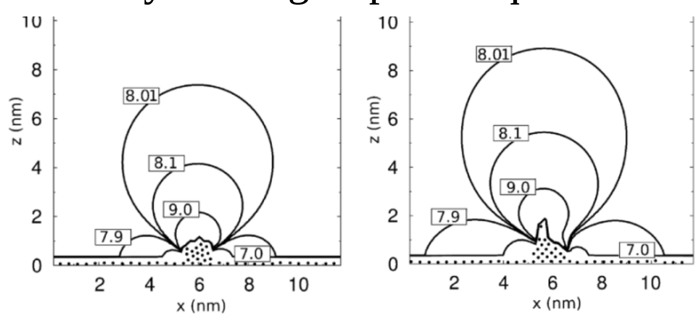
Arc-MD

Charges on surface atoms in MD



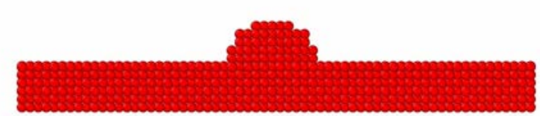
$q_{at} \leq 0.03e$

Distribution of the electric field is dynamically calculated by solving Laplace equation



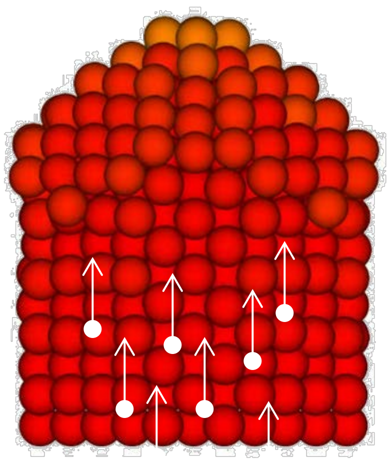
Details in F. Djurabekova, S. Parviainen, A. Pohjonen and K. Nordlund, PRE 83, 026704 (2011).

- Charges on surface atoms are calculated by using our ***helmod*** code – hybrid ED-MD code, based on classical MD (molecular dynamics) code.
- The dynamics of atom charges follows the shape of electric field distortion on tips on the surface
- The atoms leave the tip as a result of evaporation enhanced by pulling effect from the external electric field.
  - No electromigration or interaction with electrons are



Electromigration (EM) in MD

- Implemented as additional ”electron wind force” acting on atoms in protrusion as in Bly et al. [PhysRevB.53 (1995)13909]
- Force proportional to the internal electric field and effective charge of copper atoms as seen by current



