Updates on the High Gradient S Band Experiments at IFIC

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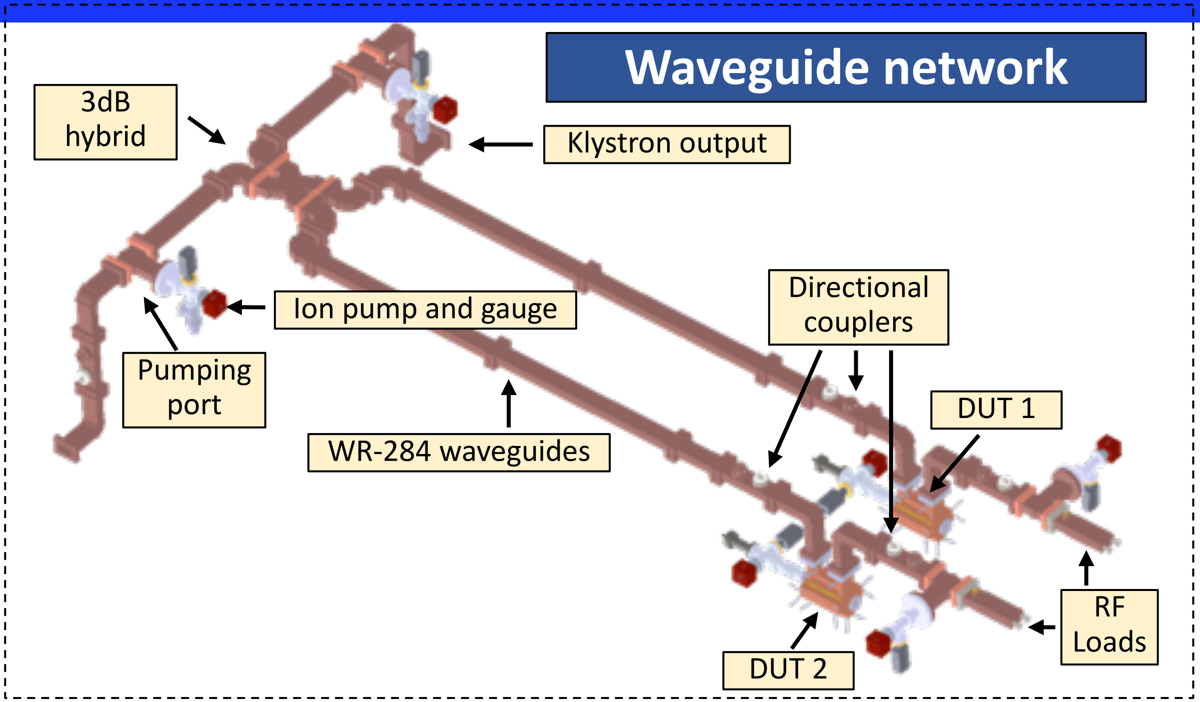
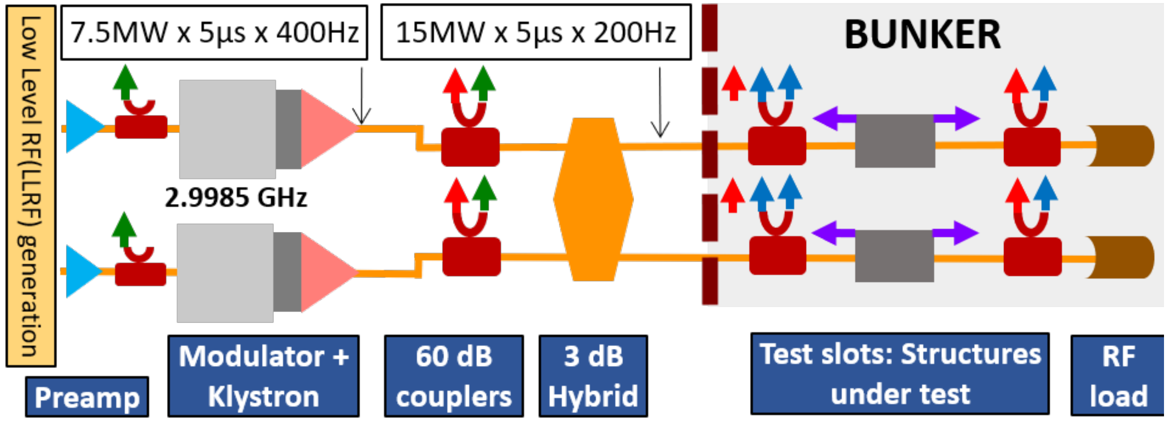
Outline

- Facility overview
- Operation summary
- S-band Backward Travelling Wave (BTW) structure studies results
  - Conditioning
  - BD localization analysis
  - BDR measurements
  - Dark current dynamics and radiation measurements
- Conclusions and future plans

The IFIC HG-RF laboratory

- ❑ High-gradient normal conducting RF cavities research topics at S-Band (2.9985 GHz) frequency.
- ❑ Very **similar to the Xbox-3 test facility at CERN** at 12 GHz but for a central frequency of **2.9985 GHz**.
- ❑ Main design parameters: **15 MW** with **5 µs pulses** and **200 Hz** repetition rate for testing two structures at the same time.

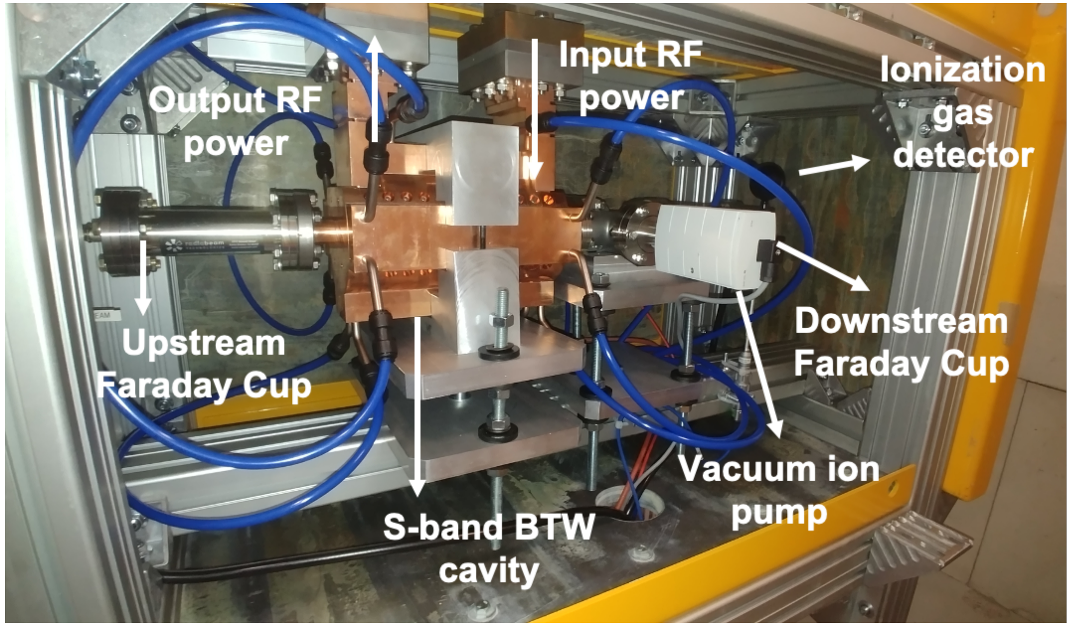




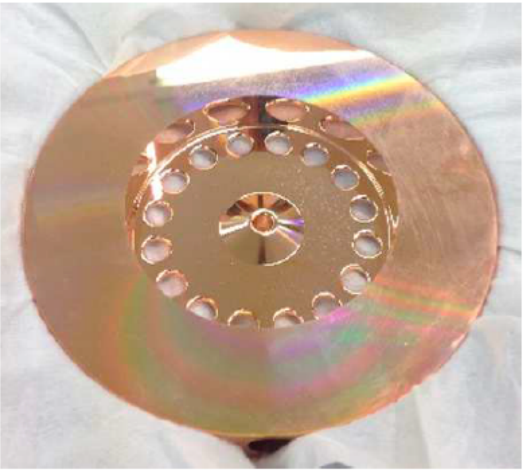
The CERN S-band BTW structure

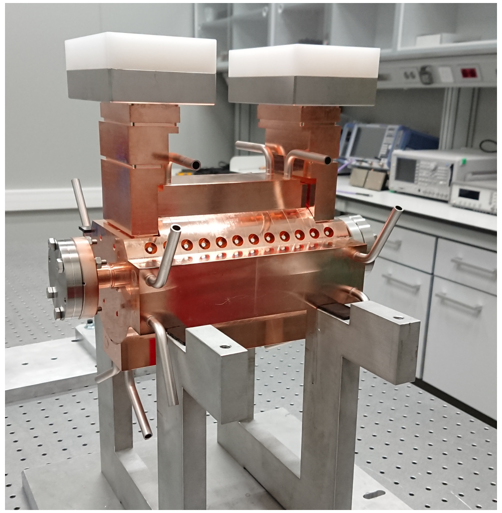
- **CERN designed** two S-band accelerating structures **based on CLIC high-gradient design methodology** for protons.

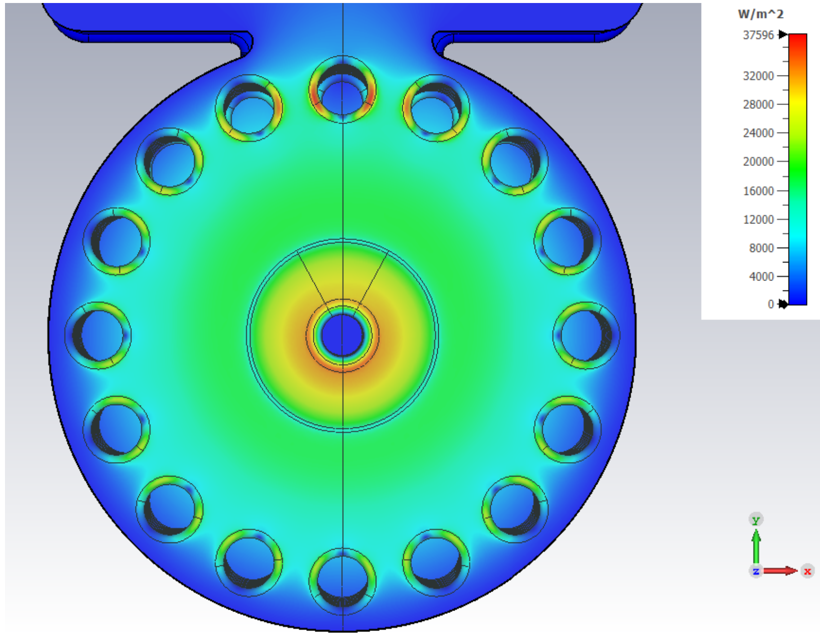
- 2.9985 GHz at 32°C
- β = 0.38
- 12 cells with $\Delta\phi$=150°
- Filling time: 224 ns
- Structure length: 189.9 mm
- Group velocity: 0.39/0.21 %c



Beam





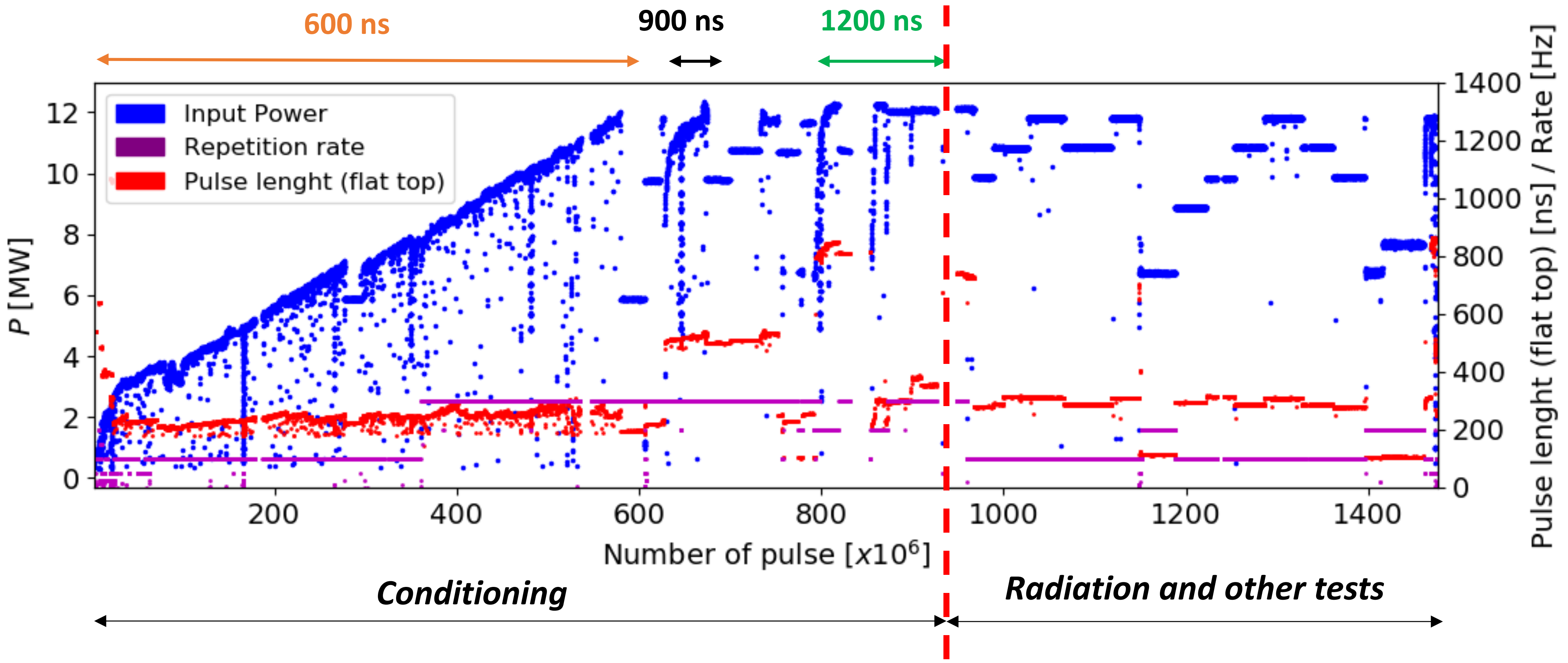


Modified Poynting vector S_C:

- Irises
- Coupling holes

Operation summary

- **Vacuum:** Below ~1x10^{-8} mbar
- **Temp. structure**: 22-23°C (2.9990 GHz)
- **Maximum power 12 MW** in ~570M pulses (short pulse length).
- **Pulse length:**
  - R:100 ns + FT: 200 ns + F:300 ns
  - R:100 ns + FT: 500 ns + F:300 ns
  - R:100 ns + FT: 800 ns + F:300 ns

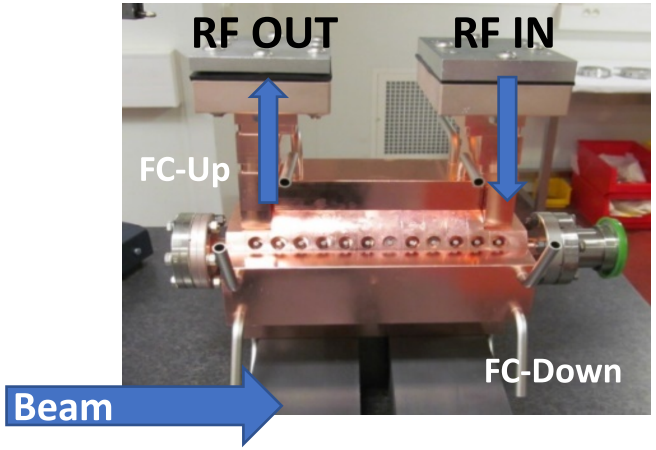


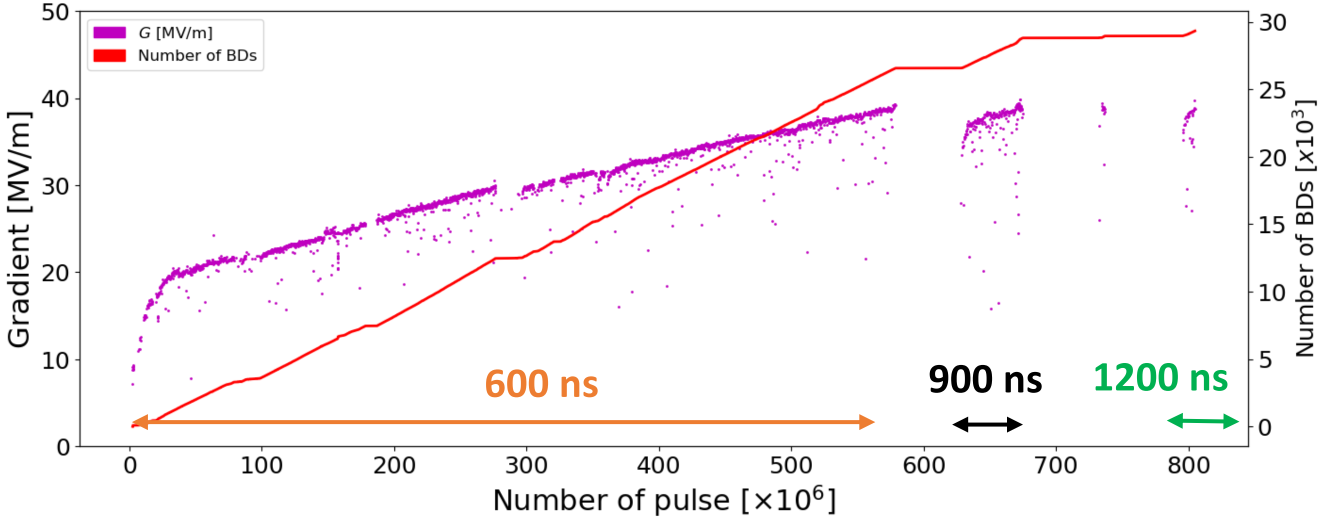
Conditioning summary I

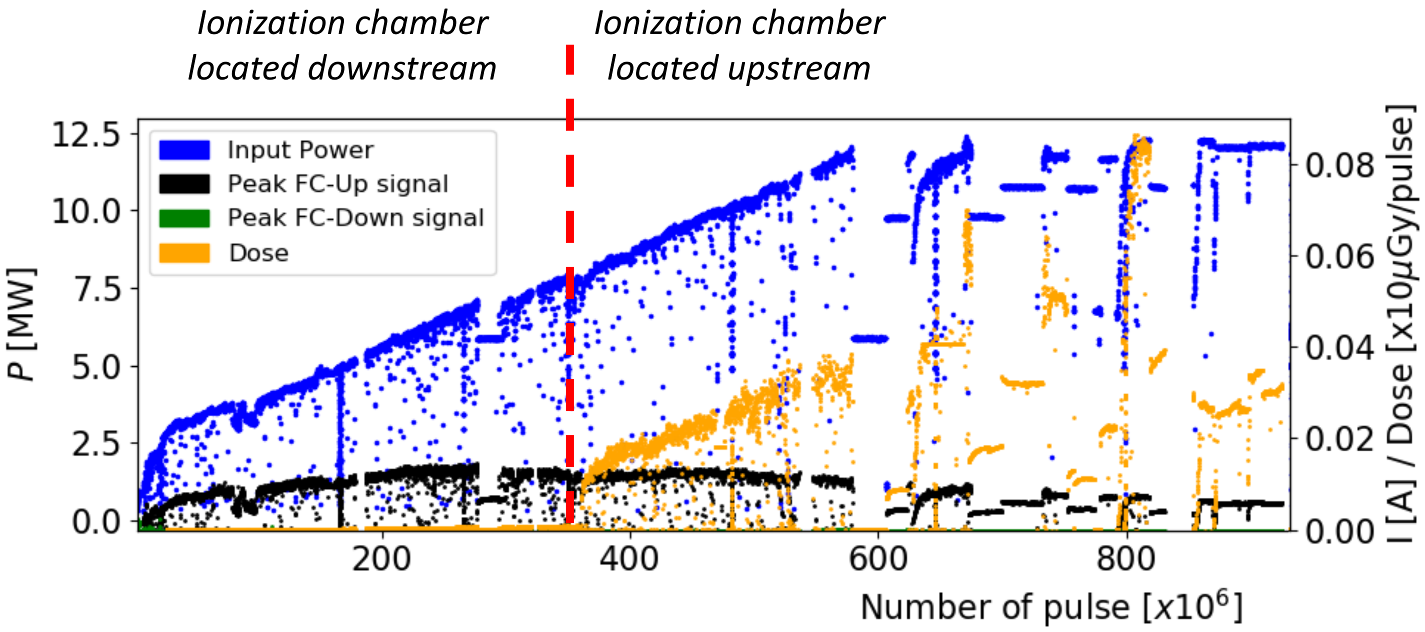
- With current set-up we reached an **accelerating gradient of ~39 MV/m**.

