

MeVArc

10th International Workshop on the Mechanisms of Vacuum Arcs

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Working on materials studies for the WP10 – RFQ3 Design

MeVArc 2022

19th – 23rd of September, 2022
Chania, Greece

Motivation of the project:

➤ Finding a new material with a better performance to a future manufacturing of a new RFQ.



Decision of using irradiation set-up and high field pulsing testing to study different materials

- At CERN a replacement RFQ is being manufactured
- Need to understand origin of enhanced breakdown rate, and find a mitigation
- Can breakdowns be correlated with beam losses ?
- Can blistering influence the lower performance?

Trying to limit
hydrogen
blister
formation

Criteria for material choice I:

- Breakdown resistance
- Usability for meter-long high gradient RF cavities

Criteria for material choice II:

- Material strength larger than copper
- Reduced dislocation movement
- Presence of trapping centers for hydrogen to prevent coalescence

Criteria for material choice III:

- Hydrogen solution must be energetically favorable
- Hydrogen must have high diffusivity at room temperature
- Hydrogen solubility limit must be high

Selected material candidates:

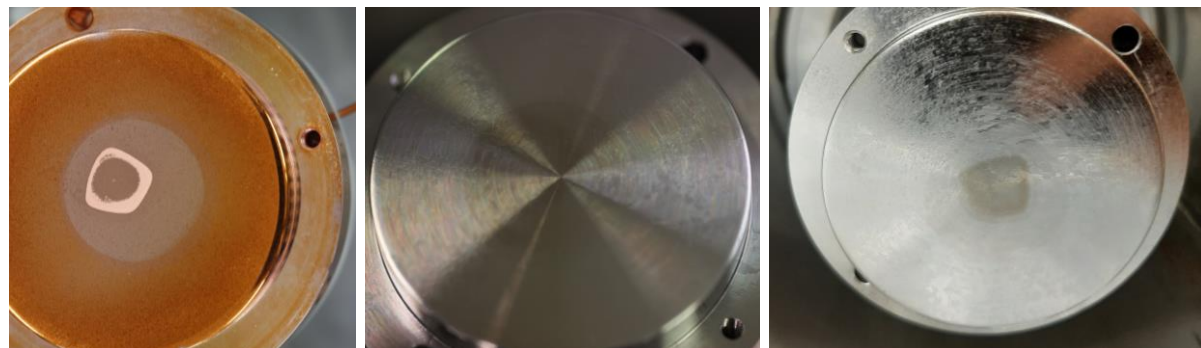
- Cu-OFE (reference)
- CuCr1Zr
- CuBe2
- Nb,
- β -Ti-6Al-4V
- Ta

Selection of materials

Cu OFE

TiAl6V4

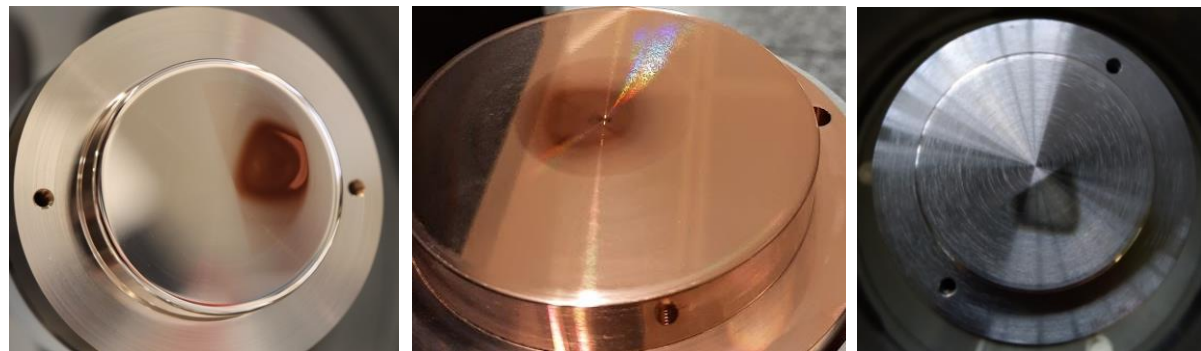
Nb



CuBe2

CuCrZr

Ta



Pictures of each electrode from each material. The pictures were taken after irradiation testing.

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	
CuCrZr	Machined at CERN Workshop	
CuBe2	Purchase from external company	
Ta	Machined at CERN Workshop	

Selection of materials

In general, materials were selected based on their:

- Usability for meter-long high gradient RF cavities
- Potential resistance to blistering
- Resistance to breakdown phenomena

Testing

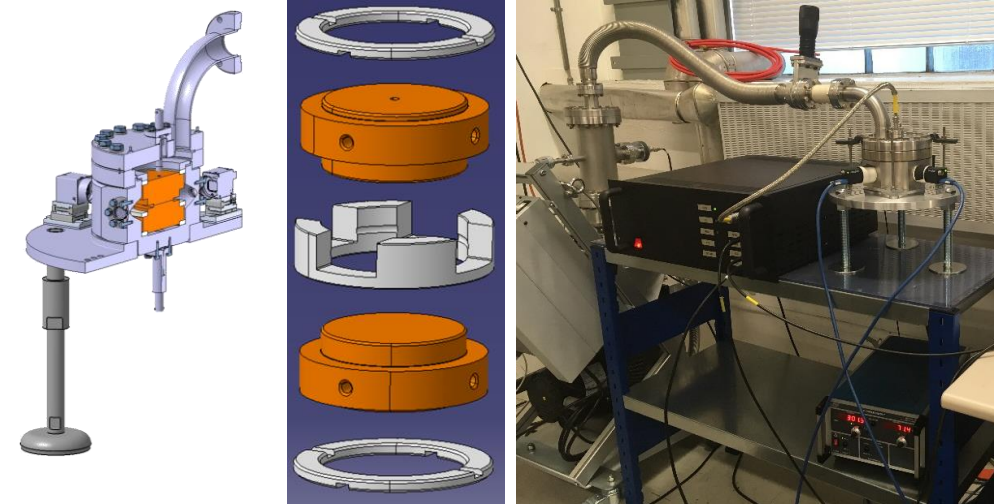
1 - Irradiation with H- beam

LINAC4 source test stand with 45 keV beam

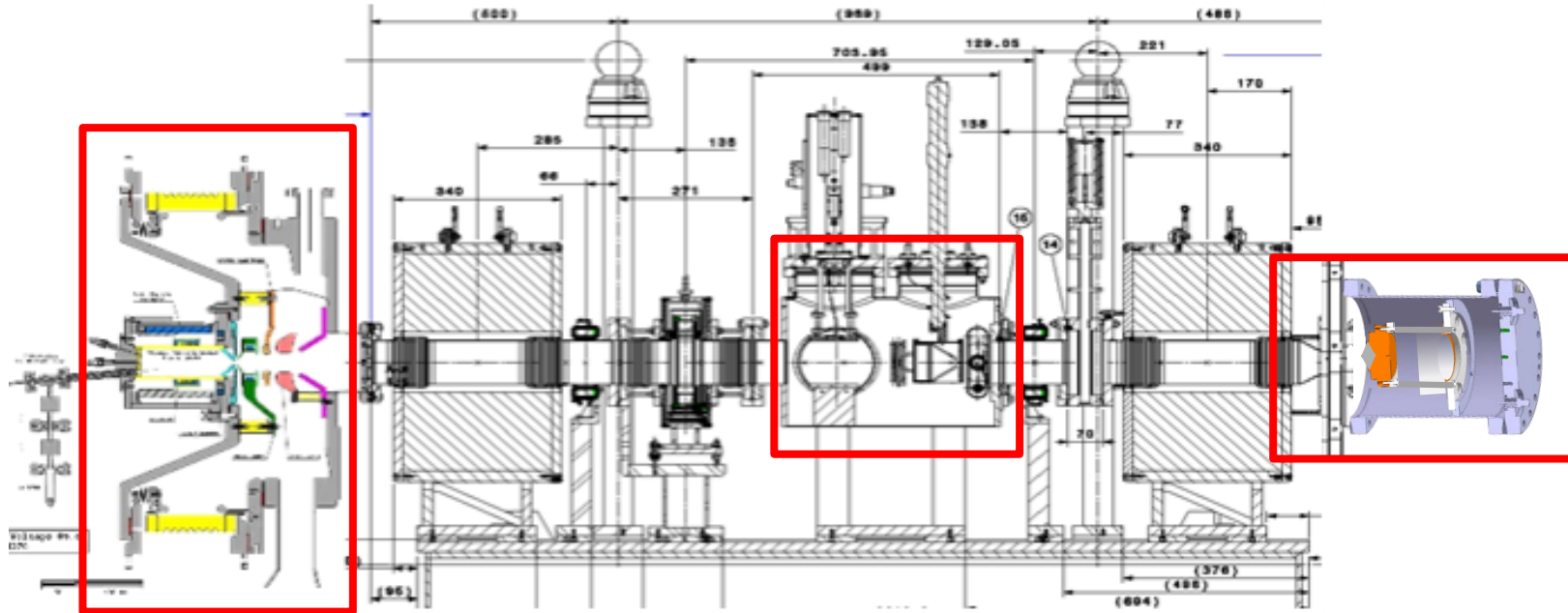
2 - High Voltage Pulsing testing with LES system

Before testing, electrodes have been through a preparation phase:

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



Irradiation setup – LINAC4 source test stand – Irradiation effects study

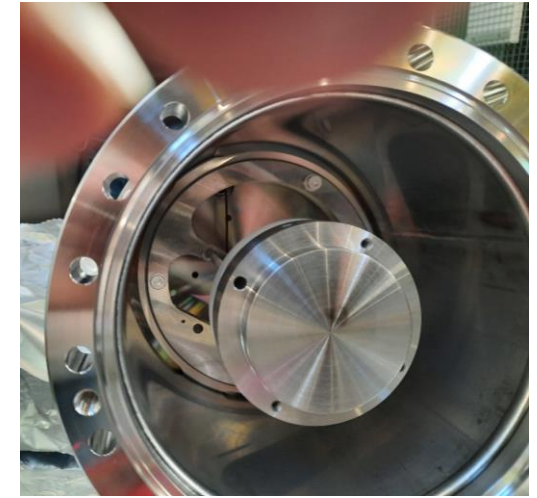


H⁻ Source 45 keV

Low-energy beam transport

Sample holder

2 Steerers, 2 Solenoids

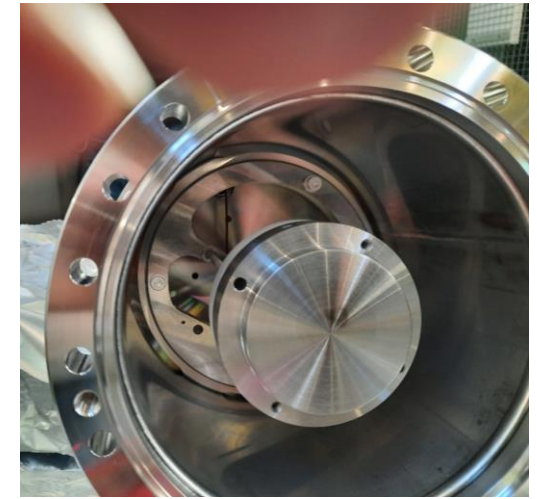
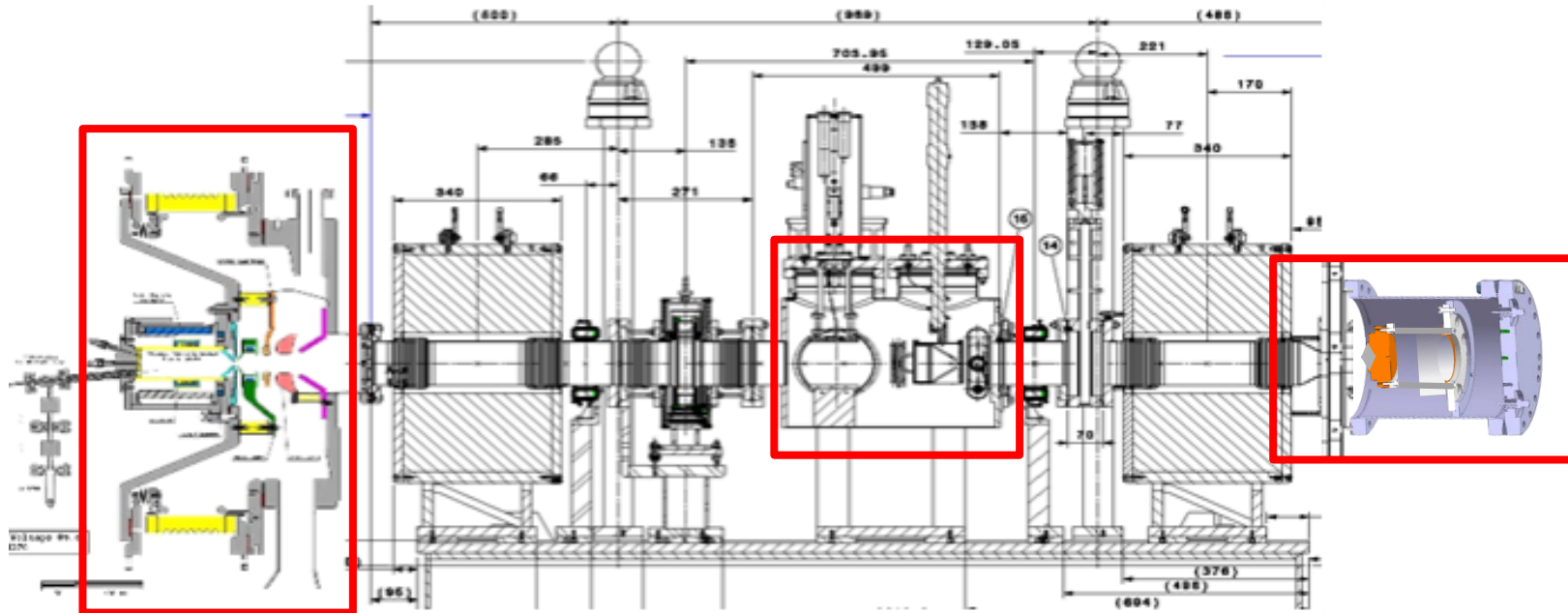


In this test stand, specific hardware was developed to use a cathode as the target for irradiation.

Allows for a rapid turn-over for various irradiation runs.

Schematic from Alessandra Lombardi

Irradiation setup – LINAC4 source test stand – Irradiation effects study



H⁻ Source 45 keV

Low-energy beam transport

2 Steerers, 2 Solenoids

Sample holder

Low Energy H- beam	45 keV
Duration	~50 hours
Pulse duration	600 μs
Repetition Rate	0.83 Hz
Peak current	20 mA
Deposition of particles on the target (*)	1.2×10^{19} H ⁻ p/cm ²

Schematic from Alessandra Lombardi

(*)Corresponds to about 10 days of beam losses during RFQ operation

Procedure for testing

1

Irradiation of materials on the LINAC 4 test stand

2

LES testing for each material.
Each time with:

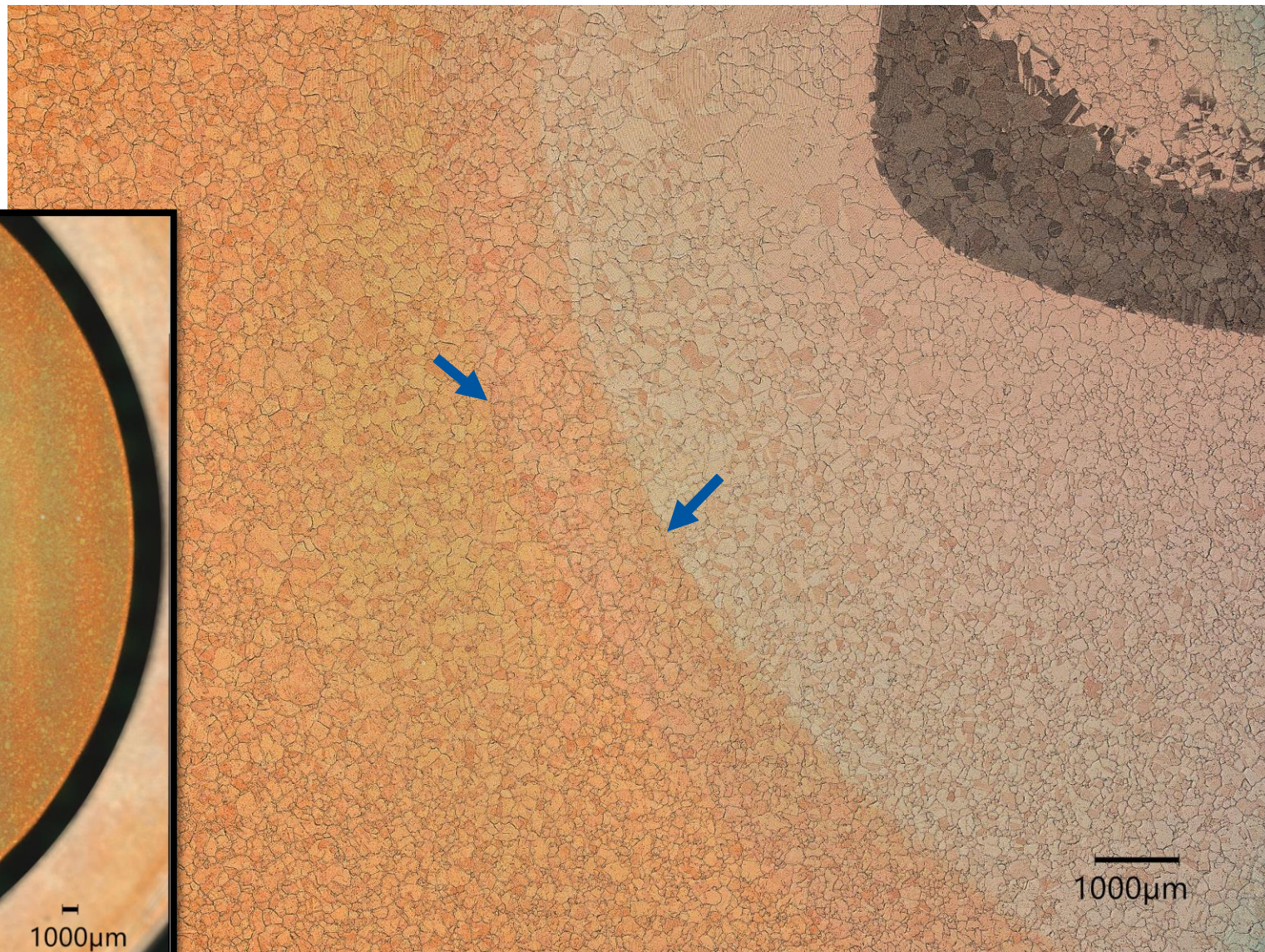
- 1 pair of irradiated electrodes
- 1 pair of non-irradiated electrodes

Will allows us:

to have a better understanding if any blistering phenomena caused by the beam irradiation could have a consequent effect in triggering breakdowns

Next slides will show some optical microscopic and SEM imaging from the different electrodes after the different tests

