Field Emission and Multipactor Simulations in High-Gradient RF Accelerators

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- Longitudinal Dark Current
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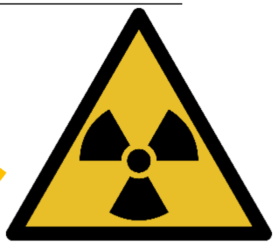
- Conclusions

Introduction

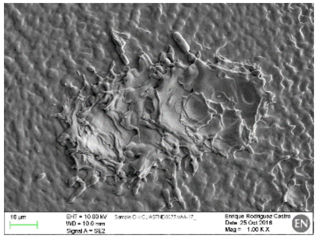
Effect of field emission on high gradient operation



- Initially emitted in the high field areas of the structure, field emitted electrons are captured by the RF fields over a certain gradient threshold. This produces the dark current: causing radiation during test, even without beam, and possibly distorting BPM measurements.

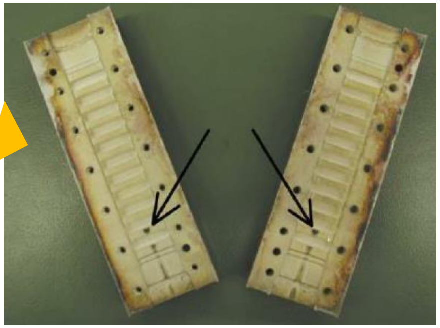
[1]

- Field emission can turn into an explosive process causing the damaging breakdowns that limit HG performance.



[2]

- Field emission also causes electron seeding in low field areas potentially triggering Multipactor effect.



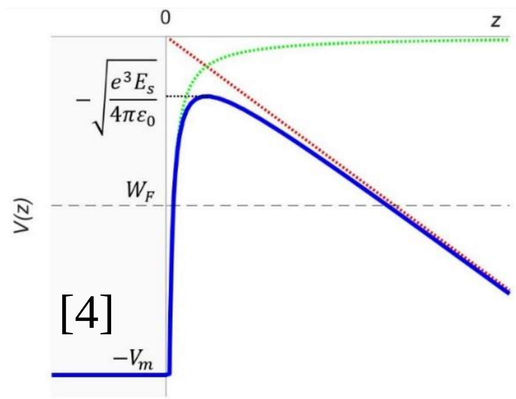
[3]

[1] Beam Position Monitor. CLIC Project Implementation Plan. CERN. 2018.
[2] Microscope picture from Enrique Rodriguez Castro.
[3] Burnings in a low pass filter caused by Multipactor, picture from Benito Gimeno.

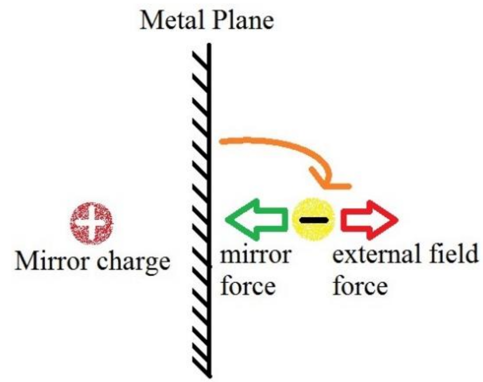
Introduction

Field emission theory

Quantum tunneling of the potential barrier gives an electron current

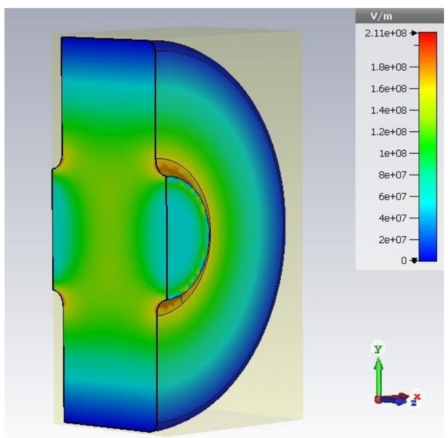


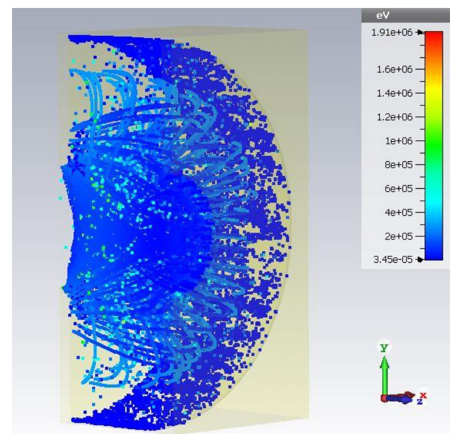
[4]



Fowler Nordheim

$$J = aE^2 e^{\frac{-b}{E}}$$





[4] Jorge Giner Navarro. Breakdown studies for high gradient RF warm technology in: CLIC and hadrontherapy linacs. PhD thesis, Universitat de València, 2016.

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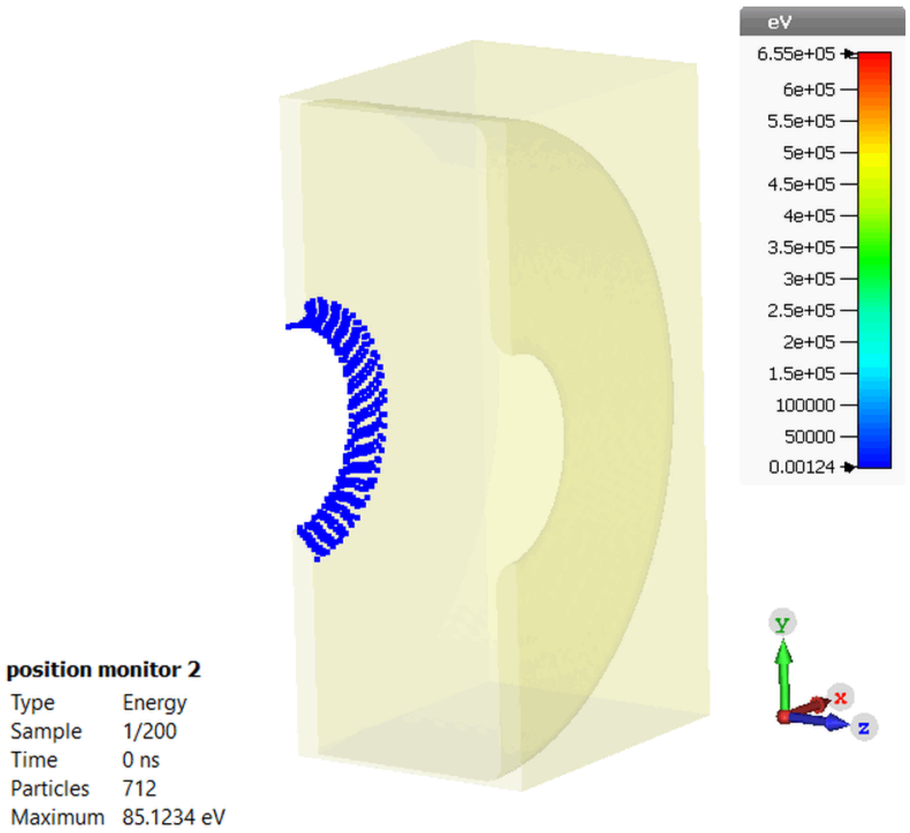
Longitudinal Dark Current

Field emission in a single cell of a CLIC T24

In this animation we present a closer look to the trajectories of the electrons emitted in the left iris.

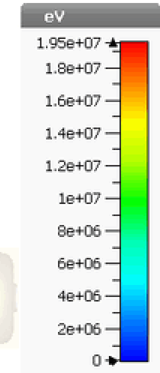
The particle simulations presented in this work have been carried out with CST particle in cell solver.