- **Pulse length:**
  - R:100 ns + FT: 200 ns + F:300 ns
  - R:100 ns + FT: 500 ns + F:300 ns
  - R:100 ns + FT: 800 ns + F:300 ns

- **Dark current and radiation:**
  - Faraday cups.
  - Ionization chamber.





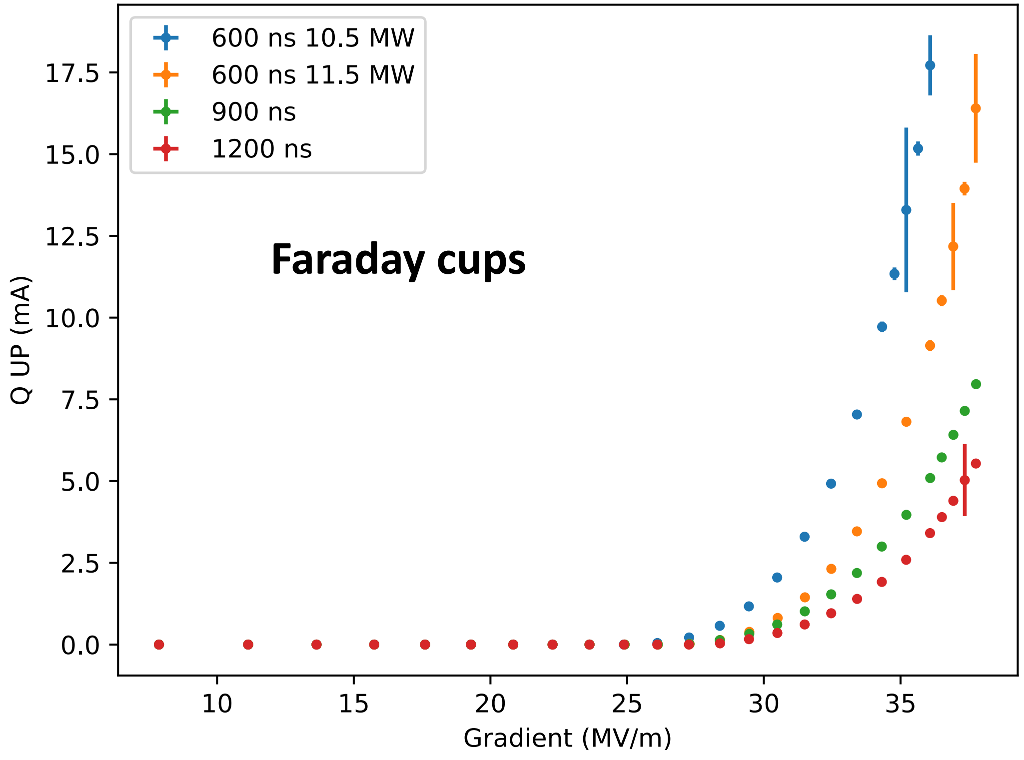


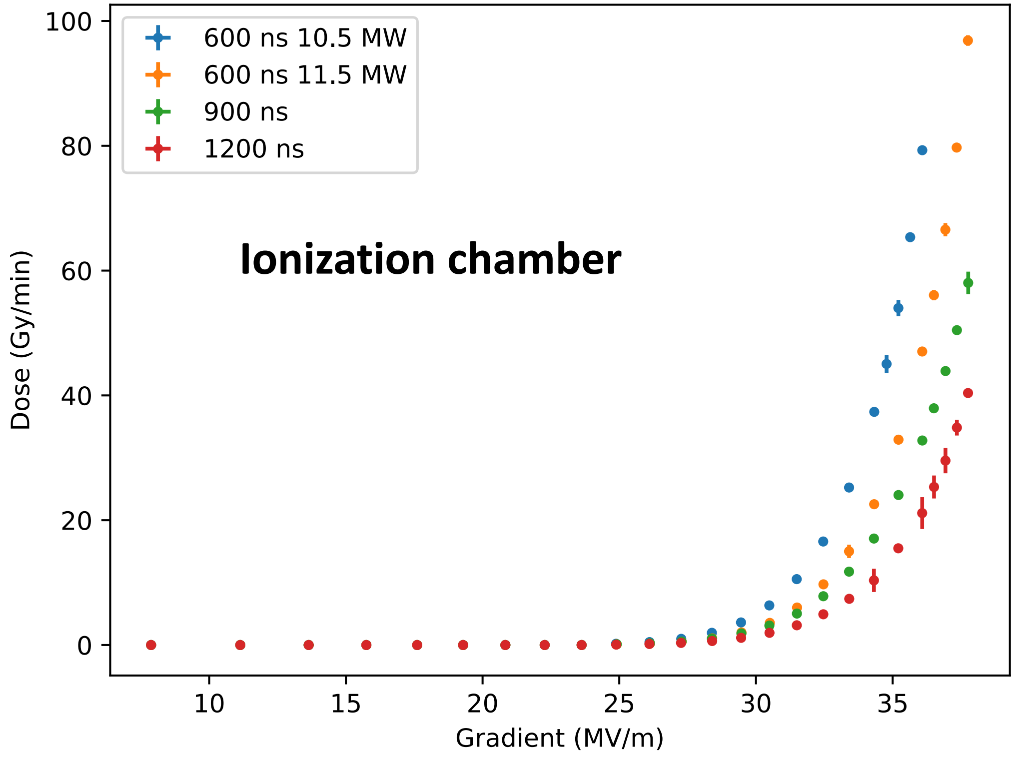
Conditioning summary II

- ❑ Dark current and radiation scans as a function of the gradient at different moments in the conditioning.
- ❑ Radiation studies and enhancement factor calculations.

$$Q_{UP}\ (mA) = \frac{Q_{UP}\ (nC)}{flat\ top\ (\mu s)}$$

$$Dose\ (Gy/min) = \frac{mean\ Dose\ (\mu Gy/min)}{rate\ (Hz) \cdot flat\ top\ (\mu s)}$$





Enhancement factor β estimation

- **Fowler-Nordheim** equation: electrons are emitted through tunneling due to **high surface electric field**.

$$I_F = \frac{A \cdot S}{\phi} (E)^{2.5} \exp\left(-\frac{B \cdot \phi^{\frac{3}{2}}}{E}\right) \text{ [A]}$$

Statistical Analysis of Field emission Currents. ***Phys. Rev. Applied 16, 024007 – Published 4 August 2021.***

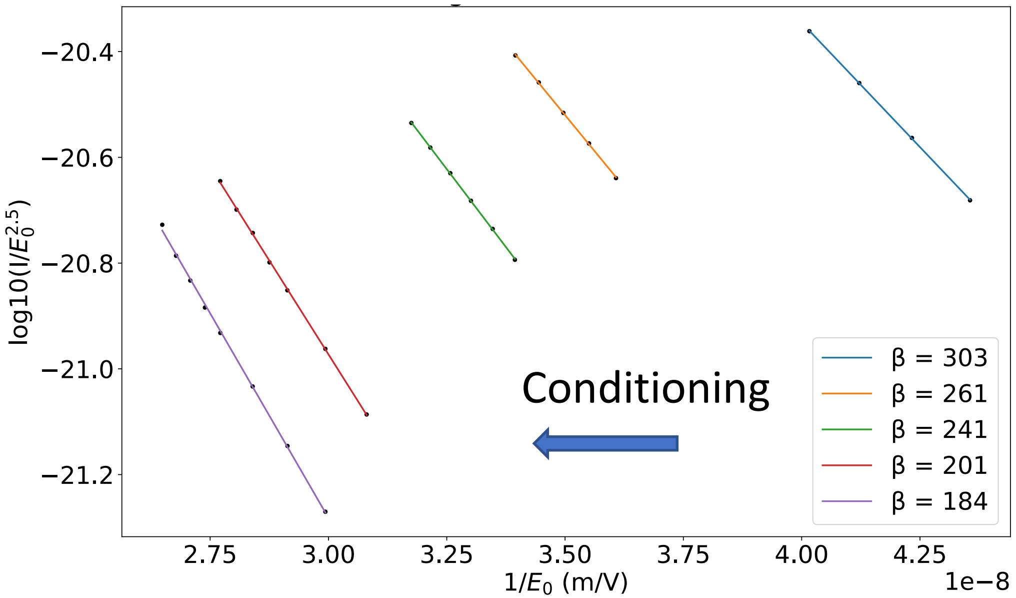
$$E = \beta E_0$$

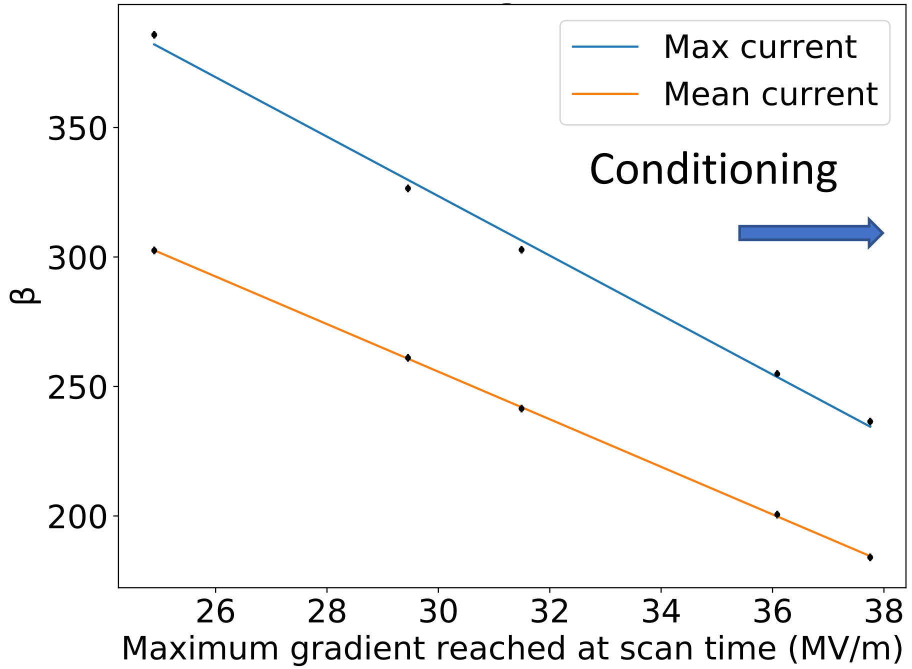
$$\log_{10}\left(\frac{I_F}{E_0^{2.5}}\right) = -\frac{B \cdot \phi^{\frac{3}{2}}}{\ln 10 \cdot \beta} \cdot \frac{1}{E_0} + \log_{10}\left(\frac{A \cdot S \cdot \beta^{2.5}}{\phi}\right)$$

$$y = m \cdot x + b$$

A, B: Constants FN model
S: Emitters surface
$\boldsymbol{\phi} = 4.65\ eV$ Copper work function

E : Surface electric field
$\boldsymbol{E_0}$: Acceleration gradient
$\boldsymbol{\beta}$: total enhancement factor

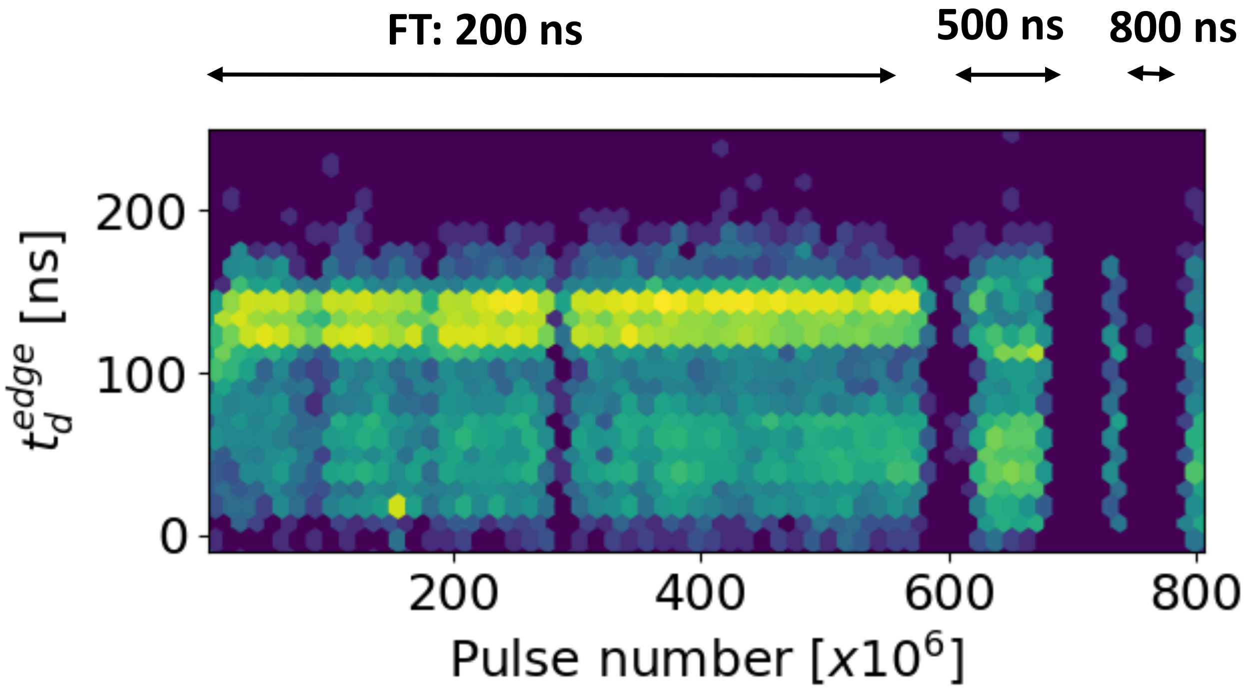


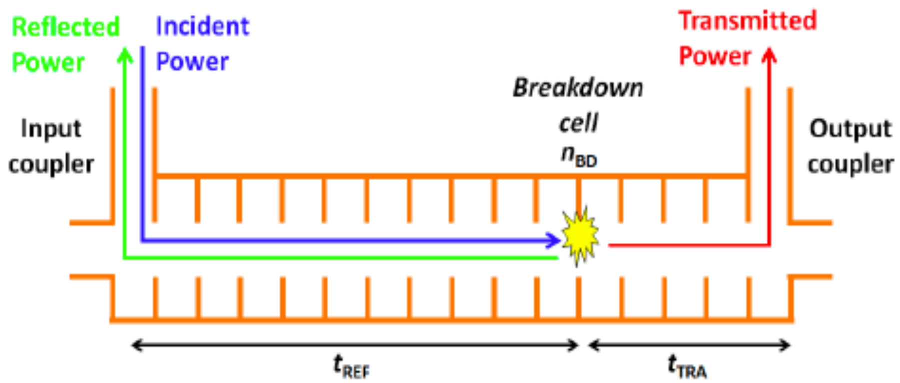


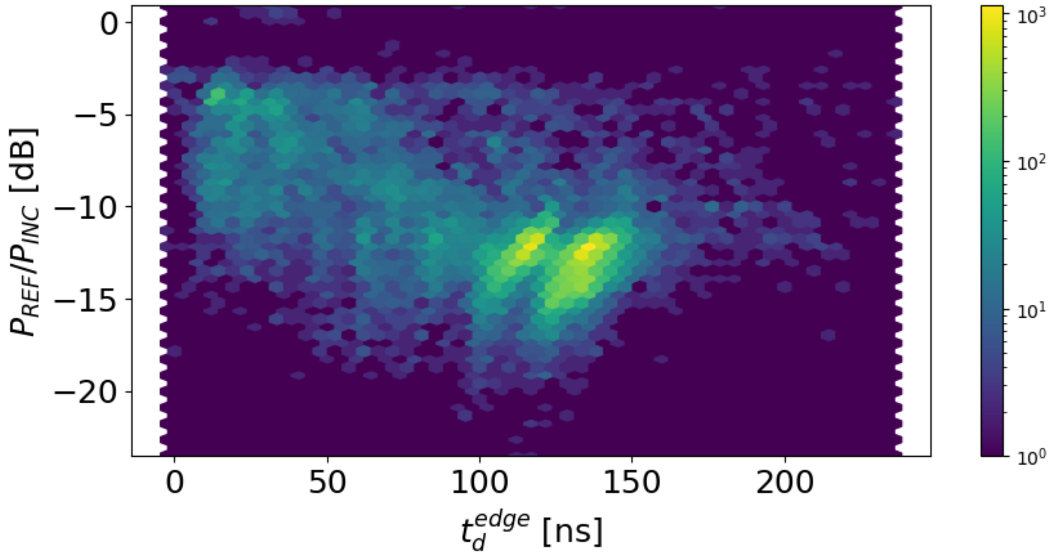
BD localization analysis: edge method

- Using the typical methods based on the timing difference between the **reflected signal rise and transmitted signal fall** we can determine the t_d .

