Combined dark current and radiation simulations and comparison with experiment

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RF development meeting

29/07/2020

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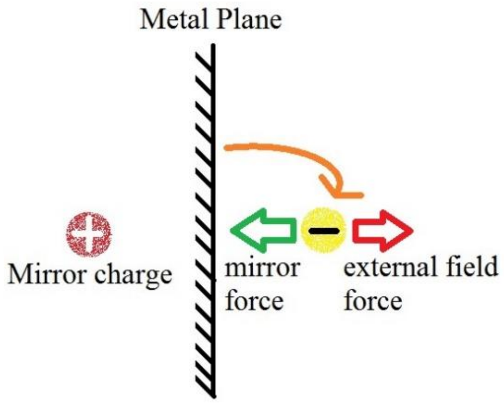
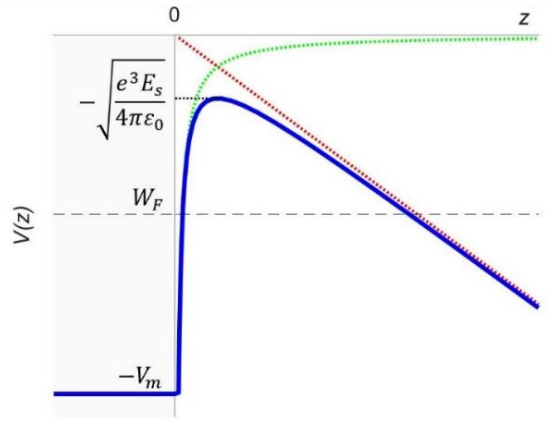
Introduction: Field emission theory

- In the presence of an external E field surface electrons can jump out to the vacuum by means or quantum tunneling. The resulting current increases exponentially with the field following the Fowler-Nordheim equation.



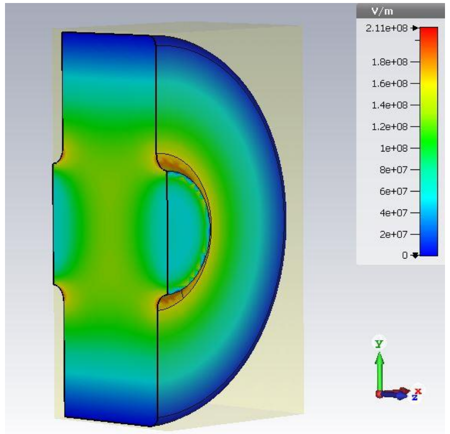


Fowler-Nordheim eq

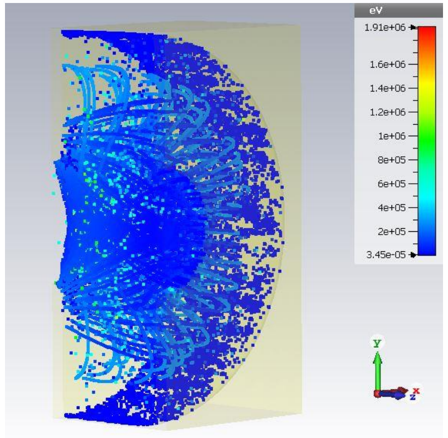
$$J = aE^2 exp\left(\frac{-b}{E}\right)$$

Enhancement factor in a tip

$$E_{emitter} = \beta E$$



- In a CLIC cell the surface E field is highest in the iris.

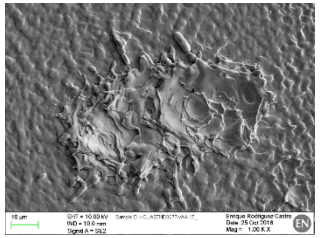


- In this example field emissions occurs in the left iris of the cell.

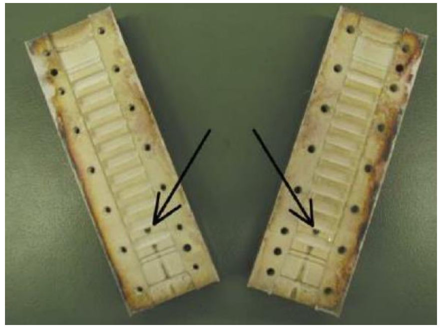
Introduction: Field emission issues

Field emission related issues during high gradient operation:

- Field emitted electrons can get captured by the RF fields, producing the so-called dark currents:
  - Potentially distorting beam position monitors.
  - Electrons can reach 20 MeV in a single CLIC structure, being a source of ionizing radiation by themselves and generating X-rays when colliding with the material walls.



- Field emission can turn into an explosive process causing the damaging RF breakdowns that limit HG performance.
- Field emission also causes electron seeding in low field areas potentially triggering Multipactor effect.



Introduction: Dark current and radiation

- Dark current electrons can reach 20 MeV in a single CLIC structure. Being a source of ionizing radiation by themselves and generating X-rays when colliding with the material walls.
- This is one of the main problems related to dark current. It makes necessary to put the experiment inside a protective bunker for operation, even without beam.
- It will be the main subject of this talk. From now one we will show: the experimental area, dark current and radiation measurements, followed by computer simulations.

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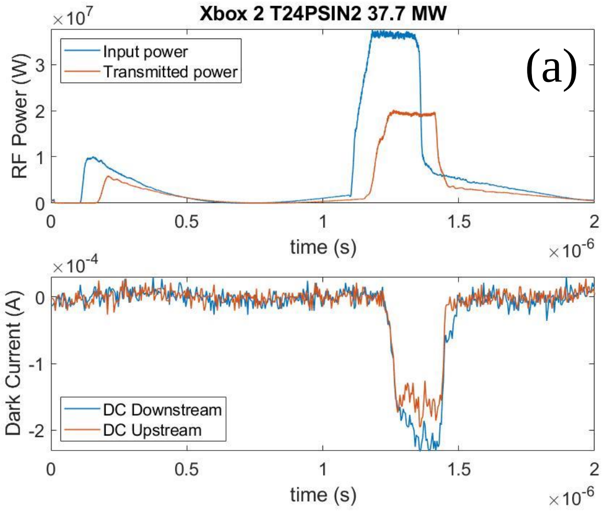
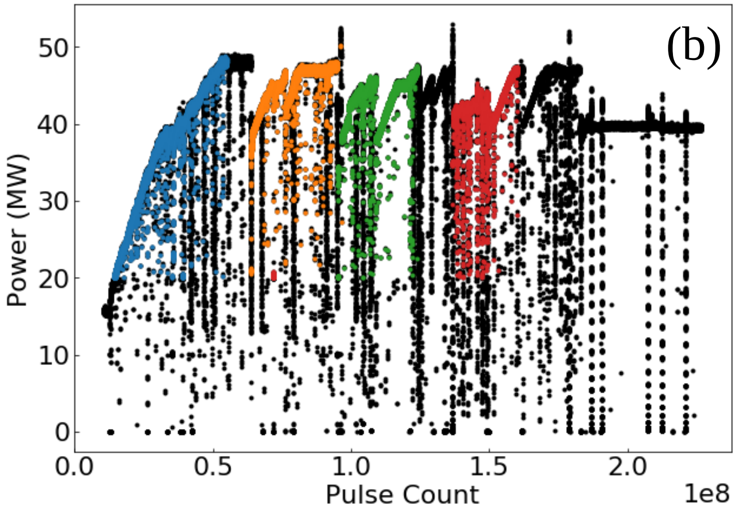
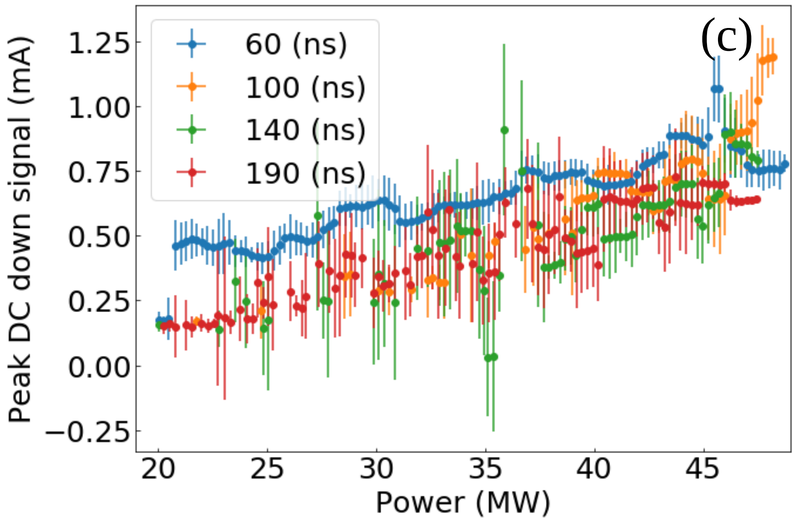
Dark current measurements



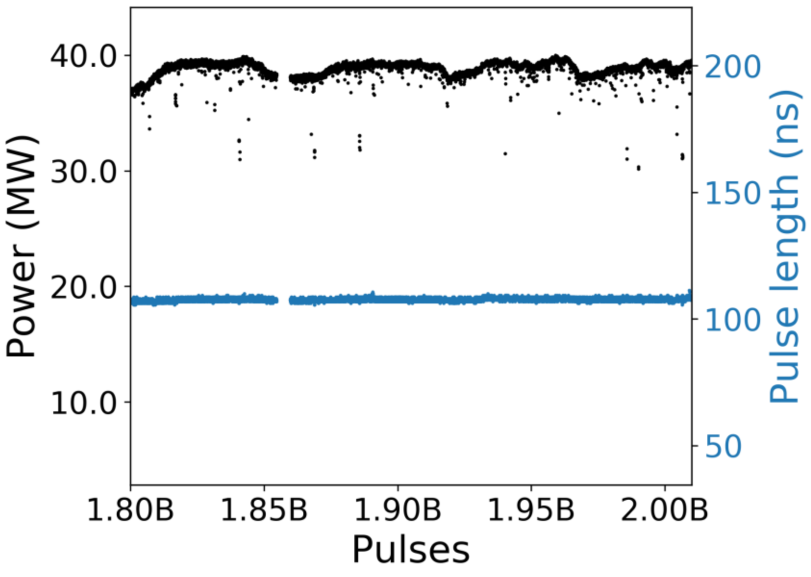




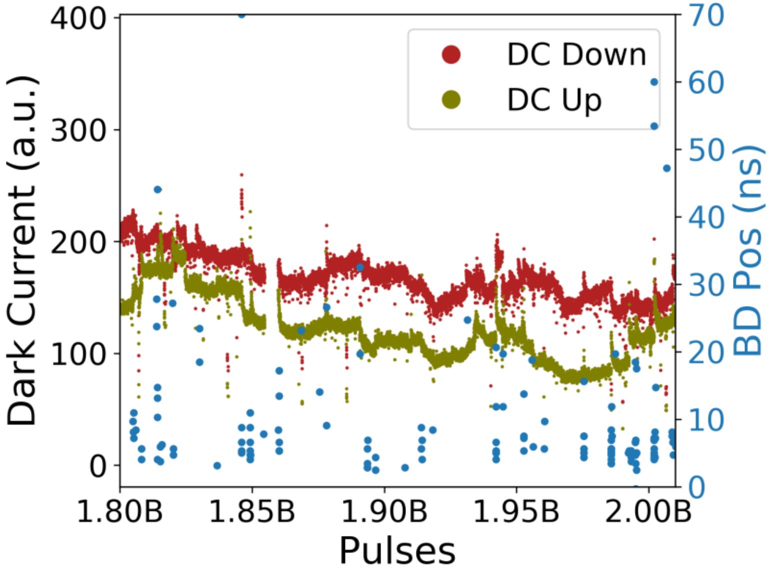
- During conditioning of CLIC cavities we periodically record pulses like the one showed in (a). With the RF power and the dark current measured in the Faraday cups.
- Analyzing those pulses we get the conditioning power graph (b), and the dark current measured as a function of power in the different pulse length regions (c), see color legend.
- Main conclusions: dependence is linear instead of exponential. Dark current goes down with the breakdown conditioning.
- Require short time scans to see Fowler-Nordheim dependence.

Dark current measurements

(a)



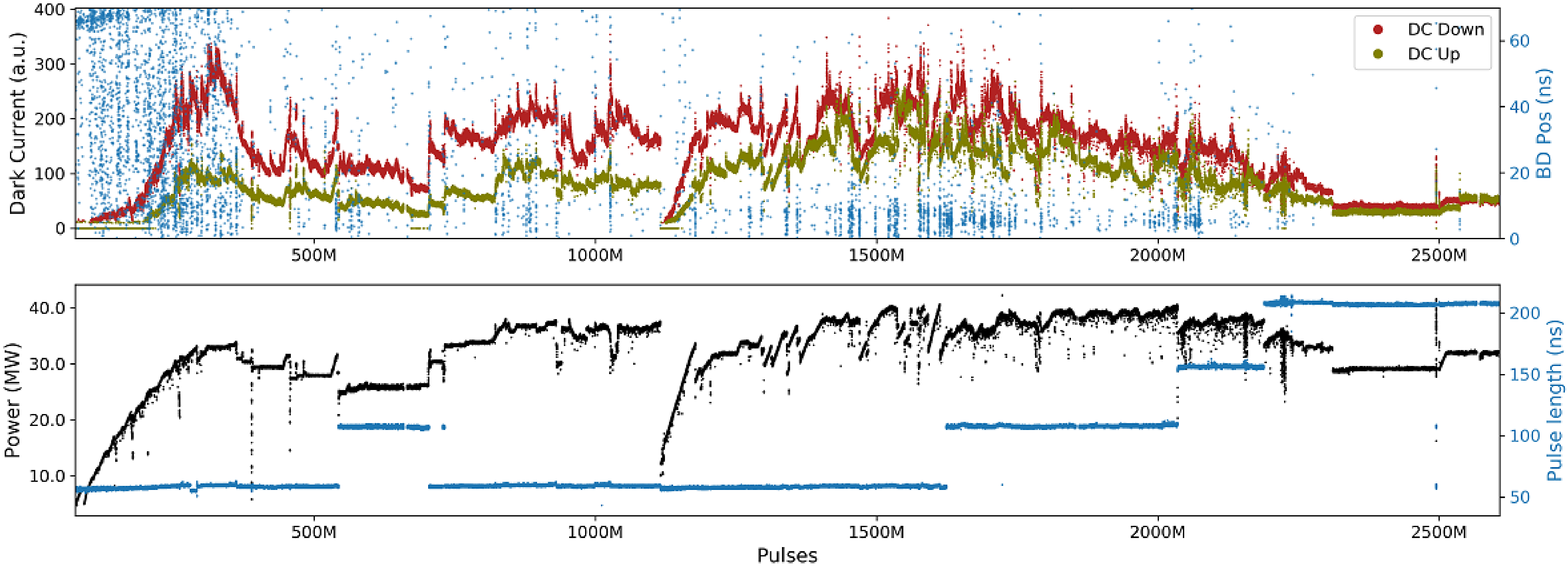
(b)



- Here we present a fragment of conditioning where power and pulse length remained constant (a).
- However, we see how dark current goes down (b), that's the effect of breakdown conditioning.
- The blue dots in (b), mark the breakdown localization in the structure, 0 ns being the first cell and 70 ns the last one. Calculated with the time of flight of the reflected signal, and compared to the filling time.

