Comparative material study of breakdown threshold and robustness to low-energy proton irradiation

Catarina Serafim & Ruth Peacock

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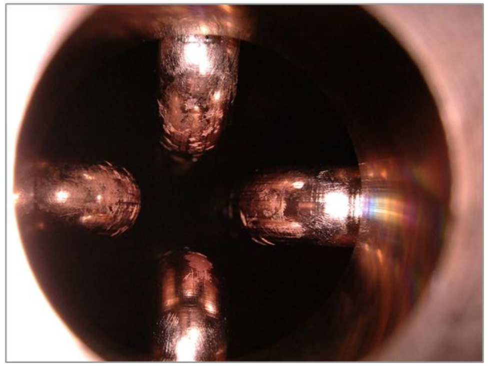
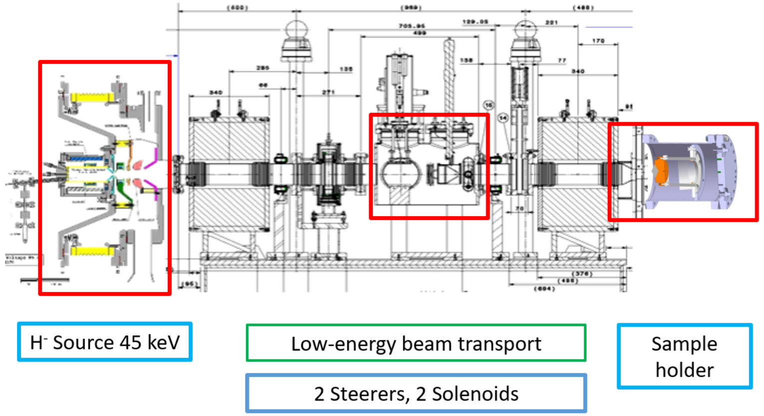
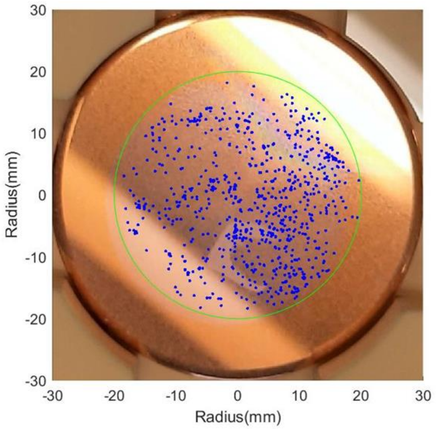
COMPARATIVE MATERIAL STUDY OF BREAKDOWN THRESHOLD AND ROBUSTNESS TO LOW-ENERGY PROTON IRRADIATION

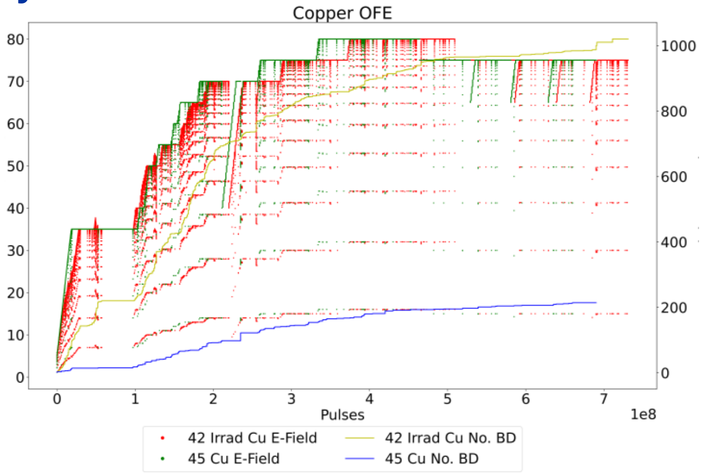
Authors: Catarina Filipa Da Palma Serafim, Ruth Peacock, Walter Wuensch, Sergio Calatroni, Ana Teresa Perez Fontenla, Alexej Grudiev, Alessandra Lombardi, Stefano Sgobba, Suitbert Ramberger, Giulia Bellodi, Edgar Sargsyan - CERN Organisation Européenne pour la Recherche Nucléaire, Geneva, Switzerland

RFQ H- Beam Loss Damage → Irradiated Electrode → Condition in the Pulsed DC System

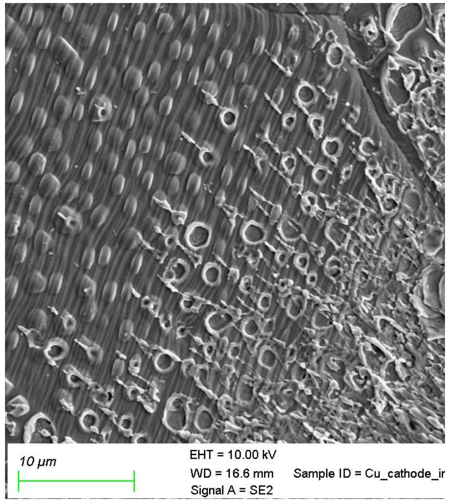


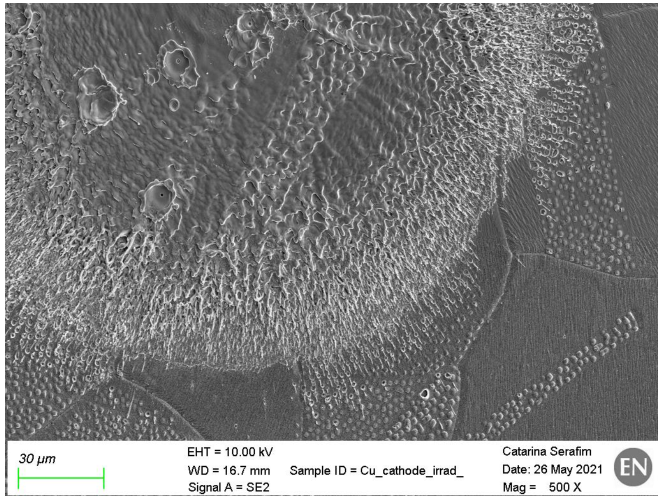


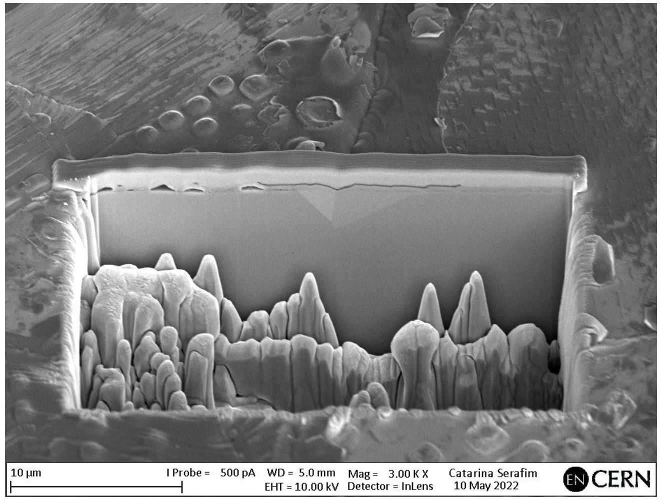




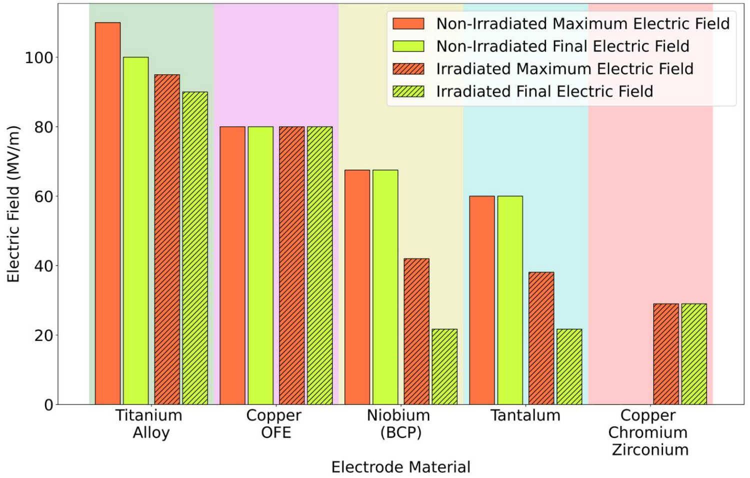
Microscopy Analysis





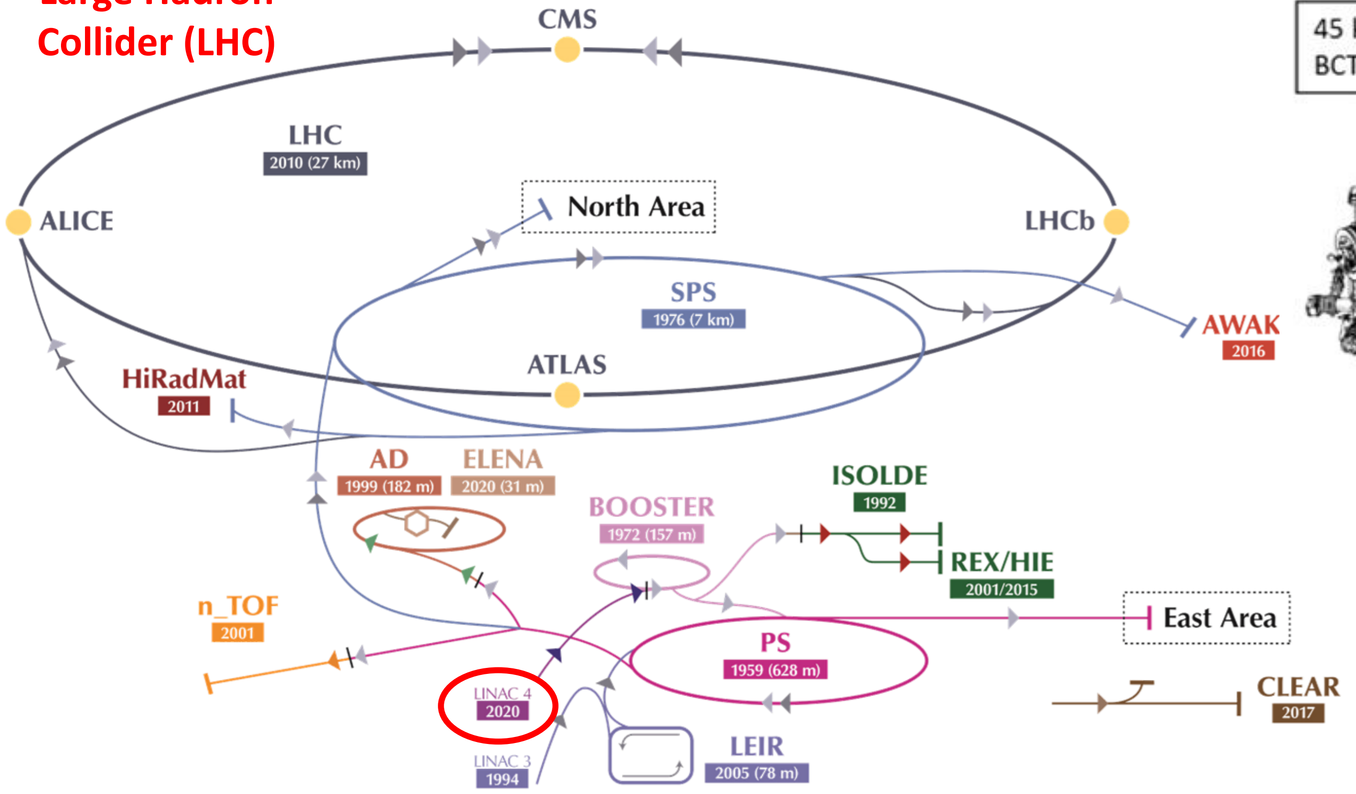


Summary

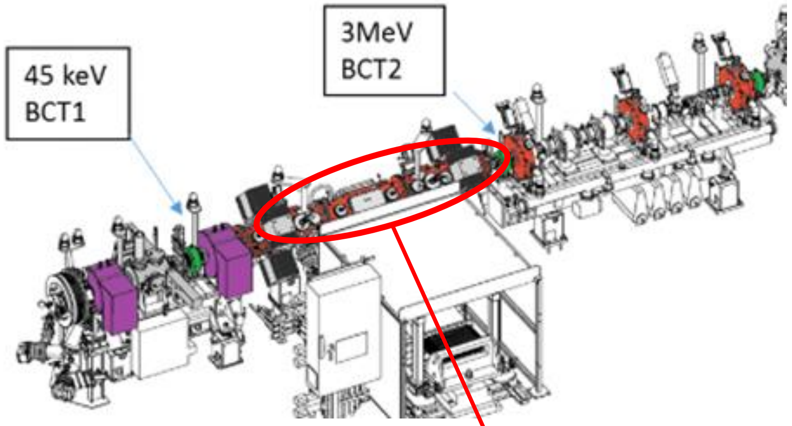


RFQ vane damage due to H- Beam loss

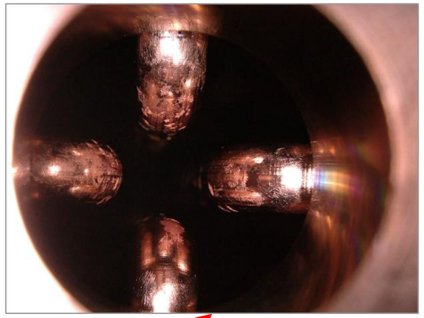
Large Hadron Collider (LHC)

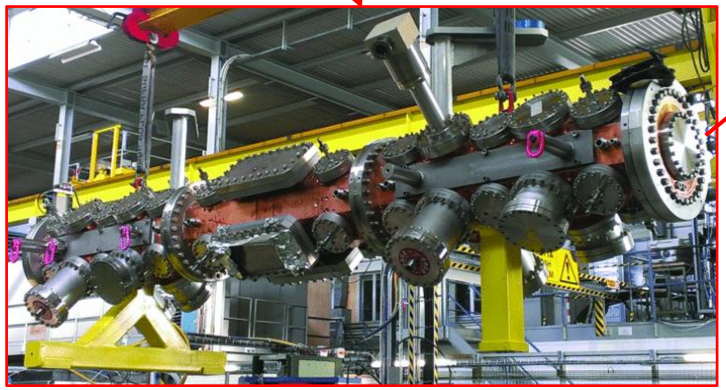


Linear Accelerator (LINAC) 4



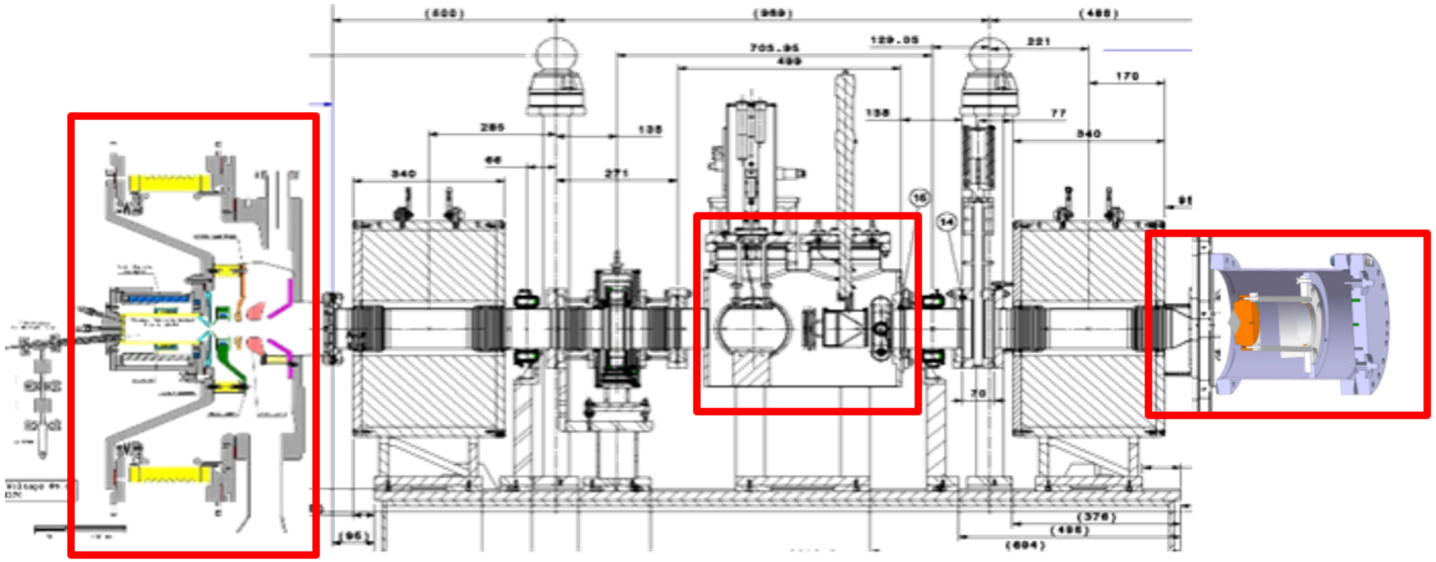
RFQ vane damage





Radio Frequency Quadrupole (RFQ)