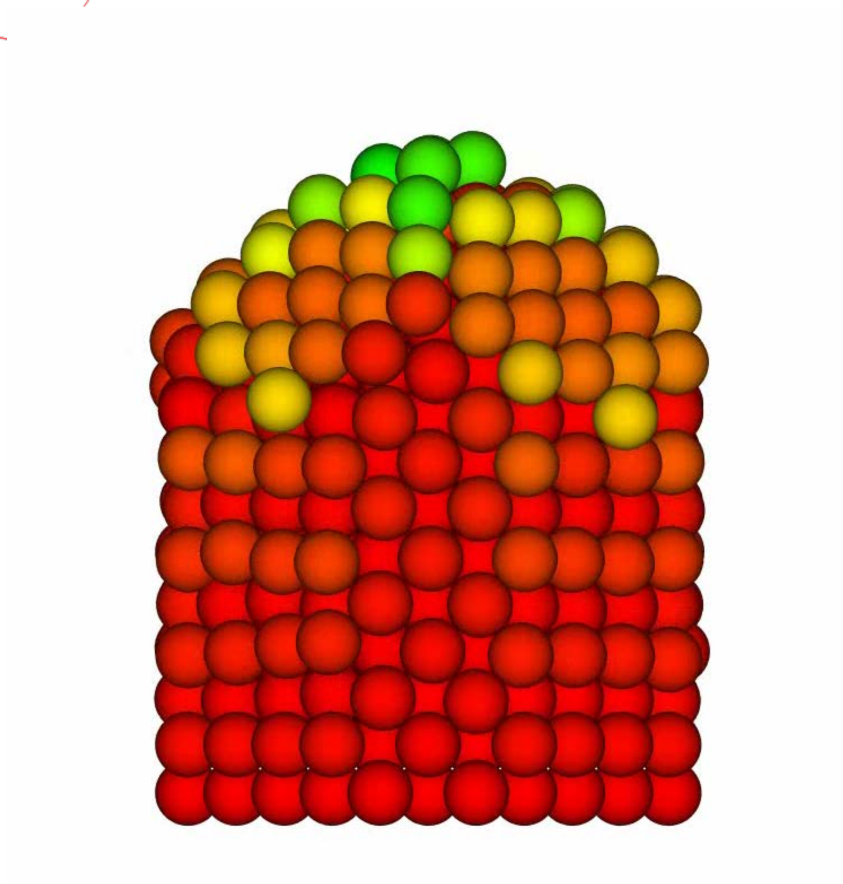
$$F = E_{\text{int}} Z_{eff}$$

$$E_{\text{int}} = J_{GTF} / \sigma$$

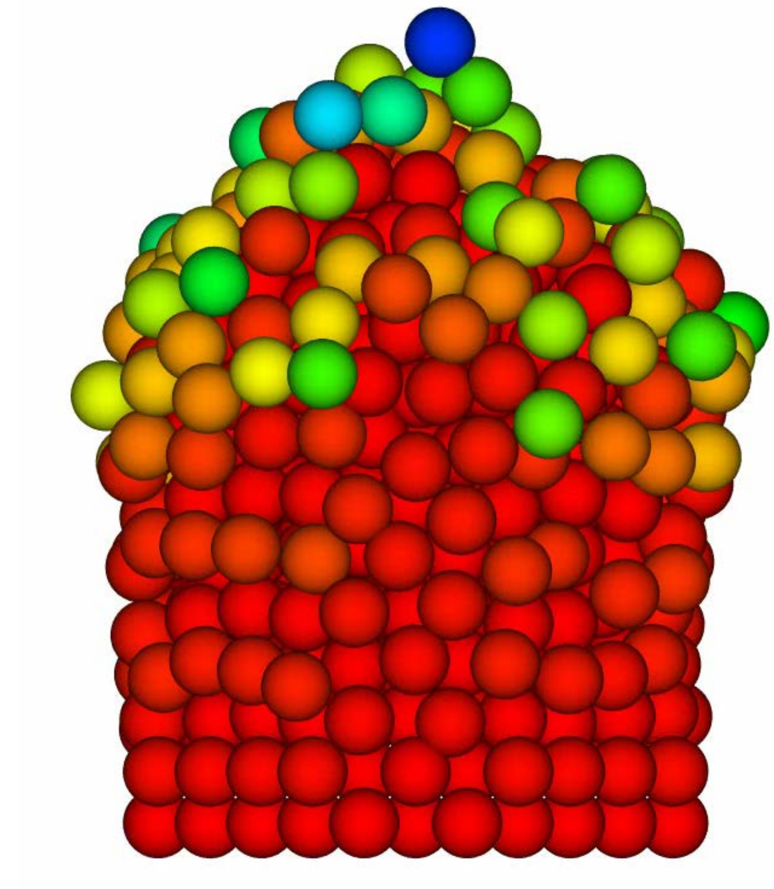
$$Z_{eff} \approx \sout{10}\ 40$$

- Assume current (and force) is going straight upwards
- Assume effective charge $Z_{\text{eff is constant}}$

With electromigration protrusion grows taller



EF only

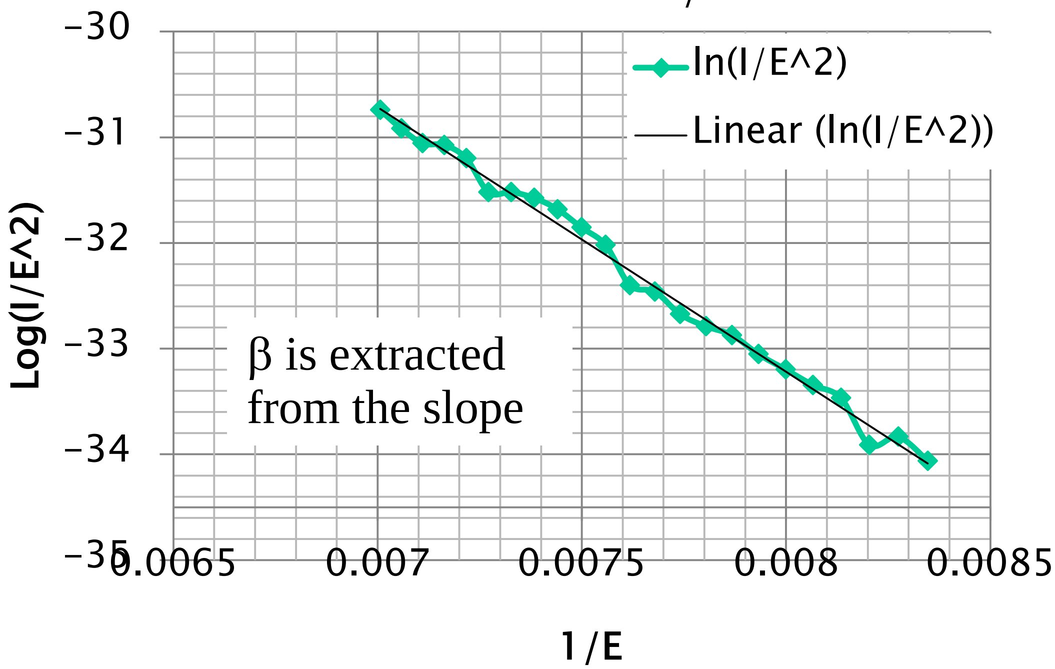


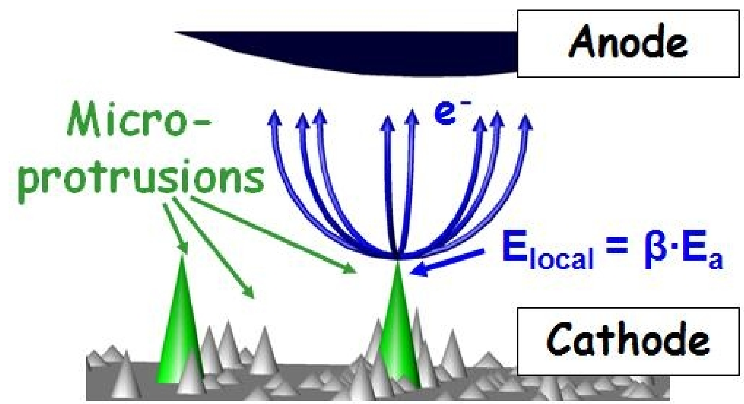
EM + EF

Field emission - β measurement

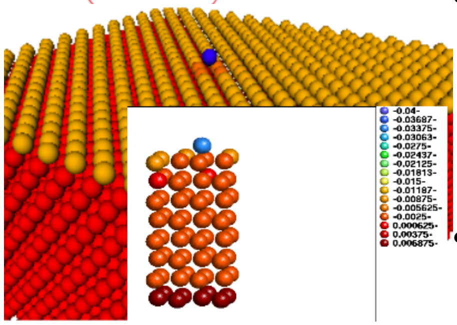
- An I-V scan is performed at limited current, fitting the data to the classical Fowler-Nordheim formula, where $[j_{FE}]$ = A/m², [E] = MV/m and [φ] = eV (usually 4.5 eV).

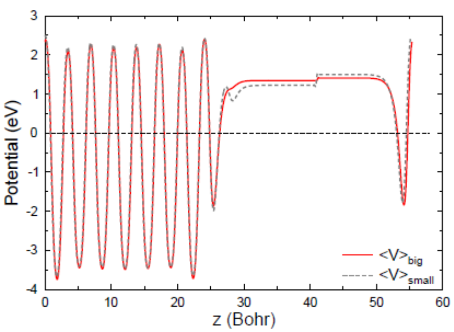
$$j_{FE} = \frac{1.54\cdot 10^{6}(\beta\cdot E)^{2}}{\phi}\exp(10.41\cdot\phi^{-1/2})\exp\left(\frac{-6.53\cdot 10^{3}\phi^{3/2}}{\beta E}\right)$$