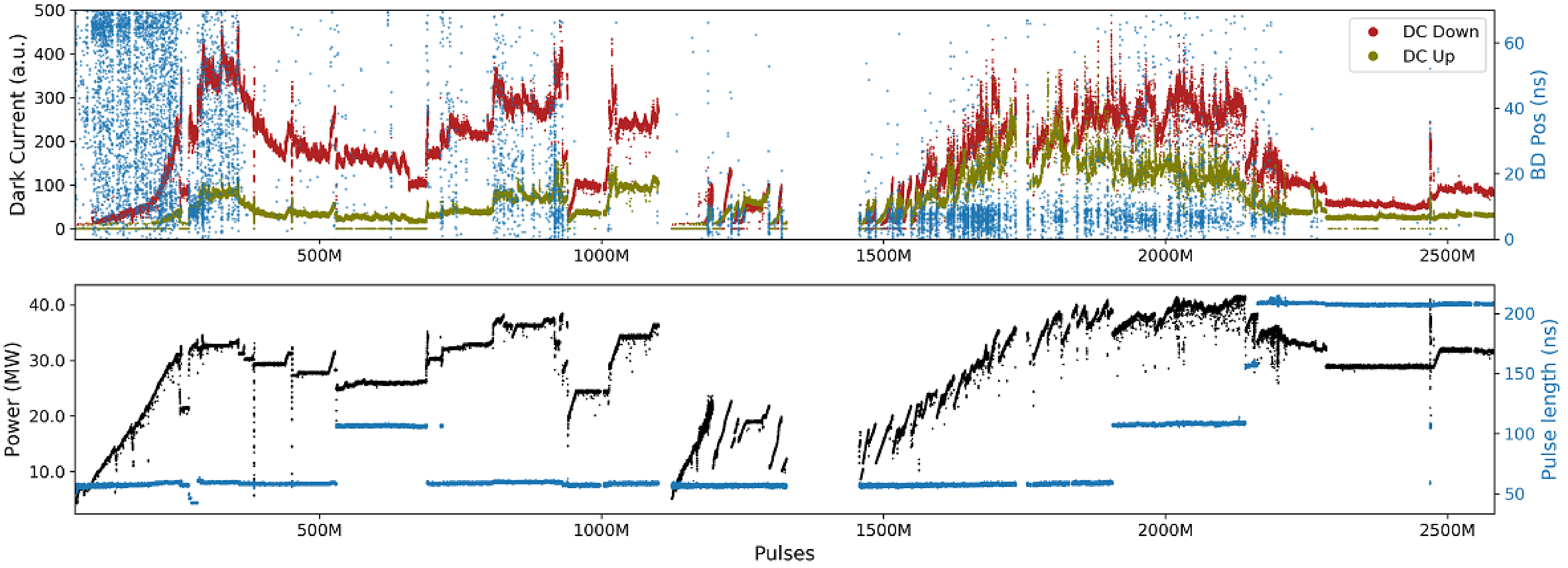
Dark current measurements

Full conditioning plot TD24BO prototype



Dark current measurements

Full conditioning plot TD24UBO prototype



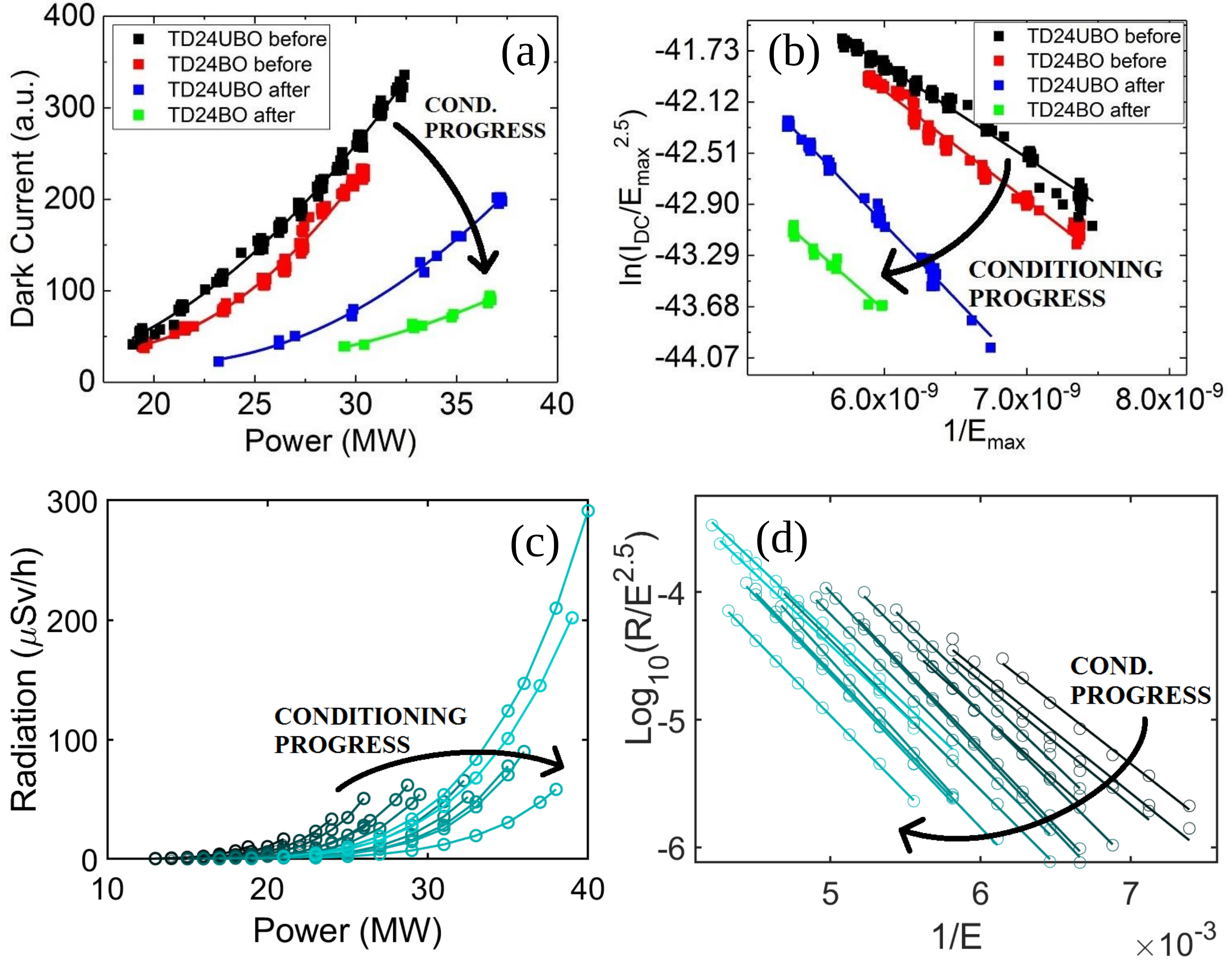
Dark current measurements

Main conclusions from the previous two plots:

- Breakdown positioning and source of field emission are correlated.
- At the beginning all the cells are emitting with the same intensity, therefore the downstream current is bigger than the upstream as the RF capture efficiency is better (more on this in the simulations section).
- At the end of the conditioning most of the breakdowns occur in the first cells, emission occurs there, closer to the upstream Faraday cup, resulting in a bigger signal, more comparable to the downstream.
- Breakdown conditioning reduces the dark current magnitude and, in consequence the breakdown rate.

Dark current measurements

Short time power scans



- Remember the exponential dependence of the Fowler-Nordheim equation:

$$J = aE^2 exp\left(\frac{-b}{\beta E}\right)$$

- When we do short time scans the exponential behavior turns visible, see (a) and (c).
- We can make Fowler-Nordheim plots and see linear dependence (b) and (d).
- A steeper line means a lower field enhancement factor beta. With lower beta, we need more electric field to reach the same emission. Conditioning progress lowers the emission and the beta measured. TD24BO's beta goes down from 80 to 70, while TD24UBO's goes from 94 to 60.
- Both dark current and radiation show the same behavior. However, radiation has an extra dependence with field, as electron energy has an effect. More about this in the next section.

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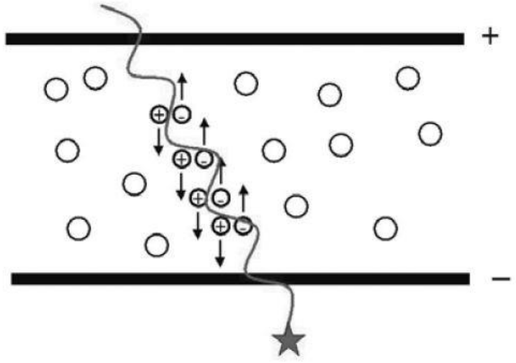
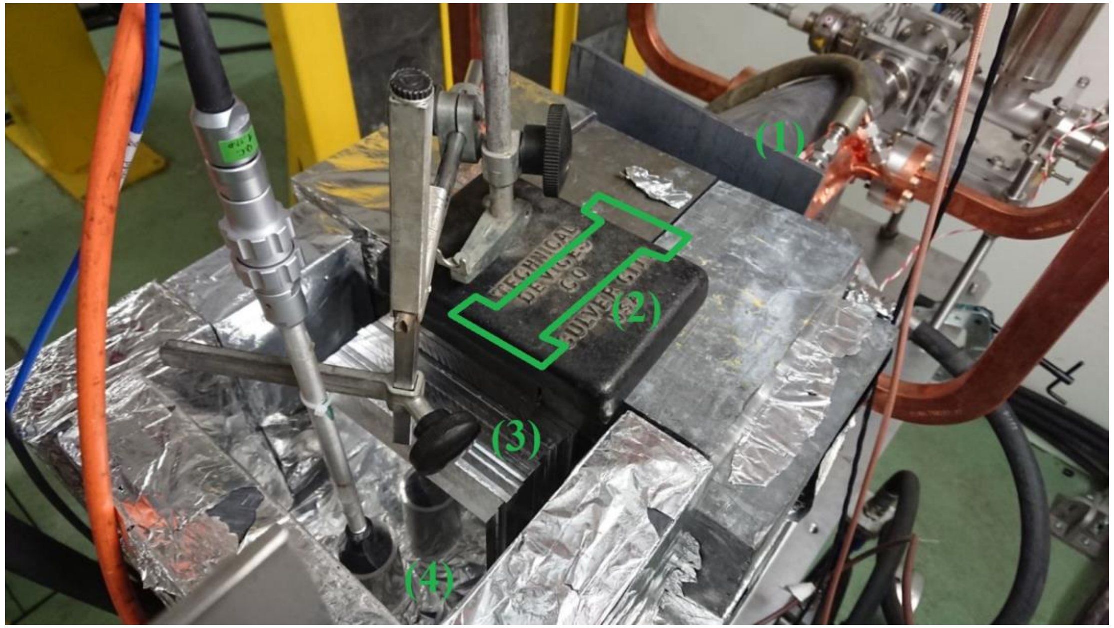
- Dark current measurements
- Radiation measurements
- Dark current simulations
- Radiation simulations
- Conclusions

Radiation measurements: Setup

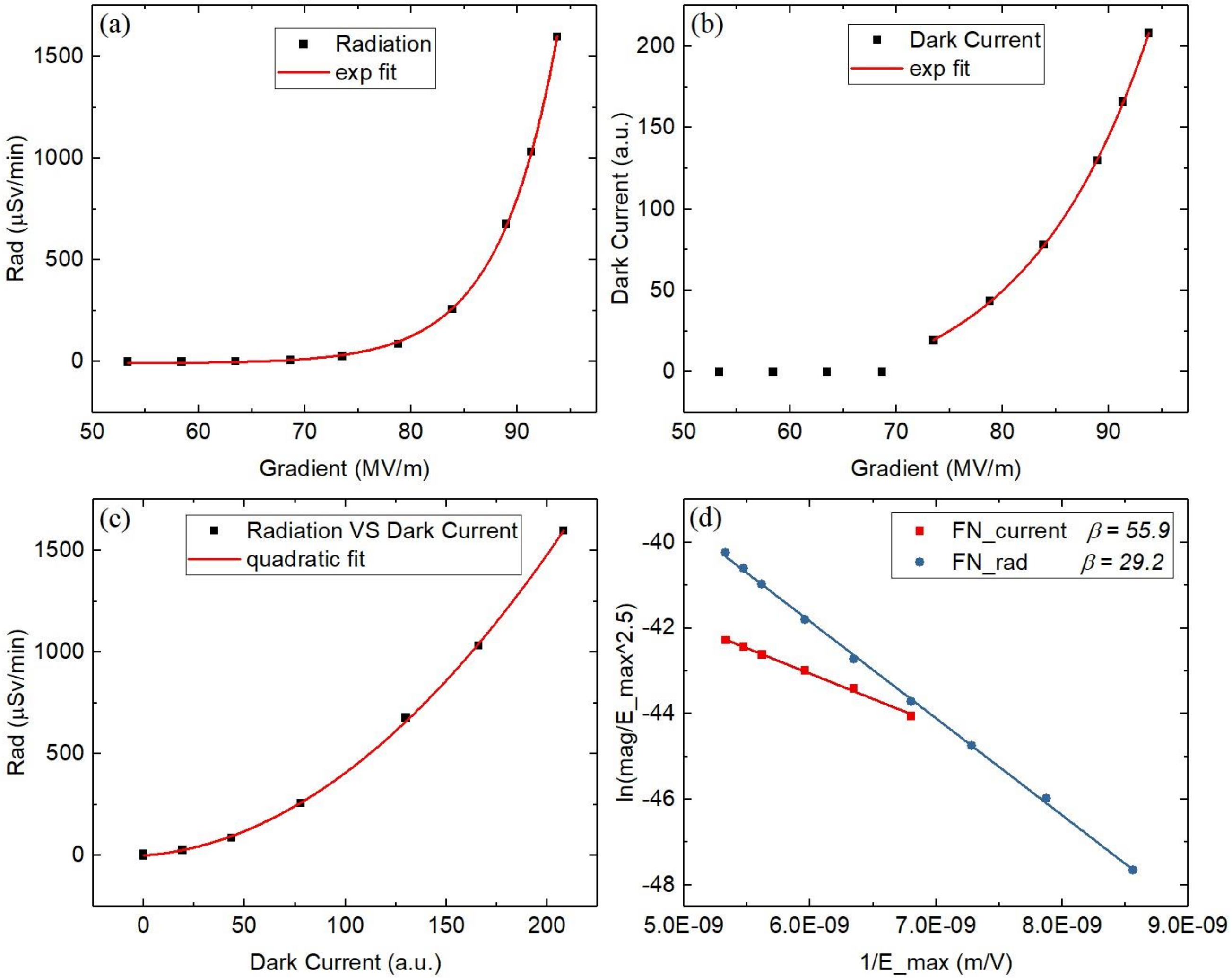




(1) Structure: TD24UBO, (2) Faraday cup, (3) aluminum shielding plates, and (4) ionization chamber.

- To properly see the relation between dark current and the resulting radiation we made a dedicated experiment. Placing an ionization chamber right next to the downstream Faraday cup.
- The initial source of radiation are dark current electrons, which are mostly absorbed by the FC. Nevertheless some make it out and reach the radiation monitor.
- We tried to do calorimetry by increasing the shielding in a controlled manner. Filtering the electrons from the X-ray dose, at different power levels (or electron energies).

Radiation measurements: Rad VS dark current



Radiation measurements: Rad VS dark current

$$Rad = I_{DC}^2$$

$$exp\left(\frac{-b}{\beta_{rad}E}\right) = \left(exp\left(\frac{-b}{\beta_{DC}E}\right)\right)^2$$

$$exp\left(\frac{-b}{\beta_{rad}E}\right) = exp\left(\frac{-2b}{\beta_{DC}E}\right)$$

$$\beta_{DC} = 2\,\beta_{rad}$$

Radiation measurements: Tables

Aluminum

Shielding (mm)	95 MV/m	90 MV/m	80 MV/m	70 MV/m
0	3070	1311	174.1	17.38
5	2517	1061	139.3	14.31
10	2285	968.4	129.0	13.44
15	2173	915.1	123.0	12.91
20	2117	882.4	116.5	12.16
15	2046	858.9	112.4	11.52
30	1991	819.9	108.2	11.19
35	1918	801.1	102.9	10.74
40	1839	766.3	100.2	10.28
45	1795	749.2	97.69	9.89
50	1751	720.4	93.70	9.43
55	1677	697.5	90.49	8.89
60	1599	662.0	86.50	8.70
65	1546	648.8	83.39	8.23
70	1523	636.1	81.81	8.07
75	1477	604.8	77.70	7.60

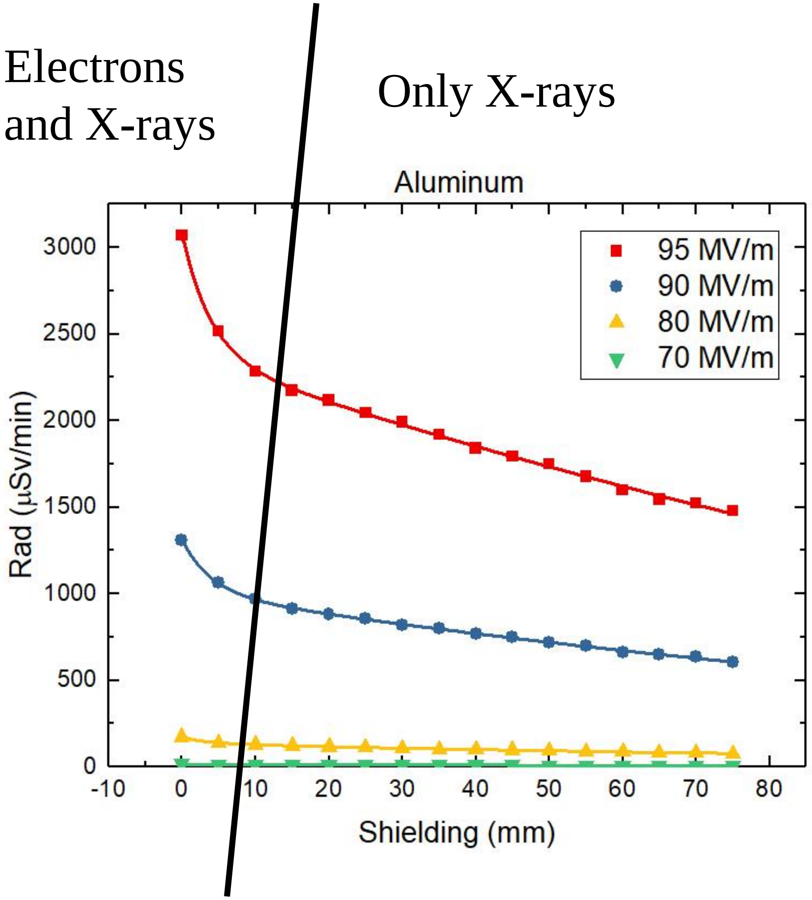
Lead

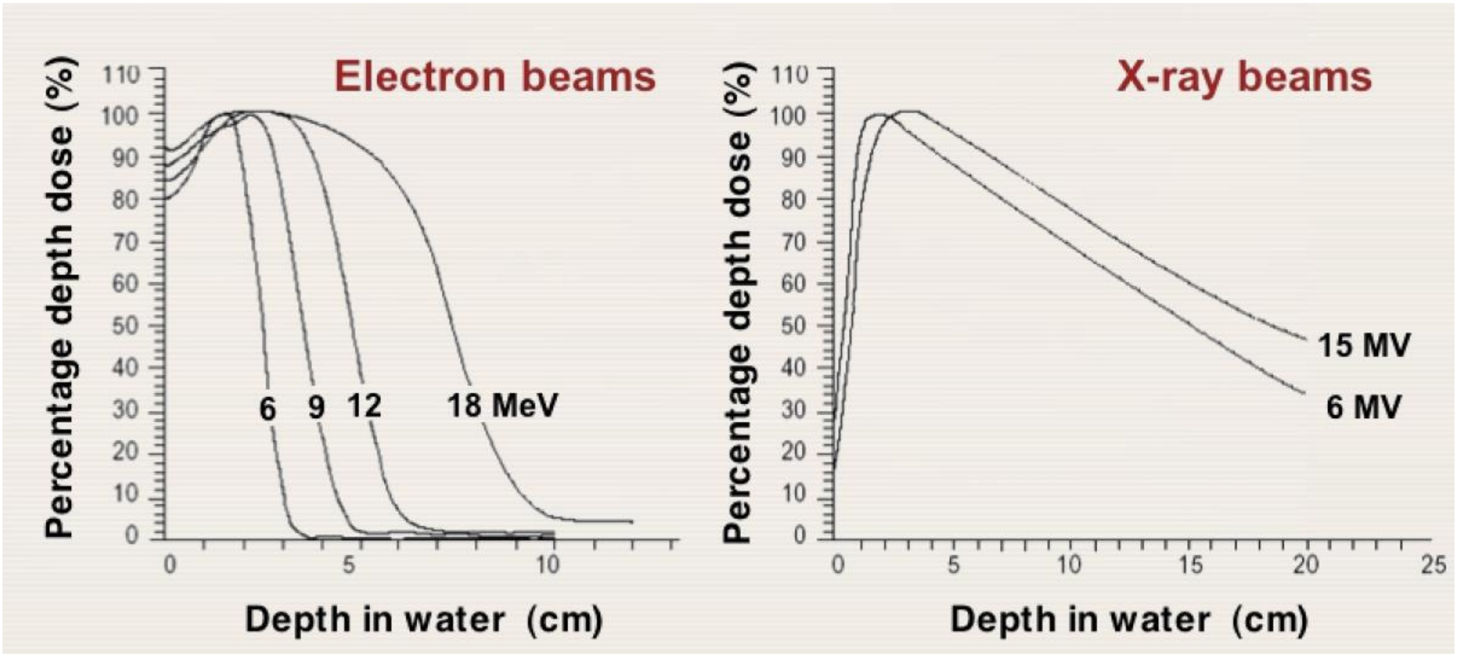
Shielding (mm)	95 MV/m	90 MV/m	80 MV/m	70 MV/m
0	2631	1102.0	132.0	12.8
5	1706	711.8	85.90	8.25
10	1362	565.5	68.88	6.47
15	1105	453.6	55.31	5.29
20	881.2	362.8	43.78	4.10
15	702.0	291.6	35.38	3.31
30	567.1	230.5	28.25	2.59
35	460.1	188.6	22.75	2.04
40	364.2	146.3	17.95	1.59
45	297.0	118.3	14.40	1.24
50	240.2	98.12	11.72	0.98
55	199.7	79.36	9.49	0.79
60	154.7	63.49	7.75	0.59
65	133.8	54.00	6.33	0.49
70	108.2	44.20	5.14	0.28