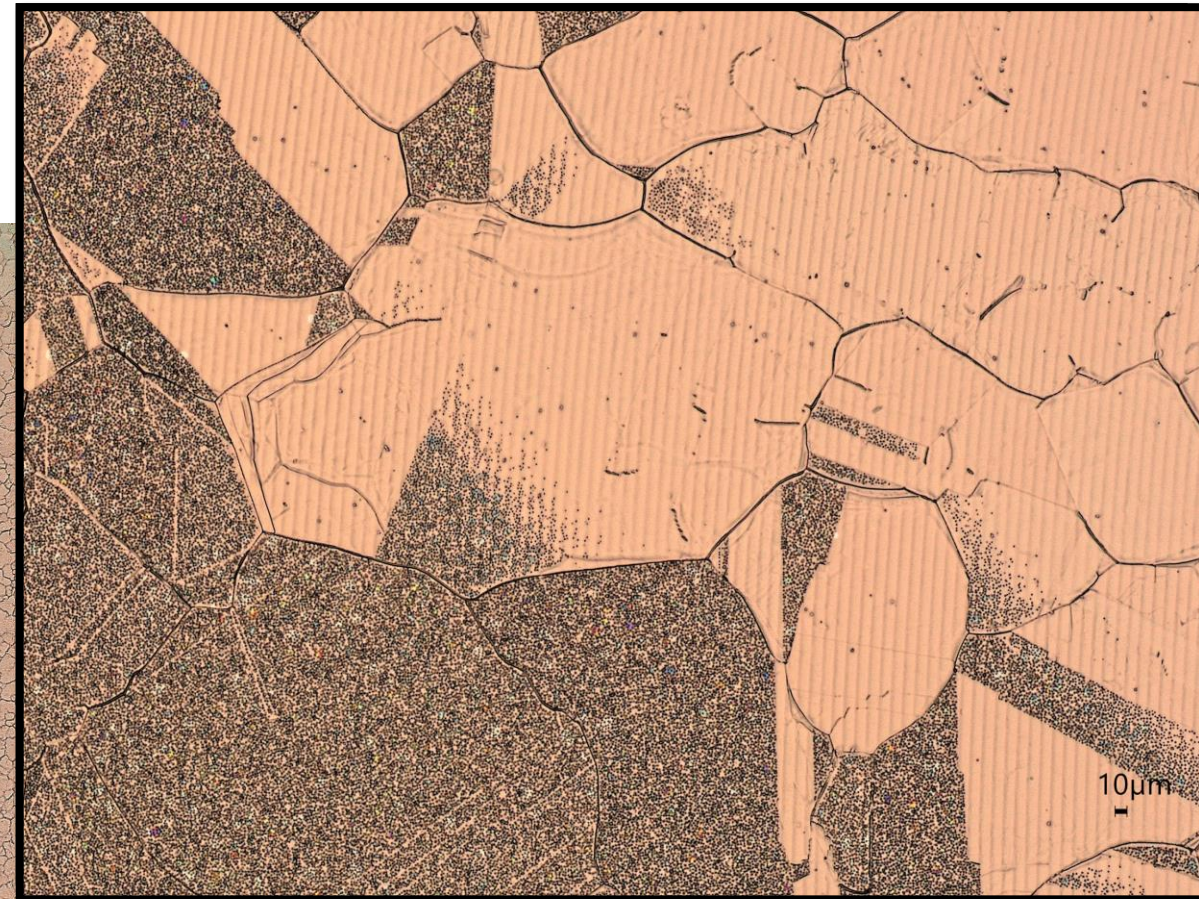
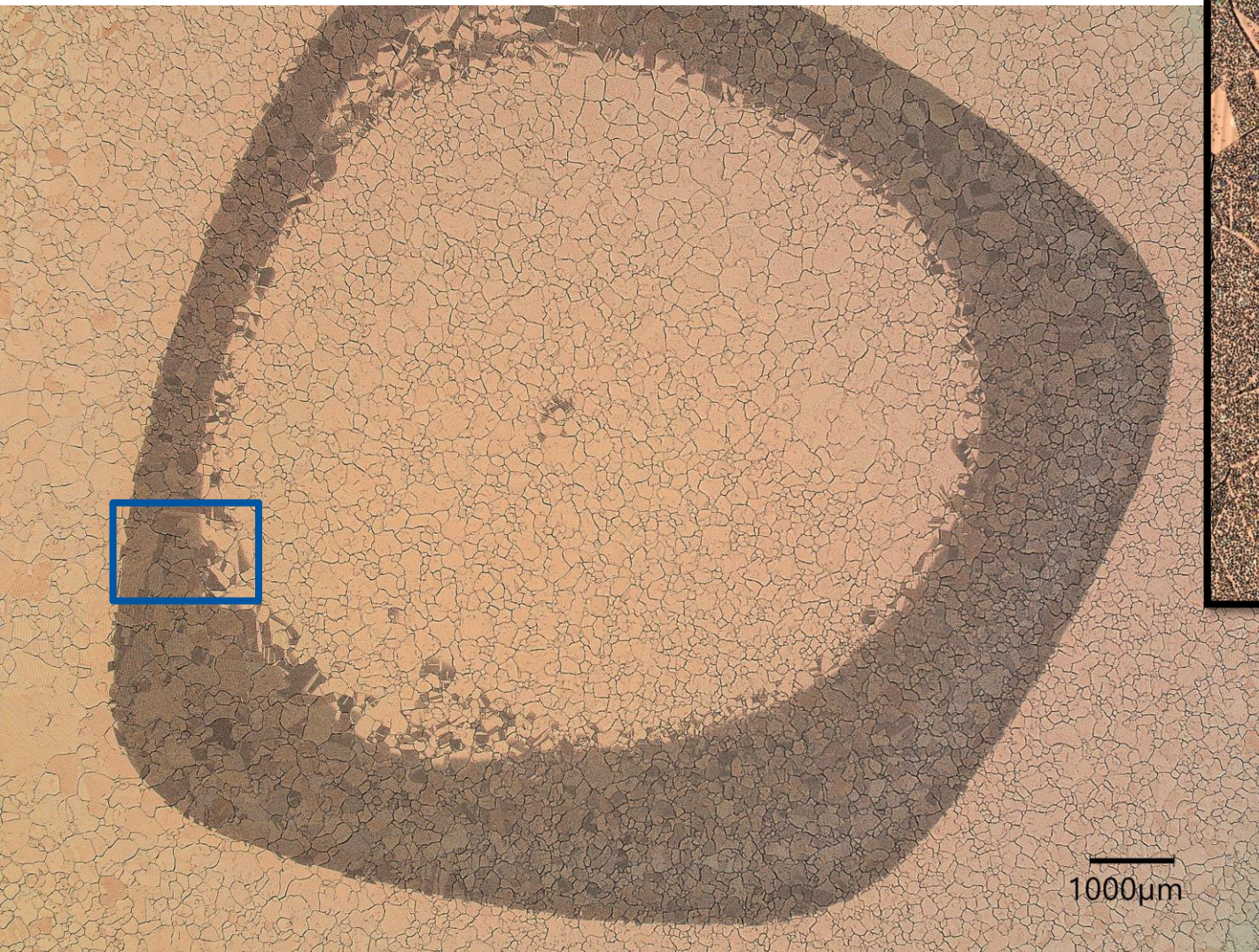
Irradiated Cu cathode



Optical microscope analysis

We can observe a first intense halo with a diameter of 26 mm (area of 544 mm²) and a less intense halo with a diameter of 30mm (area of 723 mm²) – In agreement with the gasket that was used during irradiation.

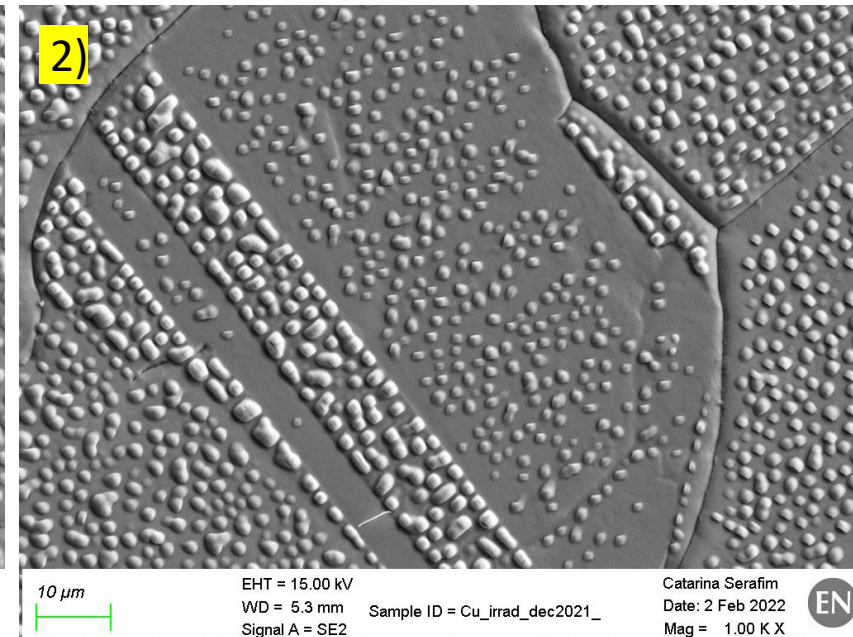
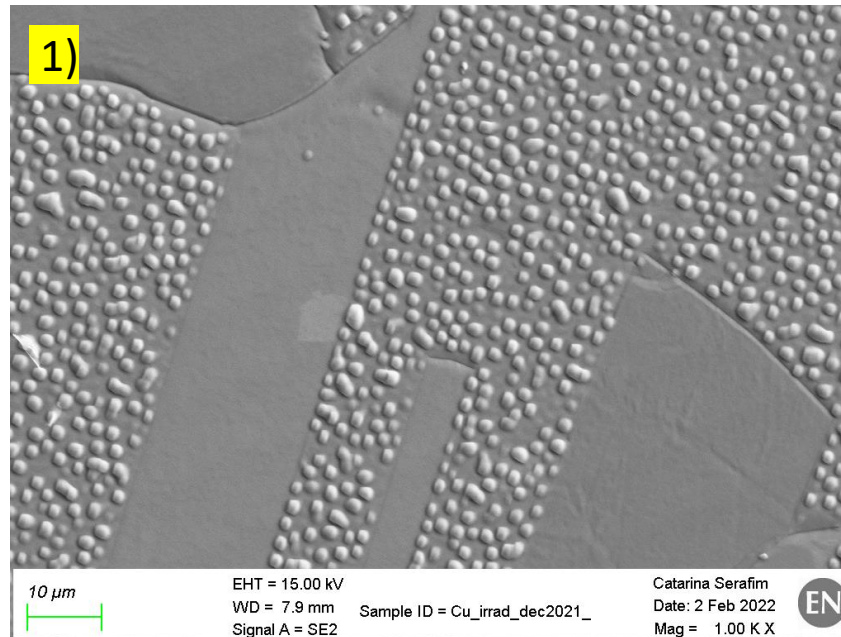
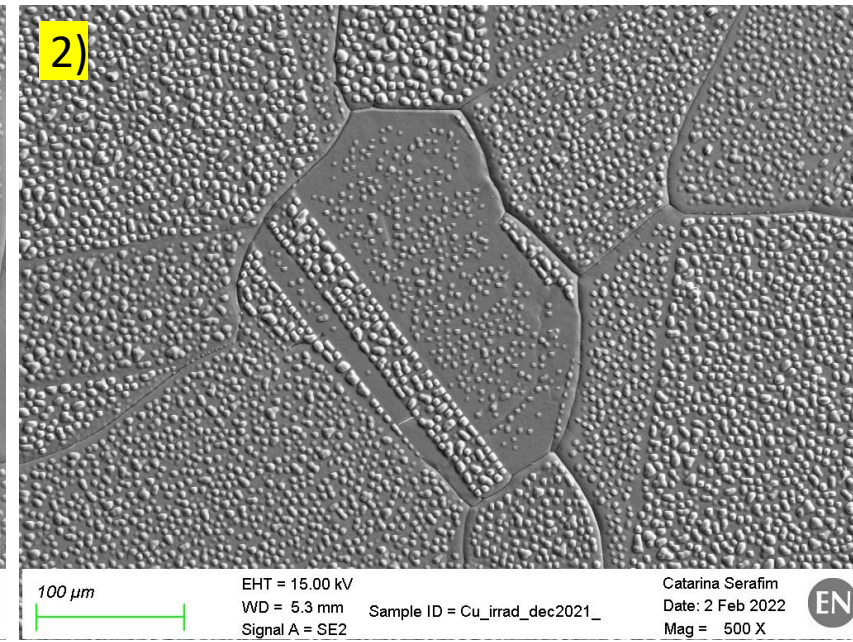
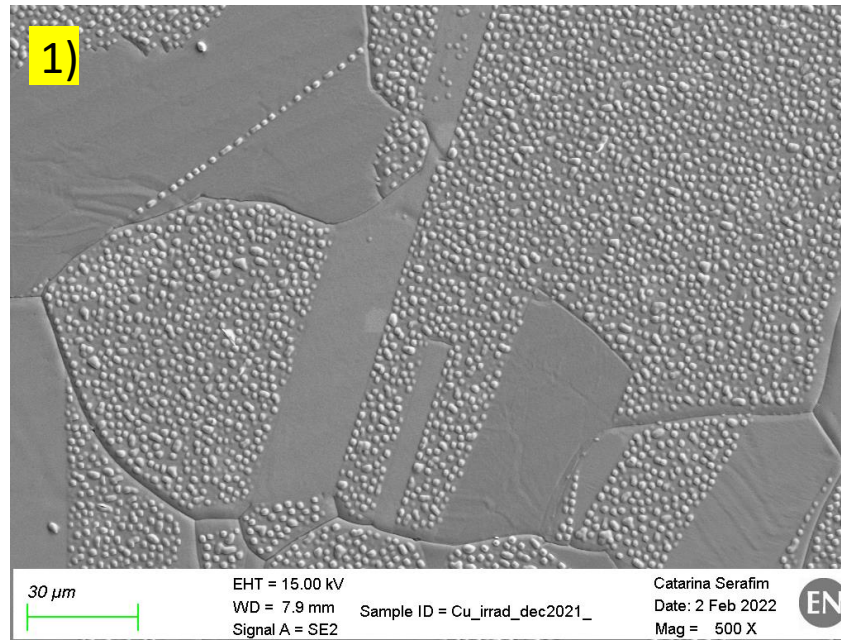
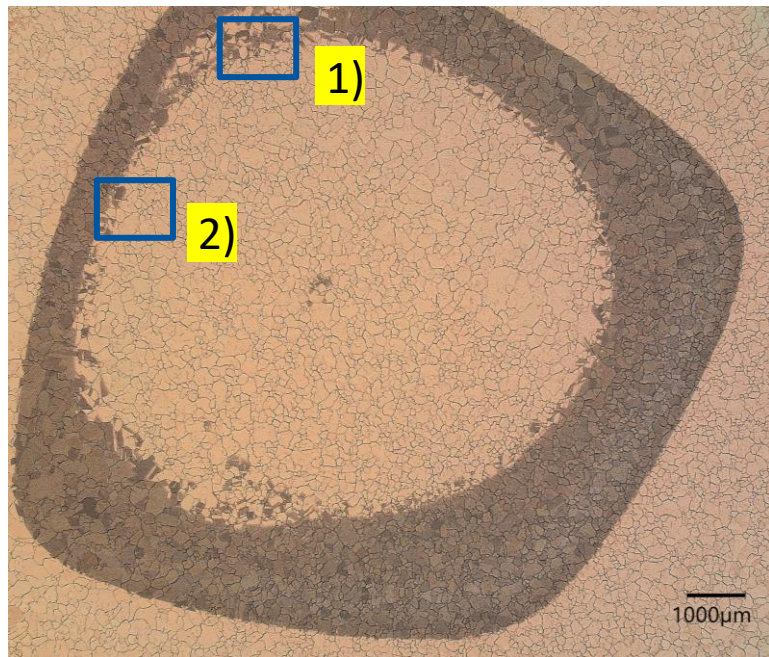
Irradiated Cu cathode



Optical microscope analysis

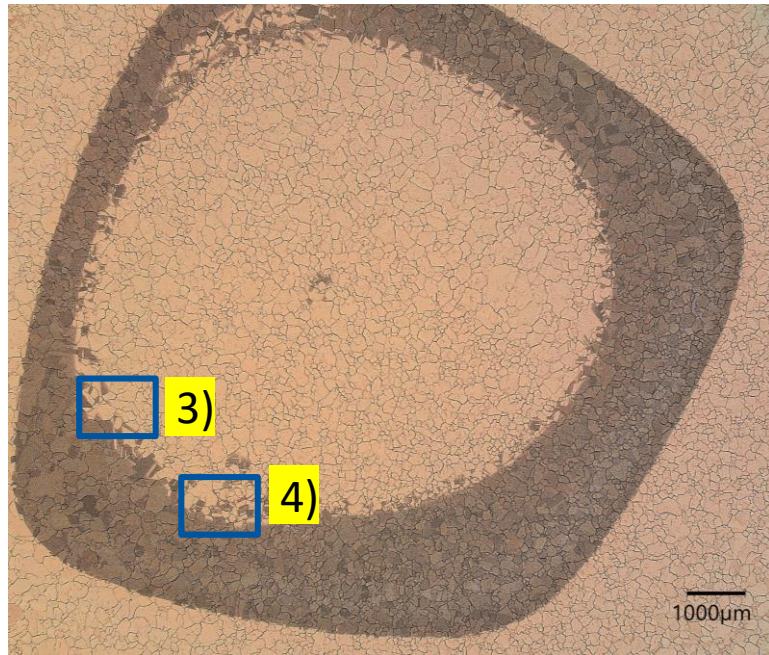
Irradiated Cu cathode

SEM observations in different areas surrounding the irradiation zone

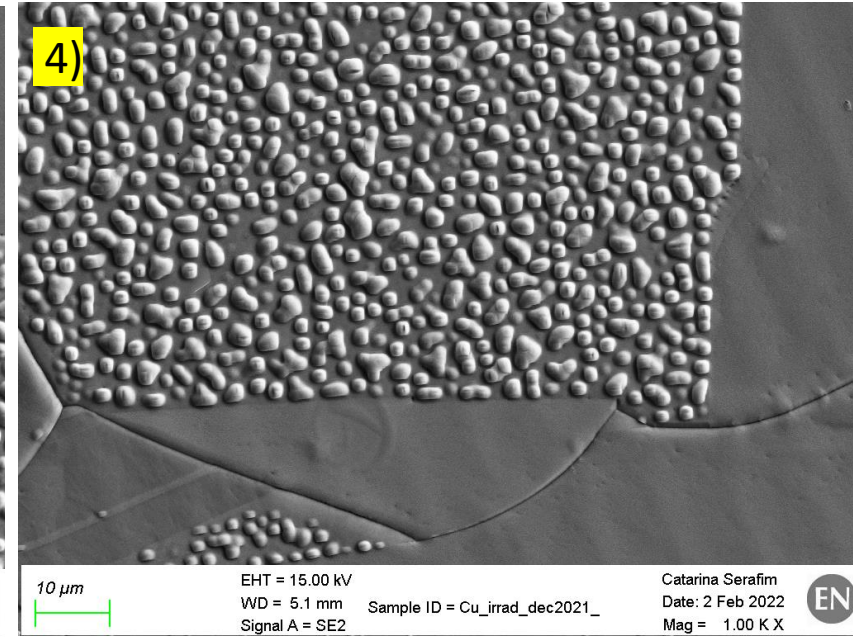
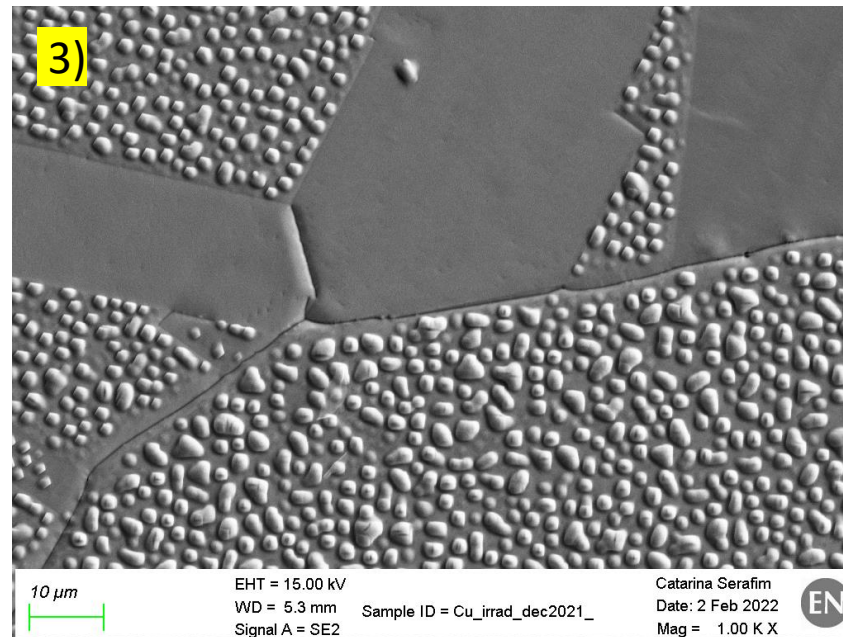
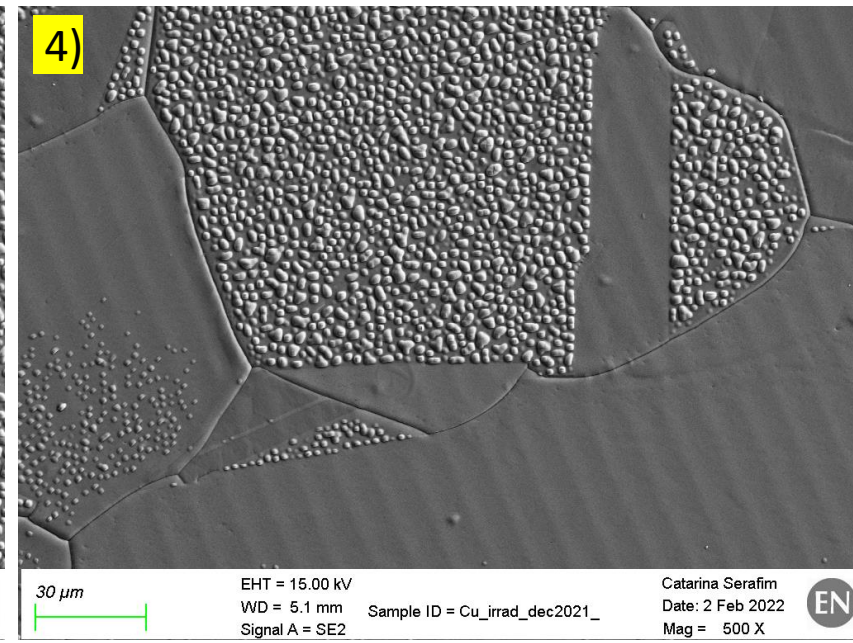
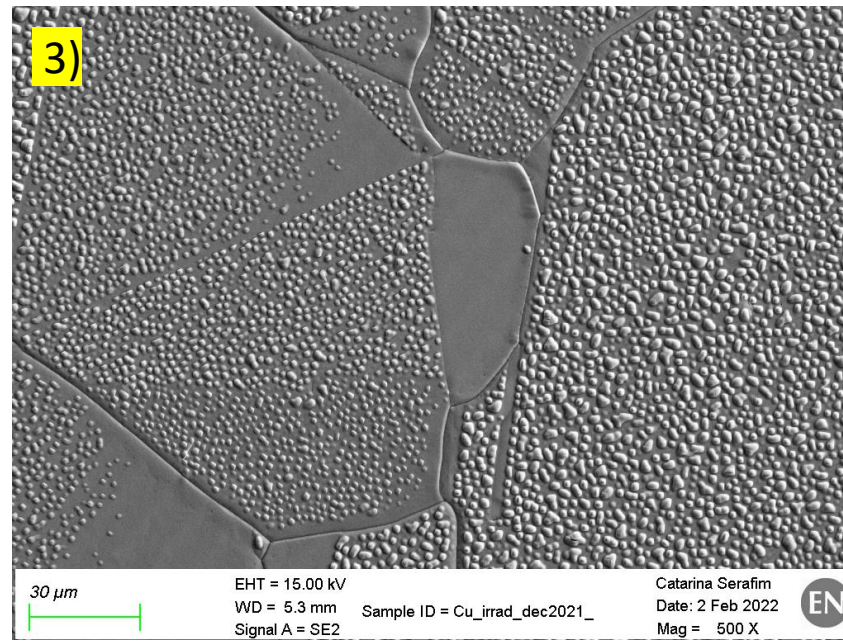


Irradiated Cu cathode

SEM observations in different areas surrounding the irradiation zone



Zone 1)

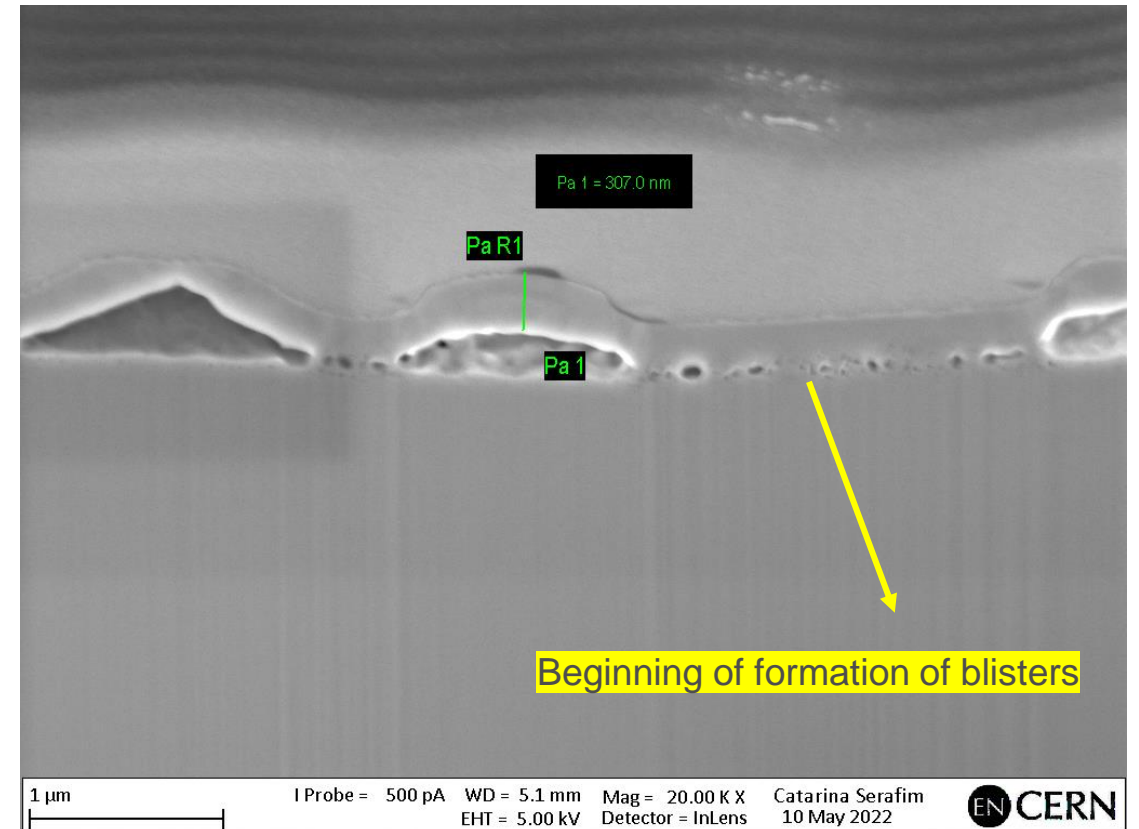


For the blistering phenomena a parallel work is under study.

