Effect of Cu surface blistering on vacuum breakdown

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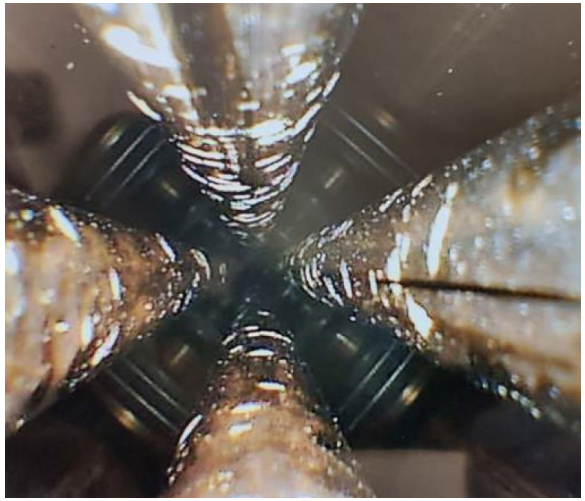
RFQ in a heart of LINAC

- Radio-Frequency-Quadrupole (RFQ) - belongs to the Linear accelerator which is the first stage of acceleration towards the LHC, at CERN.
  - Study alternative materials with a better performance to a future manufacturing of a new RFQ.
    - Need to understand the origin of enhanced breakdown and find a mitigation
    - Can blistering influence the lower performance?
    - Find materials more resistant to breakdown phenomenon



Inspection of RFQ interior vanes during the long shut-down, 2019

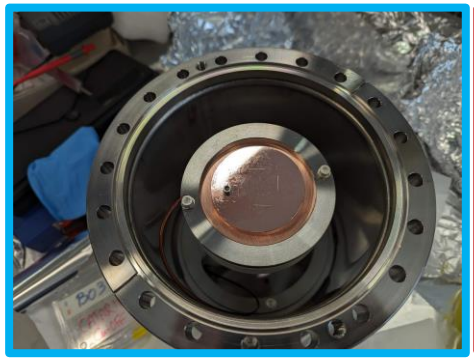
Surface damages from vacuum breakdowns and H implantation found inside RFQ's vanes

Materials for the study

- Materials were selected based on their:
  - Usability for meter-long high gradient RF structures
  - Potential resistance to blistering (trying to limit hydrogen blister formation)
  - Resistance to breakdown phenomena

Selected Materials	Source of manufacturing	Quantity
Cu-OFE	Purchase from external company	2 pairs of anode-cathode electrodes
TiAl6V4	Machined at CERN Workshop	
Nb	Machined at CERN Workshop	
CuCr1Zr	Machined at CERN Workshop	
CuBe2	Purchase from external company	
Ta	Machined at CERN Workshop	
SS316LN	Machined at CERN Workshop	

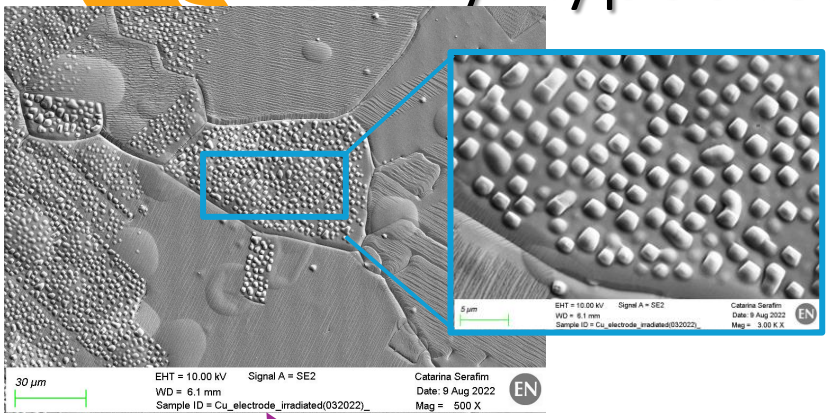
Testing
1 - Irradiation with H- beam
2 - High Voltage Pulsing testing



Before testing, electrodes have been through a preparation phase:

- Manufacturing/Machining
- Metrology and SEM finishing surface analyses
- Surface cleaning
- Thermal treatments

Study hypothesis



Testing
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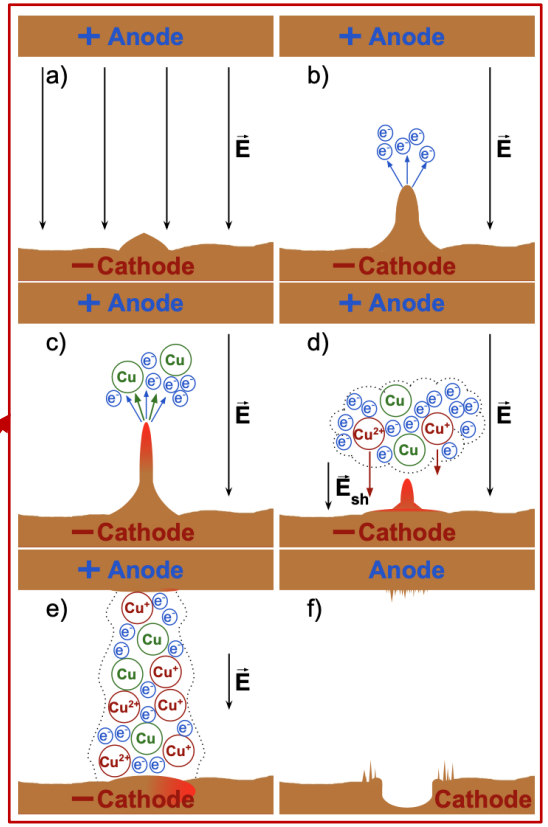
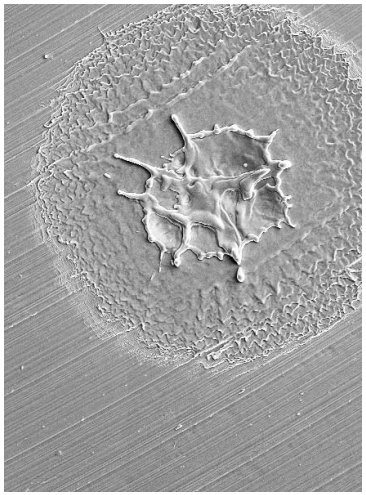
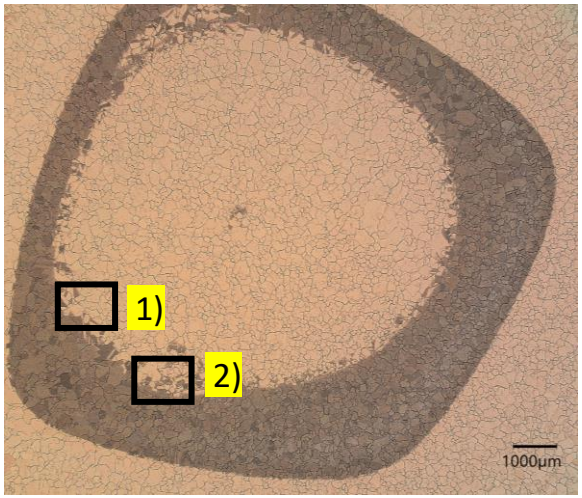


