Nanostructures induced by highly charged ions

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Ion beams in material science

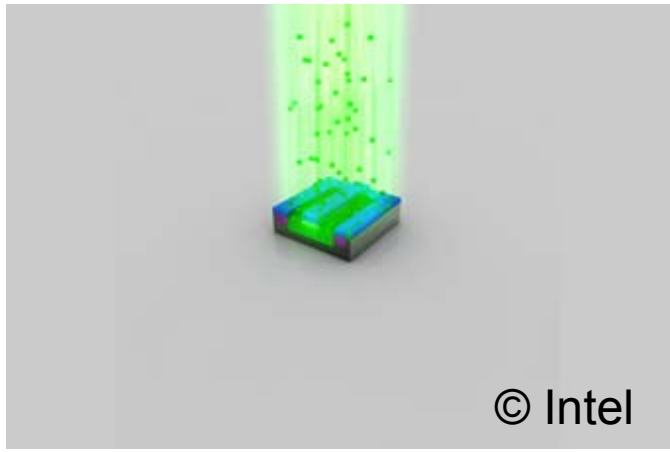
Ion beams have been traditionally used for:

Ion implantation: semiconductor industry

Surface modification: sputtering, sputter deposition
changing the surface properties

Material analysis: RBS, ERDA,
with sputtering: SIMS, SNMS,

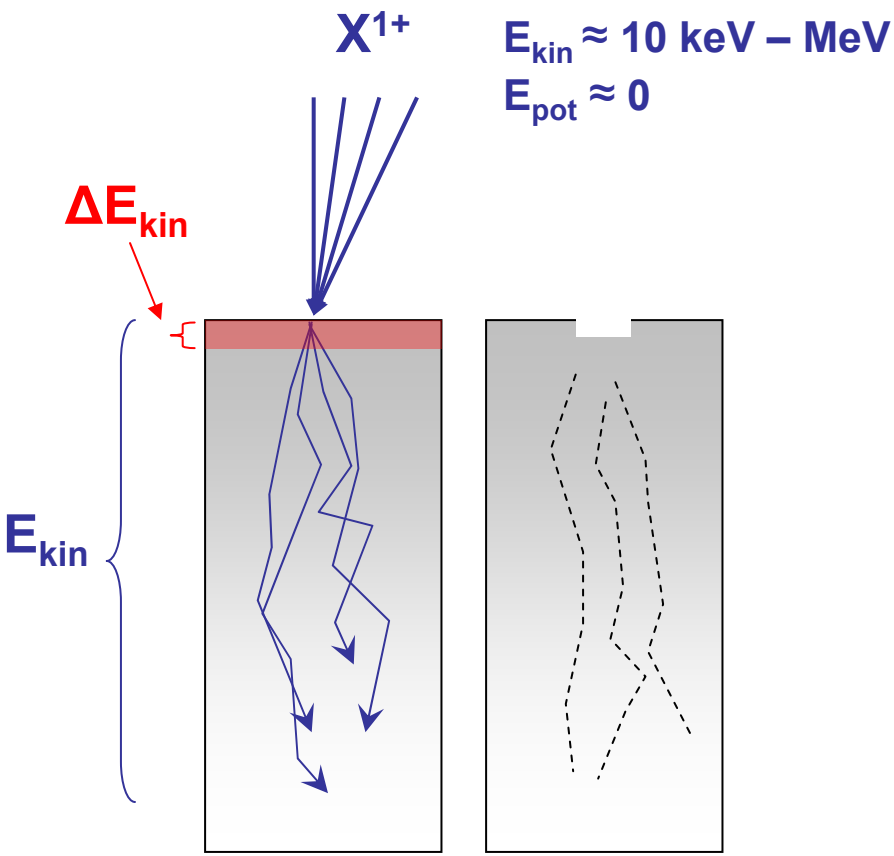
...



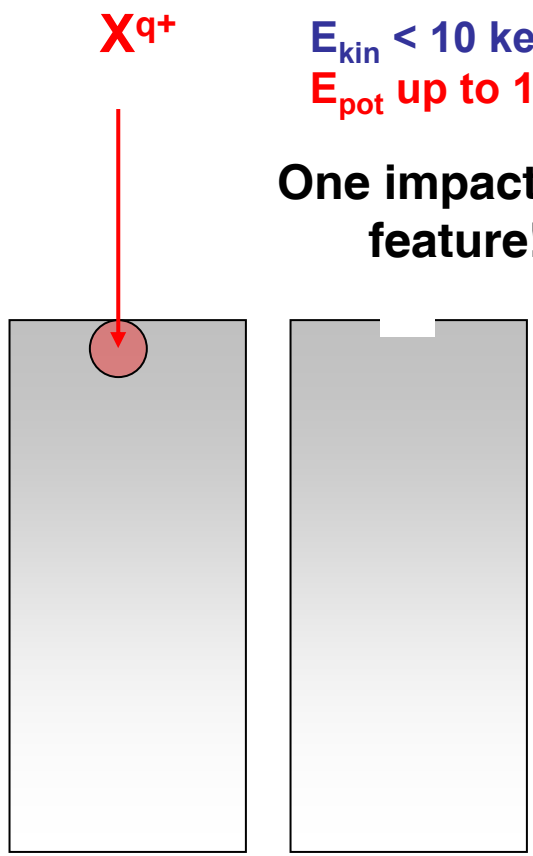
Where can highly charged ions be used with advantage?

New degree of freedom: potential energy

Conventional particle irradiation



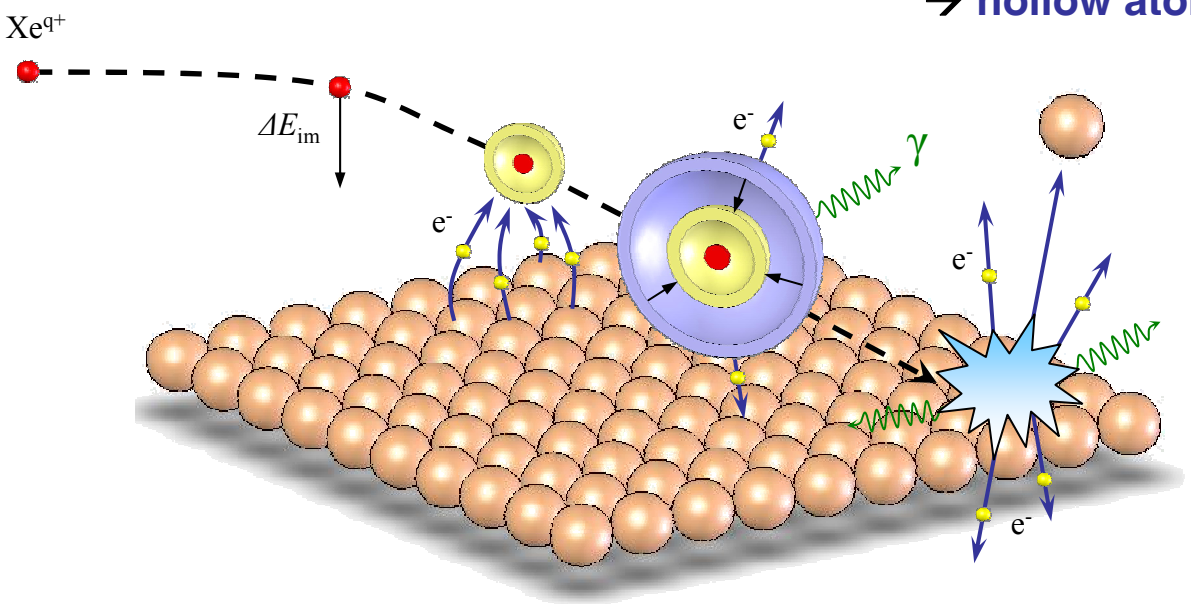
HCI irradiation



Localized electronic excitation similar to high power laser excitation!

- Interaction well understood in the frame work of the Classical Over Barrier Model (COB)

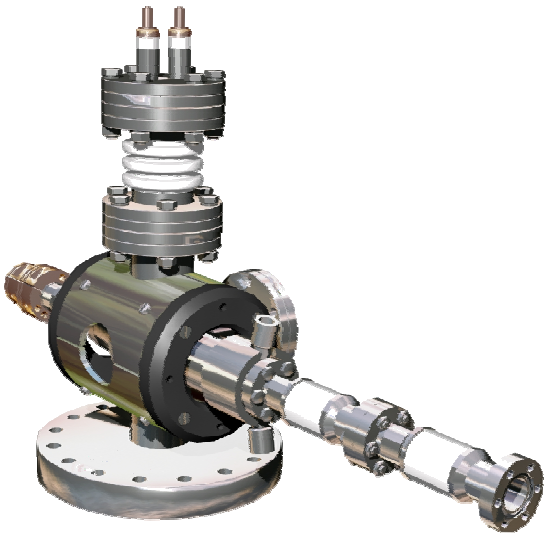
- Neutralization involves electron transfer from the surface to the projectile into Rydberg orbitals
  → hollow atom formation