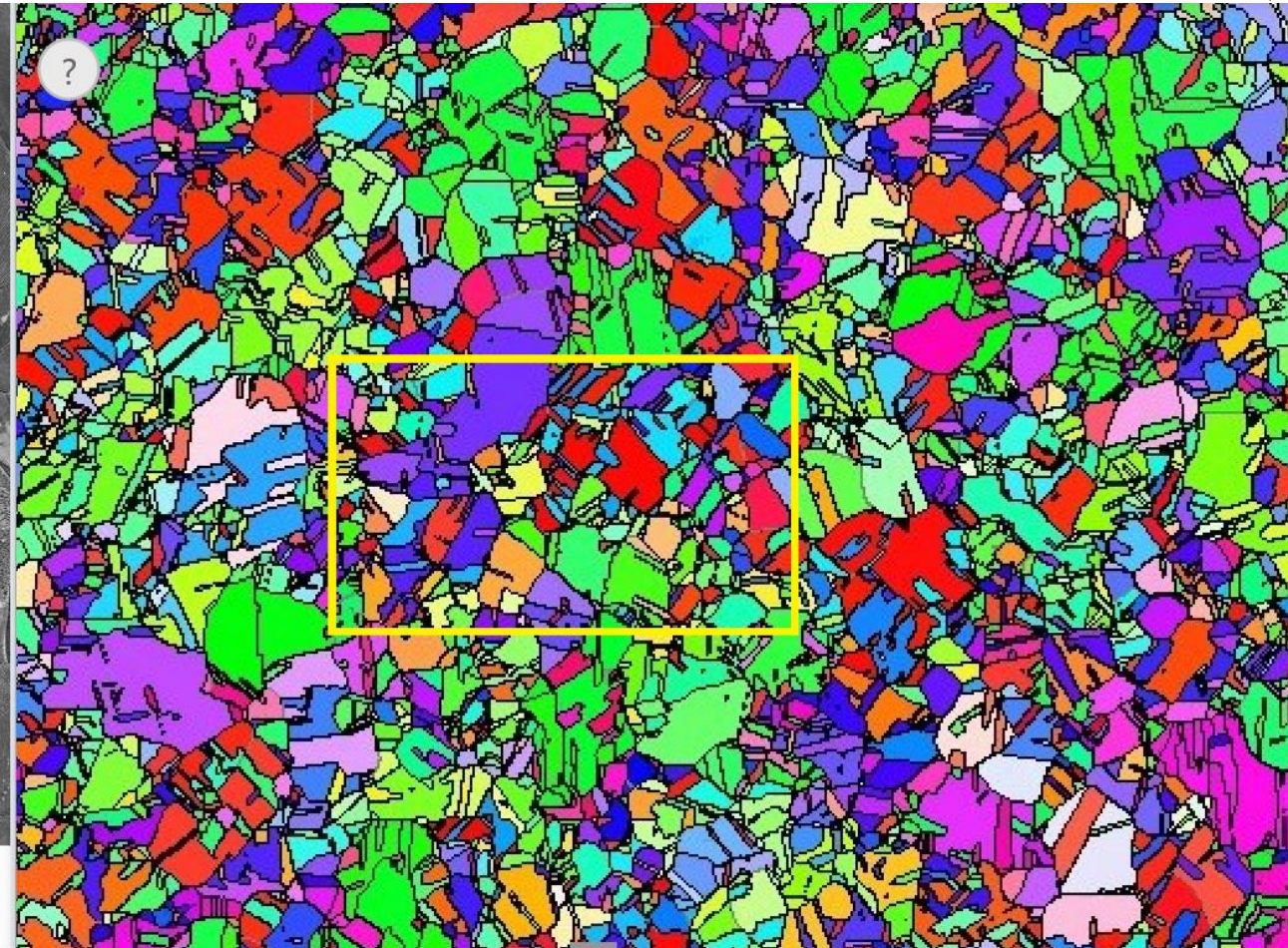
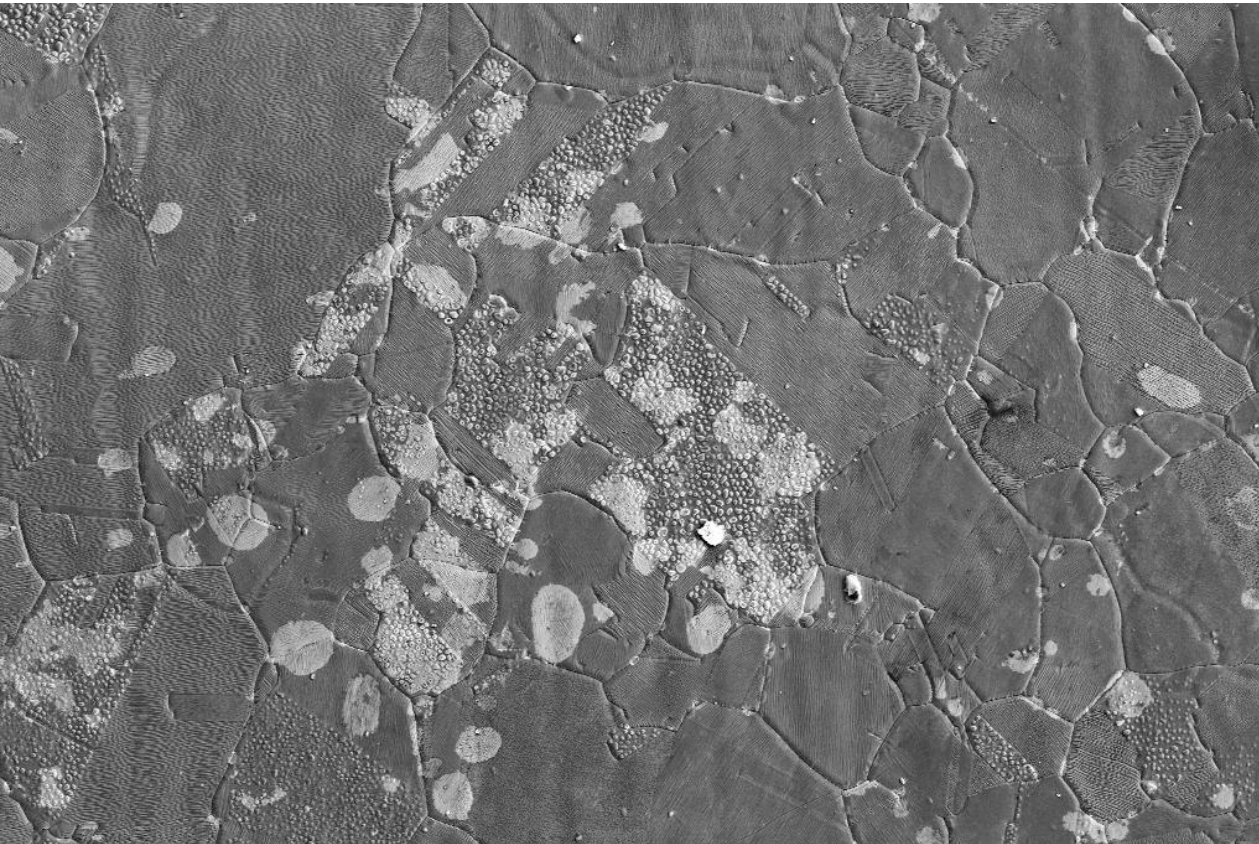
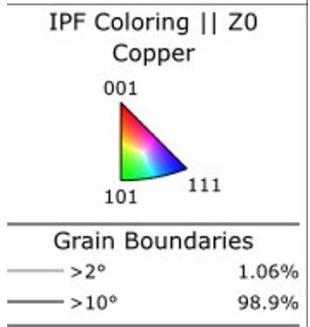
- Trying to understand correlation between **different grains orientation vs blistering**.
- Irradiated with same beam parameters Cu sample – doing analysis with EBSD mapping and FIB/SEM

We are studying 3 main orientation:

- **001** orientation – where we see the high density of blisters
- **101** orientation – where we see lower density of blisters
- **111** orientation – where we see few/no blisters

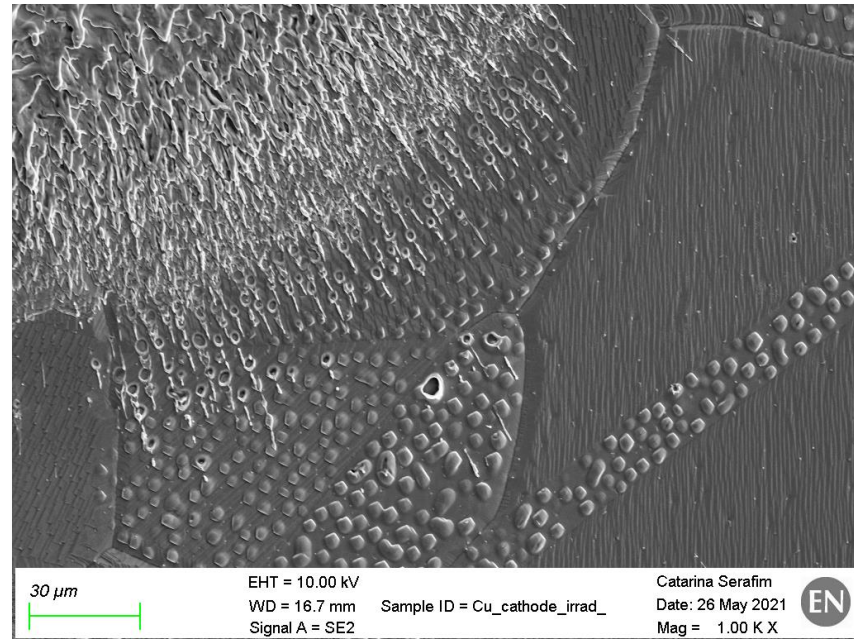
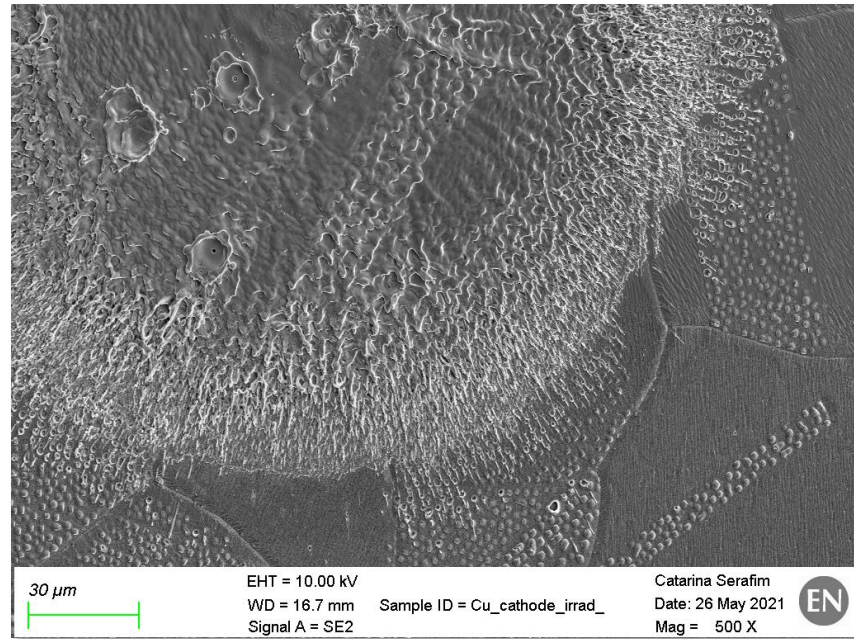
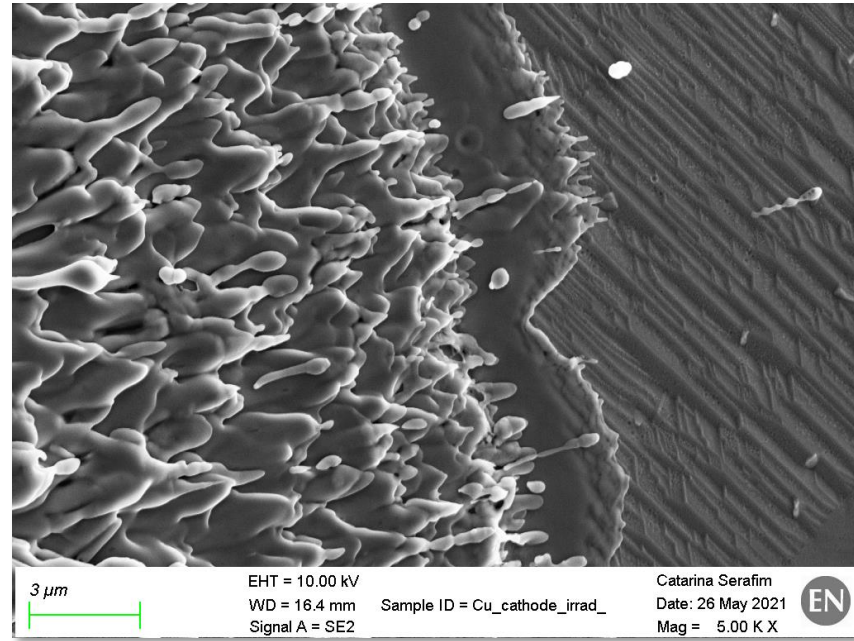
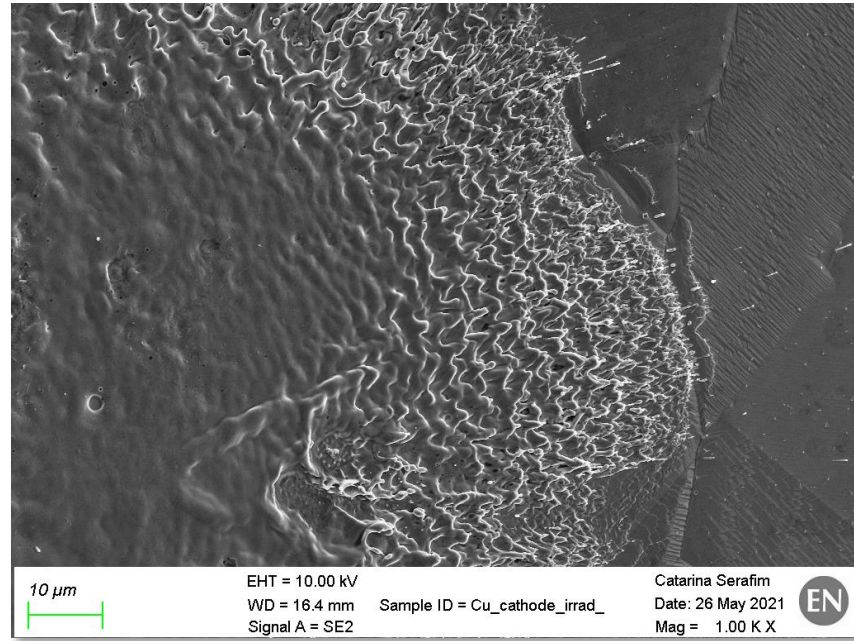
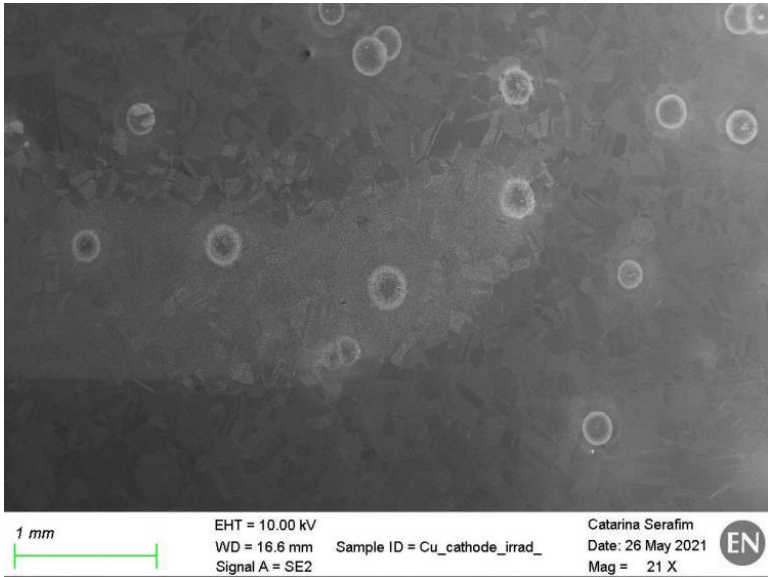


- The grains presenting red color were associated with high density of blisters.
- Grains presenting blue and green colors have showed to have less blisters/no blisters.