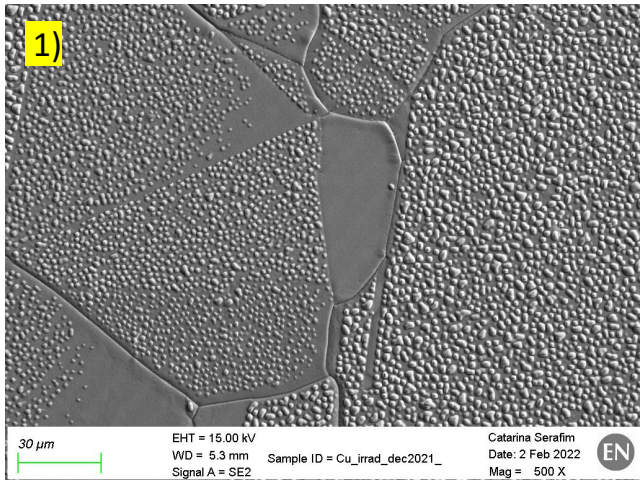


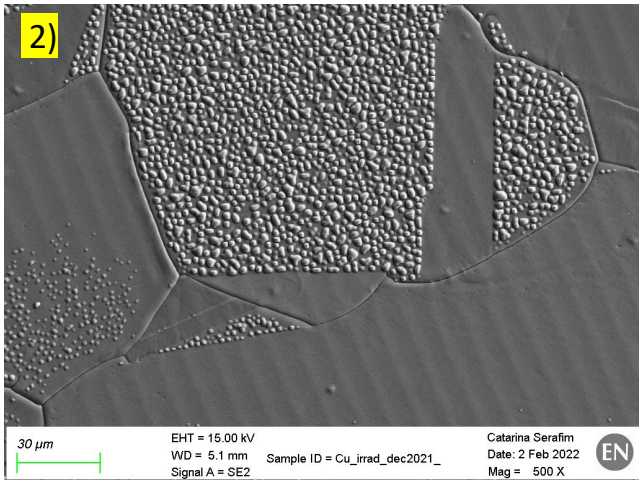
Vacuum Breakdown

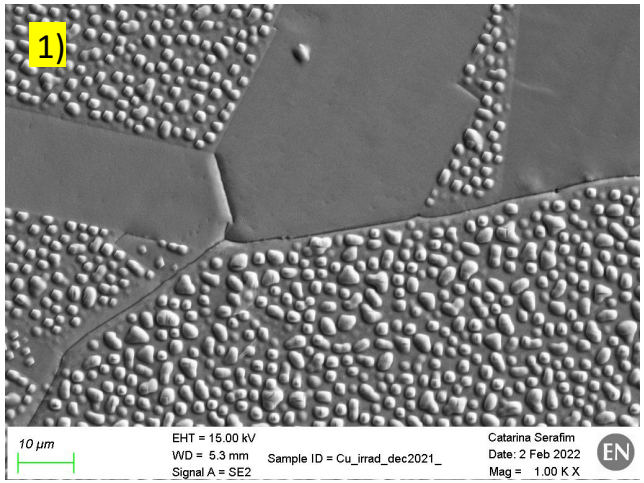
- When applying a high voltage potential, if the electric field on the surface is high enough, the emissions of neutrals, and their sequential ionization will form a conductive plasma within our gap and allow the flow of current.

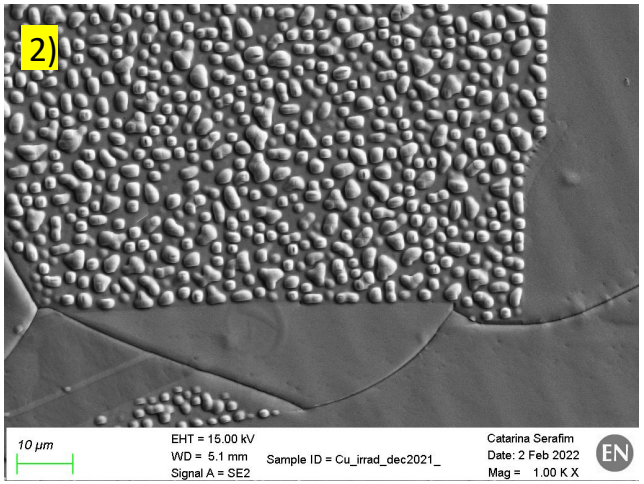
Irradiated Cu cathode





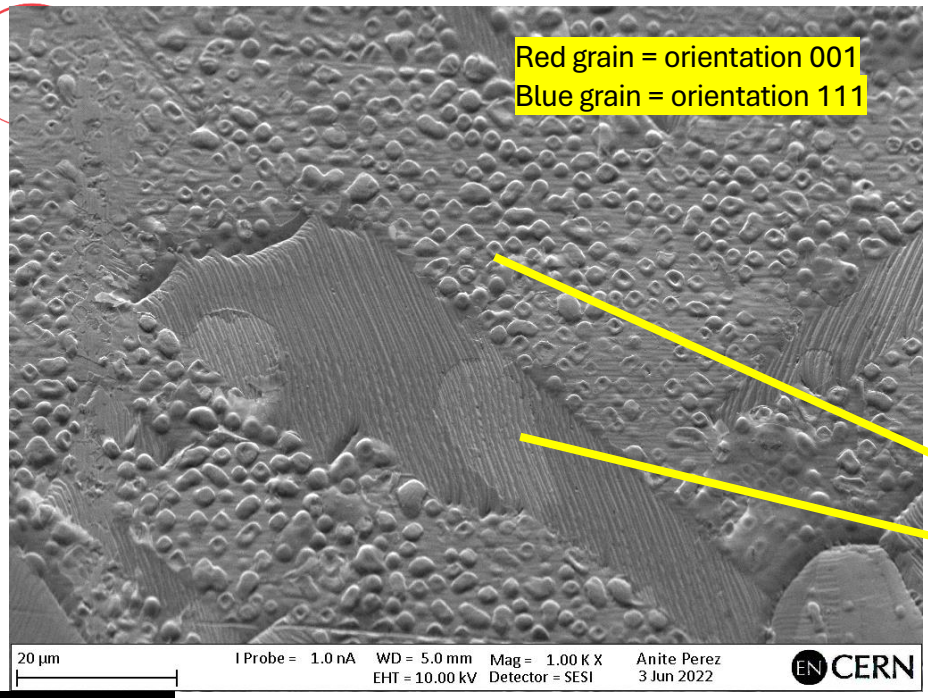


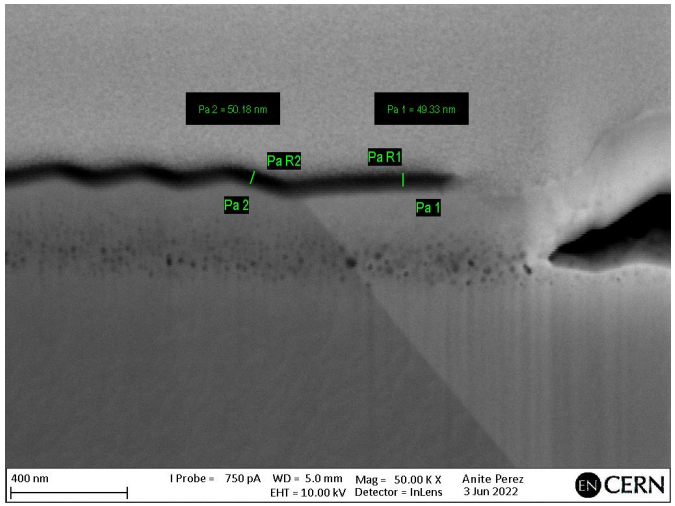


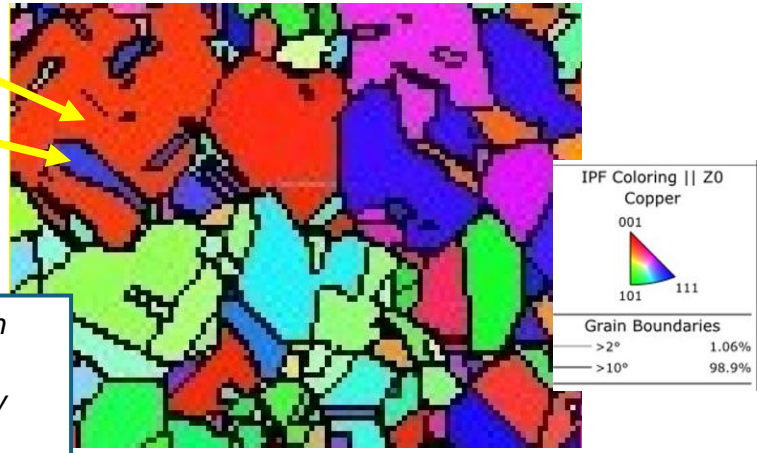


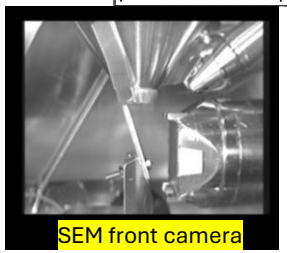
- SEM observations in different areas surrounding the irradiation zone