Longitudinal Dark Current

T24PSI using periodicity - Energy espectrums

Gradient = 100 MV/m



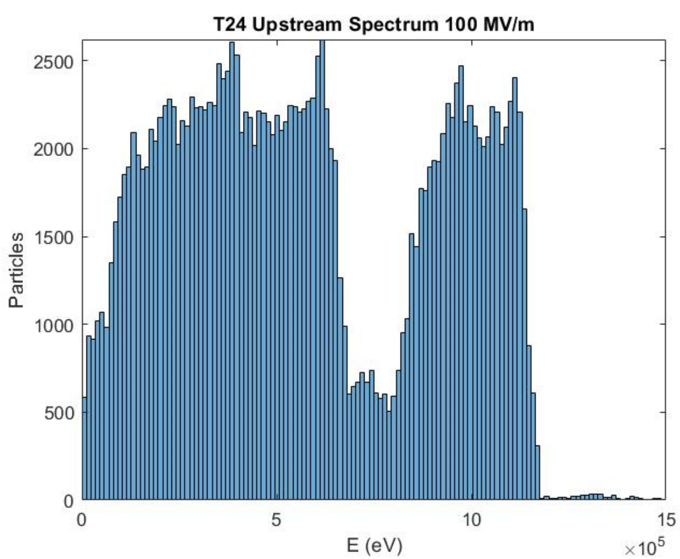
Full Structure Upstream

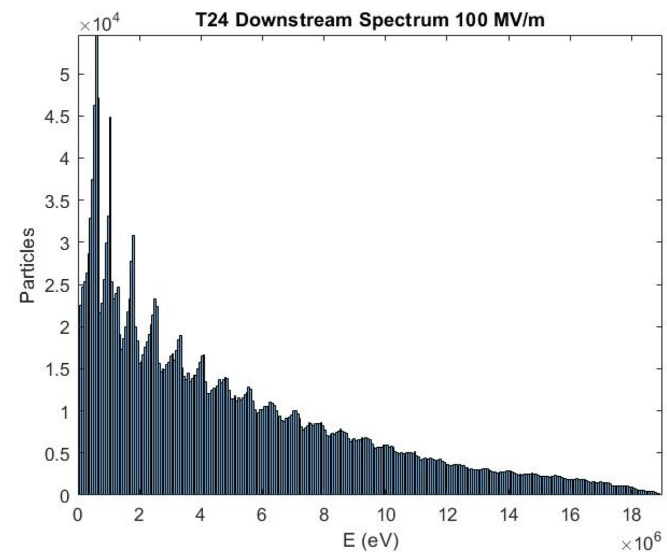
Emitting Iris

Full Structure Downstream

position monitor 1

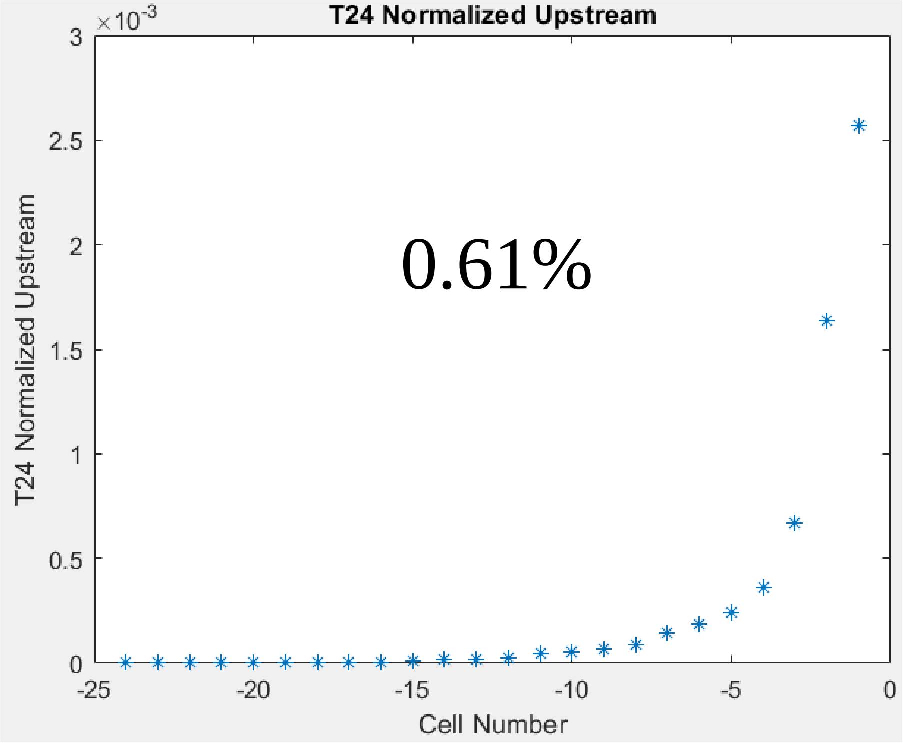
Type	Energy
Sample	1/300
Time	0.00678889 ns
Particles	132
Maximum	2.91445 eV