Irradiation of Cathodes for Pulsed DC Tests



H^- Source 45 keV

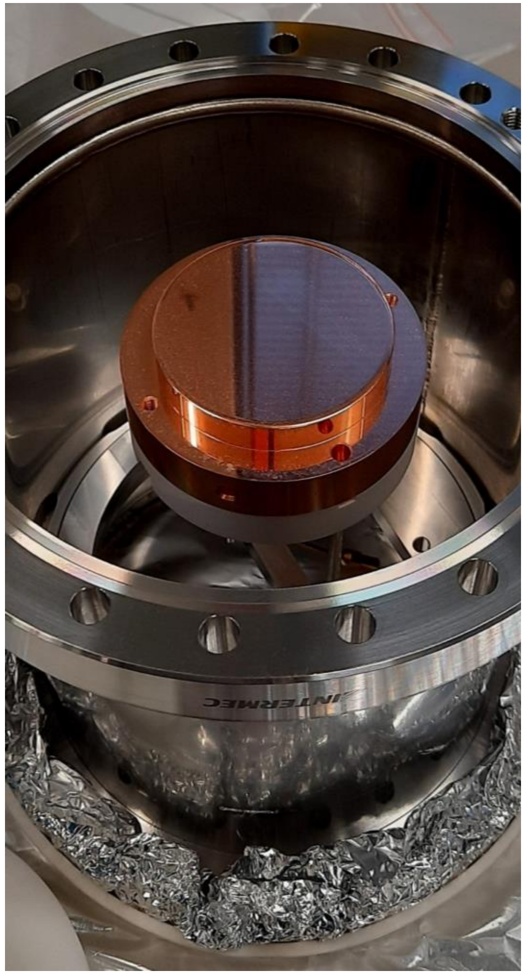
Low-energy beam transport

2 Steerers, 2 Solenoids

Sample holder

Irradiated with 10^19 H- on the target electrode

Before Irradiation



After Irradiation

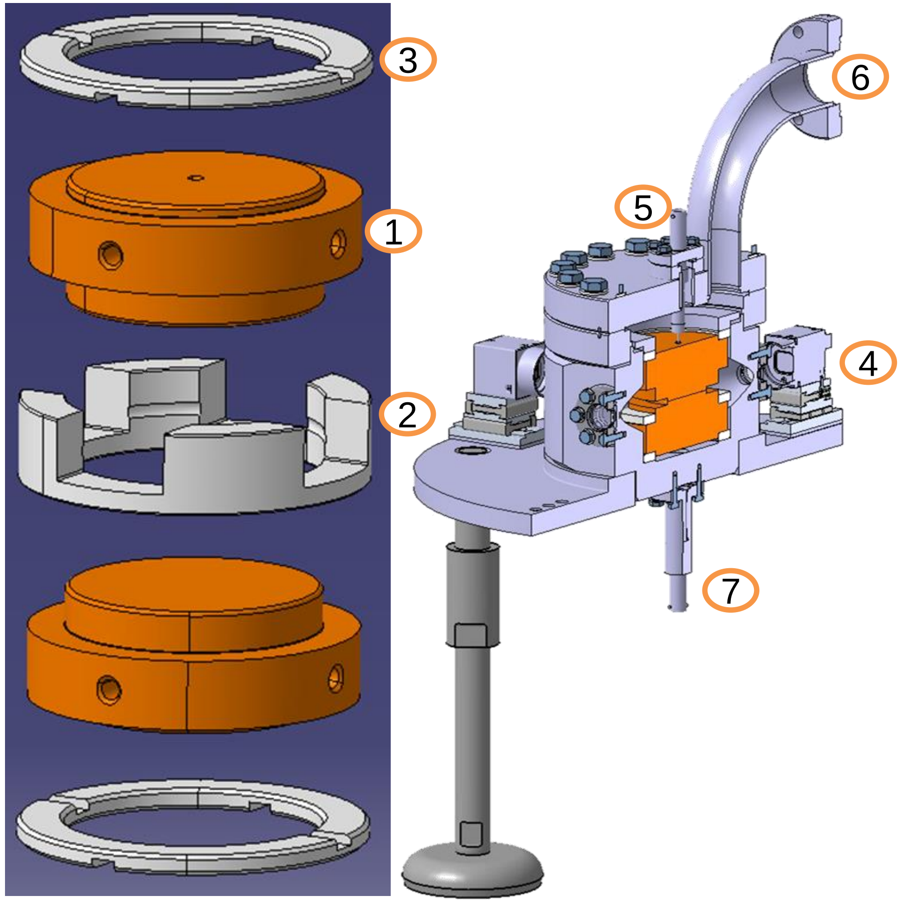
Irradiation

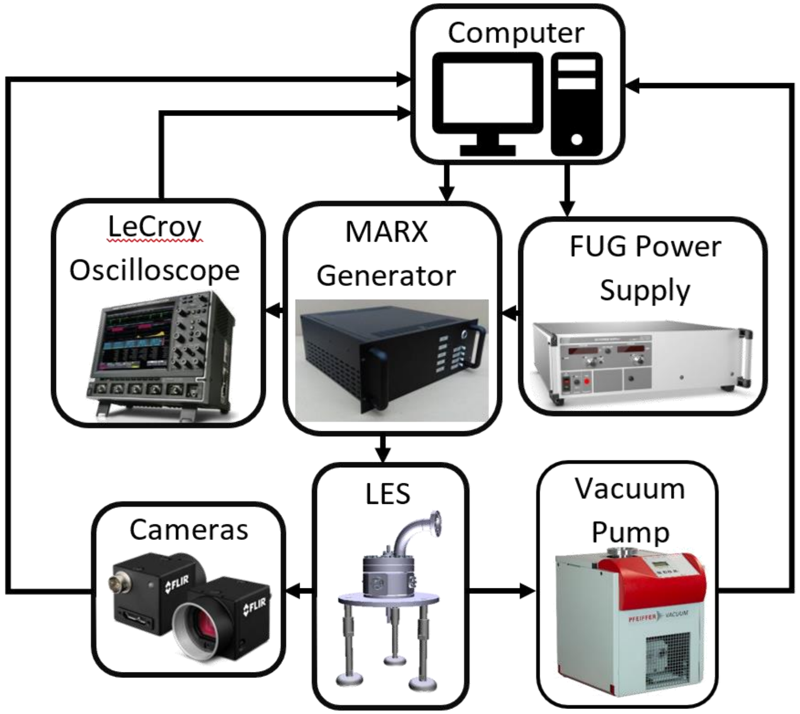
	2020	2021							2022	
	Cu-OFE	Nb	CuCr1Zr	CuCr1Zr	Ti6Al4V	Ta	Nb	Cu-OFE	CuBe2	Cu-OFE
Pair of electrodes	#40_RFQ	#43_RFQ	#50_RFQ	#50_RFQ (V2)	#47_RFQ	#XX_RFQ	#44_RFQ	#42_RFQ	#_RFQ	#_RFQ
Start Date	14/10/2020	26/01/2021	01/02/2021	03/09/2021	27/10/2021	10/12/2021	13/12/2021	16/12/2021	25/03/2022	29/03/2022
Start Time	18h00m	13h00m	13h00m	17h00m	12h50m	17h40m	16h23m	16h29m	15h00m	15h00m
End Date	16/10/2020	01/02/2021	03/02/2021	06/09/2021	29/10/2021	12/12/2021	15/12/2021	18/12/2021	27/03/2022	31/03/2022
End Time	08h30m	09h00m	14h00m	09h00m	19h40m	23h40m	20h17m	22h32m	21h25m	23h43m
Time of irradiation	40h	140h	50h	64h	55h	54h	52h	54h	55h	56h
Total N of H-	1.20E+19	4.88E+18	9.80E+18	1.31E+19	1.20E+19	1.20E+19	1.20E+19	1.20E+19	0.92E+19	1.16E+19
Current	22 - 31 mA	16 mA	16 mA	20 mA	20 mA	17 mA	21 mA	20 mA	18.5 mA	19.3 mA
Pulse length	600 us	600 us	600 us	600 us	600 us	600 us	600 us	600 us	600 us	600 us

Pulsed DC Large Electrode System

Configuration

1. 2 high precision machined electrodes (1µm tolerances)
2. High tolerance ceramic spacer between electrodes providing a gap of 20µm, 40µm, 60µm, or 100µm
3. Ceramic spacers to isolate electrodes from the chamber
4. 4 Windows and 2 perpendicular cameras
5. High voltage feed though
6. Vacuum pump output (5x10^-9)
7. Connection from the bottom electrode to ground (outside of system)





The MARX generator can pulse up to a rep rate of 6kHz and a minimum pulse length of 1µs.

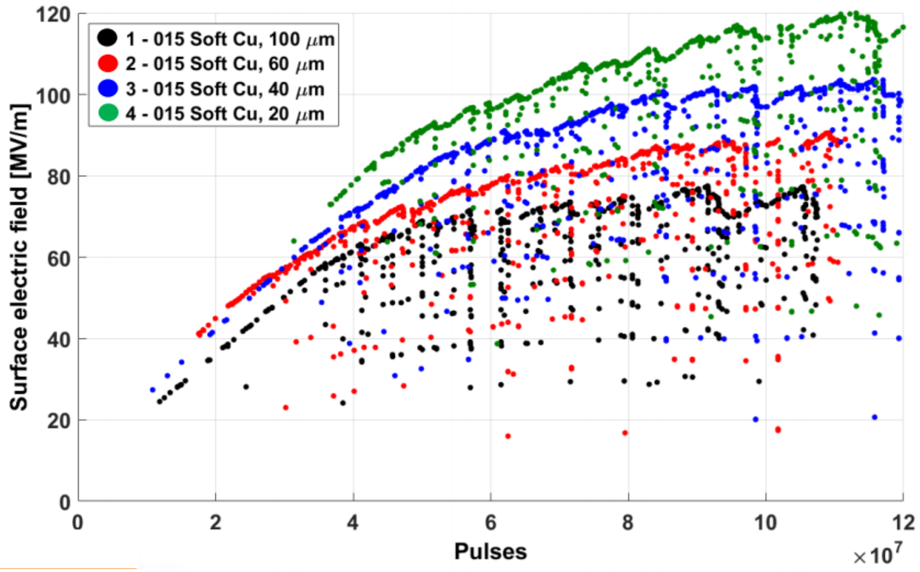
Measurements of the voltage and current supplied during a breakdown are measured whenever a breakdown is detected.

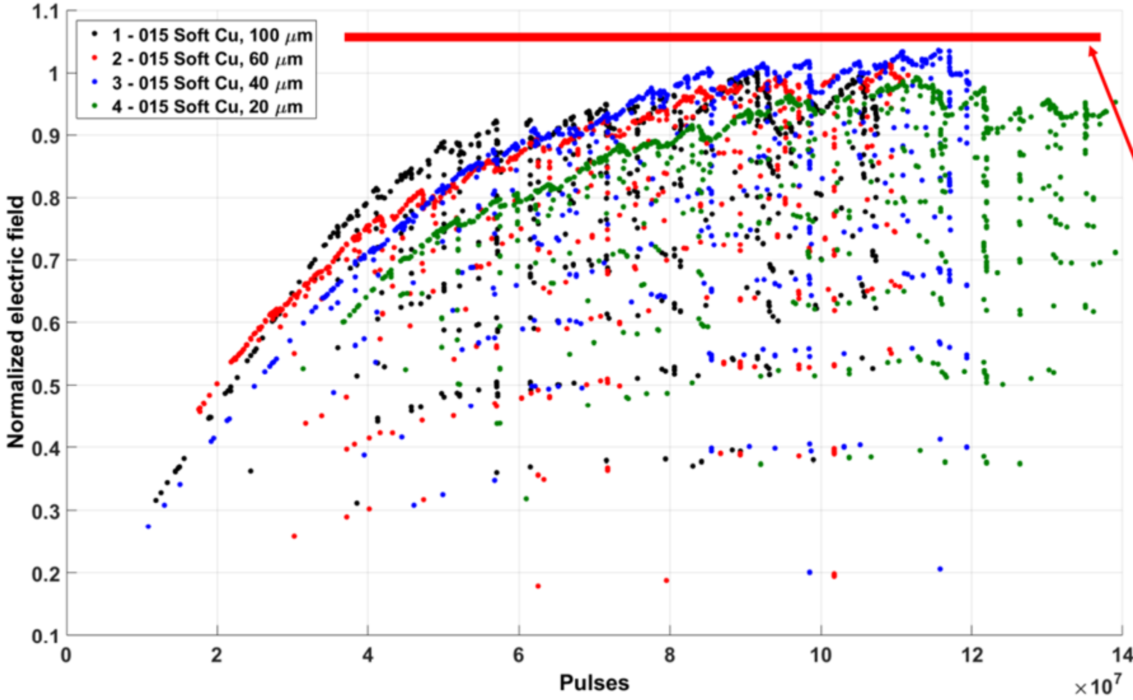
Normalised Field: Including effect of gap distance

$$E = \frac{V}{d}$$

Making one step further gives the connection: L4-RFQ <-> DC setup

$$Normalised\ Field\ Holding = \left(\frac{V}{V_{max}}\right) \times \left(\frac{d_{max}}{d}\right)^{0.72}$$





$V_{max} = 7747\ V$

$d_{max} = 100\ \mu m$

V = 78.3 kV;

Es = 34 MV/m

d = V/Es

=>

NFH = 1.05

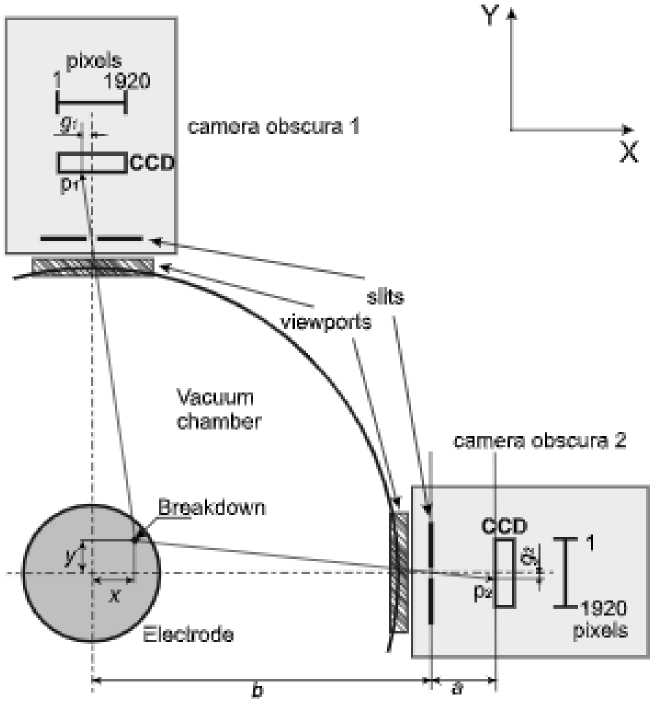
Iaroslava Profatilova - https://indico.cern.ch/event/774138/contributions/3507941/attachments/1911936/3160618/7_IProfatilova_MeVArc2019.pdf

Alexej Grudiev - https://indico.cern.ch/event/925403/contributions/3889048/attachments/2050505/3436872/20200604_WP_RFQ3_design_Introduction.pdf

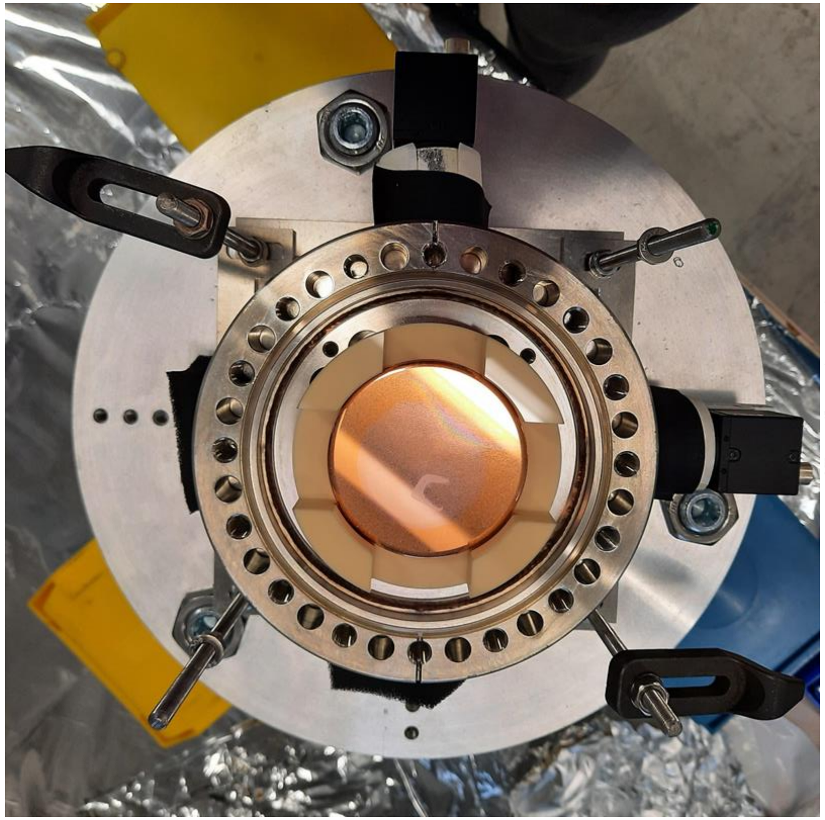
Normalised Field Holding Calculations

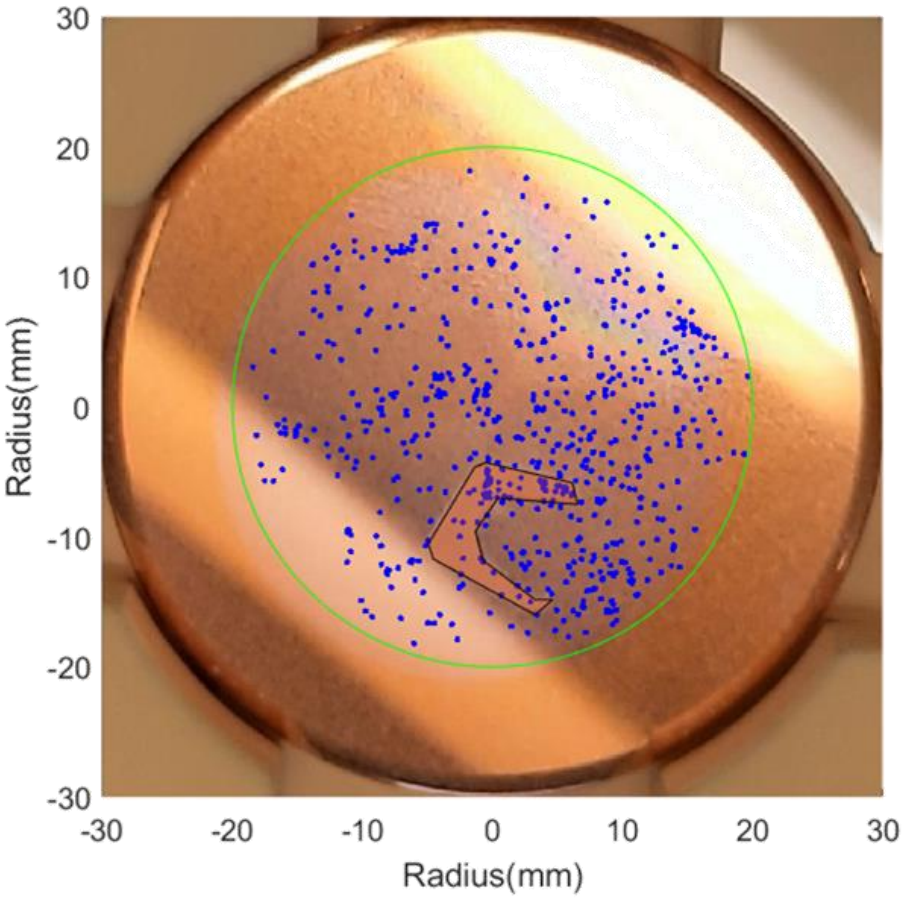
- The surface field in the RFQ is 34MV/m, the target surface electric field for this electrode test was 35 MV/m
- 35MV/m with a gap of 60μm gives a voltage of 2100V and a normalised field holding of 0.3915
- The normalised field holding of the RFQ is 1.0563 giving a voltage of 5664.9V and surface electric field for a 60μm gap of 94MV/m
- Assuming the gap size scaling holds we would need to reach a field of 94MV/m in the Pulsed DC System
- We first went to a field of 35MV/m then attempted to increase to 94MV/m

Pulsed DC System Breakdown Localisation

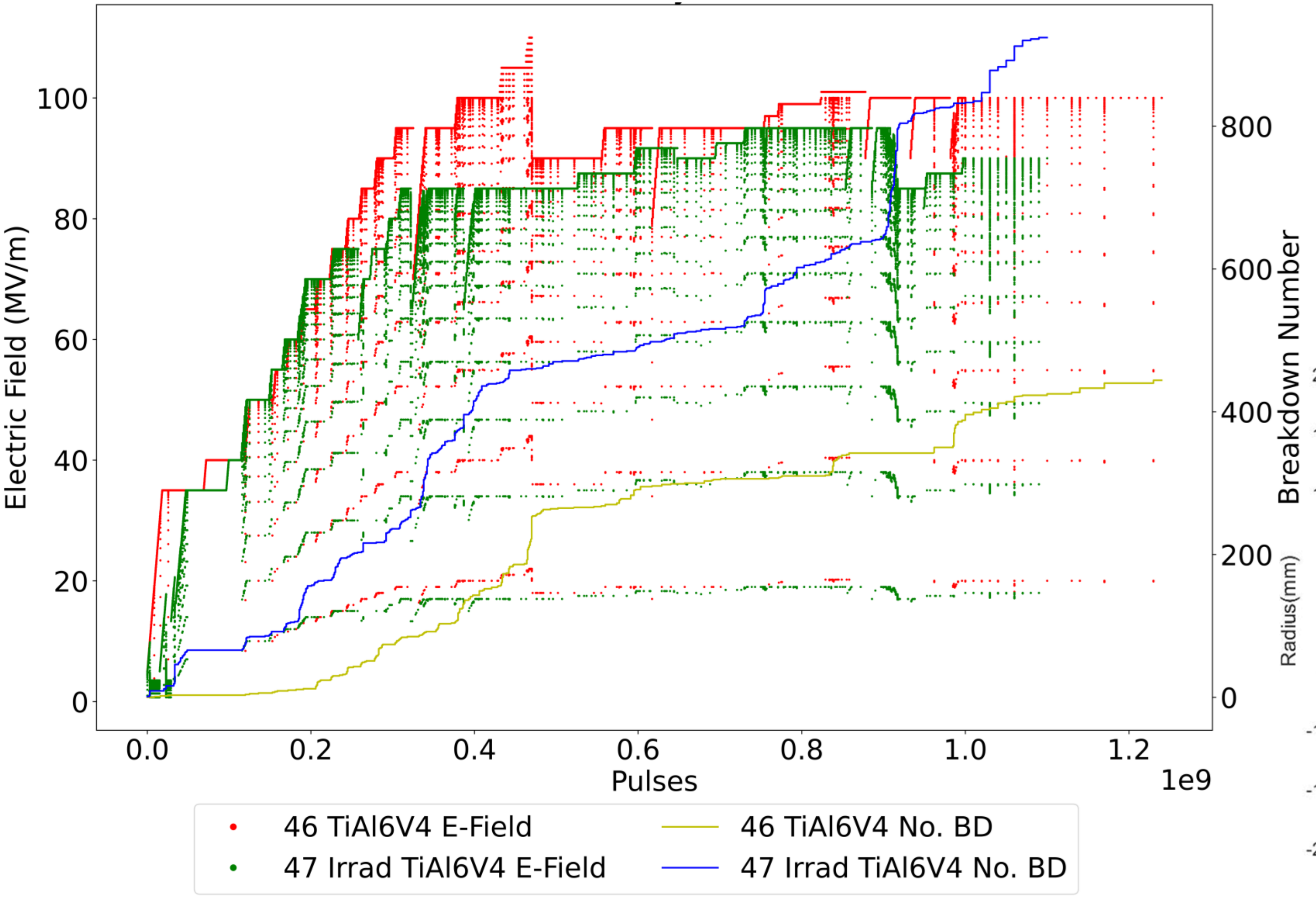


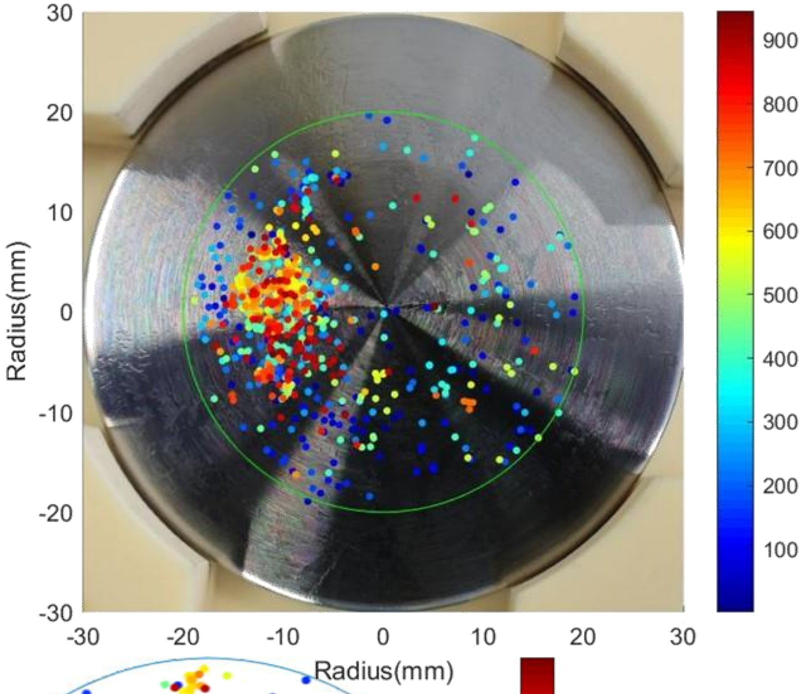
(2019). Breakdown localisation in a pulsed DC electrode system. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 953. 10.1016/j.nima.2019.163079.