$$t_d^{edge}[ns] = \frac{\Delta t_{REF} - \Delta t_{TRA}}{2}$$



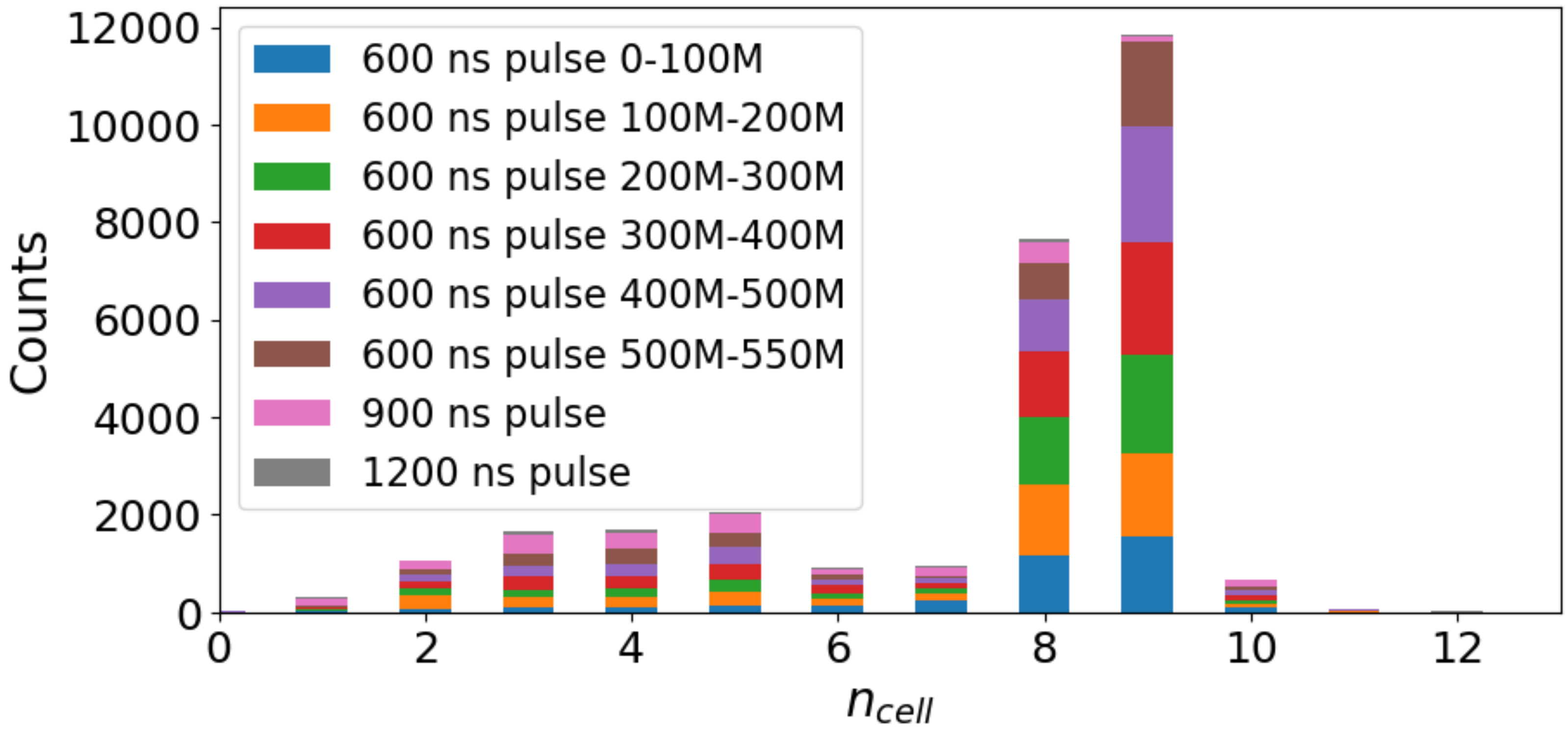




- The accumulated BDs around 120 ns have very similar reflected signal shape and peak and high dark current.
  - Working on better understanding this BD.

BD localization analysis: BDs evolution

- Using the group velocity profile the delay expected for each cell can be computed.



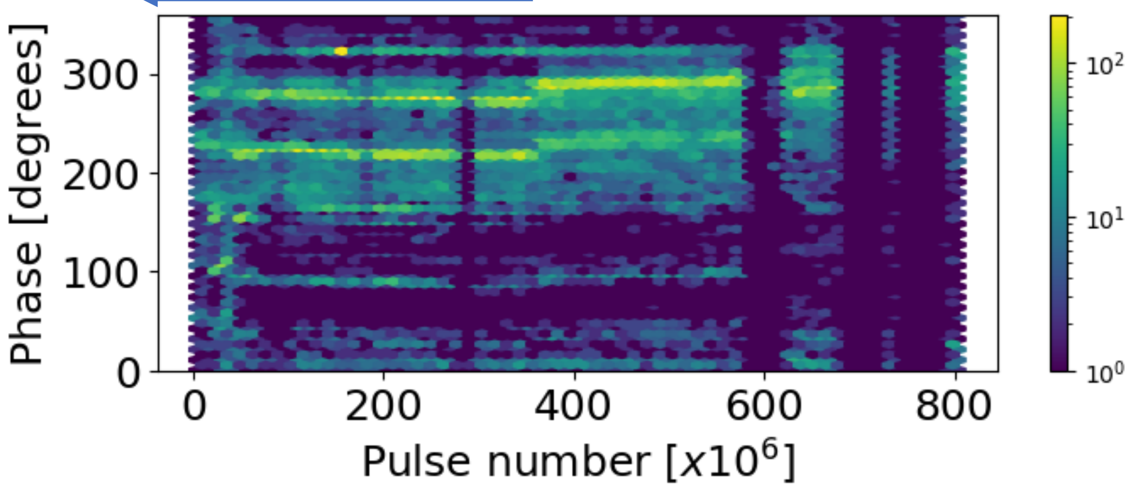
- The distribution of BDs happening along the conditioning is quite uniform.

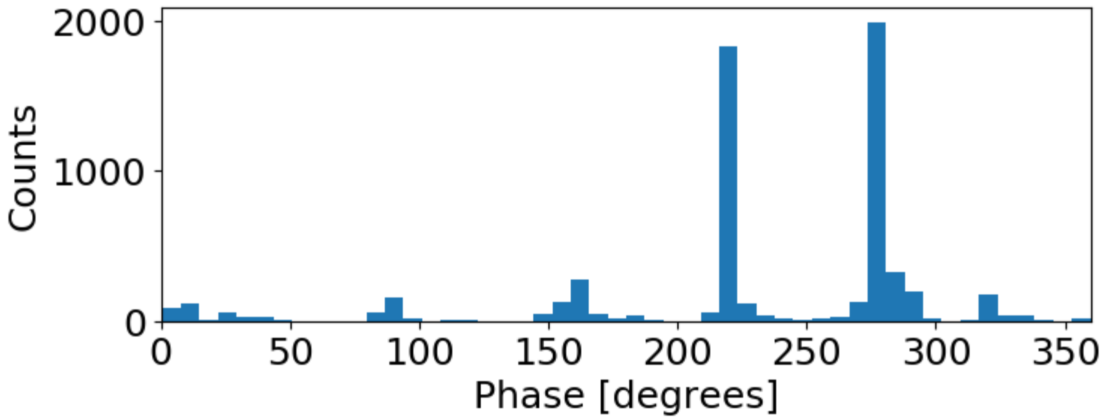
- The huge accumulation of BDs in cells 8 and 9 w. r. t. other cells for short pulses are under investigation.

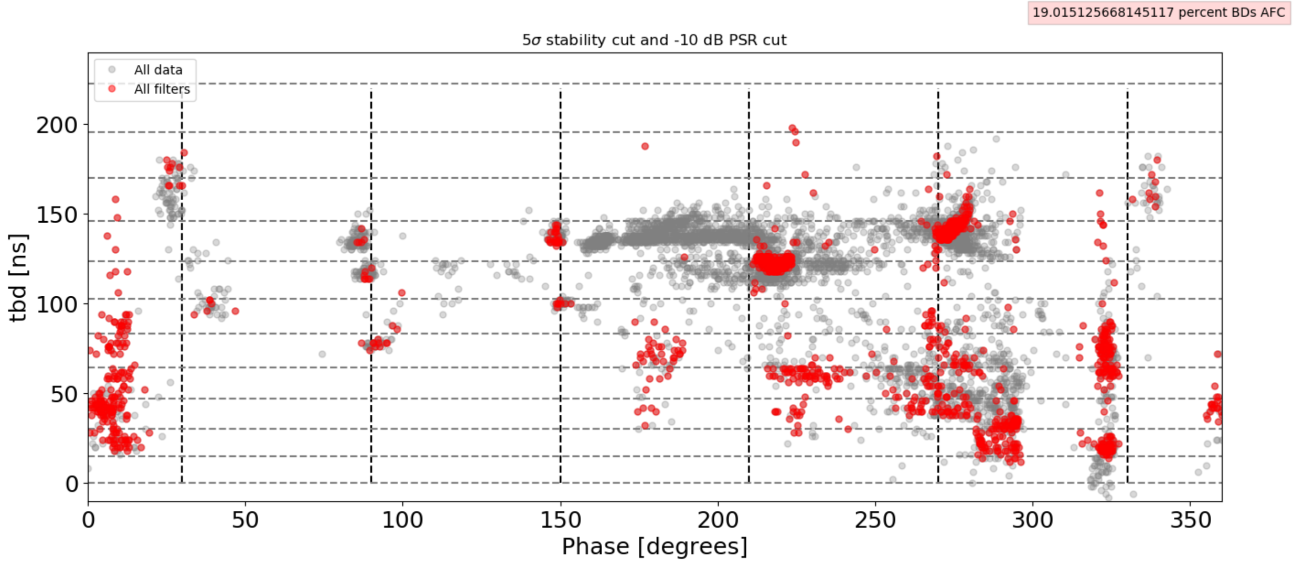
BD localization analysis: phase method

- Localization method based on the difference of the phase of the incident and reflected signals.

300 Hz $\rightarrow \Delta T$







- Not clear correlation between phase and delay time.
  - Deeper analysis on-going.

BD localization analysis: dark current method

Dark current signal method: compares the time of detection in which the reflected power rises and the time at which one of the two FC signals increase.

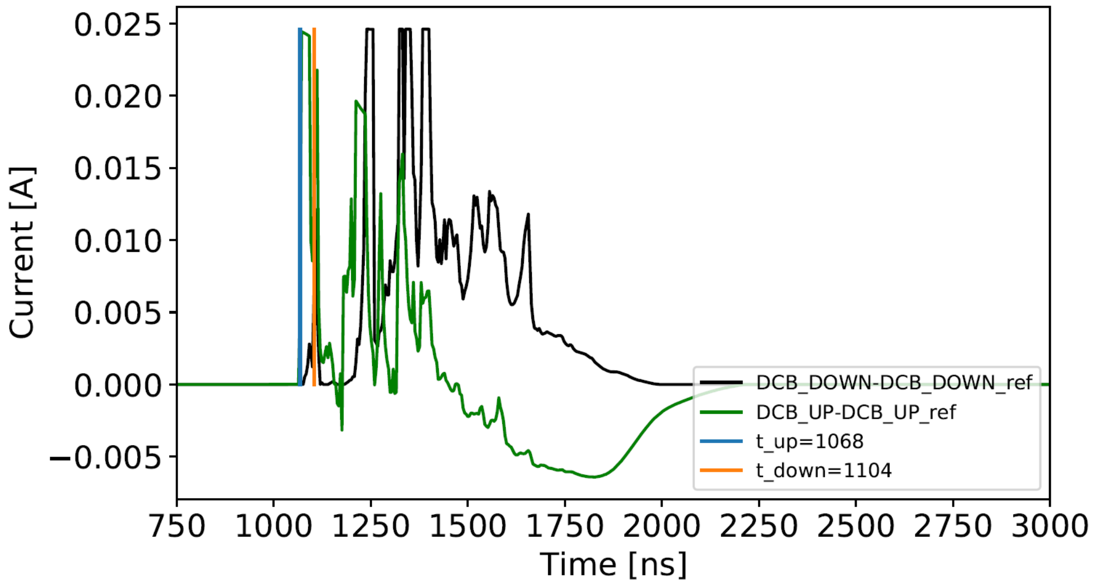
Trigger

$$t_{BD} = \min\{t_{FCUP}, t_{FCDOWN}\}$$

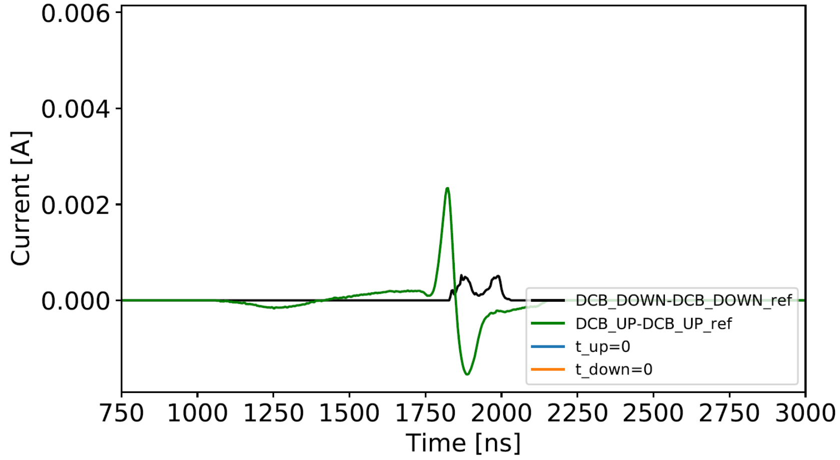
$$\begin{cases} t_d^{edge}[ns] = t_{REF} - t_{BD} & \text{Reflectection rise} \\ t_d^{edge}[ns] = t_{TRA} - t_{BD} & \text{Transmission fall} \end{cases}$$

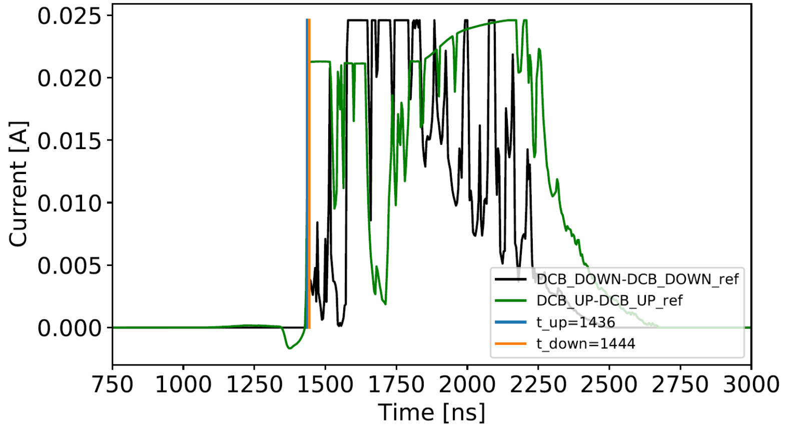
Hypothesis: Electrons must reach to the FC faster than our time resolution “4 ns” (CST simulations)

Easy case



Complex cases

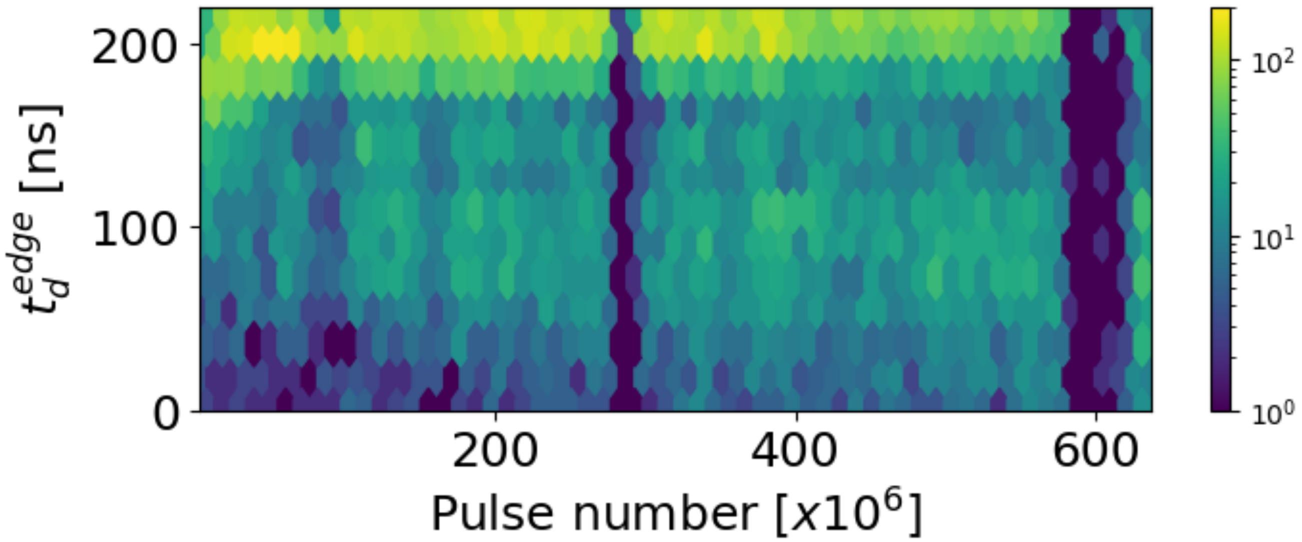




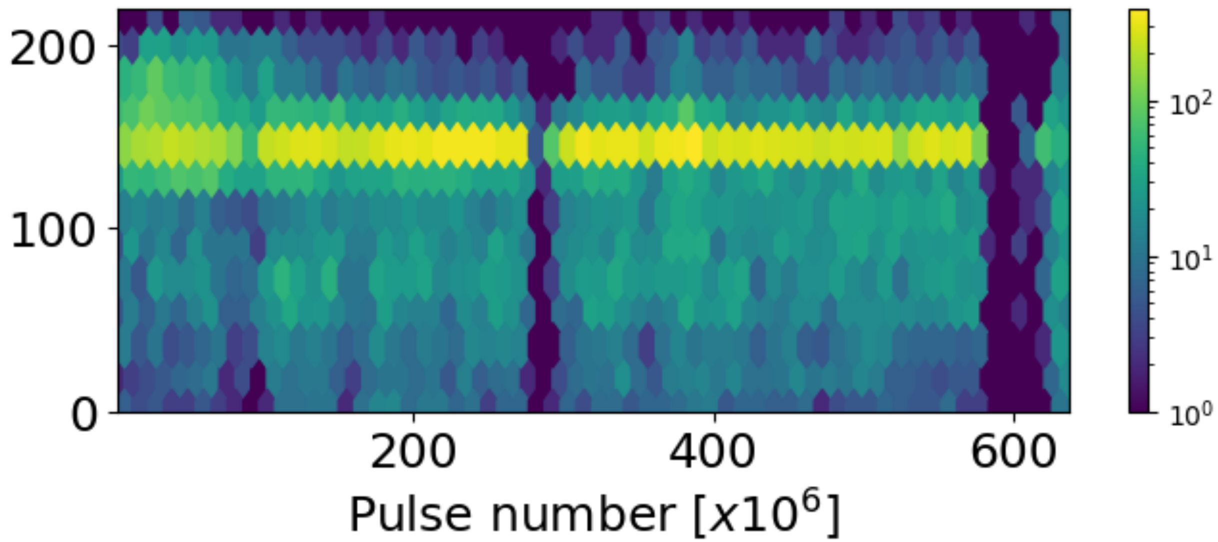
BD localization preliminary results: “current method”

