Numerical study of dark current dynamics and reflection and transmission phenomena in a High-Gradient Backward Travelling Wave accelerating cavity using the electromagnetic simulation software CST Studio

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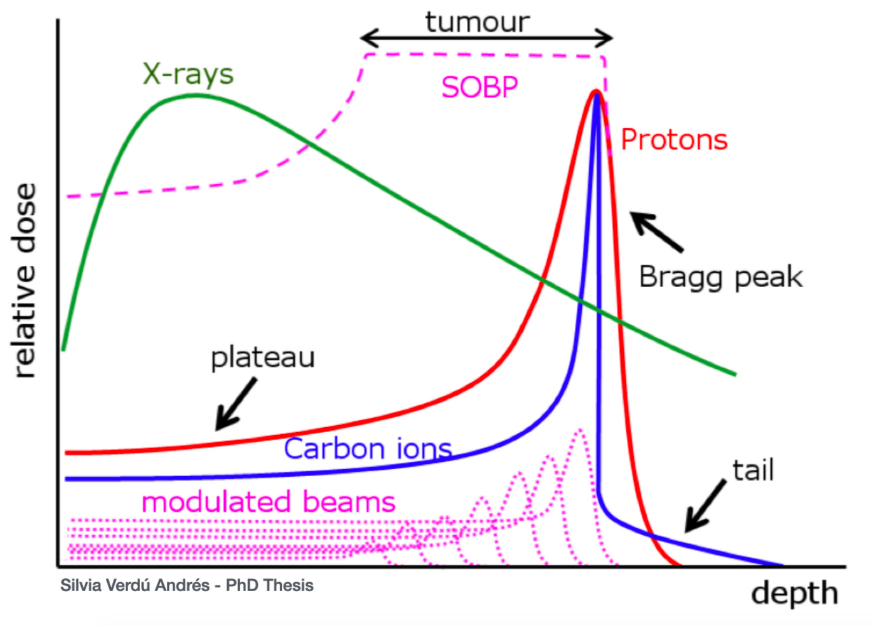
Outline

- ❑ Introduction
- ❑ Dark current dynamics in BTW S-Band cavity
- ❑ Electromagnetic studies and reflections in BTW S-Band cavity
- ❑ Conclusions