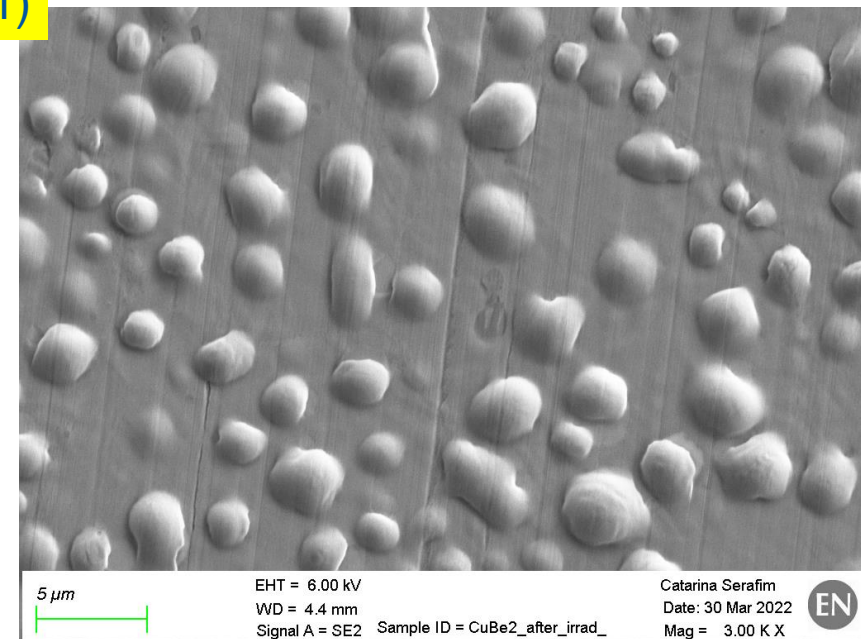
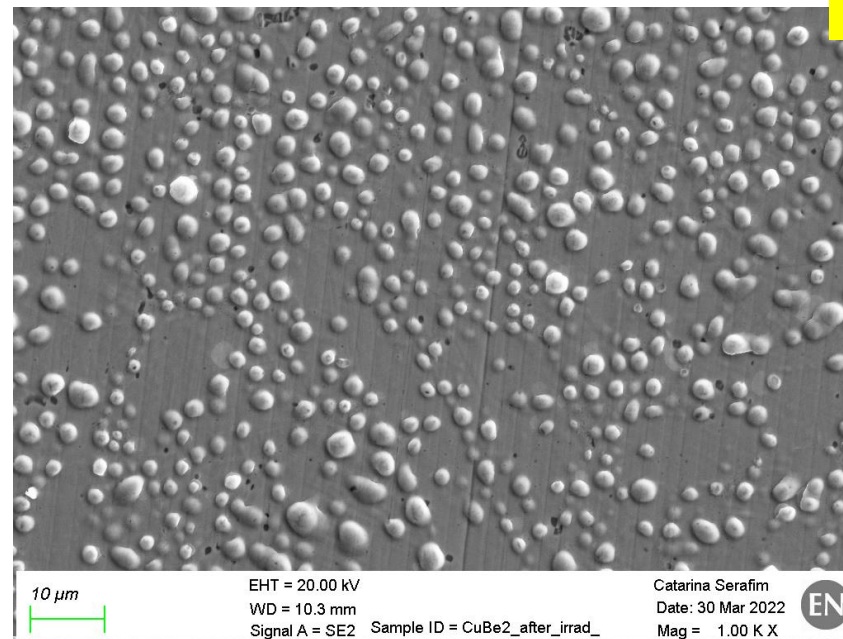
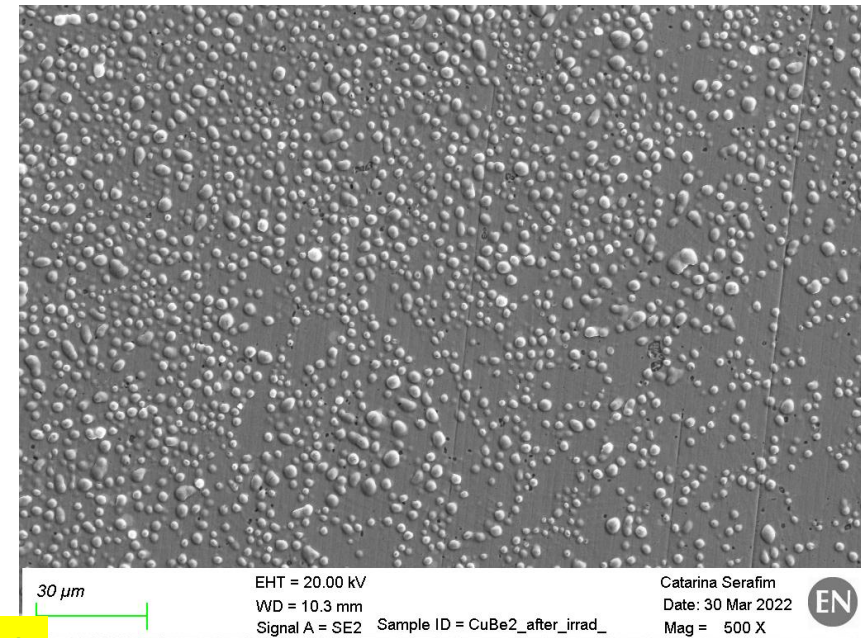
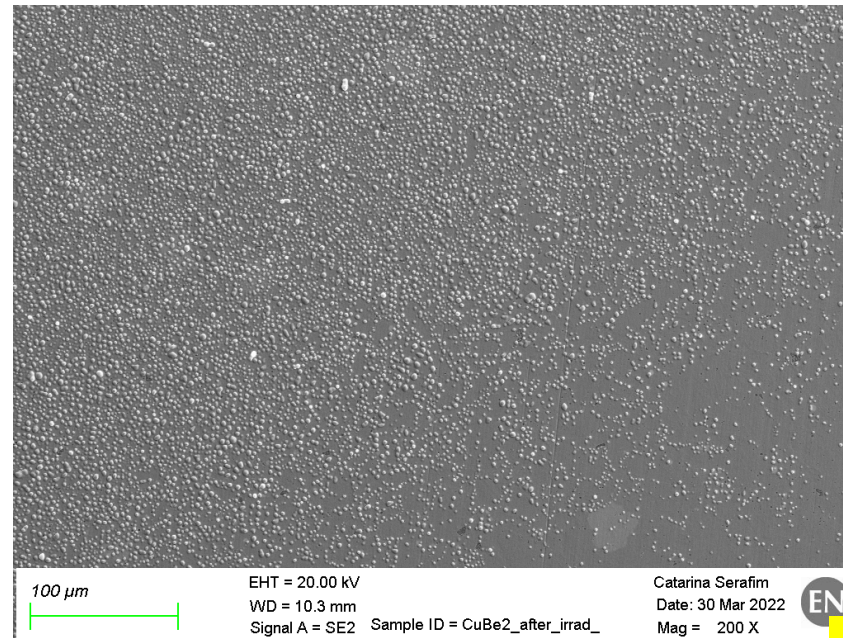
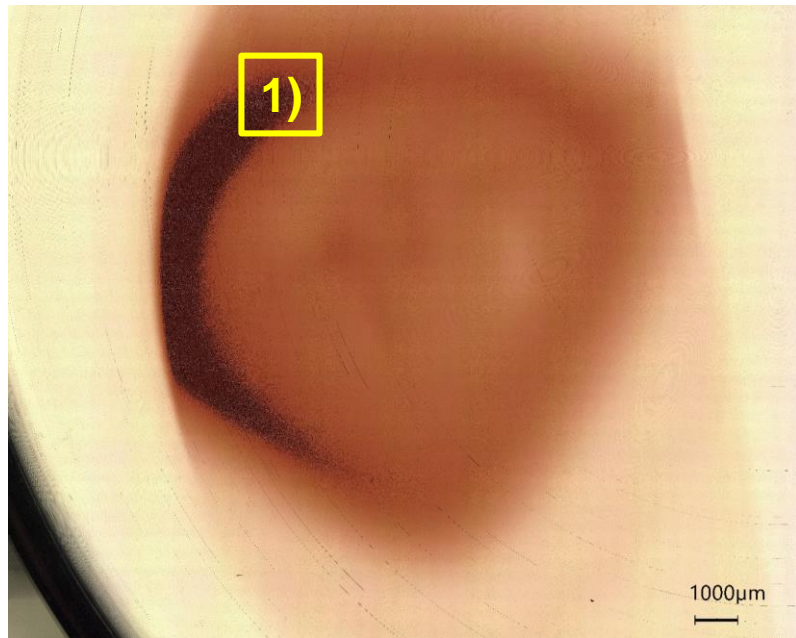


100 μm EHT = 15.00 kV
WD = 12.8 mm Signal A = SE2
Sample ID = irradi_cu_sample_ Catarina Serafim
Date: 12 May 2022
Mag = 200 X

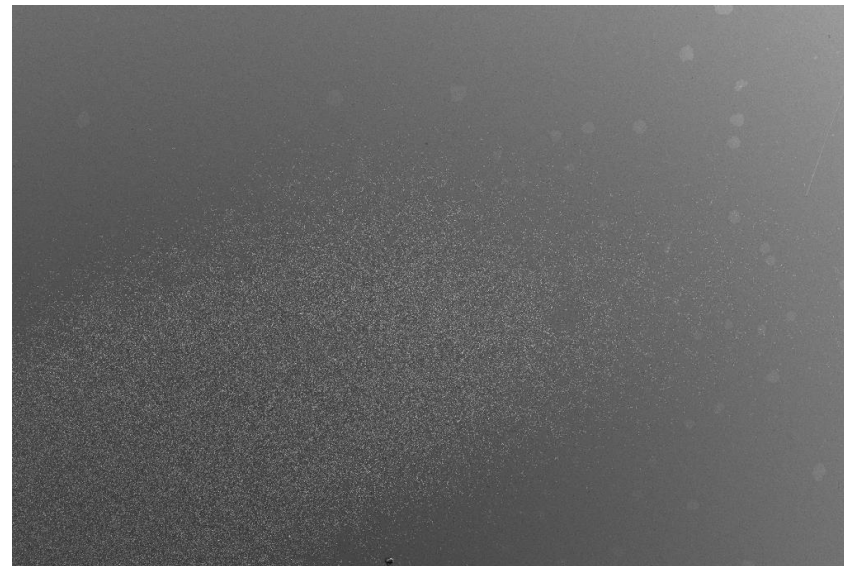
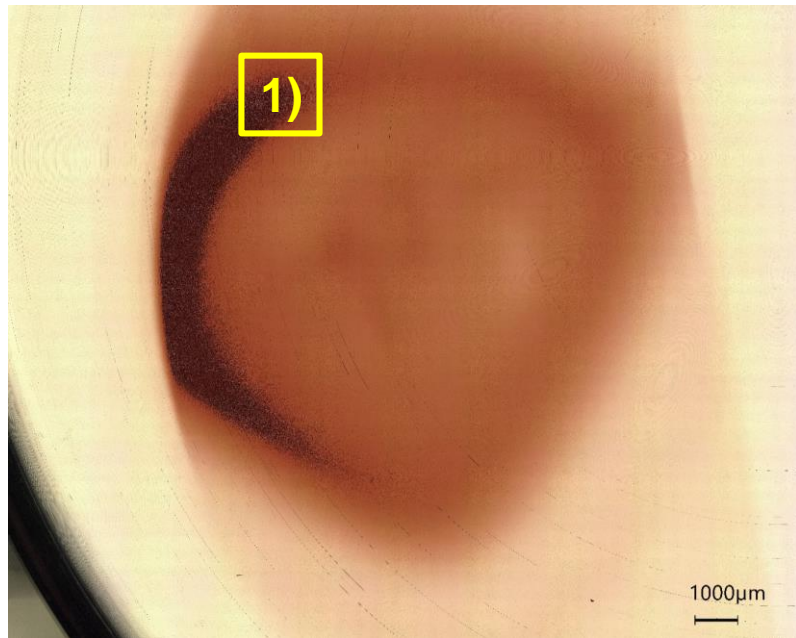
Irradiated Cu cathode after LES



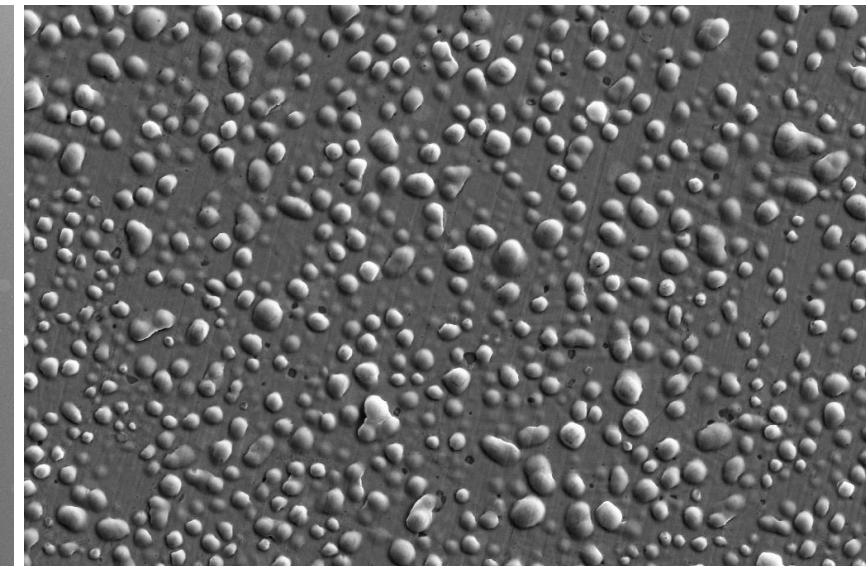
Irradiated CuBe2 cathode



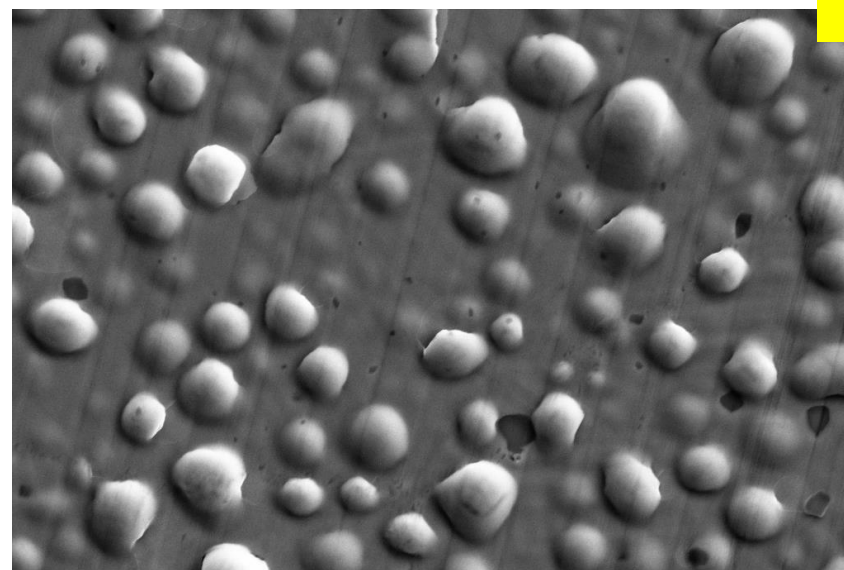
Irradiated CuBe2 cathode



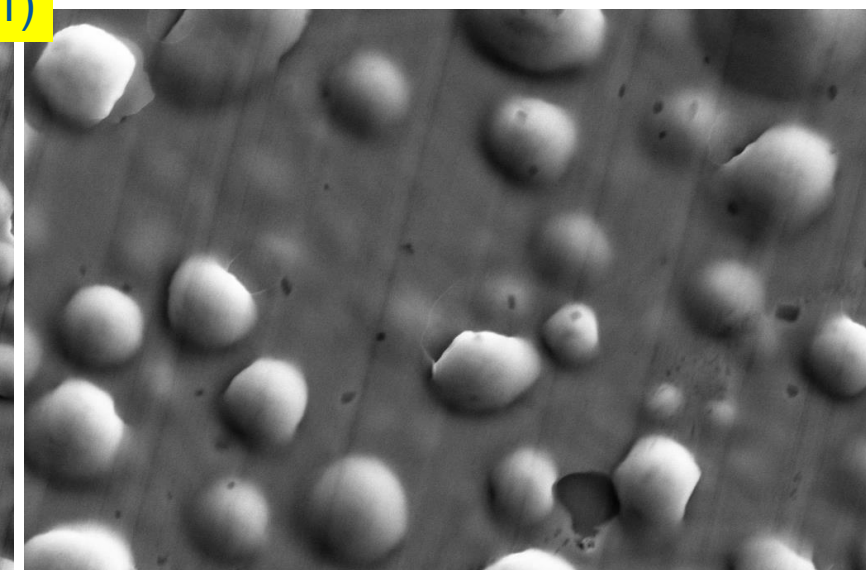
400 μm EHT = 15.00 kV
WD = 8.3 mm
Signal A = SE2 Sample ID = CuBe2_after_irrad_ Catarina Serafim
Date: 30 Mar 2022
Mag = 35 X EN



10 μm EHT = 15.00 kV
WD = 8.3 mm
Signal A = SE2 Sample ID = CuBe2_after_irrad_ Catarina Serafim
Date: 30 Mar 2022
Mag = 1.00 K X EN

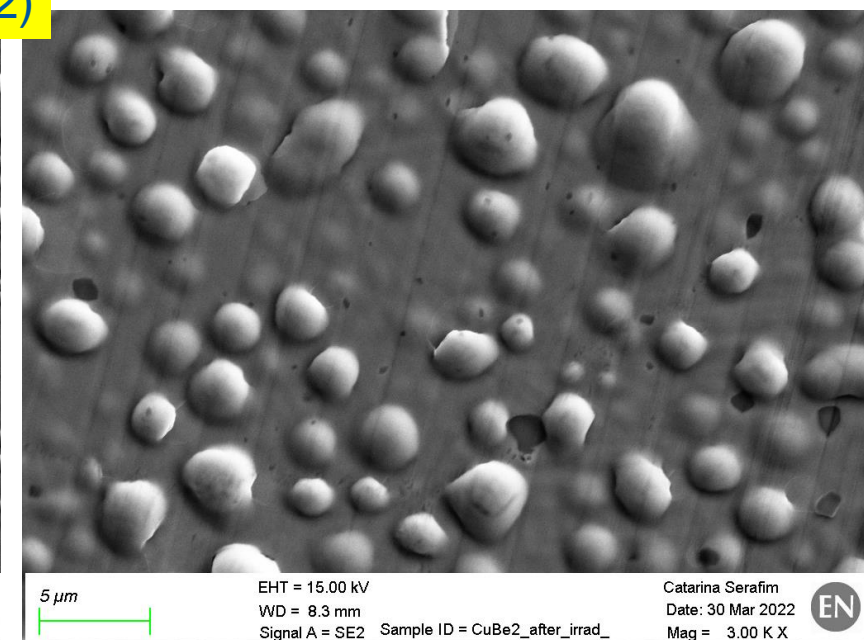
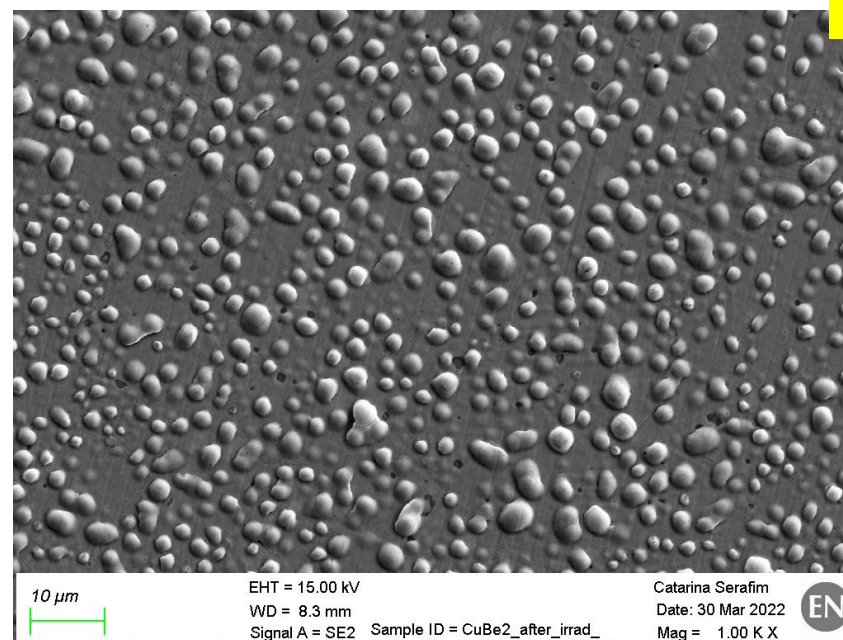
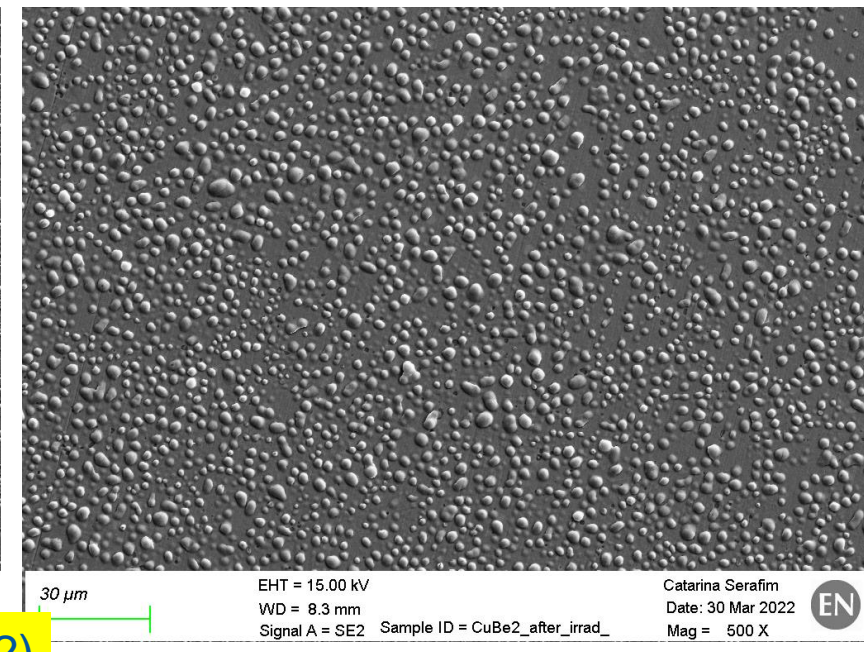
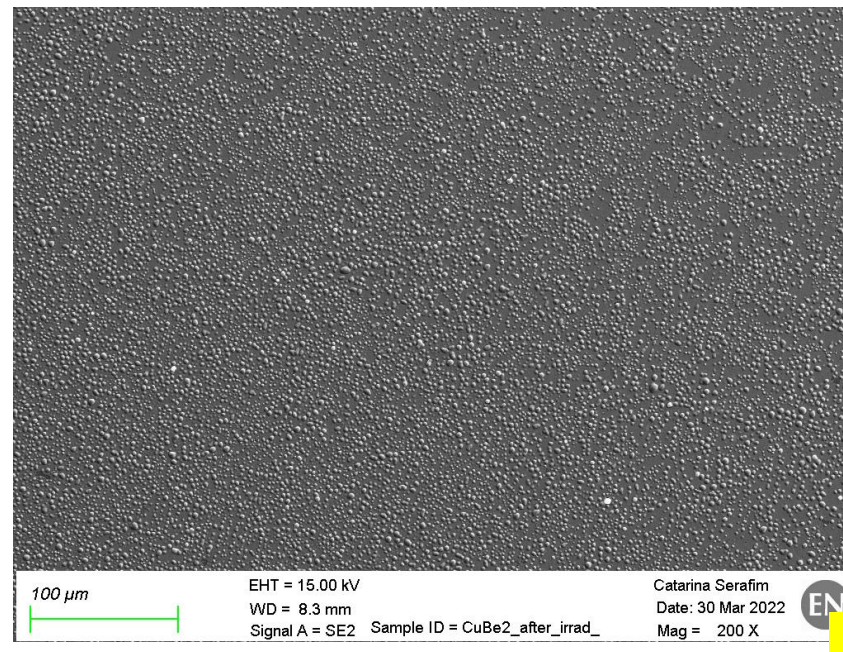
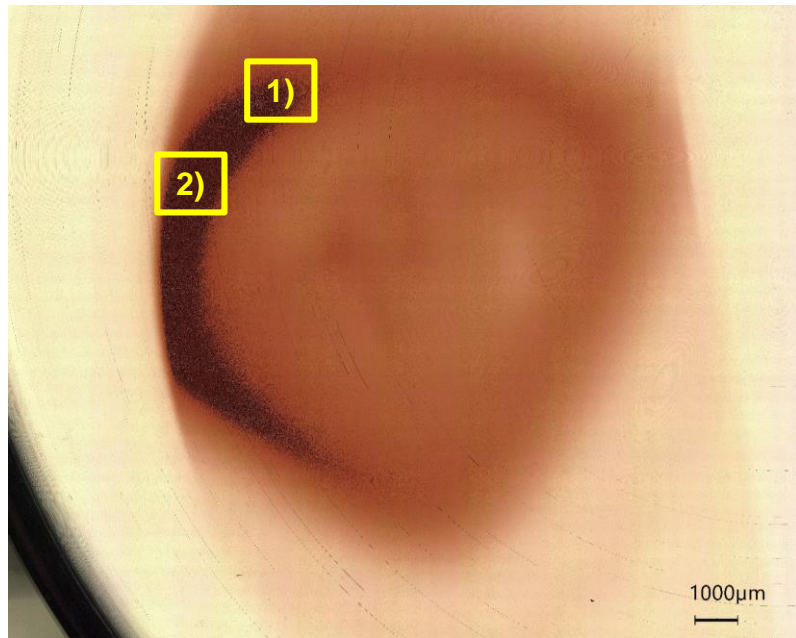


5 μm EHT = 15.00 kV
WD = 8.3 mm
Signal A = SE2 Sample ID = CuBe2_after_irrad_ Catarina Serafim
Date: 30 Mar 2022
Mag = 3.00 K X EN