Analysis of grain orientation







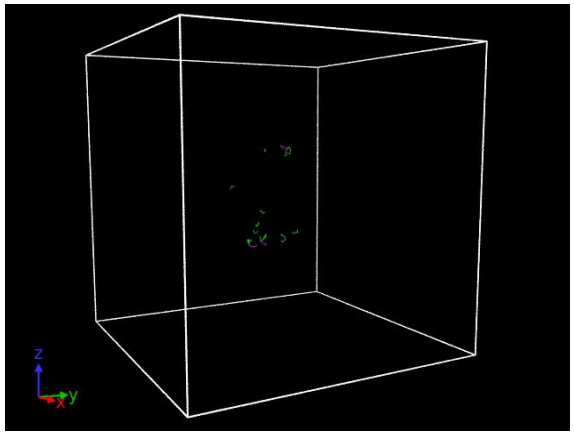


Lopez Cazalilla, A., Serafim, et.al. Effect of surface orientation on blistering of copper under high fluence keV hydrogen ion irradiation. Acta Materialia, 266(119699), Published 20th January 2024, DOI: 10.1016/j.actamat.2024.119699

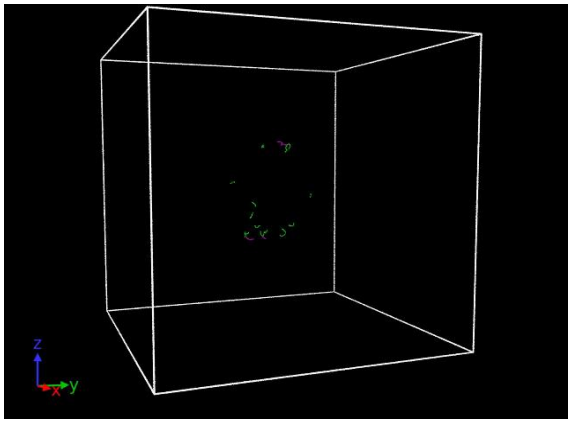
Bubble growth in Cu

- To model this effect, some computational approaches have been implemented before.
- The growth of tiny He bubble was followed in Cu, showing the dissociation of small prismatic loops [Jin et al., Sci. Rep. 11 (2021) 12839]
- We simulated a range of H concentrations (n_H/Vac = [0.5,5]) and followed the dislocation network around the bubble

$n_{H/Vac} = 4$



$n_{H/Vac} = 5$

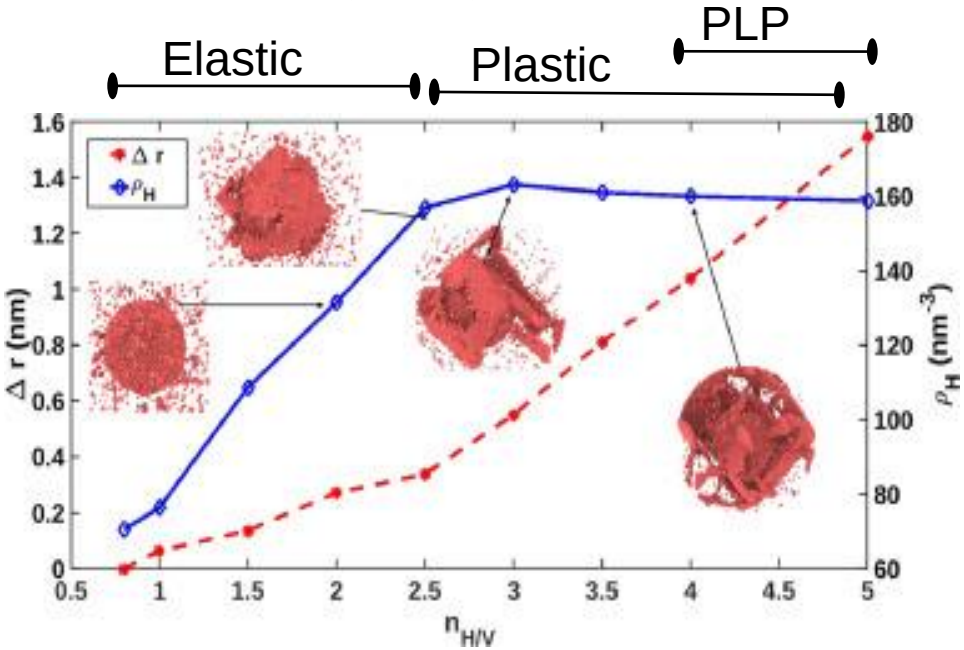


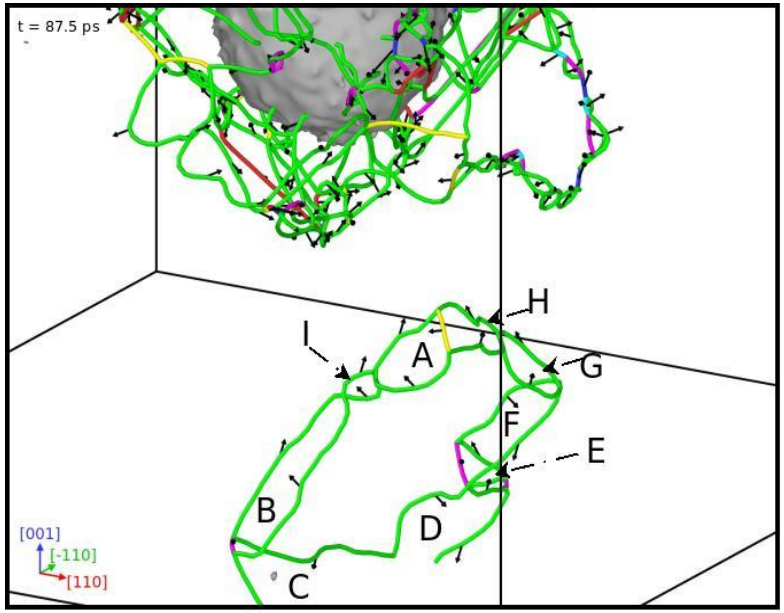
($n_{H/Vac}$: number of H per vacancy in the void)

Bubble growth in Cu

- We showed that even much larger bubbles grow via prismatic loop punching (PLP). In this case the network of shear loops is forming on adjacent {111} planes with the Burgers vector either aligned or opposite to the gliding direction of the prismatic loop

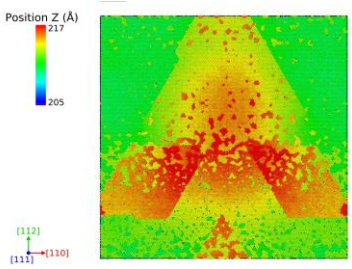
- [A. Lopez, F. Djurabekova et al. Acta Materialia 225 (2022) 117554]

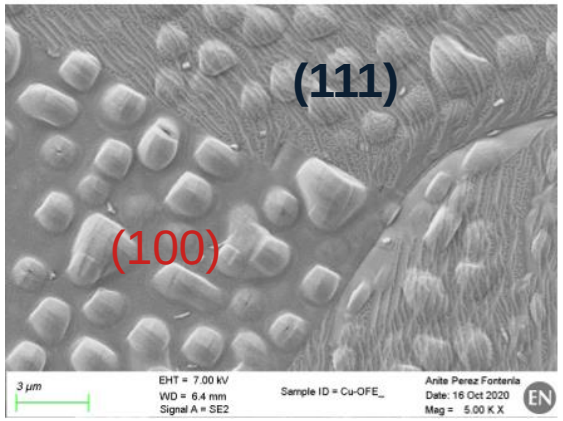


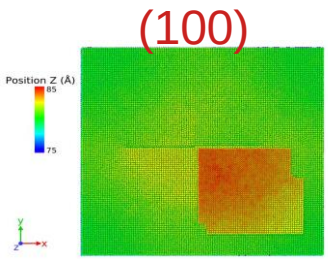


Dependence of blister shape on grain orientation

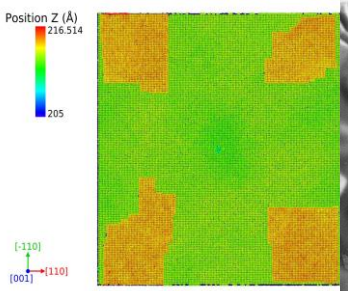
[A. Lopez-Cazalilla, C. Serafim, F. Djurabekova, Acta Materialia, 266, 119699 (2024)]