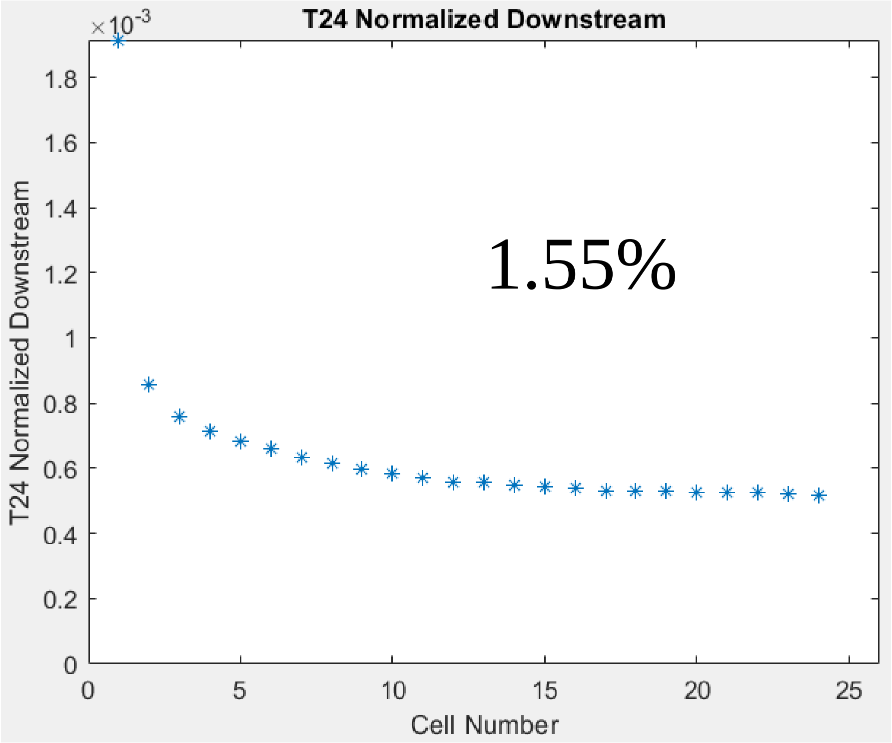


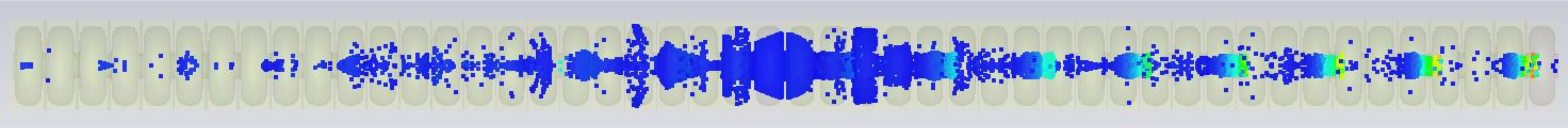


Longitudinal Dark Current

T24PSI using periodicity - Current along the structure

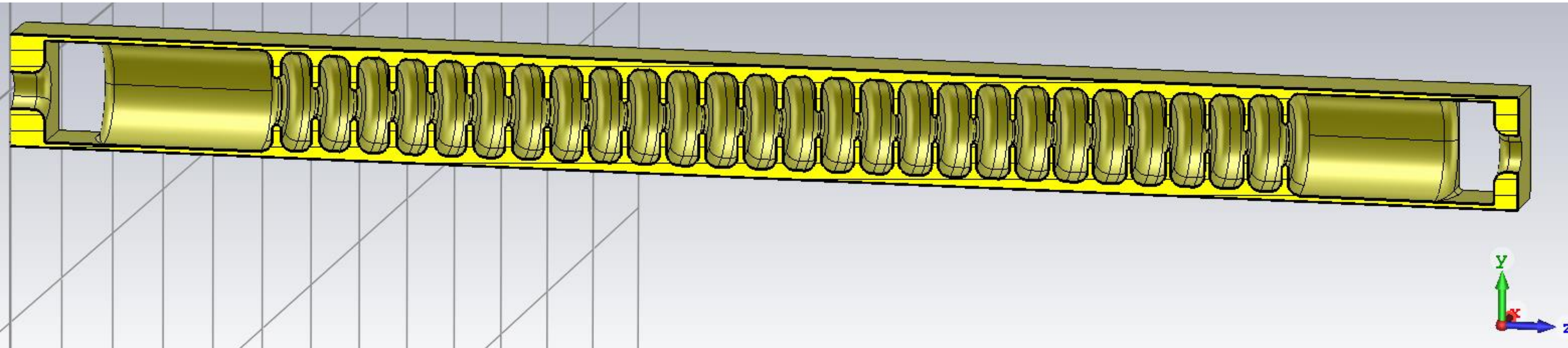


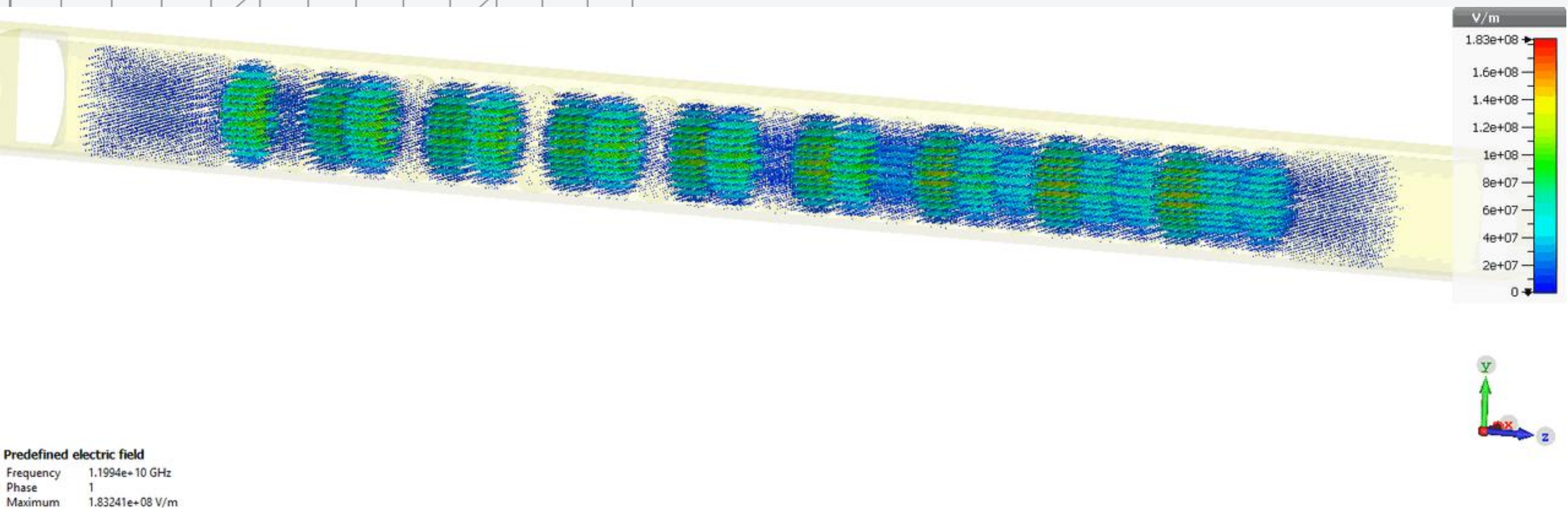




Longitudinal Dark Current

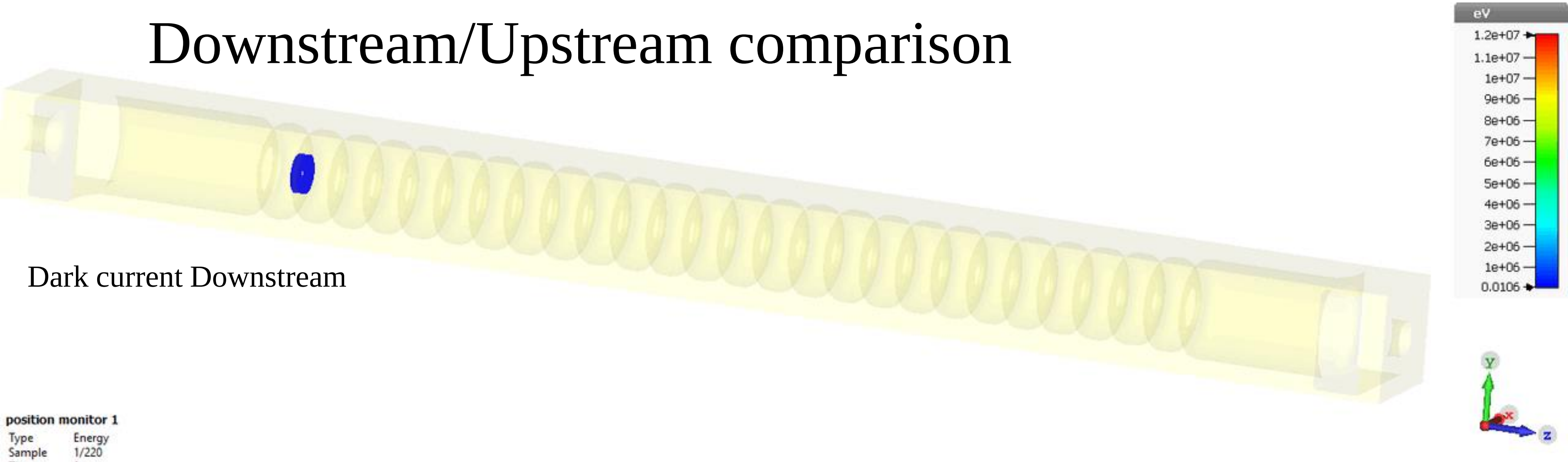
T24PSI using full field



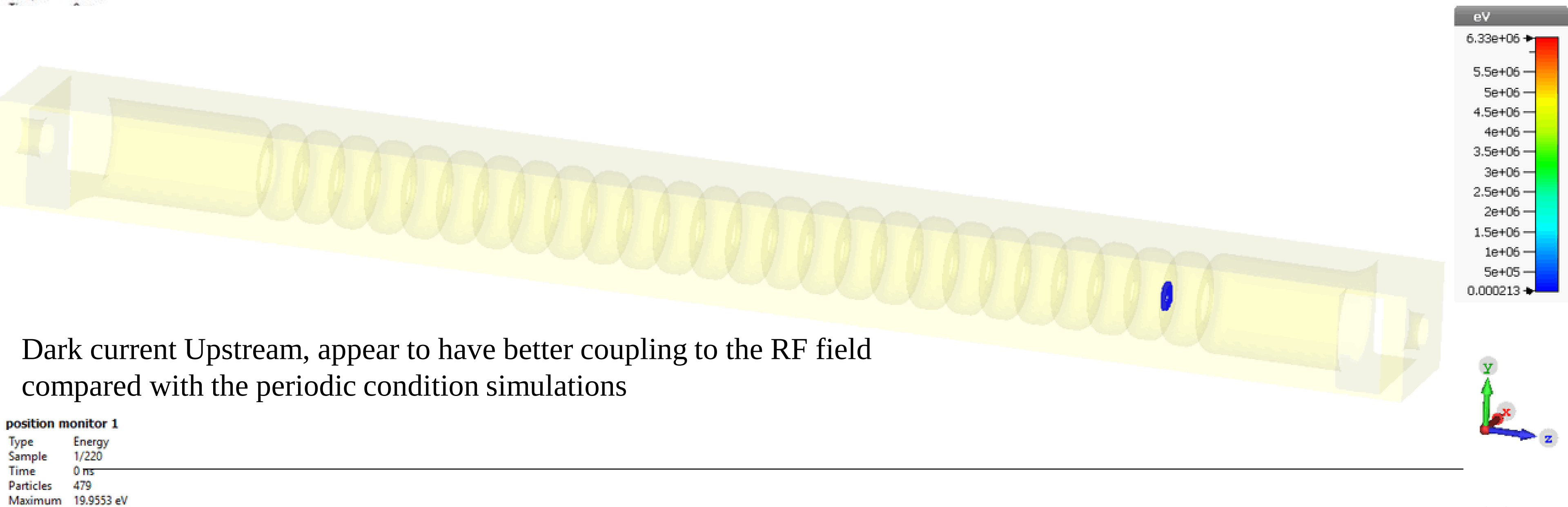


Longitudinal Dark Current

Downstream/Upstream comparison



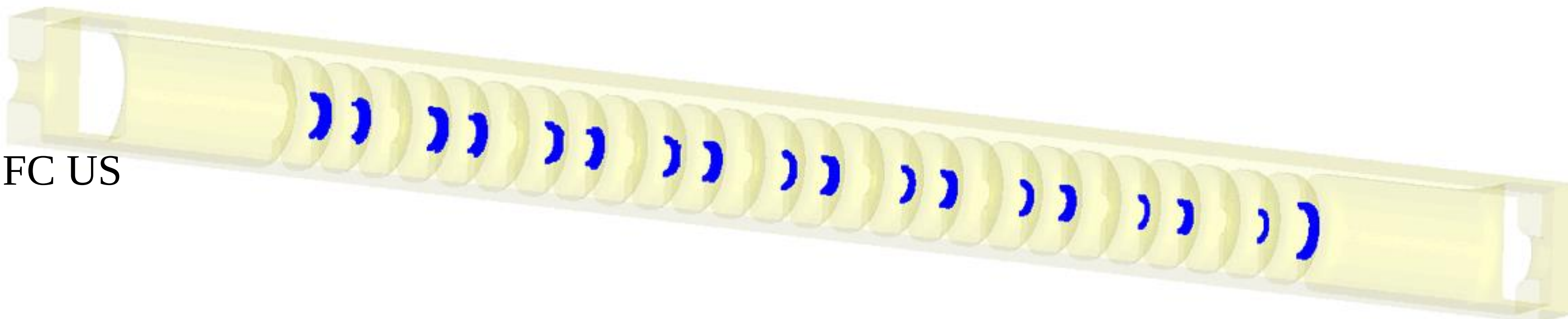
Dark current Downstream

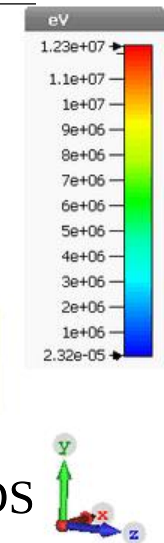


Dark current Upstream, appear to have better coupling to the RF field compared with the periodic condition simulations

Longitudinal Dark Current