Radiation measurements: Aluminum

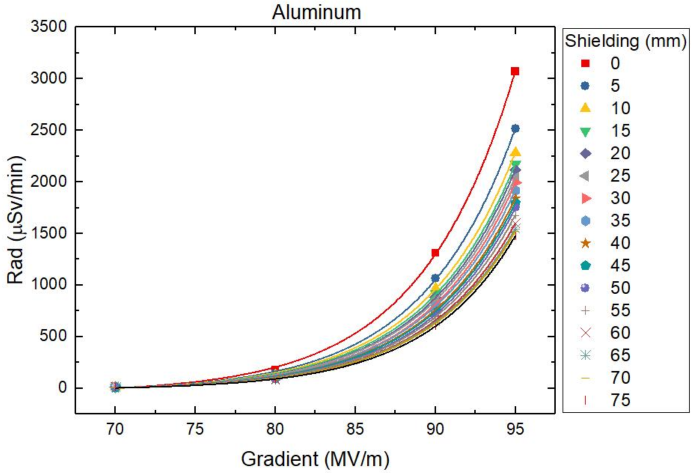
Electrons
and X-rays

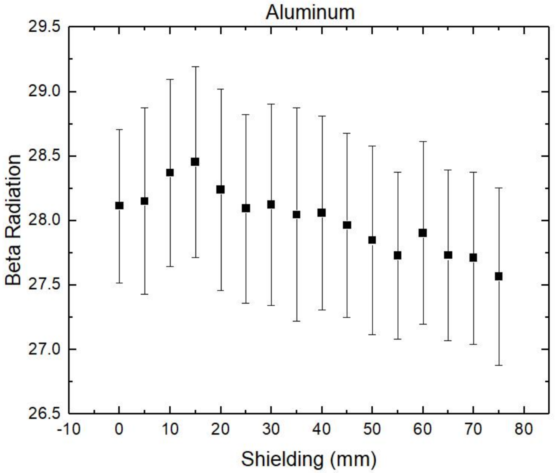
Only X-rays

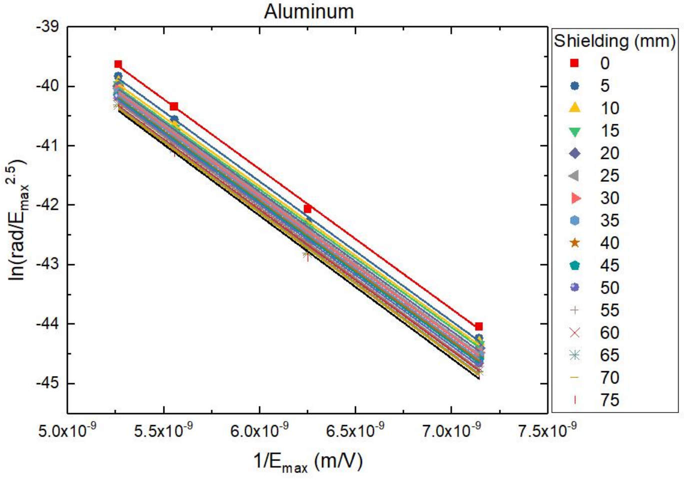


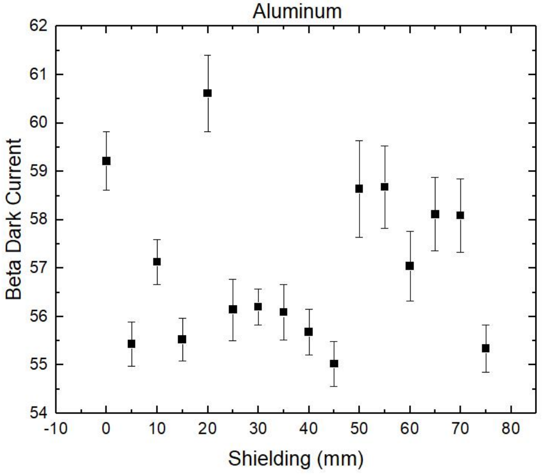


Radiation measurements: Aluminum FN plots



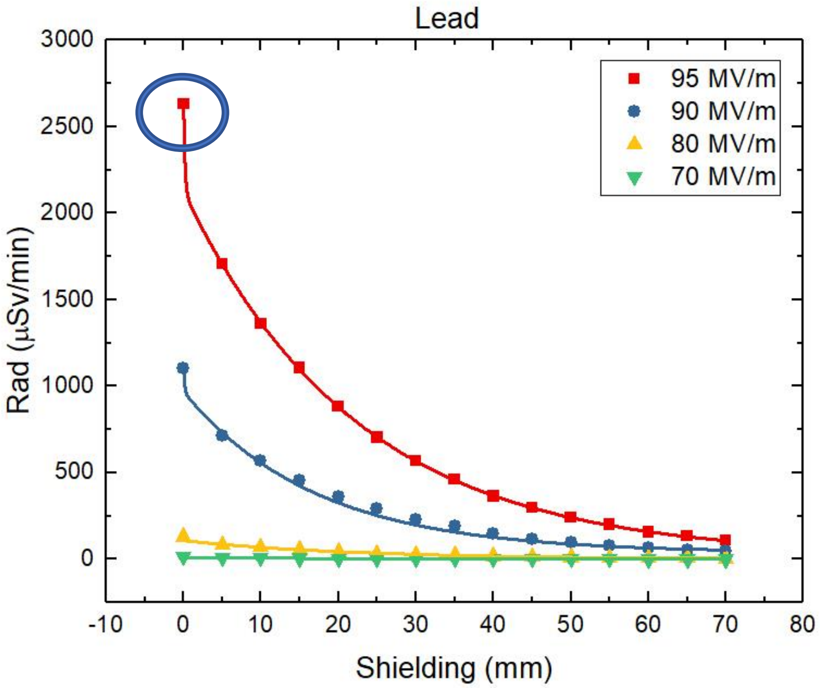


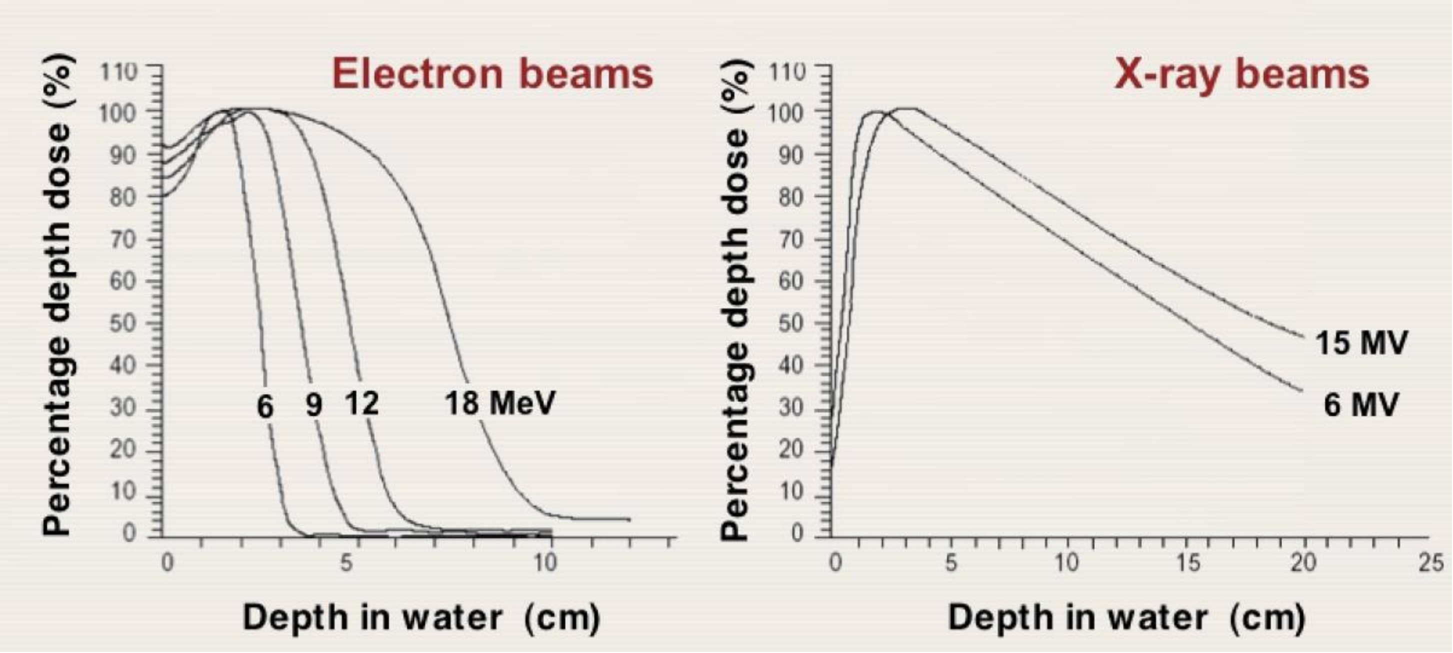




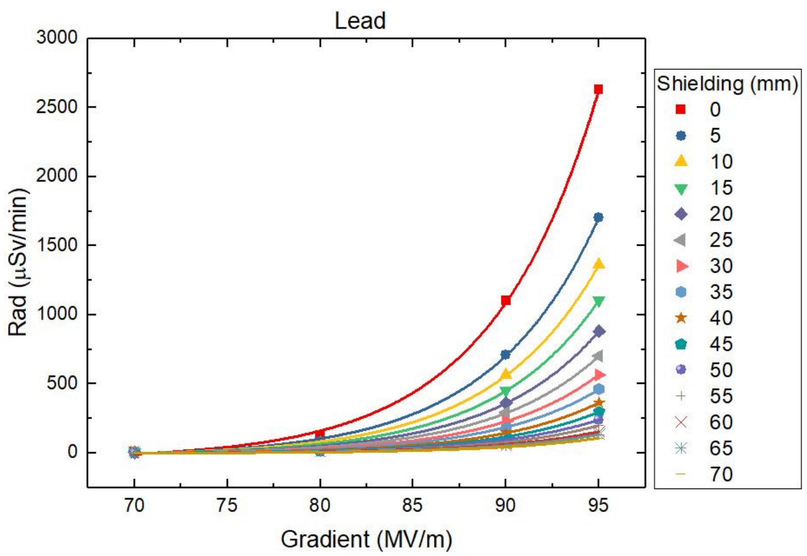
Radiation measurements: Lead

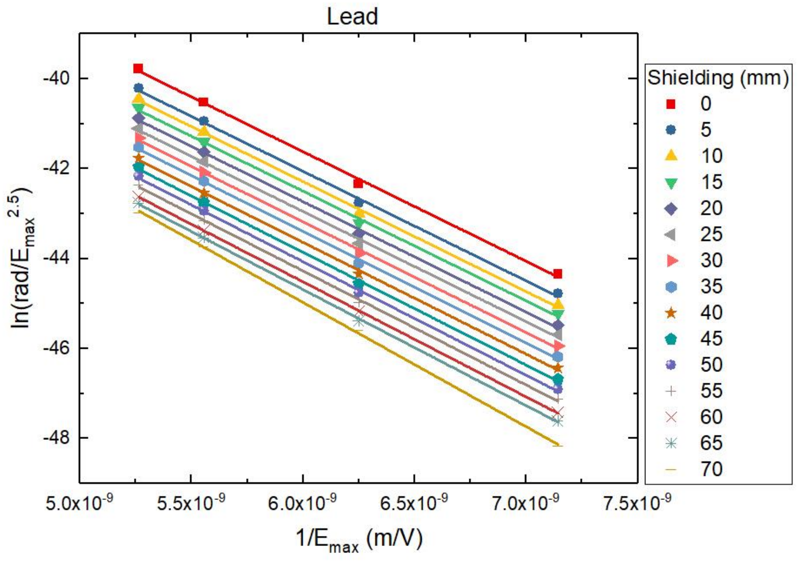
Electrons and X-rays only
in the 0-shielding point