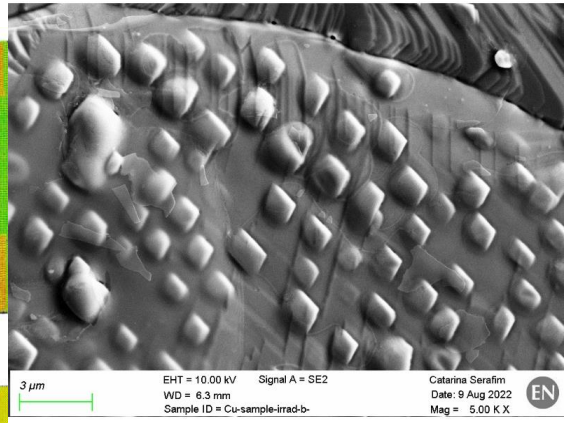


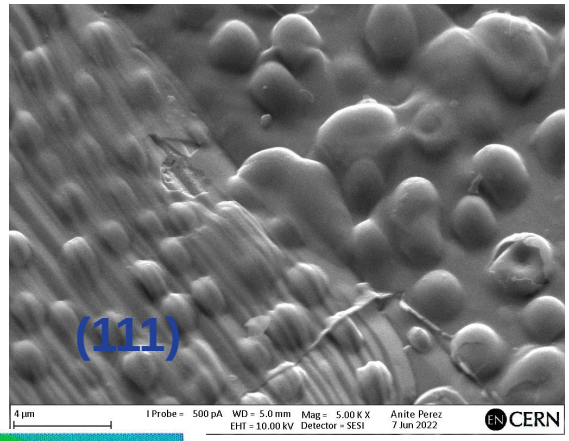




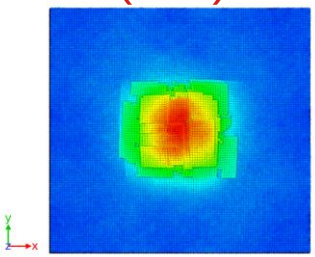
(110)

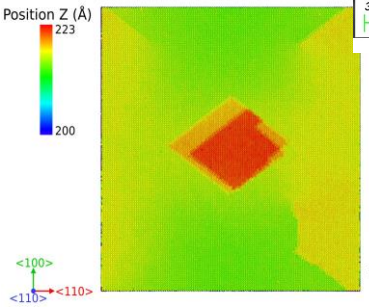






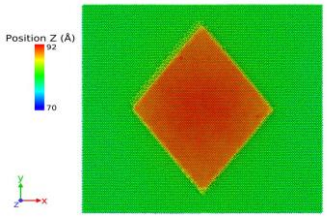
(100)



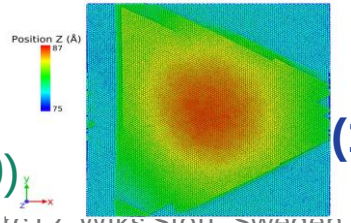


(110)

($n_{H/Vac=}$ 2)

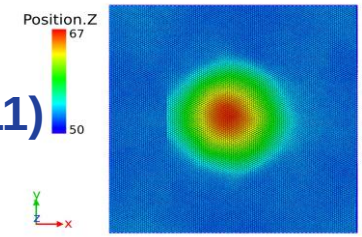


(110)

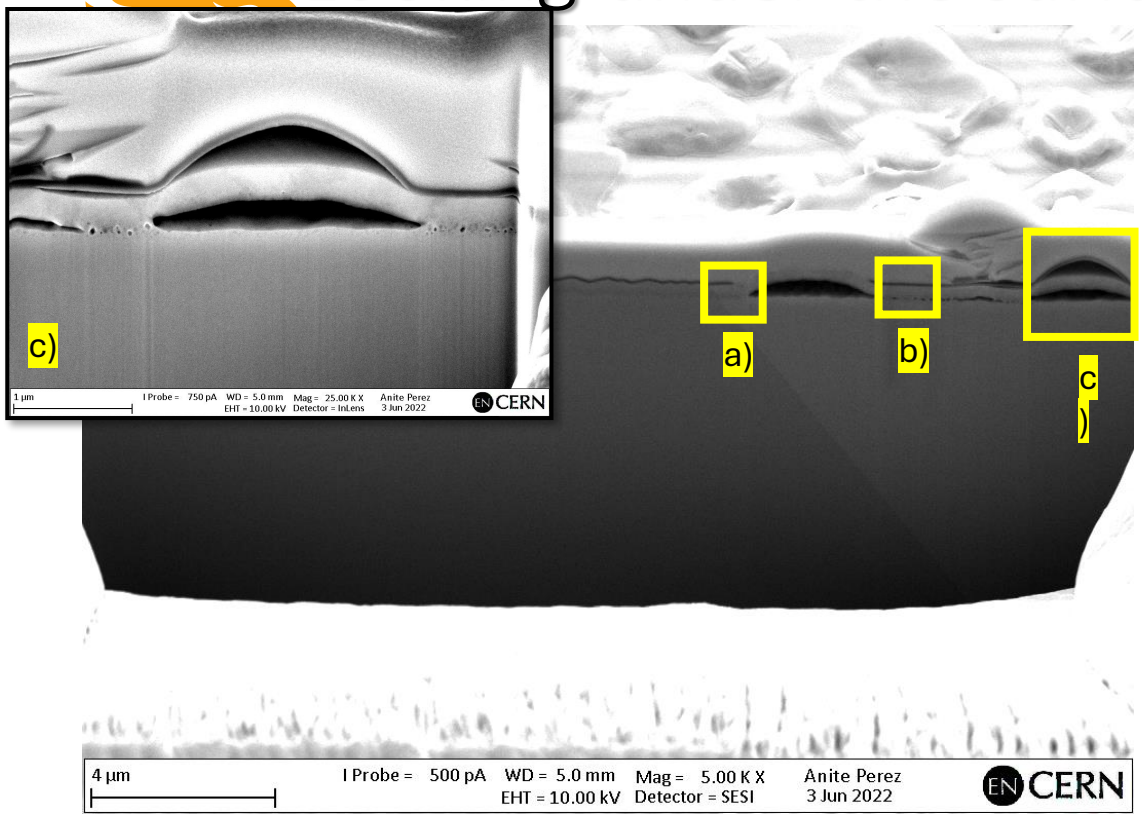


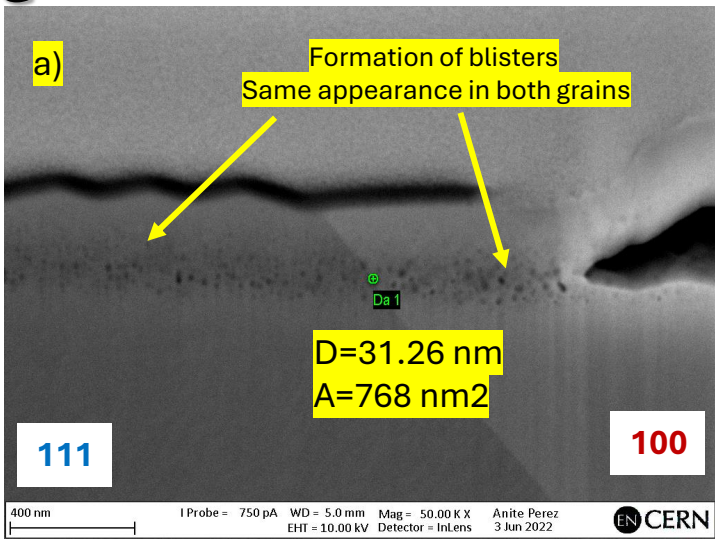
(111)

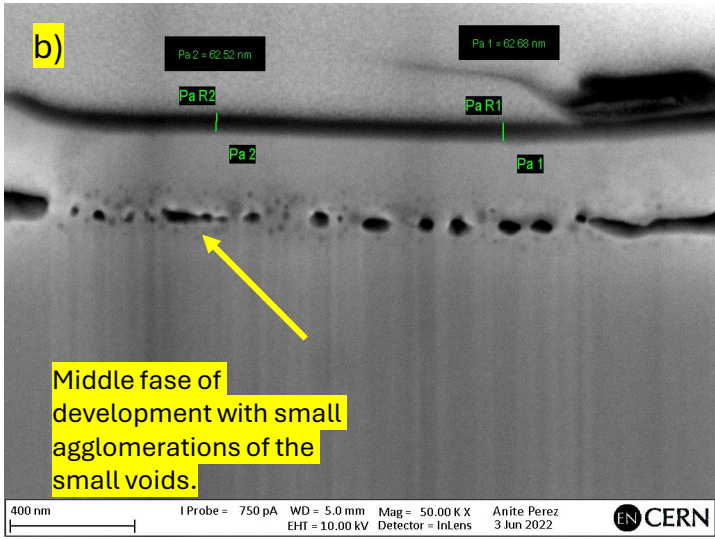
(111)