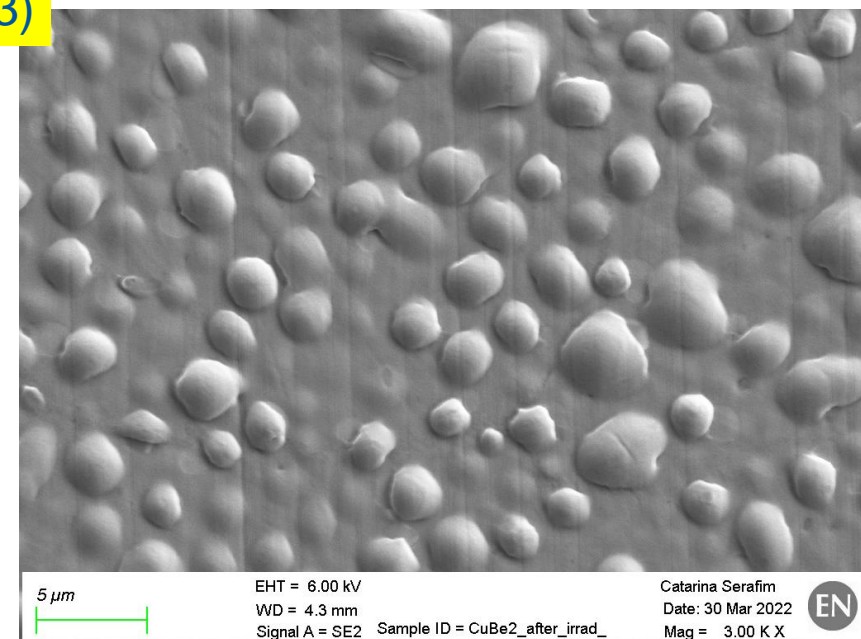
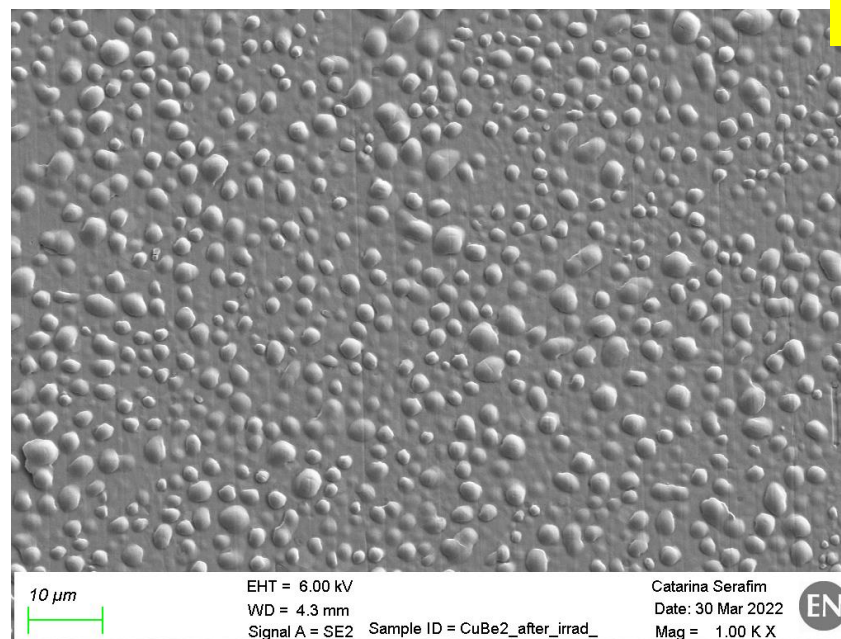
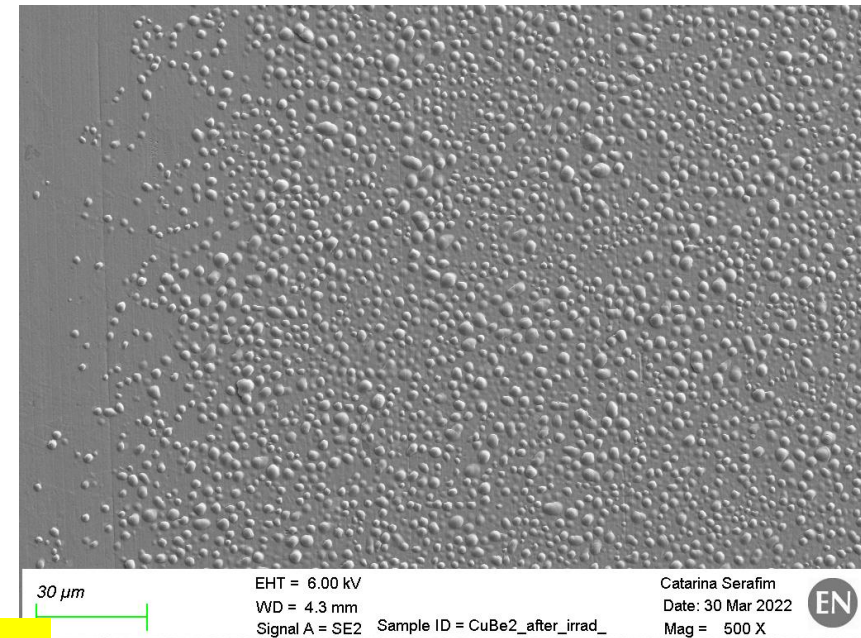
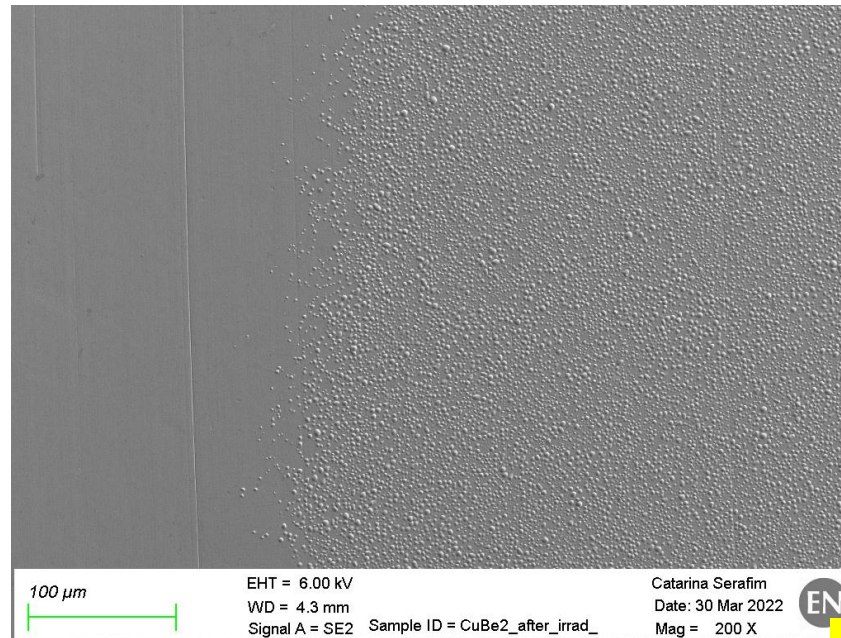
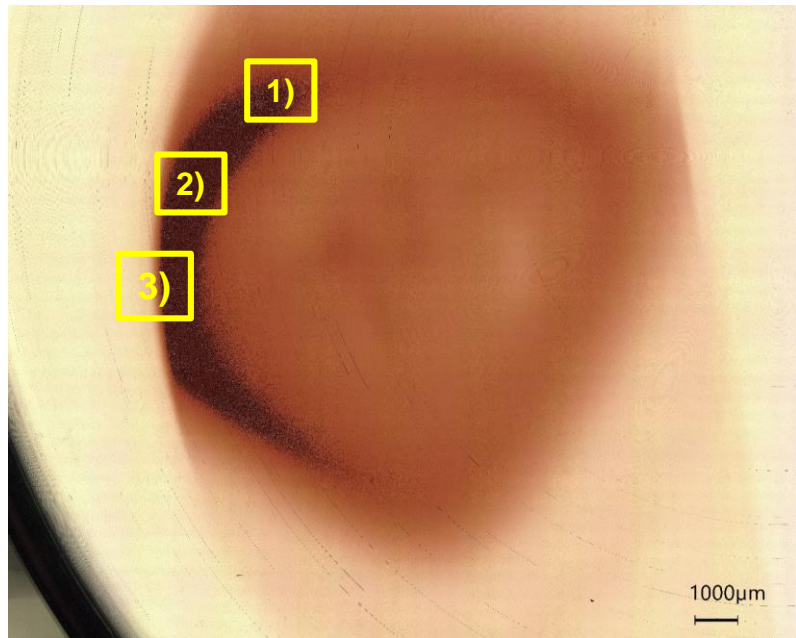


3 μm EHT = 15.00 kV
WD = 8.3 mm
Signal A = SE2 Sample ID = CuBe2_after_irrad_ Catarina Serafim
Date: 30 Mar 2022
Mag = 5.00 K X EN

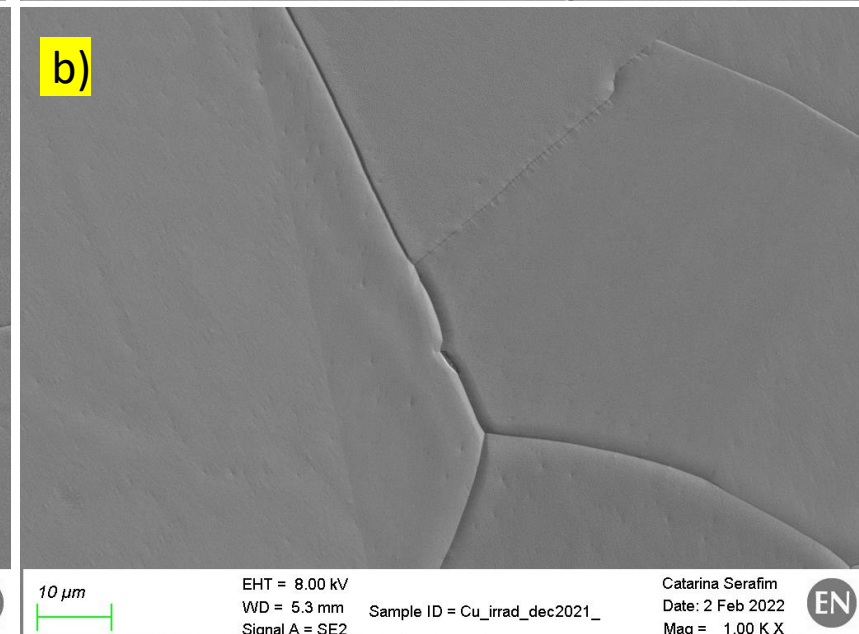
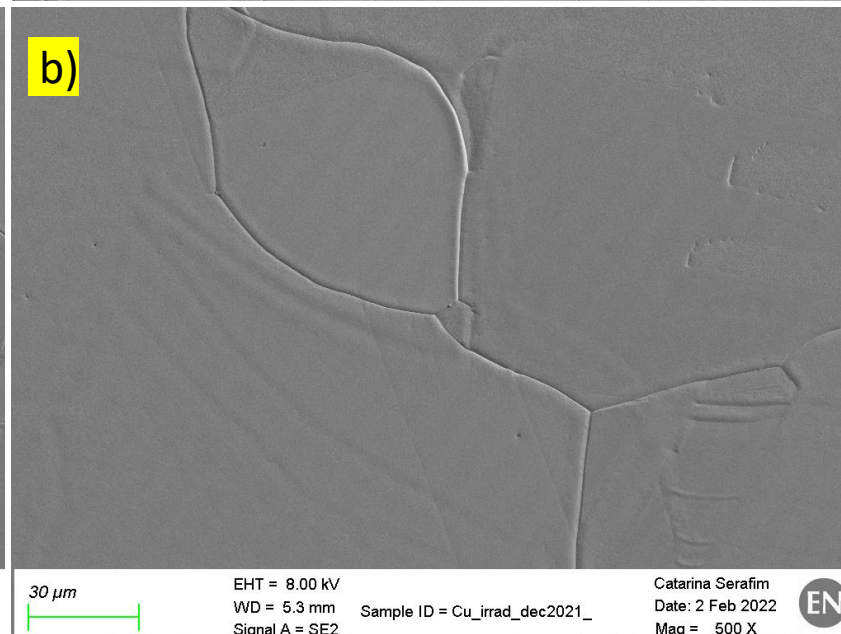
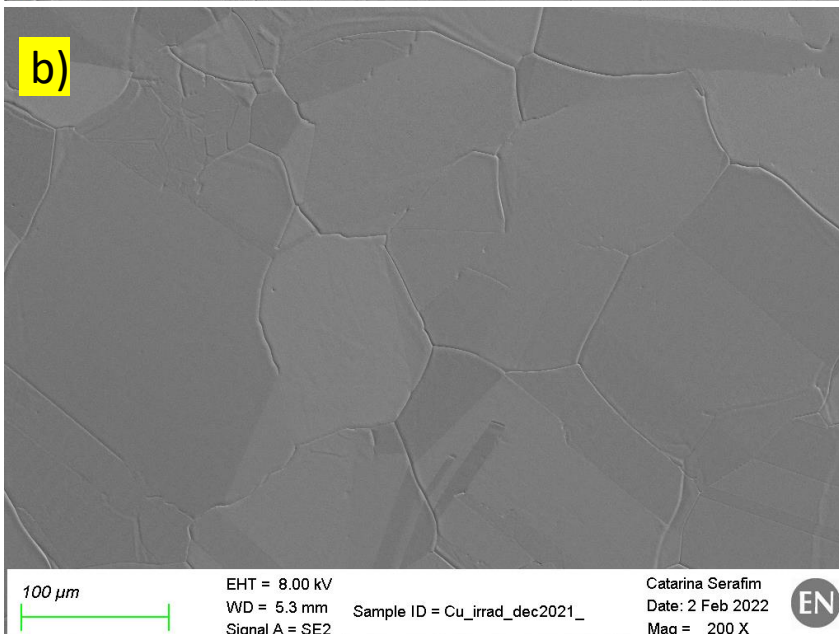
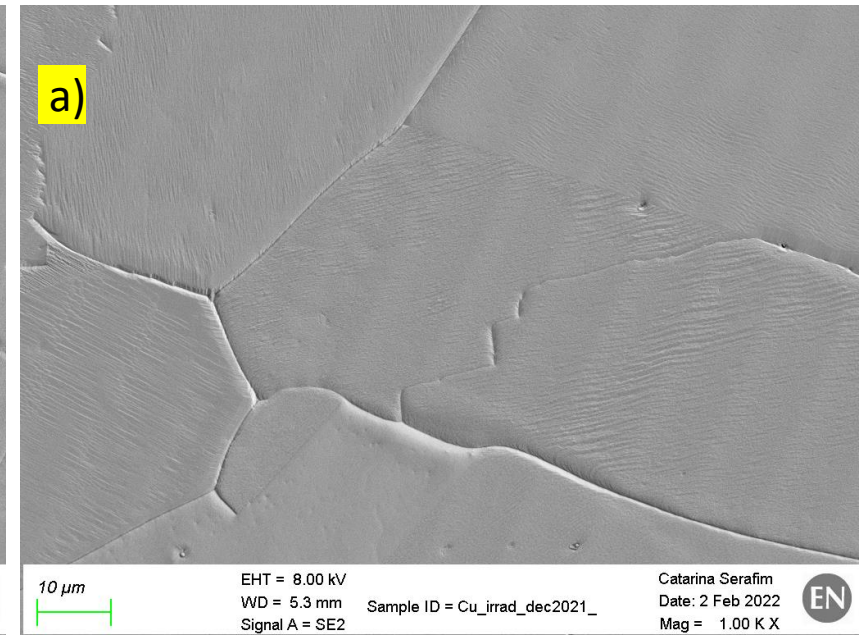
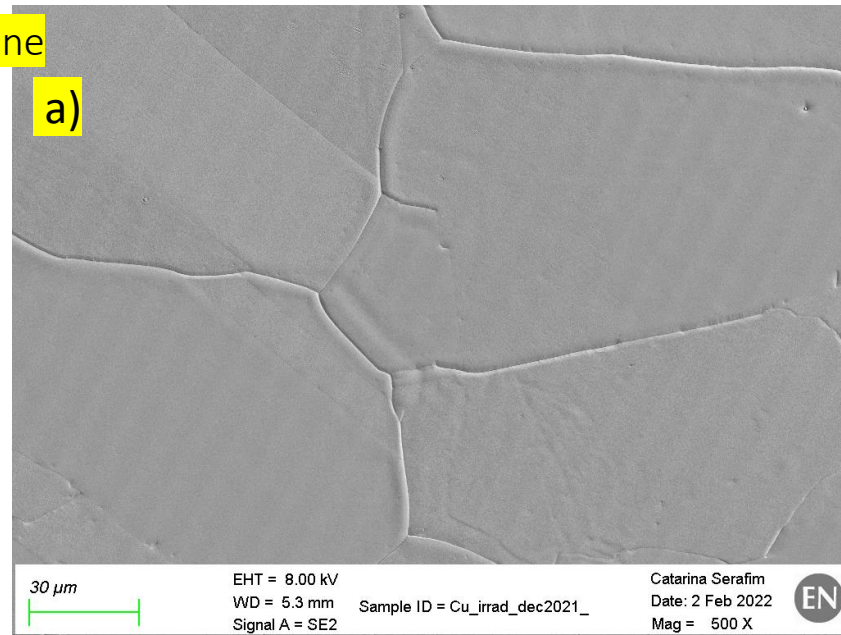
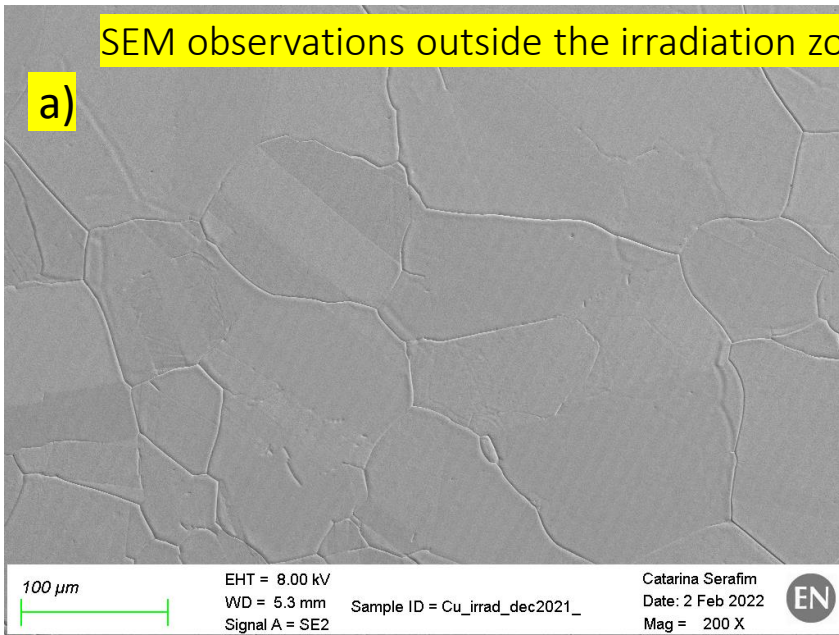
Irradiated CuBe2 cathode