- 200 ns flat top

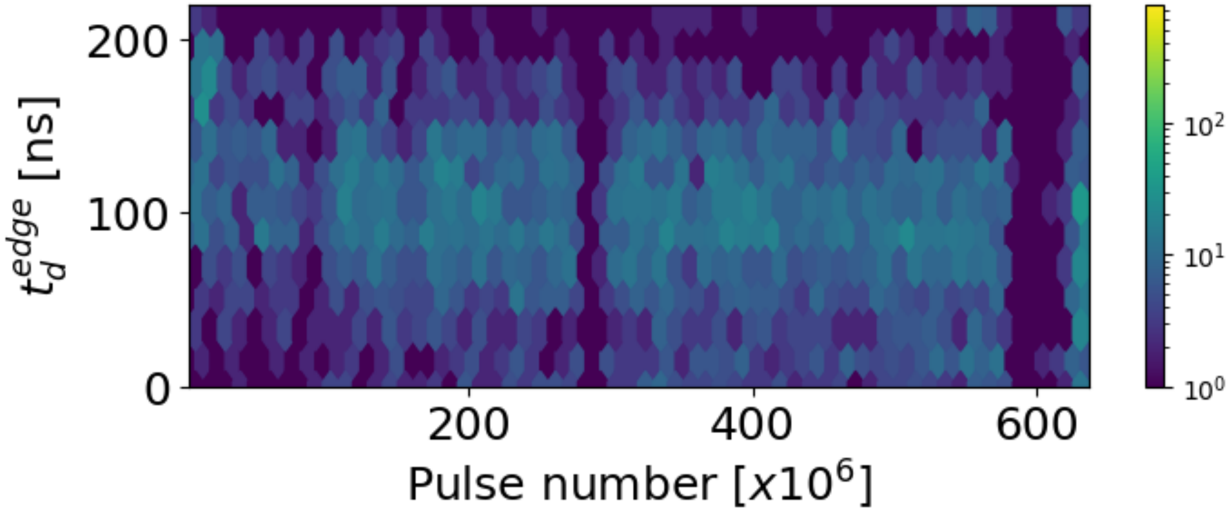
Dark Current + Reflection

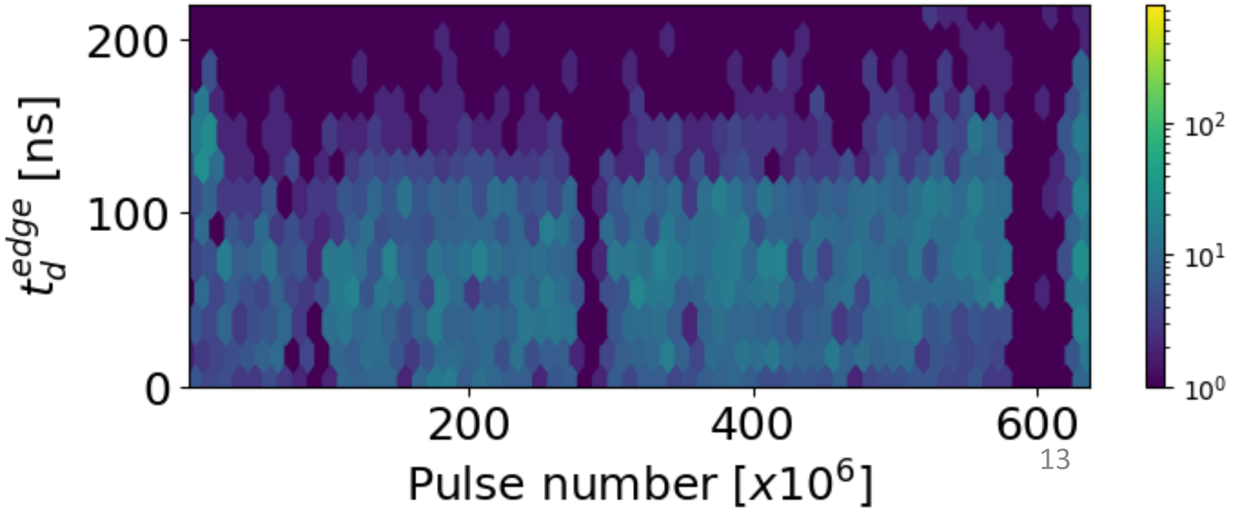


Dark Current + Transmission



- PSR^{peak} /PSI^{peak} > -10 dB



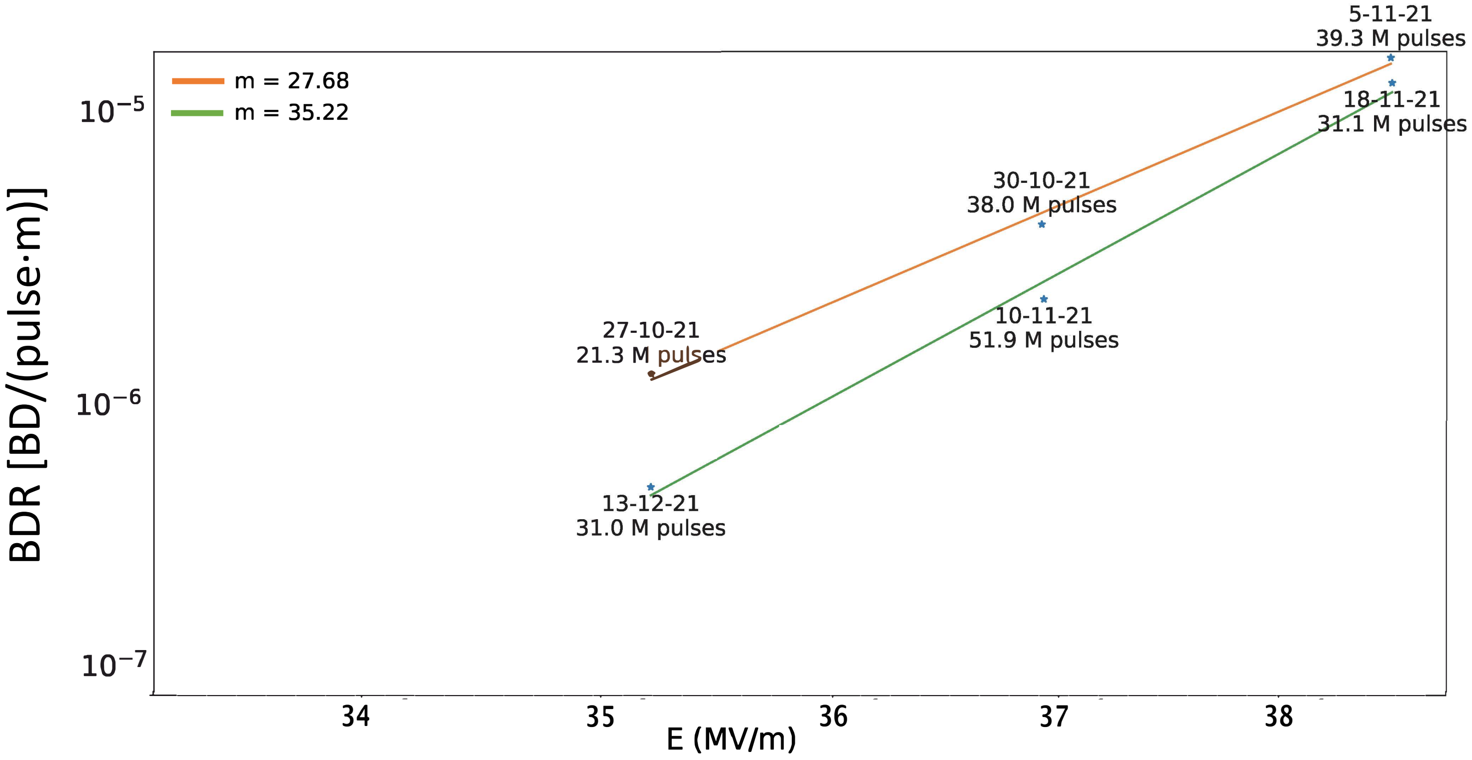


BDR measurements

Preliminary BDR study for a fix power.

BDR $\propto E_{acc}^{30}$ (for electron designs)

- Measurements performed:
  - After reaching the maximum power.
  - After 3 days at max. power.
- Results improved for the second measurement: BDR decreases if conditioning is made at constant gradient.
- BDR are above specifications for medical applications: 7.7×10^{-7} BD/(pulse·m)



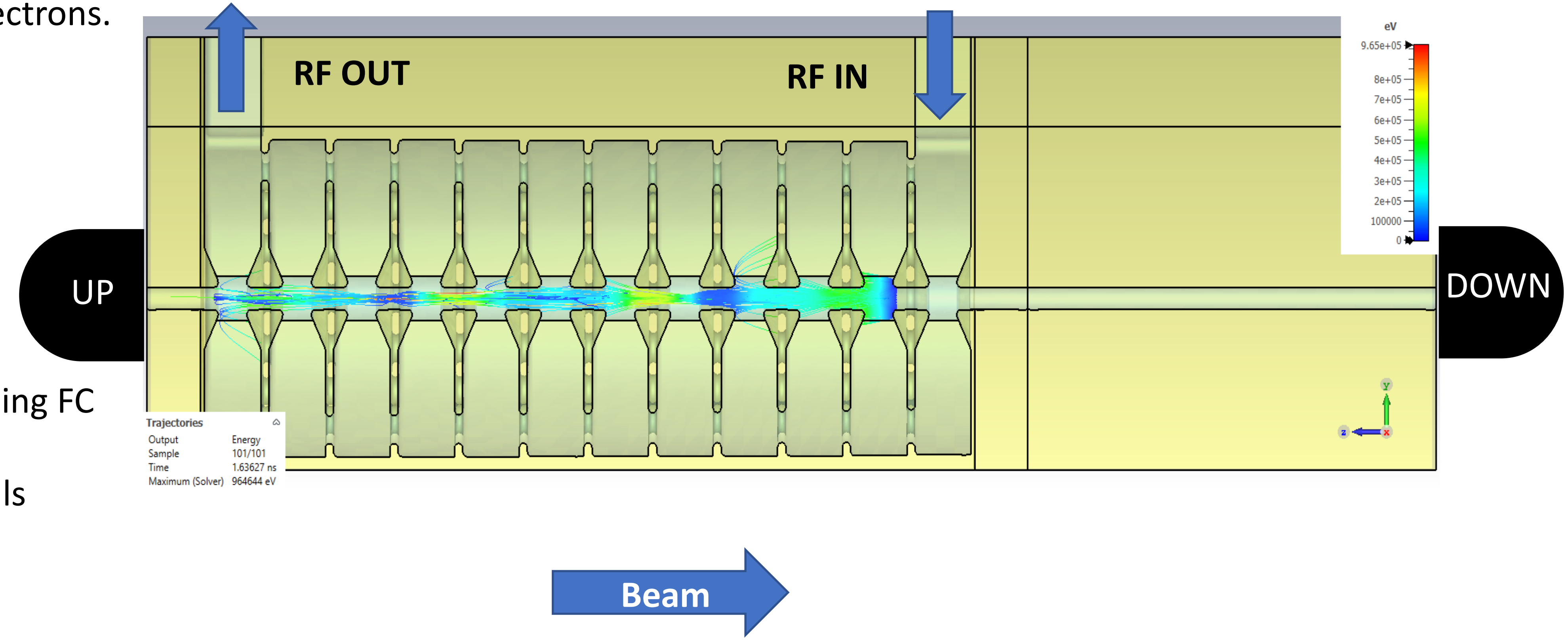
Dark current dynamics studies

Motivation:

- ❑ Model and characterize the dynamics and impact of the electrons generated by field emission.

Procedure: Using 3D EM codes (CST PS).

- ❑ Field emission from a certain cell. $J = aE^2 e^{-b/E}$
- ❑ Tracking of emitted electrons.



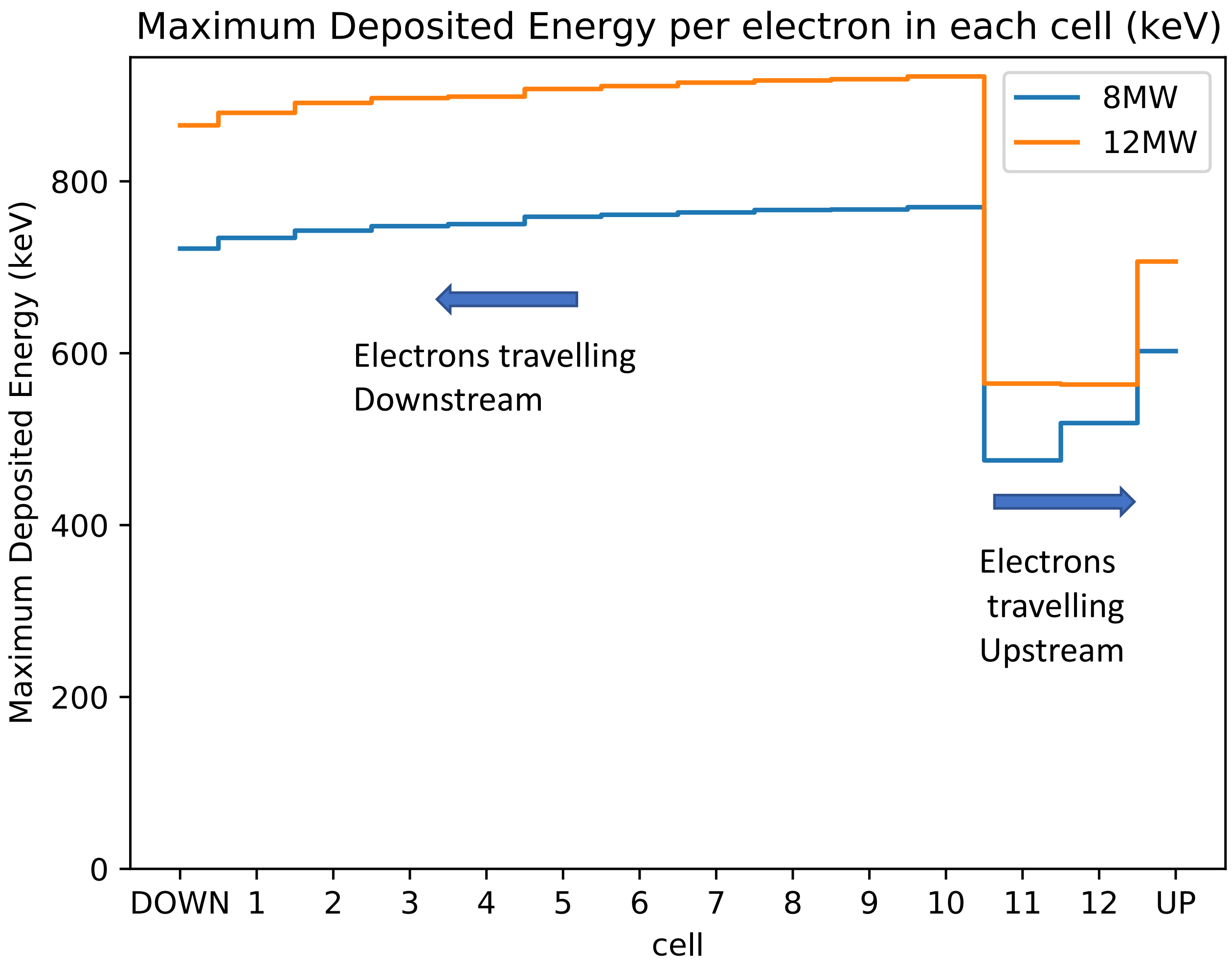
Studies:

- ❑ Ratio of electrons reaching FC
- ❑ Energy of electron in FC
- ❑ Energy deposited in walls

Scans:

- ❑ Emission cell
- ❑ RF power

Maximum energy of electrons colliding inside the cavity



Observations:

- ❑ Electrons travelling Upstream reach further distance: More electrons in the upstream FC w.r.t. beam
- ❑ Electrons travelling Downstream achieve higher energies.
- ❑ Maximum energy of electron interacting with walls 700-900 KeV (8-12 MW).

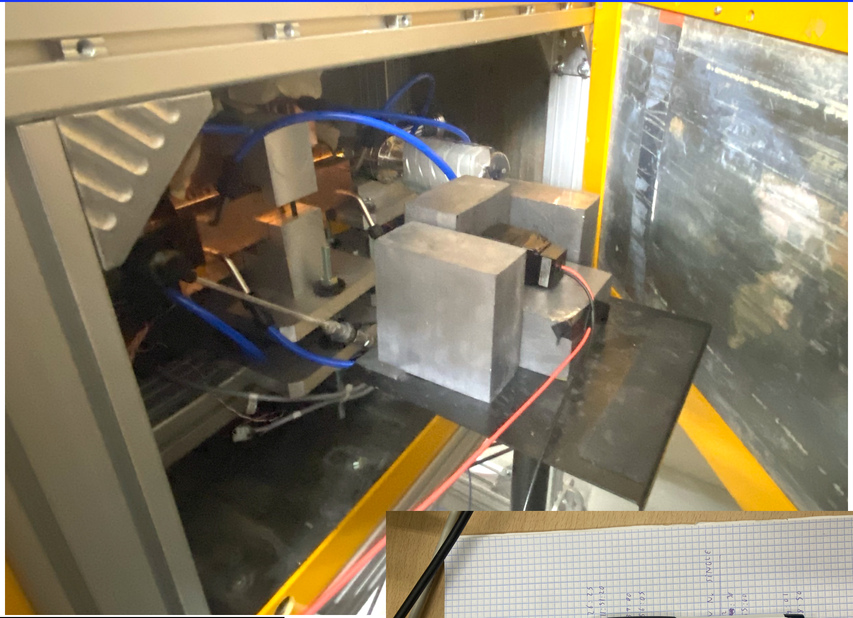
Radiation measurements

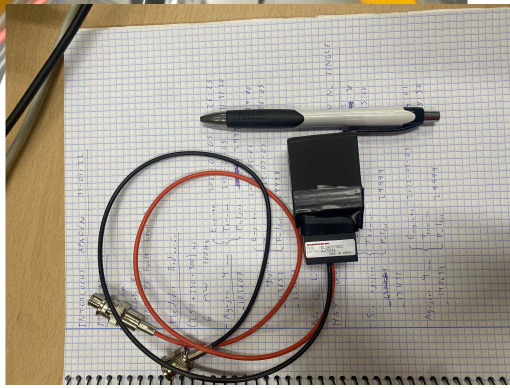
Measurements to:

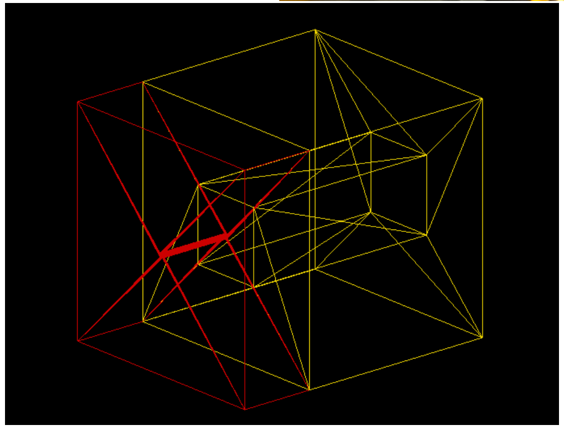
- ❑ Validate the EM model.
- ❑ Estimate the impact of the radiation produced.

Energy spectrum of photons coming out of the structure.