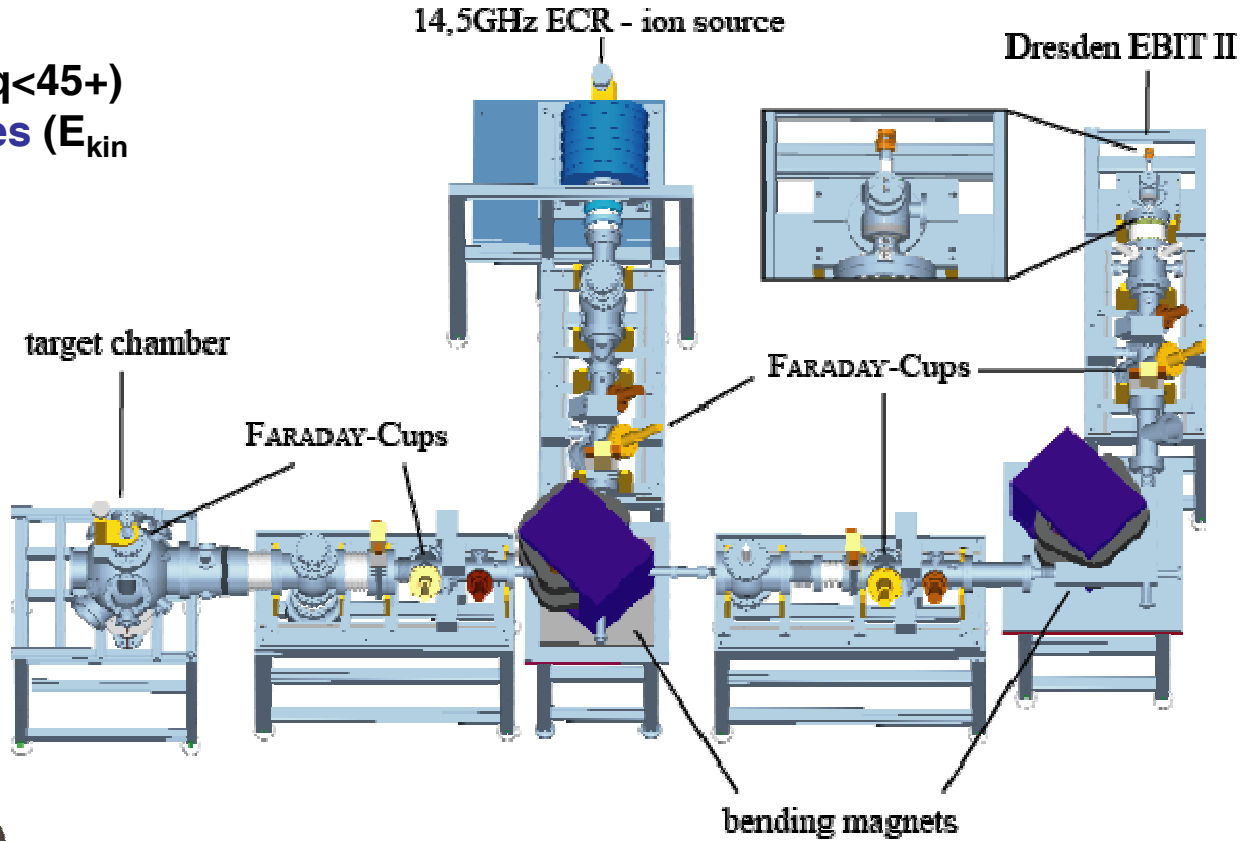


- Rapid relaxation of the HA in front of the surface leads to emission of numerous secondary electrons

- Electrons carry a major part of the ions initial potential energy into the surface and lead to permanent structures on a nm scale

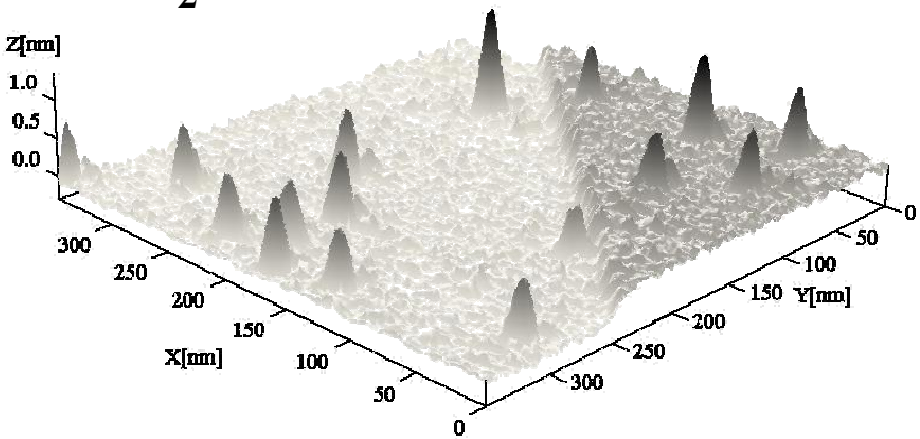
- **Irradiation experiments at Rossendorf Two Source Facility**
- **Highest charge states (q<45+) at lowest kinetic energies (E_{kin} > 20 eV·q)**