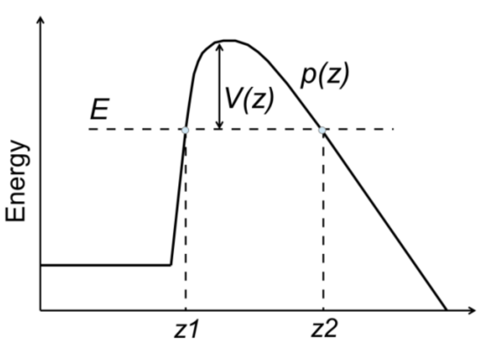




Electron current densities due to a surface adatom or step edge





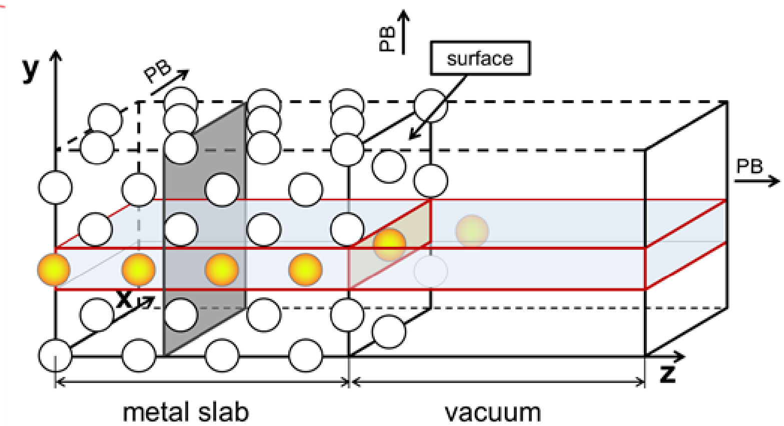


- We estimate the difference in the electron current density due to the presence of an adatom or monoatomic steps on the surface.
- Zero-temperature current density is $J_{mo} = J_F D_F$
  - Here Z_F is effective incident current density and D_F is transition coefficient for tunneling probability calculated in Wentzel–Kramers–Brillouin (WKB) approximation as

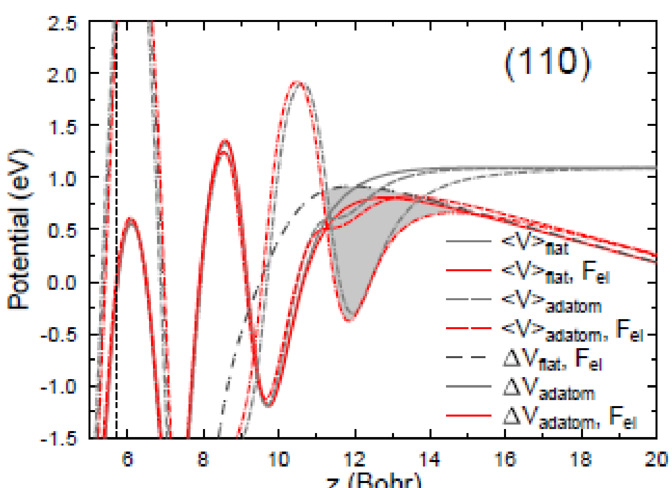
$$D_F(E) = \frac{J_T}{J_F} = \frac{\exp\left(-\frac{2}{\hbar}\int_{z_1}^{z_2} dz\sqrt{2m_e(p(z)-E)}\right)}{J_F}$$

$$\frac{J_{ad}}{J_o} = \exp\left(-\frac{g_e}{2}\int_{z_1}^{z_2} dz\frac{\Delta p}{\sqrt{p_1(z)-E_F}}\right)$$

Effect of surface defect on FE



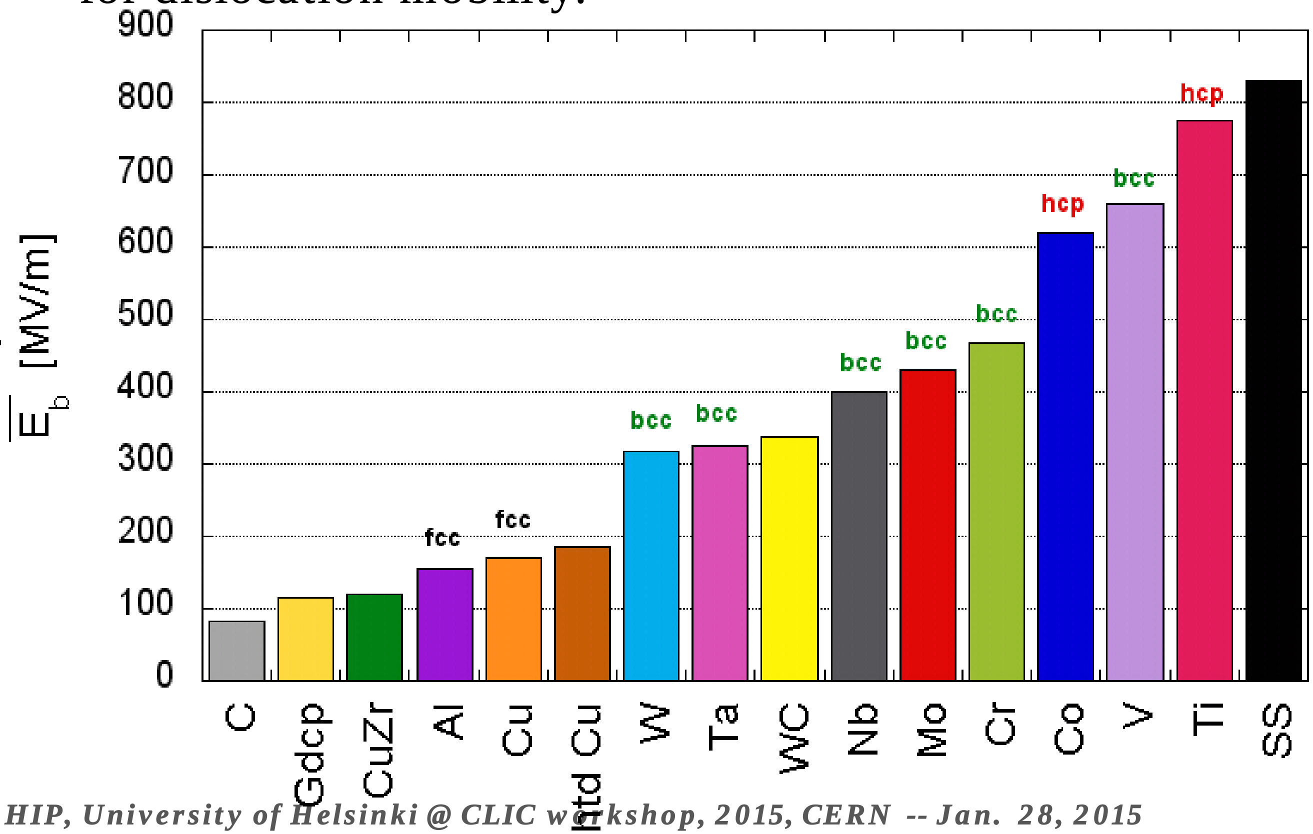
- We calculated J_{def}/J_0 and found that for both types of surface defects – atomic steps and adatoms – and found that even such insignificant drop of the work function may cause the increase of the current density more than 50%