Dark current in a T24PSI with emission in every iris

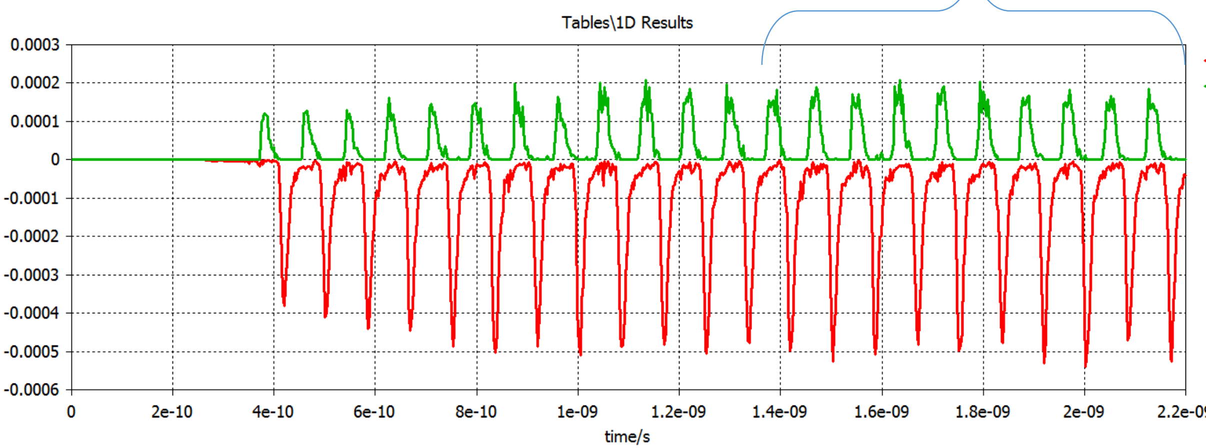




position monitor 1

Type	Energy
Sample	1/220
Time	0 ns
Particles	18465
Maximum	107.929 eV

Upstream to downstream dark current ratio integrating the last ten RF periods



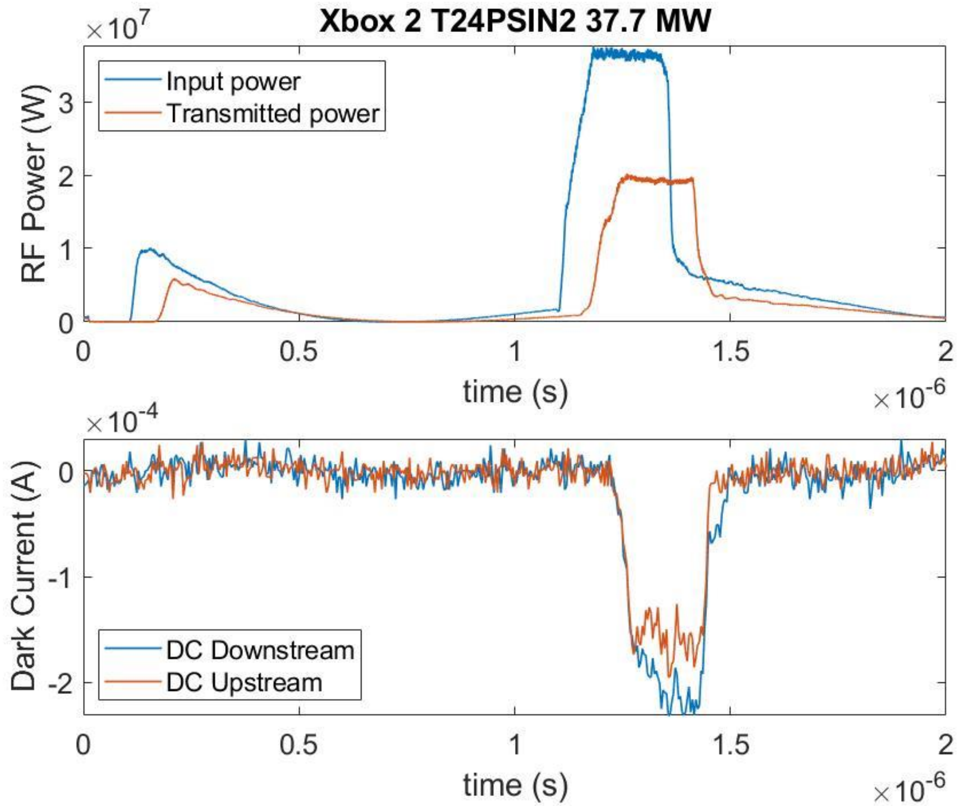
$$\frac{DC_{US}}{DC_{DS}} = \frac{4.5672 \cdot 10^{-5} A}{1.1336 \cdot 10^{-4} A} = 0.40$$

Assuming that every iris emits with the same intensity. Capture leads to this discrepancy.

Longitudinal Dark Current

Dark current measurements in the xboxes

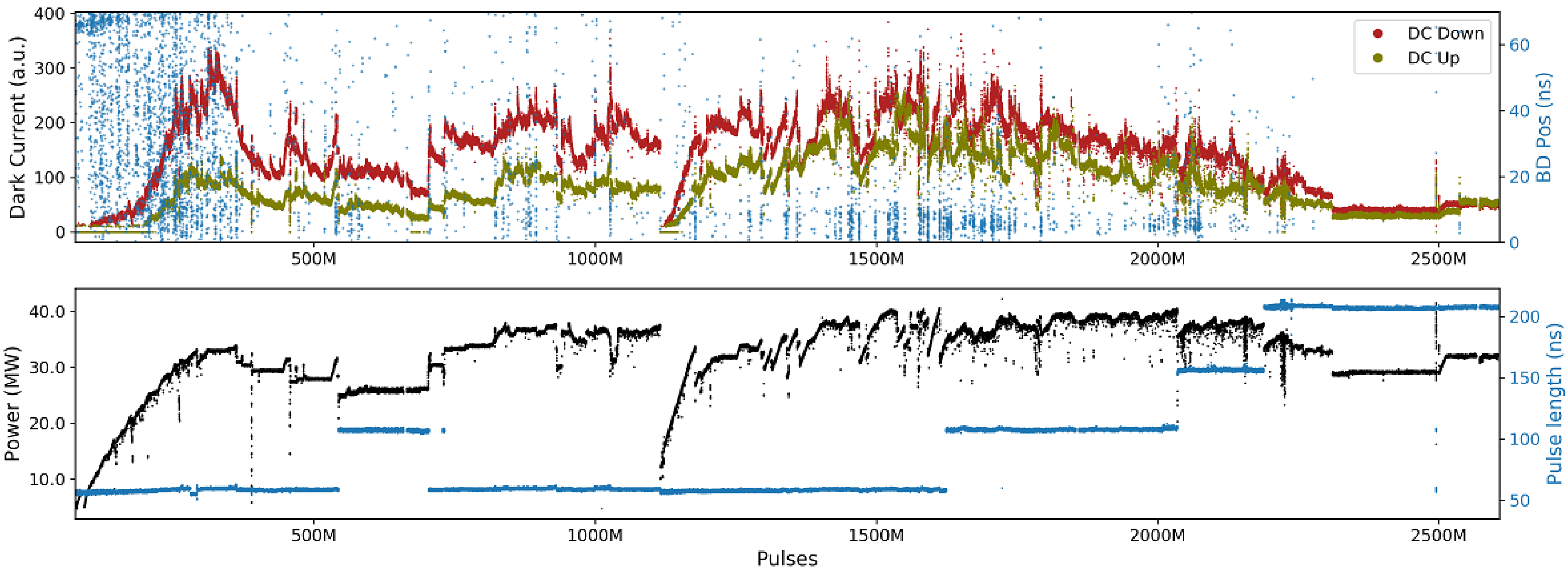
In the high gradient test stands at CERN we keep track of the dark current measured in the Faraday cups during conditioning of the structures.