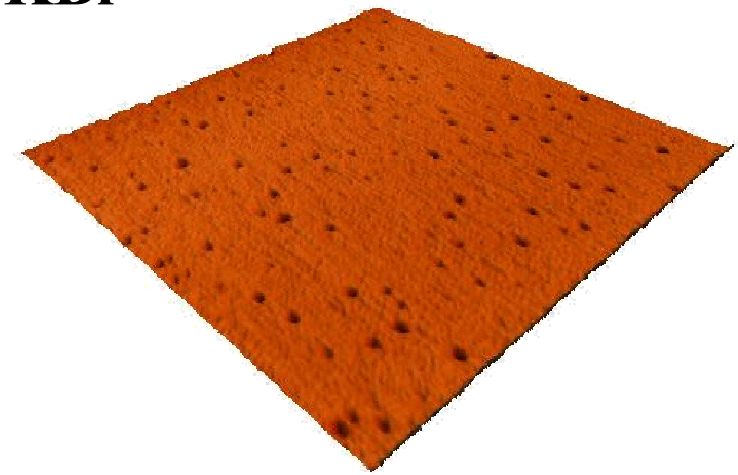


c-AFM characterization of the surface „ex-situ“

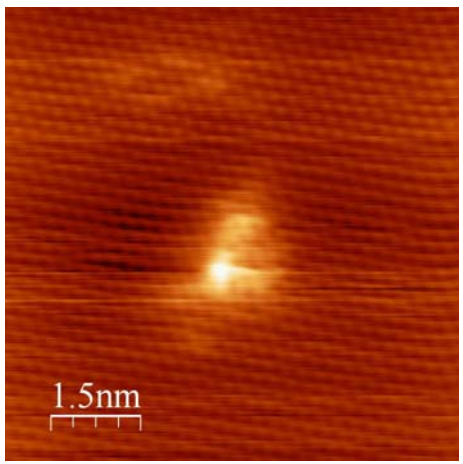
CaF_2



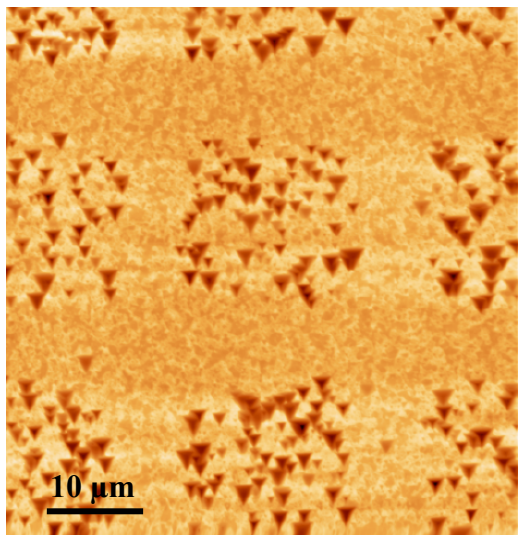
KBr



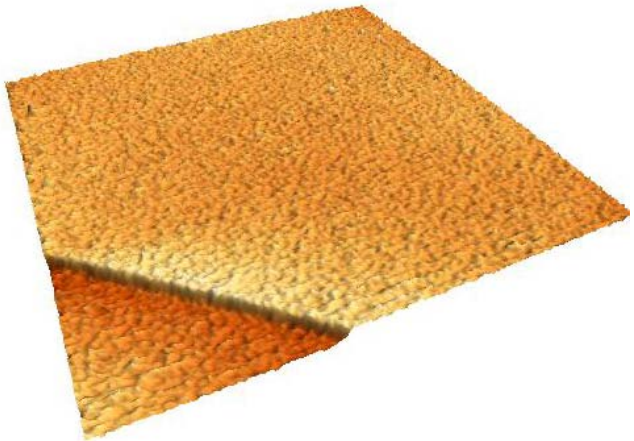
HOPG



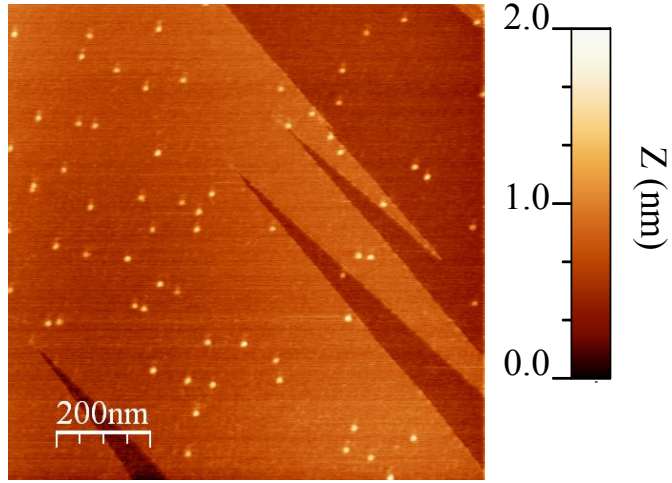
BaF_2

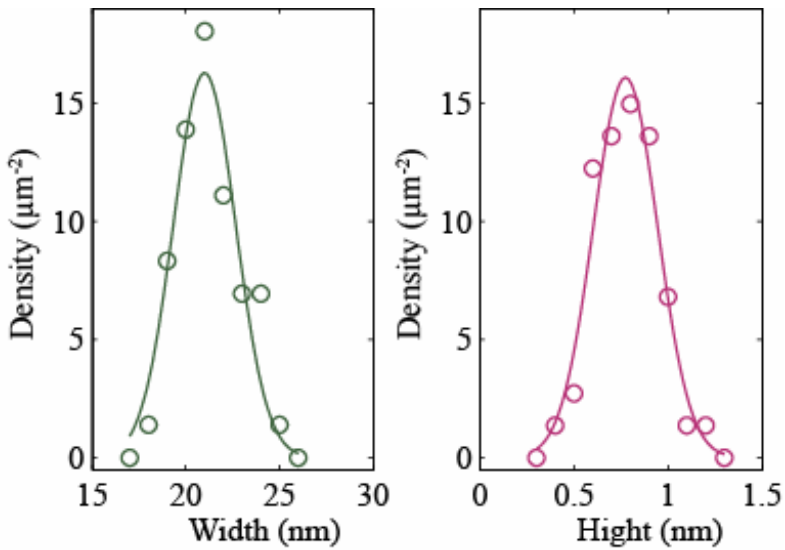


Hillocks on CaF_2 induced by highly charged ions

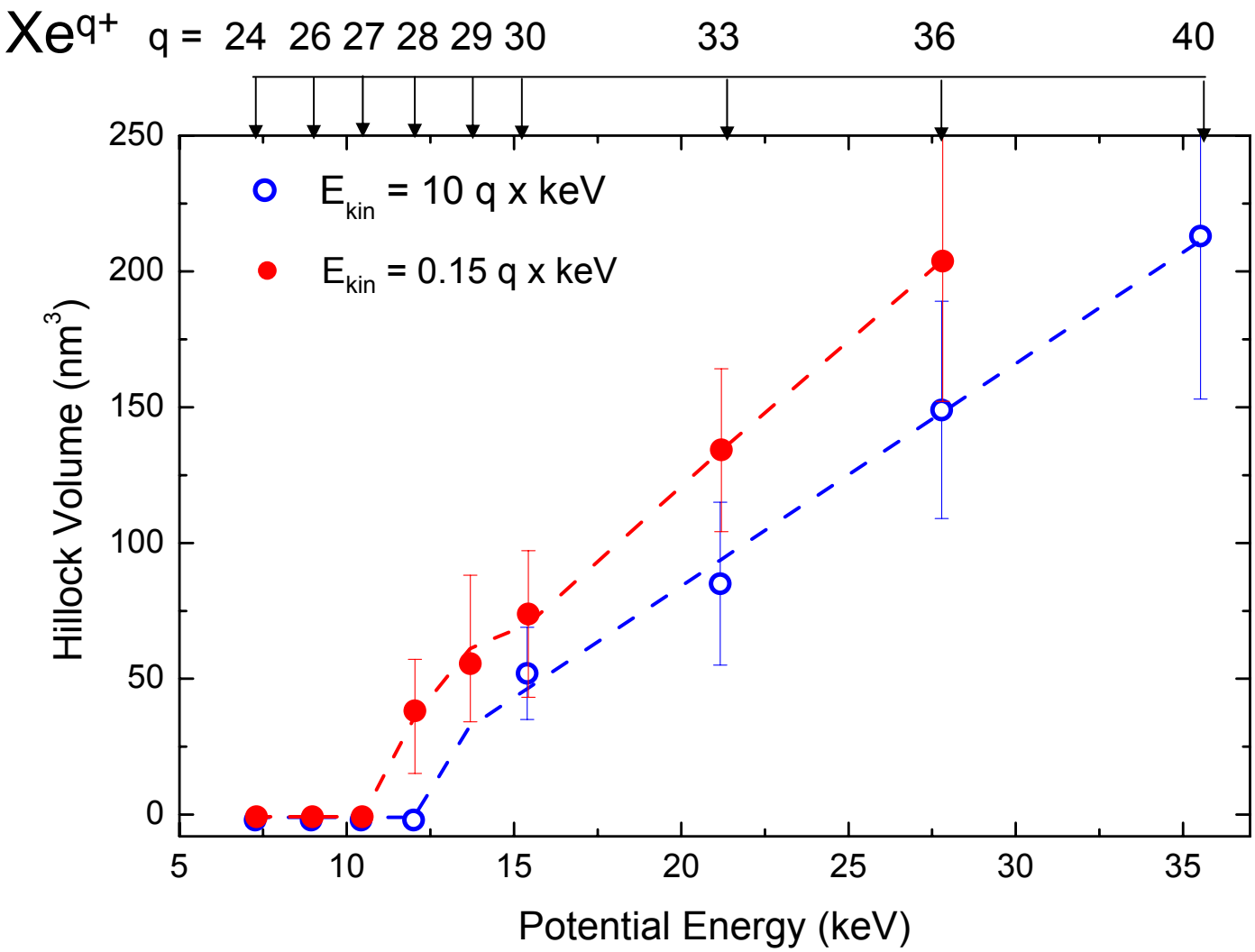


Xe^{33+}, E_{kin}= 2 keV·q



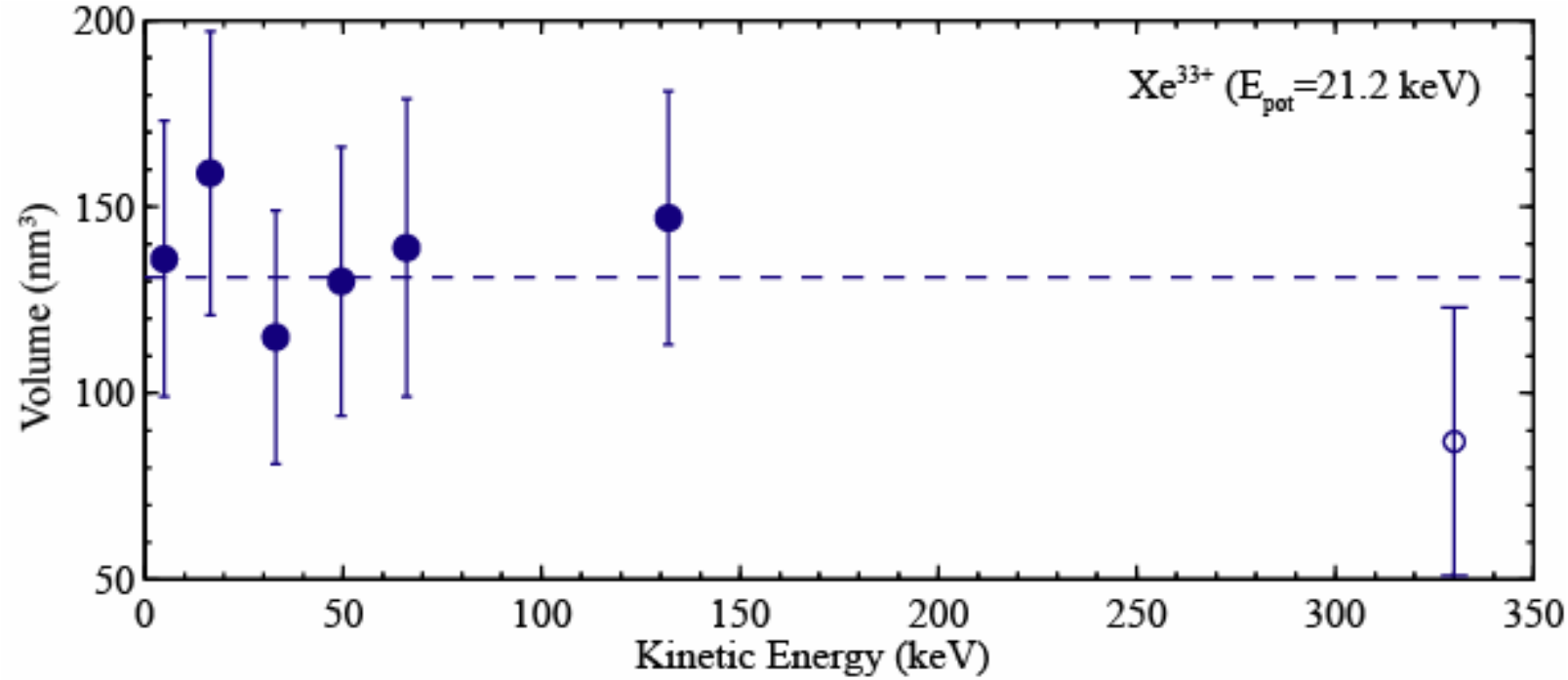


Nano Hillocks on CaF_2



- Well defined threshold for hillock formation in potential energy
- Linear increase of hillock volume with pot. energy upon $E_{crit.}$
- Slight shift of $E_{crit.}$ with increasing kinetic energy

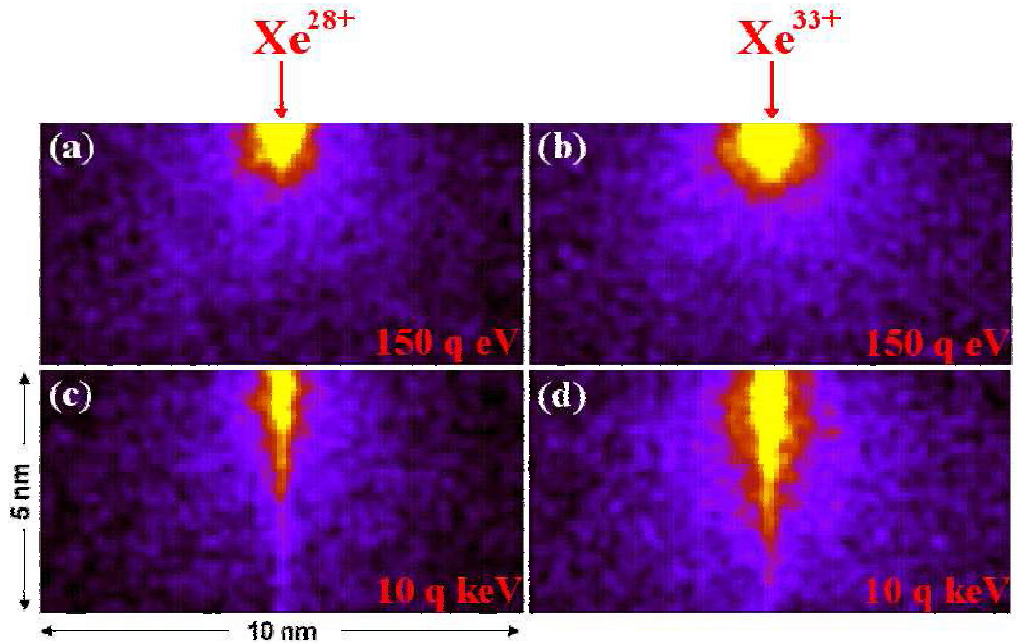
Nano Hillocks on CaF_2

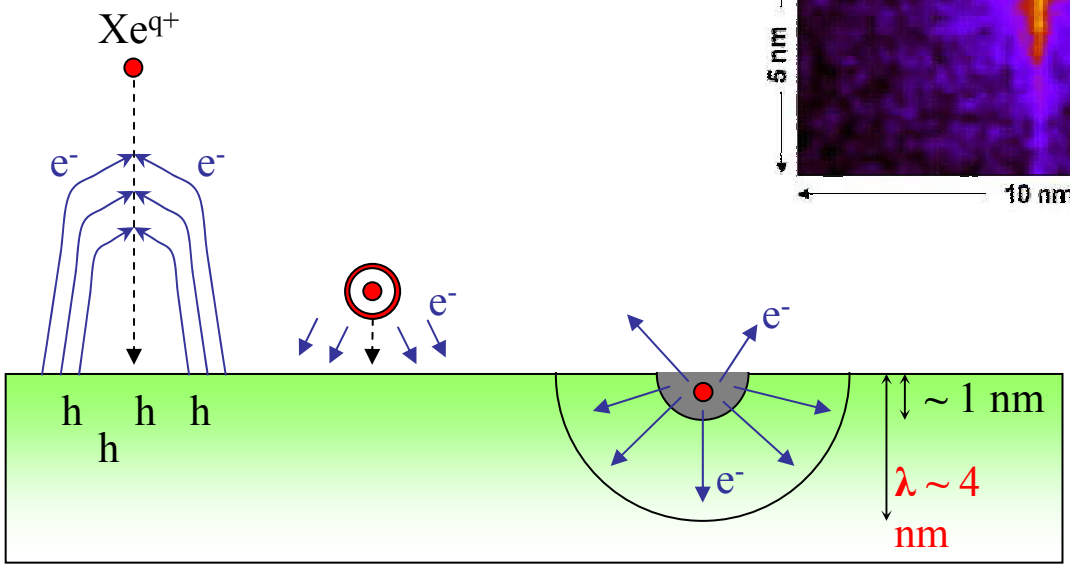


- Hillock volume **independent** on **kinetic energy** over a wide range
- For **highest E_{kin}** small shift towards **lower** hillock **volume**

Nano Hillocks on CaF_2

- **Electrons from HCl neutralization spread a major part of E_{pot} into a small region close to the surface**
- **Potential energy threshold related to melting energy**
  → Local phase transition