Face	100	110	111
Adatom	1.4	1.324	1.5
Step edge	1.64	1.36	1.74

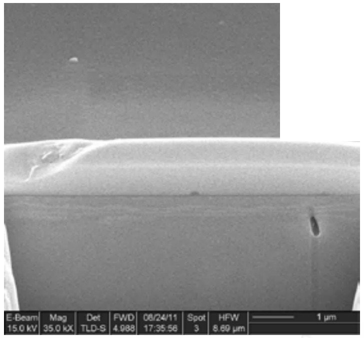
What are the field emitters? Motivation to look in under the surface

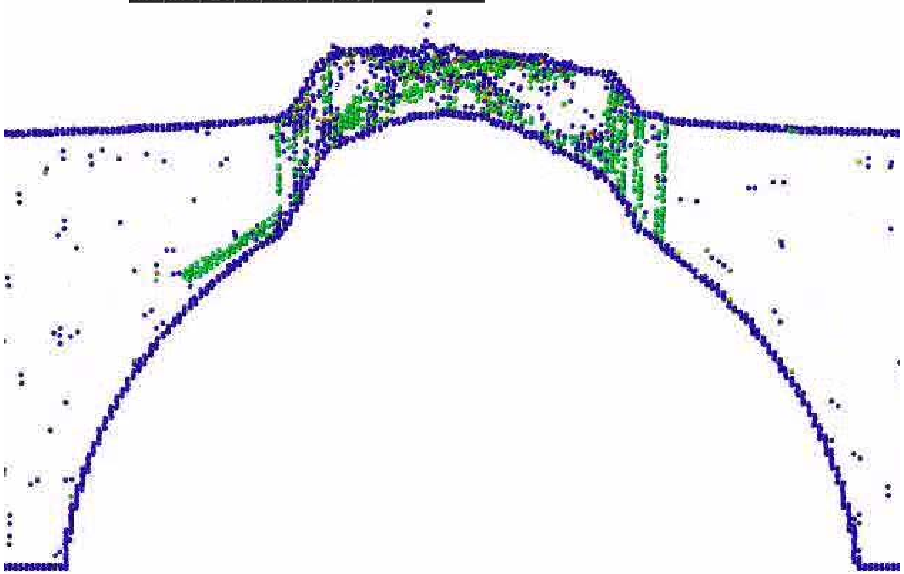
- The dislocation motion is strongly bound to the atomic structure of metals. In FCC (face-centered cubic) the dislocation are the most mobile and HCP (hexagonal close-packed) are the hardest for dislocation mobility.

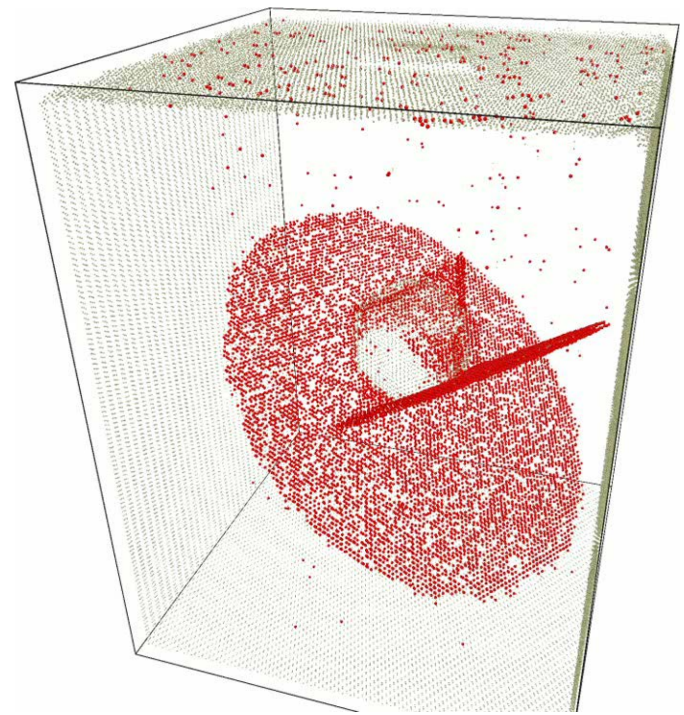


A. Descoeudres, F. Djurabekova, and K. Nordlund, DC Breakdown experiments with cobalt electrodes, CLIC – Note – 875 , 1 (2010).