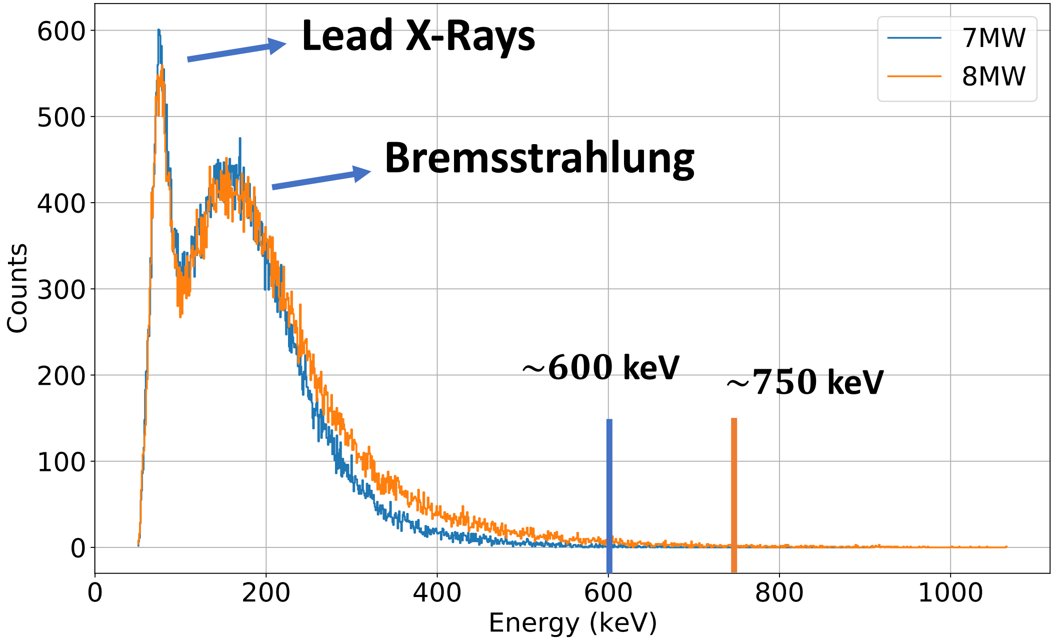
- ○ New set-up with smaller crystal of CeBr3, reading the pulses from an oscilloscope and dedicated collimator: **Faster and more flexible**







Preliminary



- ❑ Combine measured energy spectrum and dose with Geant4 simulations to estimate **the flux of photons**.

Conclusions

- ❑ Maximum power has been achieved (12 MW) with no hot cell detection.
  - Large amount of low reflection signal BDs detected for short flat top pulses.
- ❑ Enhancement factor decreases linearly with maximum field reachable.
- ❑ BDR improved if after reaching the maximum gradient, conditioning is made at fixed power.
- ❑ First CST tracking simulations are in good agreement with experimental observations:
  - Electrons going Upstream travel further distances (up to 9 cells) than Downstream (up to 3 cells).
  - Electrons going Downstream reach higher energies ($<$ 900 keV) than Upstream ($<$ 700 keV) .
- ❑ First results obtained with a new experimental set up for high photons rate detection.

<u>Future plans</u>

- ❑ Pulse compressor implementation to reach higher input power.
  - Installation: second week of June, Control software update and commissioning.
- ❑ Continue with the characterization of the BTW S-band structure at higher power.

Thank you very much for your attention!

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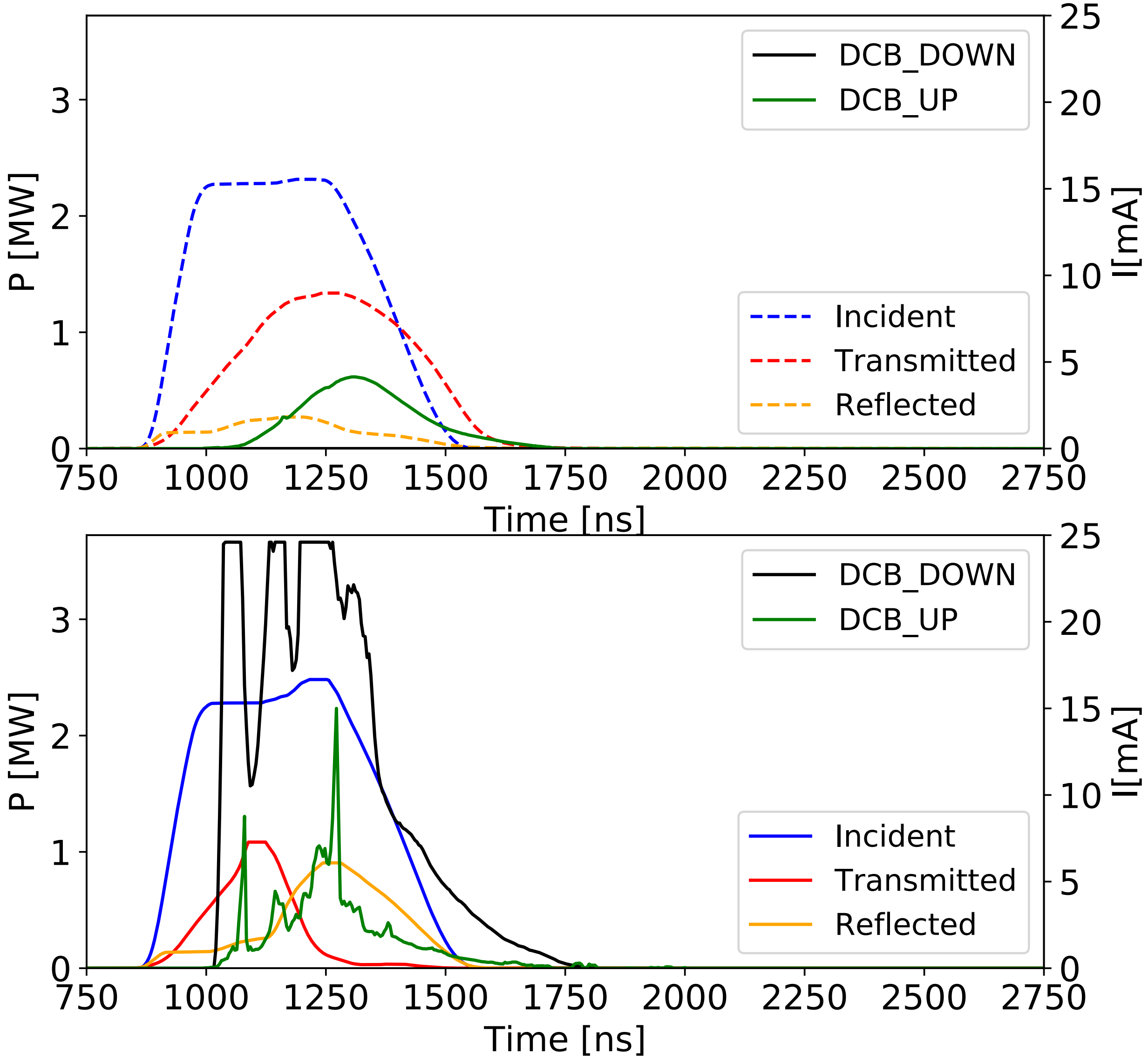
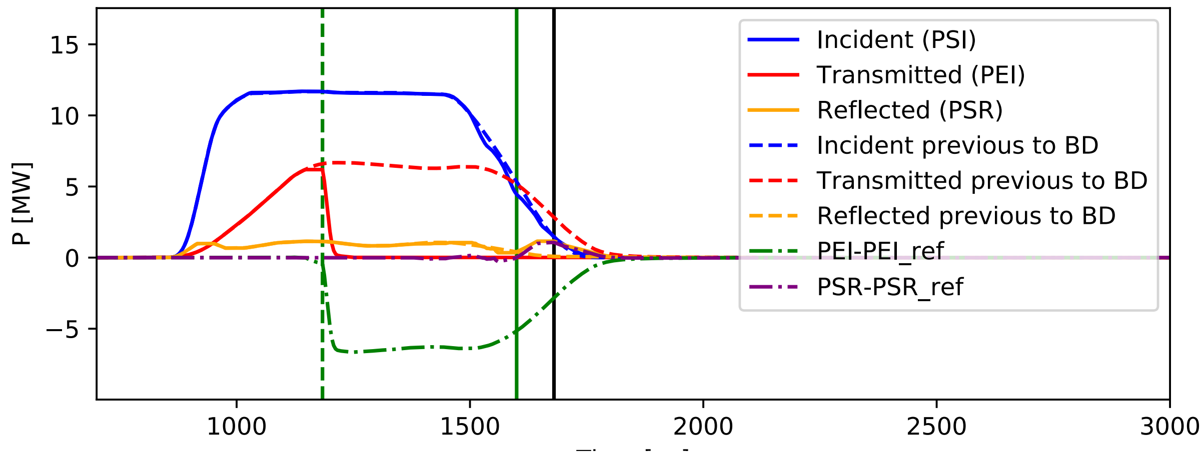
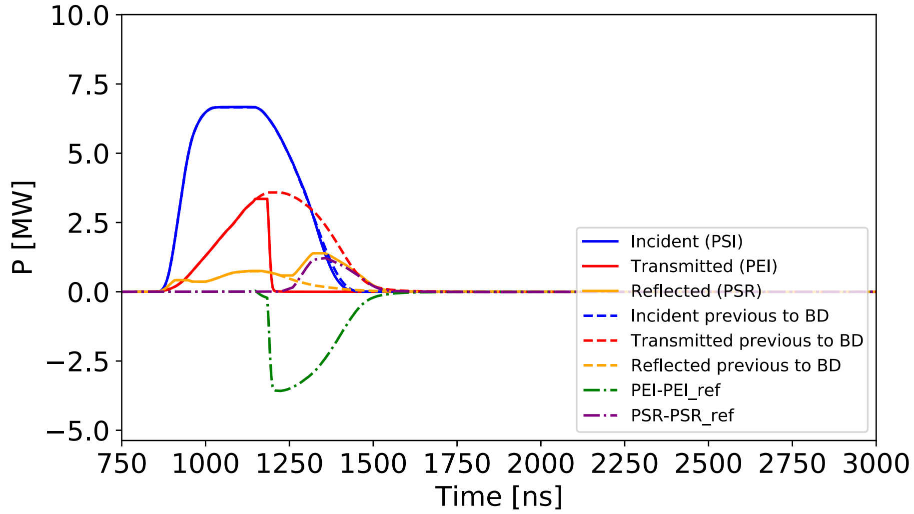
BD example

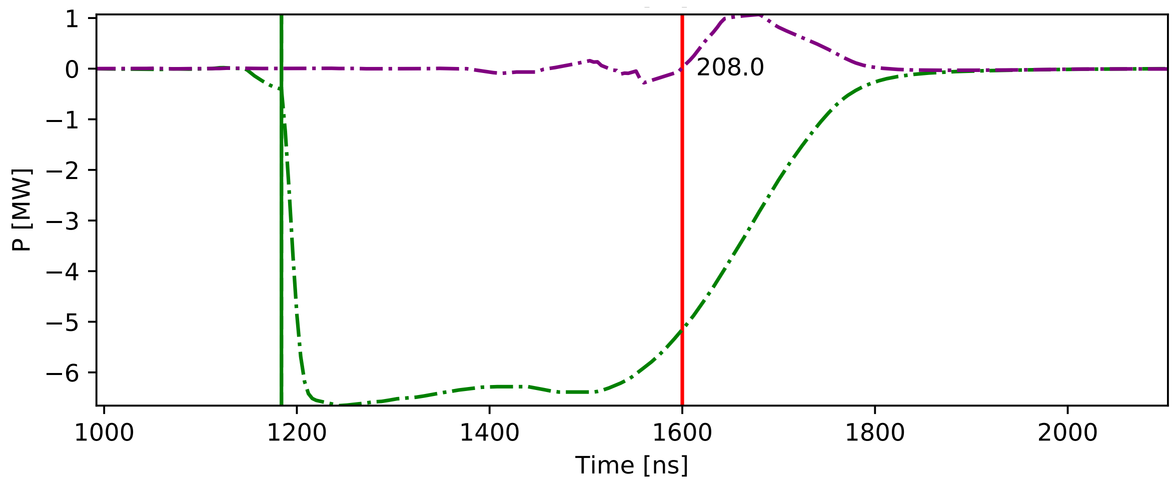


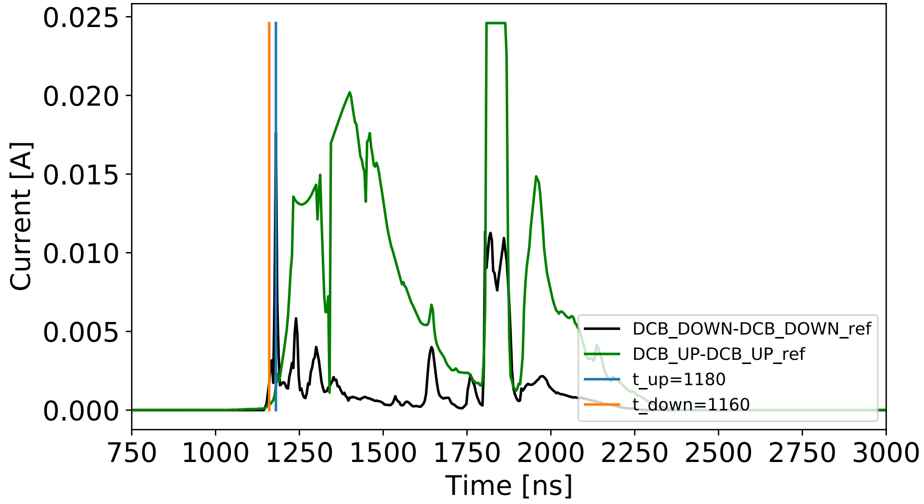
DCB_DOWN
DCB_UP
Incident
Transmitted
Reflected
P [MW]
I[mA]
Time [ns]
0
1
2
3
0
5
10
15
20
25
750
1000
1250
1500
1750
2000
2250
2500
2750
DCB_DOWN
DCB_UP
Incident
Transmitted
Reflected
P [MW]
I[mA]
Time [ns]