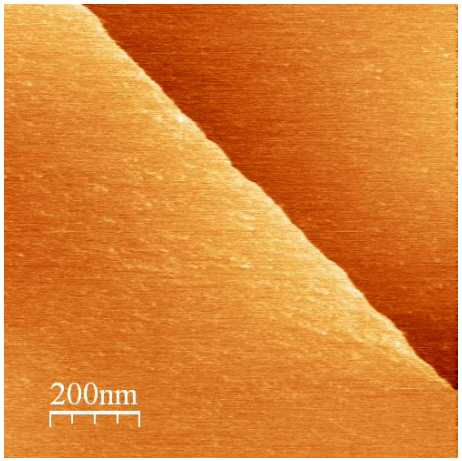
Detailed electron energy transport calculation

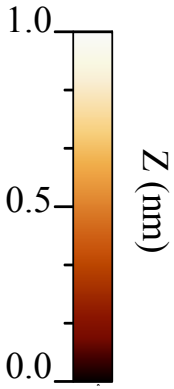
Inelastic thermal spike model (M. Toulemonde)

A. S. El-Said, R. Heller et al., PRL 100, 237601 (2008)

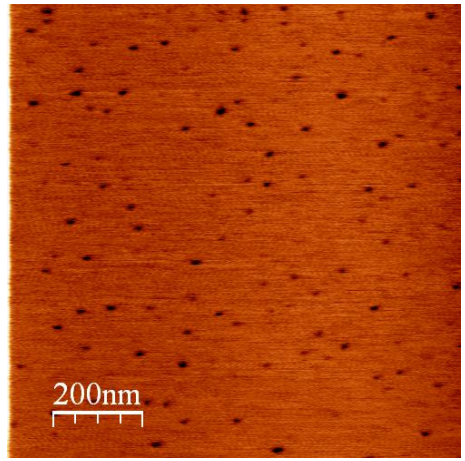
Pits on KBr
induced by highly charged ions

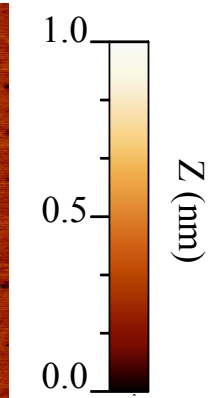
Nano Pits on KBr

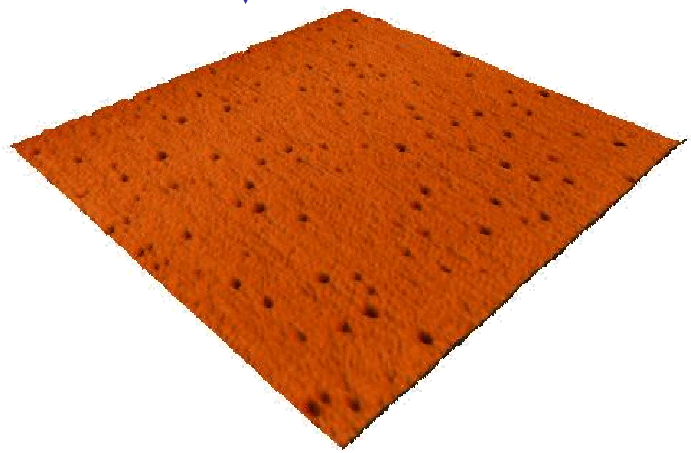


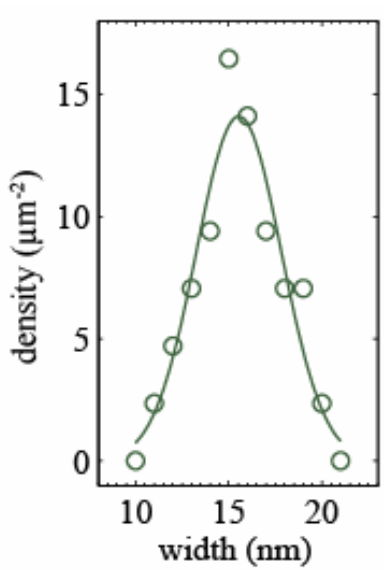


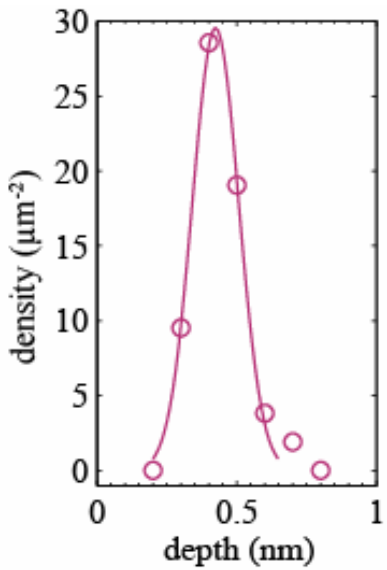
Xe^{25+}, E_{kin}= 40keV











potential energy

Xe^{5+} (E_{pot} = 0.16 keV)

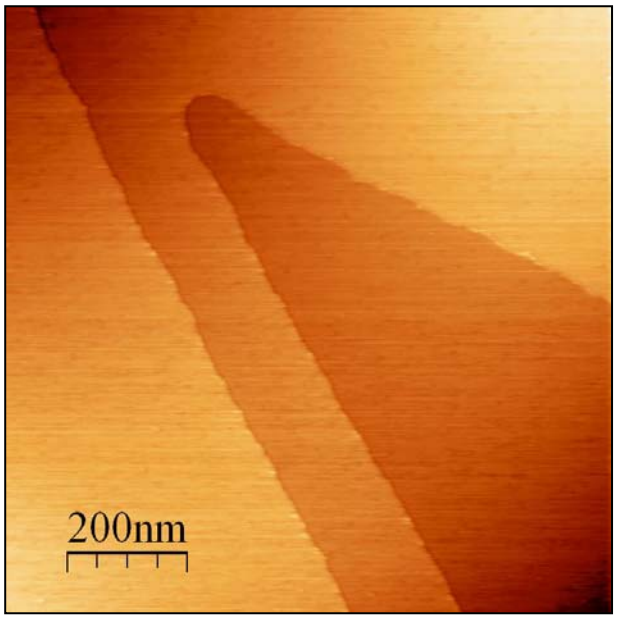
E_{kin} = 4.0 keV

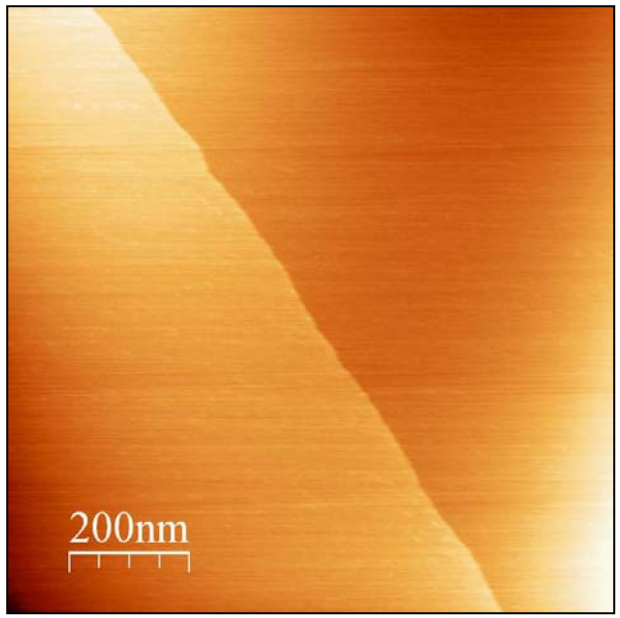
Xe^{10+} (E_{pot} = 0.80 keV)

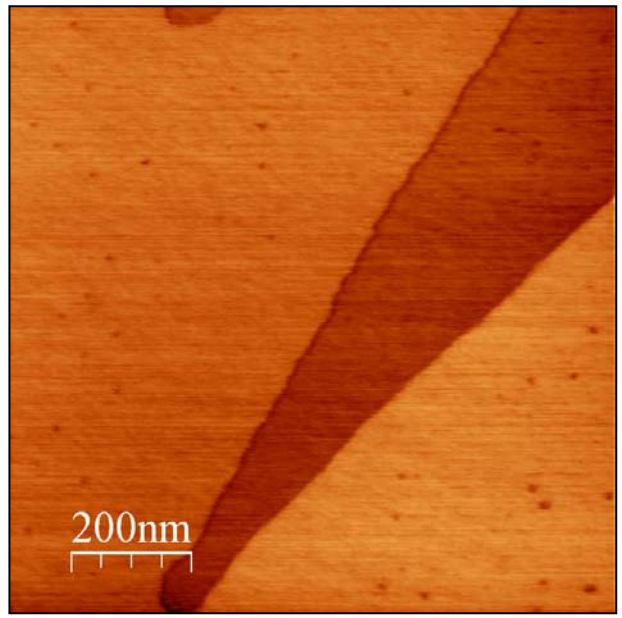
E_{kin} = 4.0 keV

Xe^{34+} (E_{pot} = 23 keV)

E_{kin} = 4.0 keV







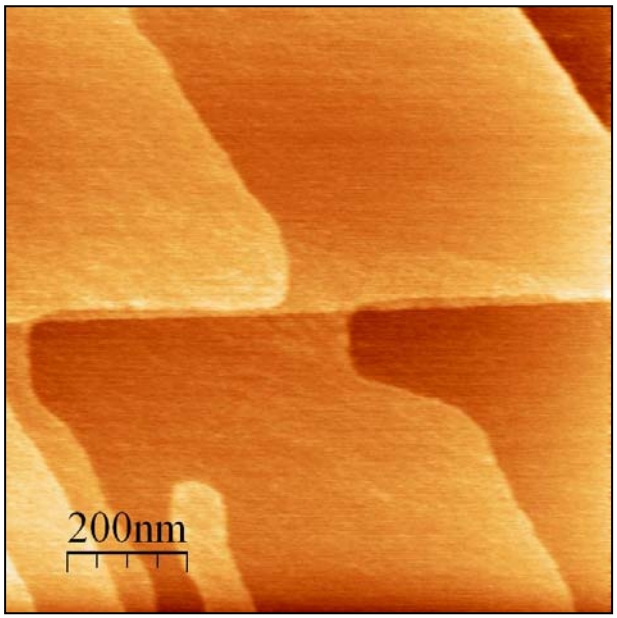
fluence < 1 · 10^{10} cm^{-2}

→ single ion impact

kinetic energy

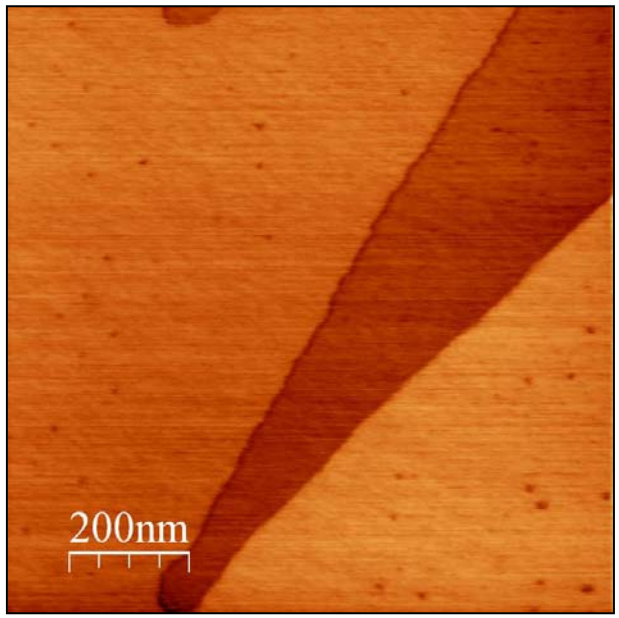
Xe^{34+} (E_{pot} = 23 keV)