Voids under tensile stress from the electric field





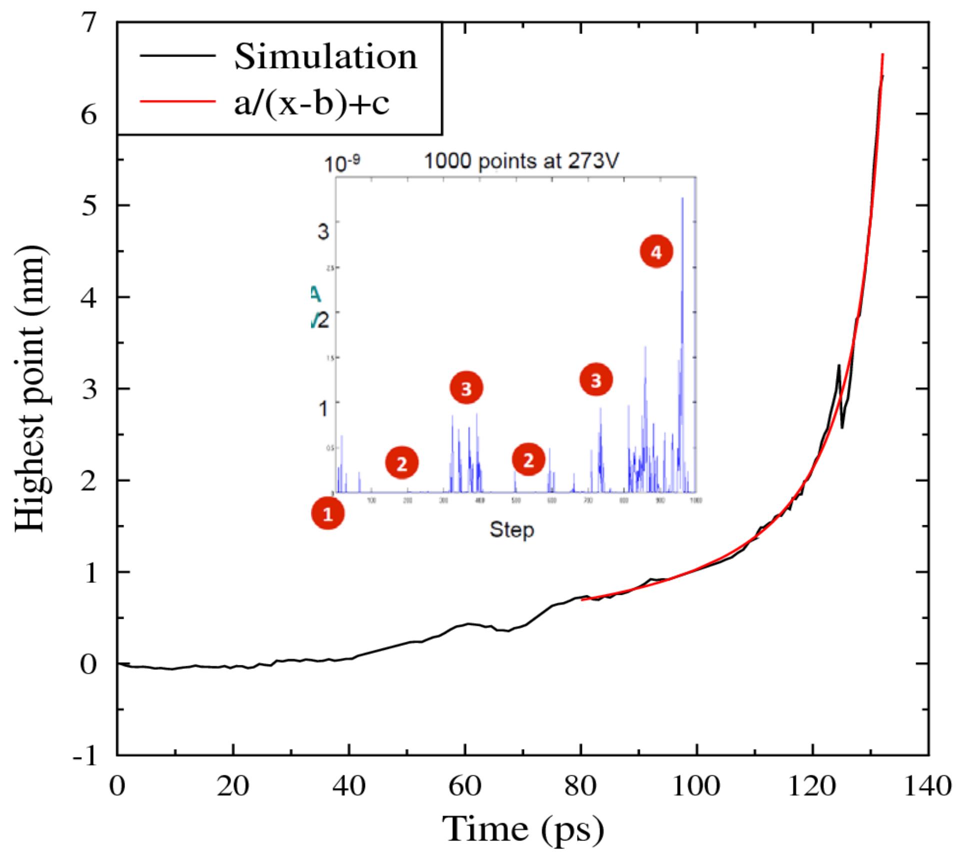


- We also analyzed the behavior of a void under tensile stress due to the electric field (Simulations now done with the ***helmod*** code, where the electric field effect is accounted explicitly)

[A. S. Pohjonen, S. Parviainen, T. Muranaka, and F. Djurabekova, JAP 114, 033519 (2013)]

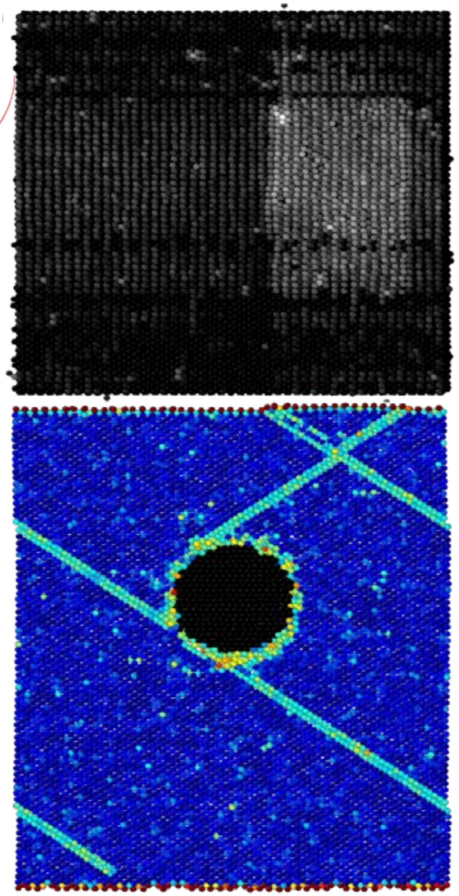
The "catastrophic" growth of a protrusion in the presence of the field

- The analysis of the protrusion height increase shows an asymptotic character. Once it starts growing, the self-reinforcing effect of the field enhancement around the tip of the protrusion causes the increase of its height in the "catastrophic" manner



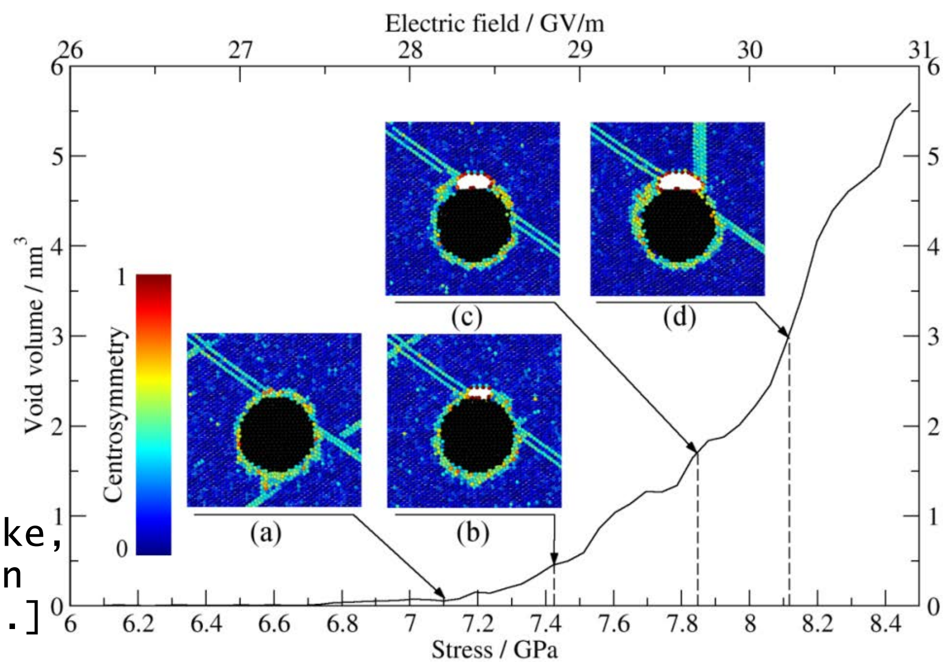
Experiment by Tomoko Muranaka, CERN

Influence of precipitates



7.15 GPa (28.4 GV/m)

- Fe precipitate in Cu
- Dislocations nucleate due to mechanical stress from the precipitate
- Two dislocations converge and form a plateau – surface roughening mechanism
- Formation of voids at the Cu-Fe interface



[S. Vigonski, F. Djurabekova, M. Veske, A. Aabloo, and V. Zadin, Mod. Sim. in Mat. Sci. and Eng. 23, 025009 (2014).]