Hadrontherapy

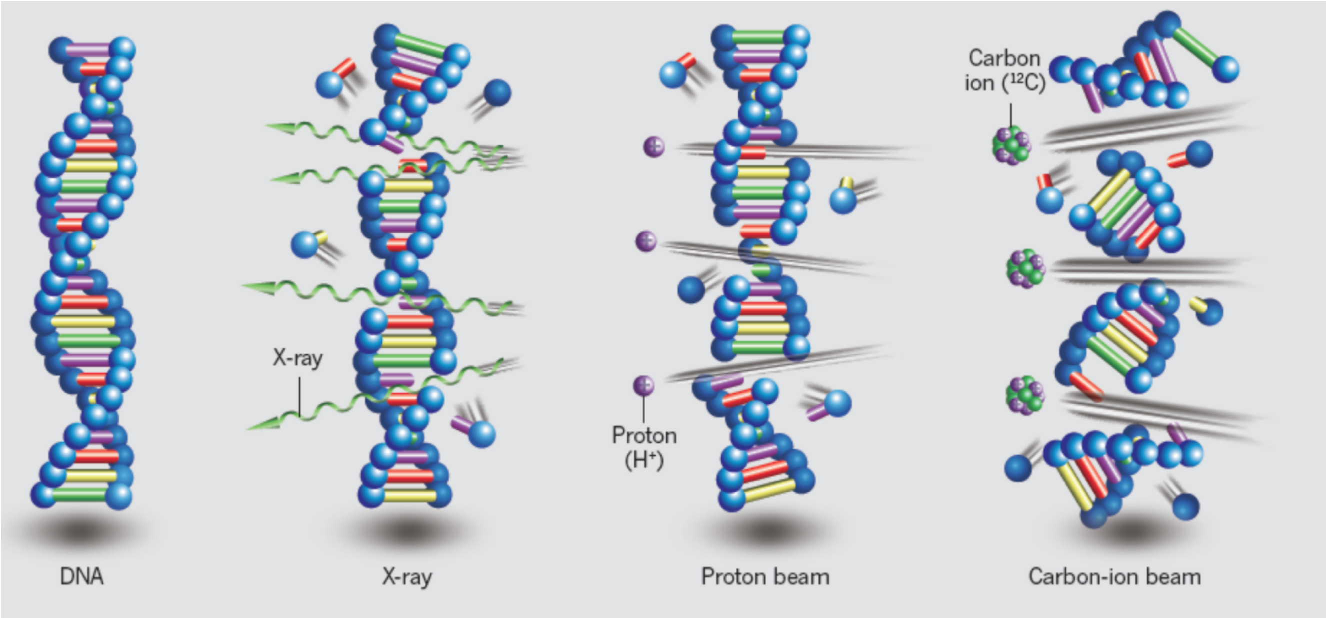


Accelerator	Beam always present during treatment?	Energy variation by electronic means?	Time needed for varying the energy
Cyclotron	Yes	No	80-100 ms (*)
Synchrotron	No	Yes	1-2 s
Linac	Yes	Yes	1-2 ms

- ❑ Relative Biological Effectiveness (RBE)
- ❑ Linear Energy Transfer (LET)

Physics challenges for linacs

- ❑ Compact accelerators



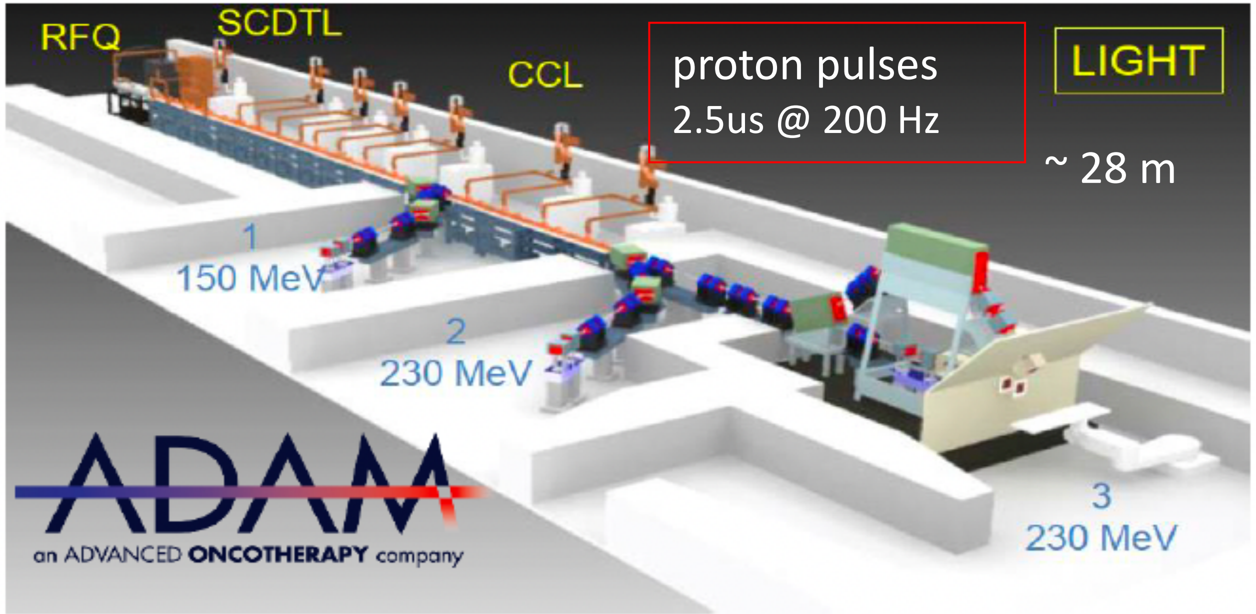
Marx, V. (2014, April 4). Sharp shooters. 508. Nature, p. 137