E_{kin} = 1.0 keV



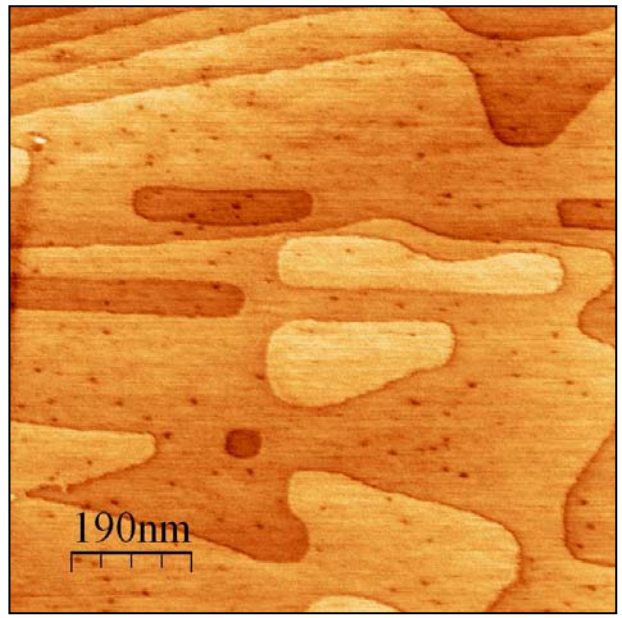
Xe^{34+} (E_{pot} = 23 keV)

E_{kin} = 40 keV



Xe^{34+} (E_{pot} = 23 keV)

E_{kin} = 153 keV

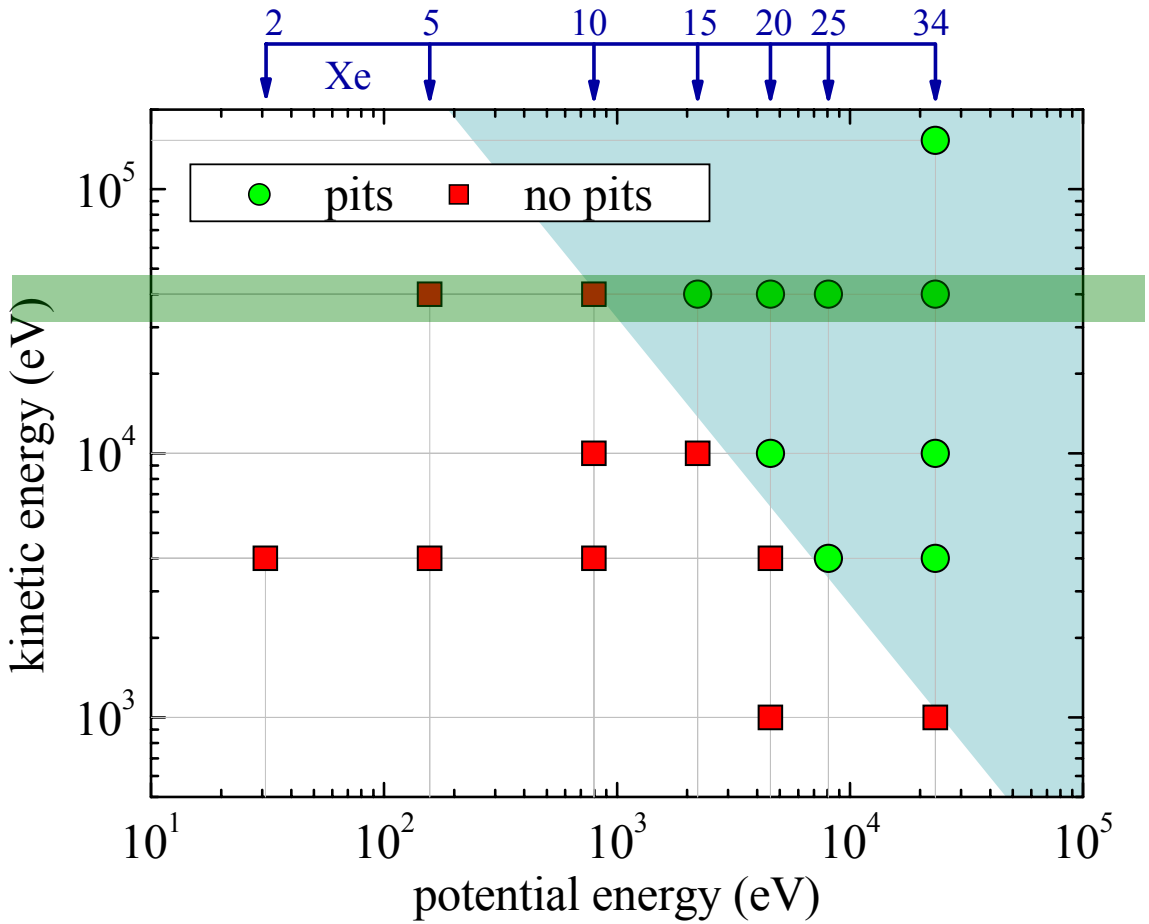


fluence < $1 \cdot 10^{10}$ cm^{-2}

→ single ion impact

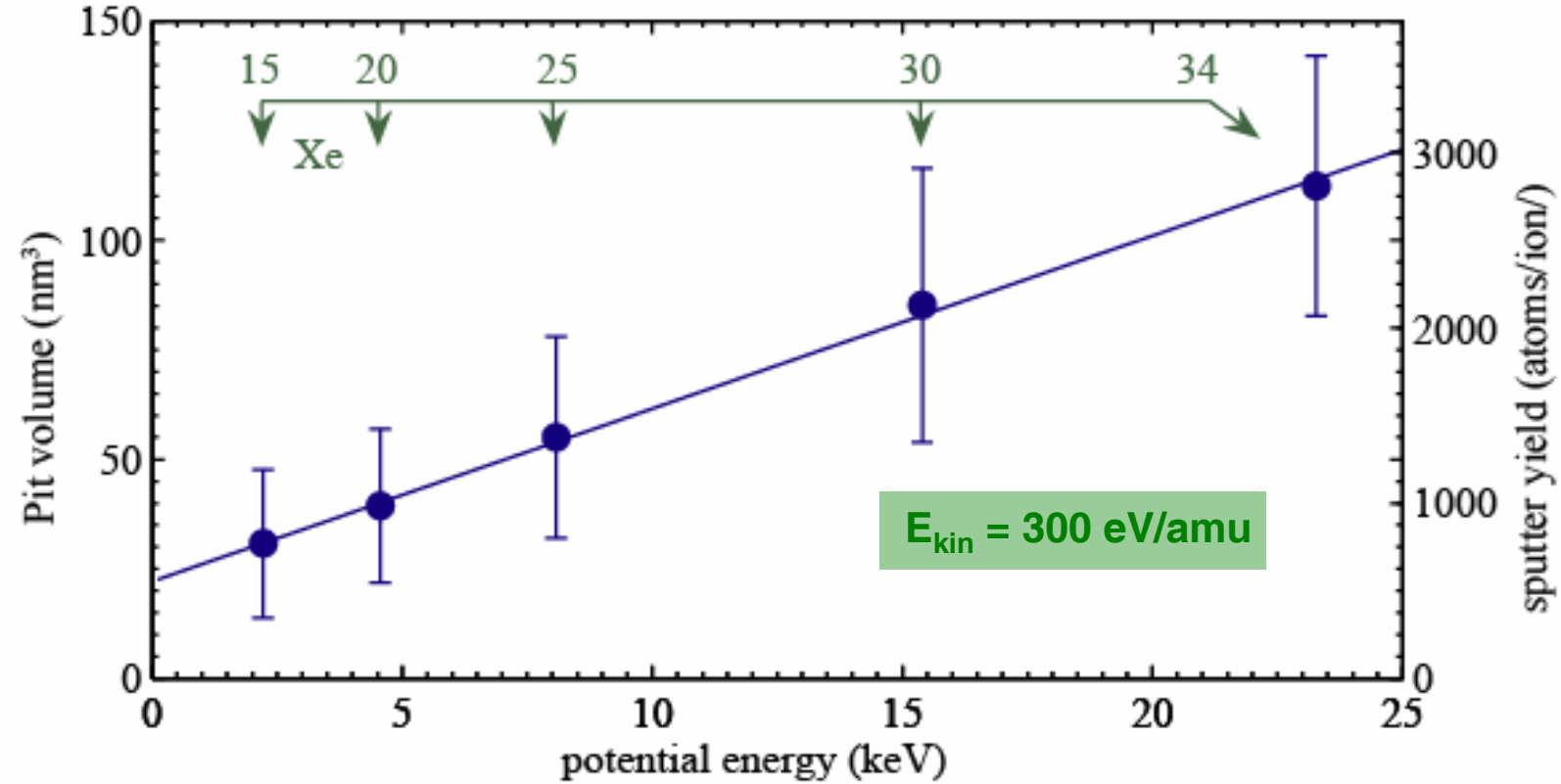
Conditions for pit formation

- **Formation of pits depends strongly on potential and kinetic energy**
- **A threshold for the formation of pits exists in potential and kinetic energy**
- **Formation of pits is a synergistic effect!**



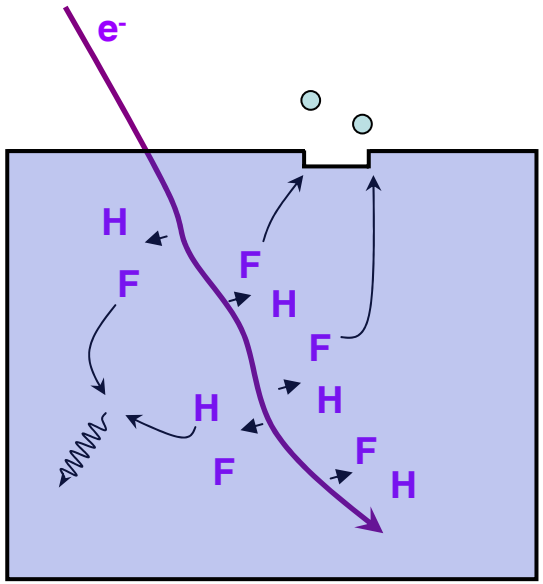
S. Facsko et al., J. Phys. Cond Matt. 21 (2009)