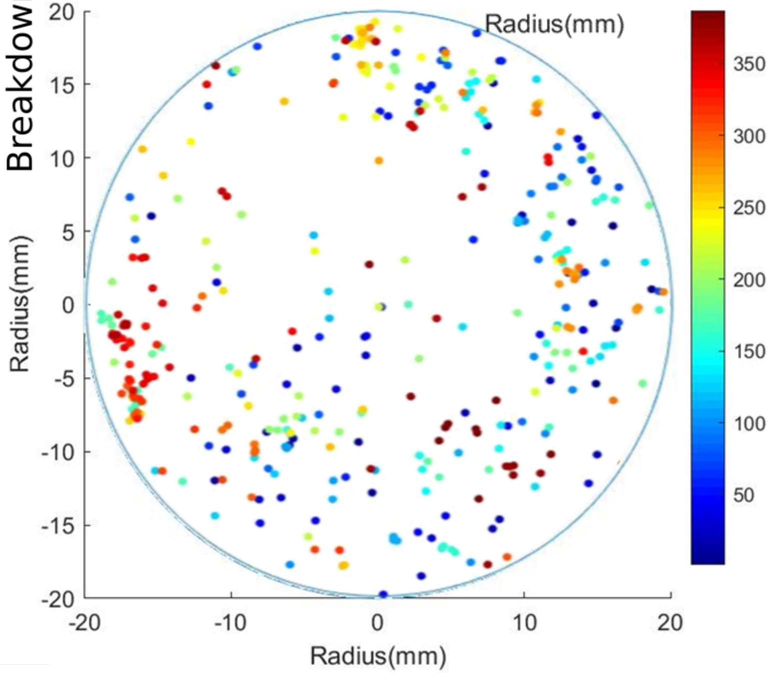




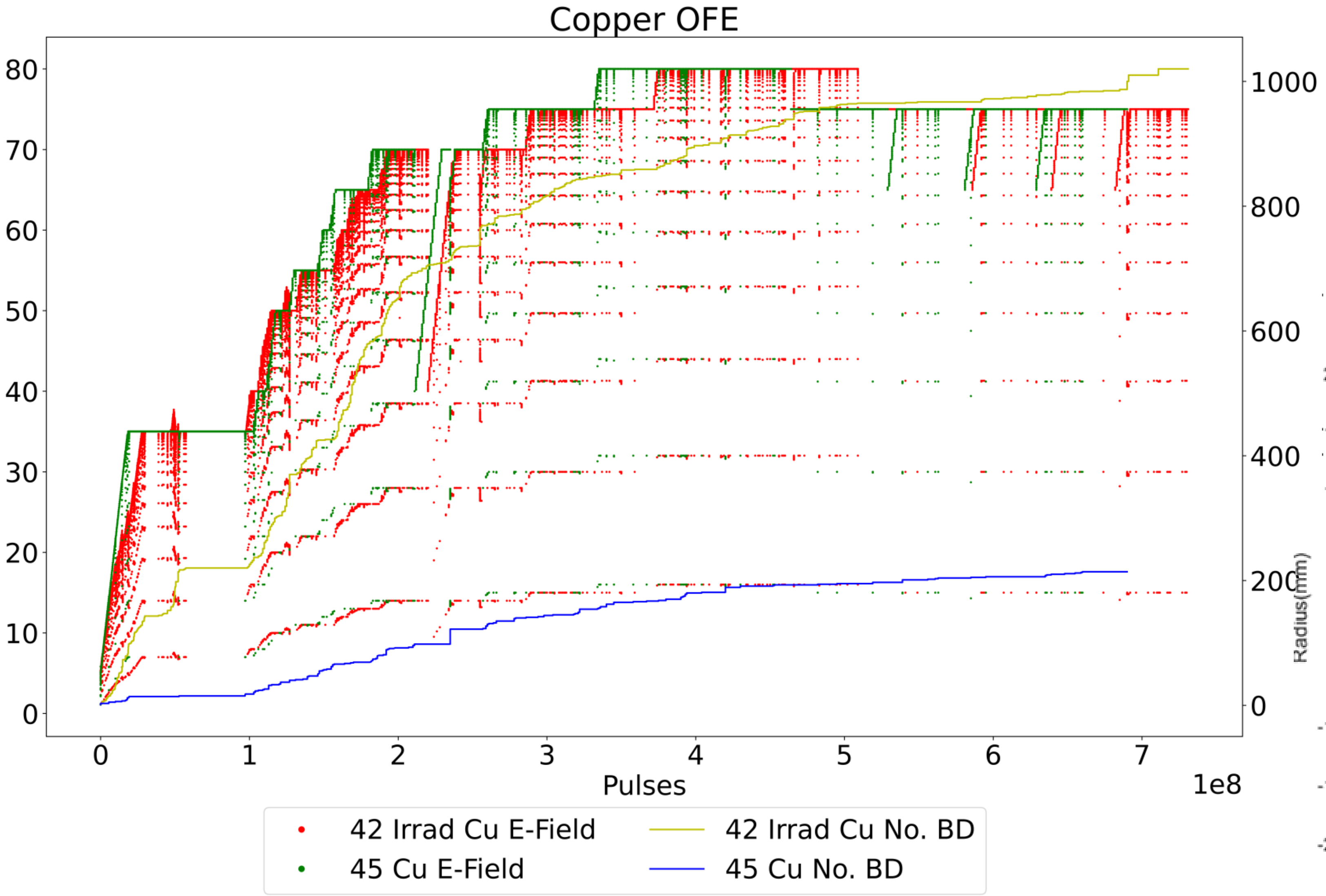
Titanium Alloy (TiAl6V4)



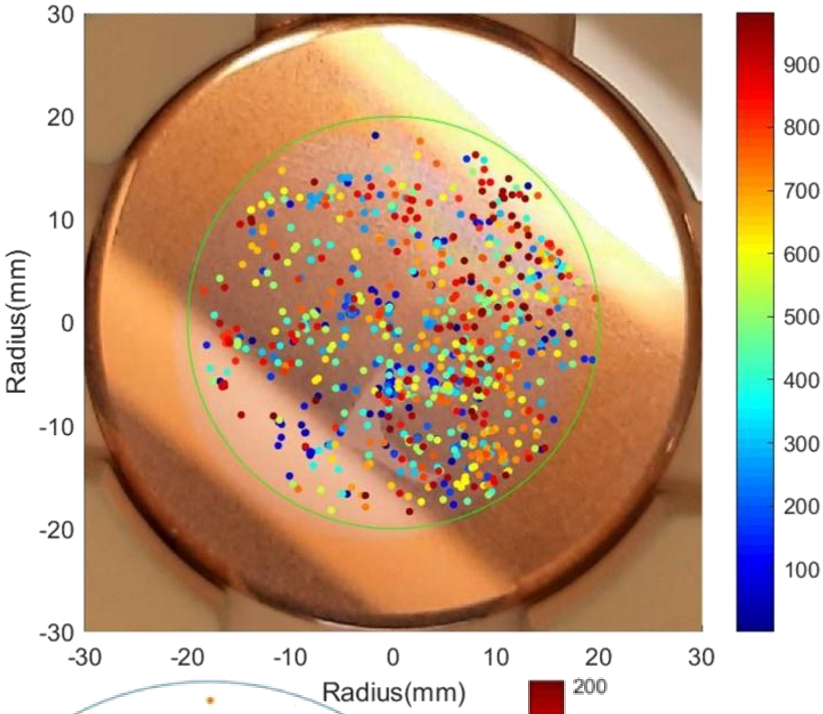




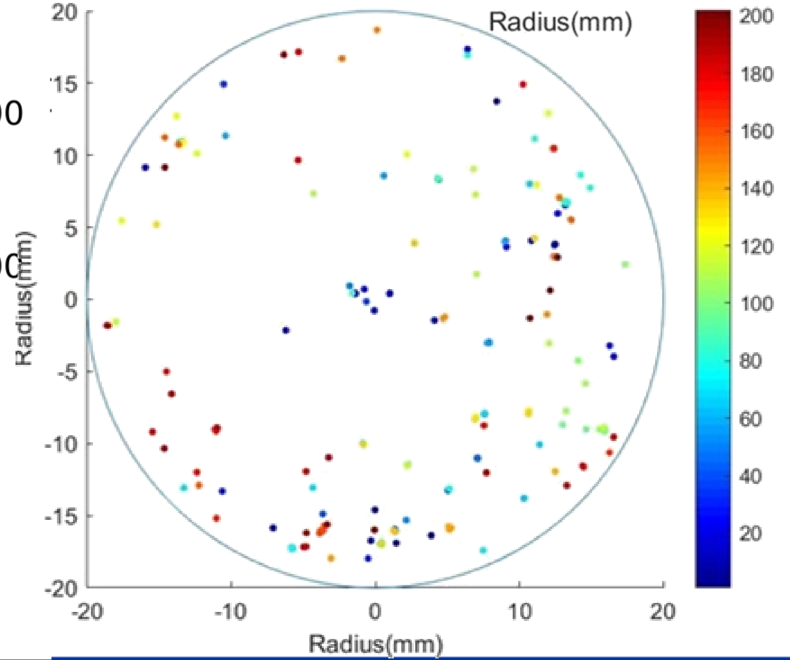
Copper OFE



Copper OFE
80
70
60
50
40
30
20
10
0
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
Pulses
1e8
42 Irrad Cu E-Field
45 Cu E-Field
42 Irrad Cu No. BD
45 Cu No. BD

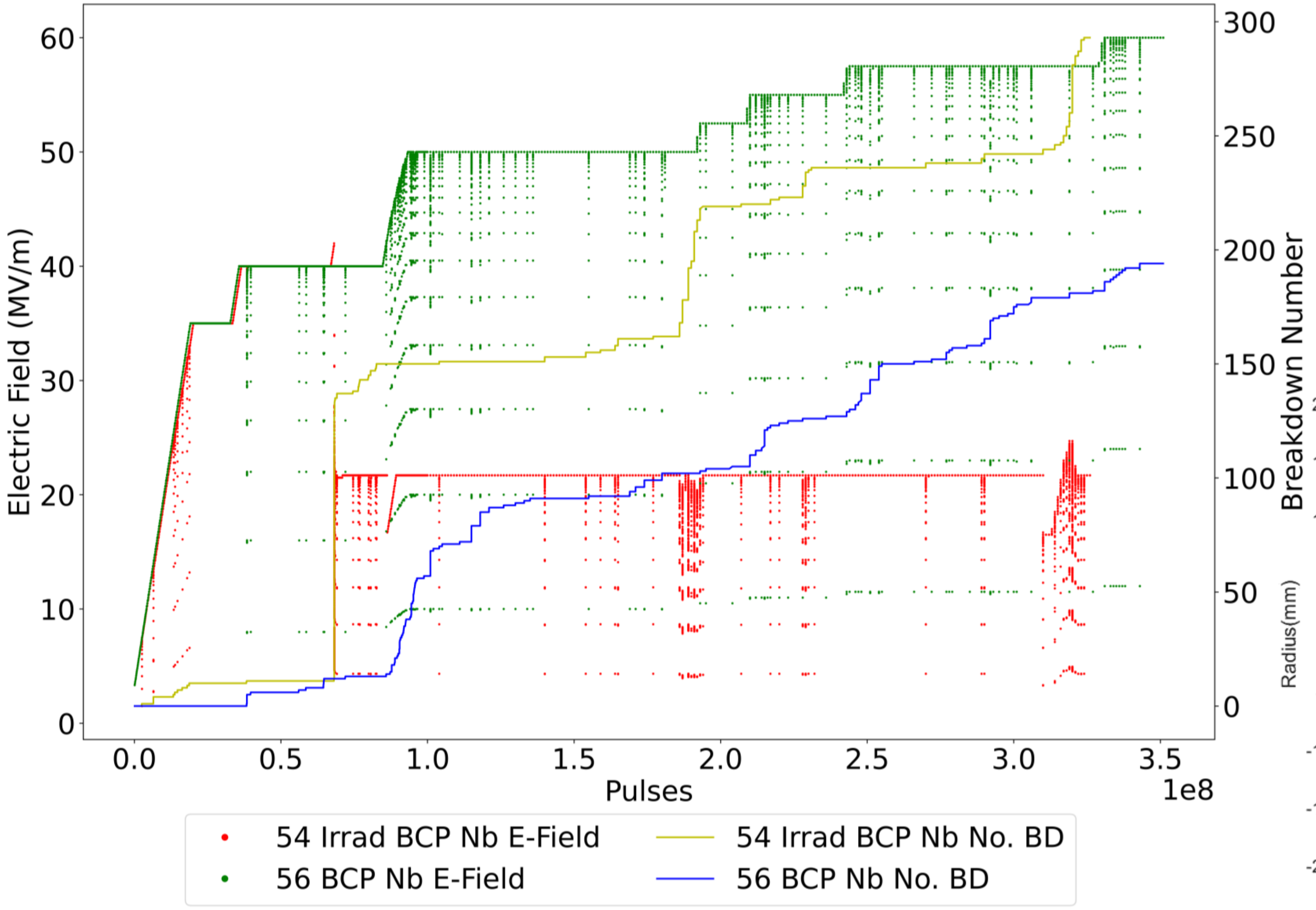


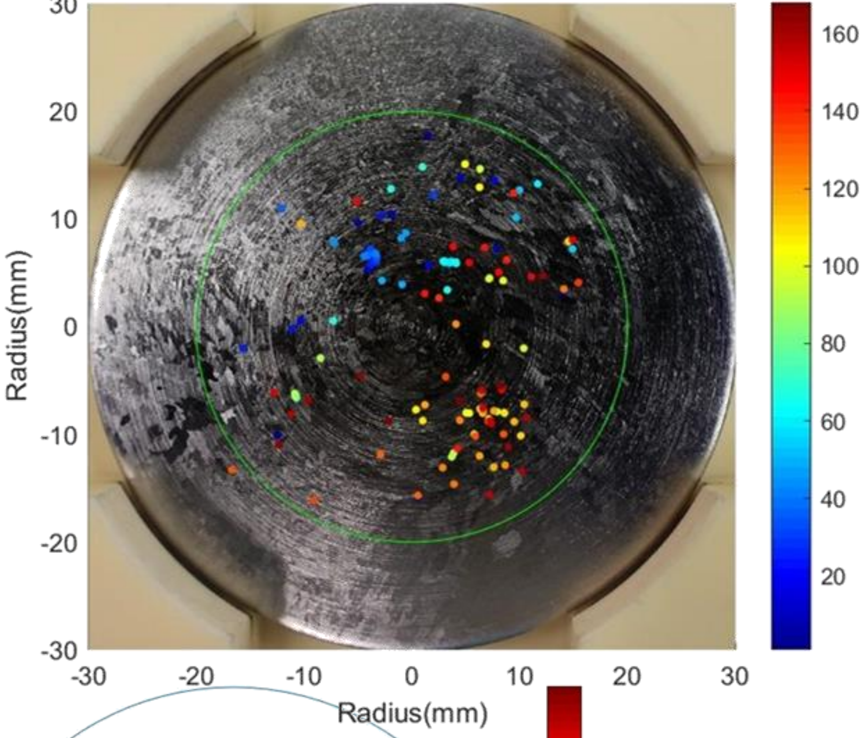
Radius(mm)
Radius(mm)
900
800
700
600
500
400
300
200
100

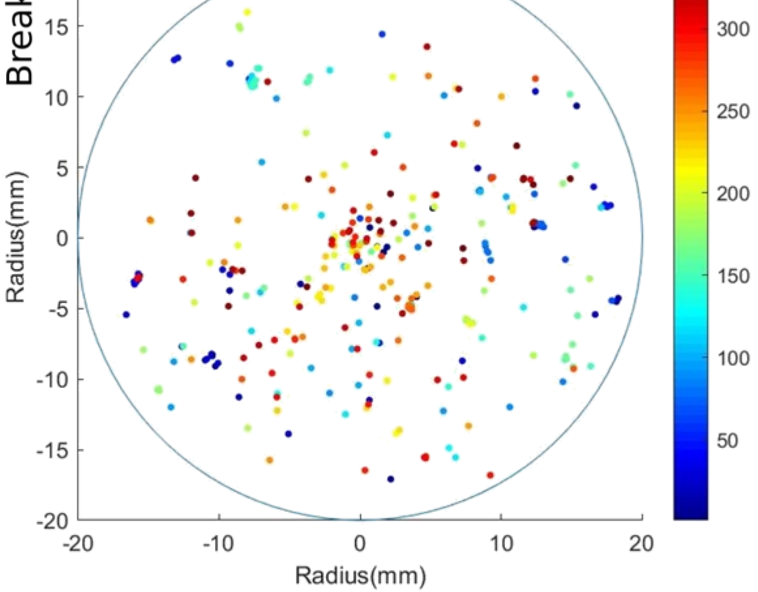


Radius(mm)
Radius(mm)
200
180
160
140
120
100
80
60
40
20

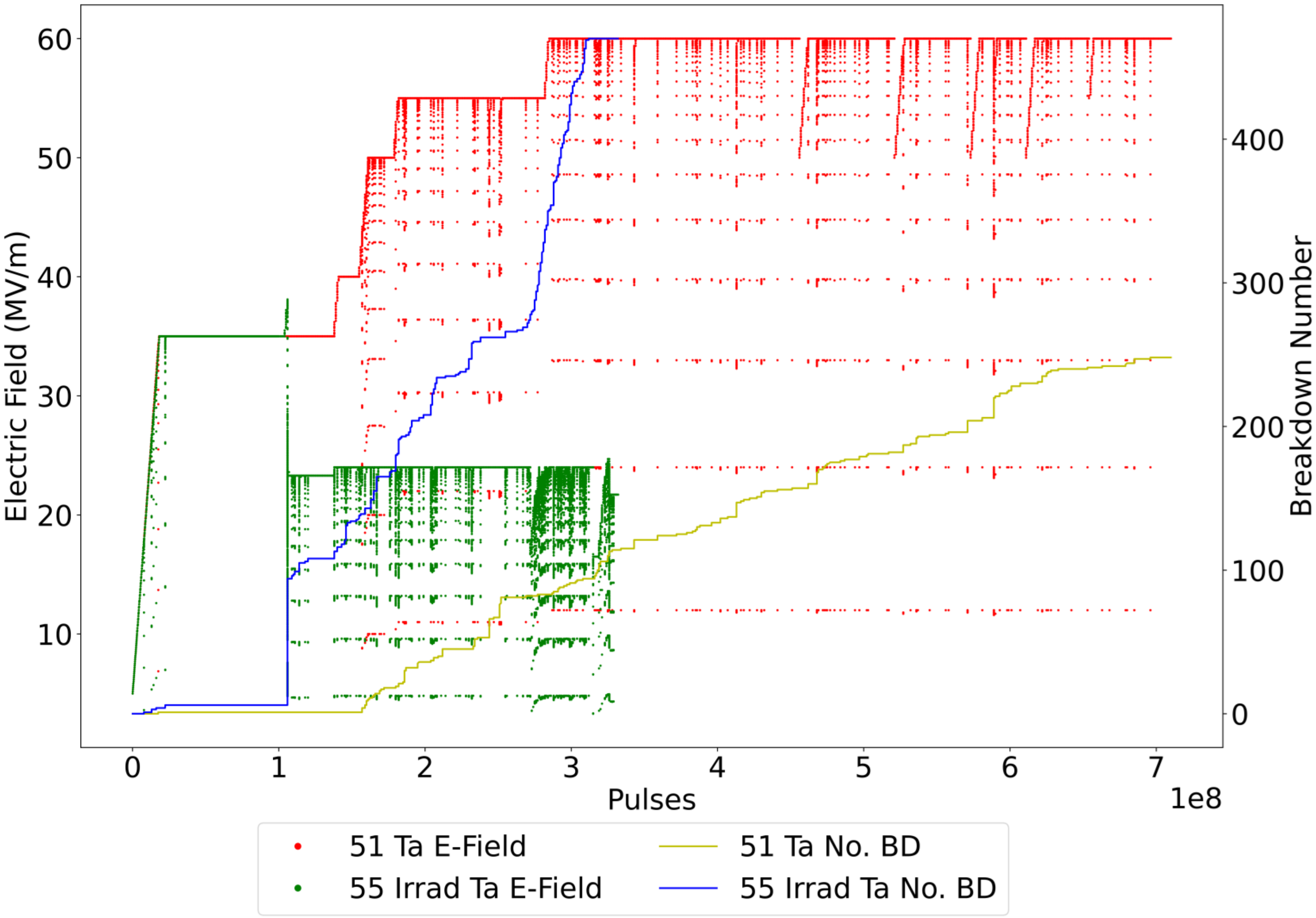
Niobium (Nb BCP)