BD localization analysis methods: Examples

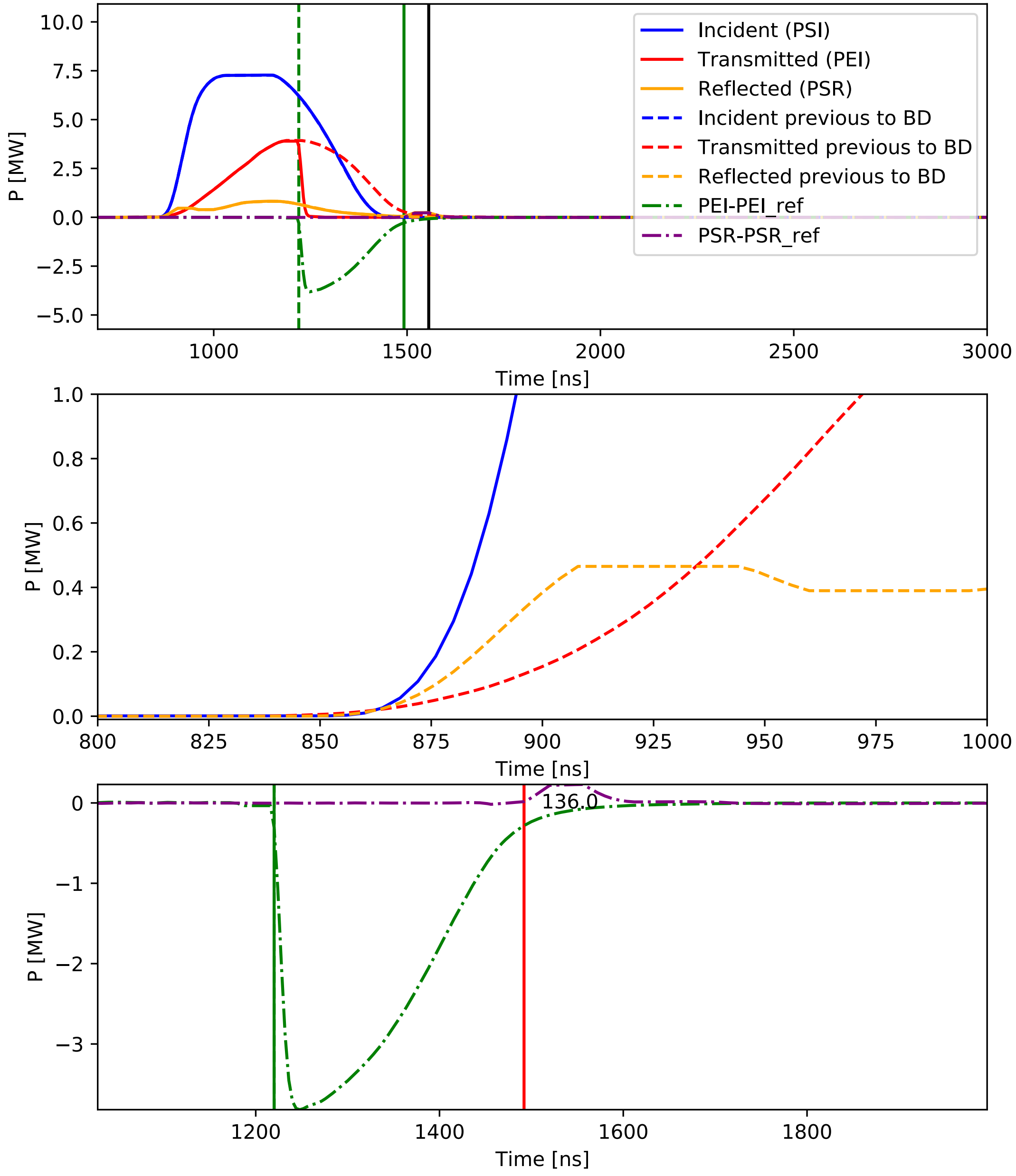


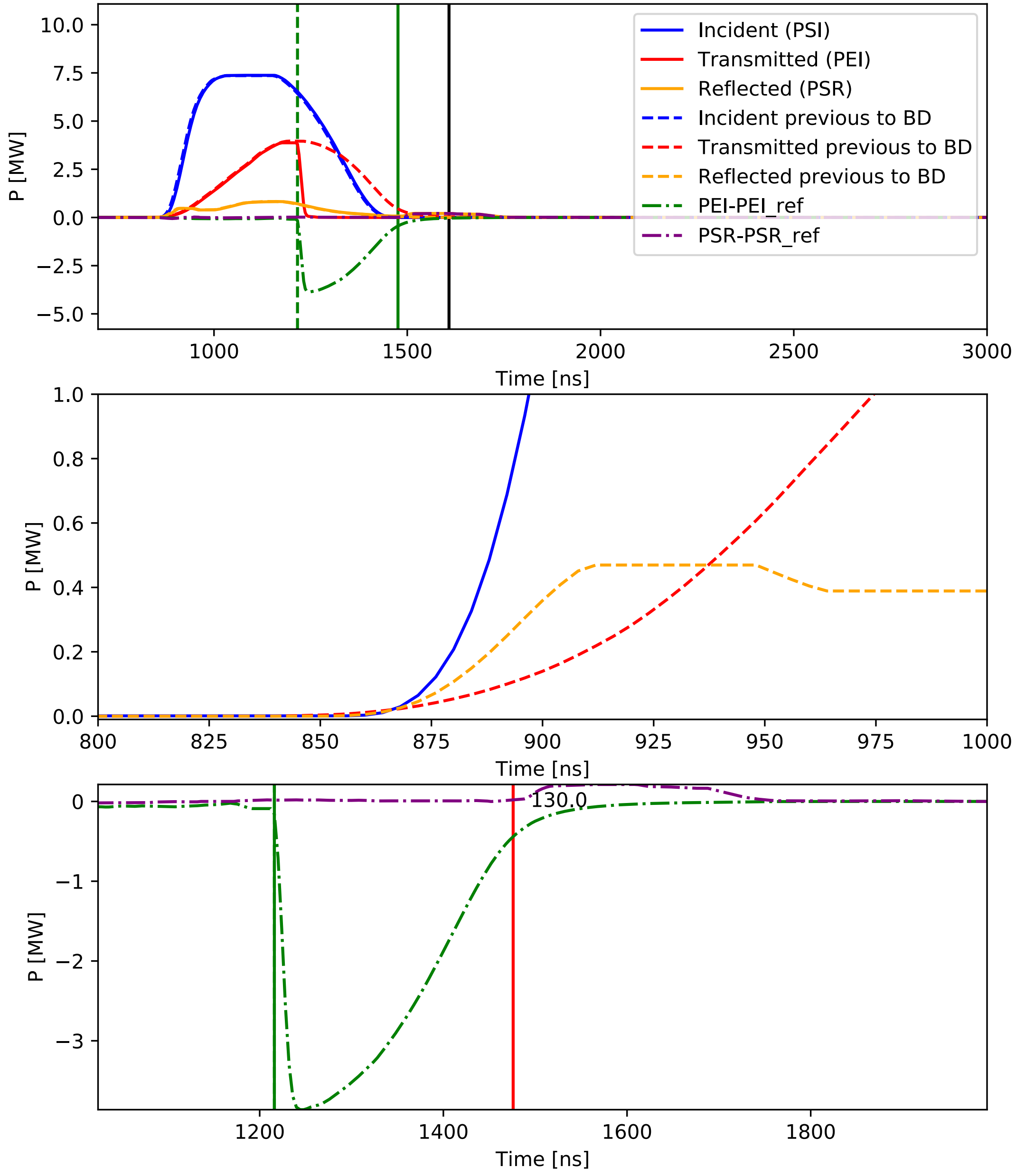






BD localization analysis methods: Most common BD





Operation summary I

Timeline

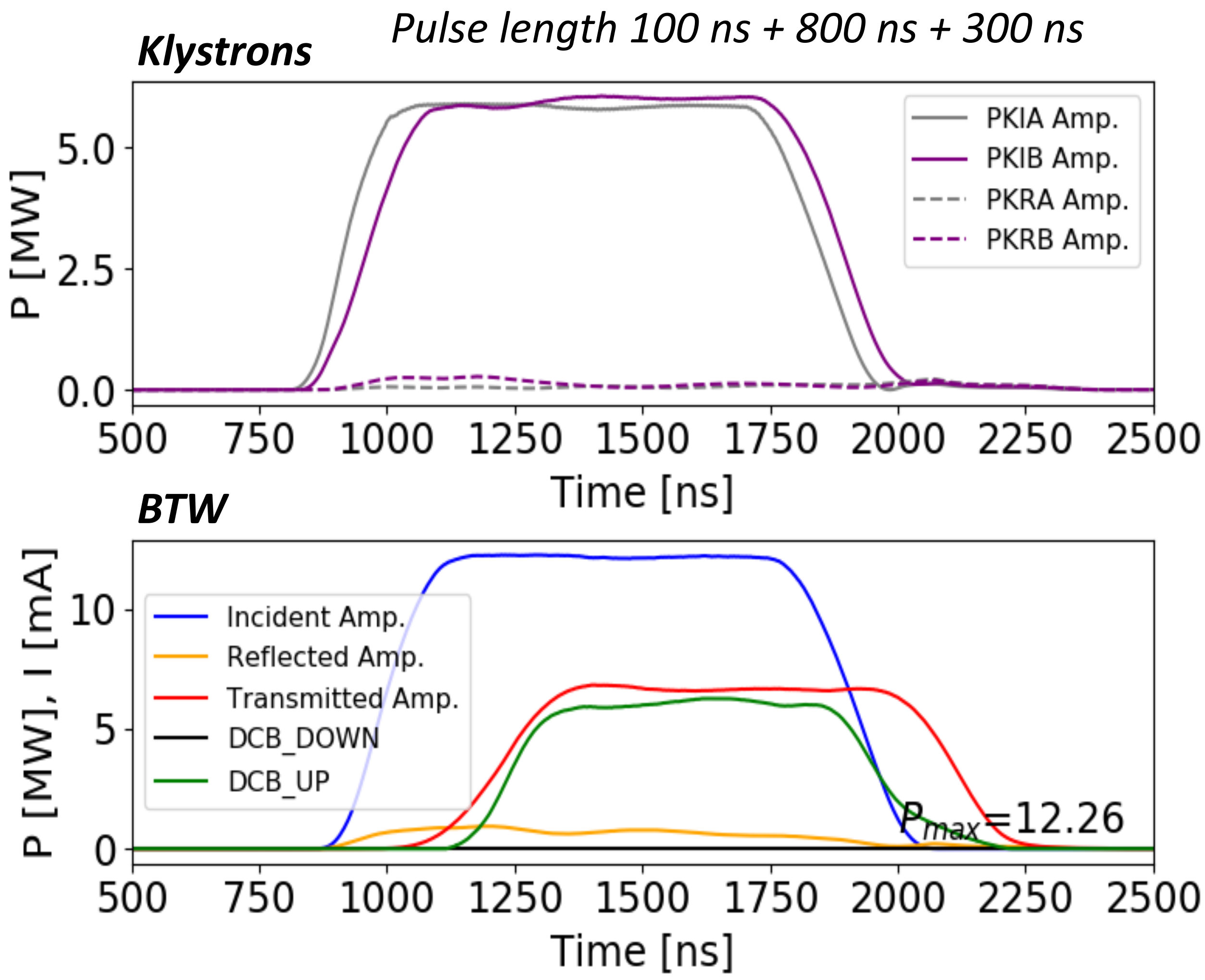
- ❑ **Commissioning of the facility** in June 2019.

- ❑ **Started testing** the BTW structure in October 2019.

    - **Conditioning**.

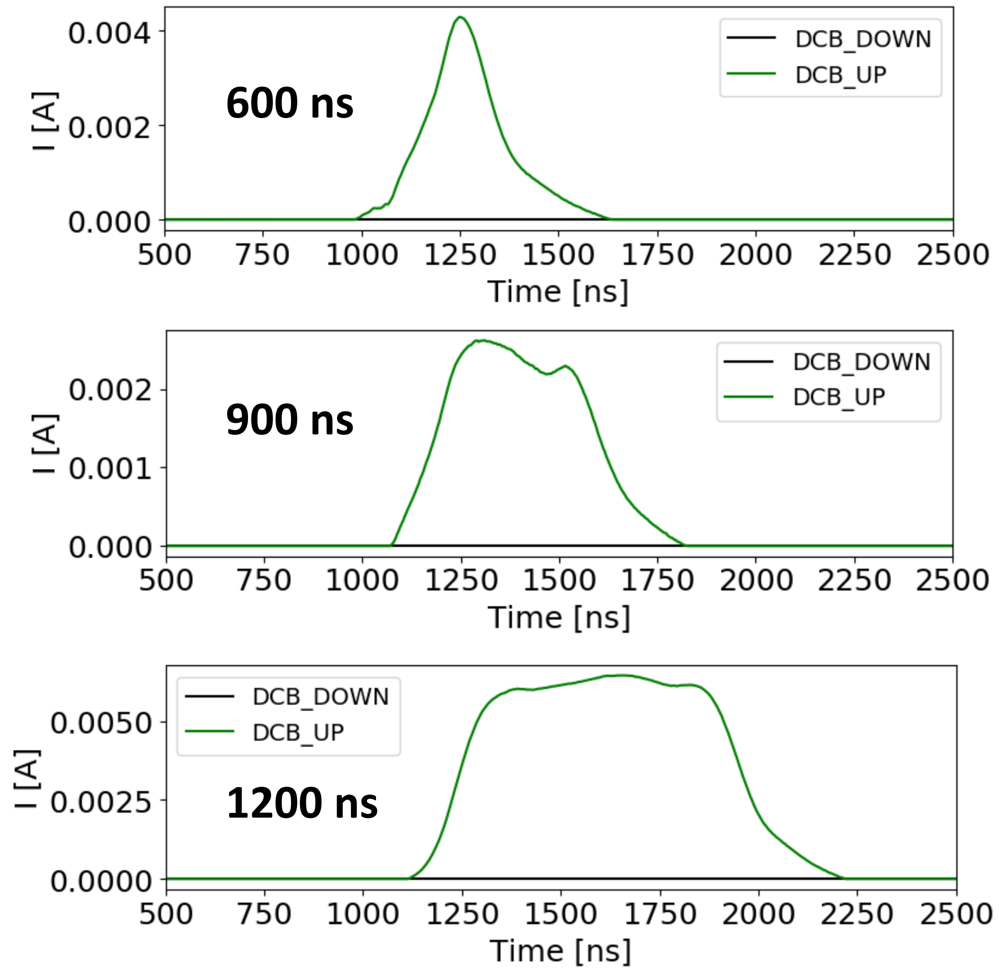
    - Explore the limitations of the **accelerating gradient** and study the **BD and dark current phenomena**.

- ❑ **Reached maximum power** allowed by current set-up in September 2021 (shorter pulse) and October 2021 (longer pulse).

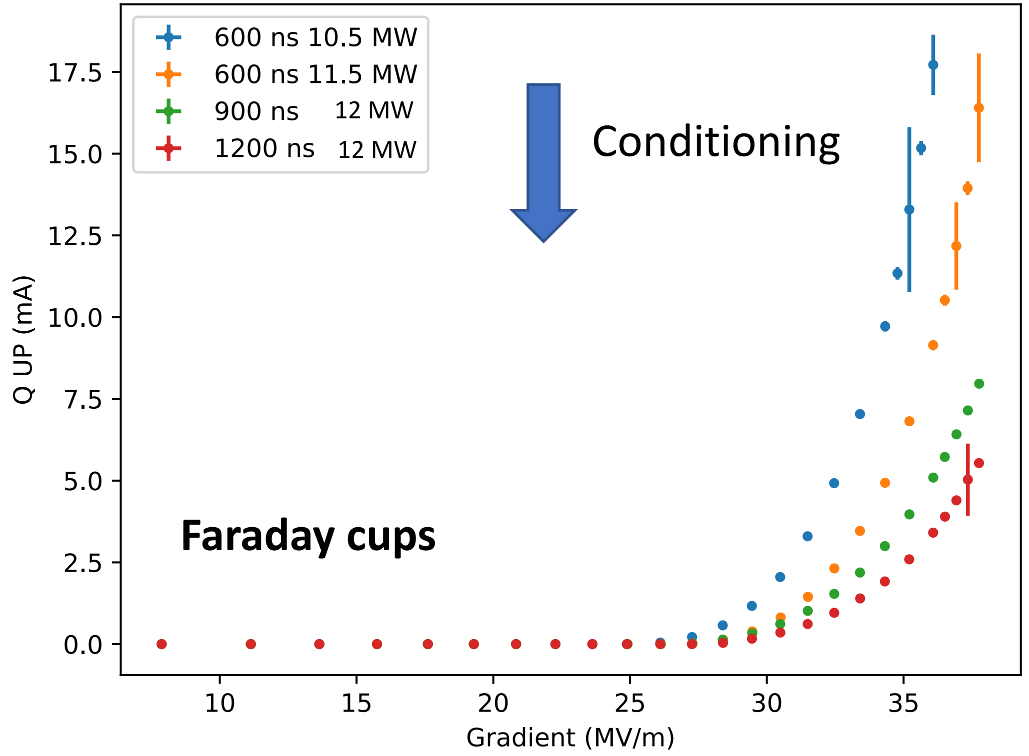


Conditioning summary II

- Dark current and radiation scans as a function of the gradient at different moments in the conditioning.
- Dark current and field enhancement factor calculations.