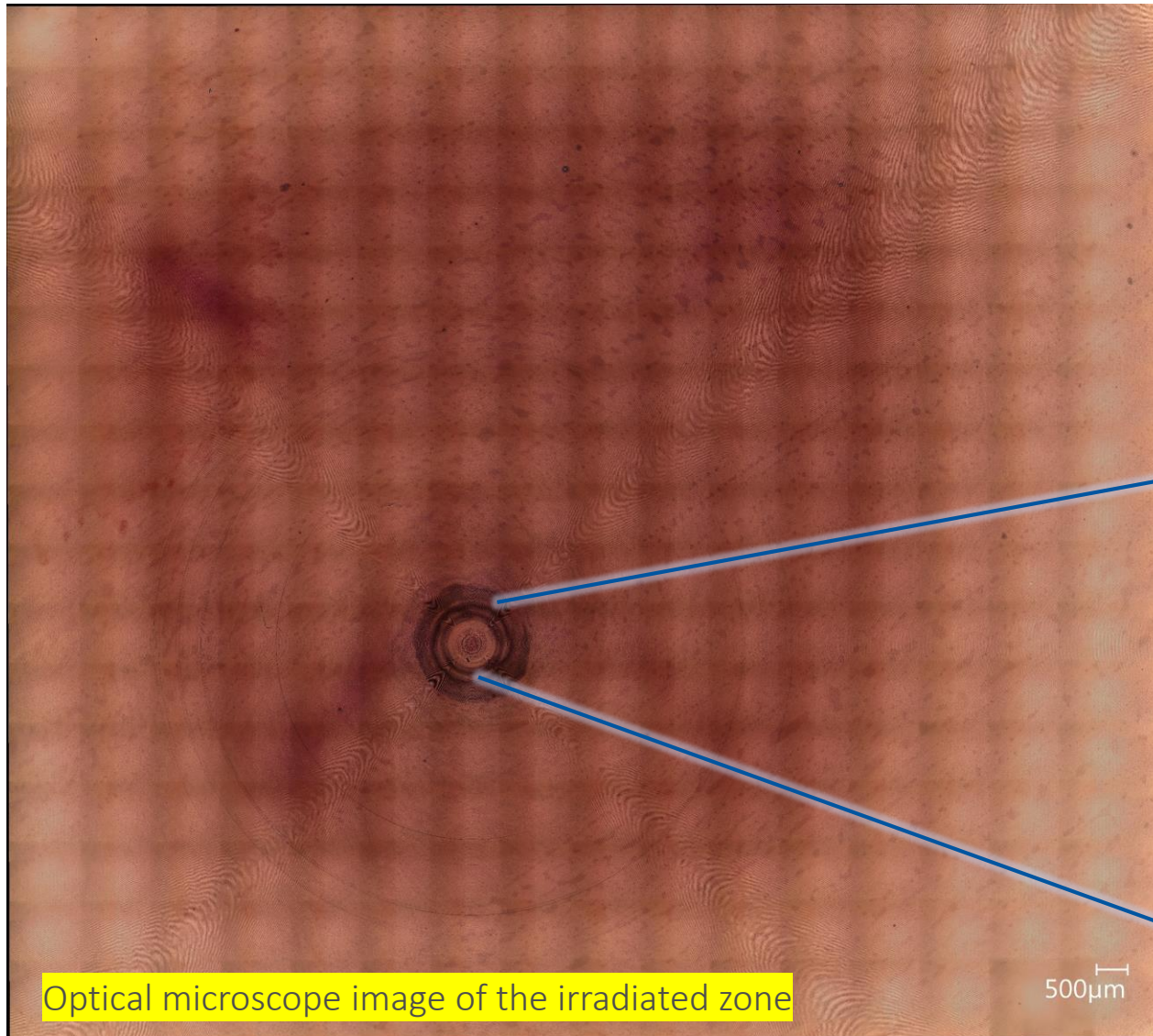
Irradiated CuBe2 cathode



SEM observations outside the irradiation zone



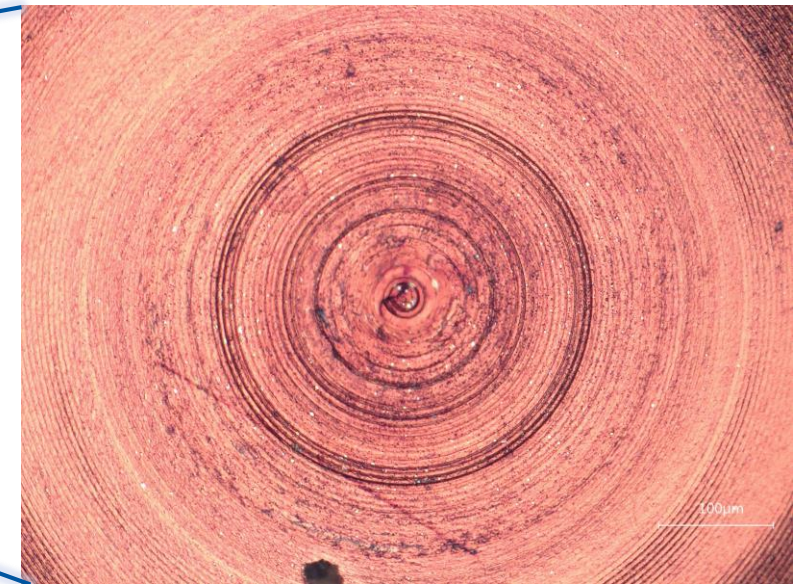
Irradiated CuCrZr cathode



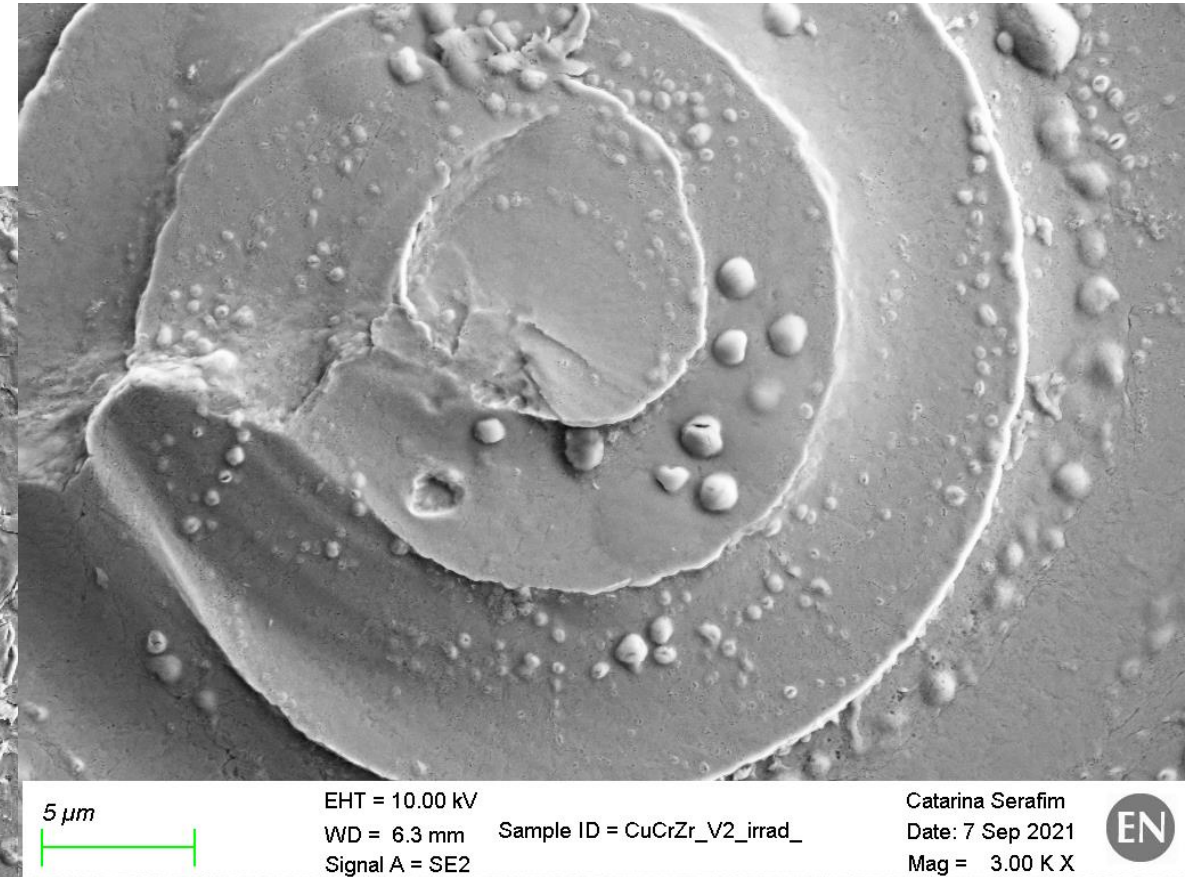
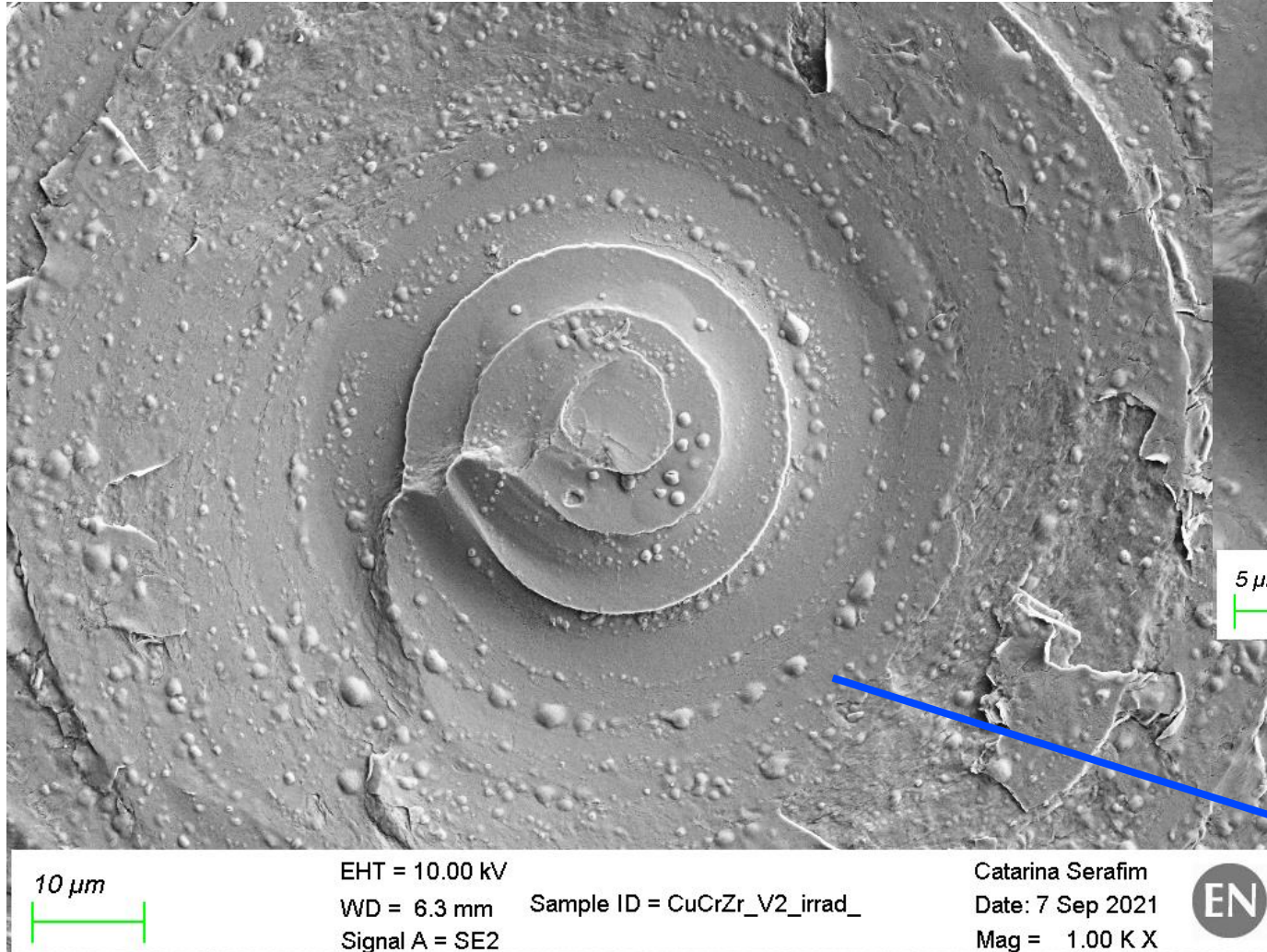
The shape of the irradiated area is consistent with the previous shapes.

The borders of the trapezoid are not as defined as the previous ones.

Some blisters are already visible on the optical microscope.



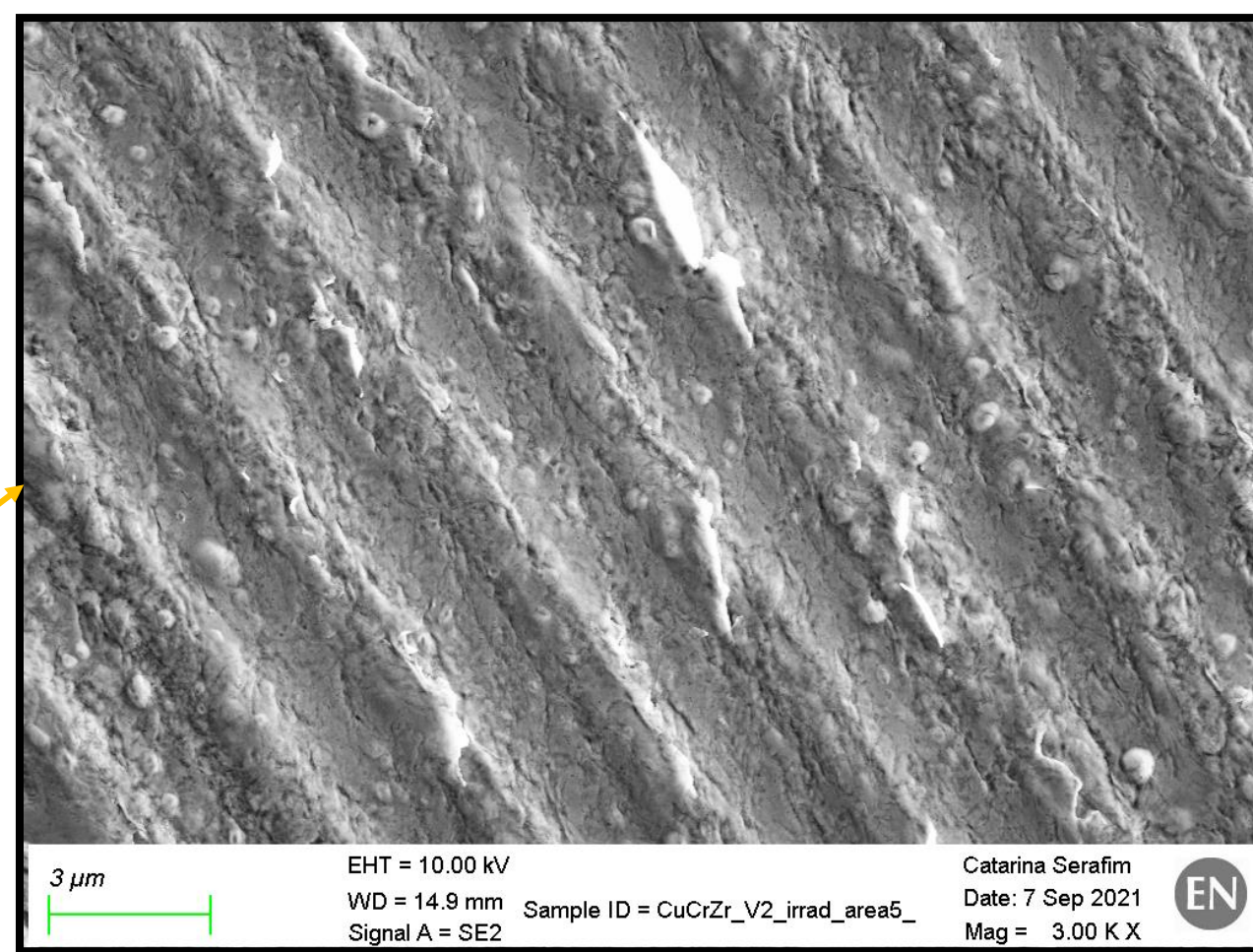
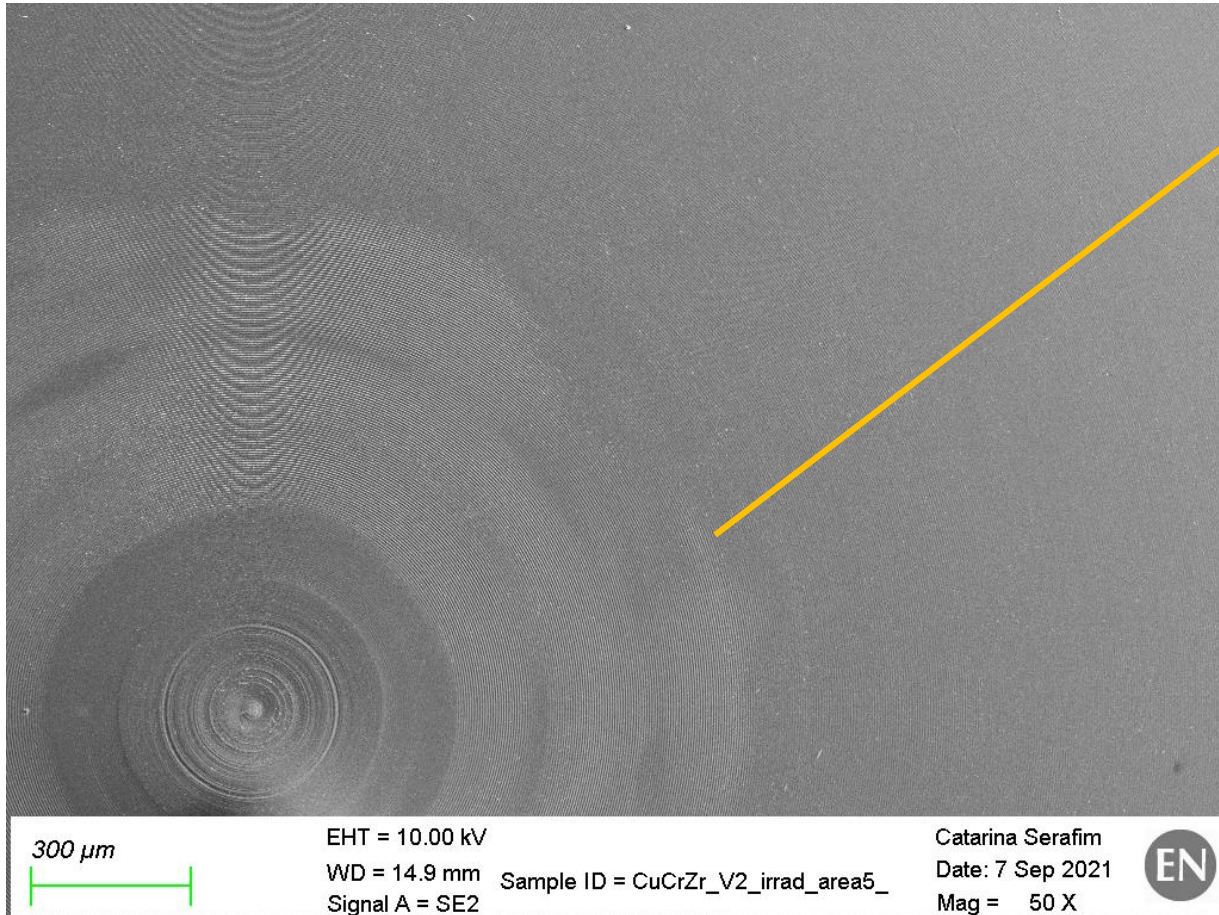
Irradiated CuCrZr cathode



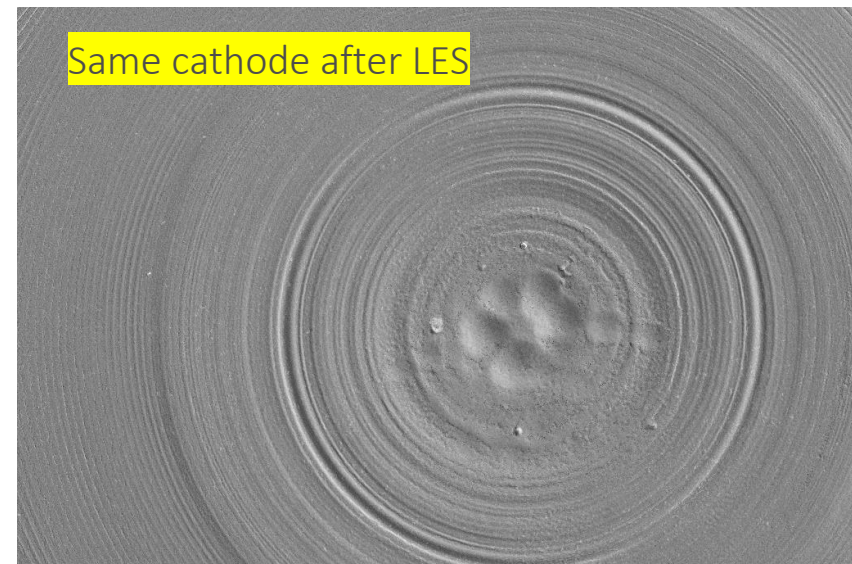
It is visible that some blisters appeared following the pattern of the machining marks.

Irradiated CuCrZr cathode

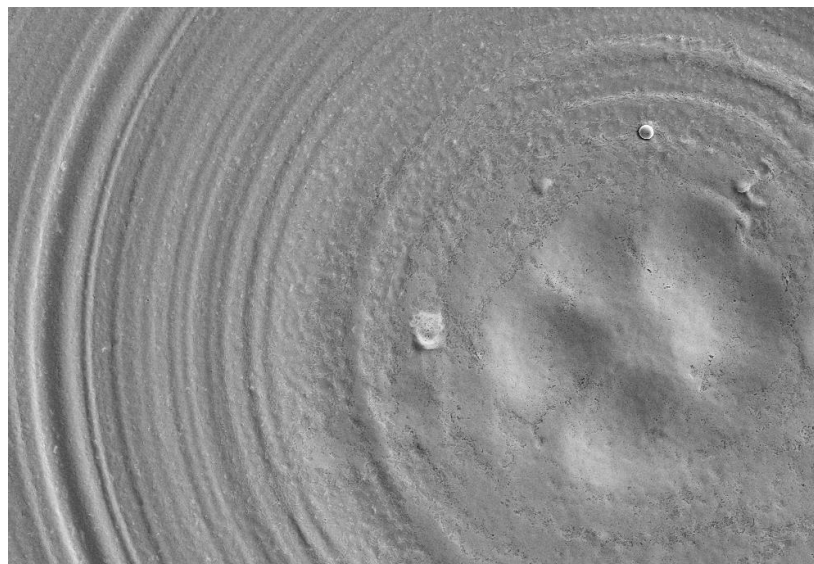
Different area inside the irradiated zone.
Blisters visible following the machining marks as showed before.