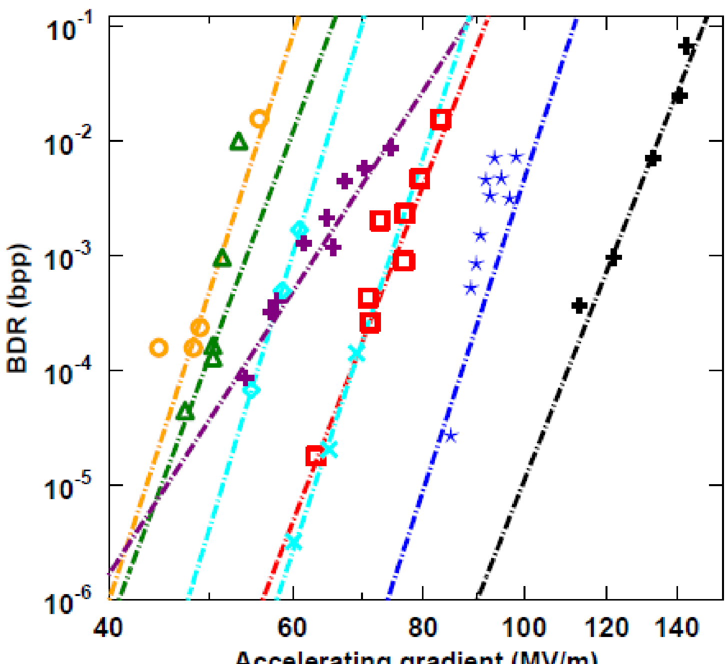
Dislocation-based model for electric field dependence

- Now to test the relevance of this, we fit the experimental data
- The result is:

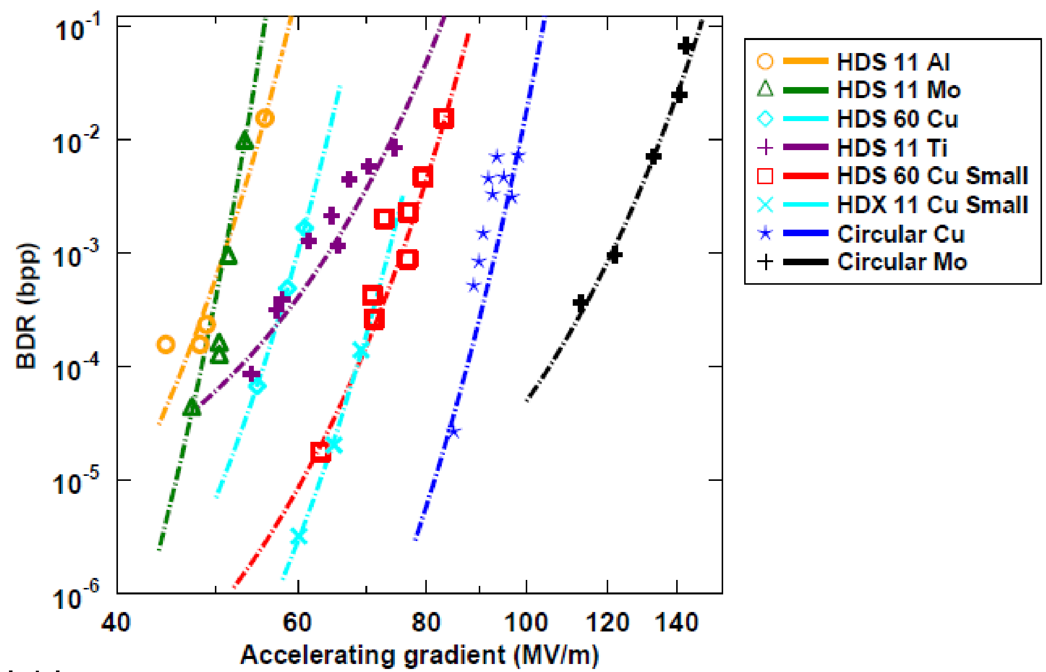
$$BDR = AE^{29}$$

$$BDR = Ae^{\varepsilon_0 E^2 \Delta V / kT}$$

Power law fit



Stress model fit

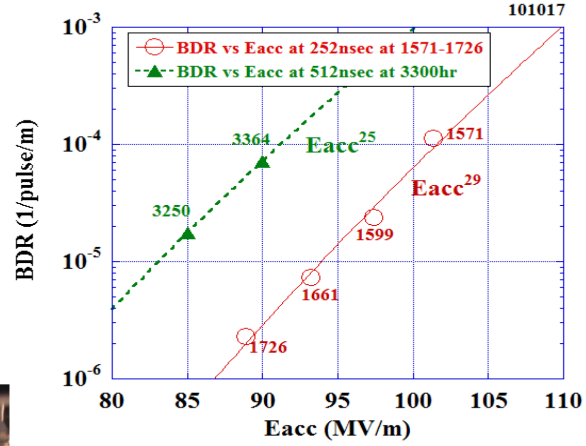


[W. Wuensch, public presentation at the CTF3, available online at http://indico.cern.ch/conferenceDisplay.py?confId=8831.] with the model.]

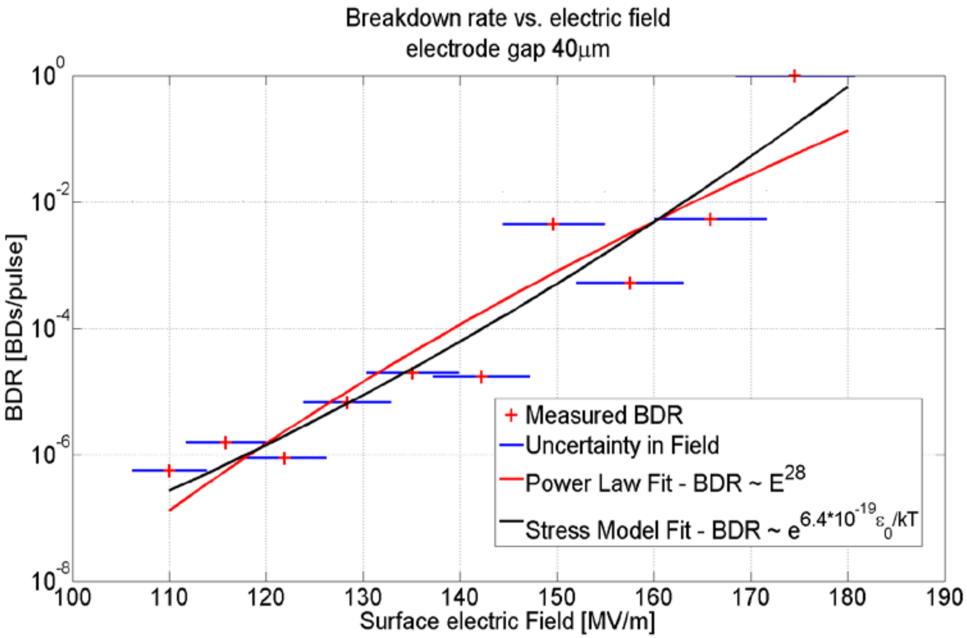
K. Nordlund and F. Djurabekova, Phys. Rev. ST-AB 15, 071002 (2012).