Linear Accelerators for Hadrontherapy

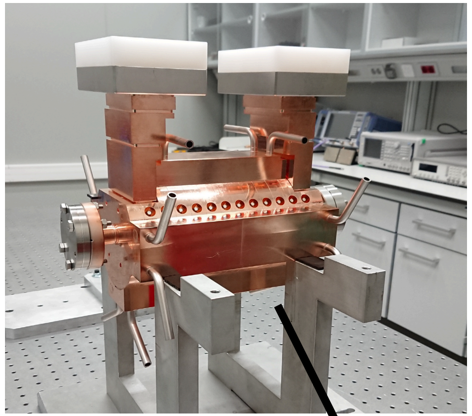
Normal Cavities

ADAM, spin-off of CERN and TERA foundation is developing a **proton linear accelerator** to be installed in a hospital in England

18-20 MV/m



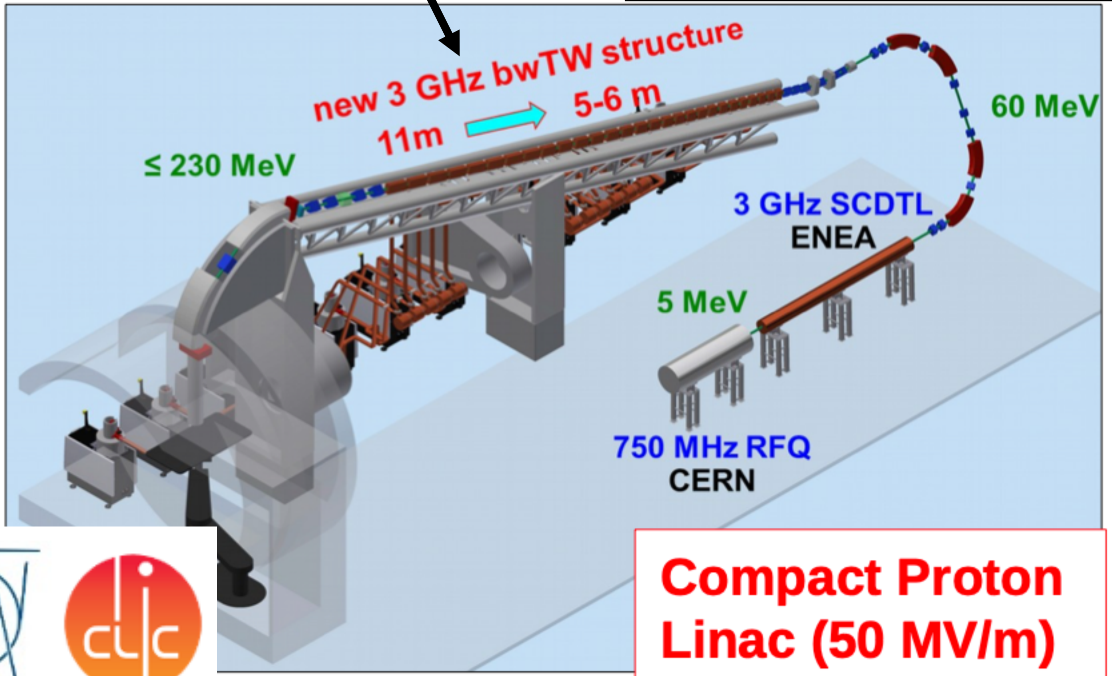
High-Gradient Cavities



Backward Travelling Wave (BTW) High Gradient cavity testing at IFIC

LINAC Conference 2014,
S. Benedetti et al.
RF DESIGN OF A NOVEL BACKWARD TRAVELLING WAVE LINAC FOR PROTON THERAPY