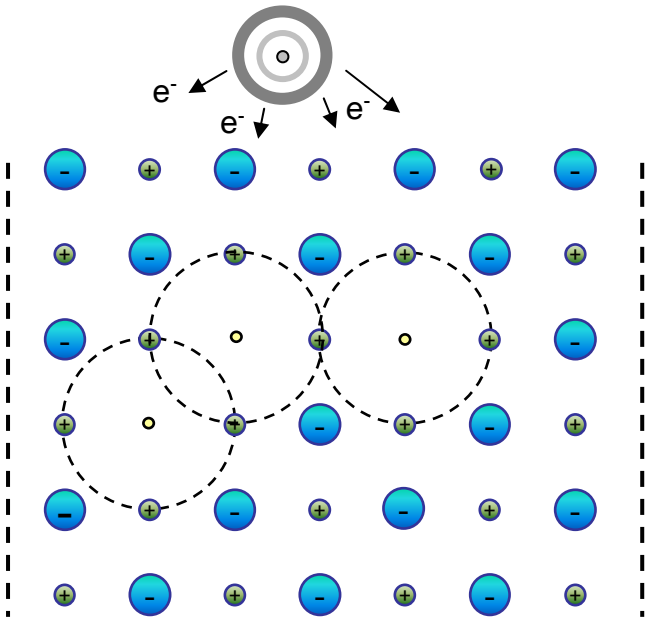
Nano Pits on KBr

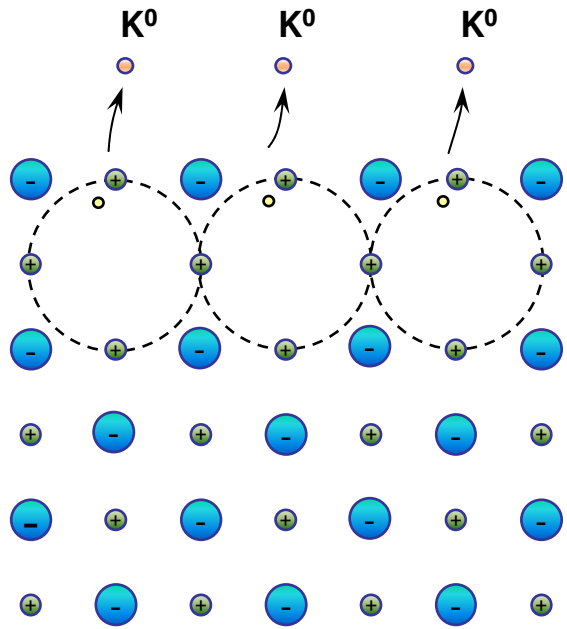


- Pit volume and corresponding sputter yield show a linear dependence on the ions potential energy.
- Pit depth is constant at one ML independent on E_{pot}

The X center



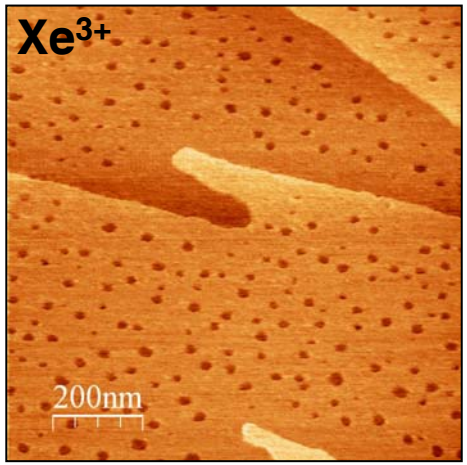


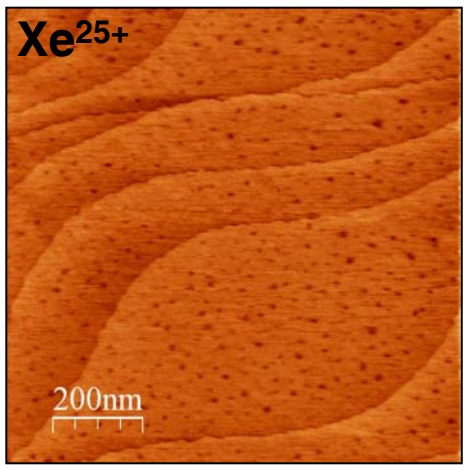


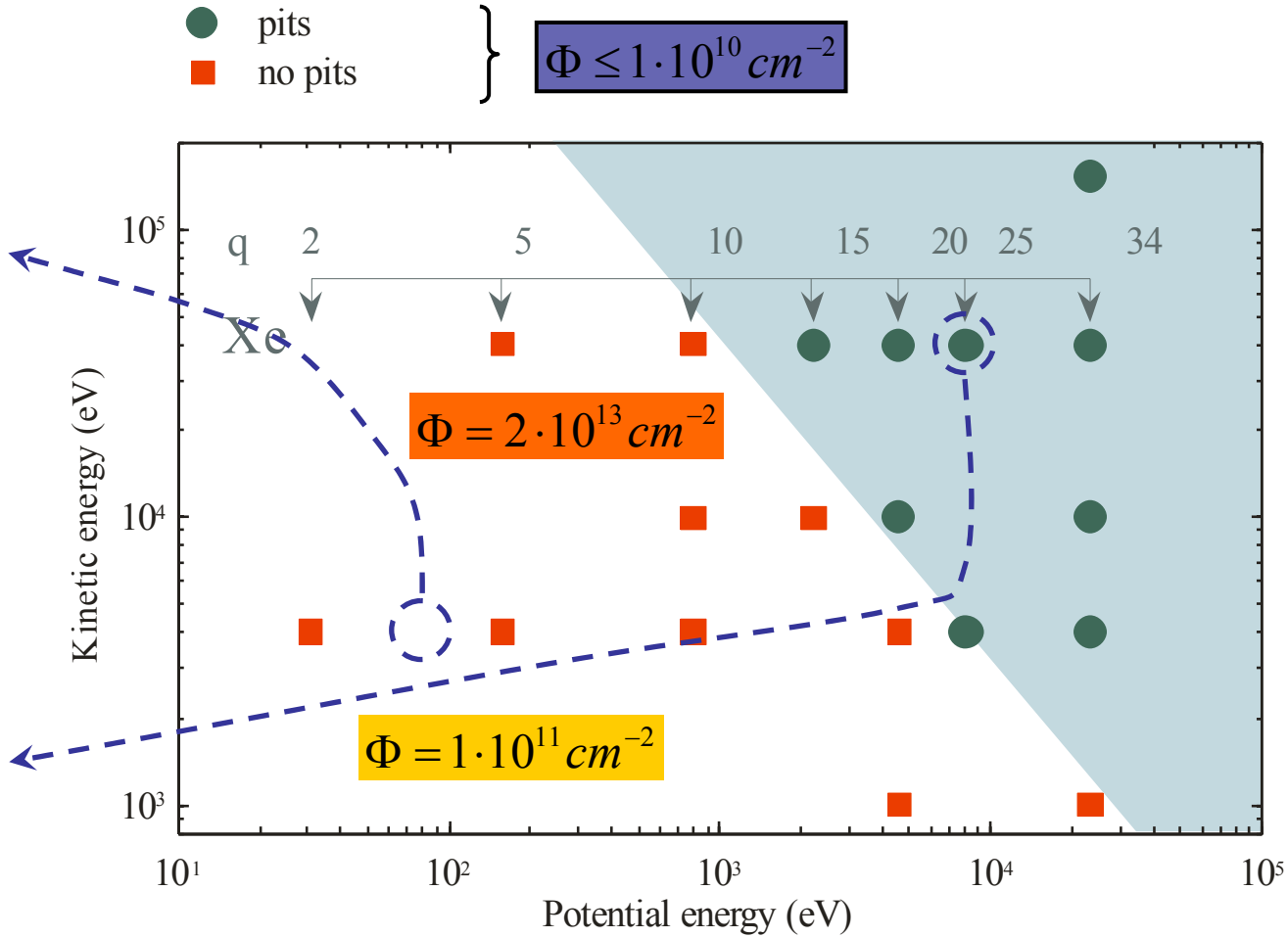
- H and F center creation along the full electron trajectory
- Cluster of 3 F-centers (X-center) created by multi-electron impact in HCl neutralization
- Cluster of 3 F-centers recombining with the surface by desorption of 3 K^0 atoms