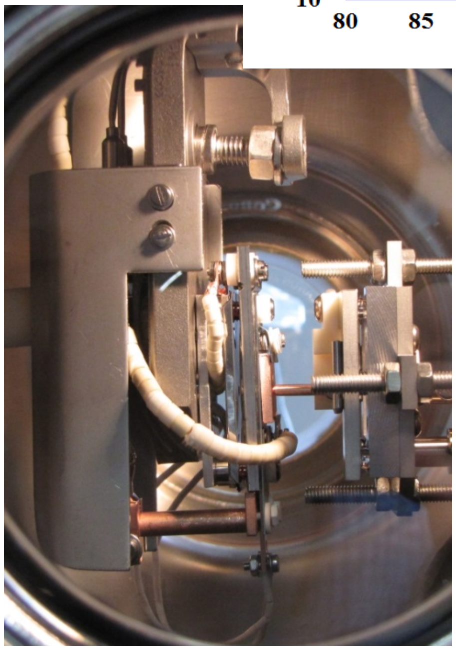
Experiments with the pulsed dc

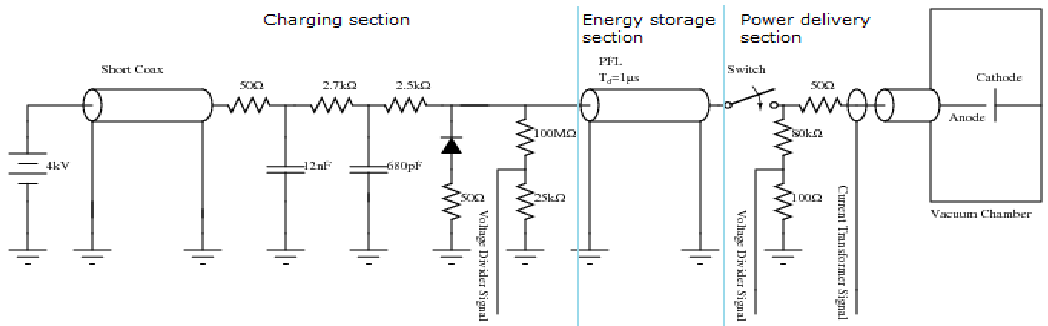
BDR in AS (KEK)

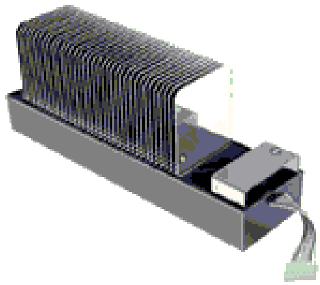


BDR in the pulsed dc (CERN)







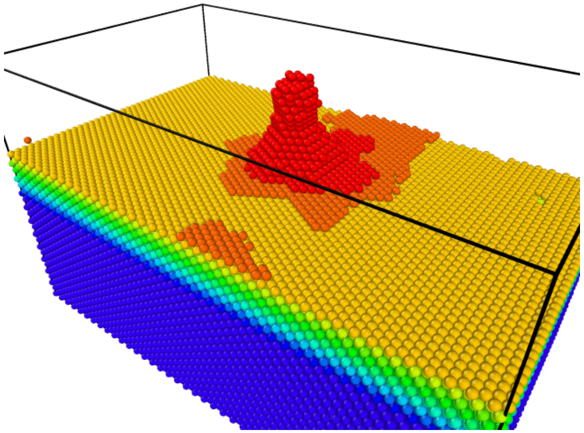


Project of Nicholas Shipman @ CERN

MOSFET switch 1kHz

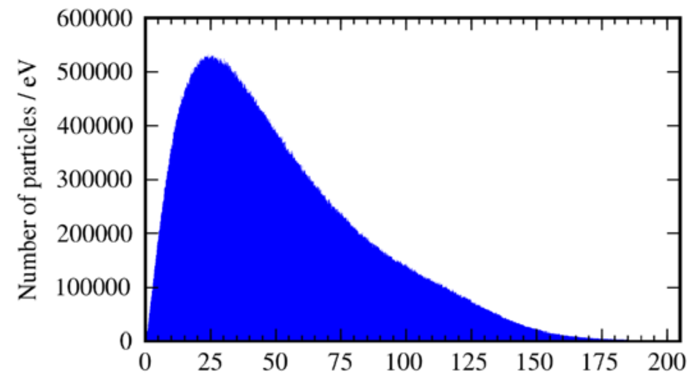
Long-term evolution of surfaces

- Within the model we also develop a Kinetic Monte Carlo code, which is based on simulation of surface atoms hopping from one lattice site to another overcoming the corresponding barriers.
- The code is now completed and is able to describe the spontaneous processes happening on surfaces with different crystallographic orientations. For details see talk by Ville Jansson
- Outlook: the model will include the surface effects, which will allow to estimate the enhancement of surface diffusion under high electric fields.