Looking under the surface



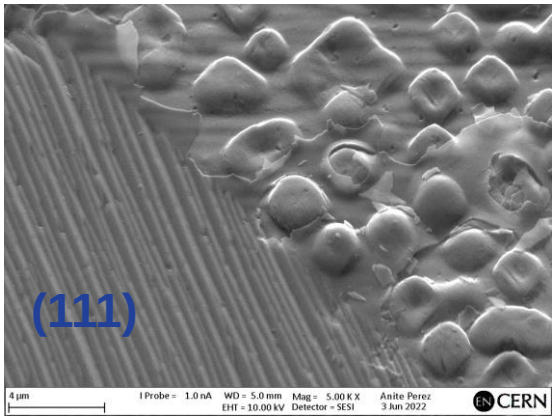




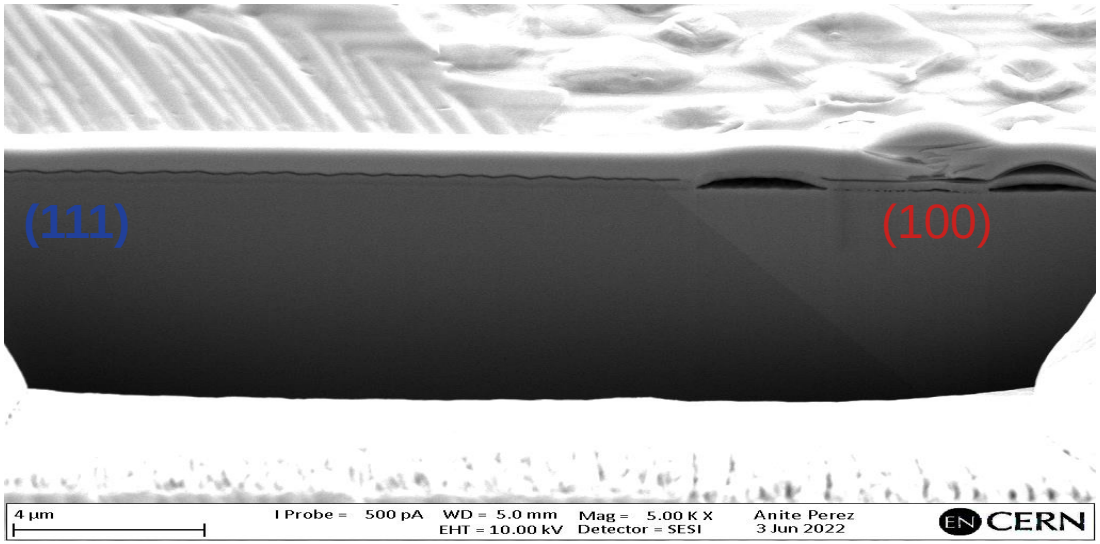
- The process of formation of blistering seems to occurs in the two different grains, at the depth between 260-280 nm.
- Slower development on the blue grain 111.

Uneven appearance of blisters on different grains

- The MD results do not provide information on why (110)/(111) are not the first surface yielding, being the glide direction/plane. We see (110) is the first yielding, contradicting the experiments.
- Since the initiation sites are formed at different depths depending on the grain orientation, we need to know how the penetration depths are for 45 keV H in Cu.
  - For this, we use MDRANGE*, while typically Monte Carlo methods are commonly applied.



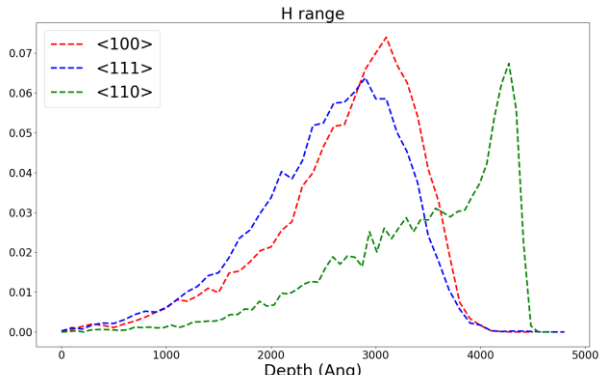
(100)



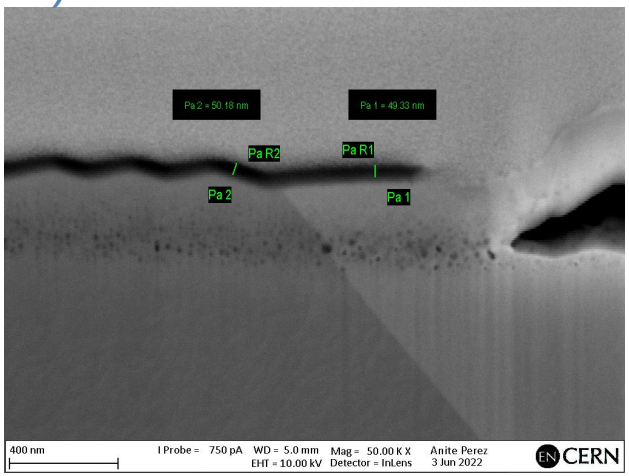
(*) K. Nordlund ,Computational Materials Science 3 (1995) 448-456

MDRANGE + BCA

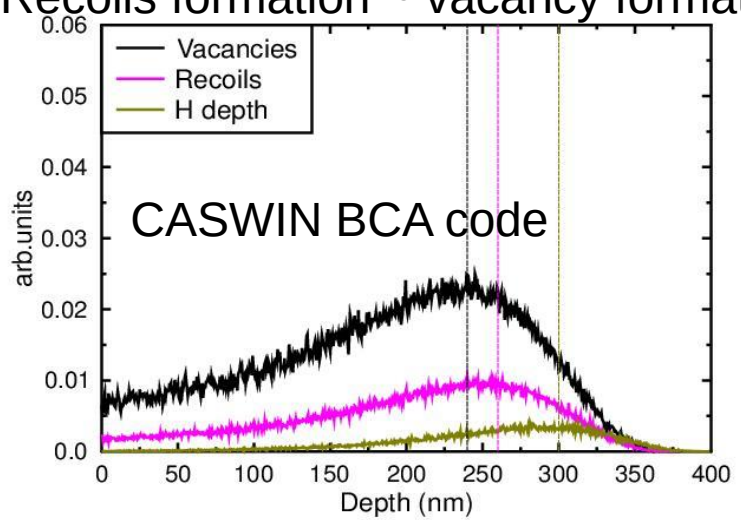
MDRANGE



(111) (100)