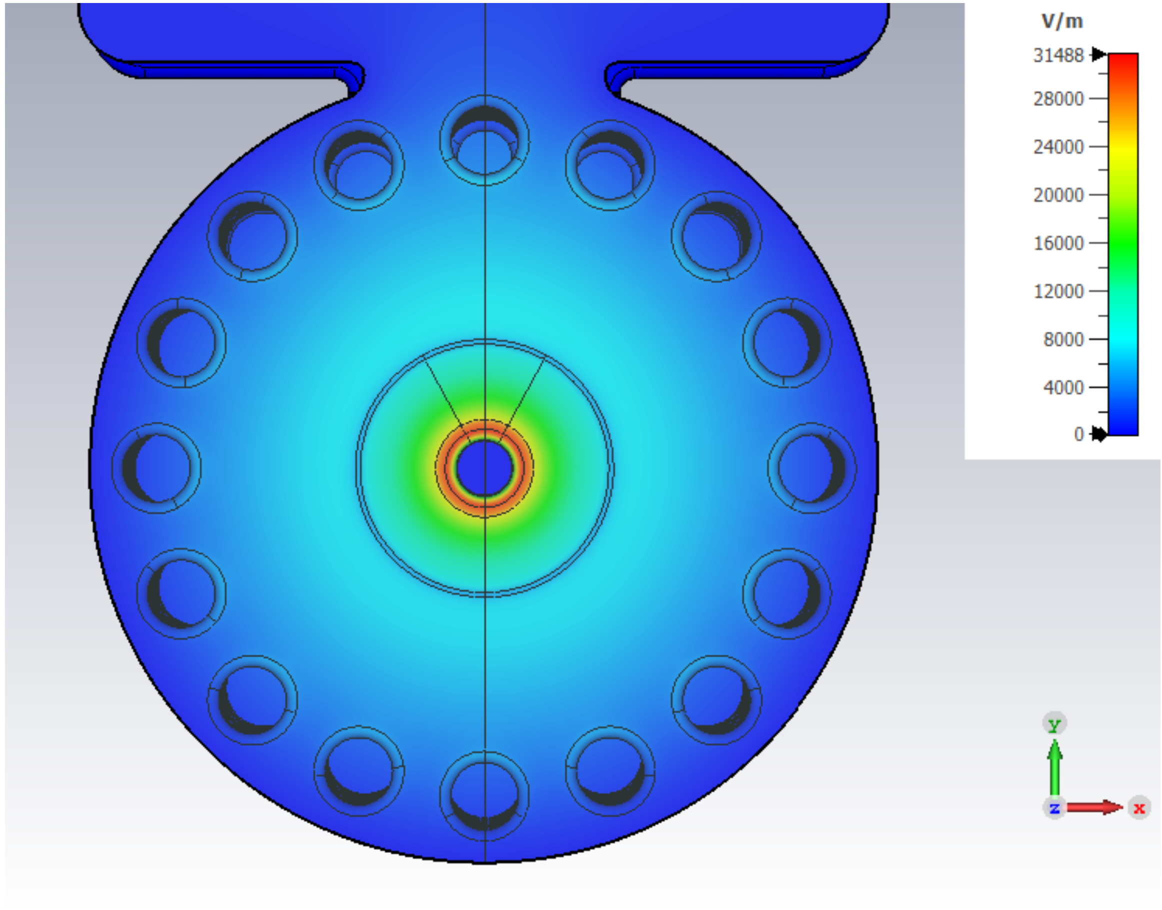


$$Q_{UP}\ (mA) = \frac{Q_{UP}\ (nC)}{flat\ top\ (\mu s)}$$

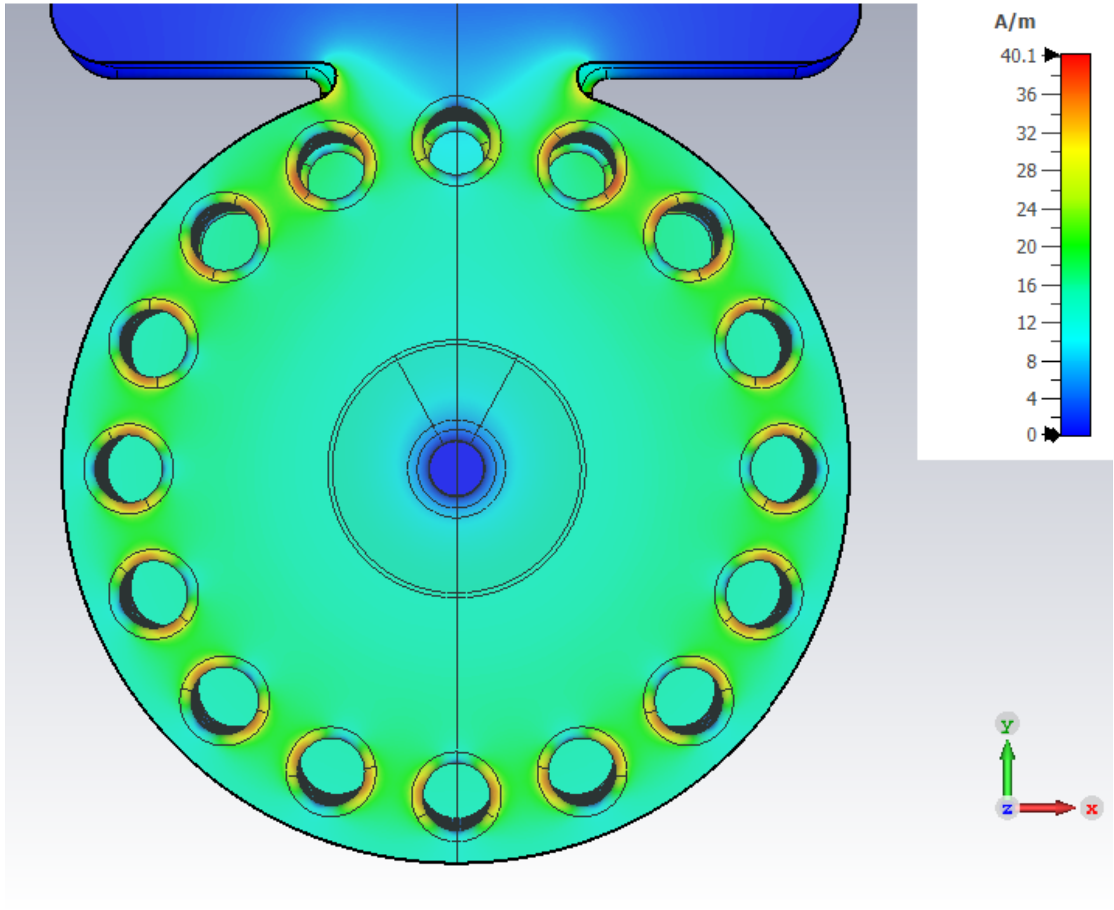


Electric and magnetic field

Electric field

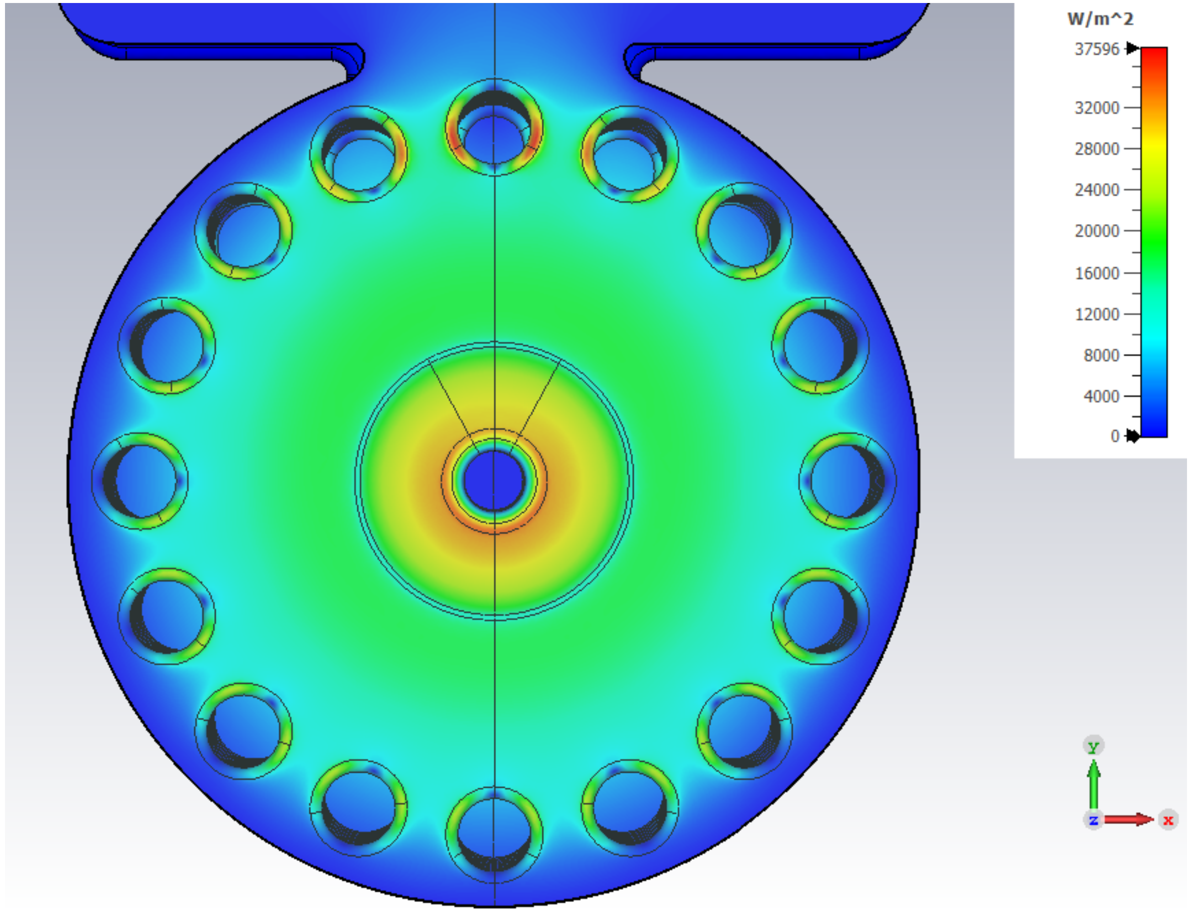


Magnetic field

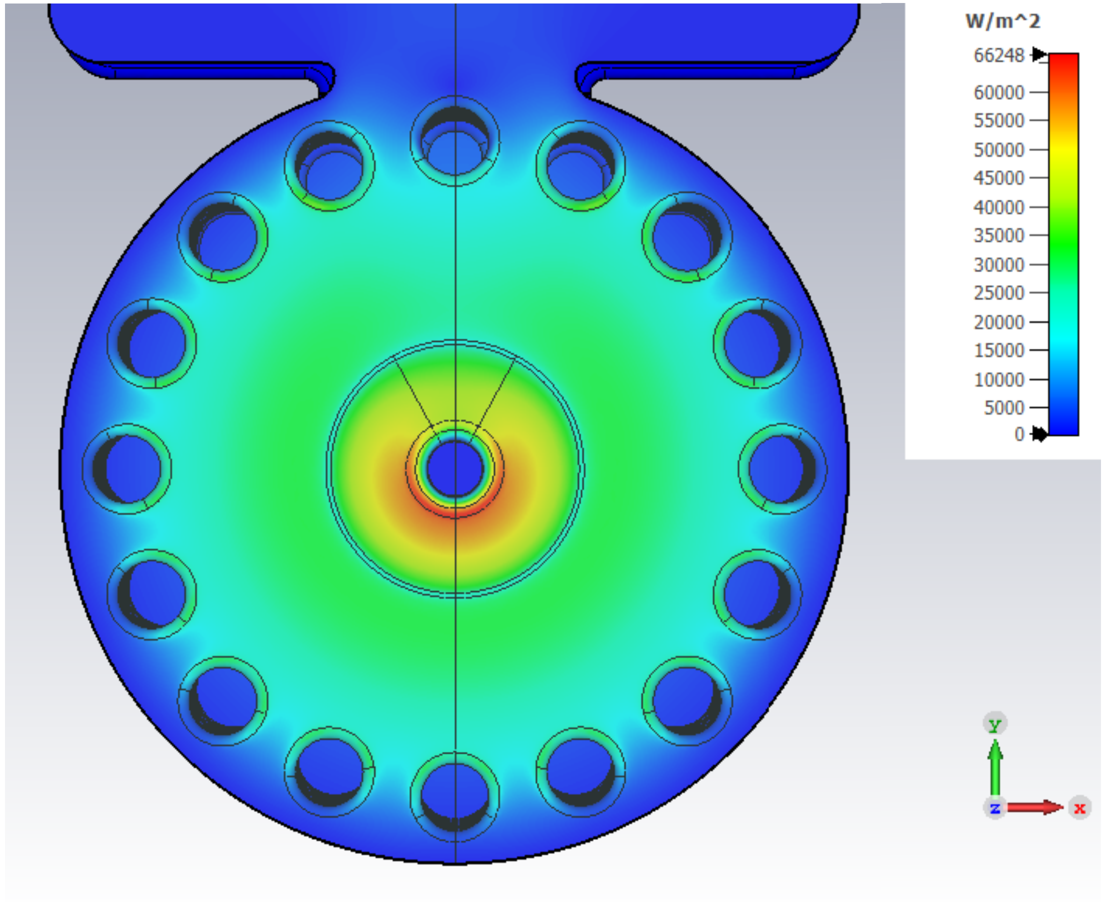


Modified Poynting vector

Design direction



Reversed



Proton dynamics

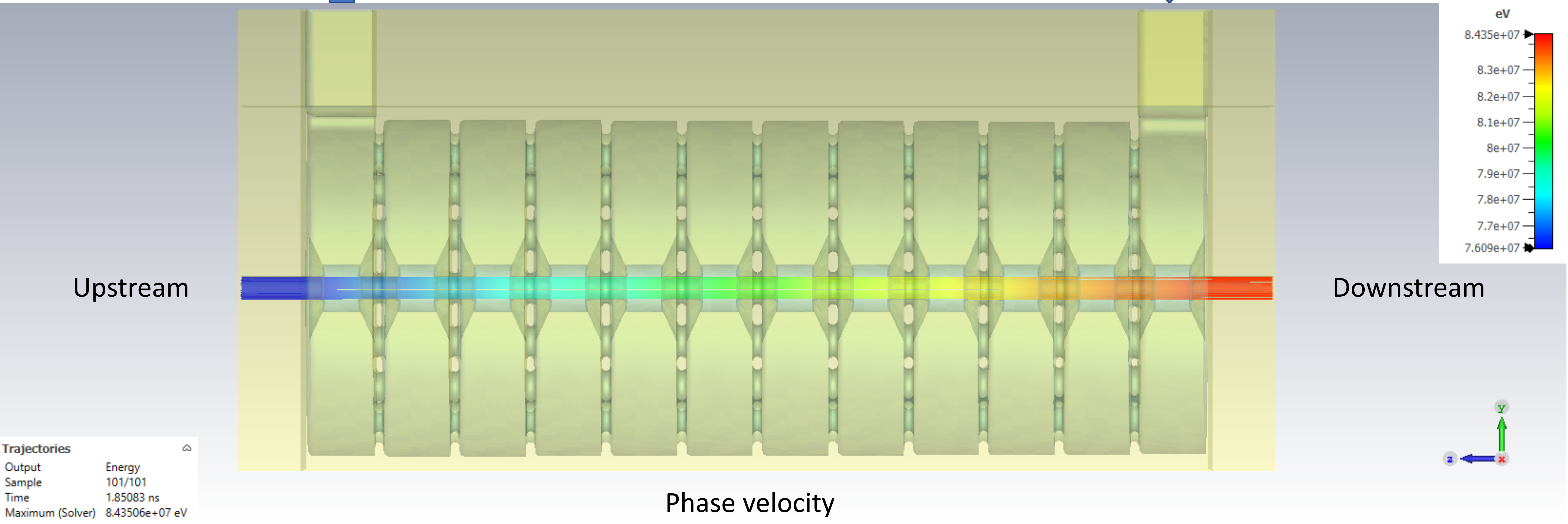
RF OUT

Group velocity

RF IN

RF Energy transmission velocity

Upstream



Downstream

Phase velocity

Beam velocity

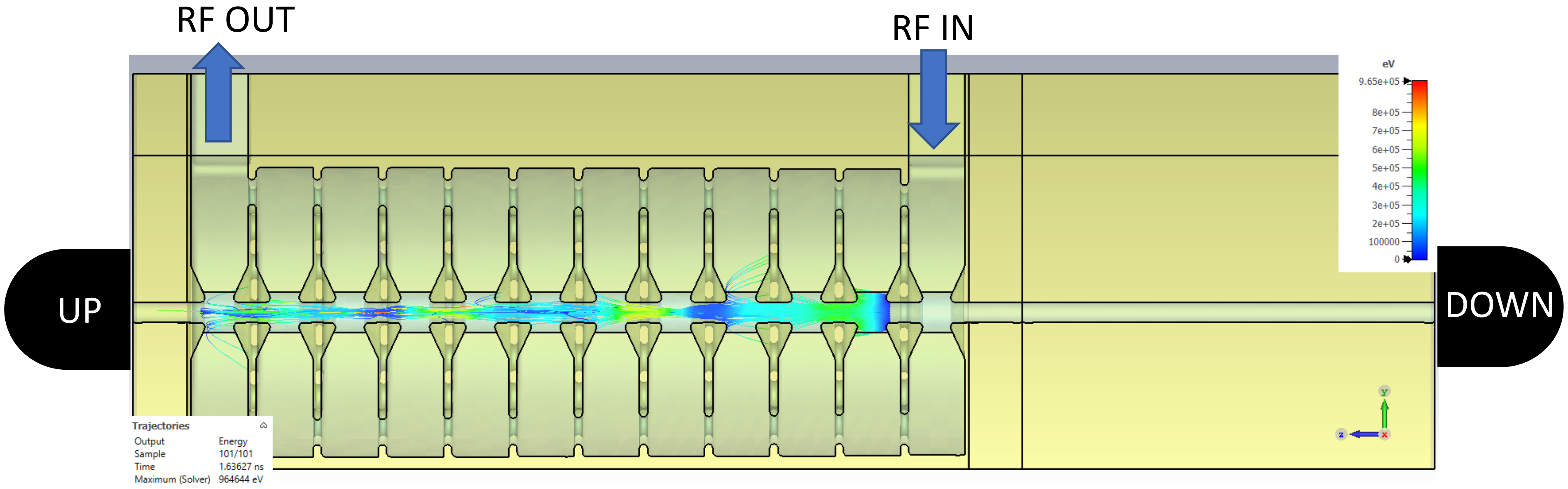
$v_0 = 0.38c$

$\gamma_0 = 1.0811$

$v_f = 0.3973c$

$\gamma_f = 1.0897$

Dark currents tracking with CST



Procedure:

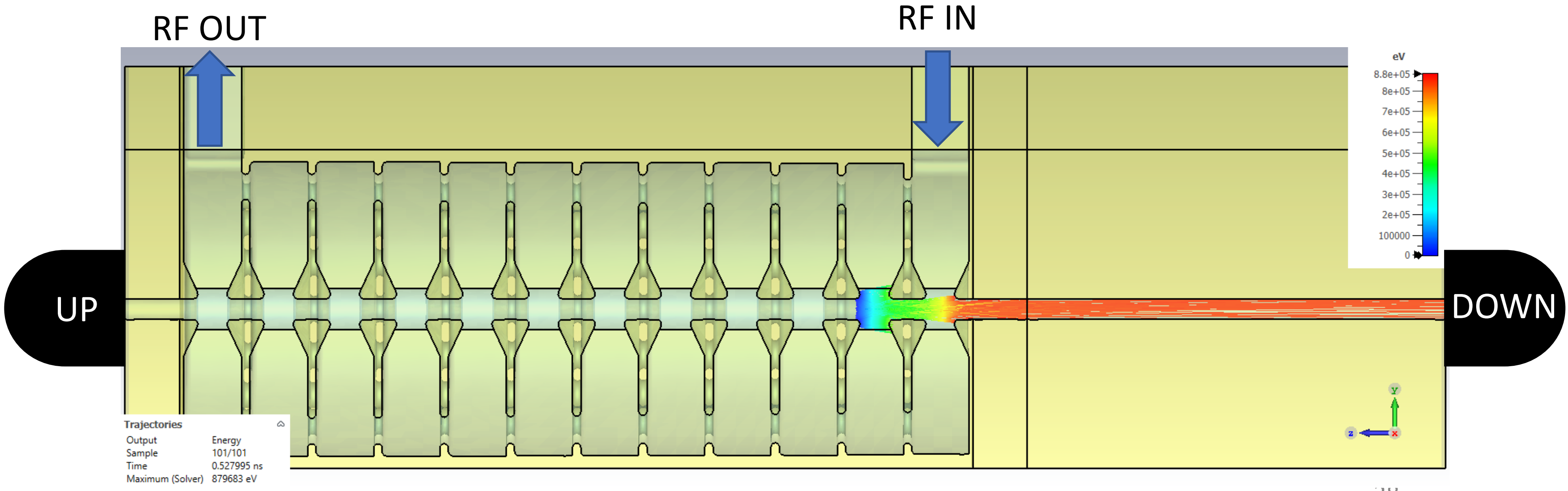
- ❑ Field emission from a certain cell.
  $$J = aE^2 e^{-b/E}$$
- ❑ Tracking of emitted electrons.

We can study:

- ❑ Ratio of electrons reaching FC
- ❑ Energy of electron in FC
- ❑ Energy deposited in walls

Scans:

- ❑ Emission cell
- ❑ RF power



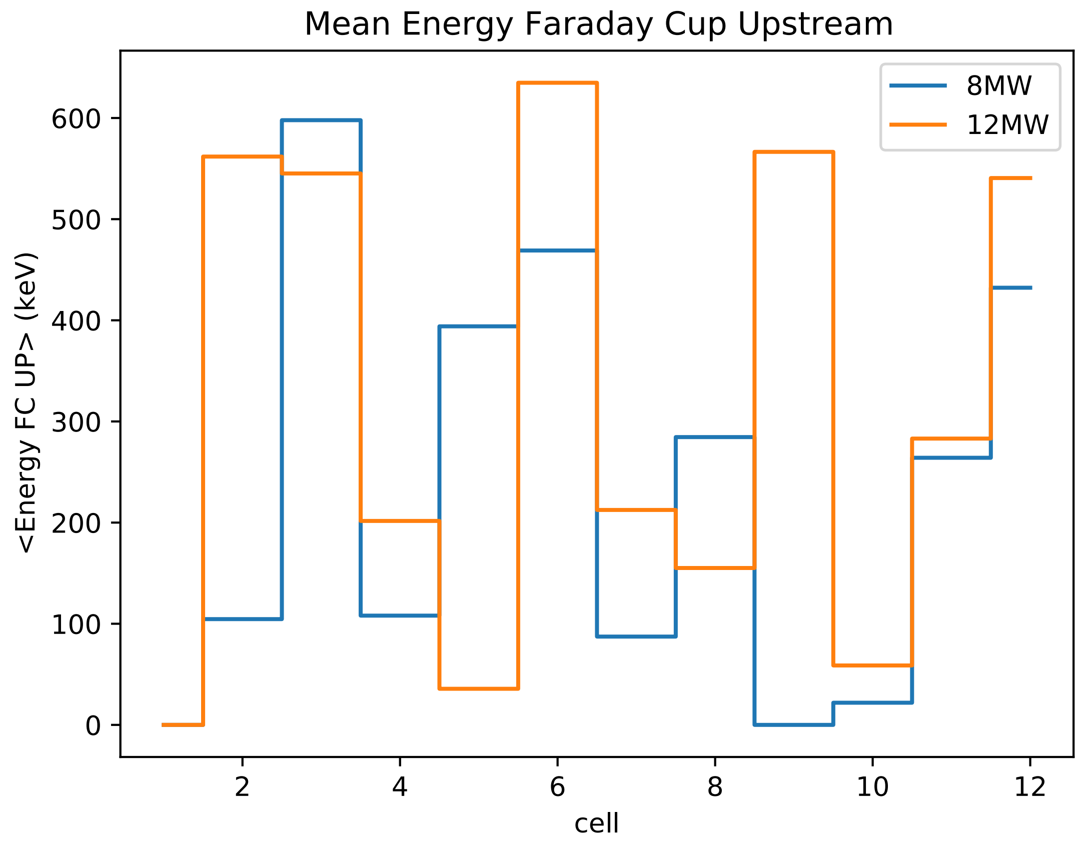
Mean Energy of electrons collected by Faraday Cups