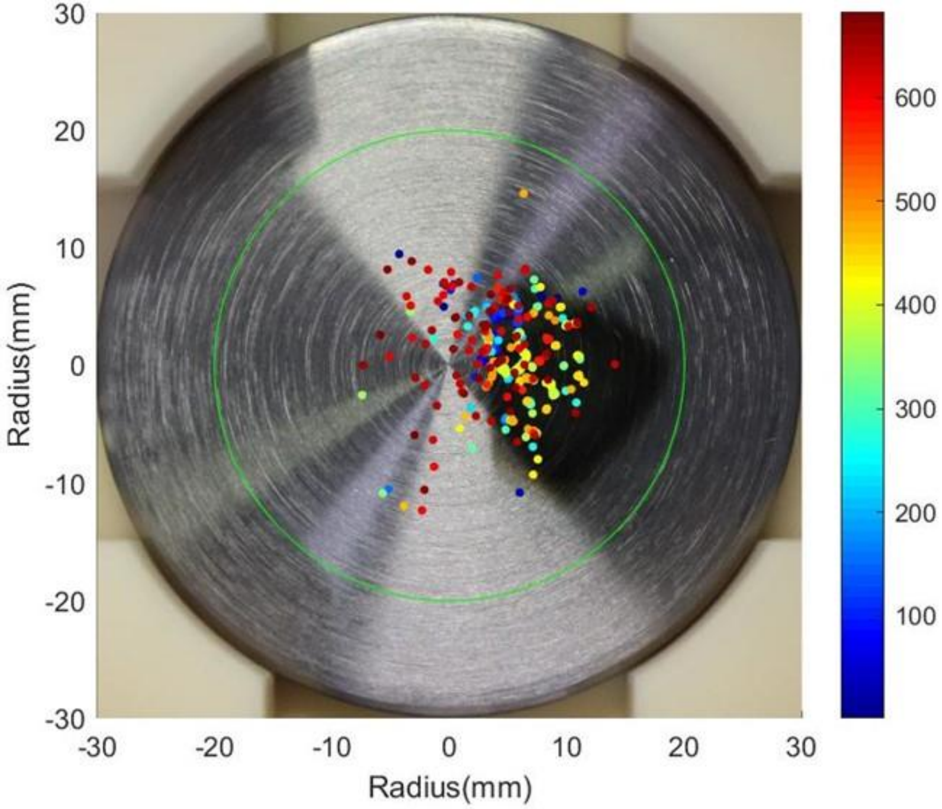




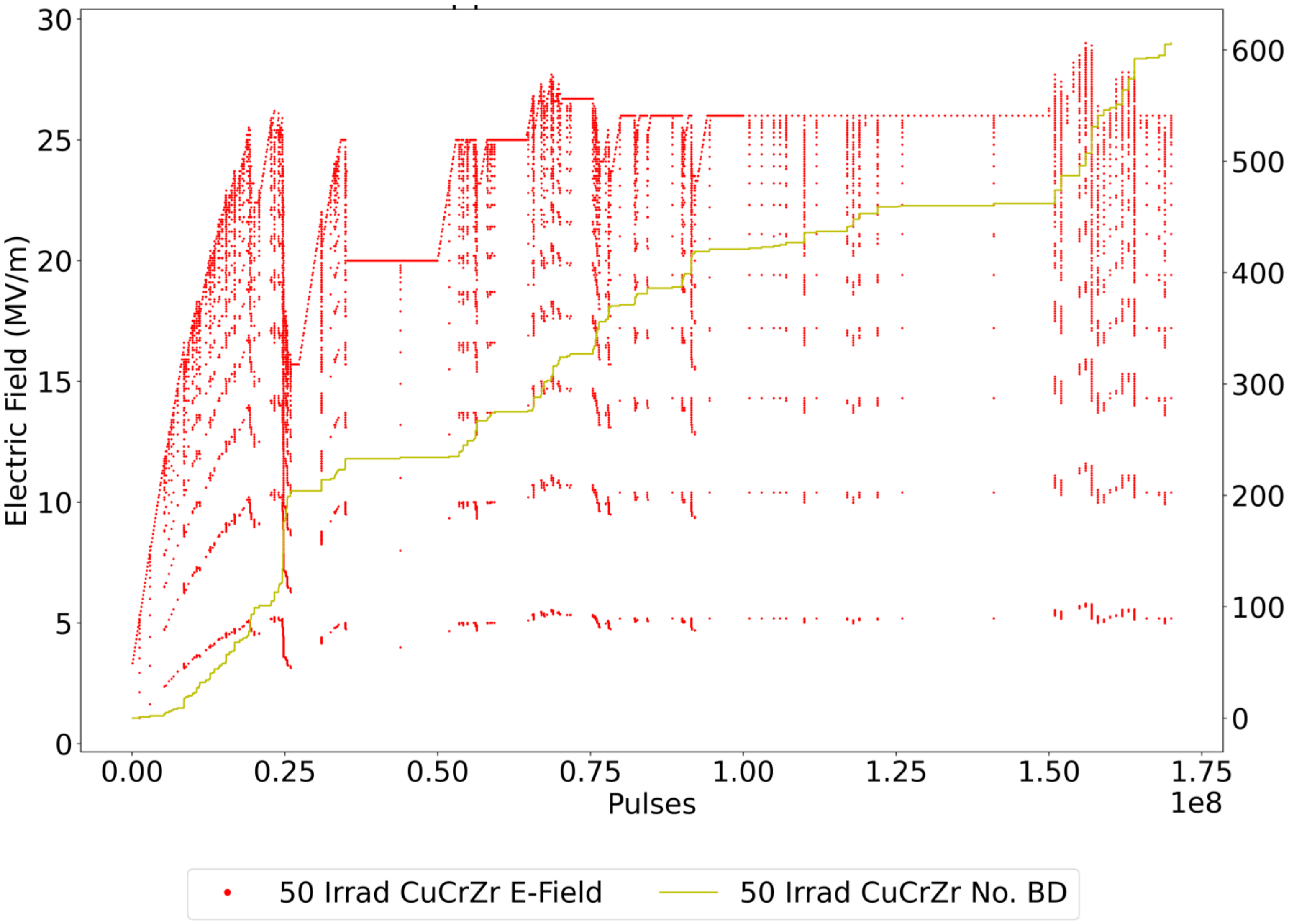


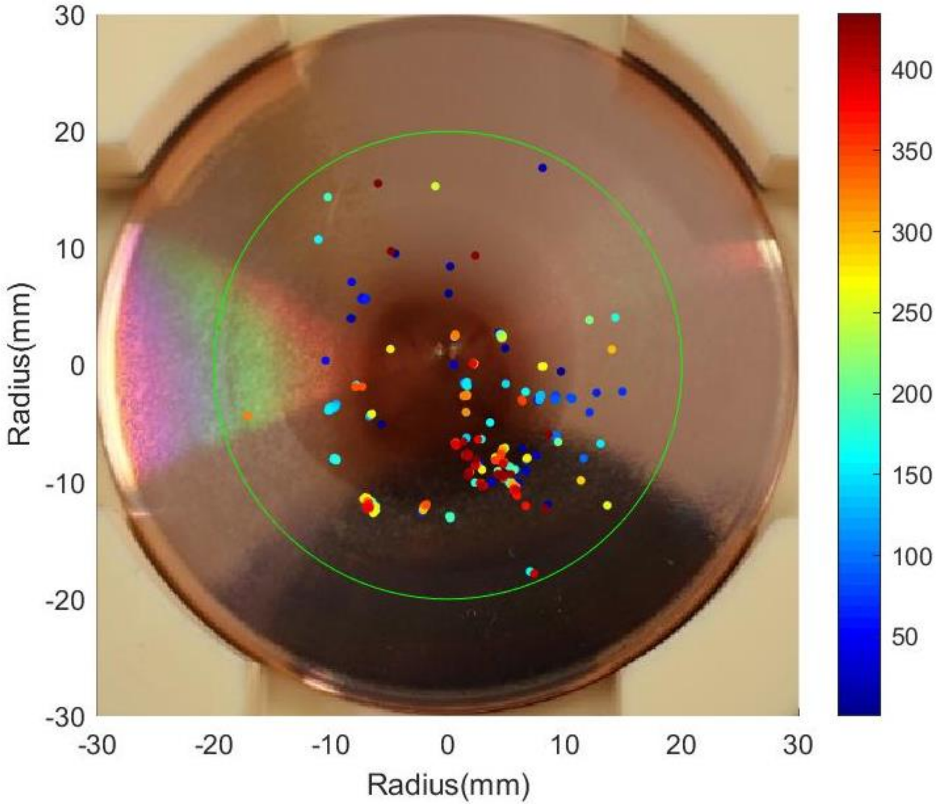
Tantalum (Ta)


60
50
40
30
20
10
Electric Field (MV/m)
0
1
2
3
4
5
6
7
Pulses
1e8
400
300
200
100
0
Breakdown Number
51 Ta E-Field
55 Irrad Ta E-Field
51 Ta No. BD
55 Irrad Ta No. BD

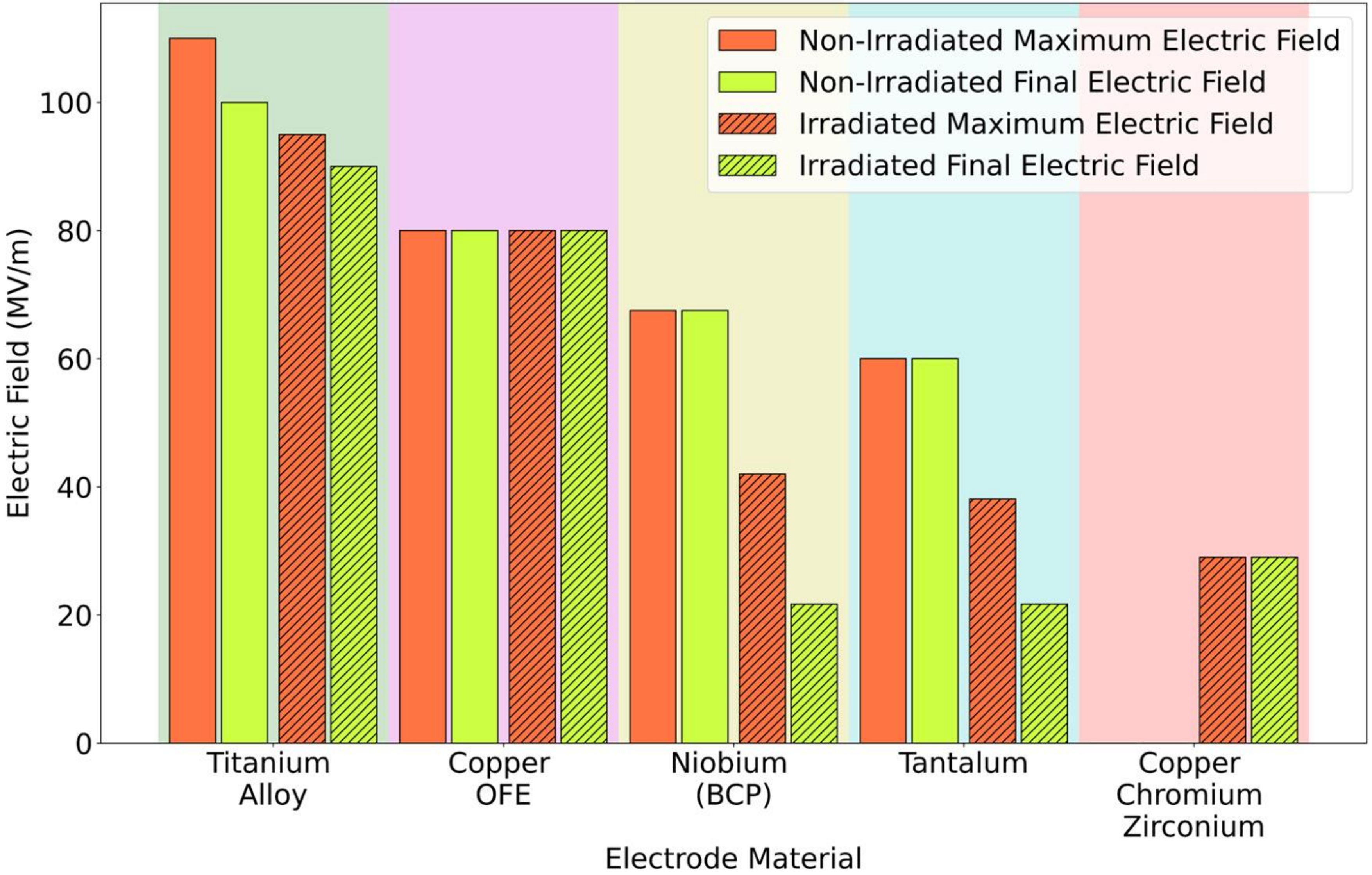

30
20
10
0
-10
-20
-30
Radius(mm)
-30
-20
-10
0
10
20
30
Radius(mm)
600
500
400
300
200
100

Copper Chromium Zirconium (CuCrZr)



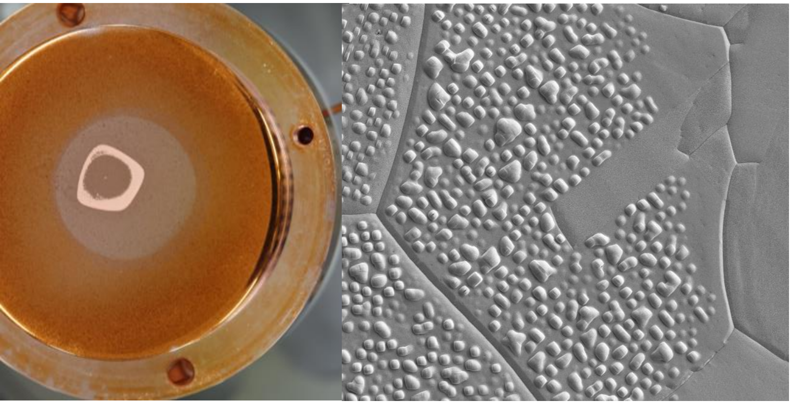


Summary

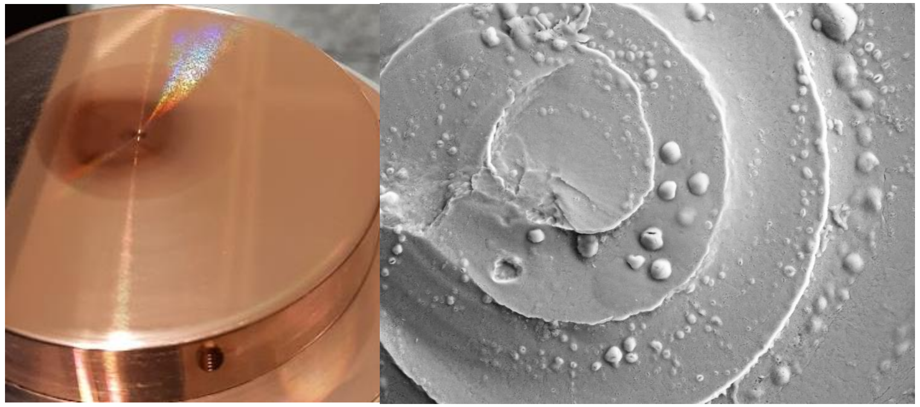


- Titanium performed the best both with and without irradiation, and after a cluster in breakdowns reducing the electric field.
- Copper appears to reach the same electric field with an initial increase in the number of breakdowns that conditions away irradiated defects.
- Niobium and Tantalum both had a significant reaction to the irradiation causing a large cluster in breakdowns that it was not possible to recover from.
- Copper Chromium Zirconium tested only with irradiation was not able to condition very high.

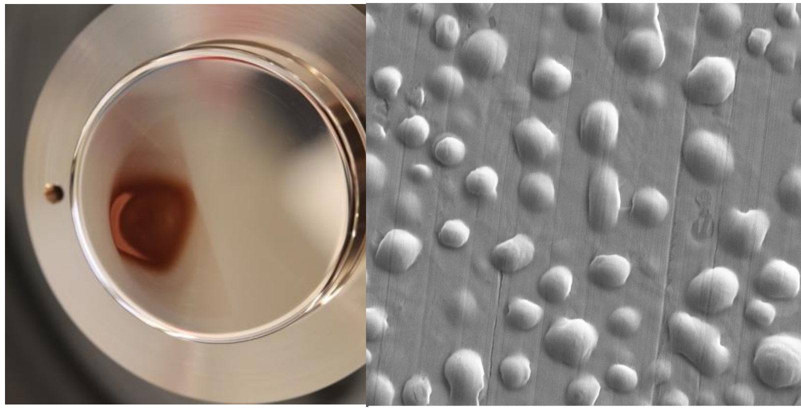
Cu OFE



CuCrZr

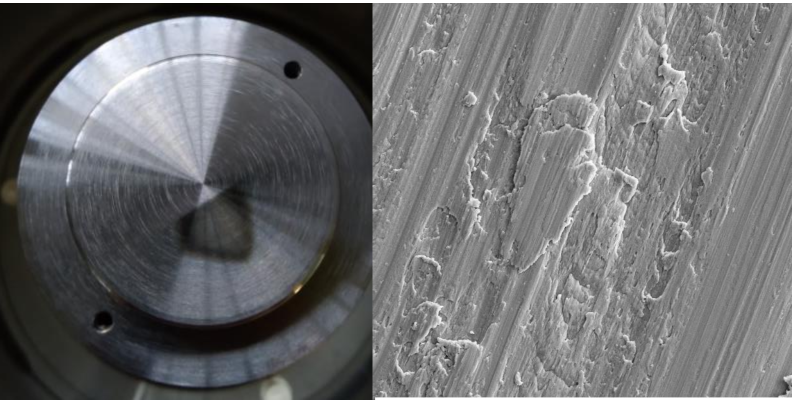


CuBe

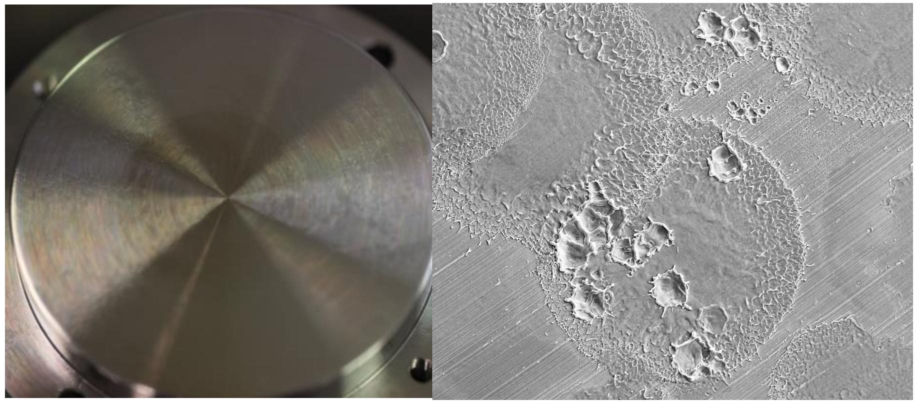


Blister formation is observed in the Cu based electrodes. The high density of blisters is coincidence with the irradiated zones. The blisters locations seems to have no influence on the formation of the breakdowns.