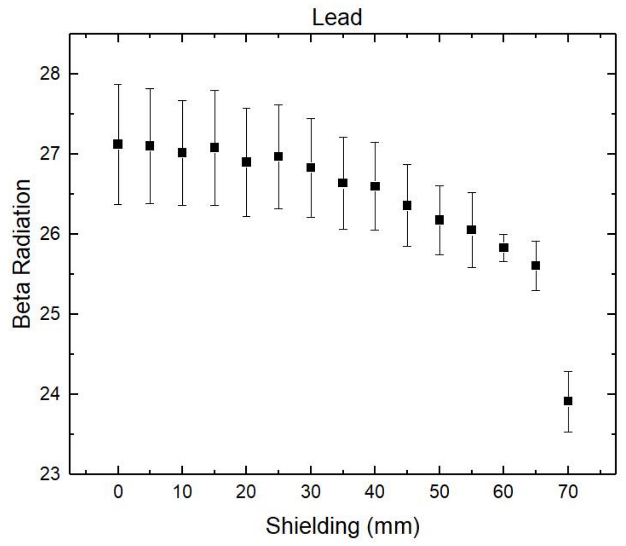




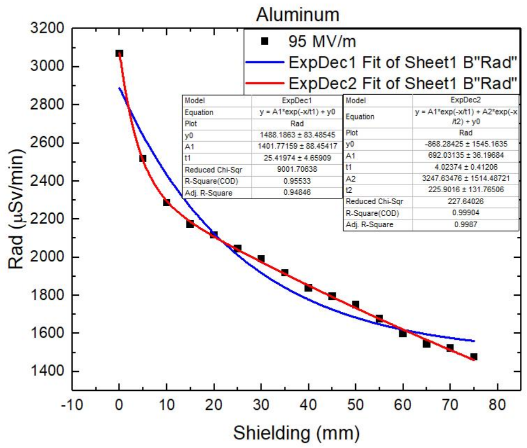
Radiation measurements: Lead FN plots

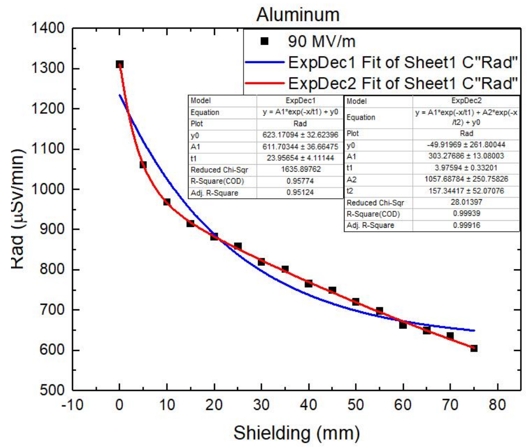


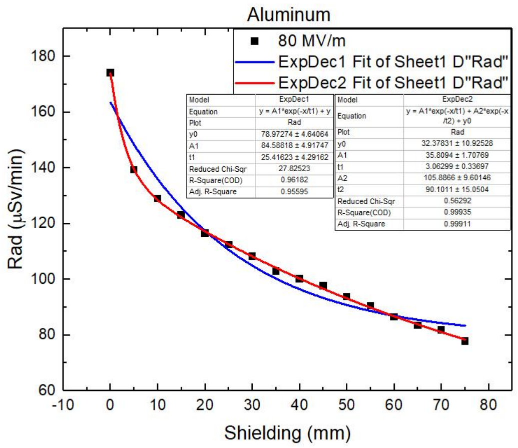


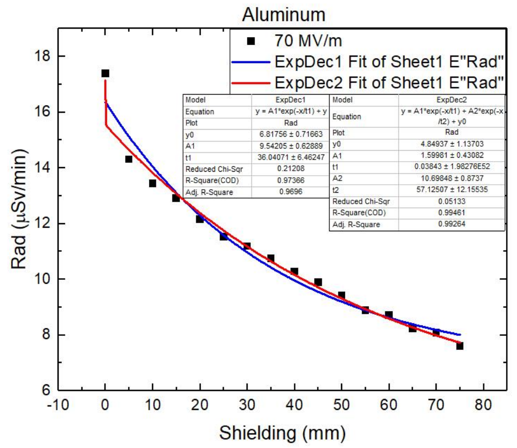


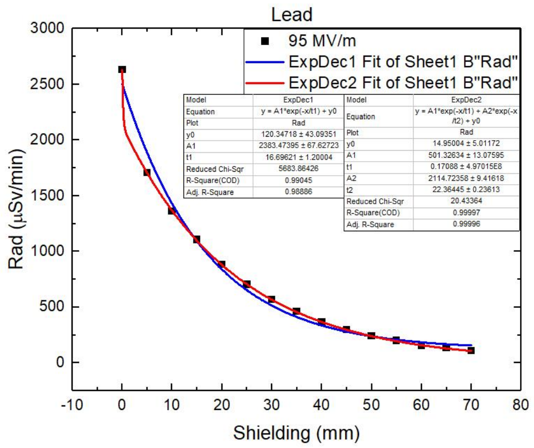
Radiation measurements: Comparison

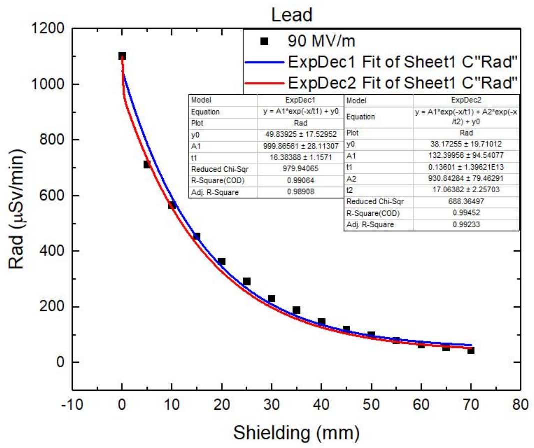


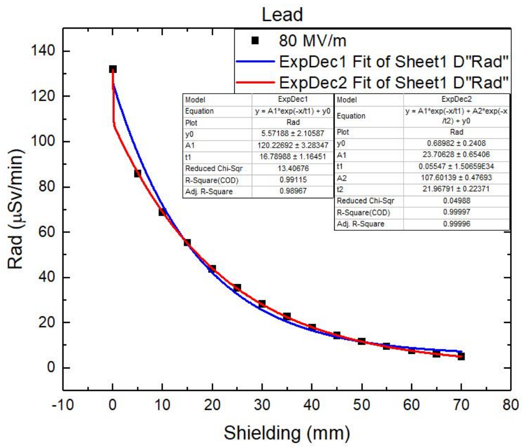


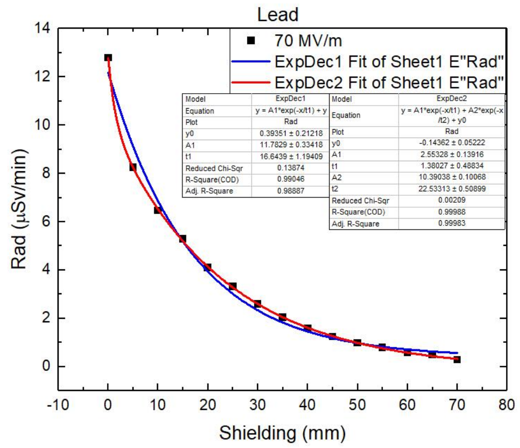




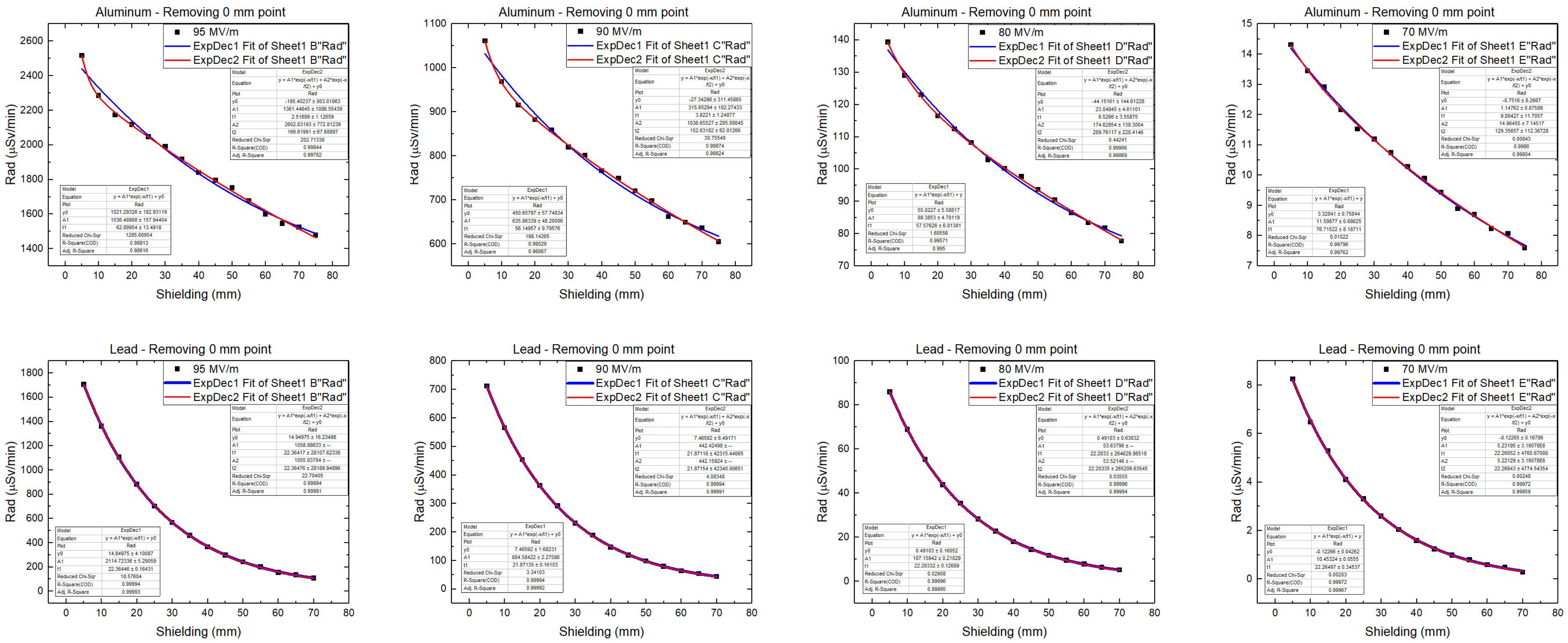




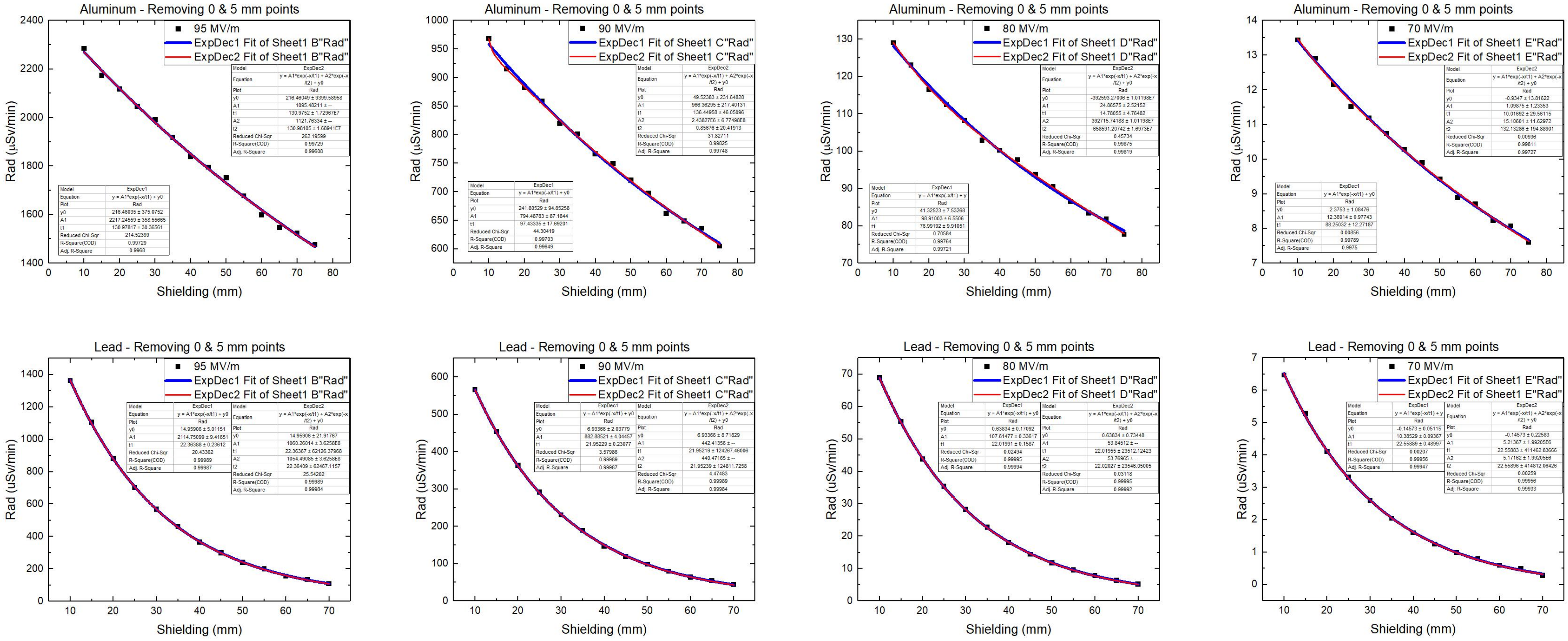




Radiation measurements: Comparison



Radiation measurements: Comparison

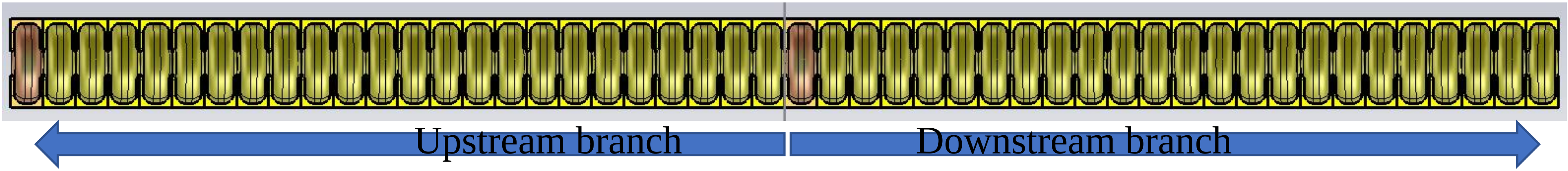


Contents

Dark current simulations: Types

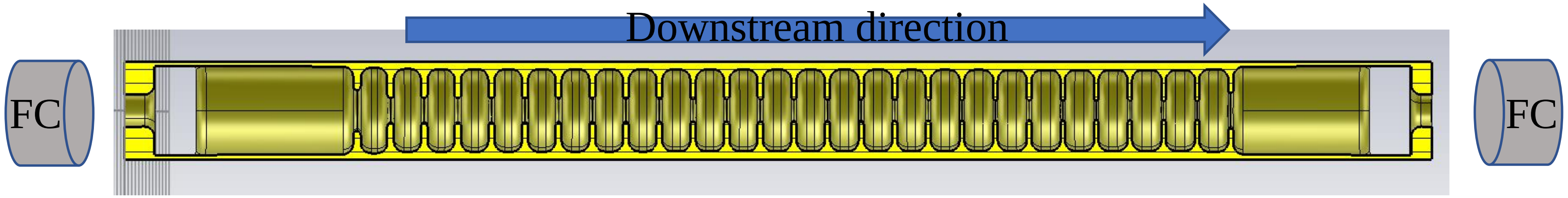
Periodic structure simulation

- The EM fields of 1 cell (Eigenmode solver) are imported and replicated using Floquet theorem with 120º of phase advance.
- Only 1 iris emitting, the central one, and the particles are analysed with a 2D monitor in each one of the other irises. It provides clean information about the charge propagation along the structure.



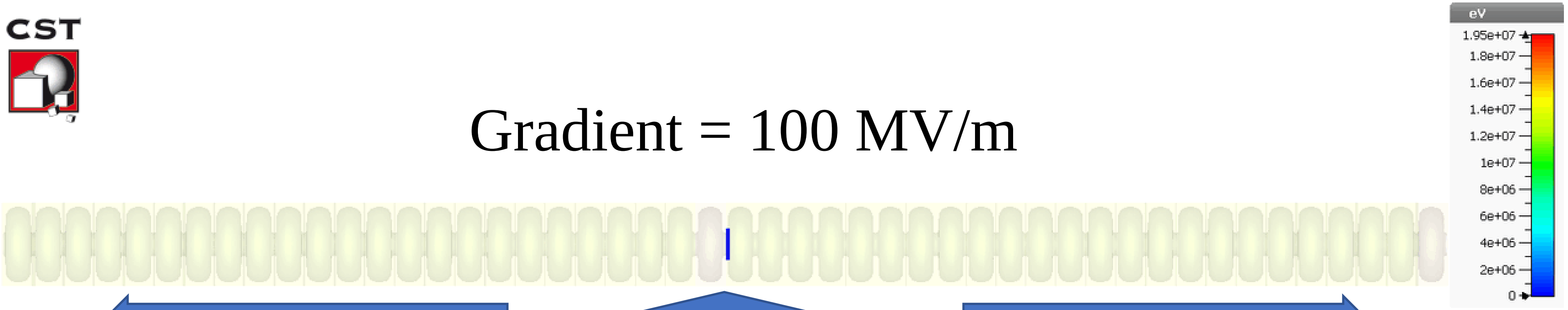
Full field simulation with tapering

- The EM fields of the hole structure (Frequency Domain Solver) are imported.
- One can choose which iris to set on, for analysing the Upstream and Downstream behaviour.
- For a realistic simulation all 27 irises are emitting (2 coupling + 25 accelerating irises). The particles are analysed with a 2D monitor in the position of the Faraday Cups.



Dark current simulations: Periodic

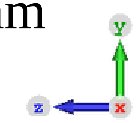
Gradient = 100 MV/m



Full Structure Upstream

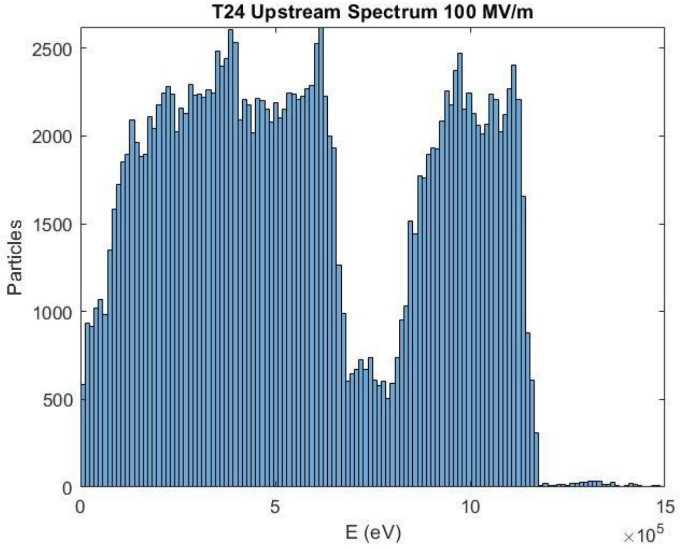
Emitting Iris

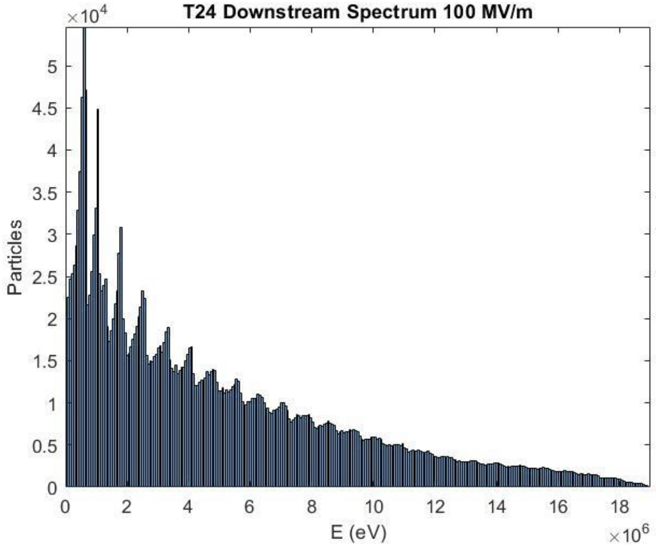
Full Structure Downstream



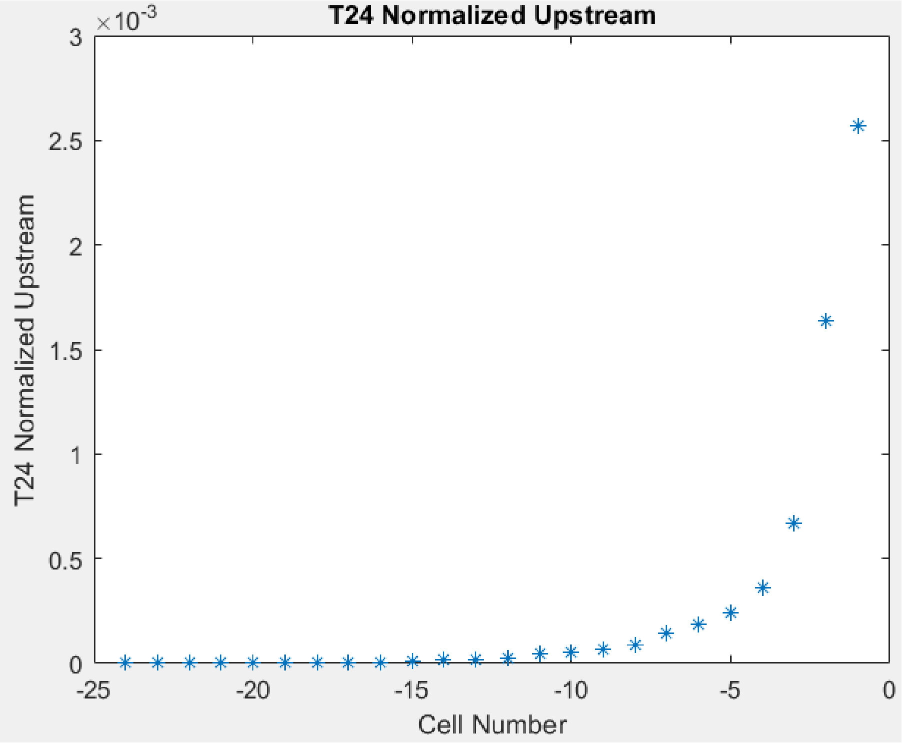
position monitor 1

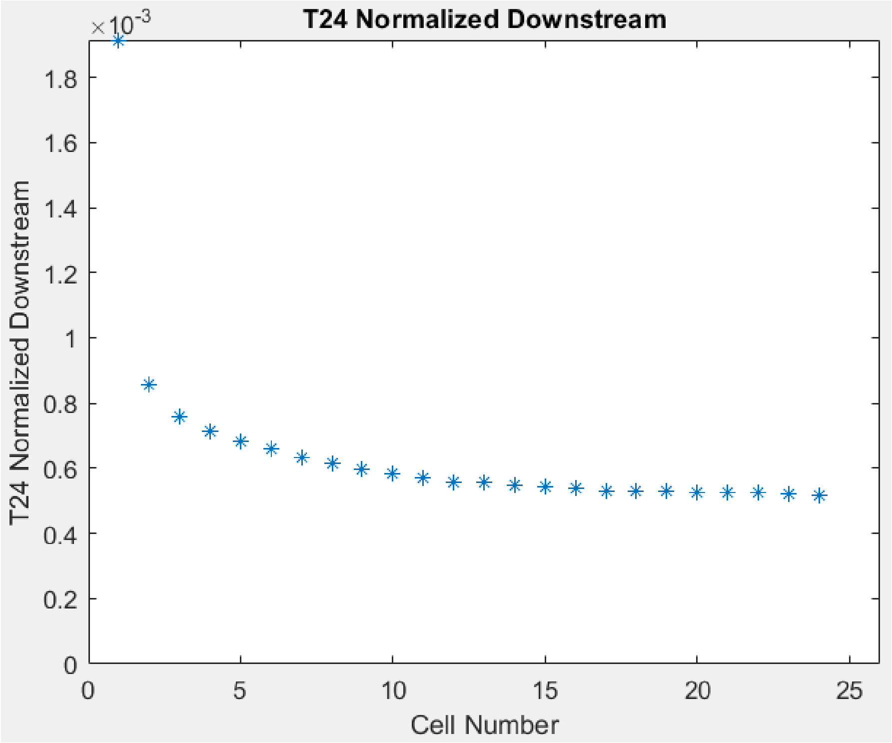
Type	Energy
Sample	1/300
Time	0.00678889 ns
Particles	132
Maximum	2.91445 eV