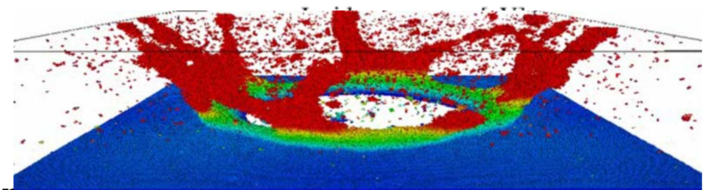


Irradiation of Cu surface with ions of low energy

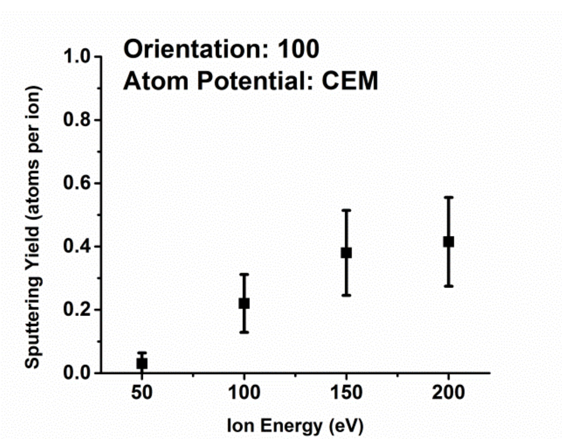
- The latest results of plasma simulations showed that the distribution of ions which arrive at the surface from plasma is

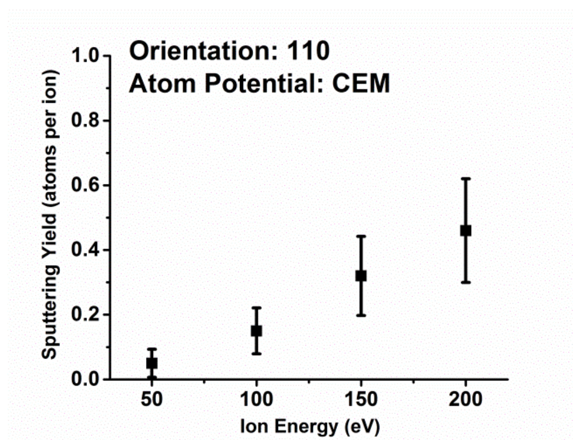


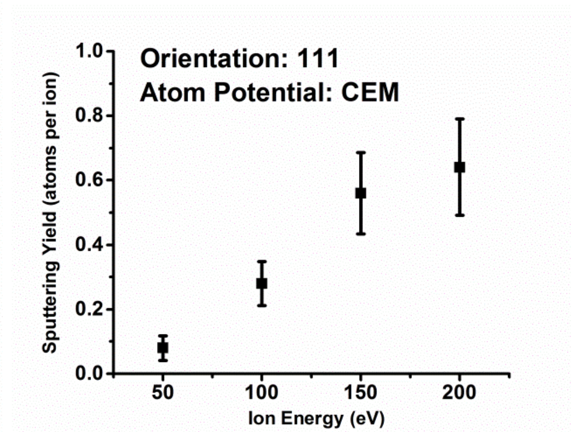
- Our previous simulations of surface damage were made by using 6 keV ions.



- Before starting the simulation of plasma impacts on surface we ran single cascade simulations on different surfaces (Dr. Zh. Wang)







Summary

- The model has been actively developed and gave many new insights in the physics of the plasma onset and surface damage
- The model underlines the importance of mechanical properties of metal surfaces
- Long term surface evolution is added into the model.
- We are starting new simulations of plasma impacts on surfaces with more realistic energy range and heating effects

Thanks to:

- Group in Helsinki
  - Postoctoral researchers:
    - Dr. Stefan Parviainen
    - Dr. Ville Jansson
    - Dr. Vahur Zadin (Tartu Univ.)
  - Former group members:
    - Dr. Aarne Pohjonen
    - Dr. Helga Timko
    - Dr. Lotta Mether
  - PhD students
    - Avaz Ruzibaev
    - Simon Vigonski (Tartu Univ.)
    - Mihkel Veske (Tartu/Helsinki)
    - Ekaterina Baibuz
    - Mrunal Parekh

- Collaborators and colleagues
  - Helsinki:
    - Prof. Kai Nordlund
    - Dr. Antti Kuronen
    - Dr. Kenneth Österberg
  - **CERN**:
    - Dr. Walter Wuensch
    - Sergio Calatroni
    - Kyrre Ness Sjoebaek
  - Hebrew university of Jerusalem
    - Dr. Yinon Ashkenazy

You can find more information at
http://research.hip.fi/hwp/acctech/accelerator-technology/m-a-t/

Thanks to:

http://research.hip.fi/hwp/acctech/accelerator-technology/m-a-t/

m arcs:

i – Sandia

Mechanisms of Vacuum Arcs-5

2-4 September, 2015

The Hebrew University of Jerusalem

Sandia National Laboratories

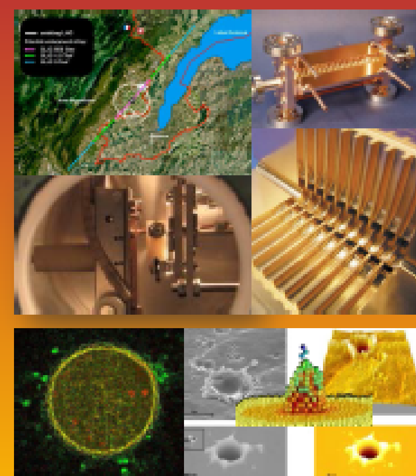
The workshop aims to combine the efforts of researchers in the different fields to understand the mechanisms underlying the highly intriguing phenomenon of electrical breakdown. The workshop will cover rf and dc types of electrical breakdowns, including theory, experiment, and simulation. The workshop will be preceded by a half-day mini-school on modeling surface (electrode) evolution processes relevant to electrical breakdown phenomena.

Topics

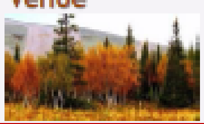
Experiments: vacuum arcs, dc spark systems, rf accelerating structures, materials, diagnostics, techniques and technologies for high gradients, and arcing in fusion devices.

Theory and simulations: surface modification under electric and electromagnetic fields, PIC and PIC-DSMC plasma simulations, dislocation activity, plasma-wall interactions, and surface damage and evolution.

Applications: particle accelerators, discharge-based devices, electrostatic failure mitigation, fusion devices, satellites and other industrial interests.



Venue



The workshop will be held in Saariselkä, Lapland. Lappish ruska is the time of beautiful autumn colors.

Organizers

Flyura Djurabekova
HIP, University of Helsinki, Finland

Walter Wuensch, Sergio Calatroni
CERN, Switzerland

Matthew Hopkins
Sandia National Laboratories, USA

Yinon Ashkenazy
Hebrew University of Jerusalem, Israel

http://indico.cern.ch/conferenceDisplay.py?confId=246618

MeVARC–5
Lapland
Finland
2015
2–4 Sept.