Longitudinal Dark Current

Dark current measurements in the xboxes

With the post processing of the data recorded we obtain information of the breakdown position and the dark current evolution. If we assume correlation between FE and BD positioning: Emission homogeneously distributed (beginning of conditioning) lead to more downstream dark current. At the end the emission is in the first cells, closer to the upstream FC, and this signal gets comparable to the downstream, even with a much worse capture level.



[5] Full conditioning plot of a TD24 CLIC prototype tested in Xbox 3. Graph courtesy of Marcà Boronat.

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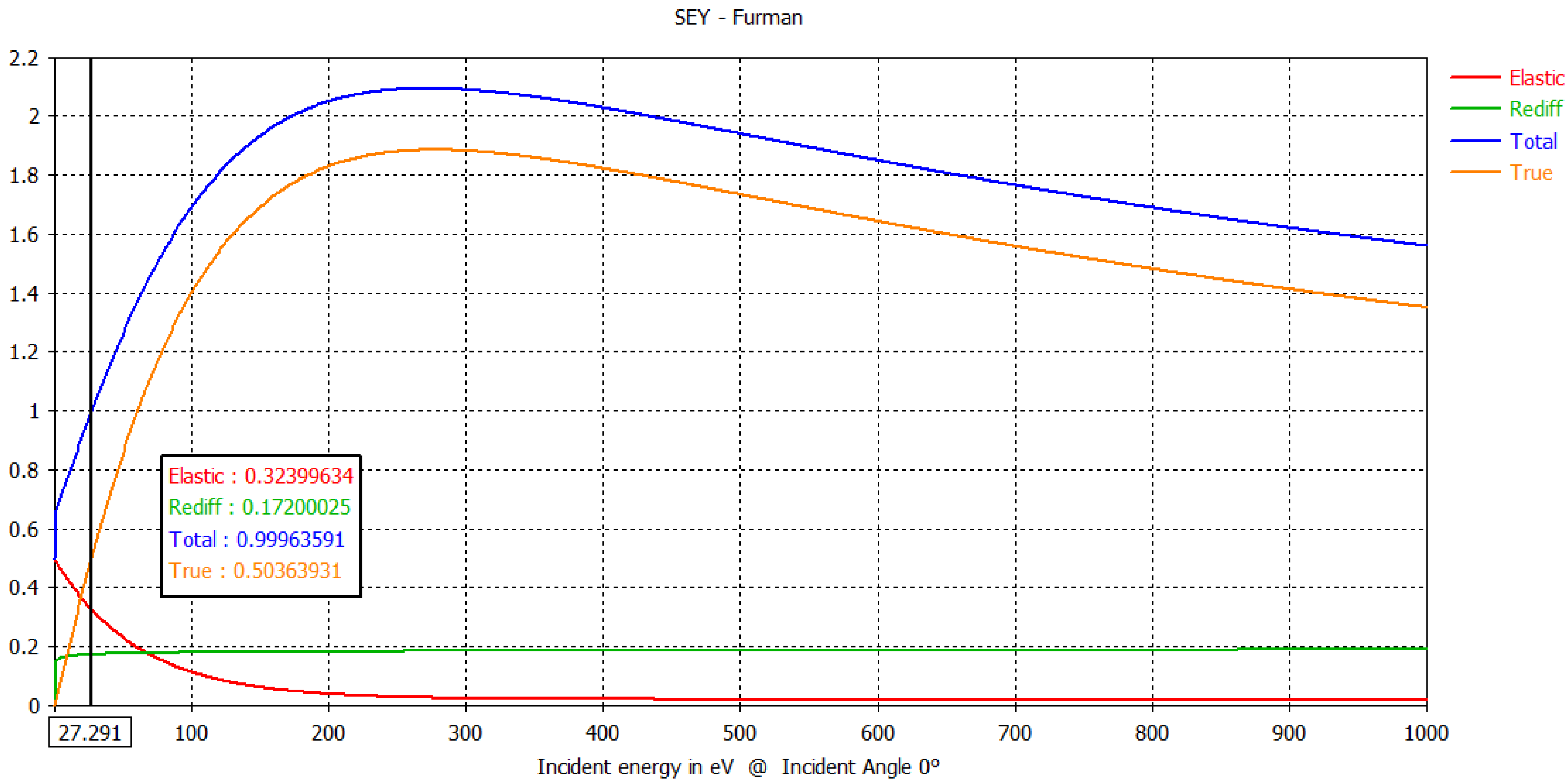
Transversal Dark Current & Multipactor

Secondary Electron Emission Yield

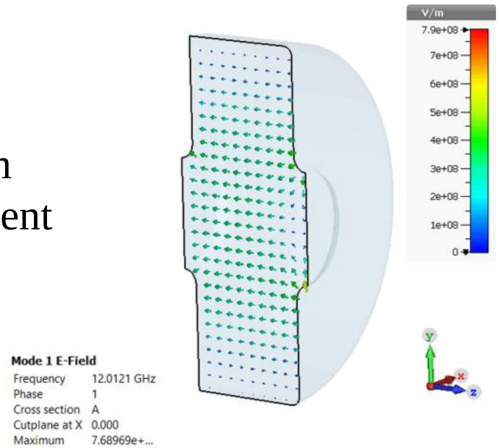


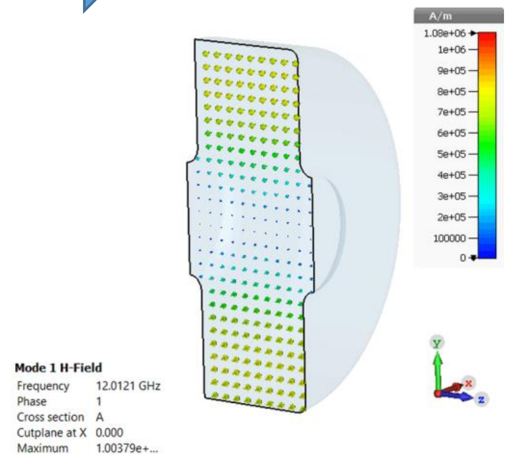
[6] M. A. Furman and M. T. F. Pivi. Probabilistic model for the simulation of secondary electron emission. Physical Review Special Topics – Accelerators and Beams, Vol 5, 124404. 2002.

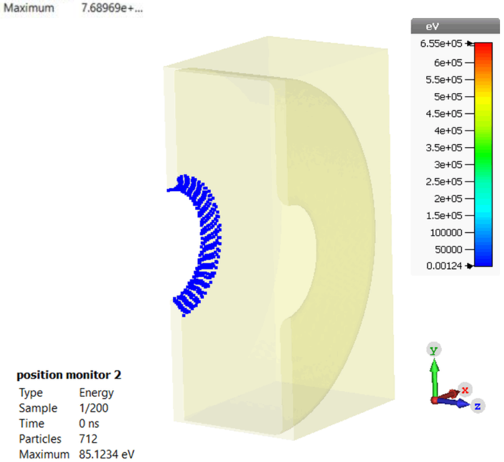
Transversal Dark Current & Multipactor

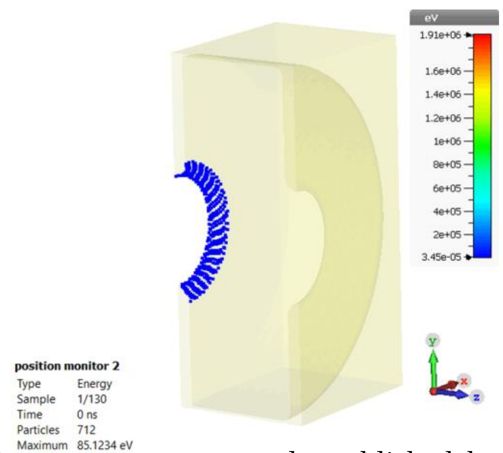
Field emission seeding + SEE Multipactor