Ta



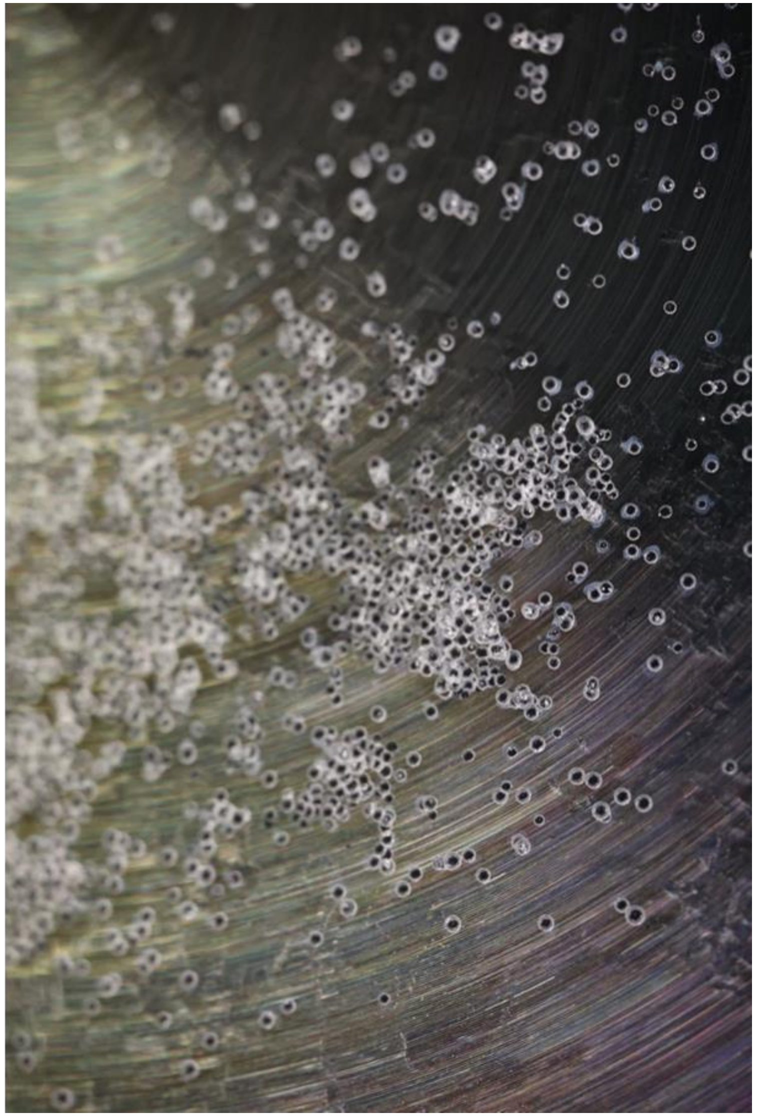
TiAl6V4

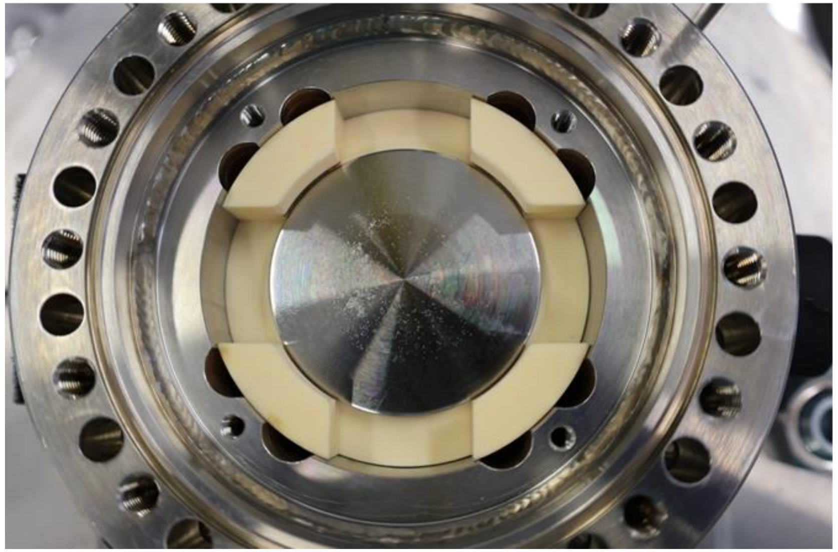


Nb

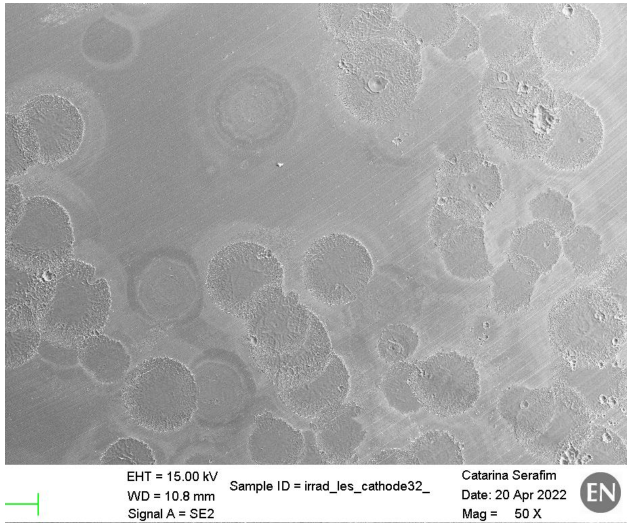
No blisters were observed on the Ta, TiAl6V4and Nb electrodes.

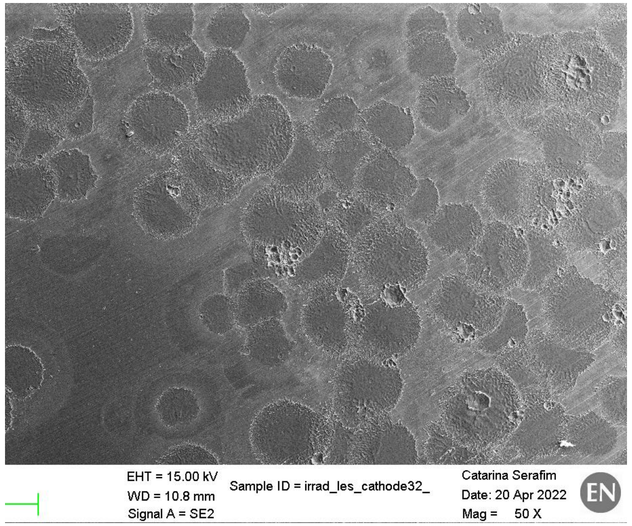
Titanium Alloy (TiAl6V4)

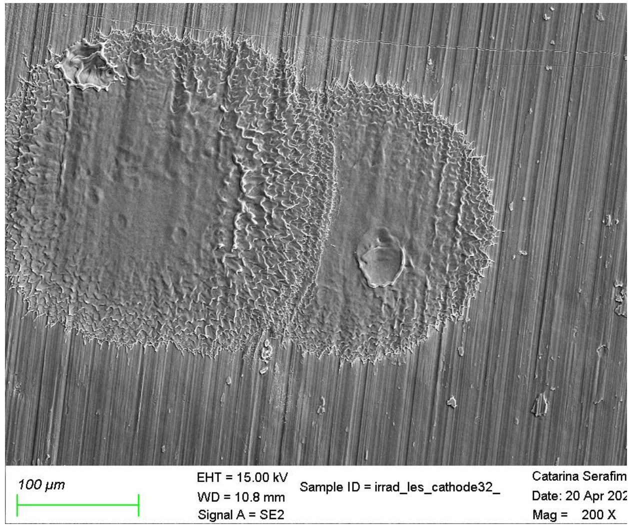


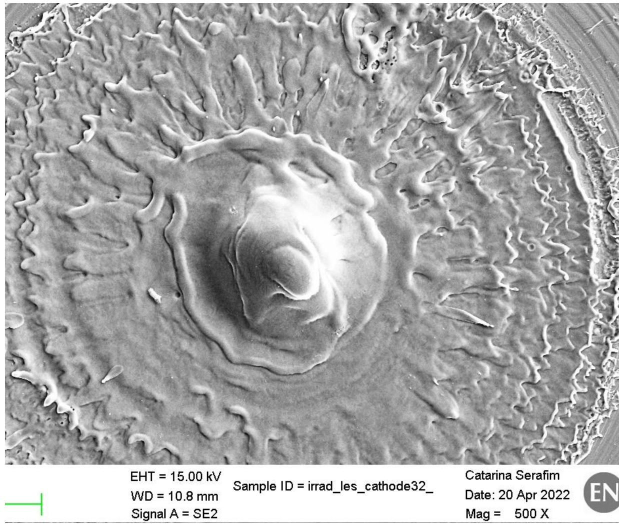


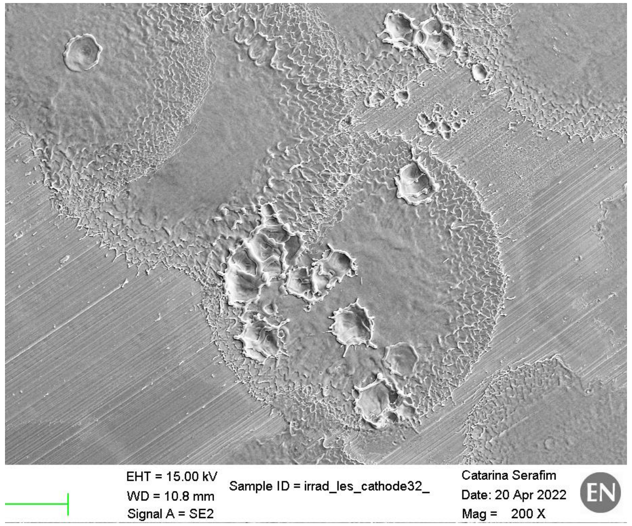
Titanium Alloy (TiAl6V4)