*R. Heller, R. Wilhelm, S. Facsko, PRL **101**, 096102 (2008)*

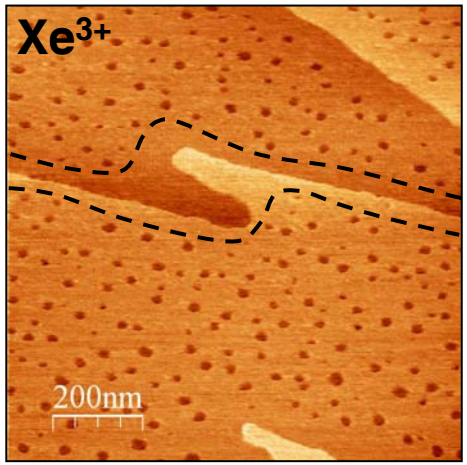
„High“ fluence irradiations



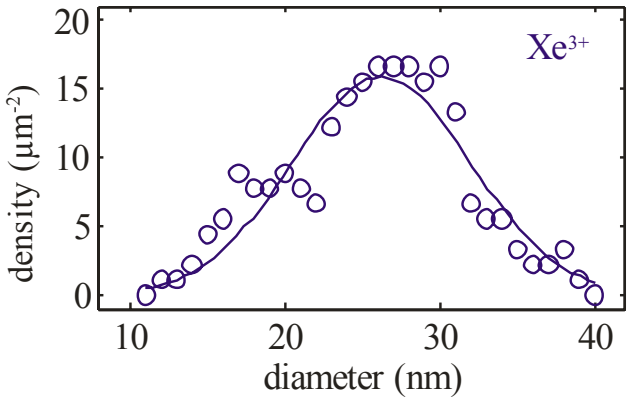


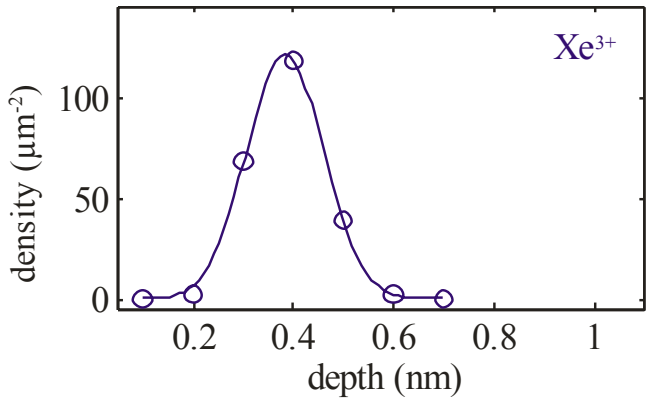


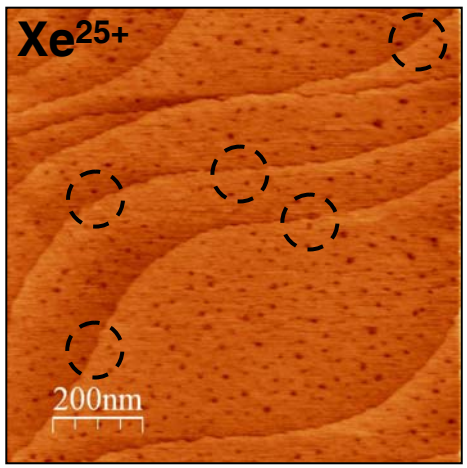
„High“ fluence irradiations



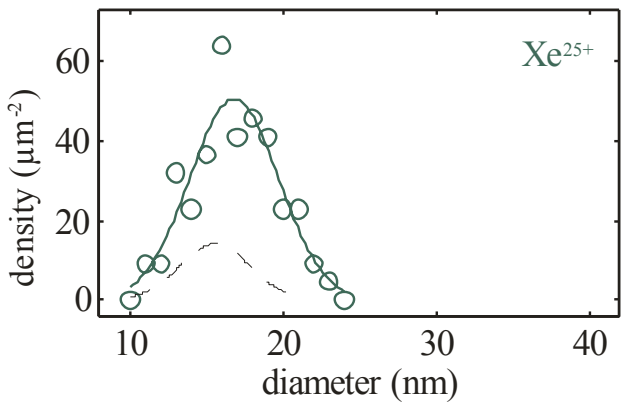
$\Phi = 2 \cdot 10^{13}\, cm^{-2}$

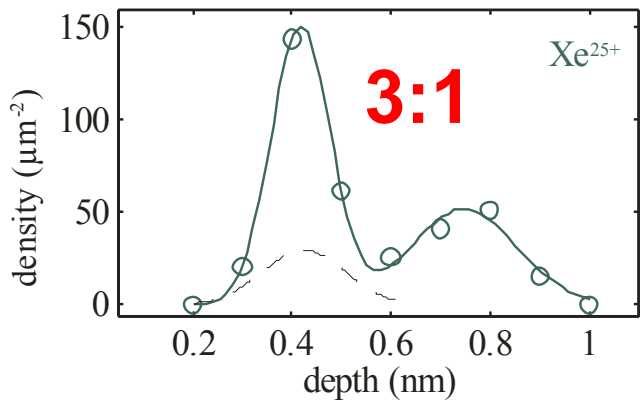






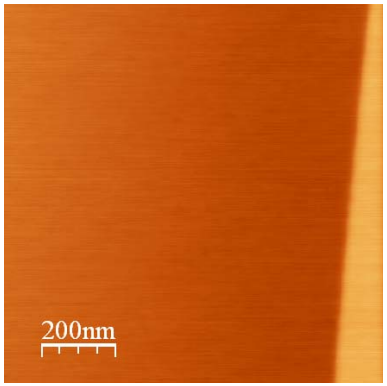
$\Phi = 1 \cdot 10^{11}\, cm^{-2}$



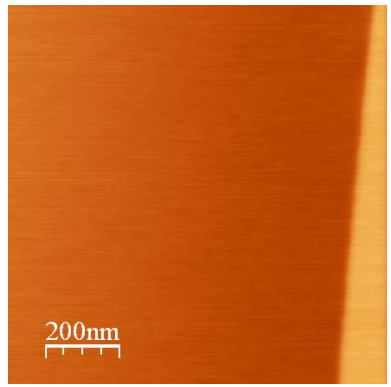


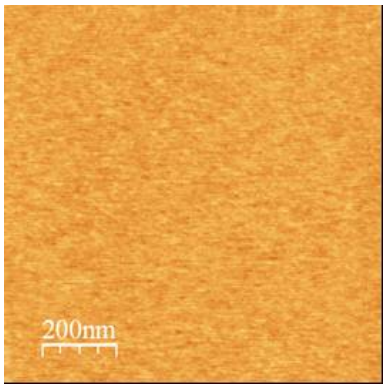
Etch pits on BaF_2 induced by highly charged ions

Etch Pits on BaF_2

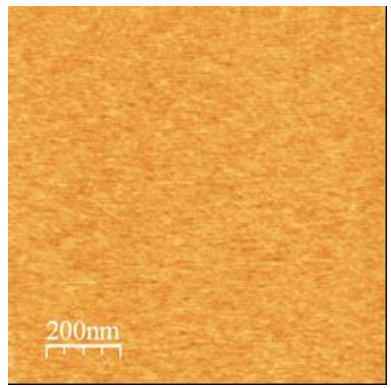


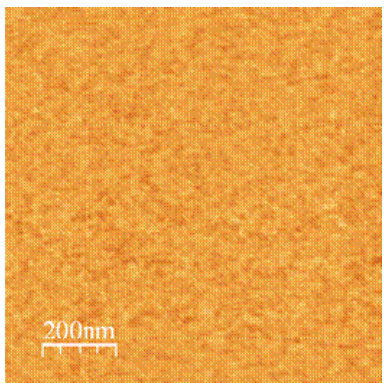
Xe^{24+}, E_{kin}= 4.5keV·q



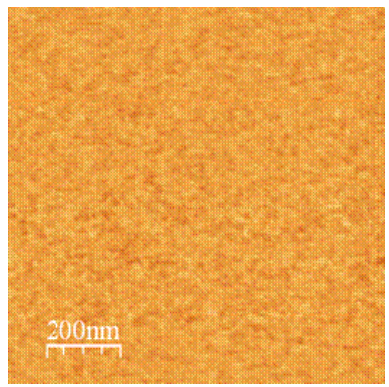


Xe^{33+}, E_{kin}= 4.5keV·q



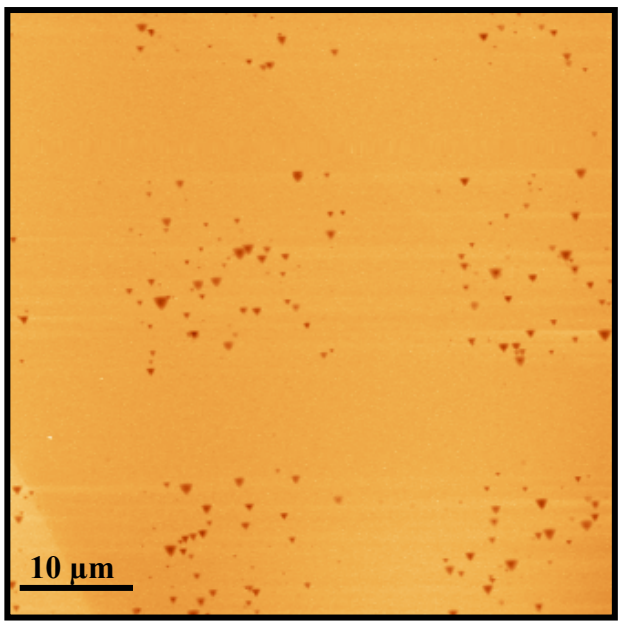


Xe^{36+}, E_{kin}= 4.5keV·q

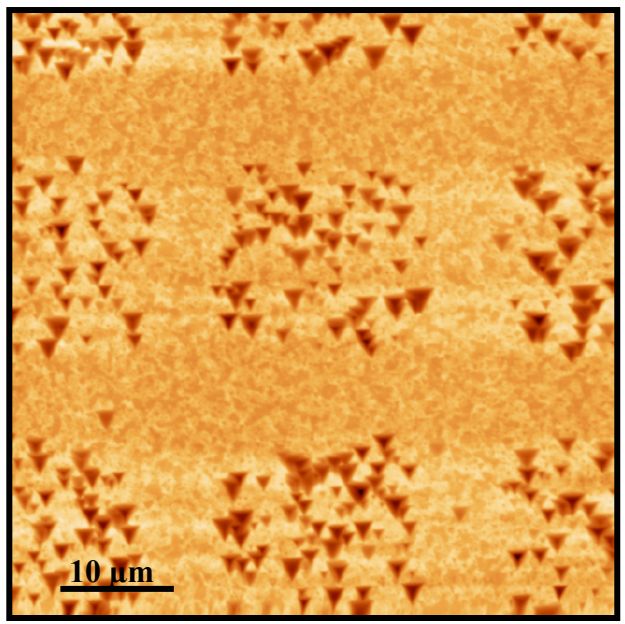


Etch Pits on BaF_2

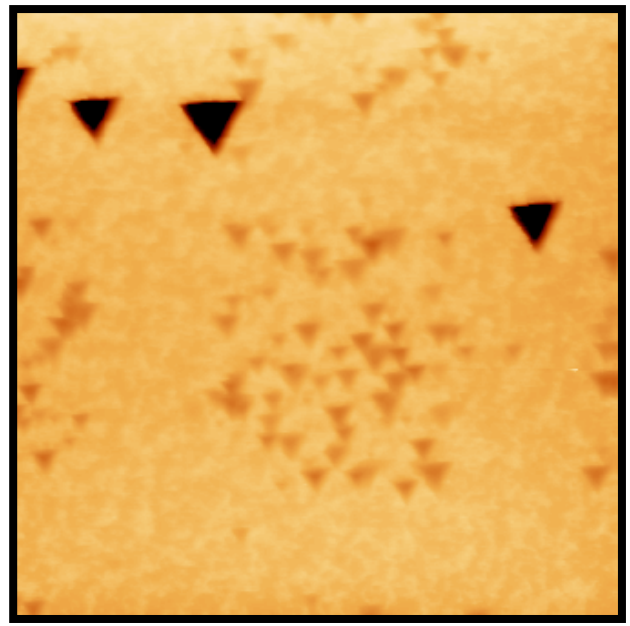
- **Same samples after etching for 5s with 1 vol.% solution of HNO_3**