For 100 MV/m
of average gradient









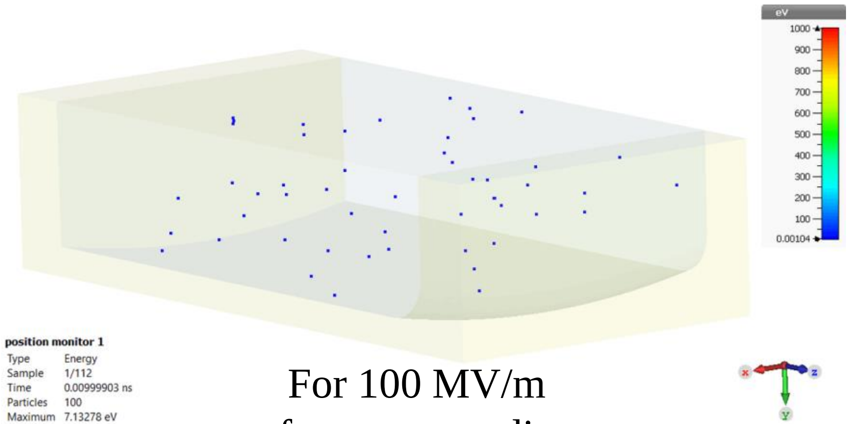
A complete study of transversal dark current and Multipactor in a HG structure was recently published by a group from MIT, involving simulation and measurements. Please see the reference for more details:

[7] H. Xu, et. al., "Measurements of internal dark current in a 17 GHz, high gradient accelerator structure." PRAB, vol. 22, no. 021002, 2019.

Transversal Dark Current & Multipactor

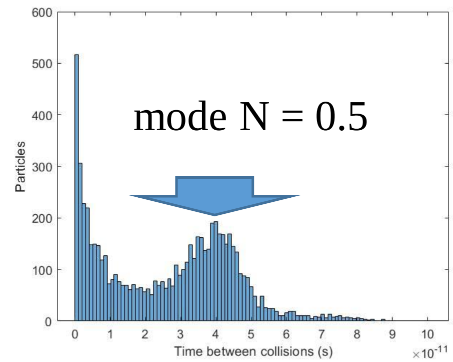
Zoom in the resonance area

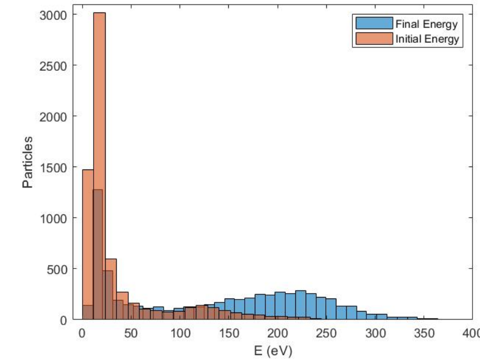
$T_{RF} = 1/(12\ \text{GHz}) = 0.0833$ ns



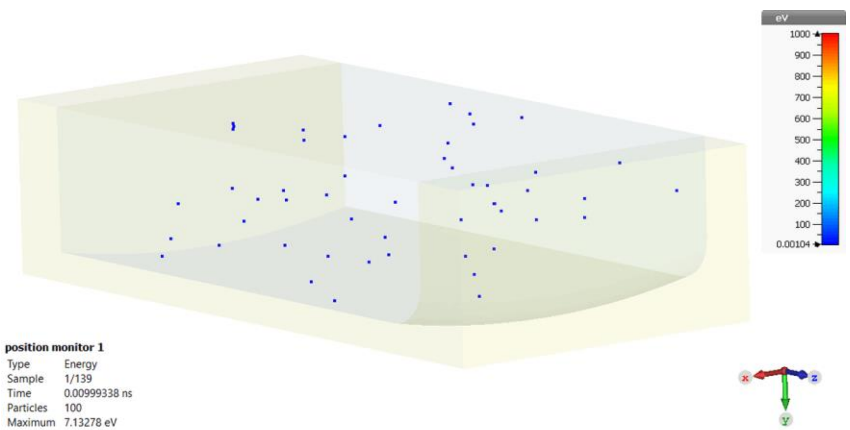
For 100 MV/m
of average gradient

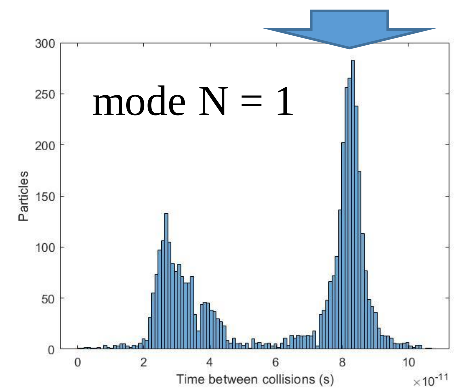
time between collisions = 0.5 T_{RF}

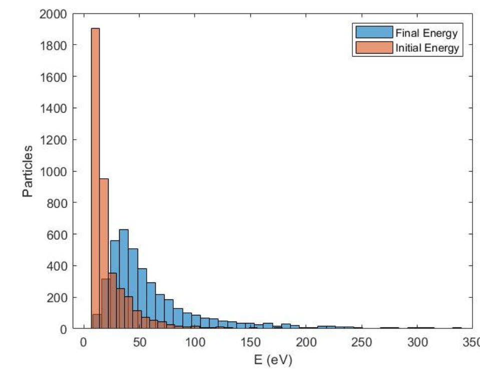




time between collisions = 1 T_{RF}







A change in the Multipactor mode normally is determined by a change in the field level or in the initial settings of the particles.

Transversal Dark Current & Multipactor

Multipactor mode characterization made by the MIT group, presented in the cited reference

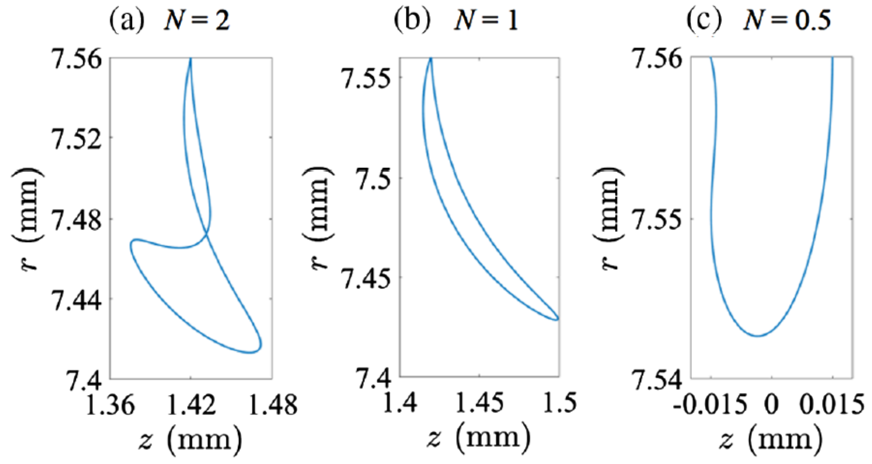


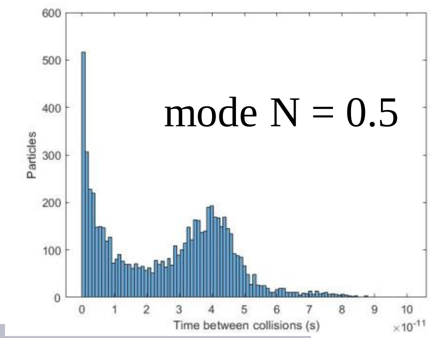
FIG. 6. Sample trajectories of the second-order one-point MP (a) at 45 MV/m, the first-order one-point MP (b) at 72 MV/m, and the first-order two-point MP (c) at 250 MV/m.

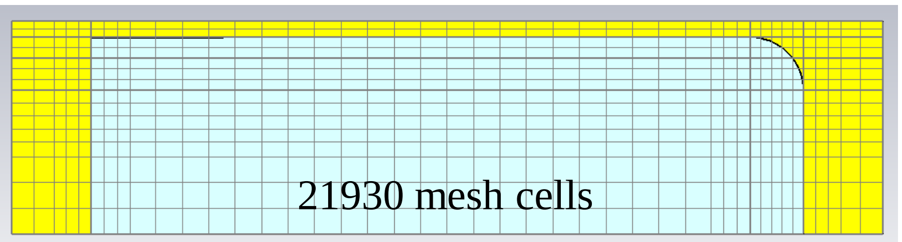
[7] H. Xu, et. al., “Measurements of internal dark current in a 17 GHz, high gradient accelerator structure.” PRAB, vol. 22, no. 021002, 2019.