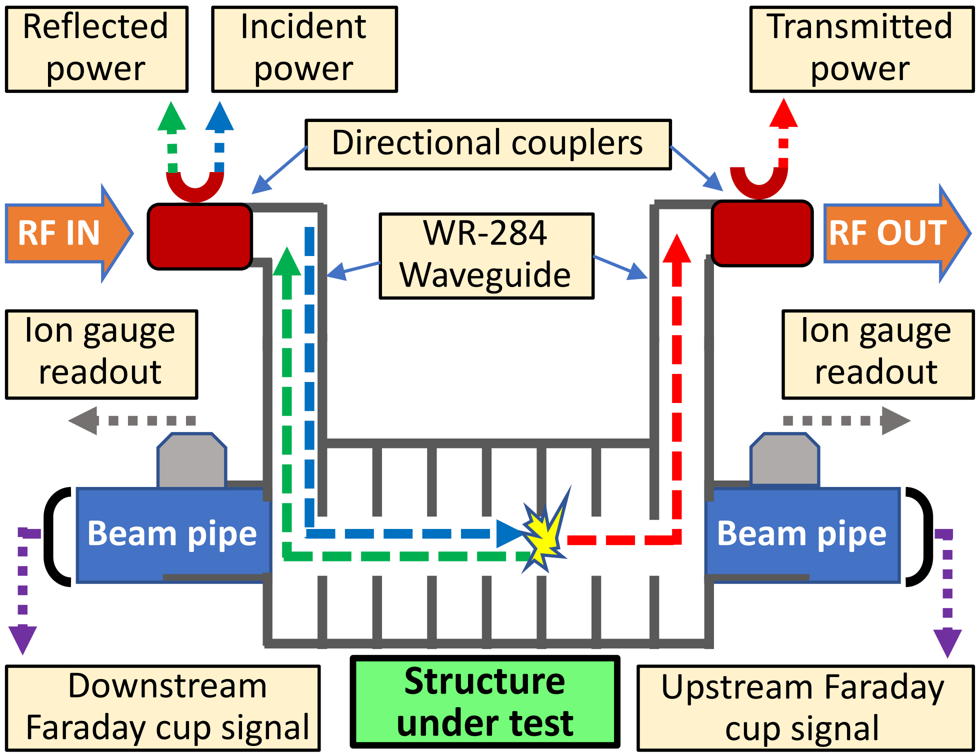
50 MV/m

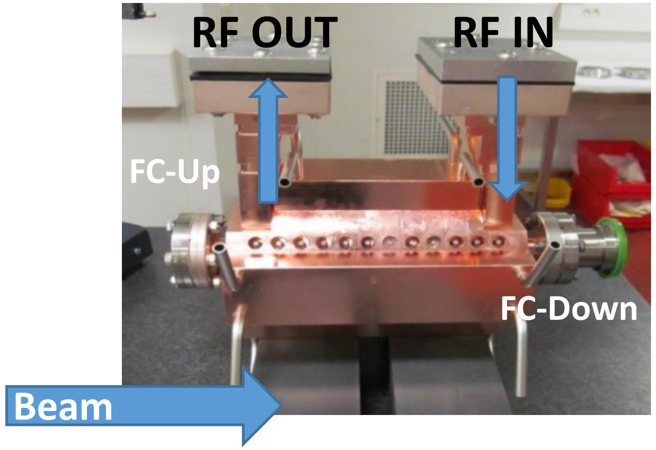


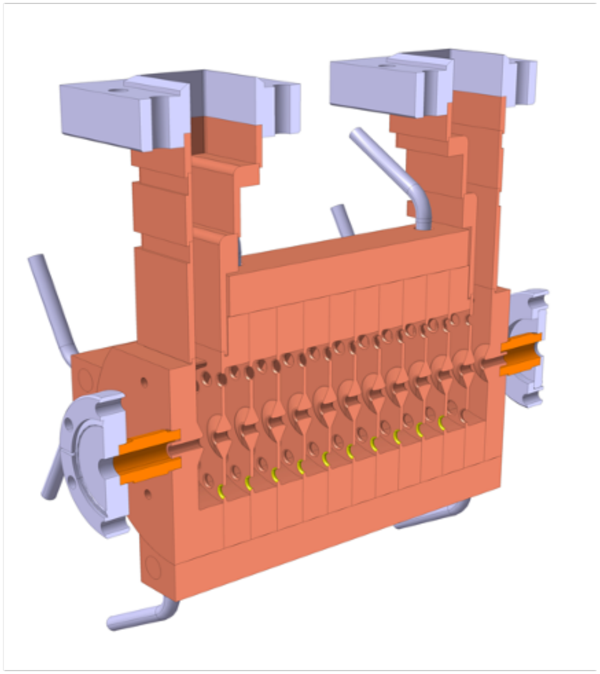
Compact Proton Linac (50 MV/m)

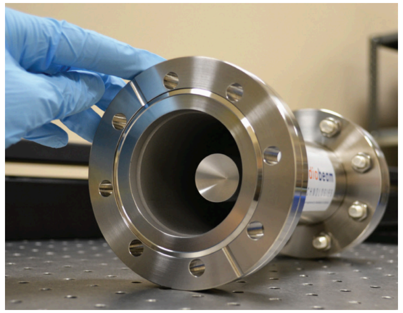
The CERN S-band BTW structure

- **CERN designed** two **S-band Backwards Travelling Wave (BTW)** accelerating structures for low energy protons.
  - **S-Band**: 2.9985 GHz at 32°C
  - **Backwards**: Phase velocity β = 0.38 (proton velocity) opposite direction to group velocity.
  - **Travelling Wave**: Group velocity 0.39/0.21 %c
  - 12 cells with Δϕ=150°
  - Structure length: 189.9 mm