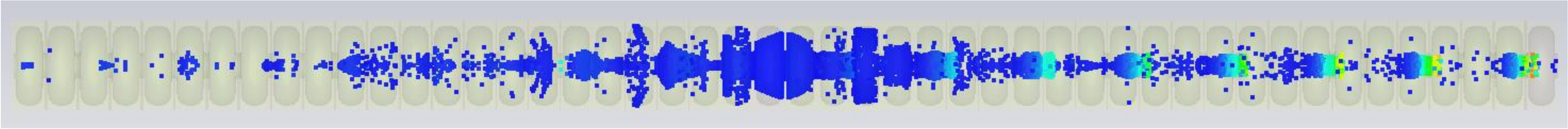




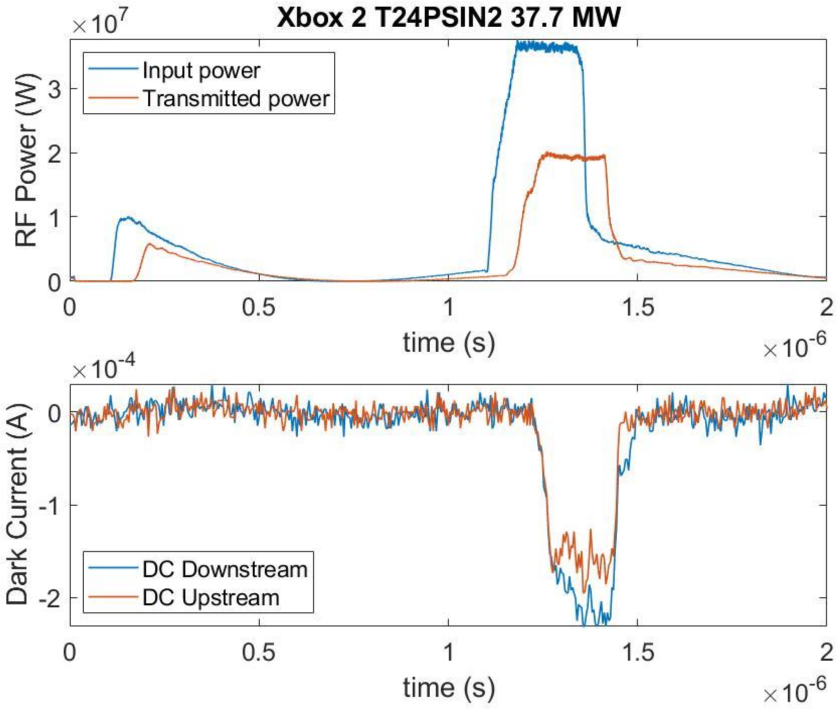
Dark current simulations: Periodic







Dark current simulations: Periodic



According with the simulation one expect the ratio between currents in the Faraday Cups Upstream and Downstream to be around 39% :

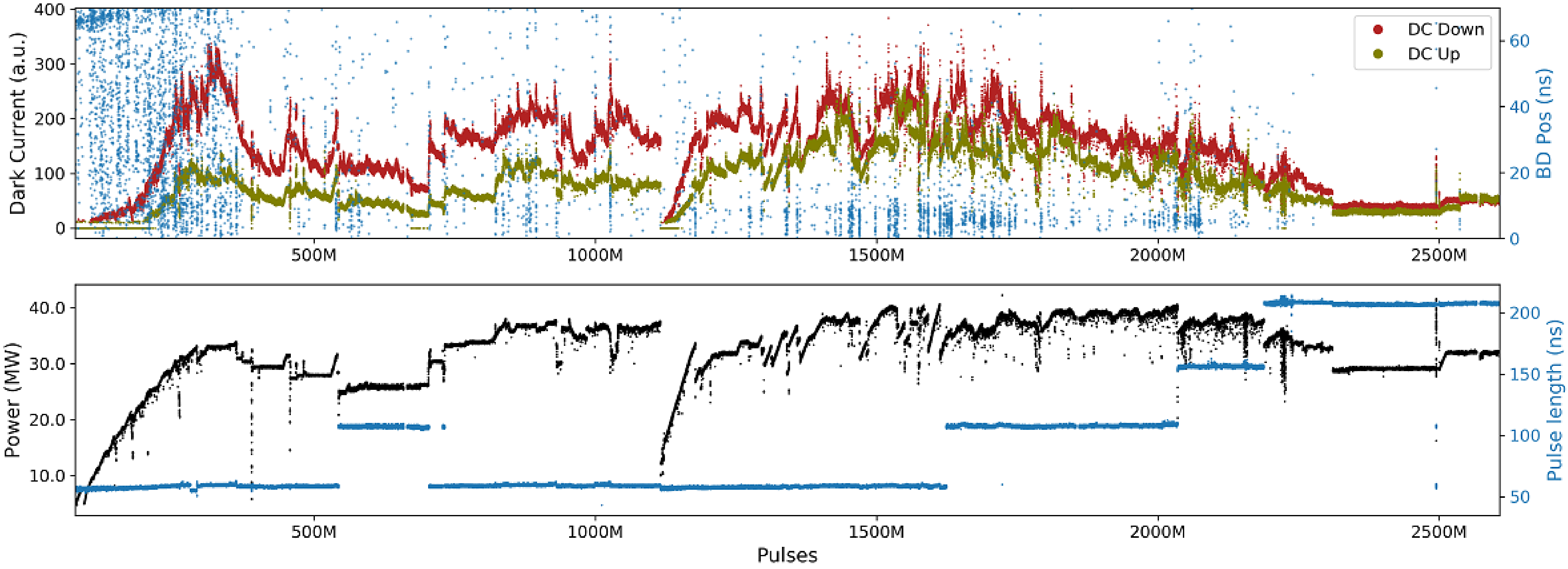
$$\frac{FC_{US}}{FC_{DS}} = \frac{0.61\%}{1.55\%} = 0.39$$

Dark current measured in this pulse show a higher ratio:

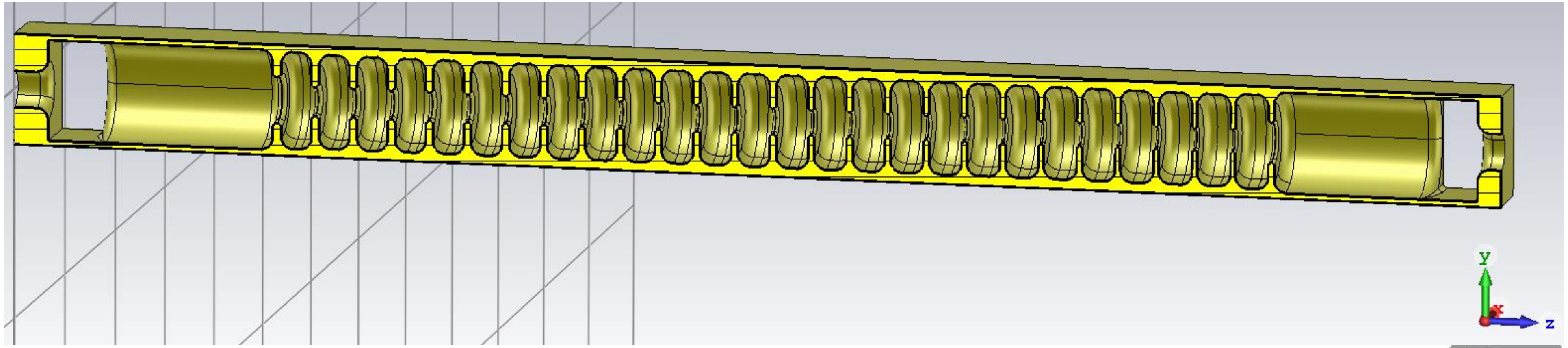
$$\frac{DC_{US}}{DC_{DS}} = \frac{-1.6024 \cdot 10^{-4} A}{-1.9871 \cdot 10^{-4} A} = 0.81$$

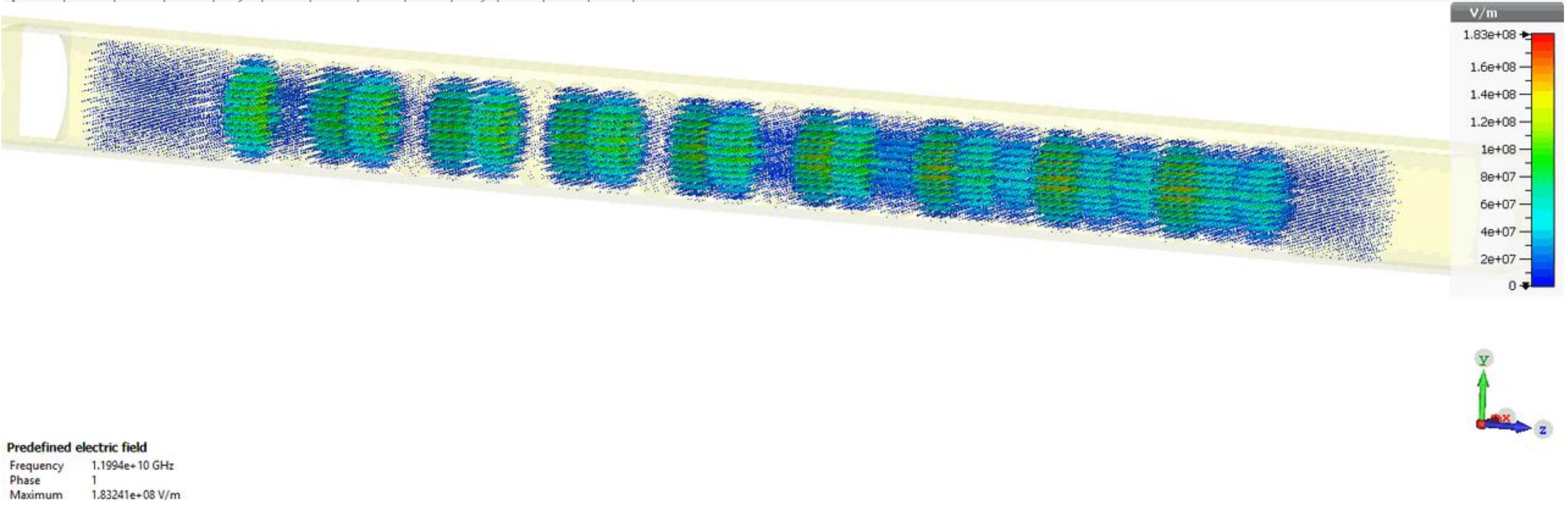
However, we have to remember that the emitters location change during conditioning, changing the ratio. So only one pulse is not deterministic of the US/DS ratio. In the simulation we assume periodic emission, so every iris emits the same amount.