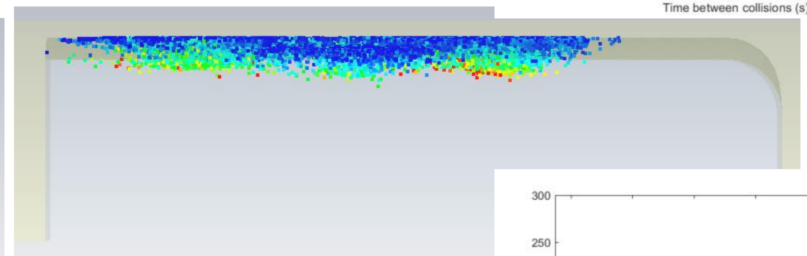
Transversal Dark Current & Multipactor

Zoom in the resonance area

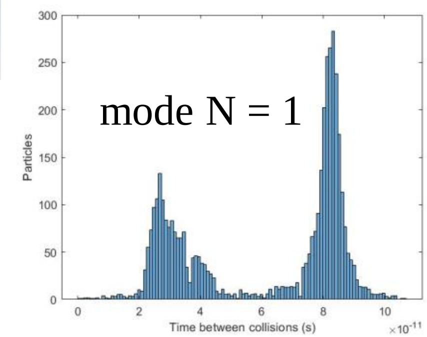
In our case what we changed was the mesh size, keeping the same field level and the same particle source.
Increasing the mesh quality also reduces the time step for the PIC simulation, this can lead to a more precise trajectory calculation, and the possibility of changing the Multipactor mode.

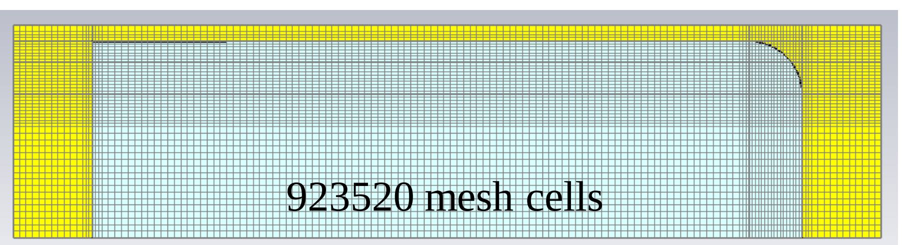


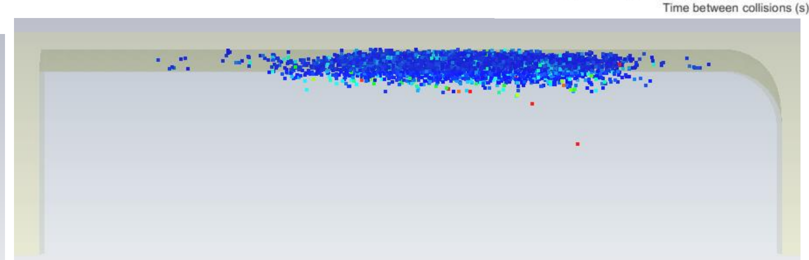




For 100 MV/m
of average gradient

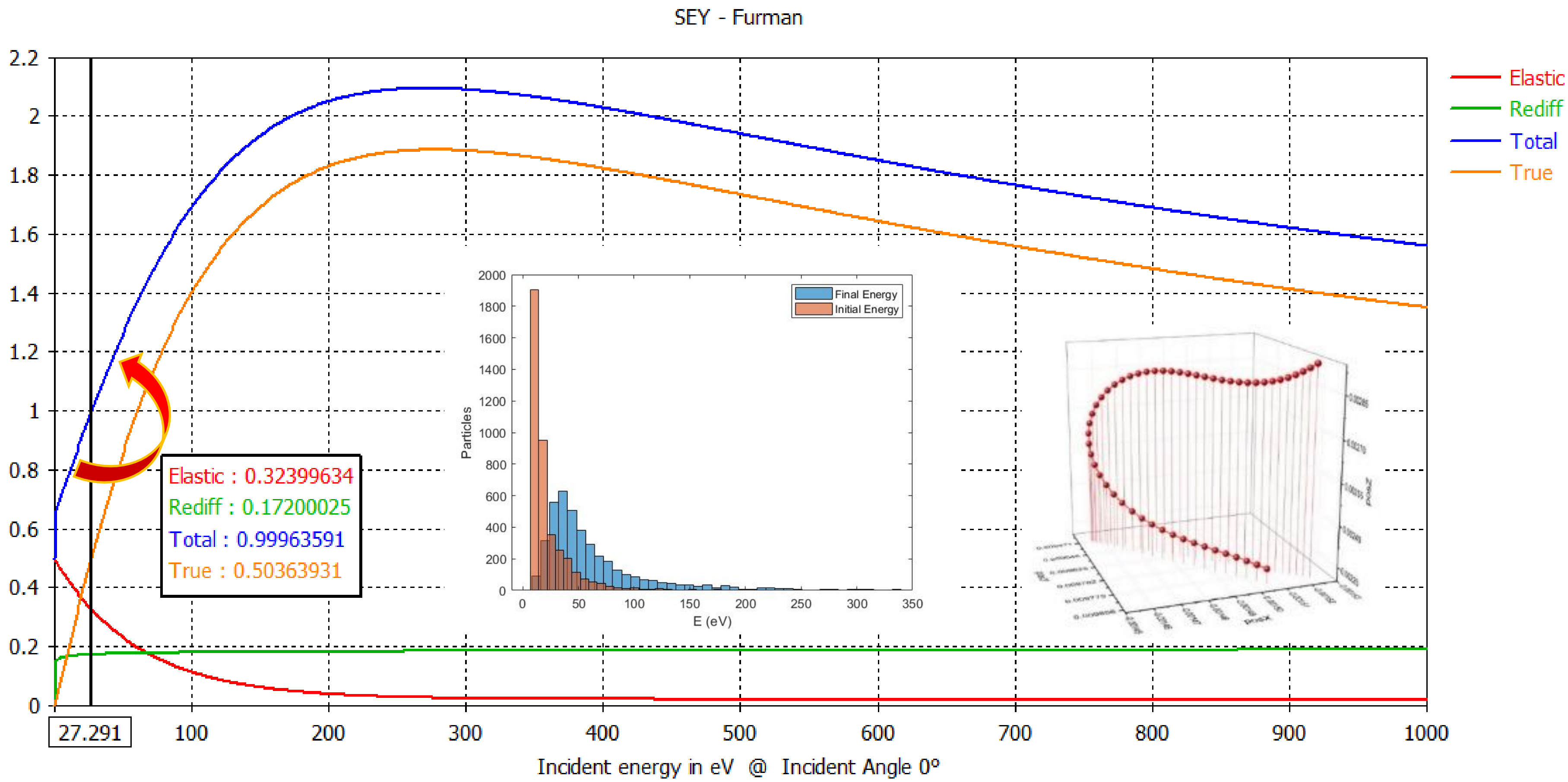






Transversal Dark Current & Multipactor

Energy gain in the Multipactor trajectories



[6] M. A. Furman and M. T. F. Pivi. Probabilistic model for the simulation of secondary electron emission. Physical Review Special Topics – Accelerators and Beams, Vol 5, 124404. 2002.