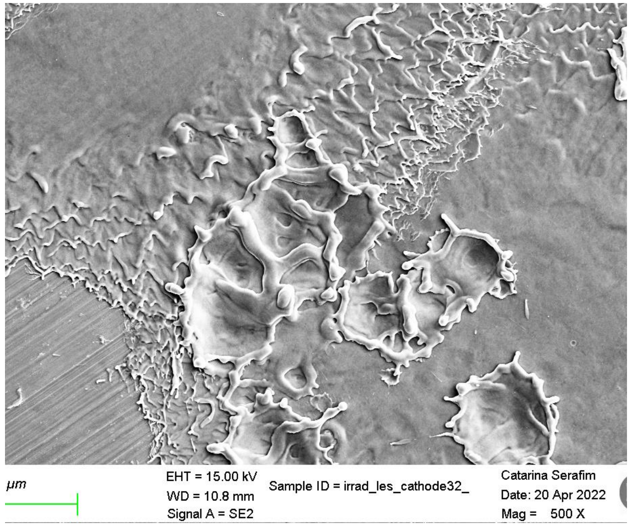


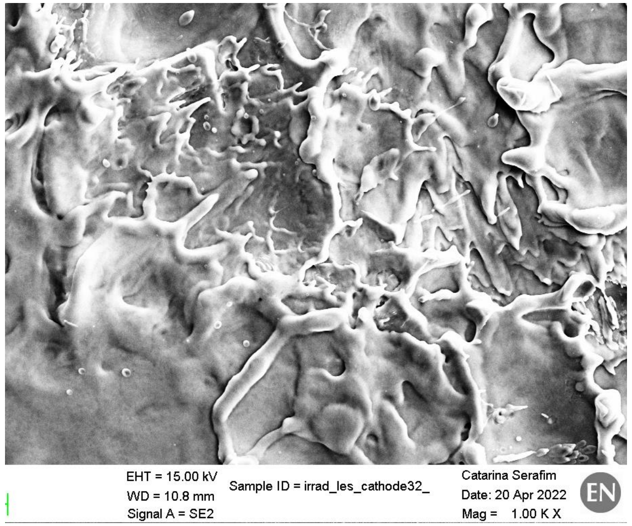


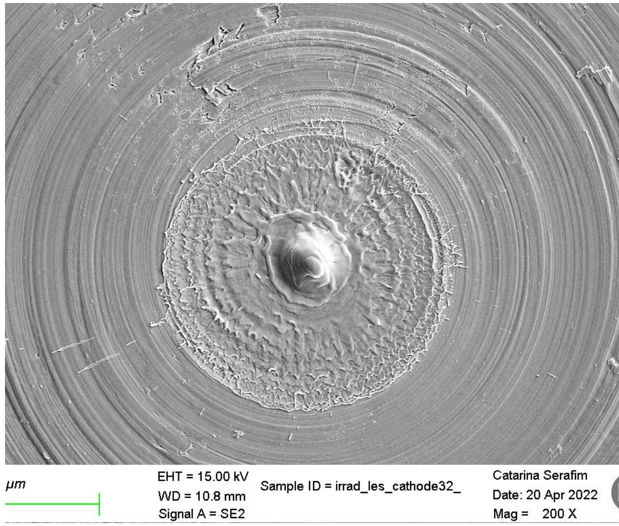




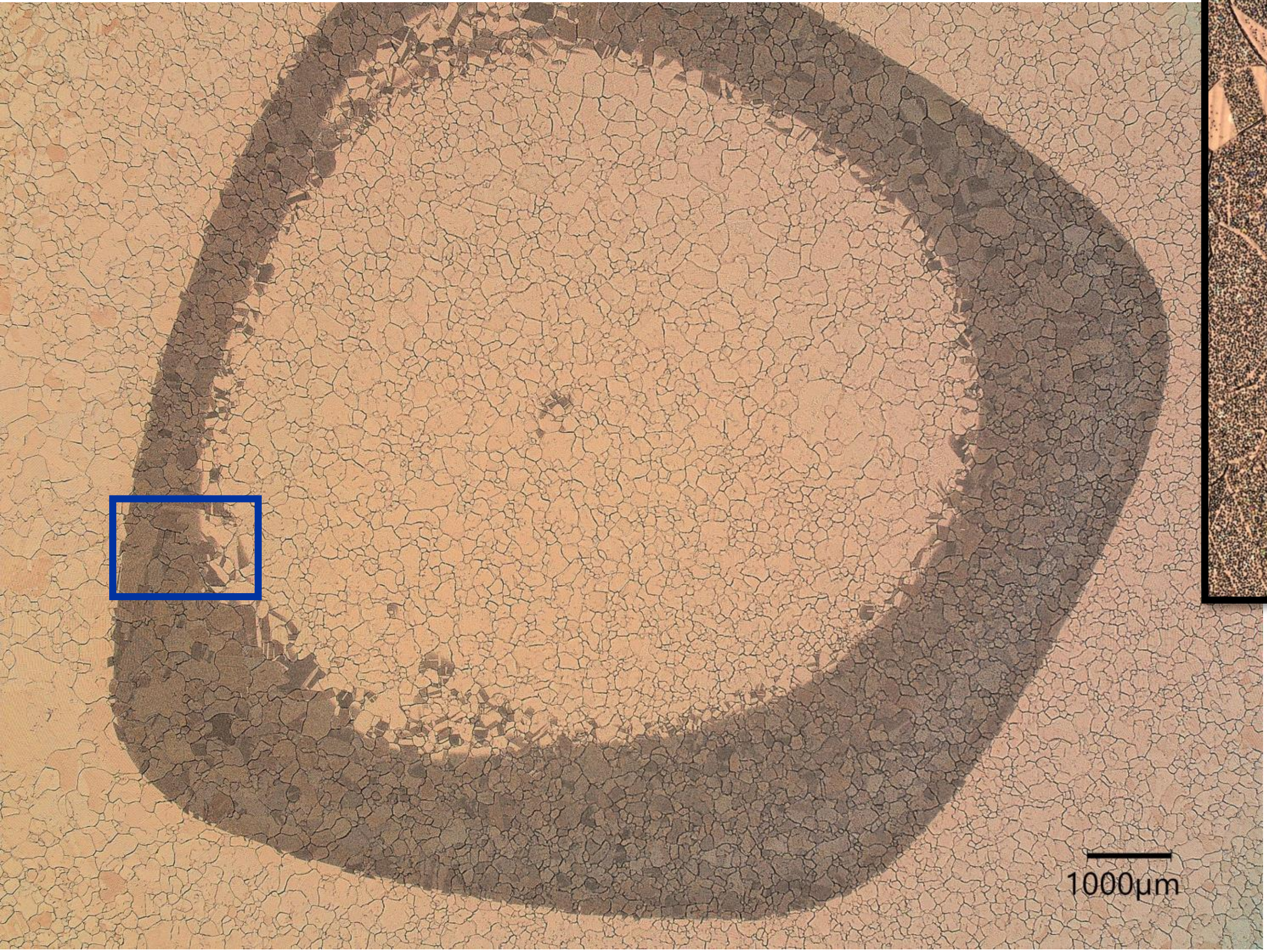


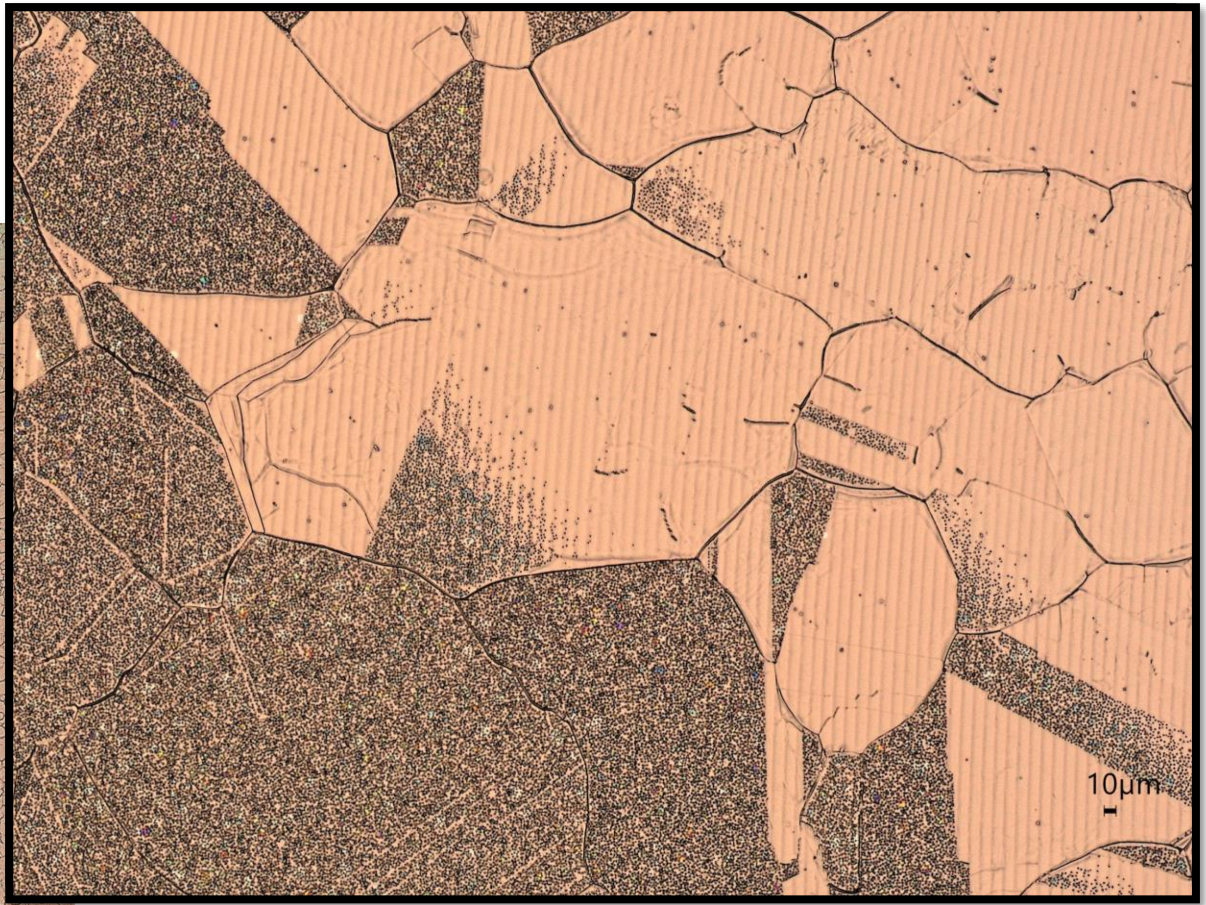




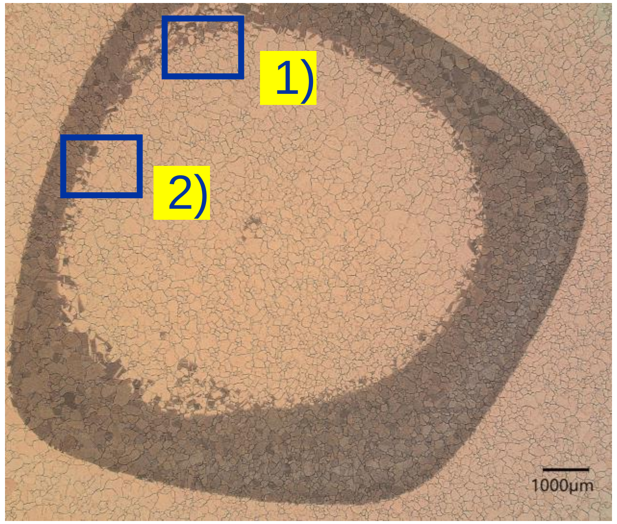


Copper OFE

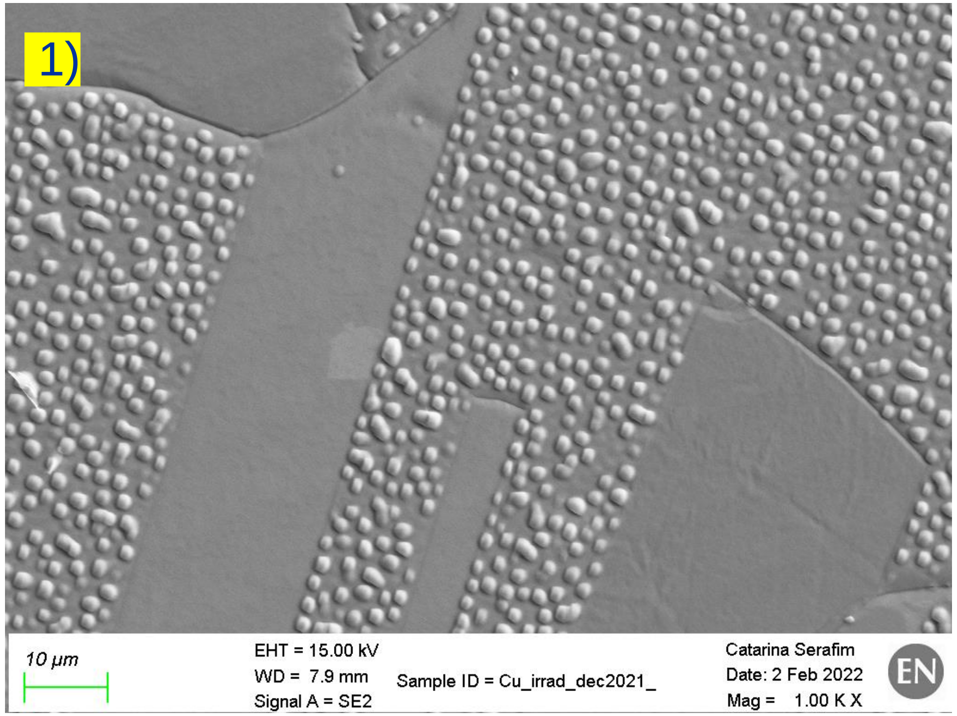




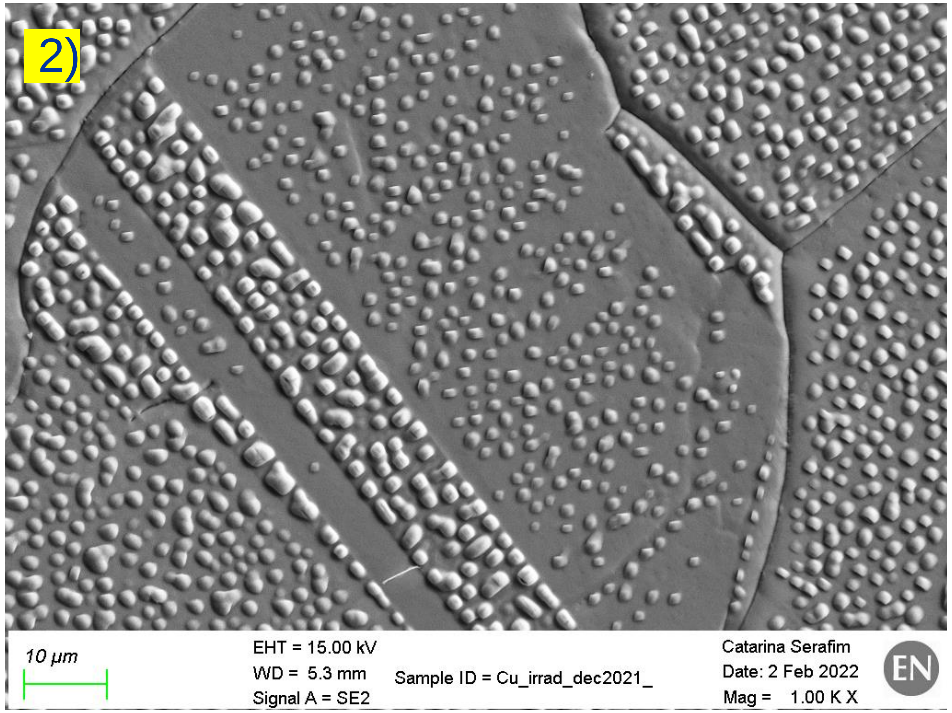
Copper OFE



1)
2)
1000µm

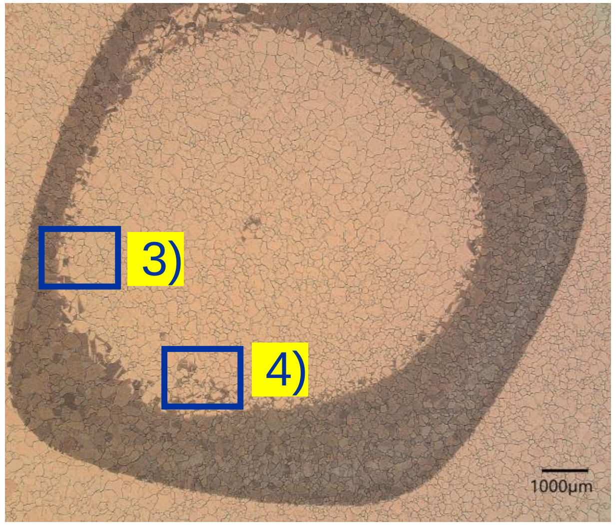


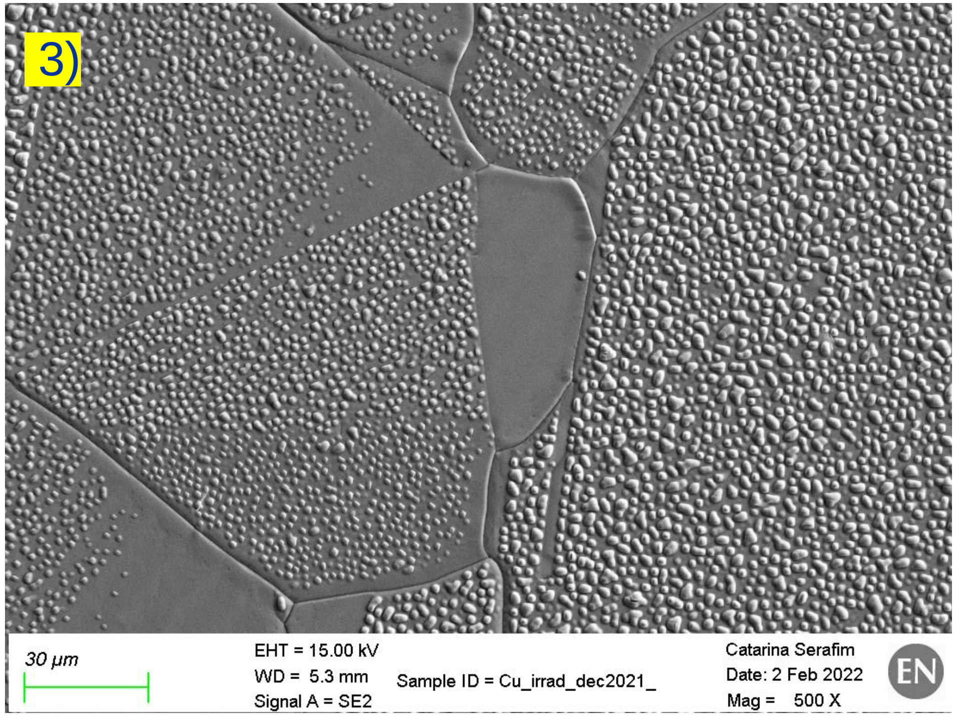
1)
10 µm
EHT = 15.00 kV
WD = 7.9 mm
Signal A = SE2
Sample ID = Cu_irrad_dec2021_
Catarina Serafim
Date: 2 Feb 2022
Mag = 1.00 K X
EN

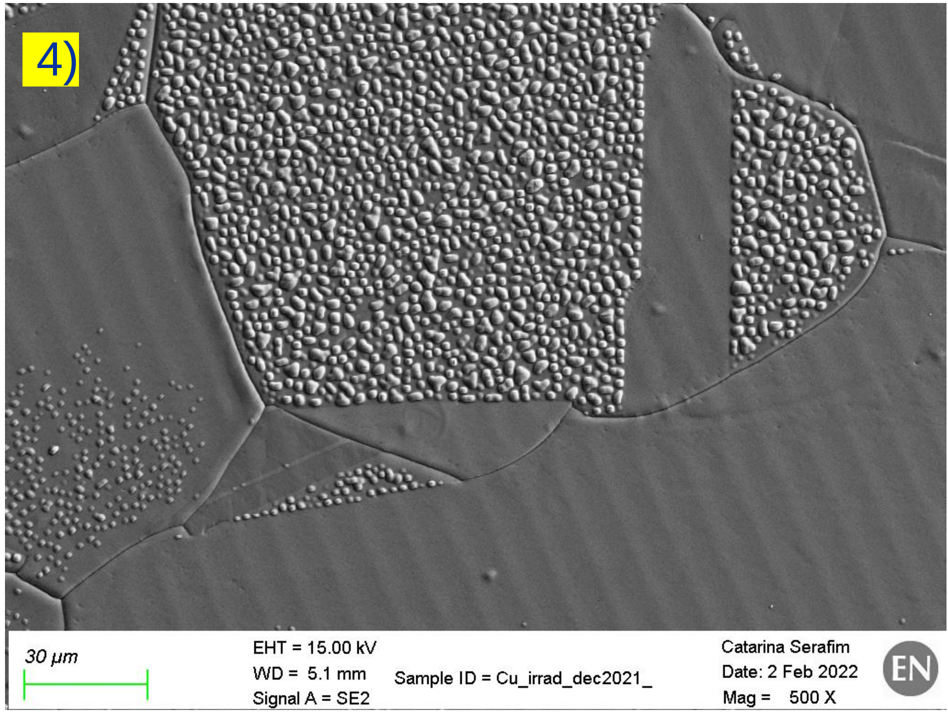


2)
10 µm
EHT = 15.00 kV
WD = 5.3 mm
Signal A = SE2
Sample ID = Cu_irrad_dec2021_
Catarina Serafim
Date: 2 Feb 2022
Mag = 1.00 K X
EN

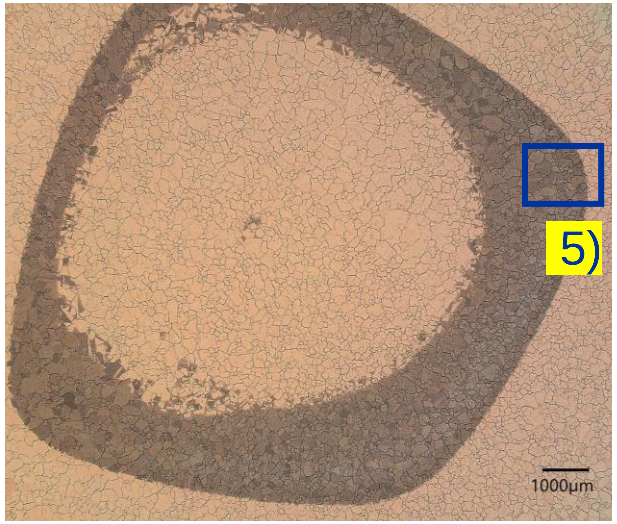
Copper OFE

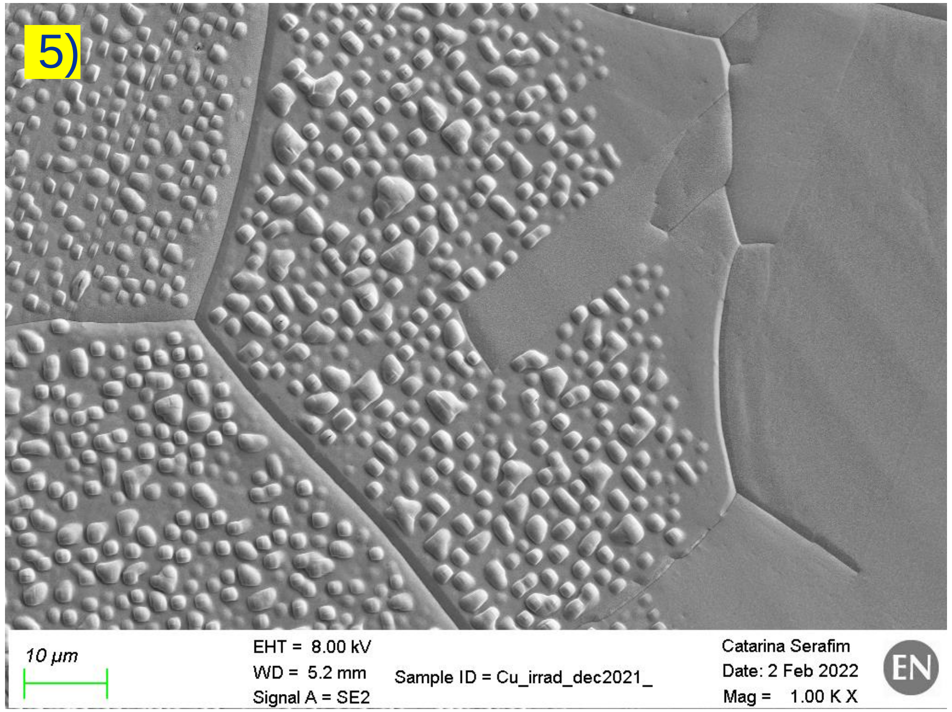

3)
4)
1000µm

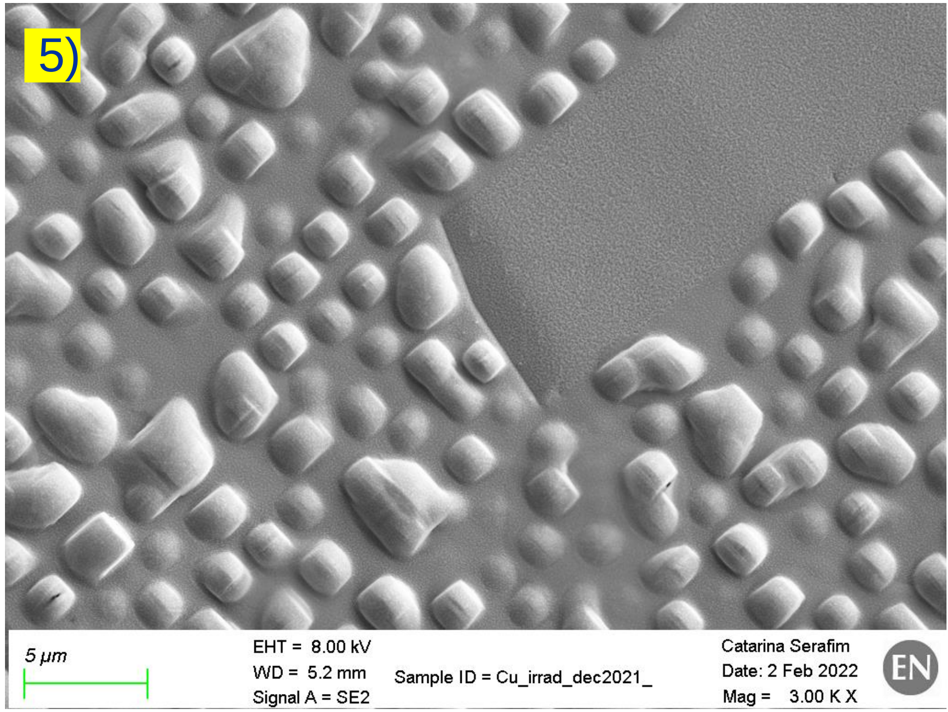

3)
30 µm
EHT = 15.00 kV
WD = 5.3 mm
Signal A = SE2
Sample ID = Cu_irrad_dec2021_
Catarina Serafim
Date: 2 Feb 2022
Mag = 500 X


4)
30 µm
EHT = 15.00 kV
WD = 5.1 mm
Signal A = SE2
Sample ID = Cu_irrad_dec2021_
Catarina Serafim
Date: 2 Feb 2022
Mag = 500 X

Copper OFE

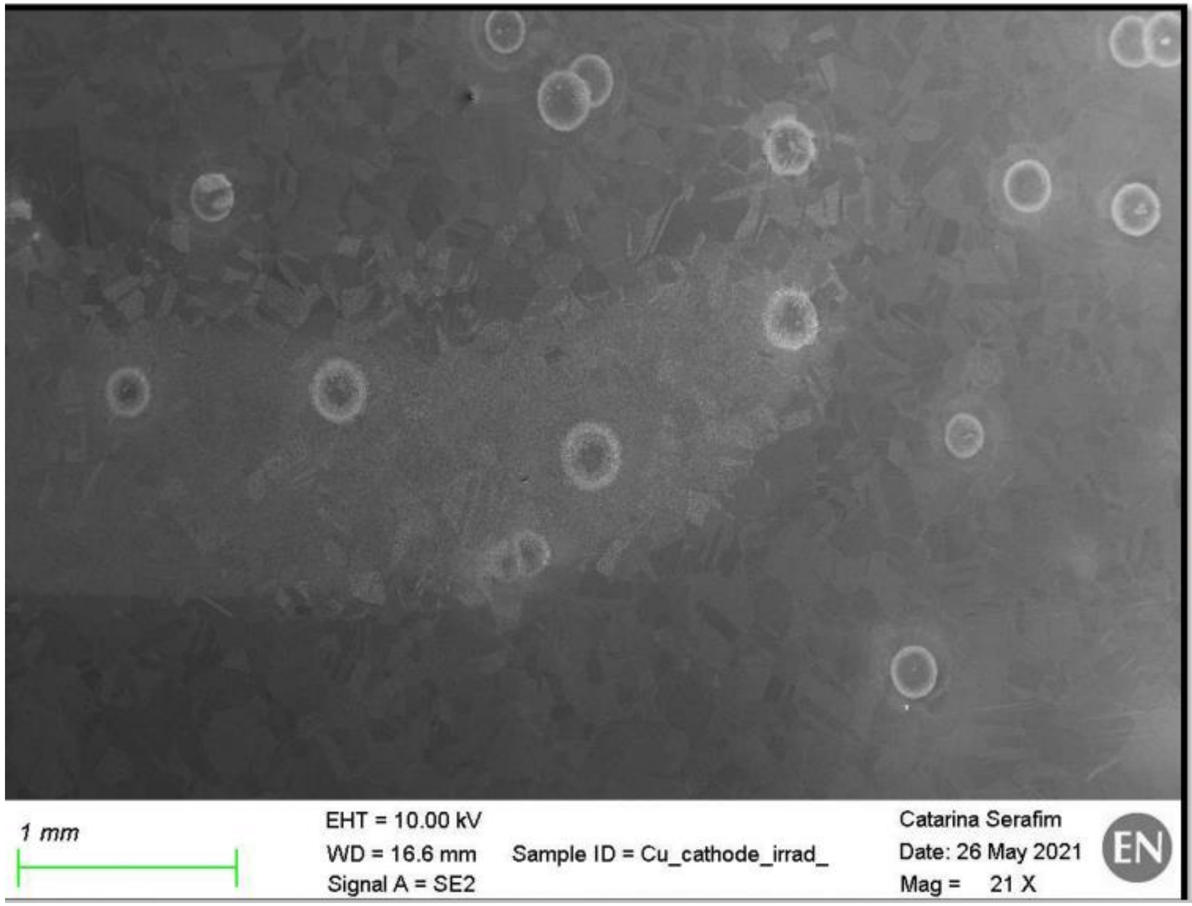

5)
1000µm

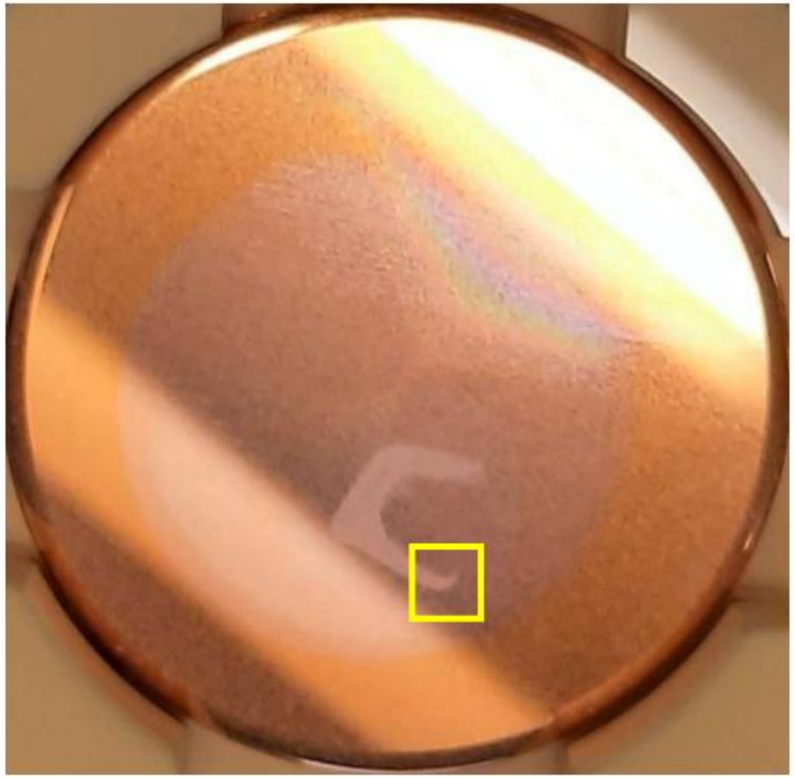

5)
10 µm
EHT = 8.00 kV
WD = 5.2 mm
Signal A = SE2
Sample ID = Cu_irrad_dec2021_
Catarina Serafim
Date: 2 Feb 2022
Mag = 1.00 K X
EN