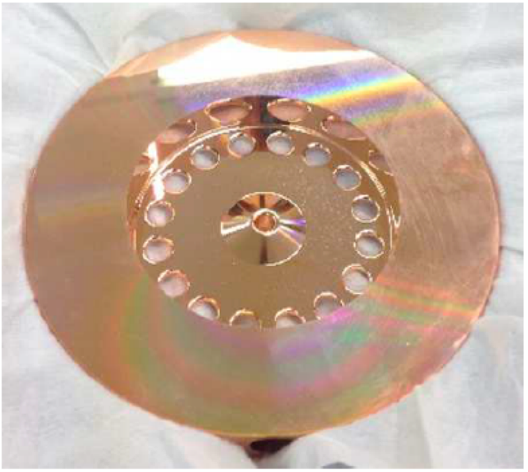








Faraday Cup (FC): Particle beam electric current measurement



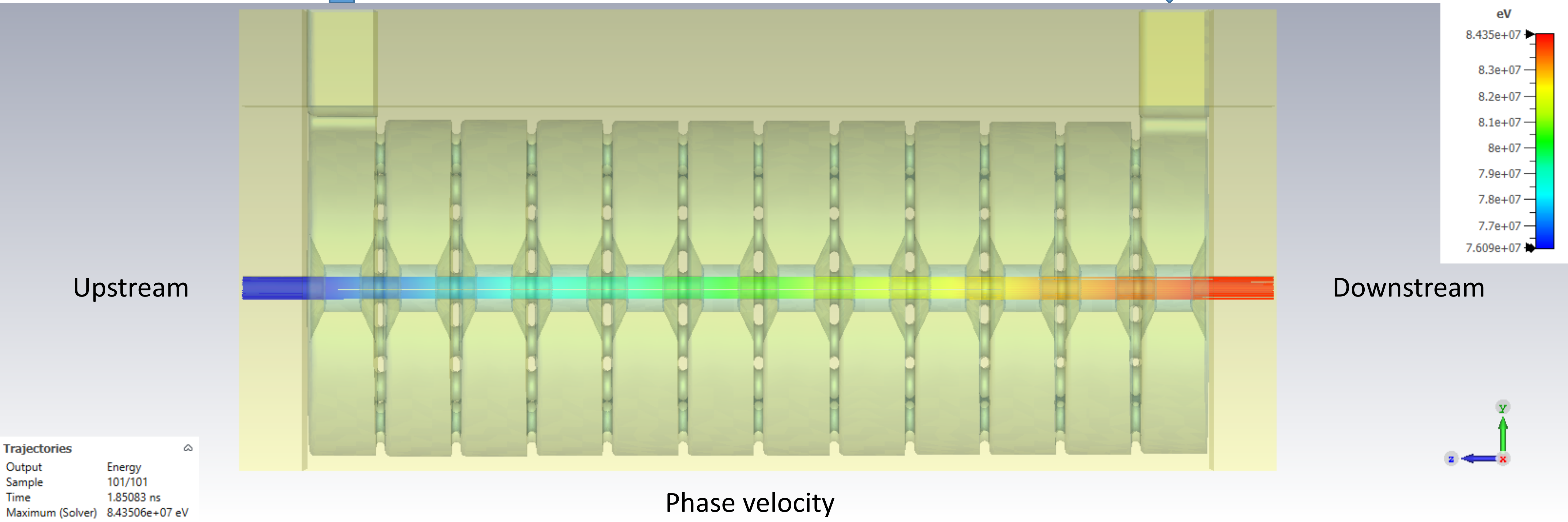
Proton dynamics

RF OUT

Group velocity

RF IN

RF Energy transmission velocity