Recoils formation ~ vacancy formation



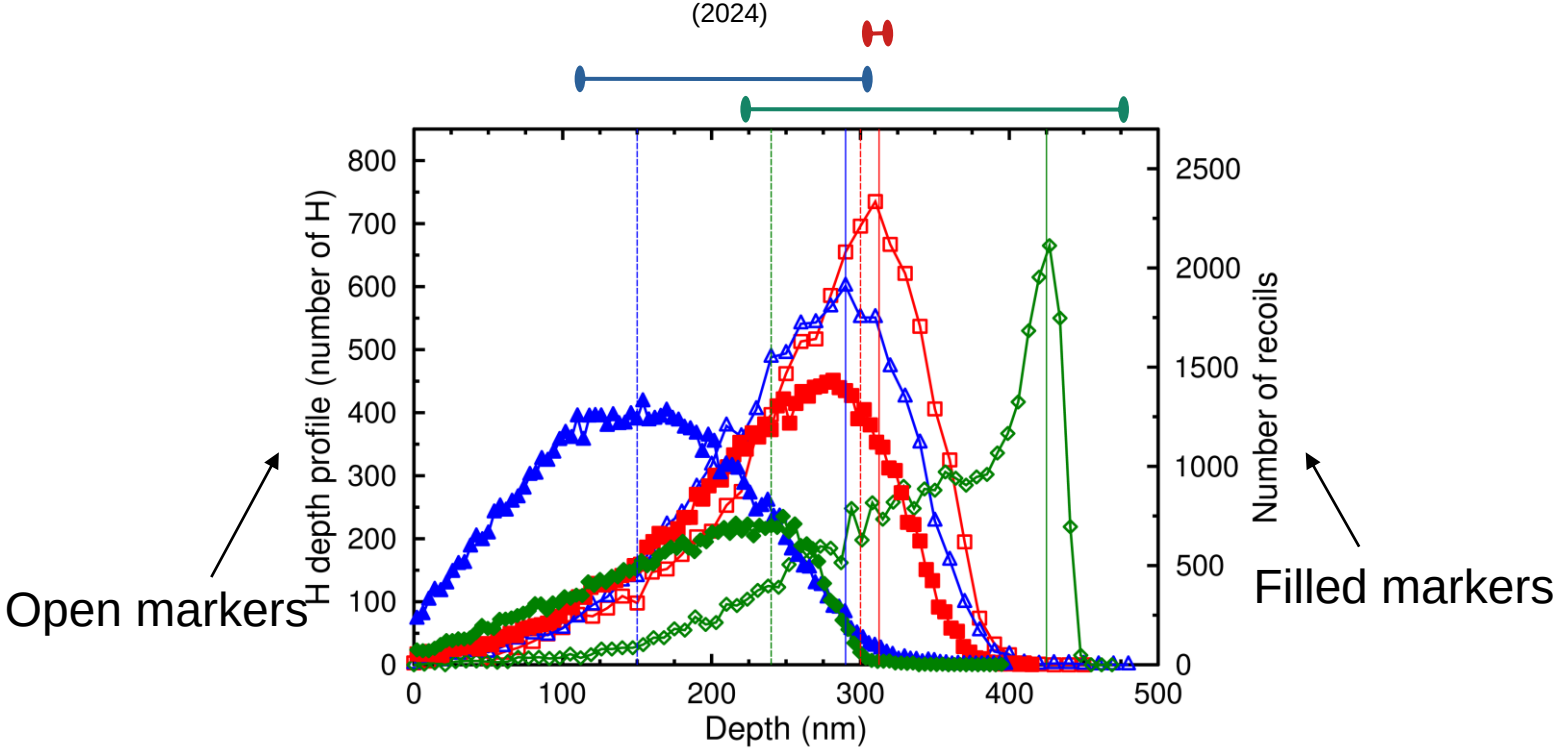
The studied grains under low fluence show that bubbles are formed at different distances, which is consistent with MDRANGE results, observing a deeper formation in (110) grains.

After a complete dataset of blisters/protrusions is obtained with MD, we understand the mechanisms of surface modification. However, we observe that under low fluences, only (100) grains experience blistering and not (111), with a similar H profile

Comparison with experiments

- We filter those recoils with kinetic energy lower than 40 eV (approximately the energy needed to create a vacancy), and we observe that for <100> the peaks are close, however the distances between them in <111> and <110> (specially the latter)

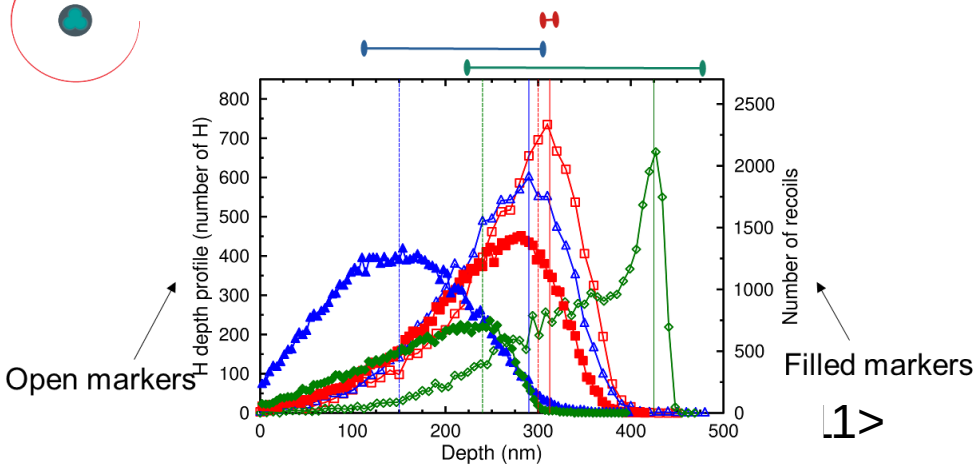
A. Lopez-Cazalilla, C. Serafim, F. Djurabekova, Acta Materialia, 266, 119699 (2024)

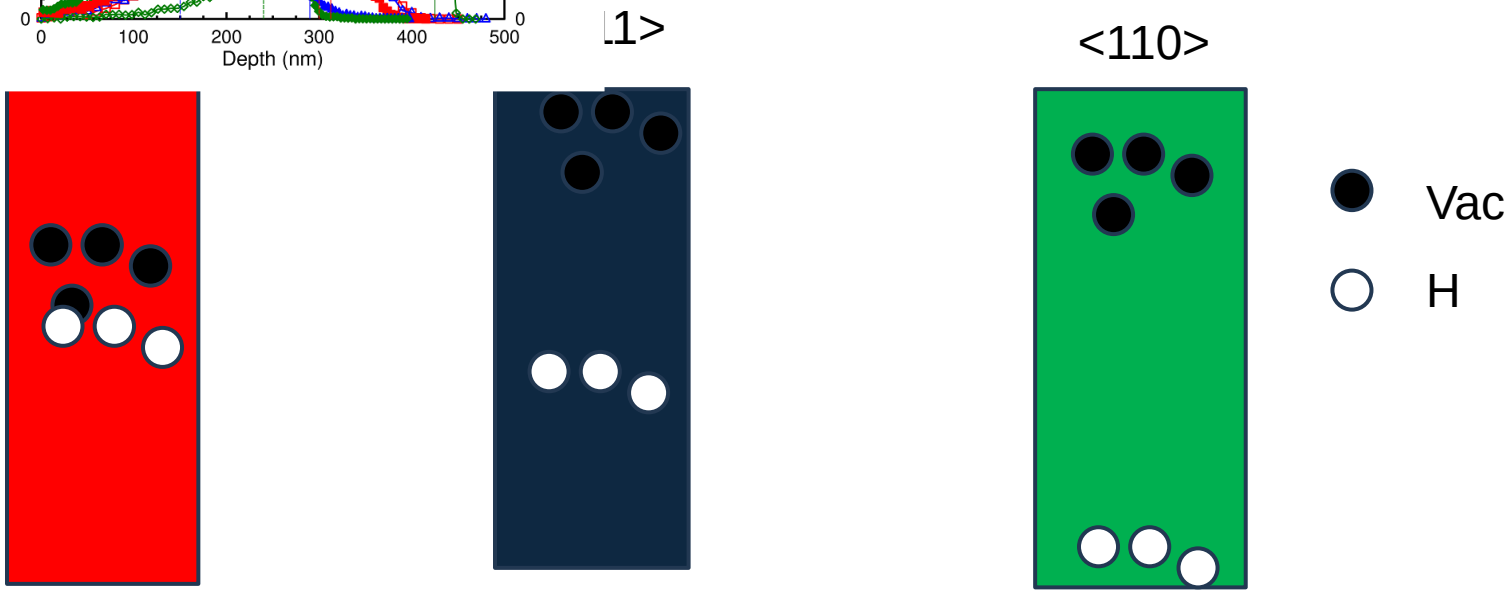


Difference in range profiles of H ions and vacancies explains the different blister growth rate!