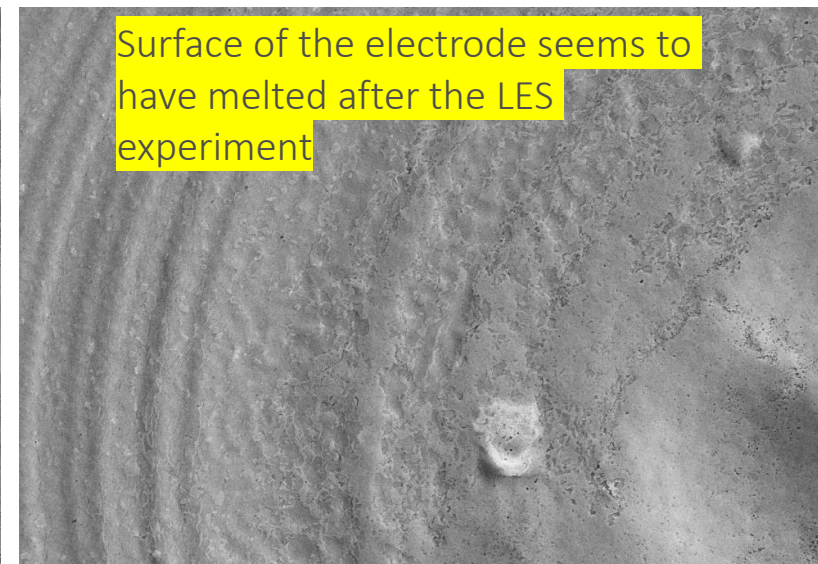
Same cathode after LES



100 μm EHT = 15.00 kV WD = 9.9 mm Signal A = SE2 Sample ID = CuCrZr_irrad_LES_ Catarina Serafim Date: 14 Apr 2022 Mag = 200 X EN



30 μm EHT = 15.00 kV WD = 9.9 mm Signal A = SE2 Sample ID = CuCrZr_irrad_LES_ Catarina Serafim Date: 14 Apr 2022 Mag = 500 X EN

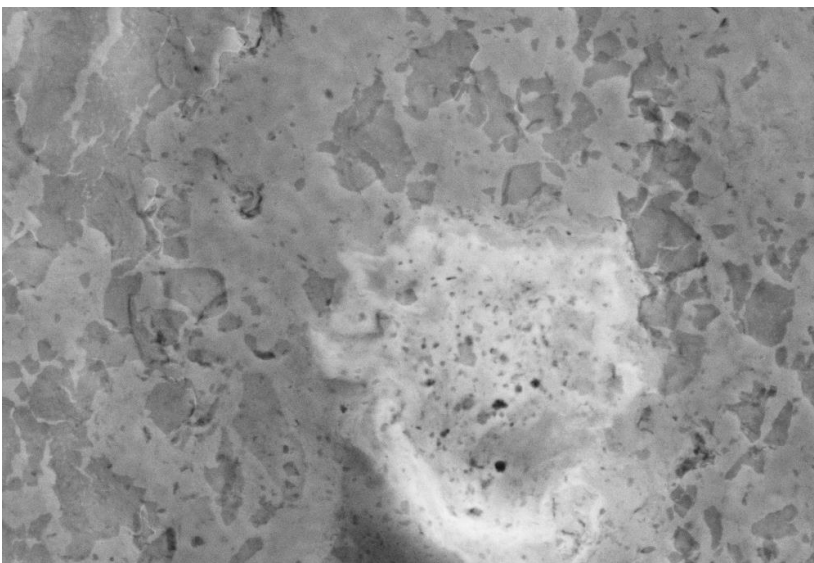


Surface of the electrode seems to have melted after the LES experiment

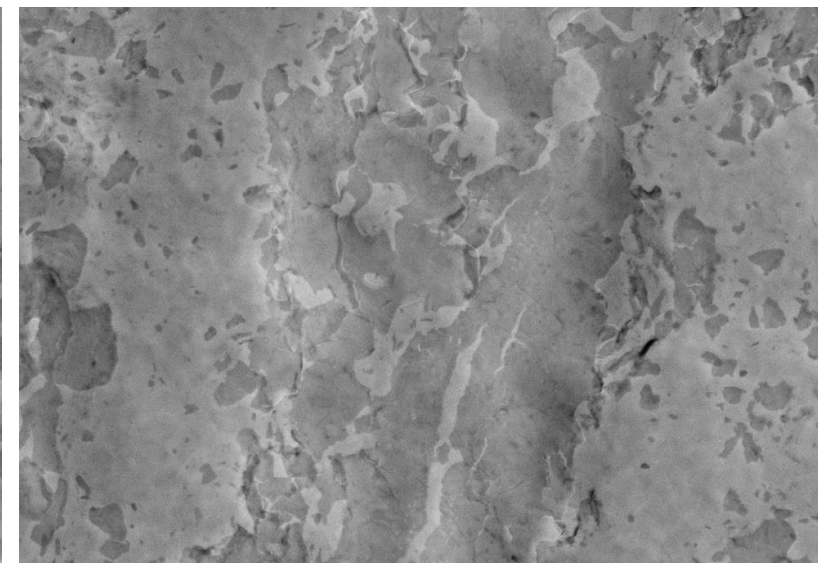
10 μm EHT = 15.00 kV WD = 9.9 mm Signal A = SE2 Sample ID = CuCrZr_irrad_LES_ Catarina Serafim Date: 14 Apr 2022 Mag = 1.00 K X EN



5 μm EHT = 15.00 kV WD = 9.9 mm Signal A = SE2 Sample ID = CuCrZr_irrad_LES_ Catarina Serafim Date: 14 Apr 2022 Mag = 3.00 K X EN

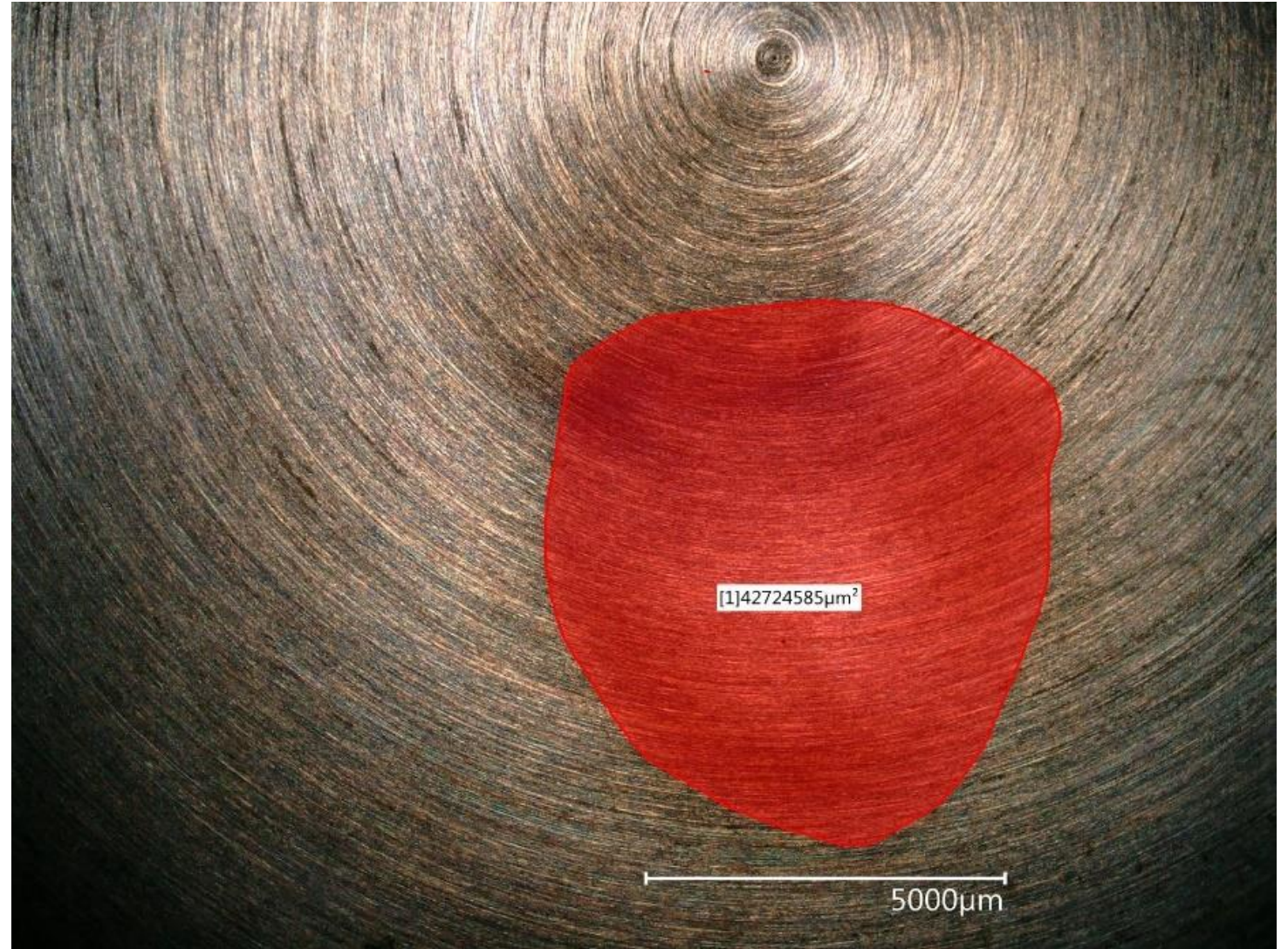
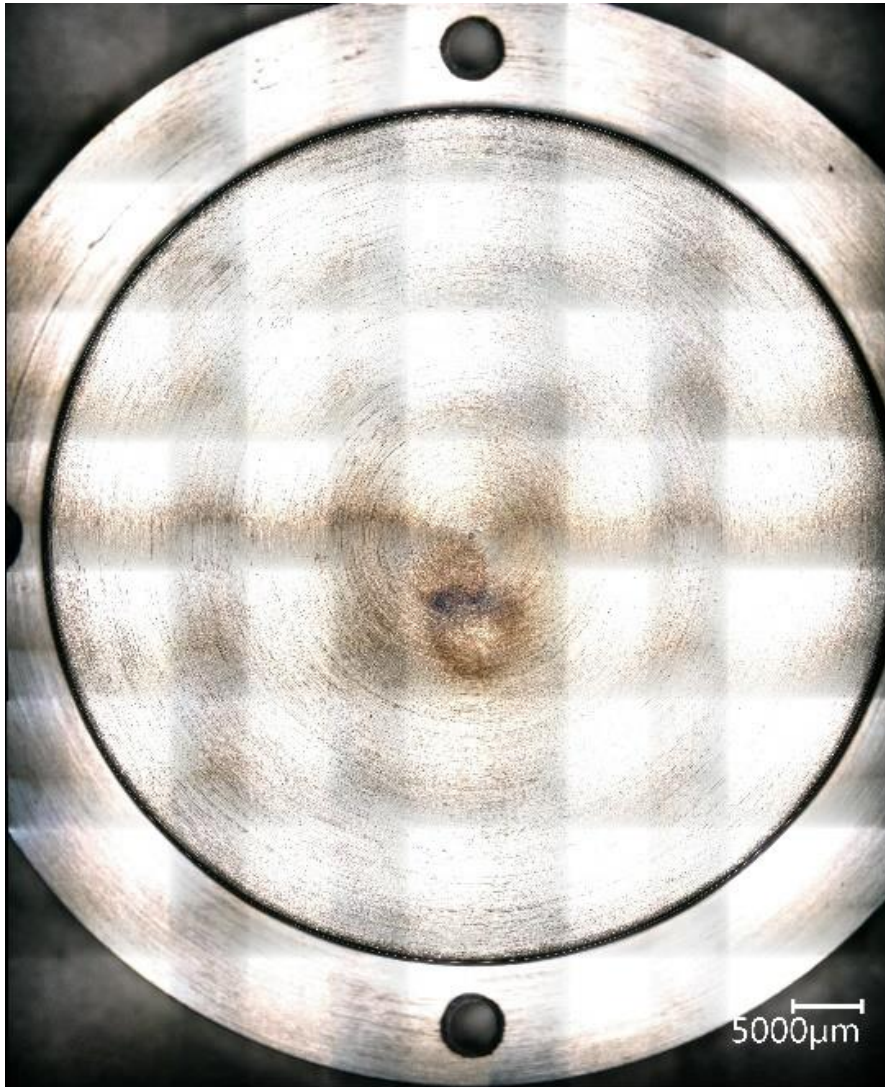


3 μm EHT = 15.00 kV WD = 9.9 mm Signal A = SE2 Sample ID = CuCrZr_irrad_LES_ Catarina Serafim Date: 14 Apr 2022 Mag = 5.00 K X EN



3 μm EHT = 15.00 kV WD = 9.9 mm Signal A = SE2 Sample ID = CuCrZr_irrad_LES_ Catarina Serafim Date: 14 Apr 2022 Mag = 5.00 K X EN

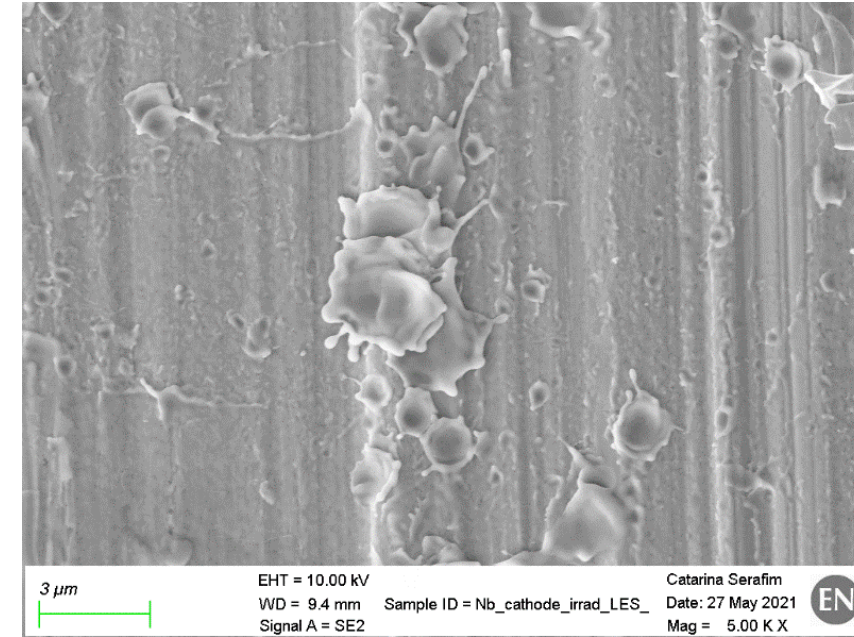
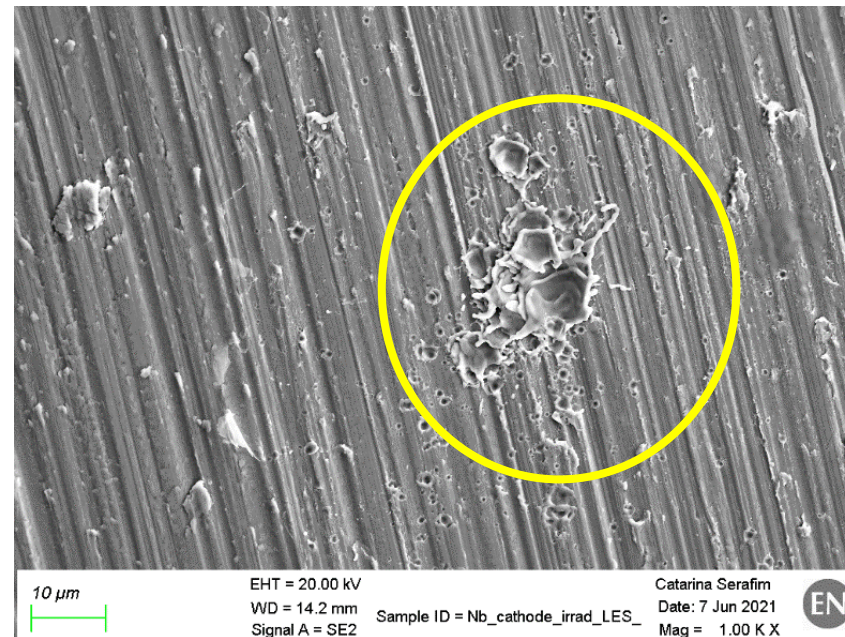
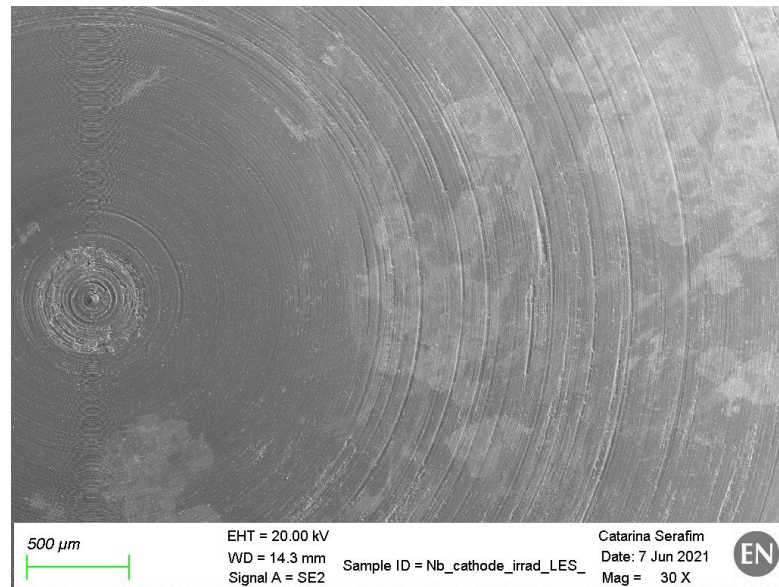
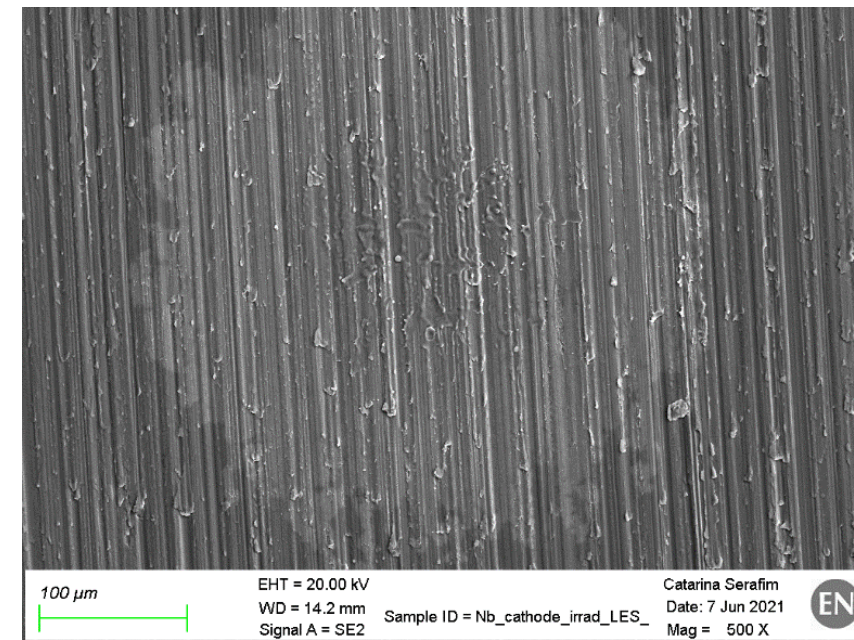
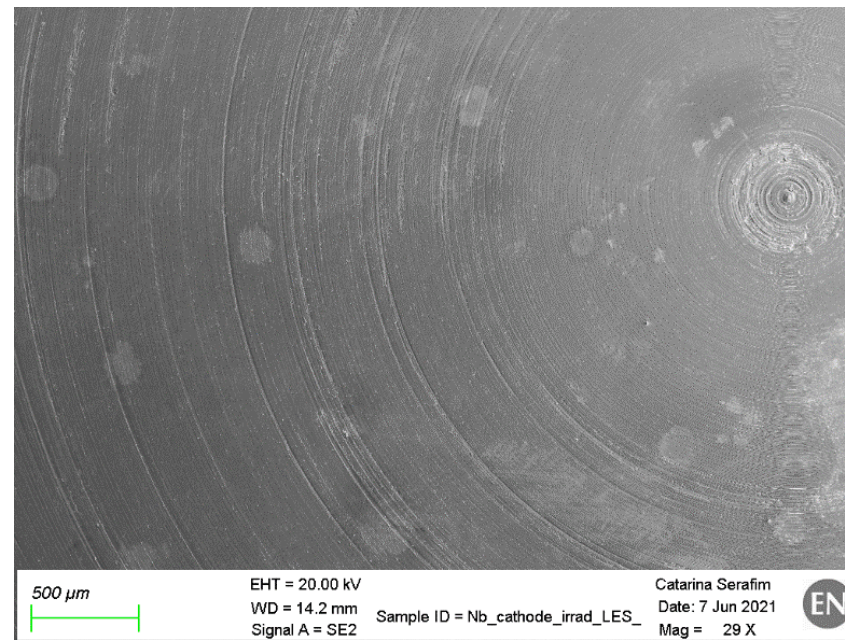
Irradiated Nb cathode