Dark current simulations: Measured plot

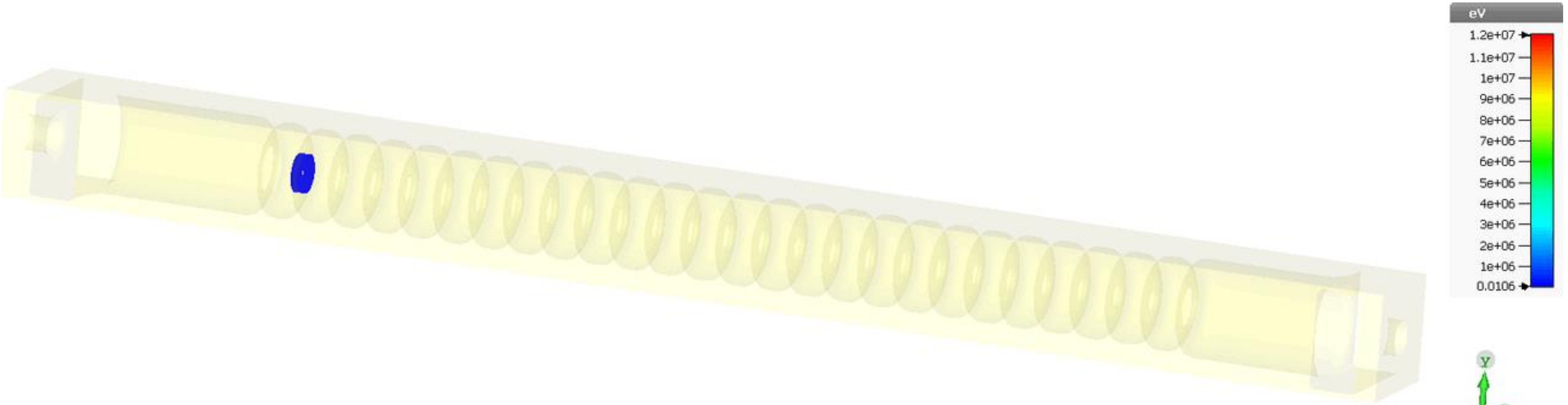


Dark current simulations: Full field

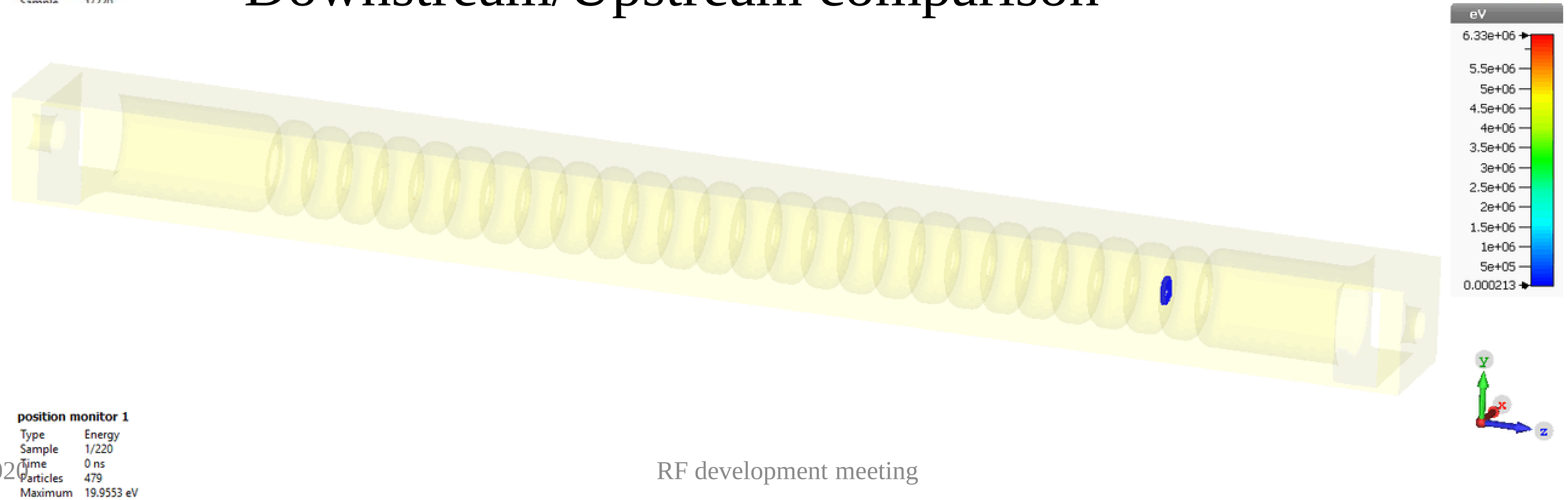




Dark current simulations: Full field

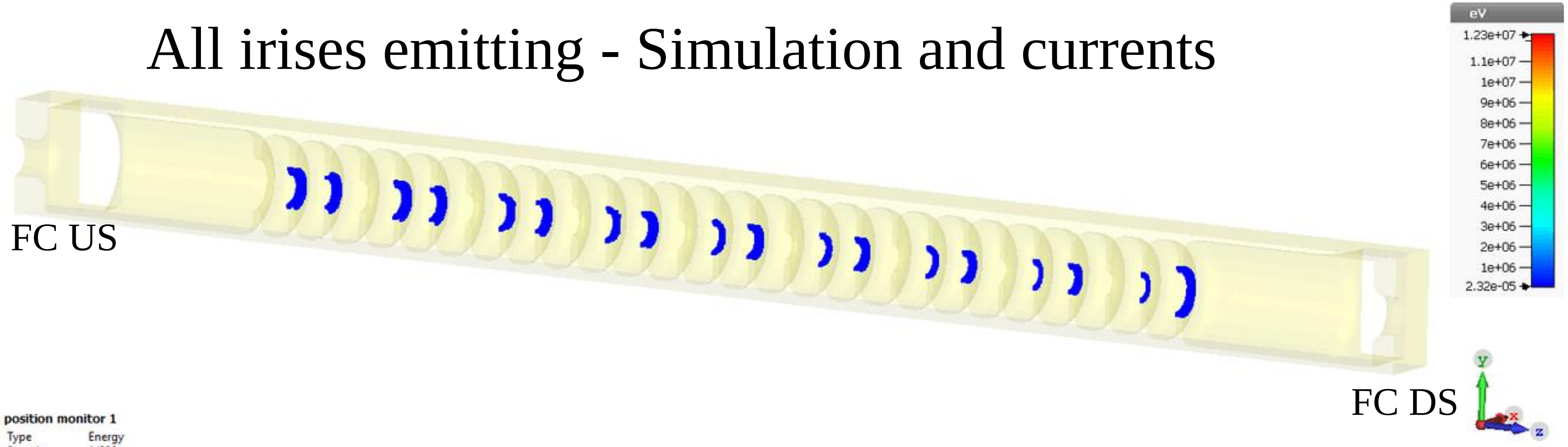


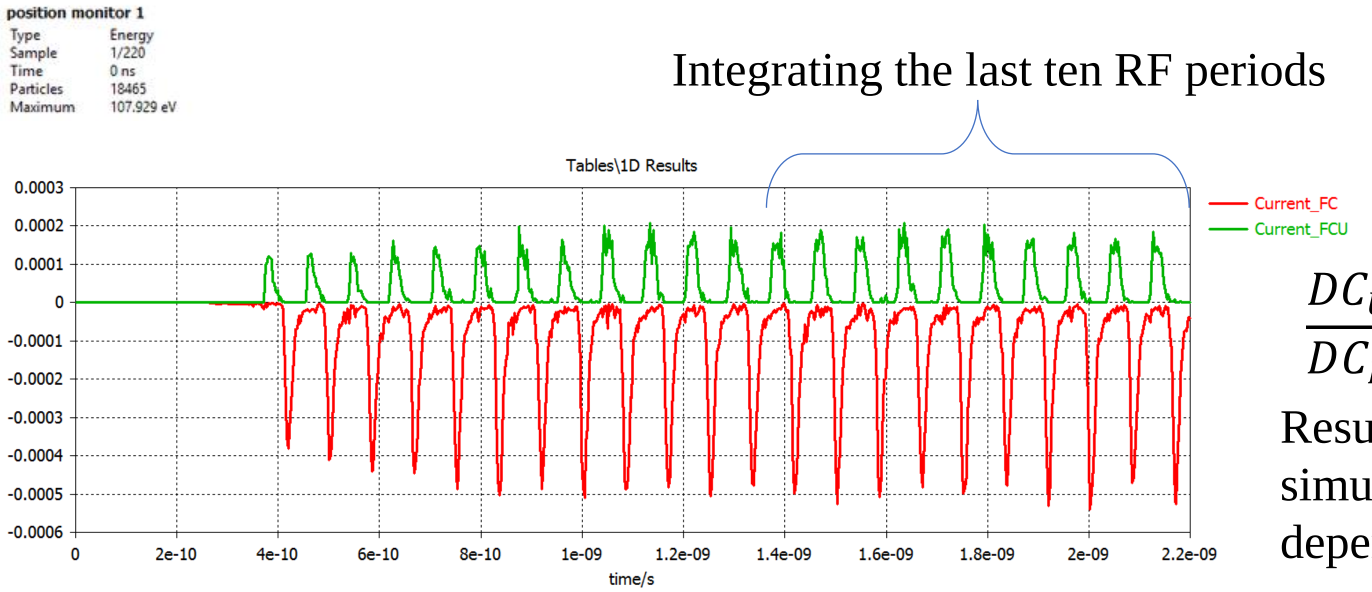
Downstream/Upstream comparison



Dark current simulations: Full field

All irises emitting - Simulation and currents



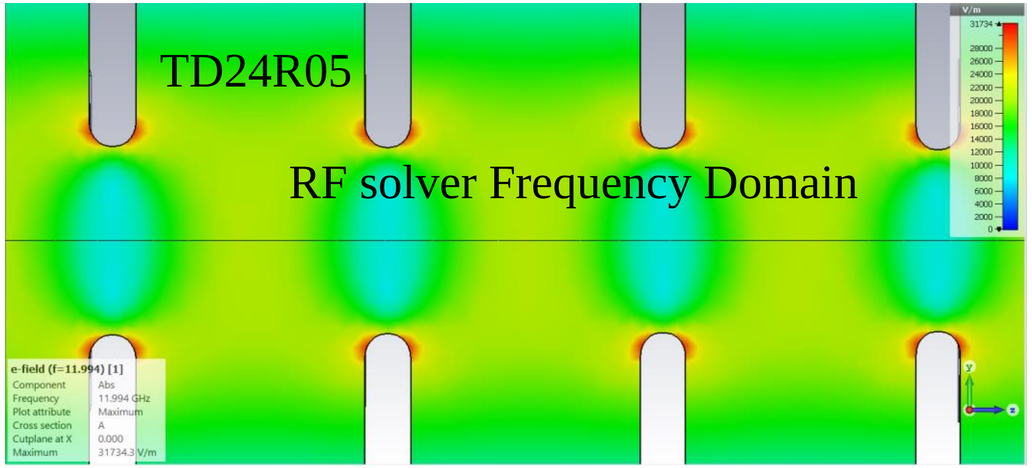


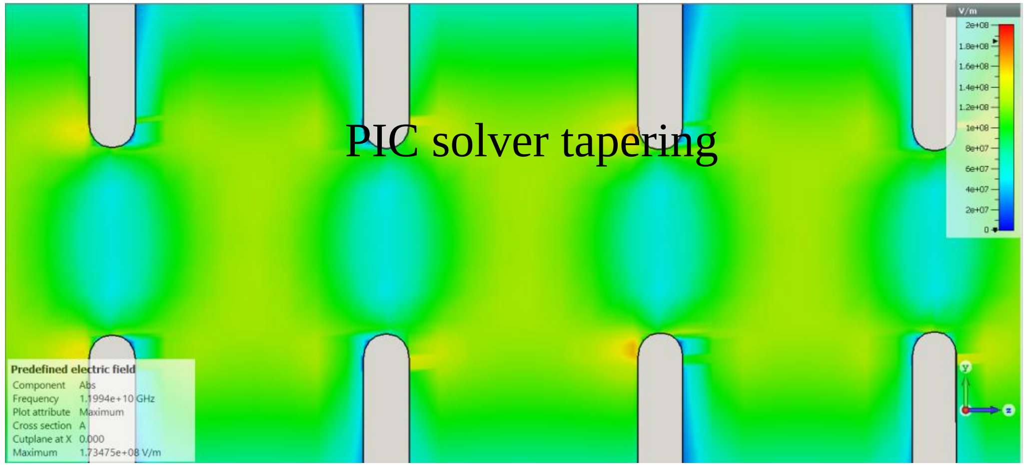
$$\frac{DC_{US}}{DC_{DS}} = \frac{4.5672 \cdot 10^{-5} A}{1.1336 \cdot 10^{-4} A} = 0.40$$

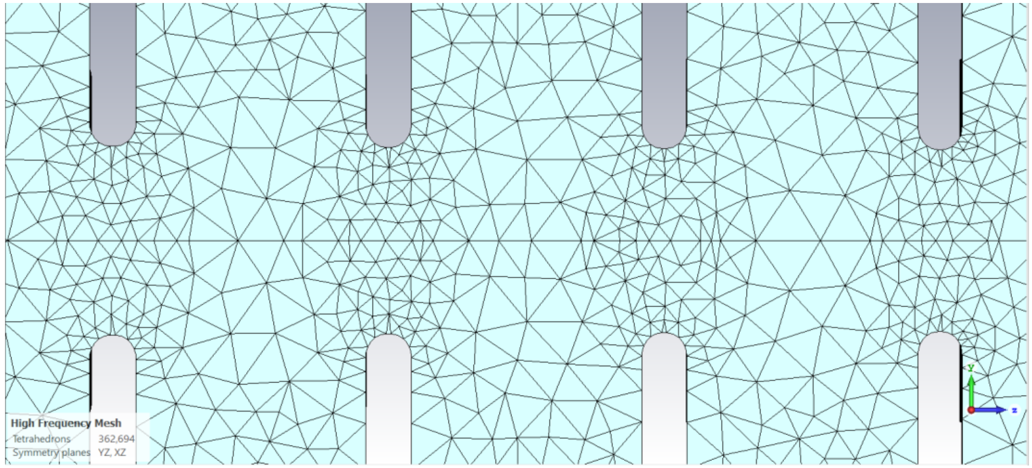
Result compatible with the periodic simulation. And with measurement, depending on the pulse we choose.

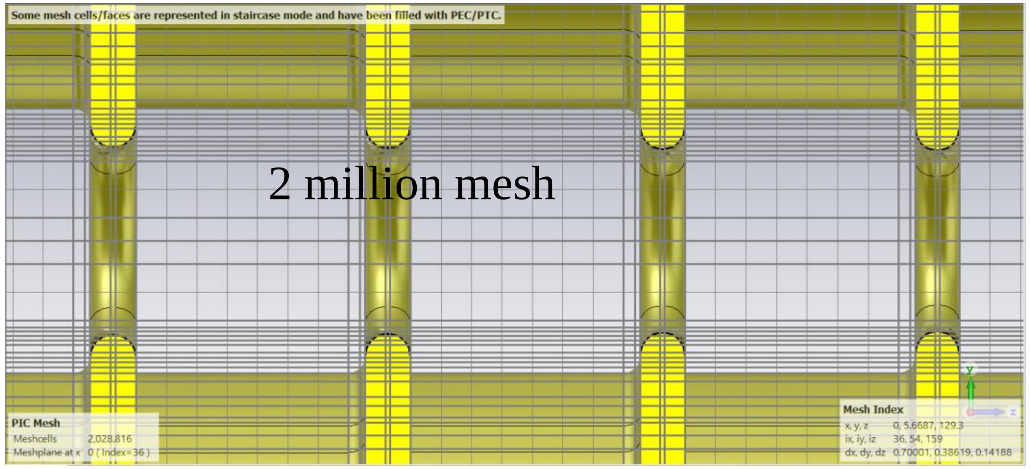
Dark current simulations: Full field old method

No way for directly importing FD solver into PIC in CST. Workaround with text file was not very efficient.



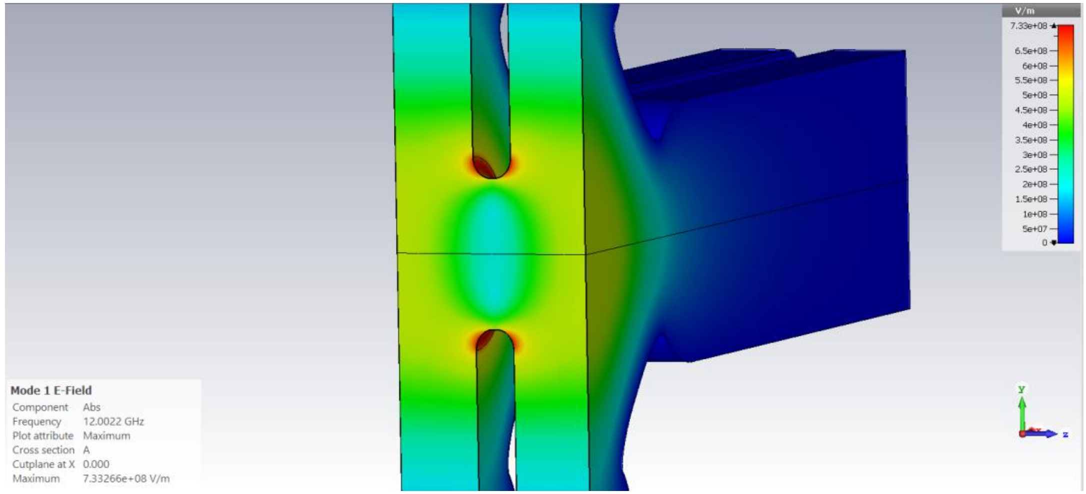


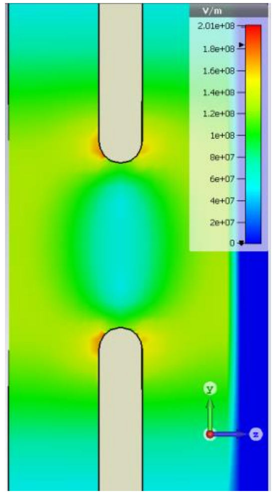


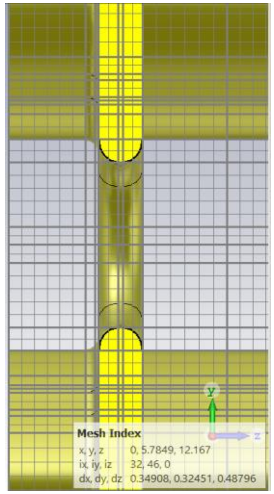


Dark current simulations: Periodic

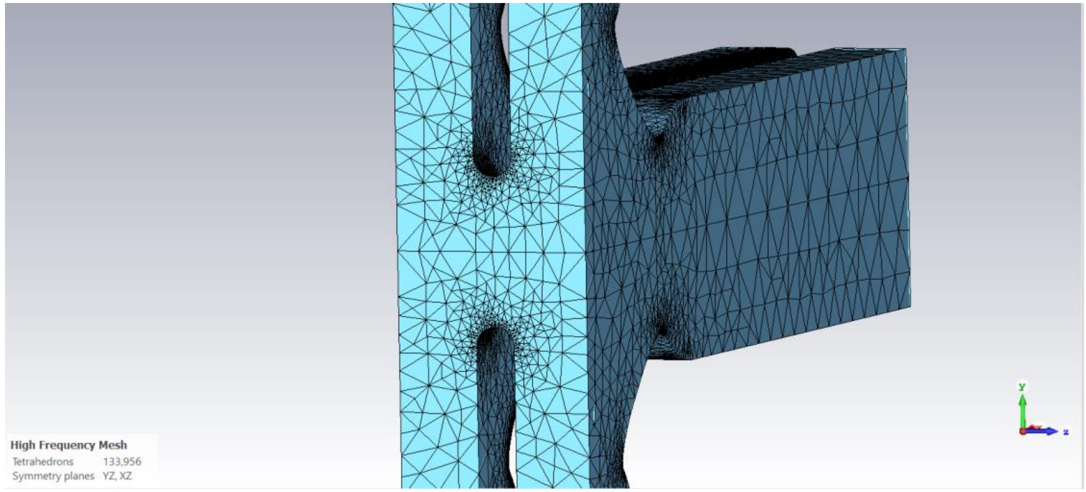
Direct import from eigenmode solver was available, and periodic simulations used to perform better.

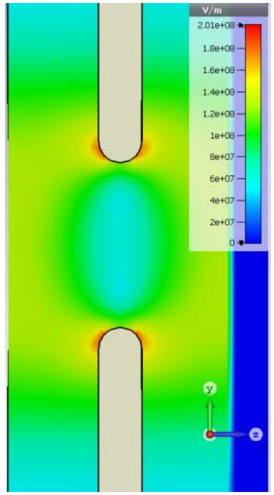


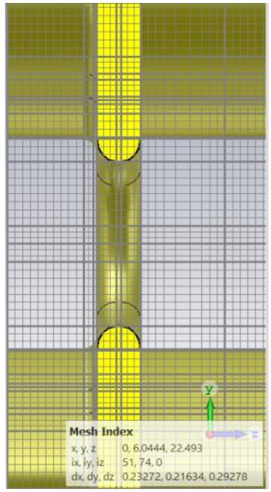




2 million mesh





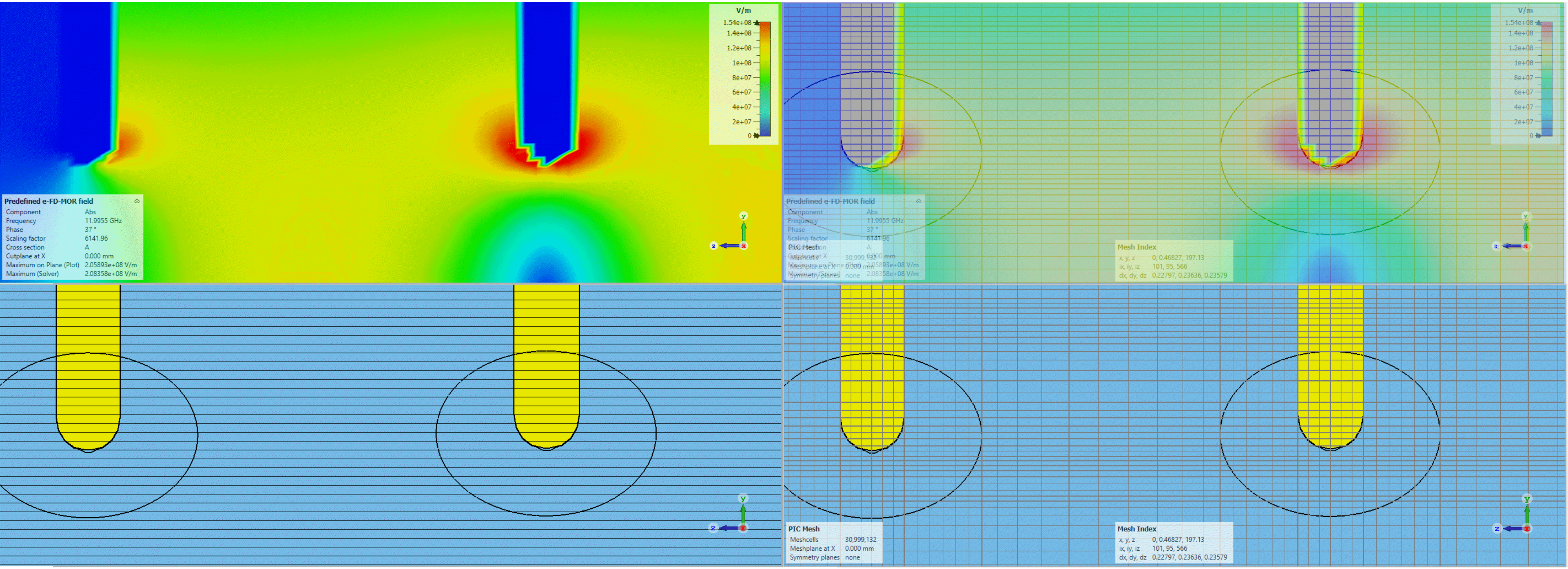


8 million mesh

Both perform much better than the tapering case

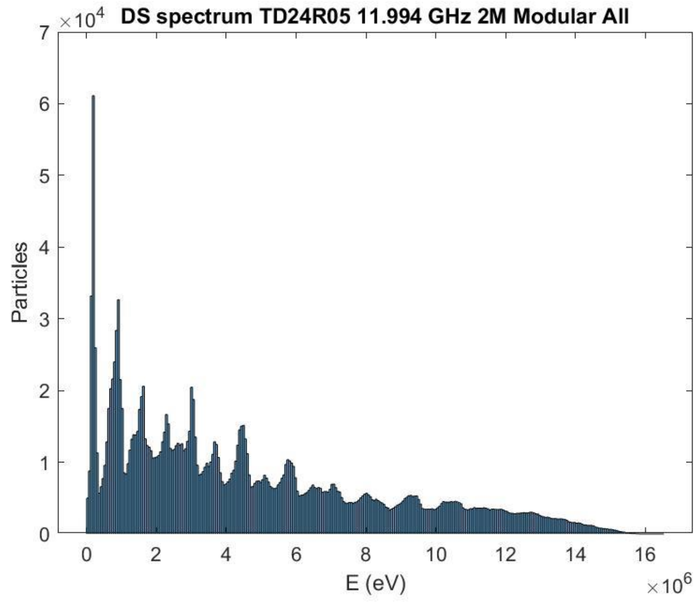
Dark current simulations: Full field new method

New way of directly importing FD solver into PIC solver. After contacting CST support.