[A. Lopez-Cazalilla, C. Serafim, F. Djurabekova, Acta Materialia, 266, 119699 (2024)]

- The formation of vacancies occurs closer to the surface in <111> and <110>grains, but the hydrogen atoms need more time (fluence) to fill these gaps and develop larger blisters visible in the surface, while in <100> is immediate



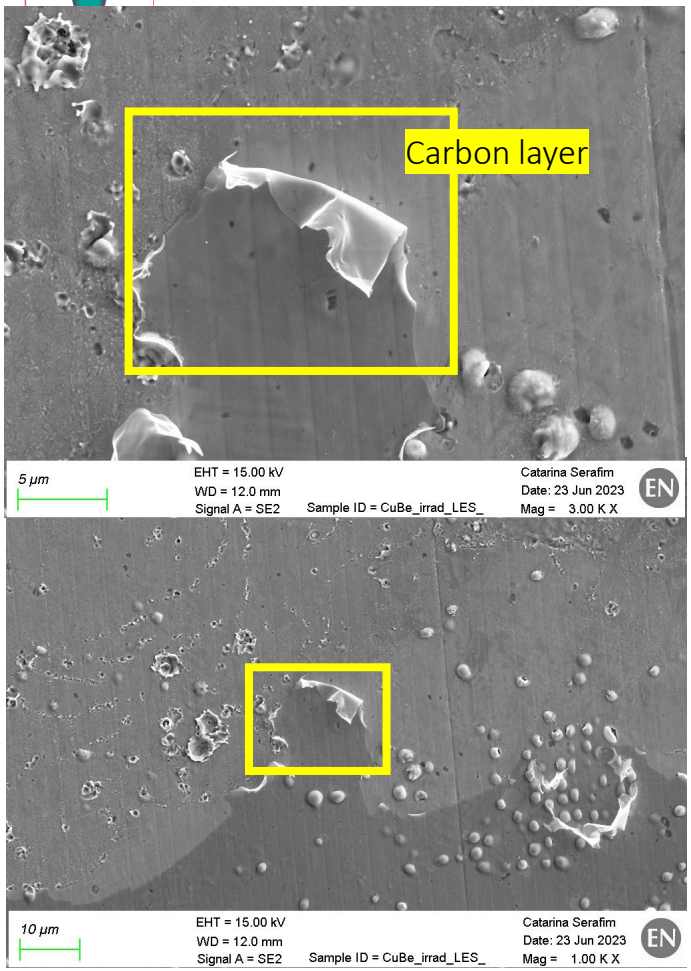


LES tests for all materials

	Non-irradiated		Irradiated	
	Max Field (MV/m)	Stable Field (MV/m)	Max Field (MV/m)	Stable Field (MV/m)
SS316LN	120	120	62.5	60
CuBe2	110	100	40	16.7
TiAl6V4	110	100	95	90
CuCr1Zr	87.5	82.5	29	25
Cu-OFE	80	80	25	20
Nb (BCP)	94	80	42	21.7
Ta	60	60	38.1	24

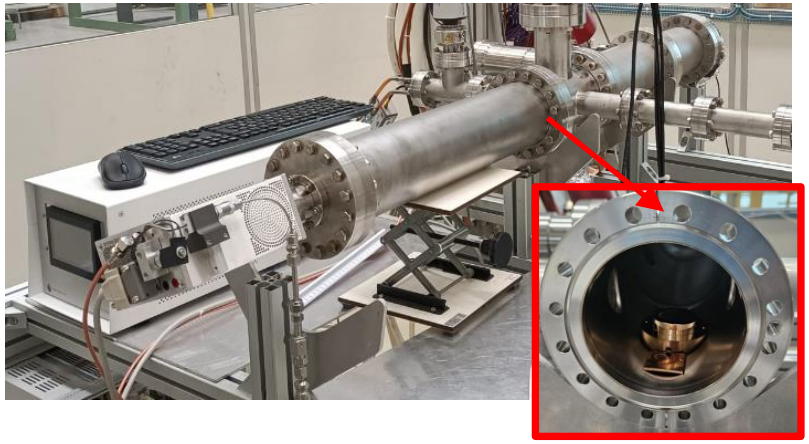
- TiAl6V4, CuBe2 and SS316 were the best materials in reaching a stable field. Followed by Cu-OFE and CuCr1Zr.
- We see very big differences in the electric fields reached between irradiated pairs and non irradiated pairs.
- The blistering effect from irradiation doesn't seem to provoke a decrease of performance on the electrodes.

Effect of carbon contamination

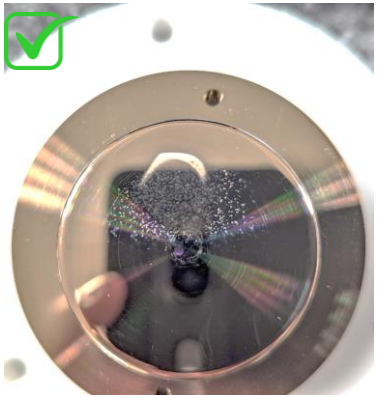


Plasma cleaning treatment
+
Repeat LES testing

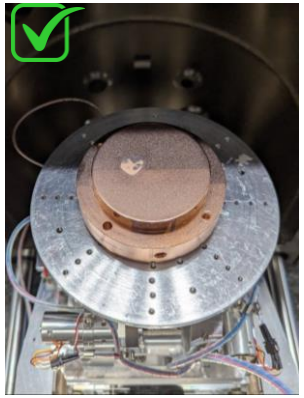
viewport



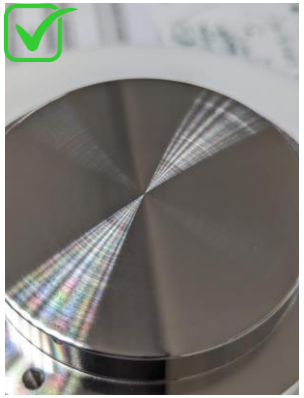
Plasma treatment of the electrodes



CuBe2



Cu-OFE

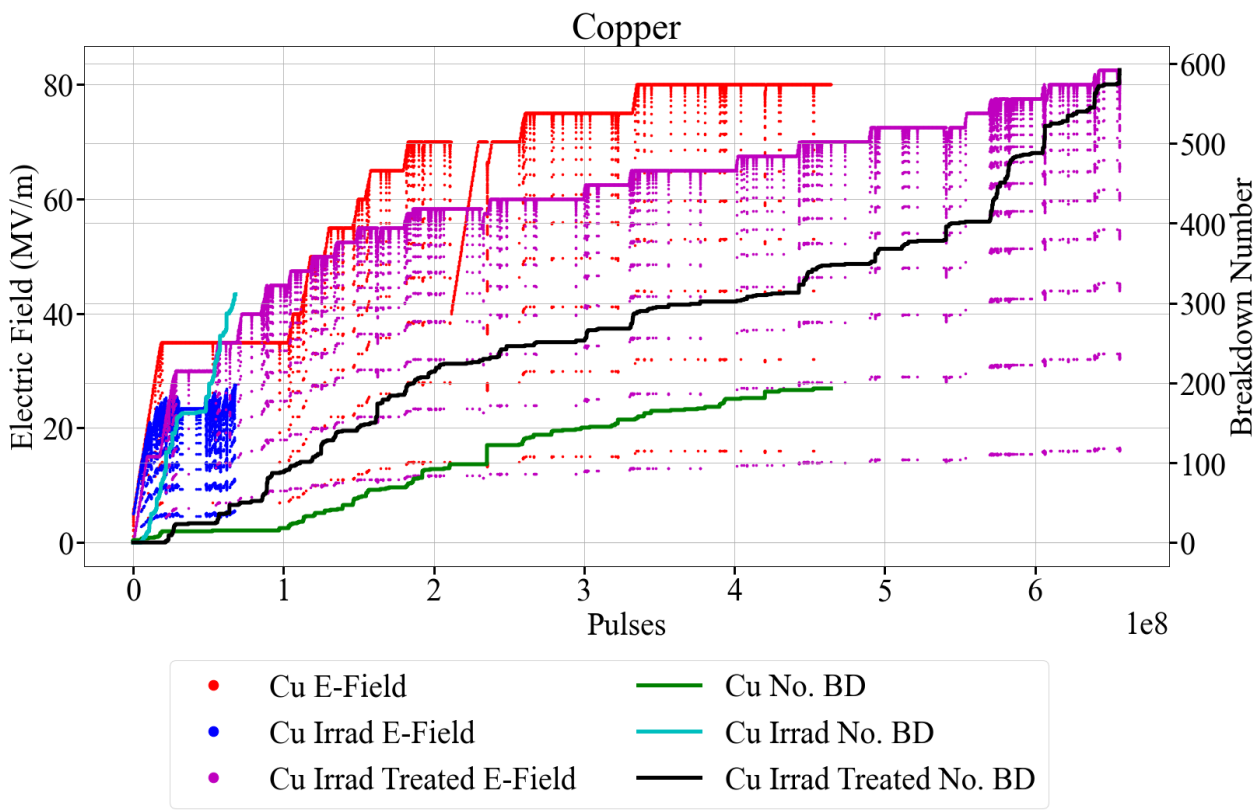


SS316

- Chemical analysis was performed in different areas before and after plasma cleaning.
  - Before plasma treatment we had 9-12% of C
  - After plasma cleaning we have 1-3% of C
- Hence, plasma treatment was a success for carbon removal from the surface.
- New electrodes (Cu-OFE and Stainless Steel)
  - manufactured -> irradiated -> plasma cleaned -> subjected to new high voltage pulsing tests.