Xe^{24+}, E_{kin}= 4.5keV·q

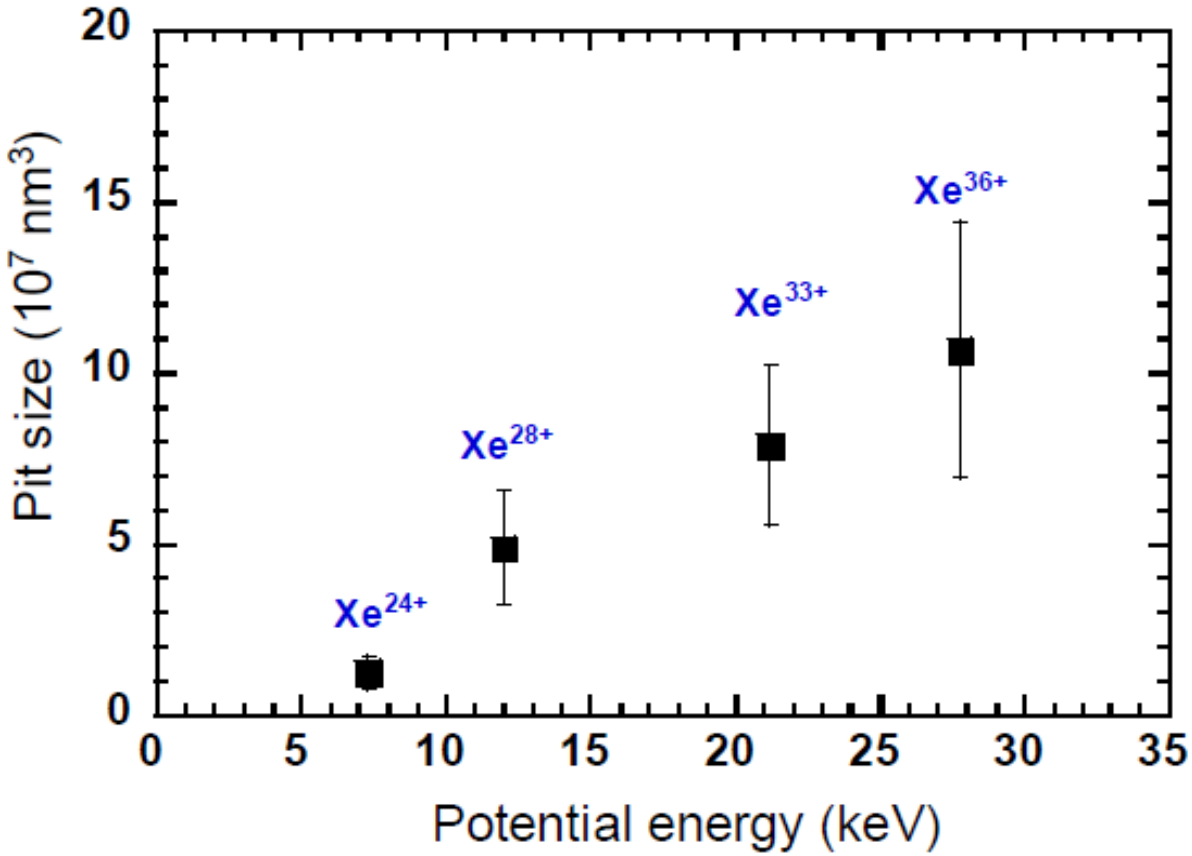


Xe^{33+}, E_{kin}= 4.5keV·q



Xe^{36+}, E_{kin}= 4.5keV·q

Potential energy create defects in the crystal!

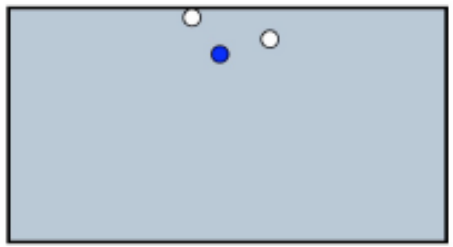


Planned experiments at HITRAP: Xe^{54+} and U^{92+} at 4 MeV/u and 500 keV/u

A. S. El-Said, R. Heller, S. Facsko and F. Aumayr, PRB (2010)

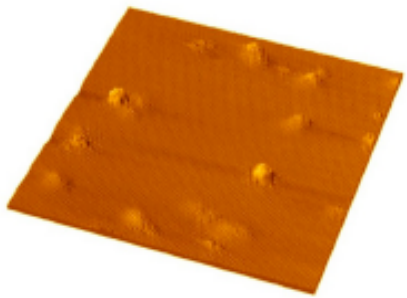
Scenario of surface modifications by HCI

low q

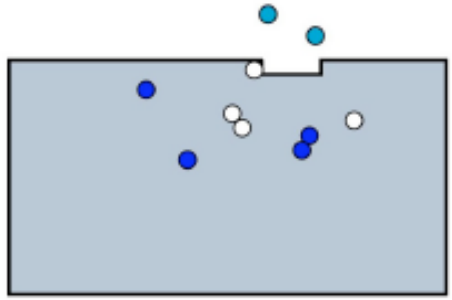


single defects

electronic defects
modified friction

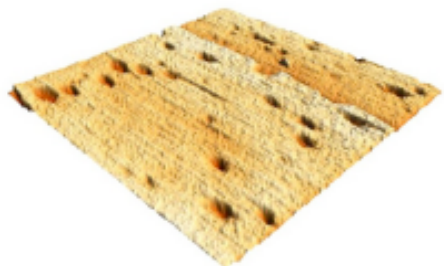


medium q

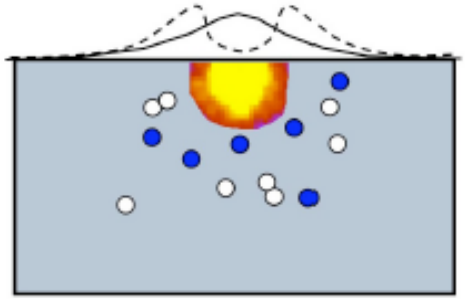


defect clusters

potential sputtering
pits, craters

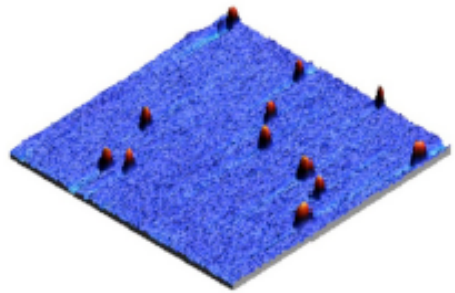


high q

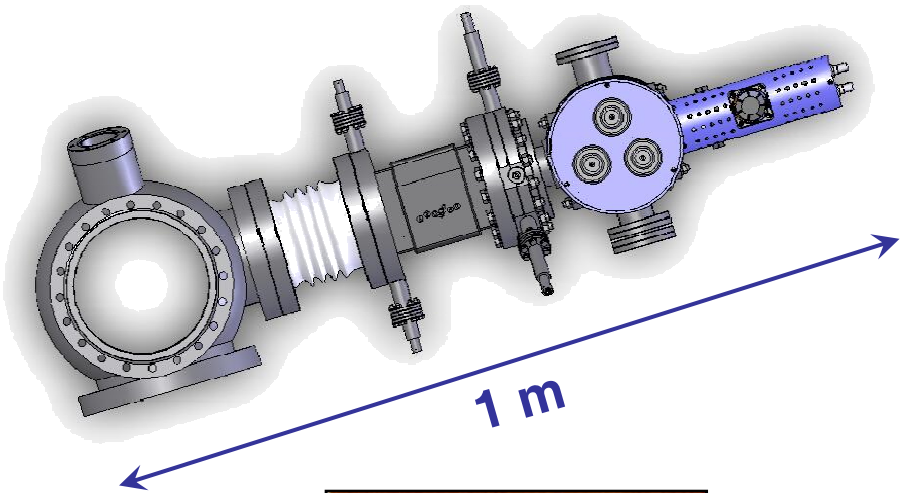


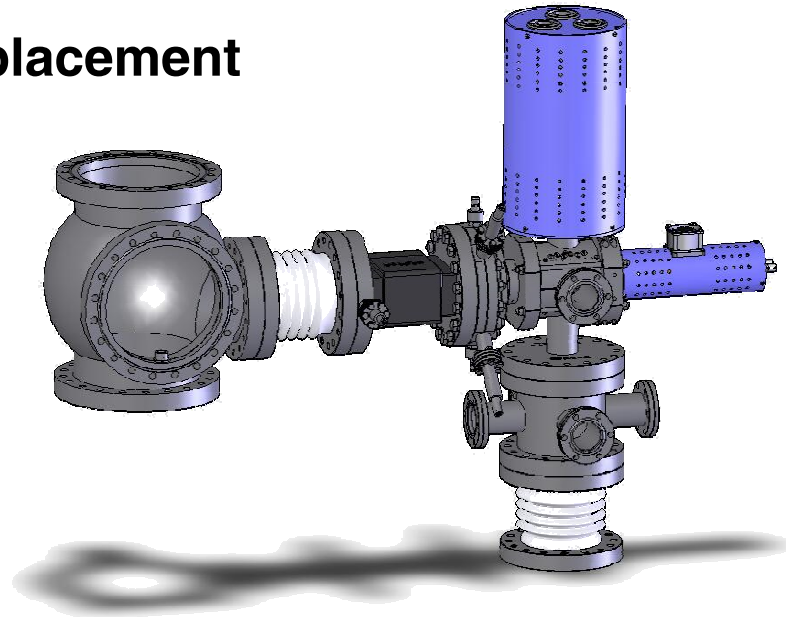
phase transitions

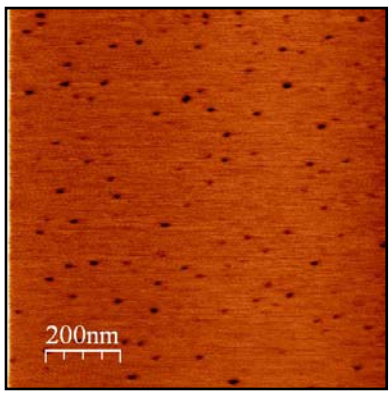
surface melting
hillocks, calderas

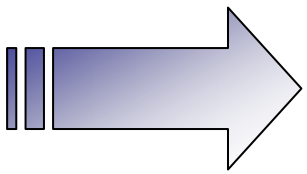


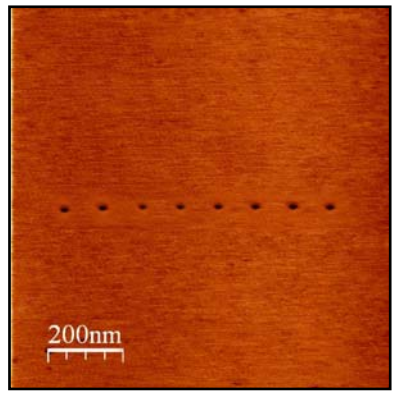
- The way to controlled single ion placement











Goal!

- HCIs can initiate the formation of individual nano structures of different types on various insulators
- Structure-formation depends on both the potential and (indirectly) on the kinetic energy of the ions
- Pit formation on KBr can be ascribed to a special kind of defect mediated desorption: X center formation
- The modified inelastic thermal spike model can successfully explain the hillock formation on CaF_2
- Further investigation on structure formation and electron emission are in progress

Thank you for your attention!