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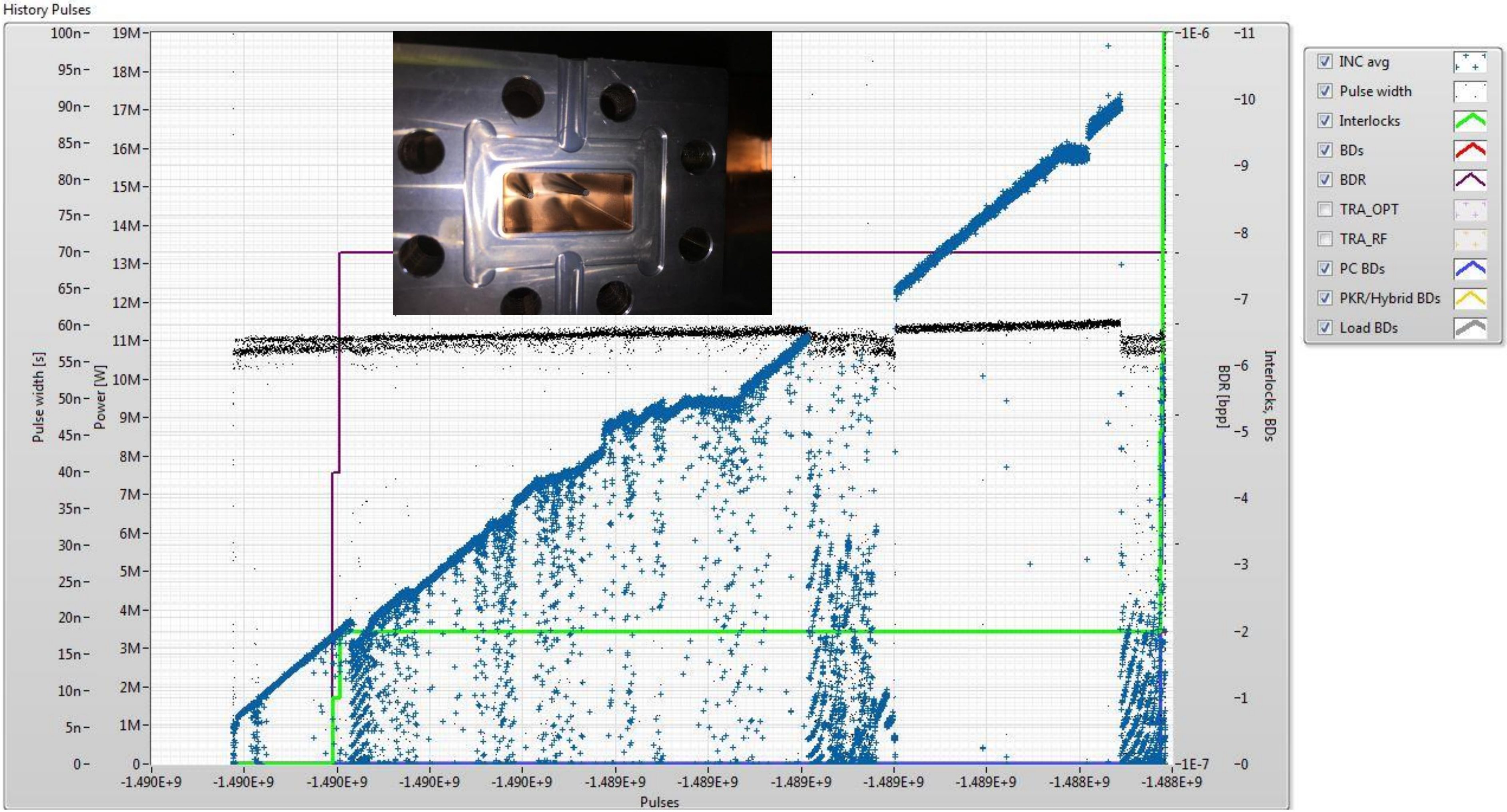
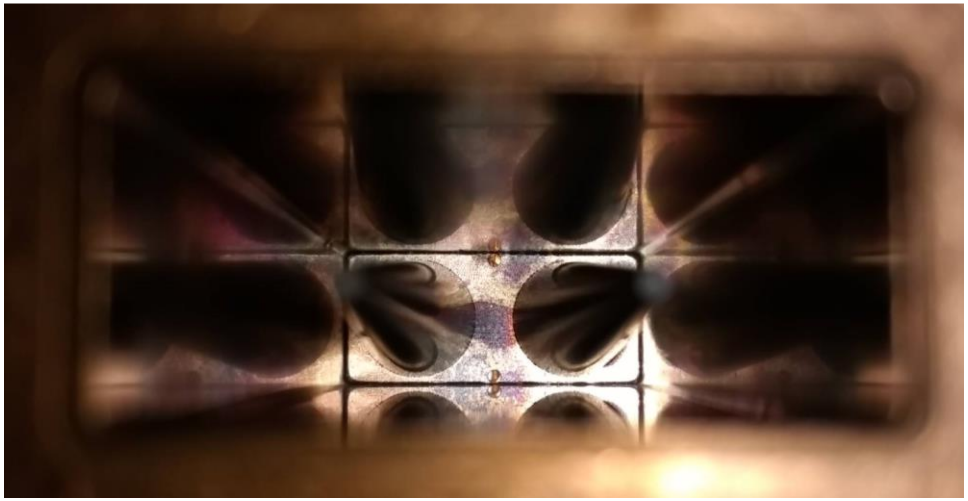
Multipactor in SiC loads

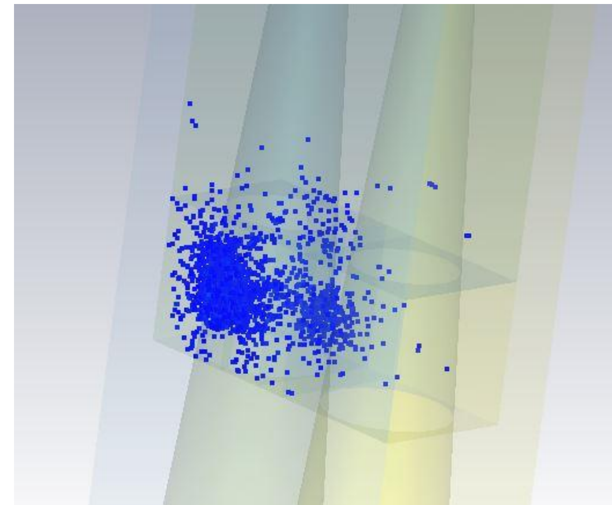
First experimental results - RF terminators tested at Xbox 3

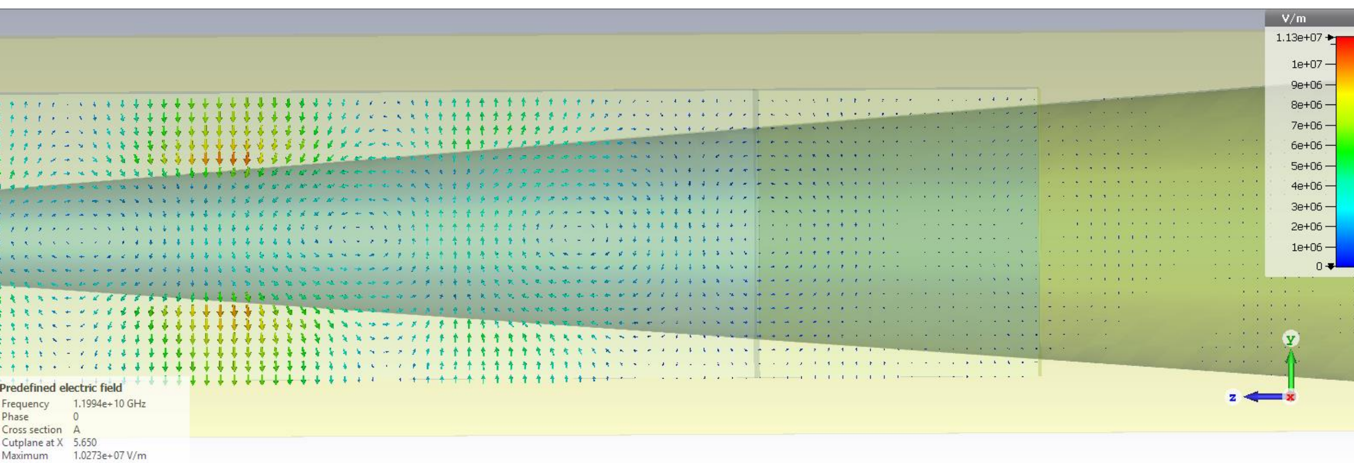


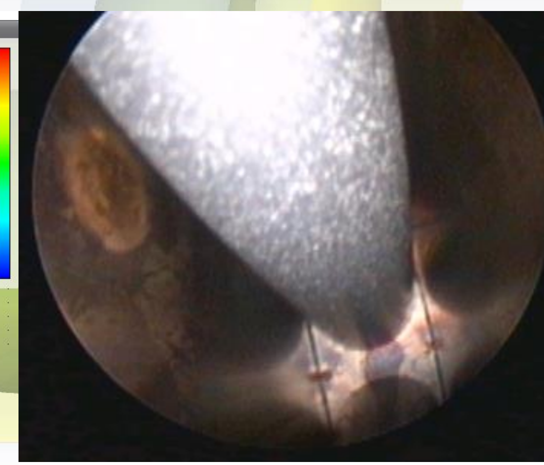
Multipactor in SiC loads

First experimental results - RF terminators tested at Xbox 3









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Conclusions

- In this talk the effect of field emission and Multipactor in high gradient structures has been presented. In different scenarios and from theoretical and experimental points of view.
- The longitudinal dark current is measured in the Xboxes for BD detection during conditioning of HG structures. An analysis of the data recorded together with CST simulations is leading to good results. Possible correlation between BD location and emission.
- The Multipactor inside the cell is analyzed from a theoretical point of view, using CST simulations.
- The Multipactor in a silicon carbide loads has been simulated, seems to be evidence also in the postmortem analysis of the components.

thanks very much for your attention