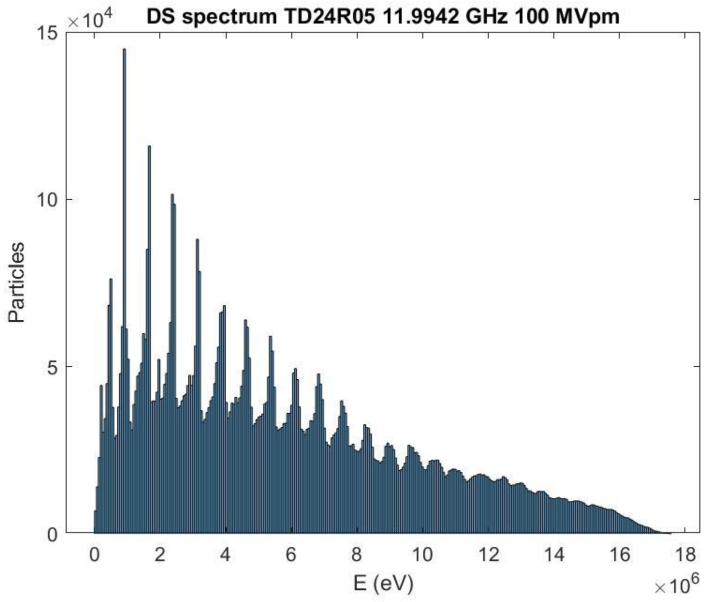


Dark current simulations: Comparison

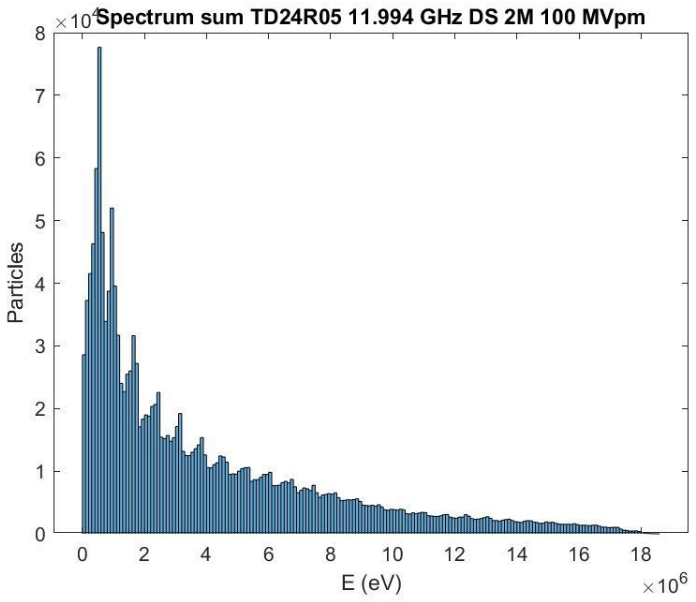
Tapering OLD



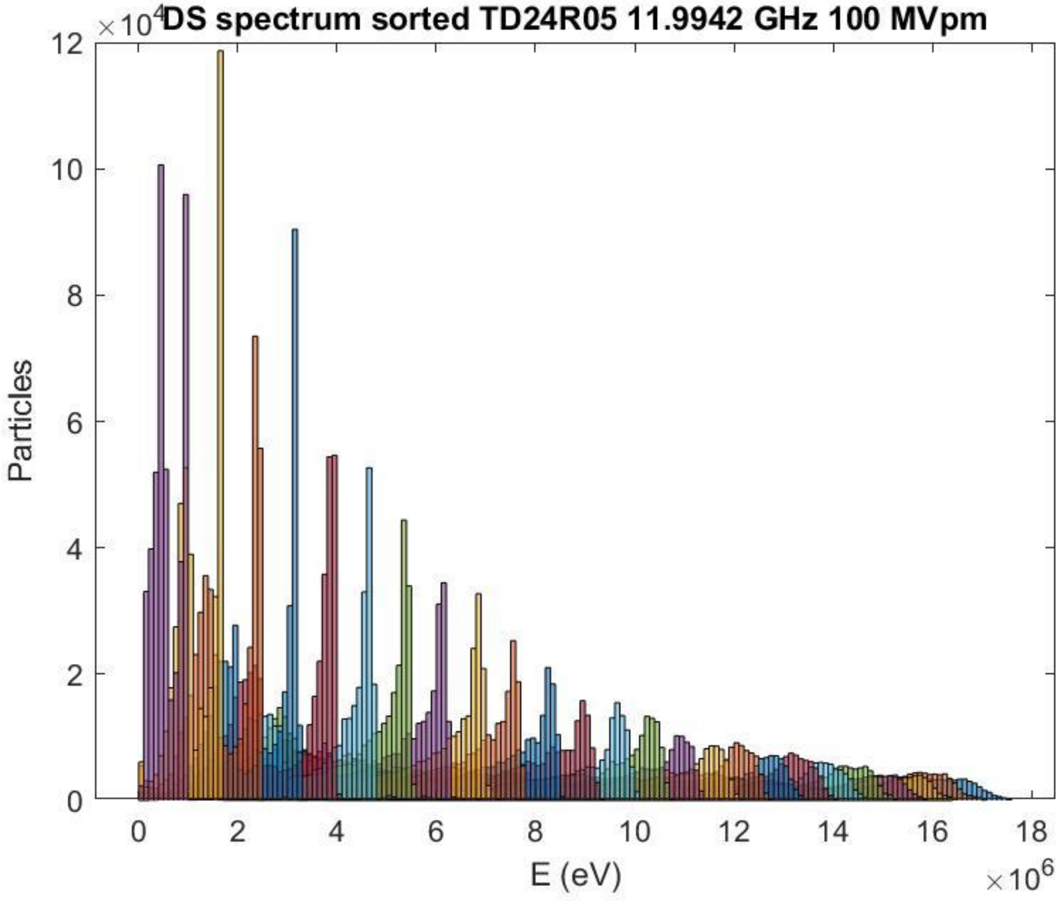
Tapering NEW

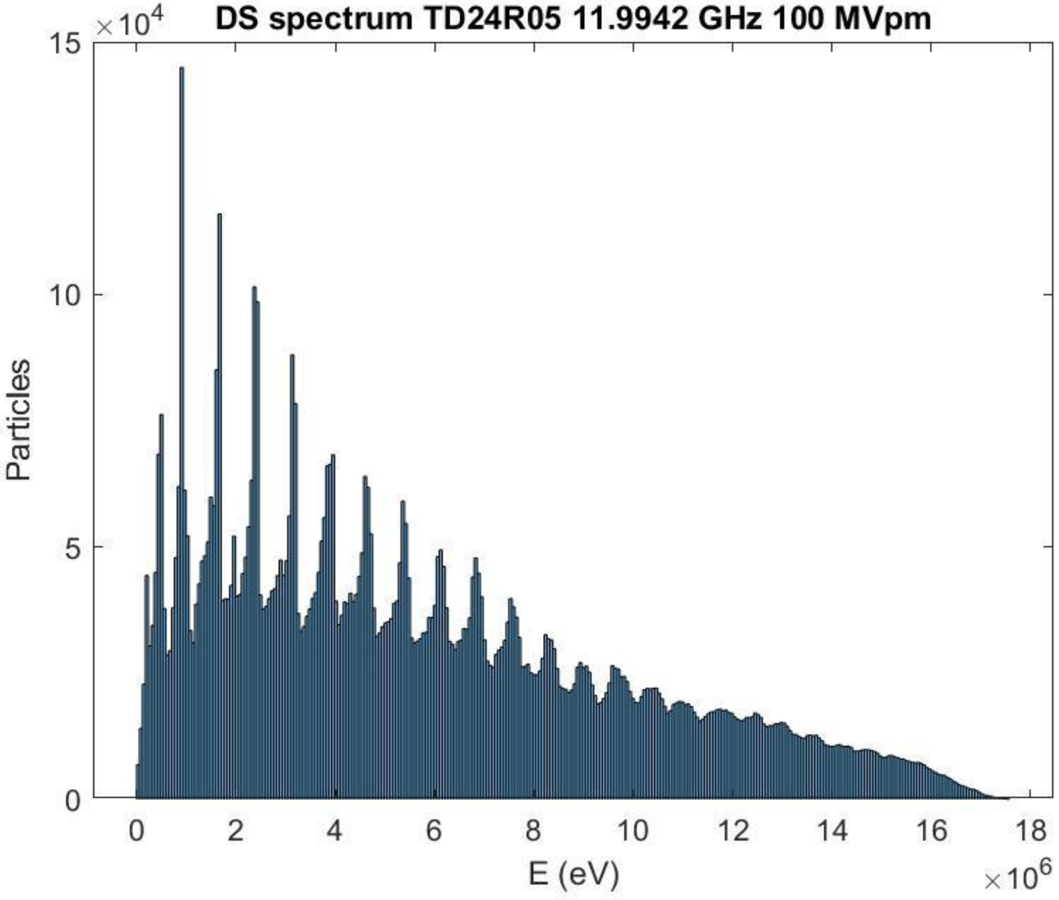


Periodic



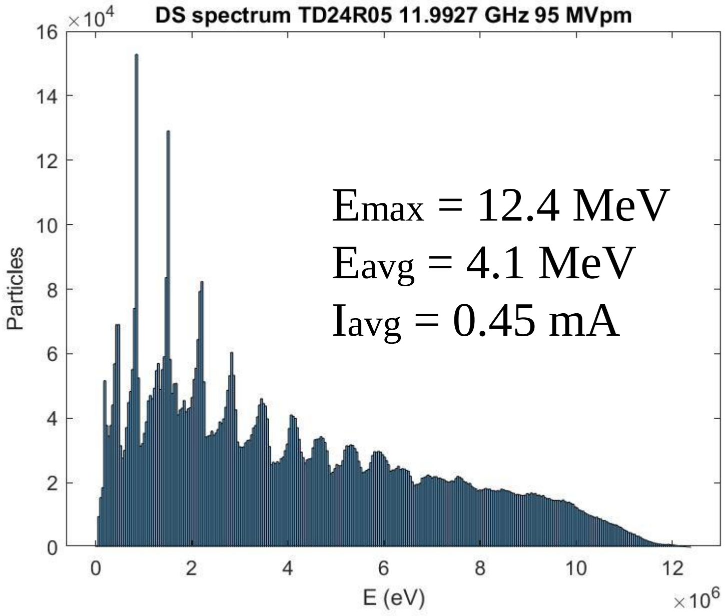
Dark current simulations: Full field new



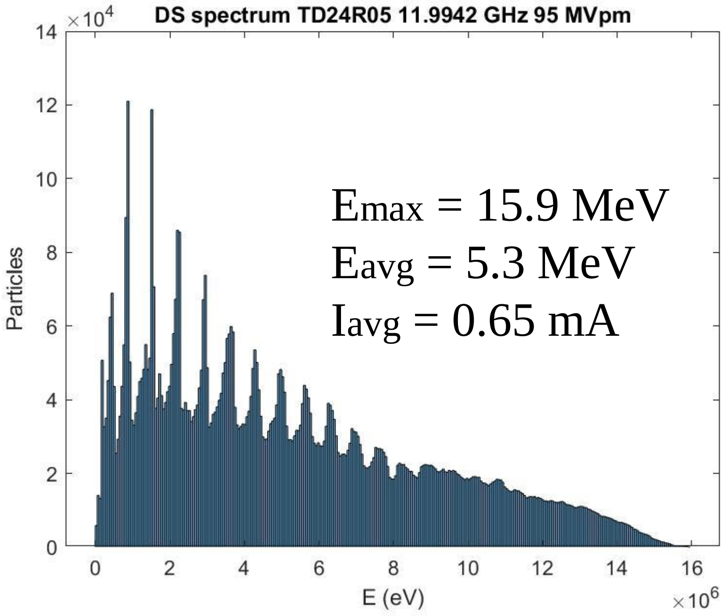


Dark current simulations: Electron energy spectrums

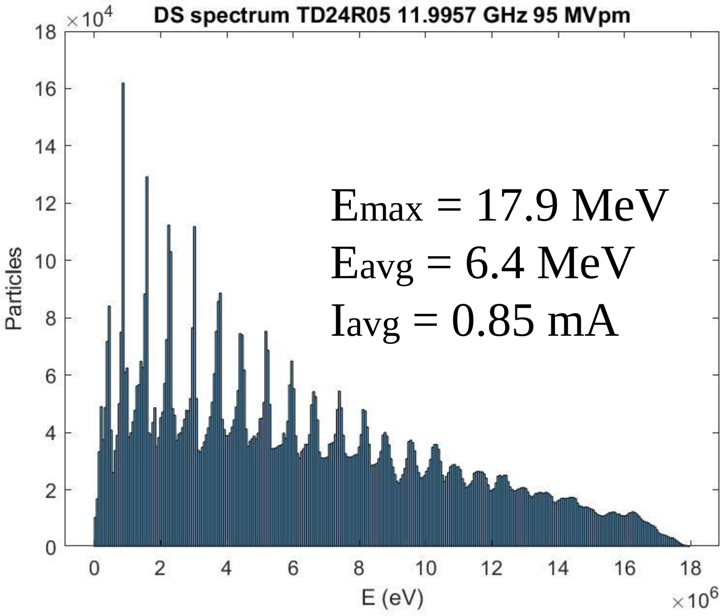
11.9927 (-1.5 MHz)



11.9942 (tuned)



11.9957 (+1.5 MHz)

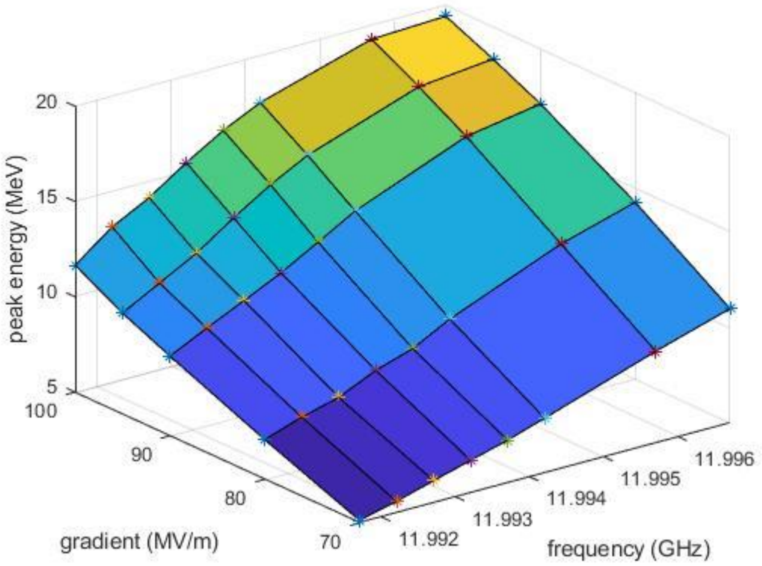


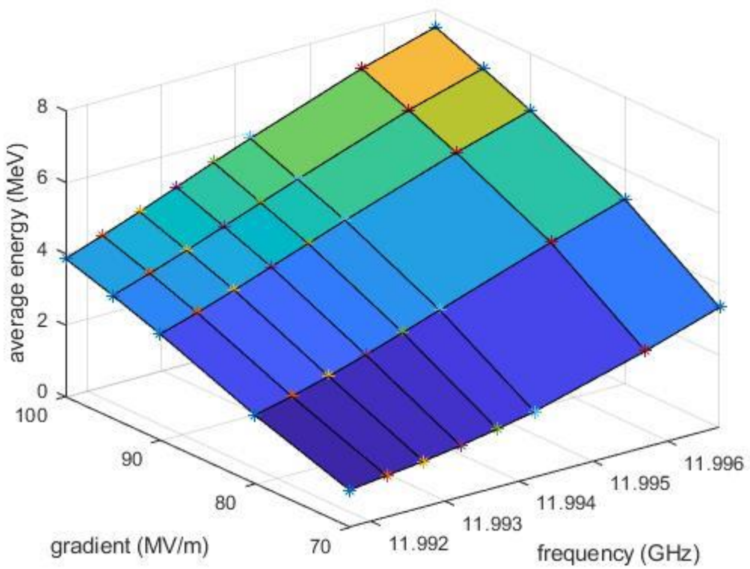
Both the maximum and the average energy of the distribution increases
Current reaching the Faraday cup also increases.
Both factors increase radiation.

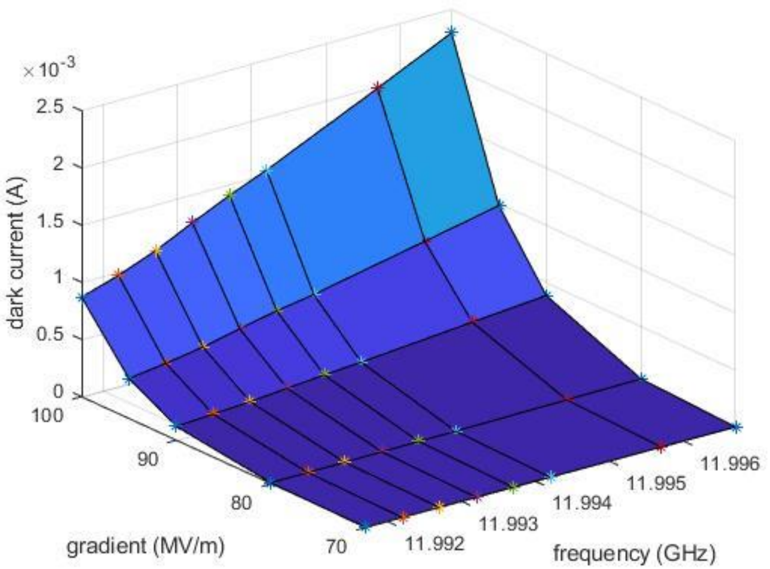
All calculations at 95 MV/m, 19 MV of accelerating voltage.

frequency	phase adavance	phase velocity
11.9927	118.79	1.0102
11.9942	120.03	0.9997
11.9957	121.31	0.9892

Dark current simulations: Effect RF frequency







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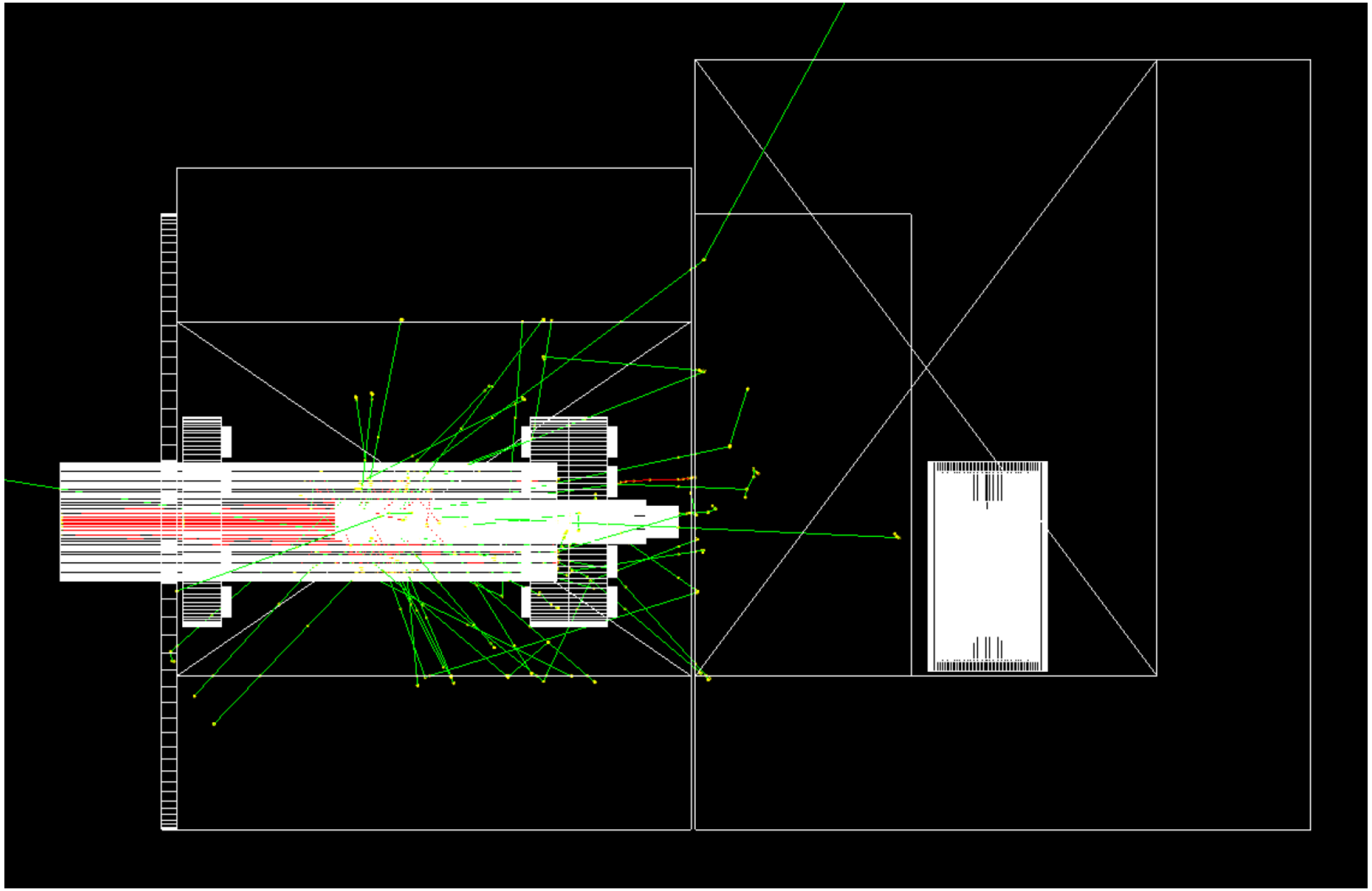
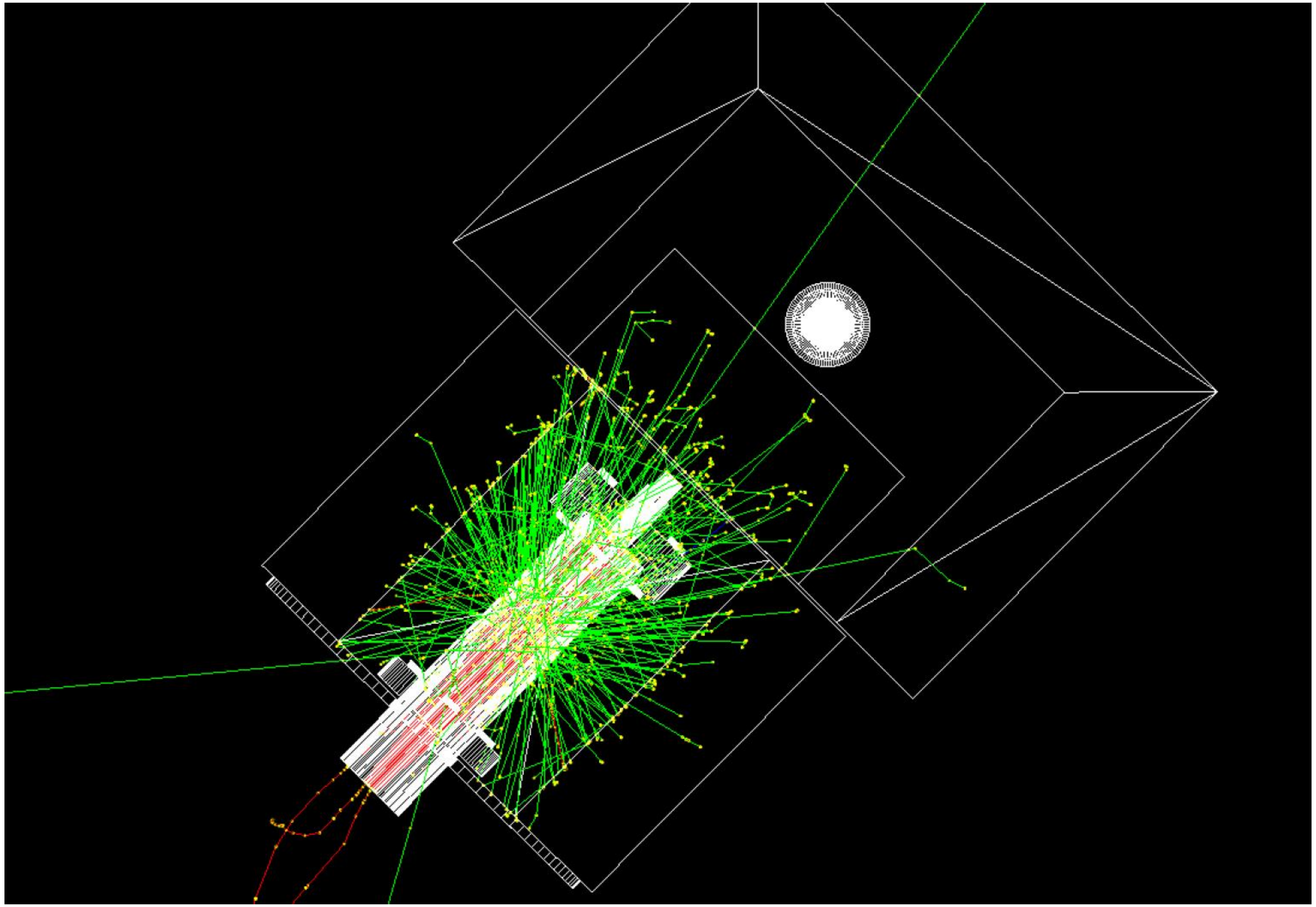
Radiation simulations: GEANT4 side view