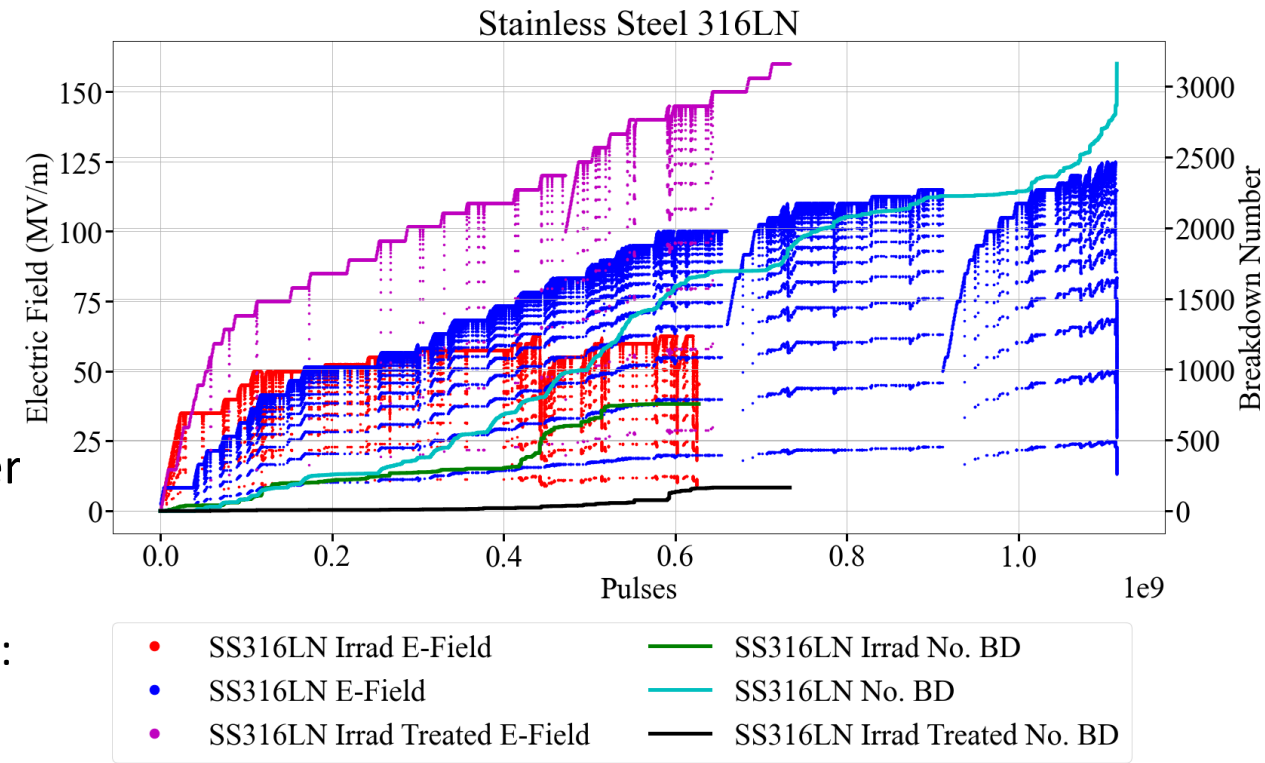
Conditioning results with and without plasma treatment

- Cu-OFE electrodes after irradiation
  - Electric field achieved: 25 MV/m
- Cu-OFE electrodes after irradiation + plasma cleaned
  - Electric field achieved 82.5 MV/m

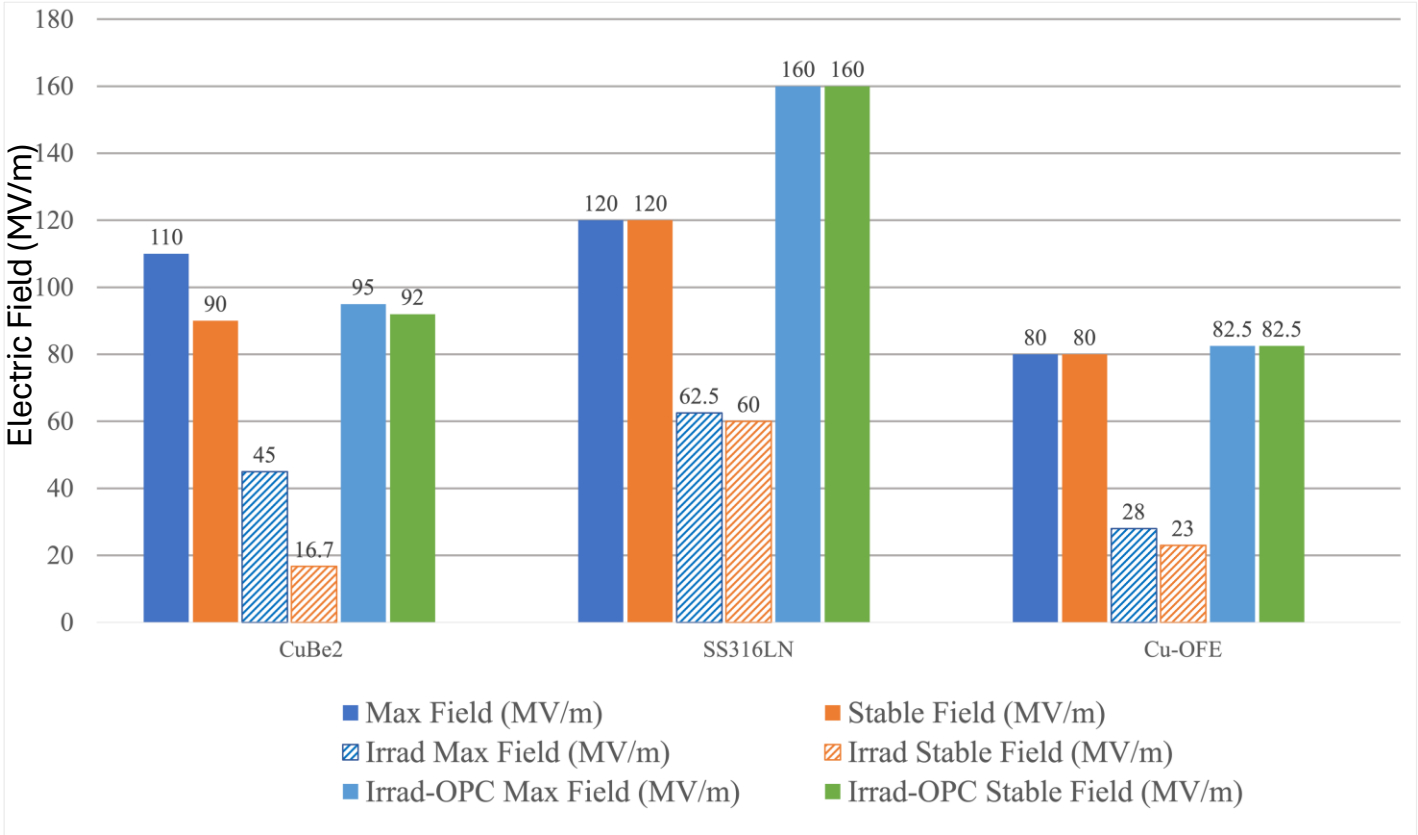


Conditioning results with and without plasma treatment

- SS316LN electrodes after irradiation
  - Electric field achieved: **60 MV/m**
- SS316LN electrodes after irradiation + plasma cleaned
  - Electric field achieved: **160 MV/m**



Conditioning results – after irradiation and oxygen plasma treatment



Conclusions

- We identify the effect of surface orientation on the shape of appearing protrusions using MD, in agreement with experiments.
- The difference between the vacancies range and the penetration depth of H in (110) and (111) grains explains the later development of blisters, complementing the previous models.
- The blisters do not induce breakdowns
- However, carbon contamination during irradiation plays a certain role in increased breakdown rate

Thank you for you attention!