5)
5 µm
EHT = 8.00 kV
WD = 5.2 mm
Signal A = SE2
Sample ID = Cu_irrad_dec2021_
Catarina Serafim
Date: 2 Feb 2022
Mag = 3.00 K X
EN

Copper OFE

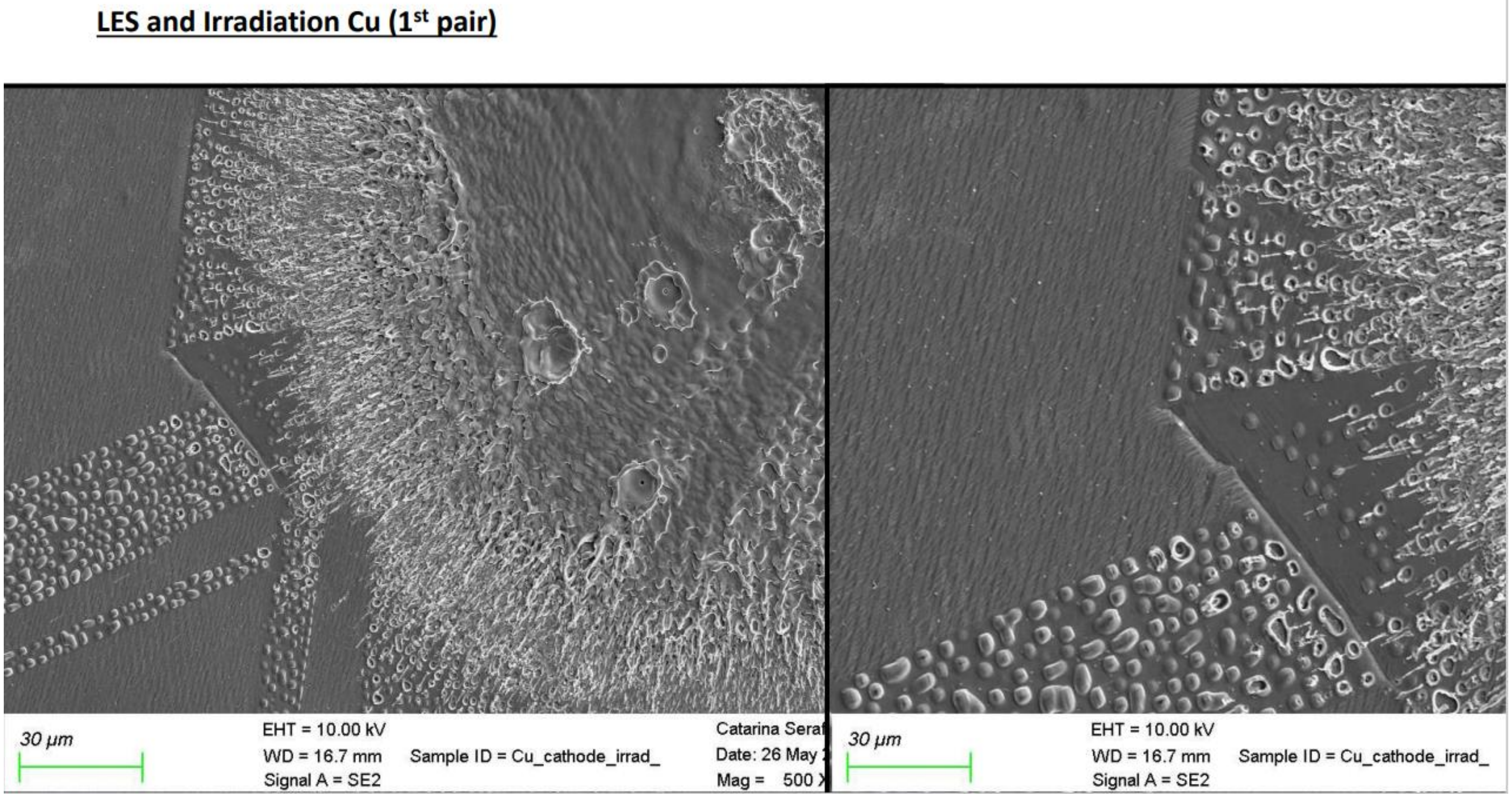
LES and Irradiation Cu (1st pair)



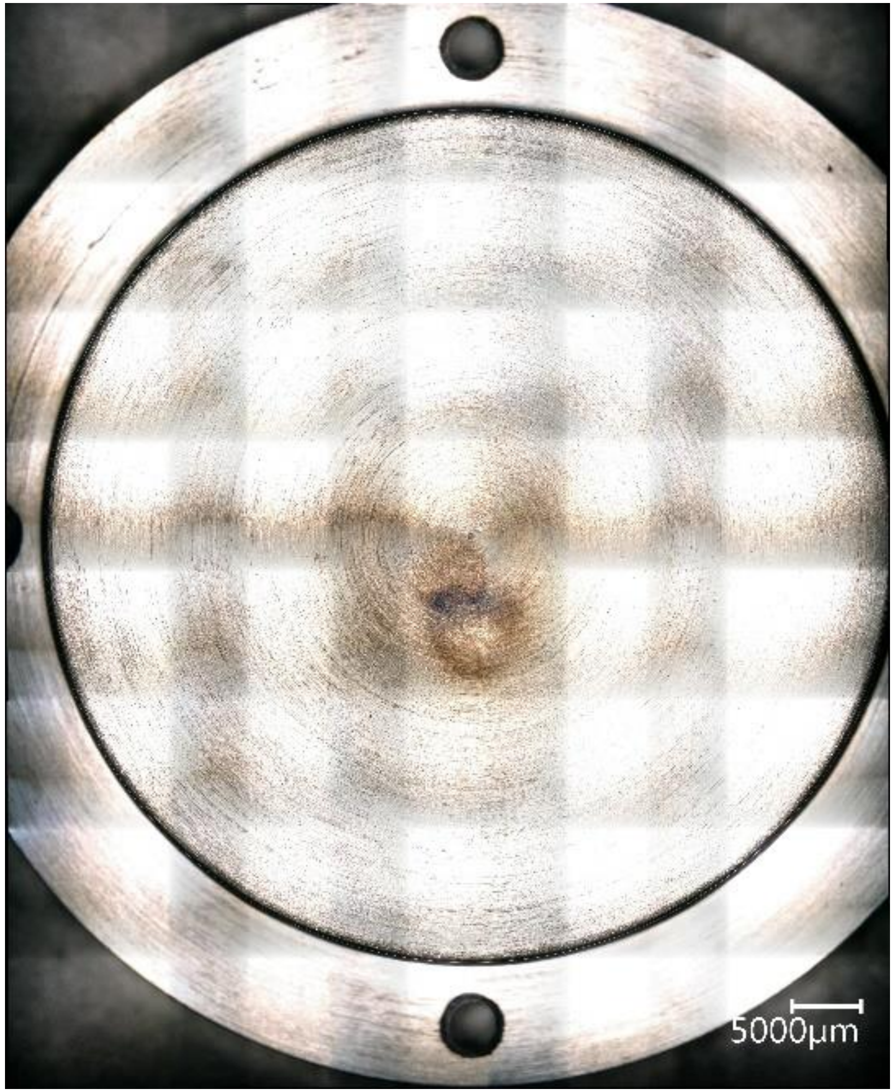


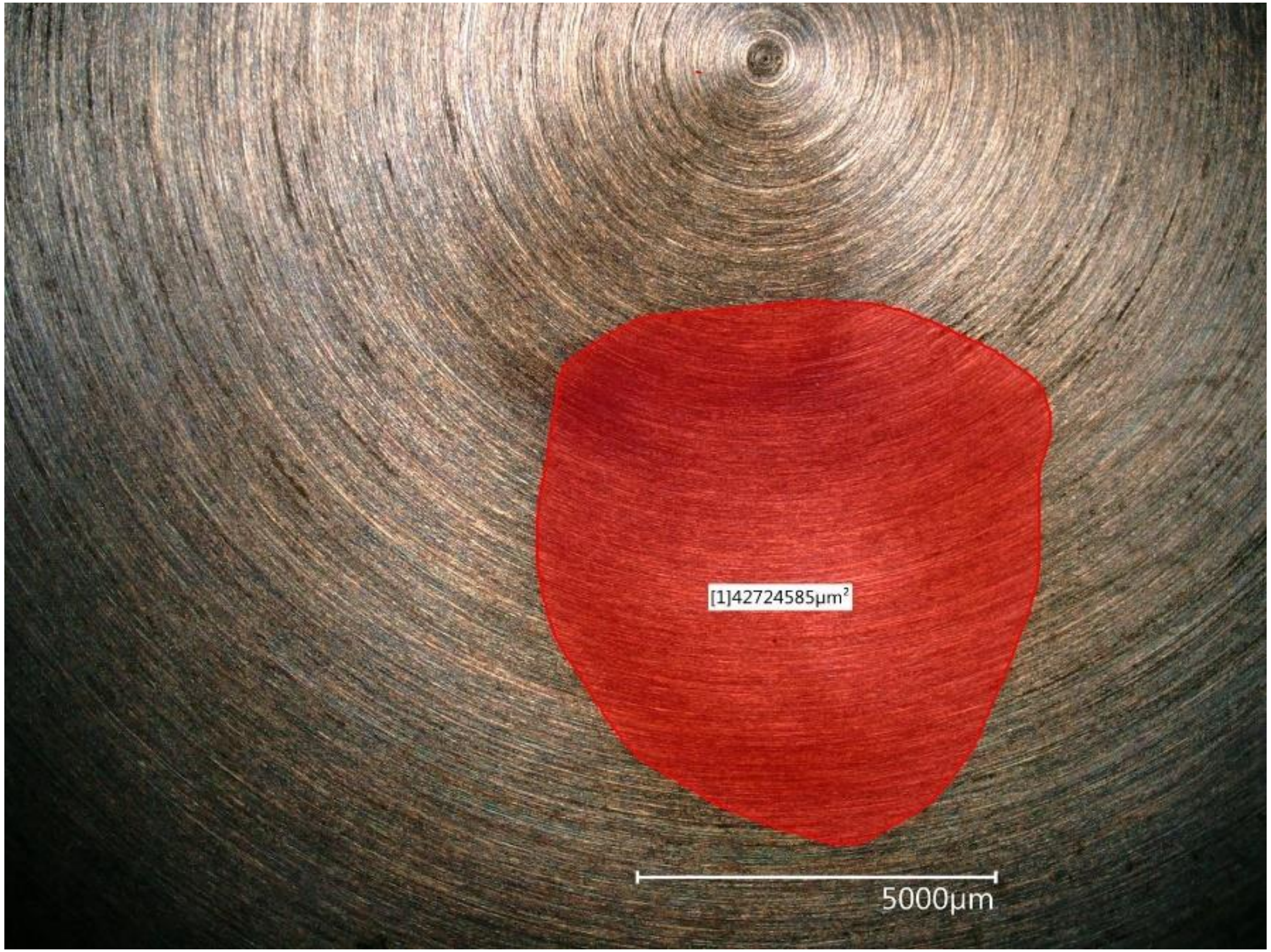
Transition between irradiation and not irradiation zone.

Copper OFE

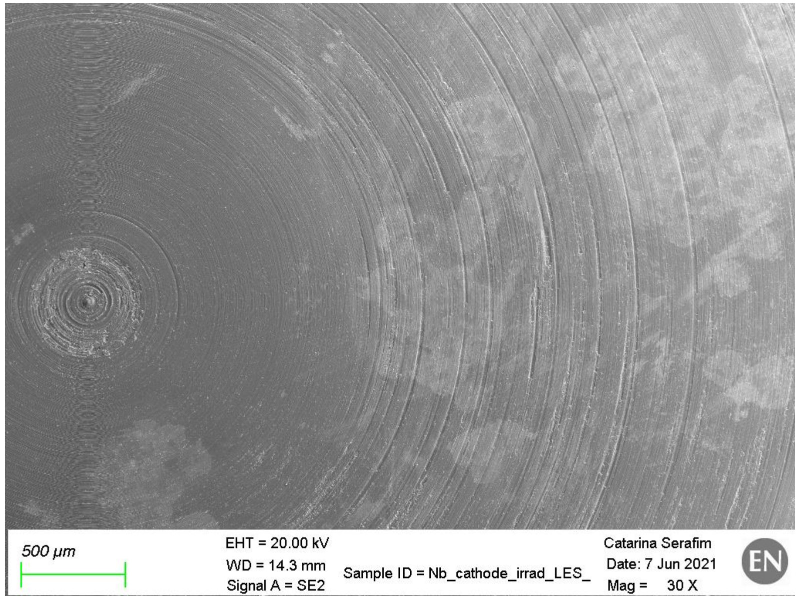

LES and Irradiation Cu (1st pair)
30 µm
EHT = 10.00 kV
WD = 16.7 mm
Signal A = SE2
Sample ID = Cu_cathode_irrad_
Date: 26 May
Mag = 500 X
30 µm
EHT = 10.00 kV
WD = 16.7 mm
Signal A = SE2
Sample ID = Cu_cathode_irrad_

Niobium (Nb)

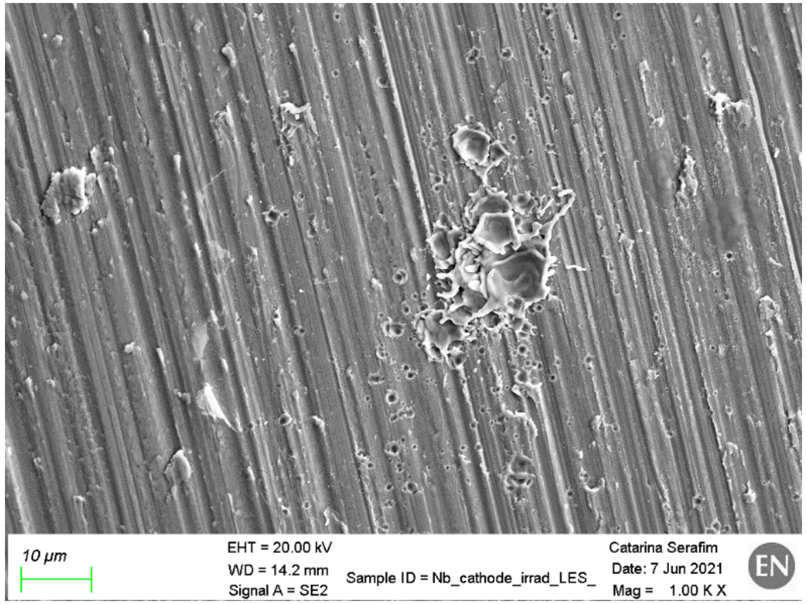




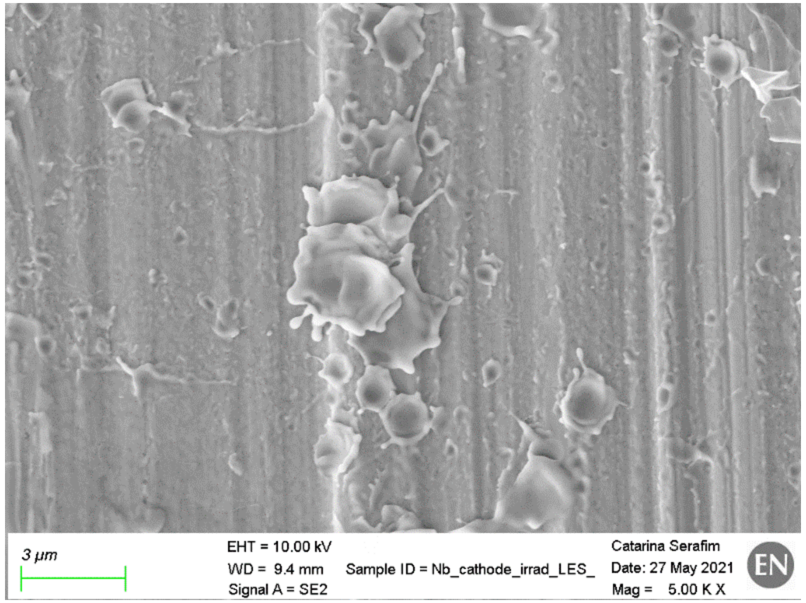
Niobium (Nb)



500 µm
EHT = 20.00 kV
WD = 14.3 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 7 Jun 2021
Mag = 30 X
EN

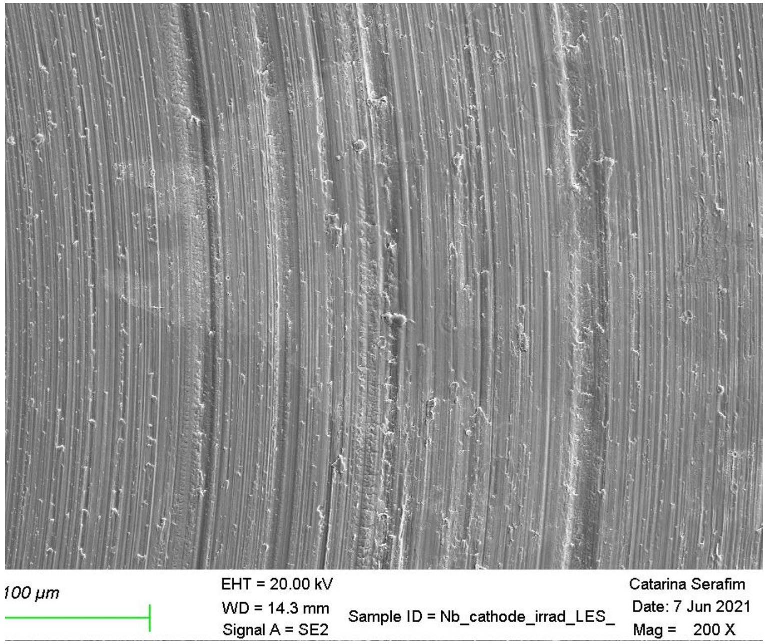


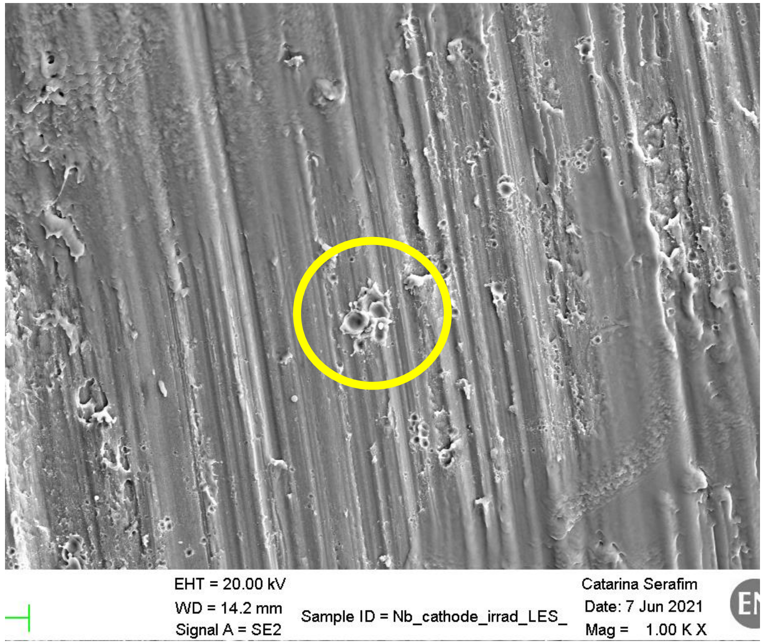
10 µm
EHT = 20.00 kV
WD = 14.2 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 7 Jun 2021
Mag = 1.00 K X
EN