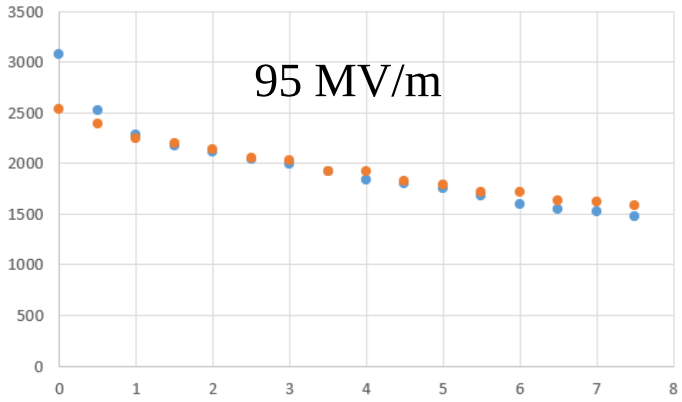
- All the shielding blocks present in the experimental setup were introduced in the GEAN4 model, as well as the Faraday cup.
- Dark current electrons reaching the Faraday cup in CST simulations were exported at different gradients and frequencies. Used as input for GEANT4.

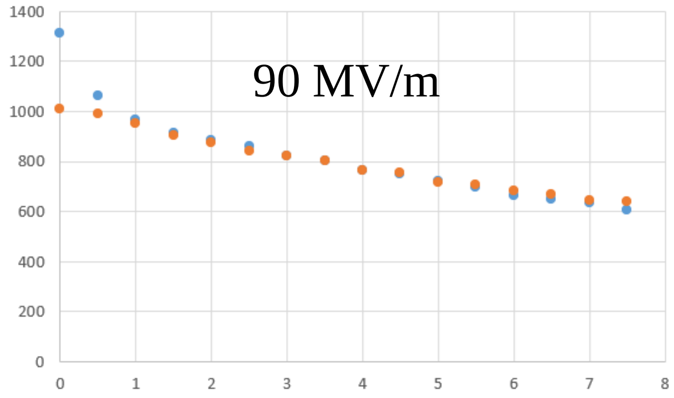
Radiation simulations in GEANT4 courtesy of my colleague Marçà Boronat.

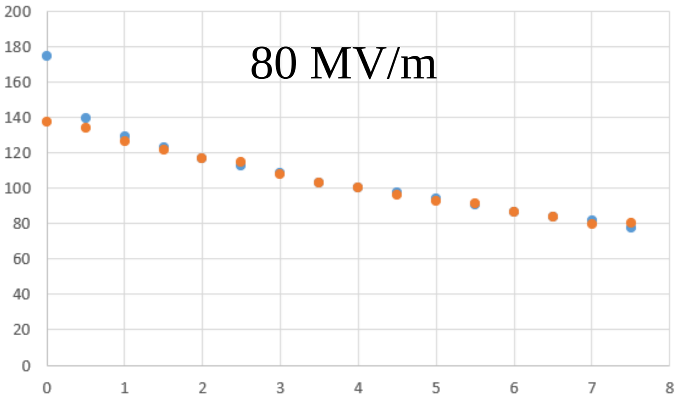
Radiation simulations: GEANT4 top view

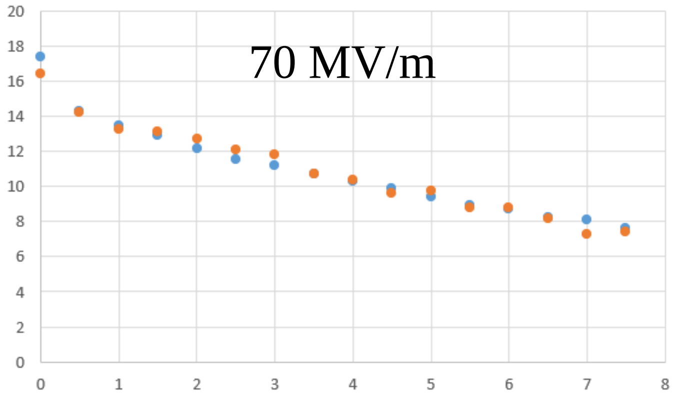


Radiation simulations: Results for aluminum at 11.9942 GHz

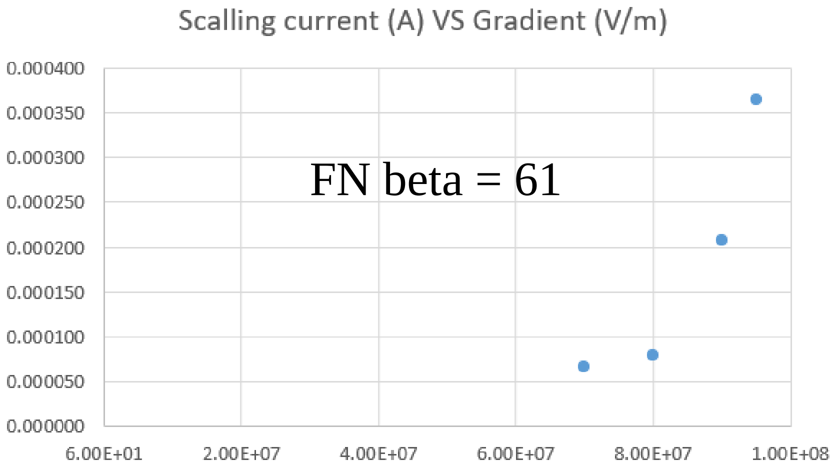








Gradient (MV/m)	Scaling factor = Current (A)
95	0.000364
90	0.000207
80	0.000079
70	0.000066



- In all plots: Radiation (uSv/min) VS Aluminum shielding (cm)
- Blue is the measured radiation and orange the simulated, showing good agreement.

Contents

- Introduction
- Dark current measurements
- Radiation measurements
- Dark current simulations
- Radiation simulations
- Conclusions

Conclussions

- Field emitted electrons are captured by RF fields and form a beam, which gives a measurable current in the Faraday cups, known as dark current. Those electrons can reach up to 20 MeV in CLIC cavities, being a strong source of radiation. Experiments need to be place in a protective bunker.
- We have shown experimental measurements for both dark current and radiation, leading to interesting conclusions. Such as the relation between radiation and current, the change in the emitters' location during conditioning, and the change in the electron energy at different gradient levels.
- Computer simulations were also developed, trying to represent the experimental environment with accuracy. This helped for the better understanding of both the dark current and the radiation measured during operation of high-gradient accelerators.

Thank you very much for your attention!

☺

Dark current simulations: Effect RF frequency

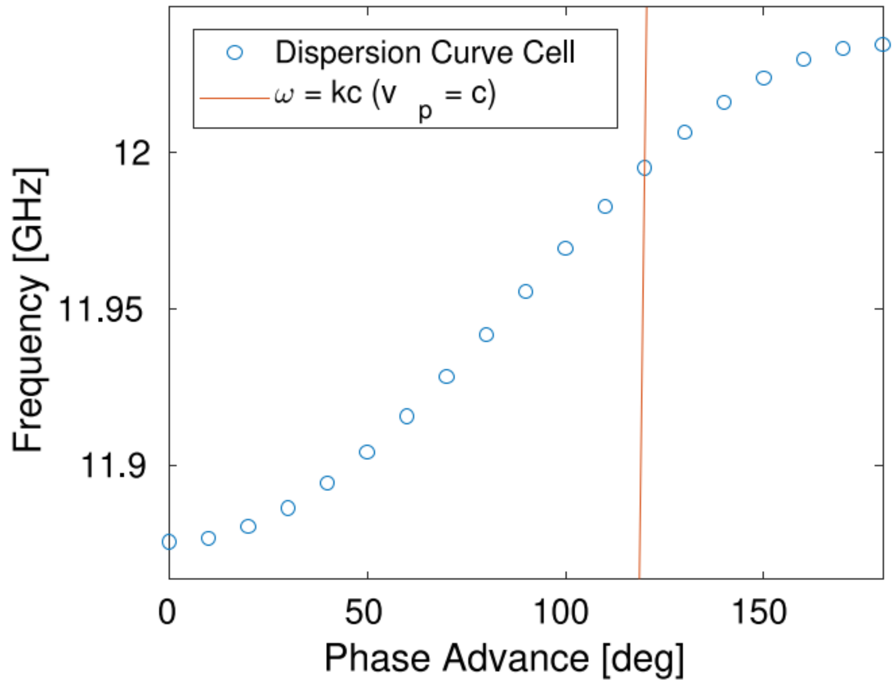


Fig. 1. Operational points on the dispersion curve for the TD26CC middle cell.

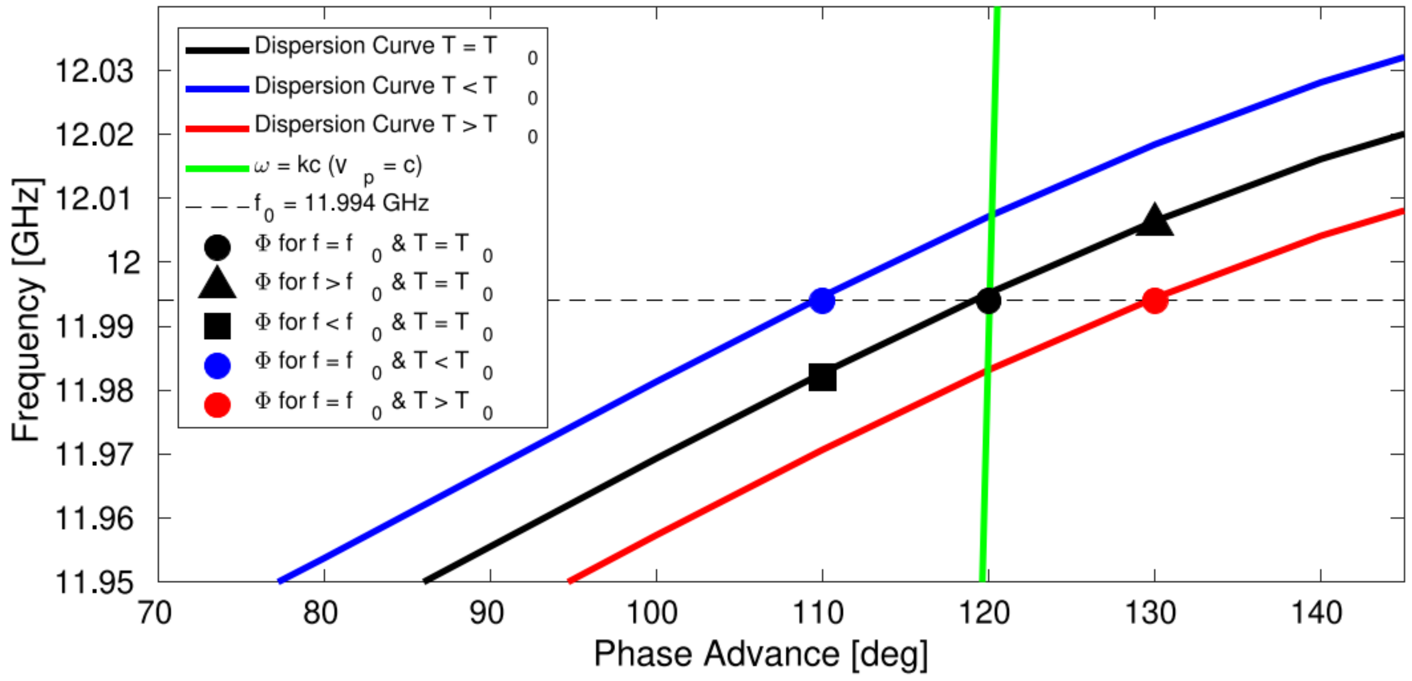
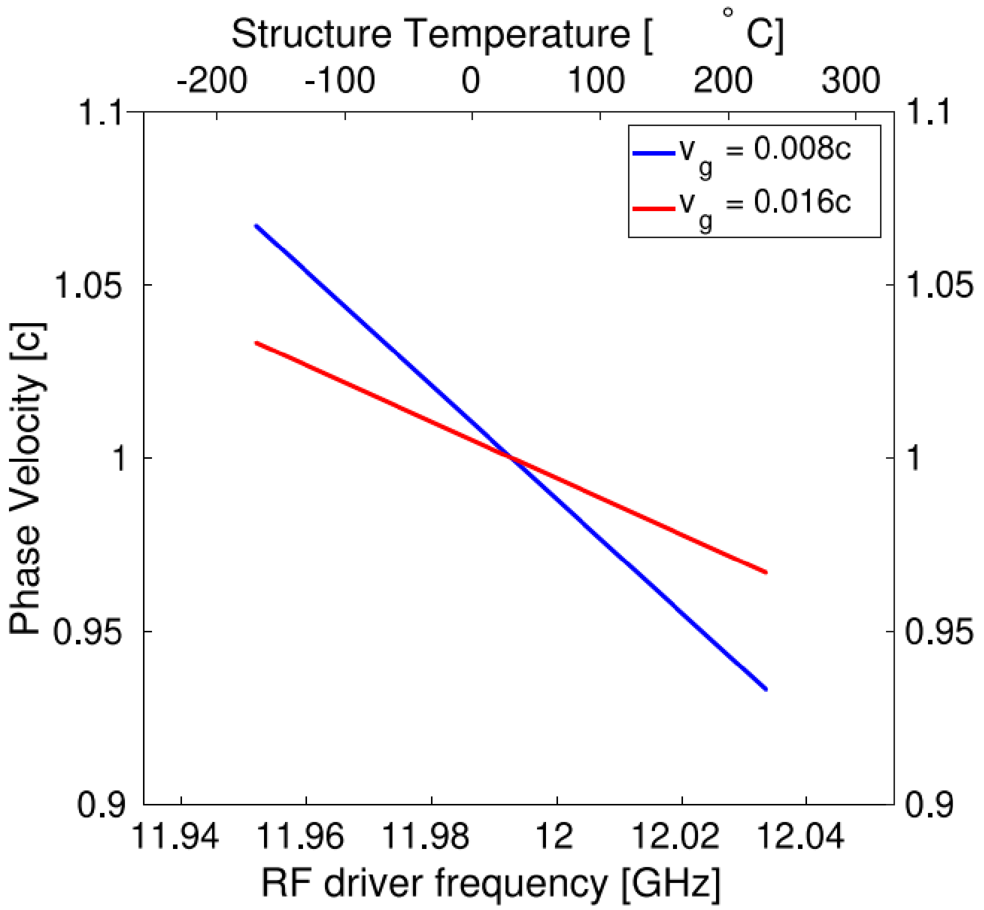


Fig. 2. Operating modes for three structure temperatures and three RF driver frequencies.

[1] T. G. Lucas et. al. "Dependency of the capture of field emitted electron on the phase velocity of a high-frequency accelerating structure". Nuclear Inst. And Methods in Physics Research, A. 2019

Dark current simulations: Effect RF frequency



- A reduction in the phase velocity means capture of lower energy electrons. Which translates in more radiation.

$$E_0 \geq \frac{\pi m_0 c^2}{\lambda e} \left(\frac{v_p - v_0}{v_p + v_0} \right)^{\frac{1}{2}}$$

- Bigger phase advance translates in lower phase velocity, as it is proportional to the wave-vector k.

$$v_p = \frac{\omega}{k}$$

- At constant temperature, increasing RF frequency over the resonance frequency will lead to lower phase velocity and more radiation.

- At constant frequency, increasing temperature will lead to lower phase velocity and therefore more radiation.