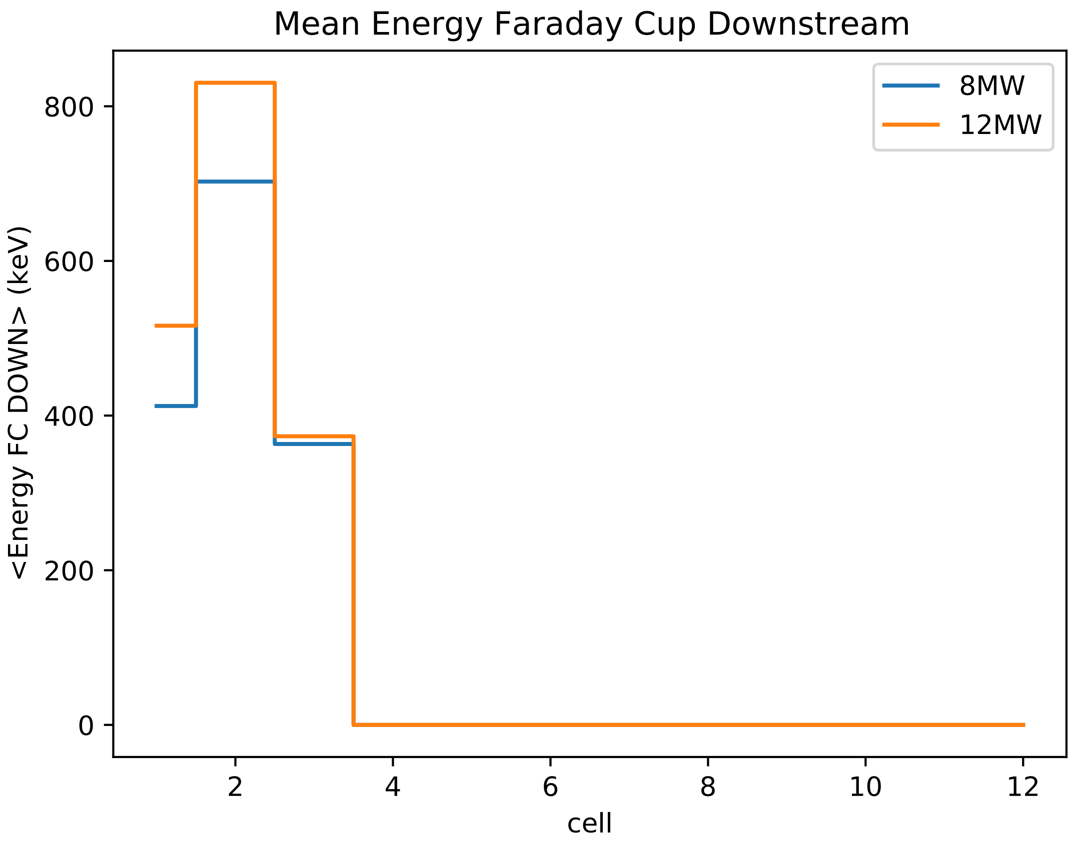
$$< E_{cell}^{FC} >= \frac{\sum_i w_i E_{cell_i}}{\sum_i wi}$$

i: macroparticles reaching FC emitted from cell i

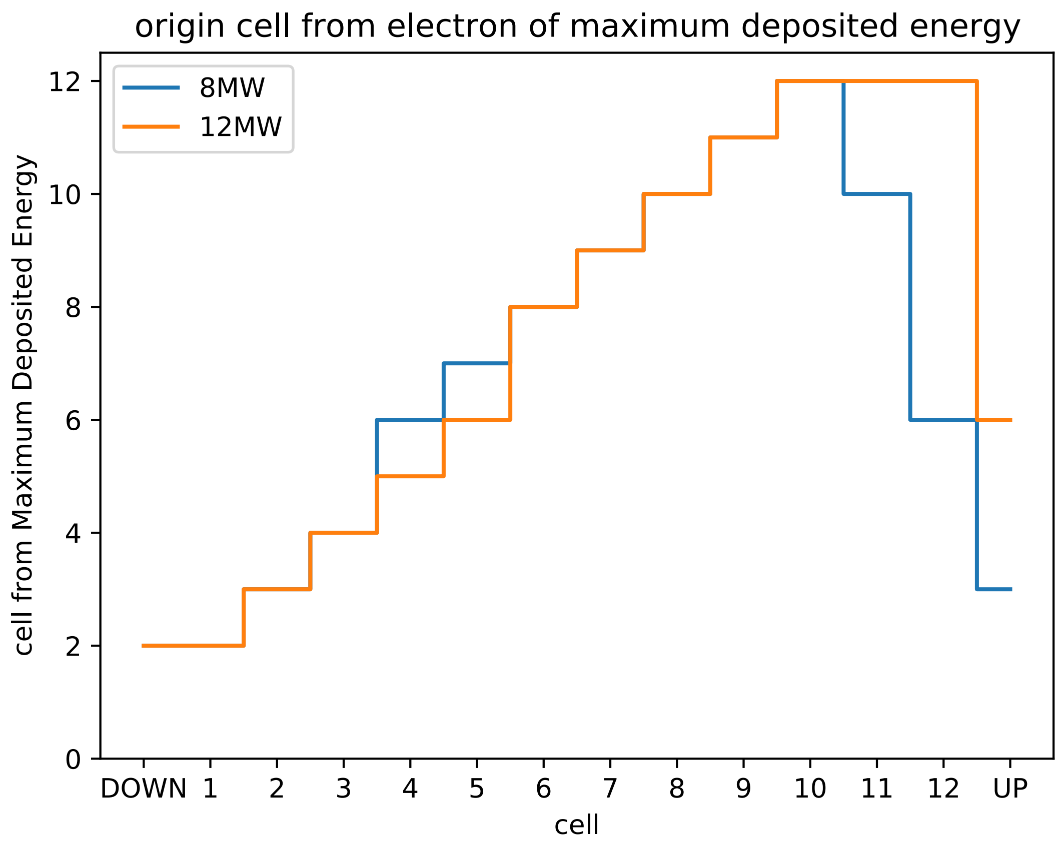
$w_i = Q_i$: macroparticle charge

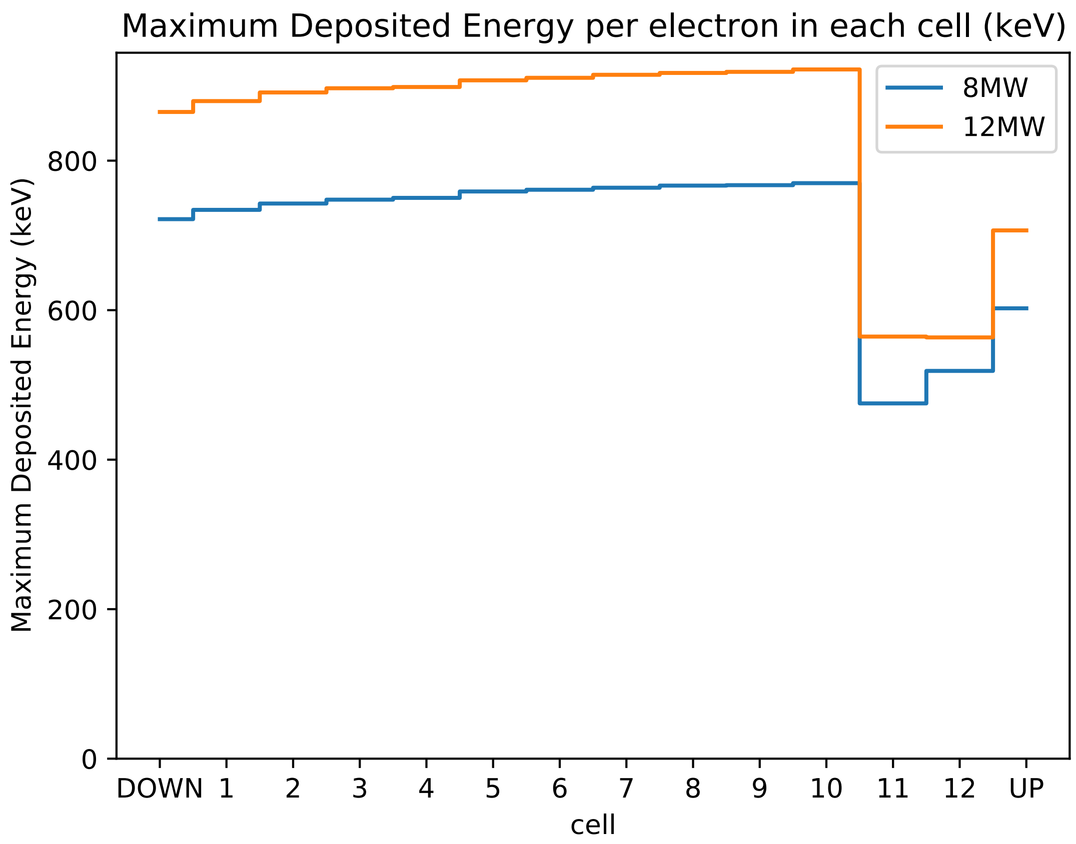
E_{cell_i}: macroparticle energy





Maximum energy of electrons colliding inside the cavity

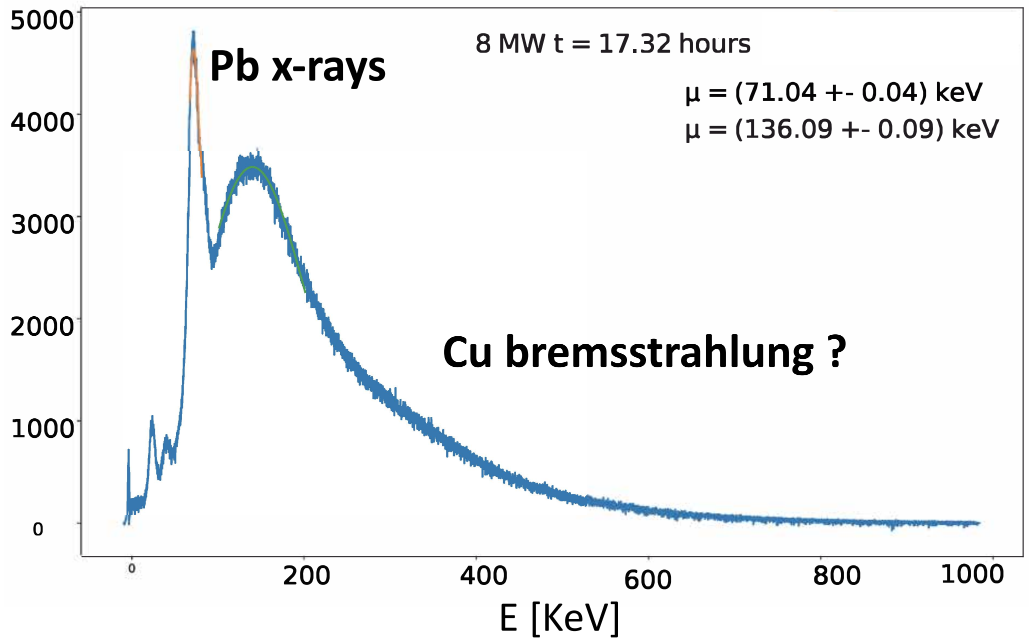


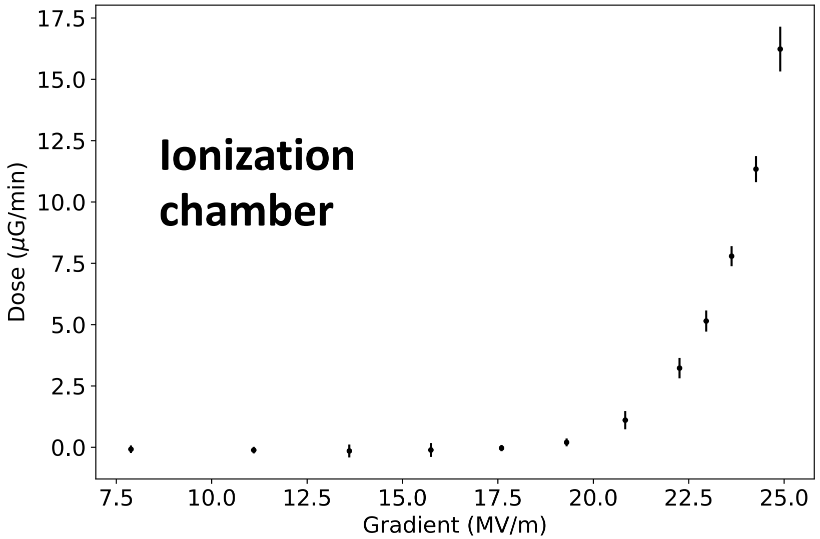


Dark current dynamics studies II

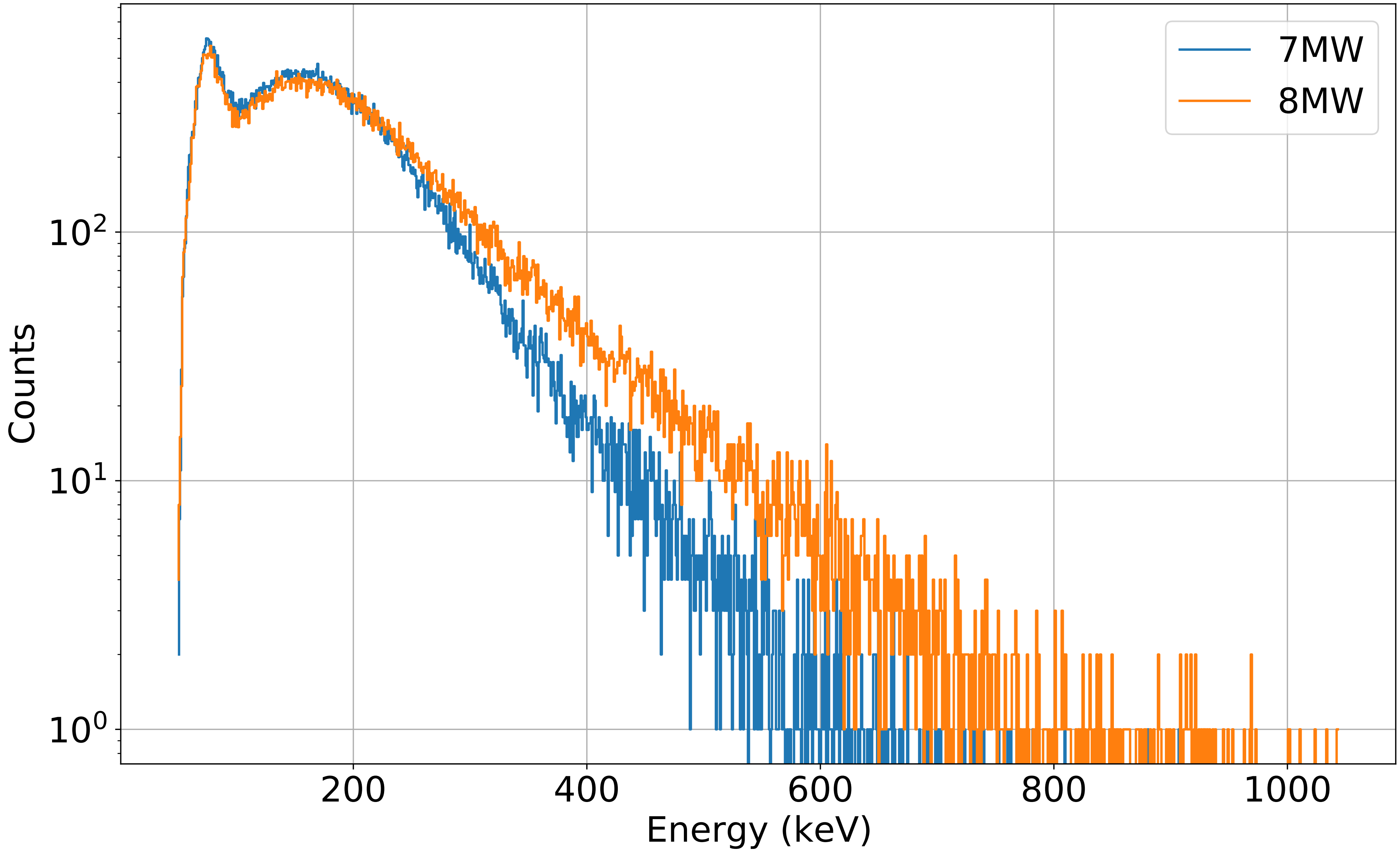
Measurements to "validate" the EM model and estimate the impact of the radiation produced:

- ❑ Electrons collected by Faraday cups.
- ❑ Setting-up scintillator detectors for energy spectrum of photons measured outside of the RF cavity.
  - ○ Preliminary measurements made with NaI.
  - ○ New set-up with smaller crystal of CeBr3 and dedicated collimator.
- ❑ Dose measurements (Gy/min).
  - ○ Combine with measured energy spectrum and Geant4 simulations to estimate the flux of photons.

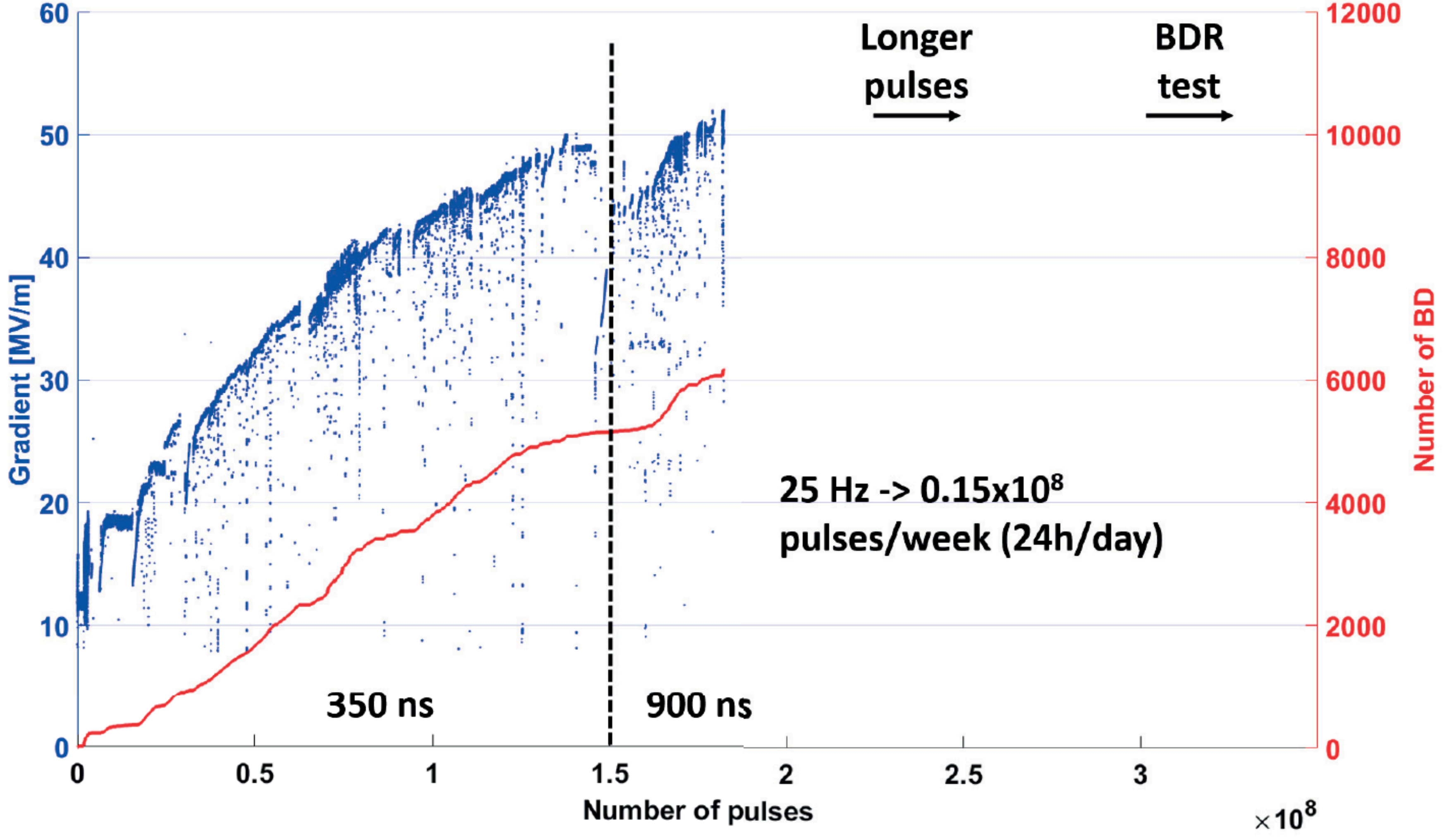




Bremsstrahlung



CERN BTW conditioning



Duty cycle

Stefano Benedetti thesis: 0.0075 % duty cycle for a 50 MV/m gradient

Benedetti, S. (2018). *High-gradient and high-efficiency linear accelerators for hadron therapy* (Doctoral dissertation, Ecole Polytechnique Fédérale de Lausanne).

G (MV/m)	MAX DUT(%)	Rate (Hz)	Flat top (ns)	DUT (%)
50	0.0075	75	1000	0.0075
39	0.0126	300	200	0.006
39	0.0126	300	500	0.015
39	0.0126	200	800	0.016