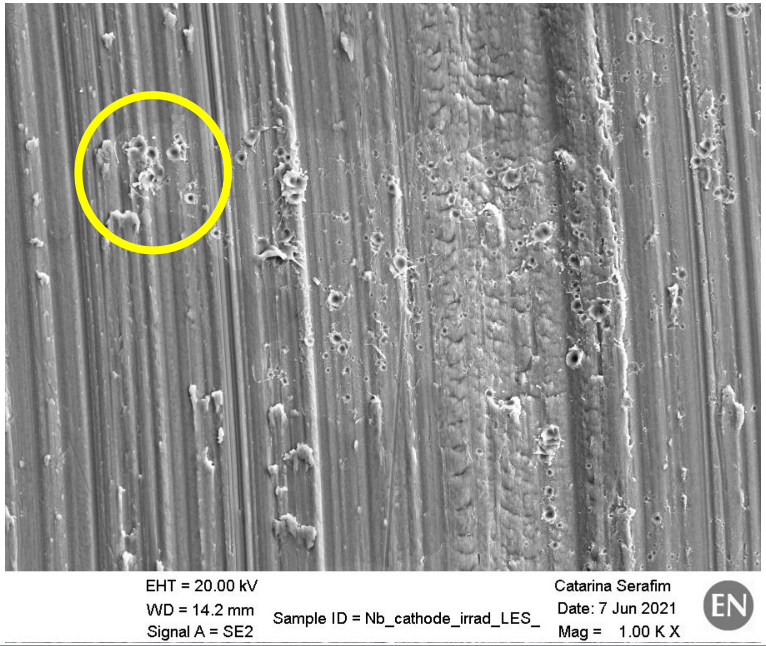


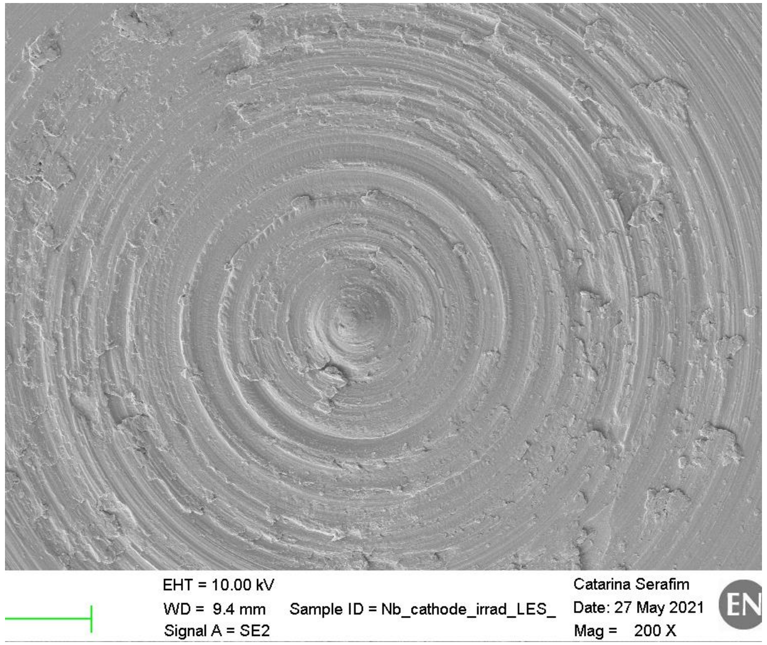
3 µm
EHT = 10.00 kV
WD = 9.4 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 27 May 2021
Mag = 5.00 K X
EN

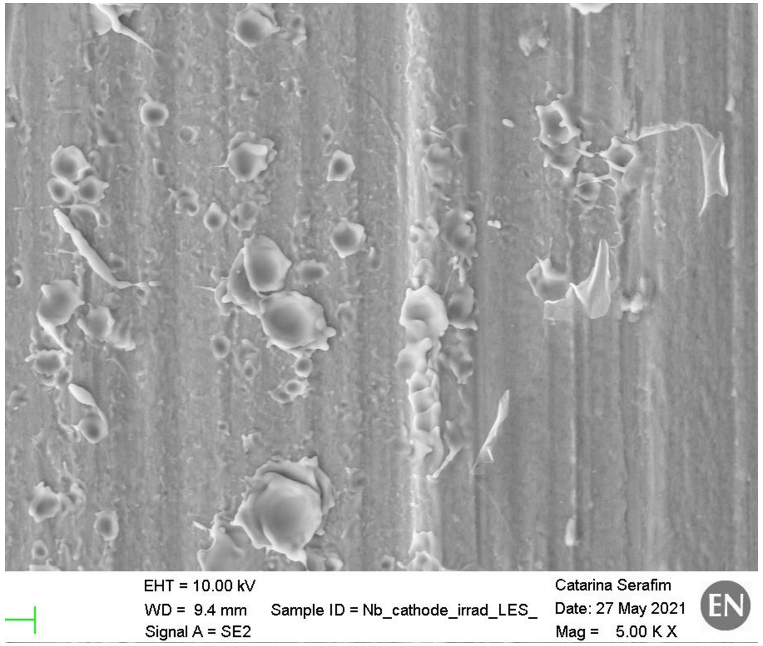
Niobium (Nb)


100 µm
EHT = 20.00 kV
WD = 14.3 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 7 Jun 2021
Mag = 200 X

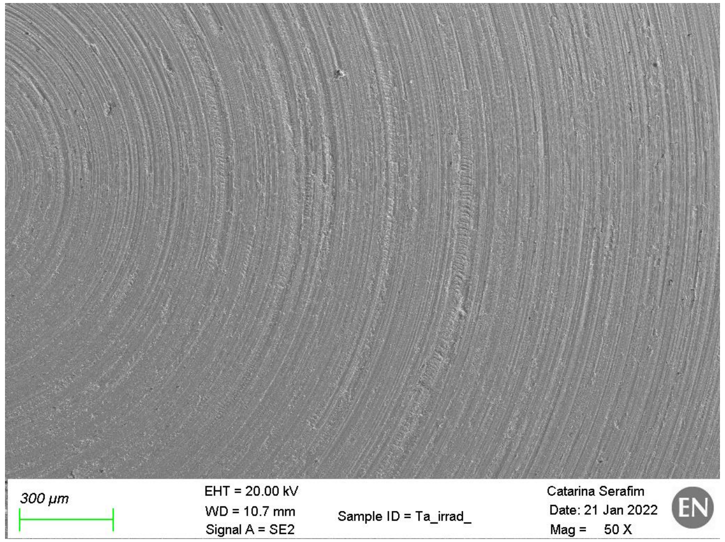

EHT = 20.00 kV
WD = 14.2 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 7 Jun 2021
Mag = 1.00 K X

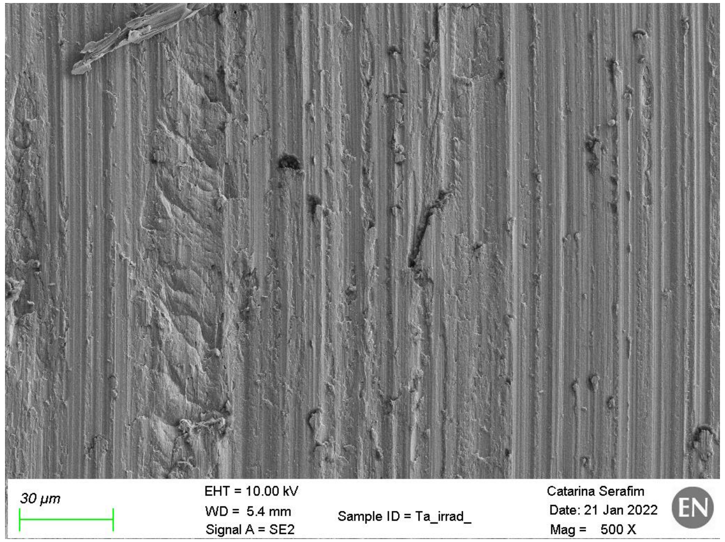

EHT = 20.00 kV
WD = 14.2 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 7 Jun 2021
Mag = 1.00 K X

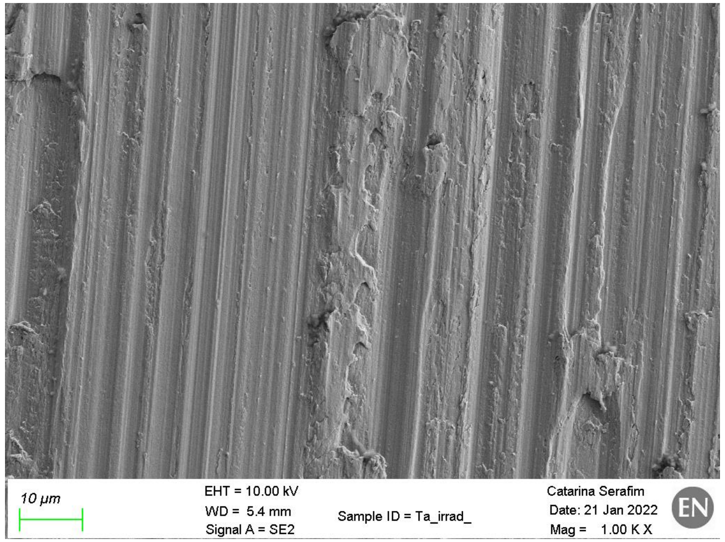

EHT = 10.00 kV
WD = 9.4 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 27 May 2021
Mag = 200 X

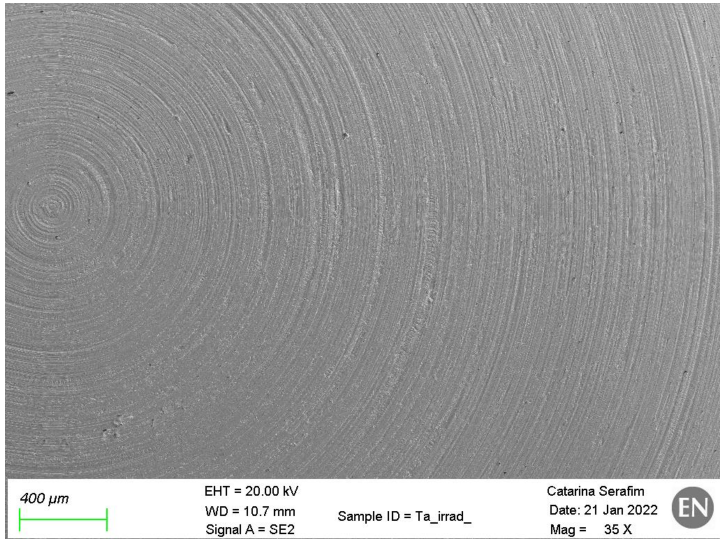

EHT = 10.00 kV
WD = 9.4 mm
Signal A = SE2
Sample ID = Nb_cathode_irrad_LES_
Catarina Serafim
Date: 27 May 2021
Mag = 5.00 K X

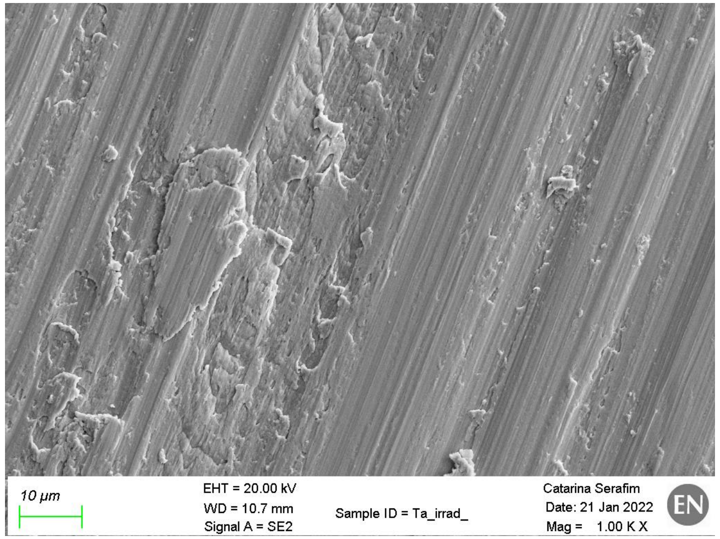
Tantalum (Ta)

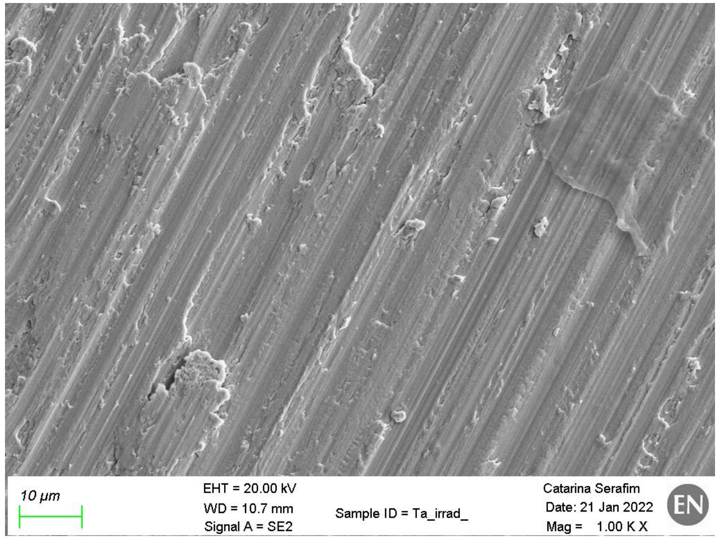

300 µm
EHT = 20.00 kV
WD = 10.7 mm
Signal A = SE2
Sample ID = Ta_irrad_
Catarina Serafim
Date: 21 Jan 2022
Mag = 50 X
EN


30 µm
EHT = 10.00 kV
WD = 5.4 mm
Signal A = SE2
Sample ID = Ta_irrad_
Catarina Serafim
Date: 21 Jan 2022
Mag = 500 X
EN

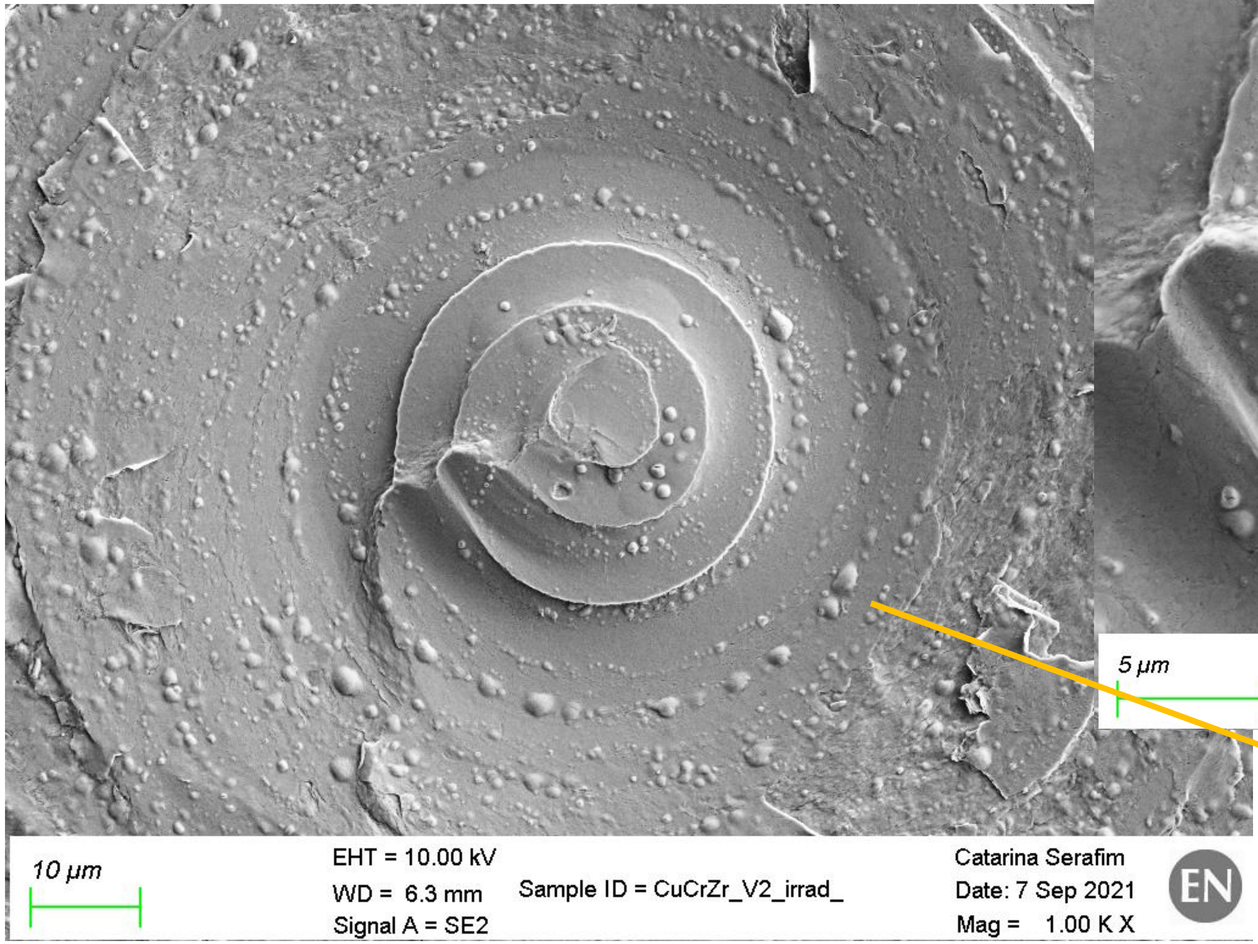

10 µm
EHT = 10.00 kV
WD = 5.4 mm
Signal A = SE2
Sample ID = Ta_irrad_
Catarina Serafim
Date: 21 Jan 2022
Mag = 1.00 K X
EN

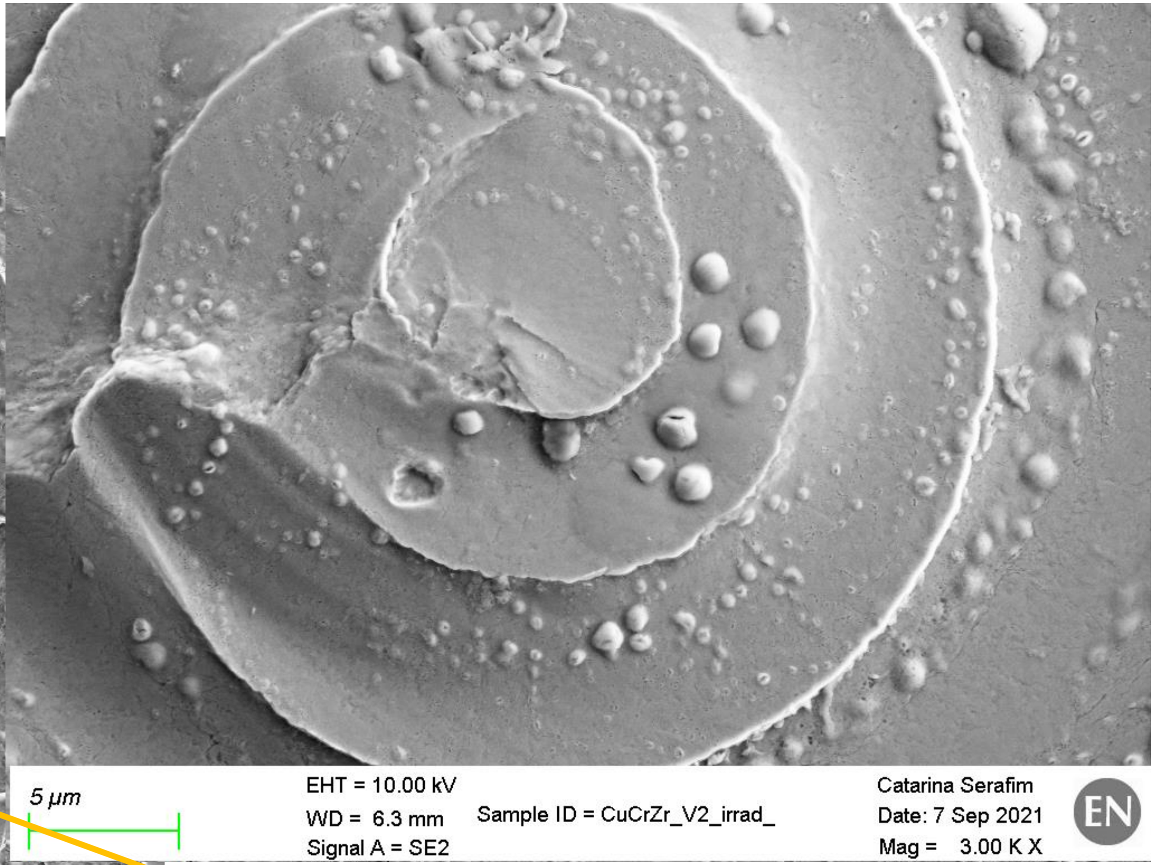

400 µm
EHT = 20.00 kV
WD = 10.7 mm
Signal A = SE2
Sample ID = Ta_irrad_
Catarina Serafim
Date: 21 Jan 2022
Mag = 35 X
EN


10 µm
EHT = 20.00 kV
WD = 10.7 mm
Signal A = SE2
Sample ID = Ta_irrad_
Catarina Serafim
Date: 21 Jan 2022
Mag = 1.00 K X
EN


10 µm
EHT = 20.00 kV
WD = 10.7 mm
Signal A = SE2
Sample ID = Ta_irrad_
Catarina Serafim
Date: 21 Jan 2022
Mag = 1.00 K X
EN

Copper Chromium Zirconium (CuCrZr)





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

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