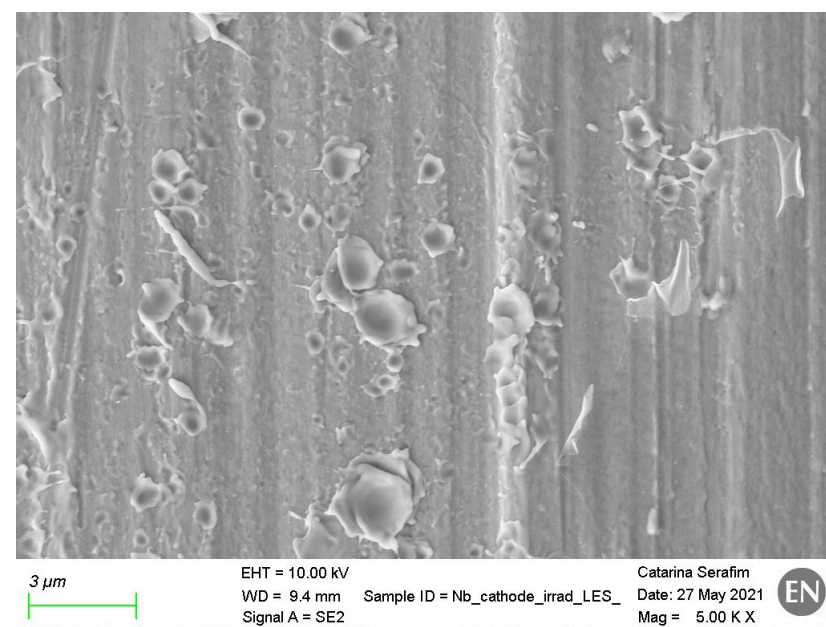
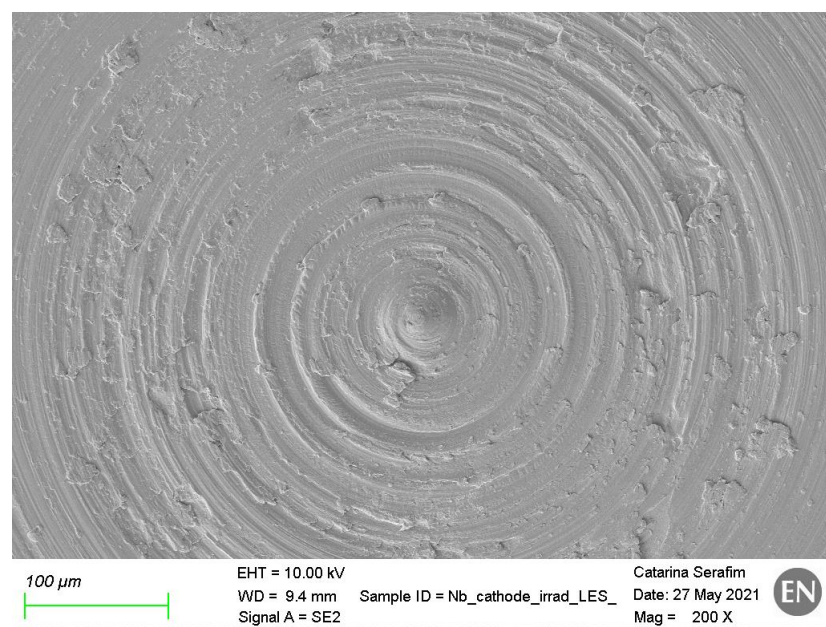
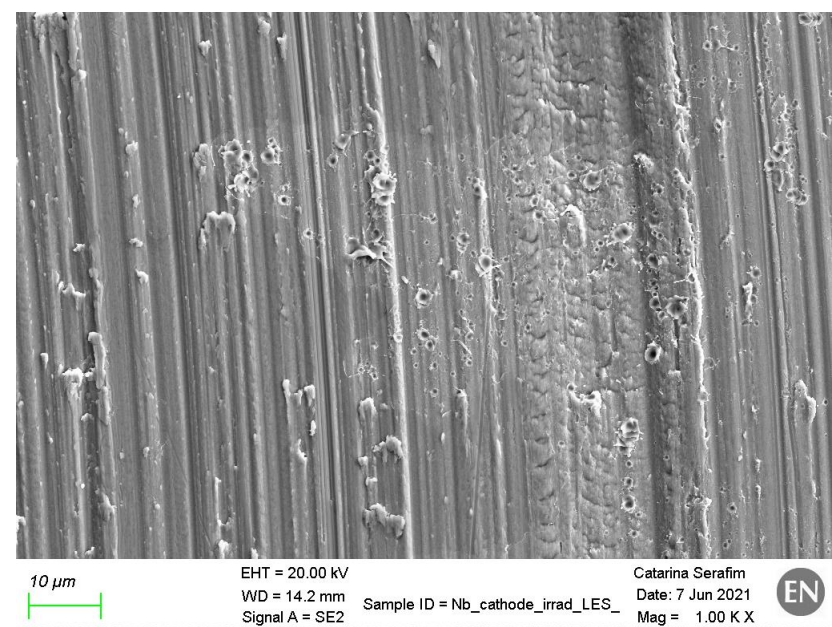
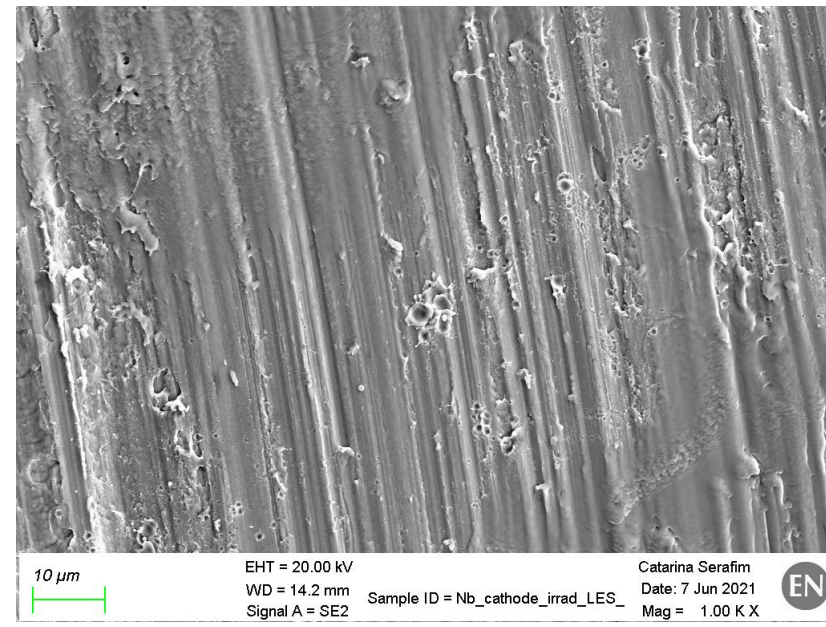
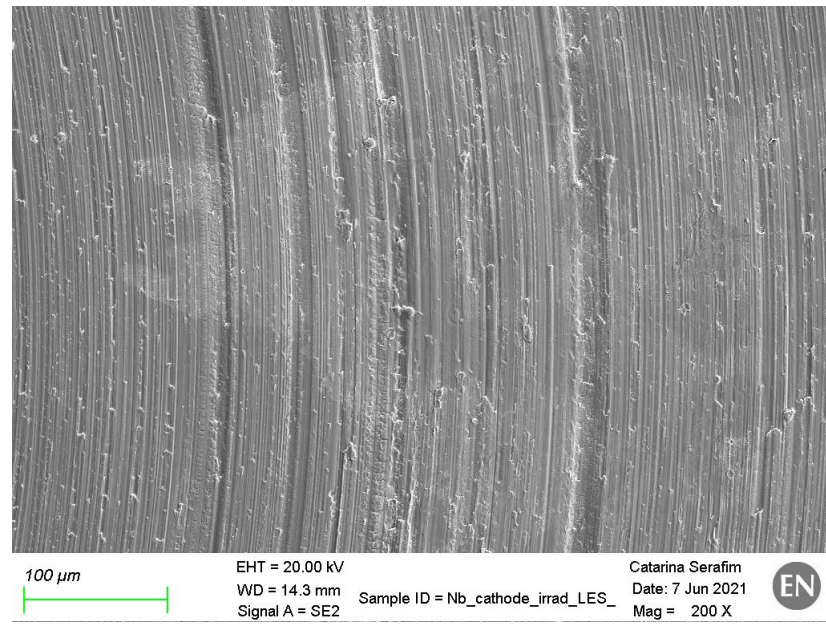
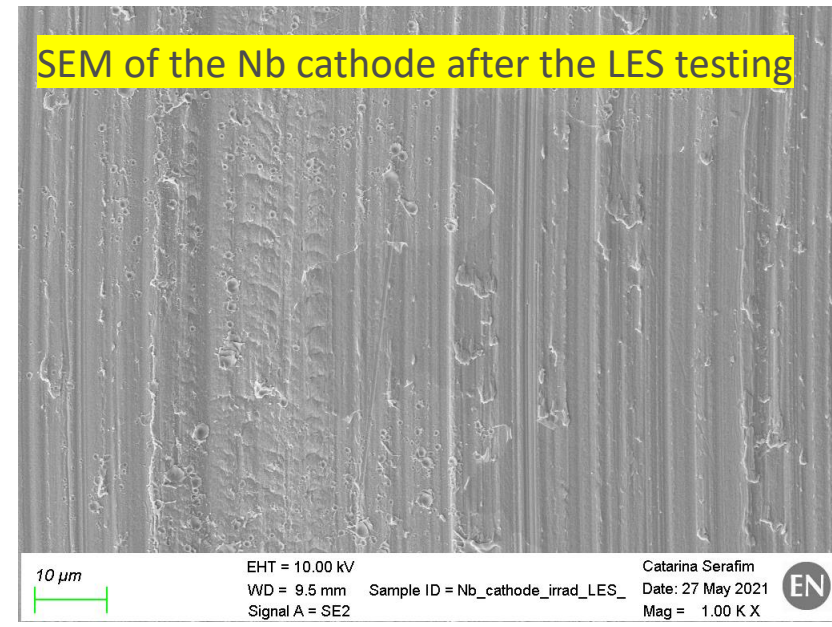
Optical Microscope image after irradiation. 2D Stitching 20x (left) and area of irradiated zone (right).

Irradiated Nb cathode

SEM images after LES testing -
Small breakdowns were
observed

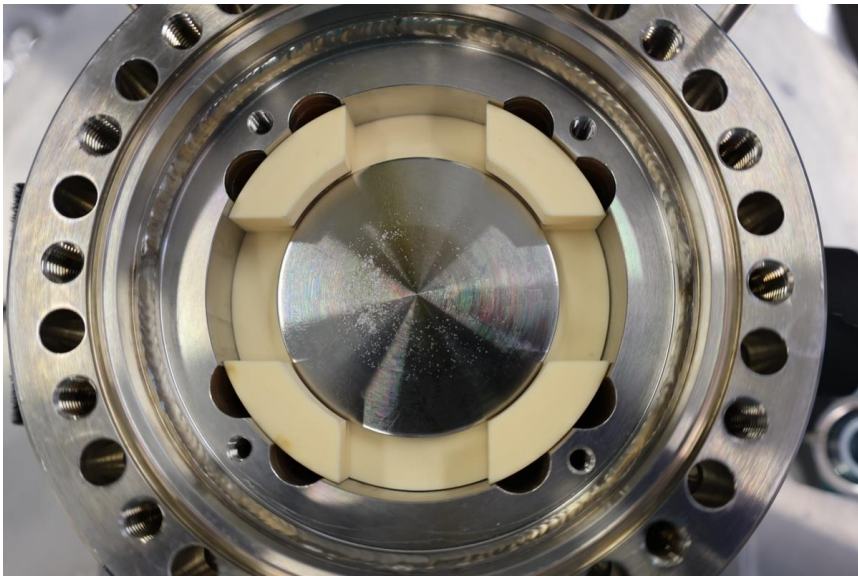
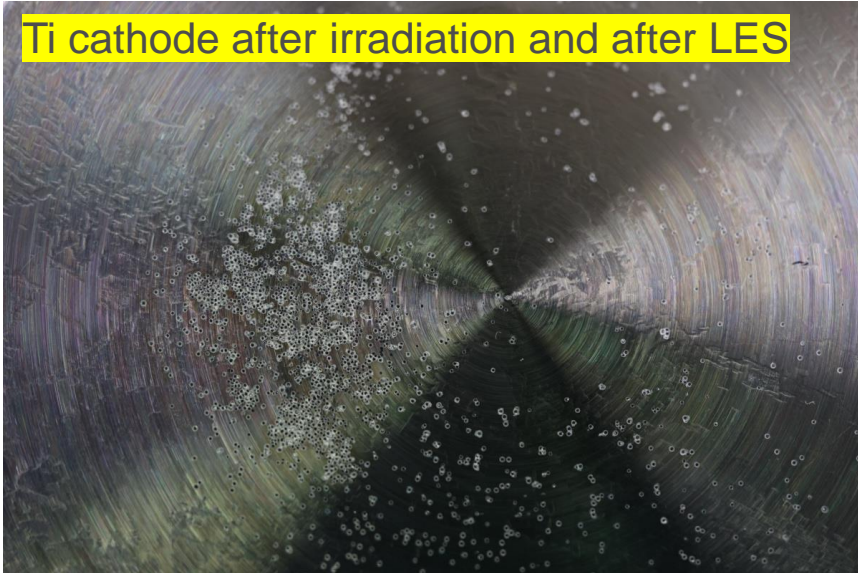


SEM of the Nb cathode after the LES testing

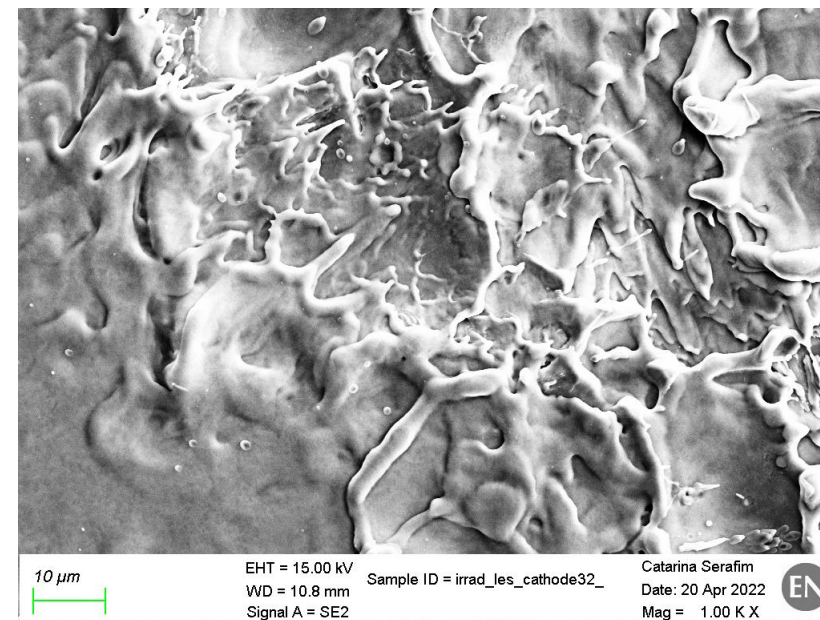
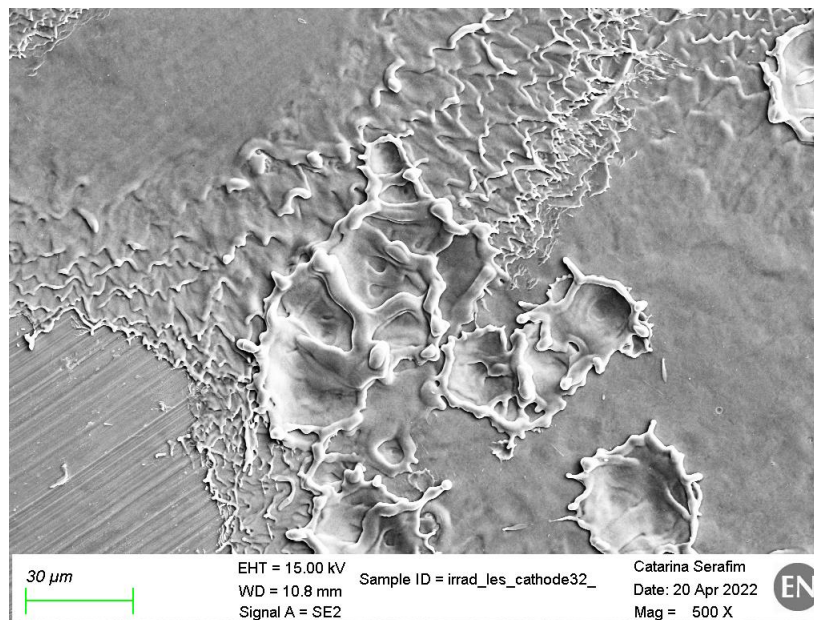
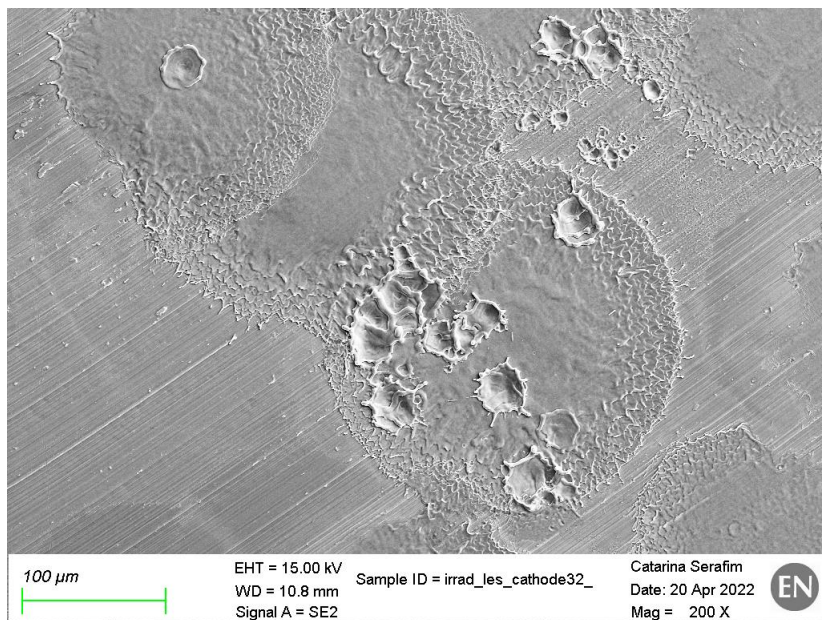
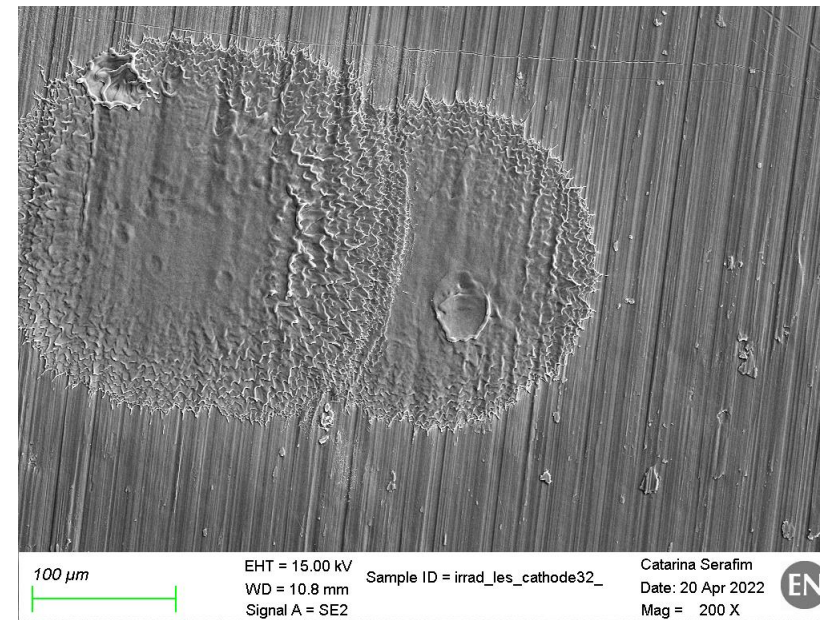
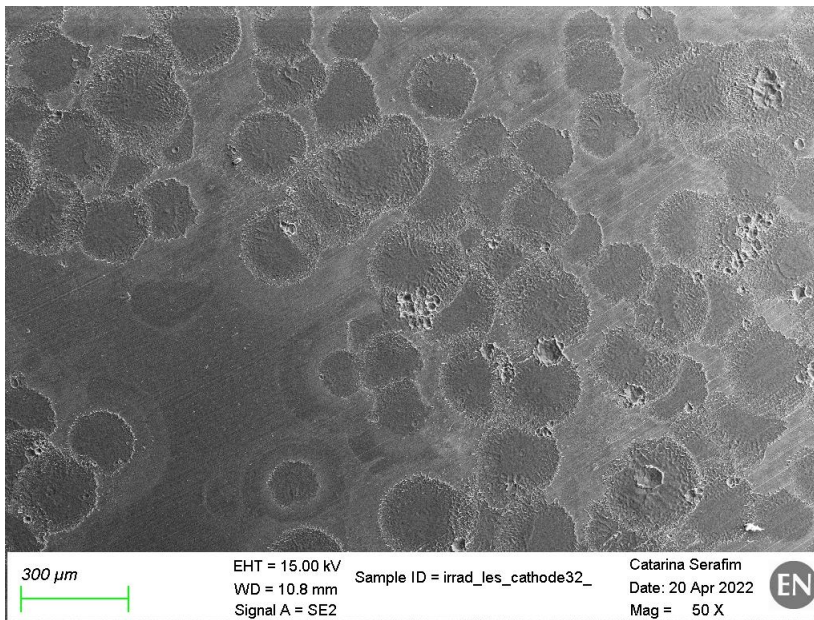
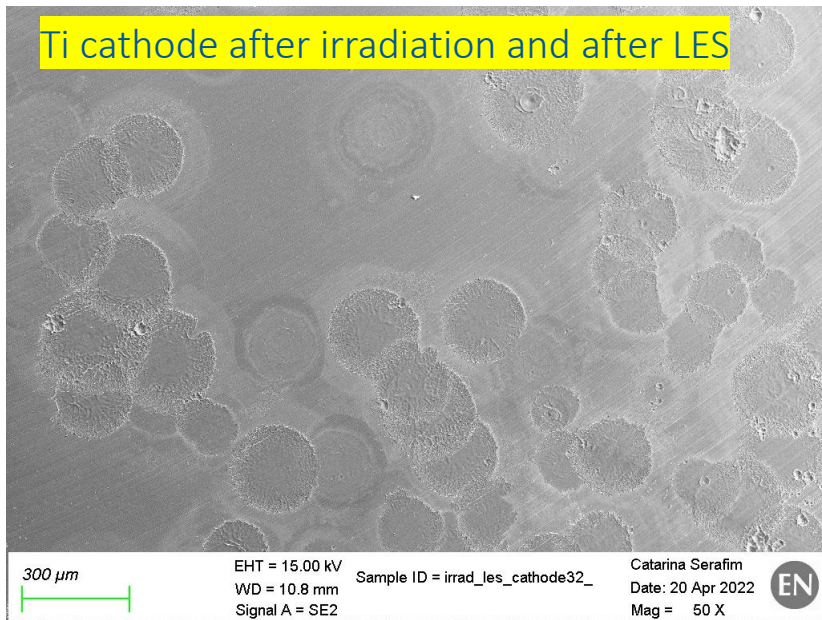


Irradiated Ti cathode after LES

Ti cathode after irradiation and after LES



Ti cathode after irradiation and after LES



SEM Conclusions from irradiation

Materials that we see blistering effects from irradiation:

- Cu-OFE
- CuCrZr
- CuBe2

No Blistering effects from irradiation:

- TiAl6V4
- Nb
- Ta

- ✓ These blisters are concentrated on the impact zone.
- ✓ It is visible that the areas where we had the maximum deposition of beam the blisters have a higher density in quantity comparing with zones where the beam was less intense.
- ✓ Blisters with different shapes and sizes

We have designated transition zone for the area where we start to see a decrease of density of blistering.

- ✓ In this zone it is visible that only some grains are affected by blisters.
- ✓ Blistering is more evident in just some of the grains may be correlated with the grain orientation of the material.

Additional studies are under study!

General Conclusions from LES

Material	Max E-Field (MV/m)	Stable E-Field (MV/m)	Pair of electrodes
Cu OFE	80	80	Irradiated pair
	83	83	Irradiated pair
	80	80	Non-irradiated pair
TiAl6V4	110	100	Irradiated pair
	95	90	Non-irradiated pair
CuCr1Zr	85	85	Irradiated pair
	29	26	Non-irradiated pair
Nb	94	80	Irradiated pair
	42	21.7	Non-irradiated pair
Ta	60	60	Irradiated pair
	38.1	24	Non-irradiated pair

Values from the LES system. Courtesy of Ruth Peacock.

- ✓ In general, breakdowns are located in all the surface of the electrode with no evidence of being triggered by any topographic feature caused by the irradiation.
- ✓ For the non-irradiated electrodes breakdowns have shown to be dispersed throughout all the surface.
- ✓ We have not observed, for all materials except Ta, a higher concentration of breakdowns in the irradiated zone.
- ✓ The materials CuCrZr, Nb and Ta present a big decrease of performance on the breakdowns testing after this electrodes have been submitted to irradiation.

General Conclusions

Material	Max E-Field (MV/m)	Stable E-Field (MV/m)	Pair of electrodes	Blistering from Irradiation
Cu OFE	80	80	Irradiated pair	Yes
	83	83	Irradiated pair	
	80	80	Non-irradiated pair	x
TiAl6V4	110	100	Irradiated pair	No
	95	90	Non-irradiated pair	x

- ✓ Cu-OFE and TiAl6V4 seem to be the best materials in reaching a stable field.
- ✓ The blistering effect from irradiation don't seem to provoke a decrease of performance on the electrodes

Future Work

- Continuing the study with the different materials;
- Additional studies with a new material (stainless steel) and bonding testing with TiAl6V4 + Cu
- Better understanding of Carbon deposition on the materials surface. Probably coming from irradiation;
- Study evolving Cu grain orientations and effects from irradiation/blistering.
- Possible irradiation experiments in Helsinki for comparison of results.