Phase velocity

Beam velocity

$v_0 = 0.38c$

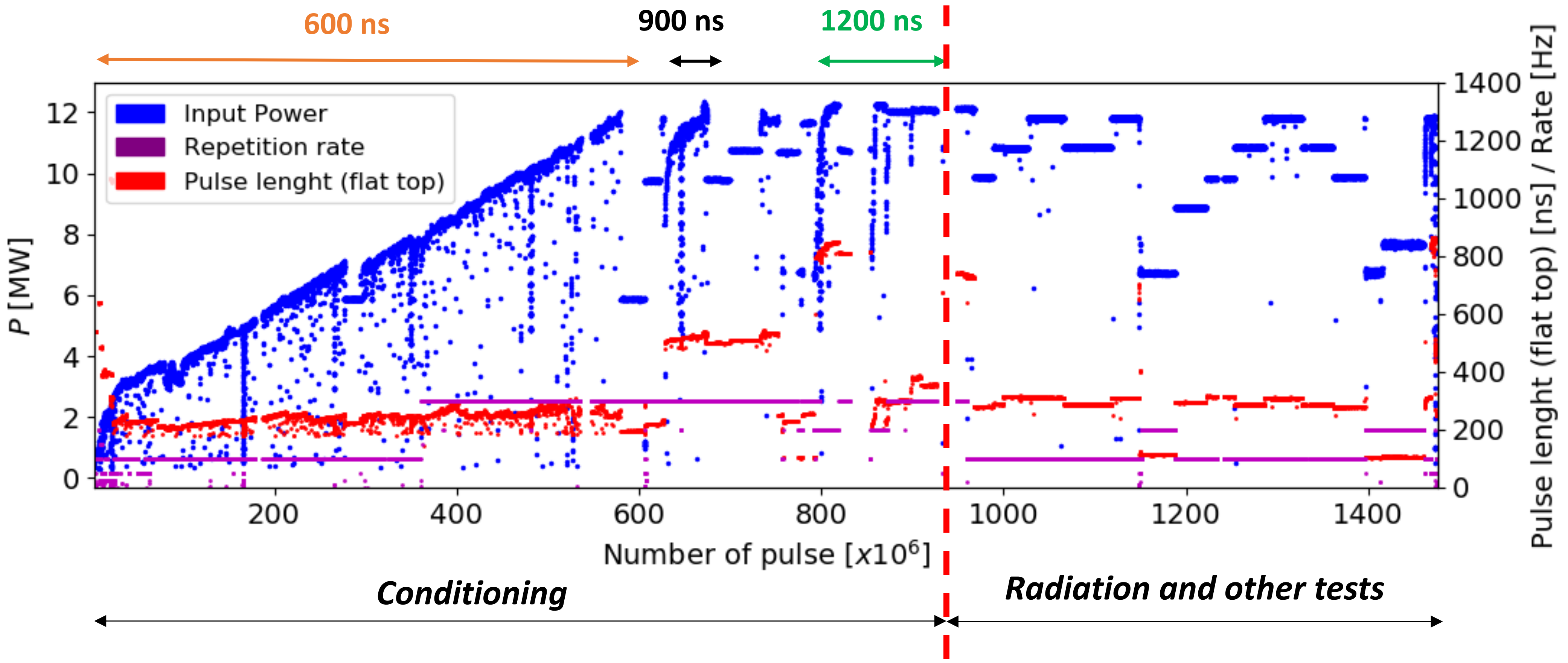
$\gamma_0 = 1.0811$

$v_f = 0.3973c$

$\gamma_f = 1.0897$

Operation summary

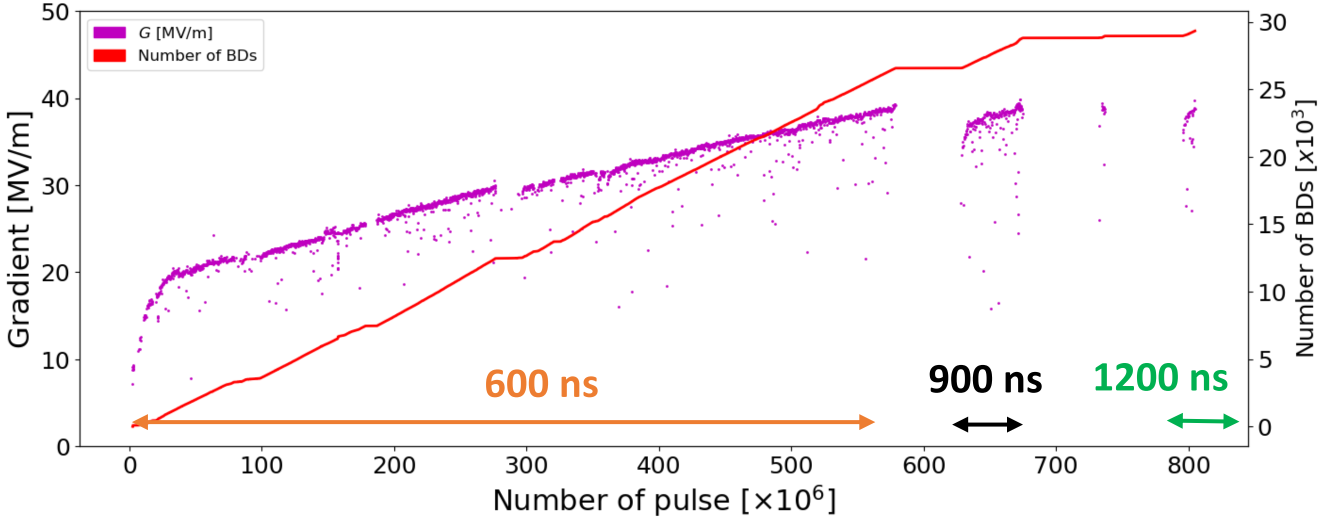
- **Vacuum:** Below ~1x10^{-8} mbar
- **Temp. structure**: 22-23°C (2.9990 GHz)
- **Maximum power 12 MW** in ~570M pulses (short pulse length).
- **Pulse length:**
  - R:100 ns + FT: 200 ns + F:300 ns
  - R:100 ns + FT: 500 ns + F:300 ns
  - R:100 ns + FT: 800 ns + F:300 ns



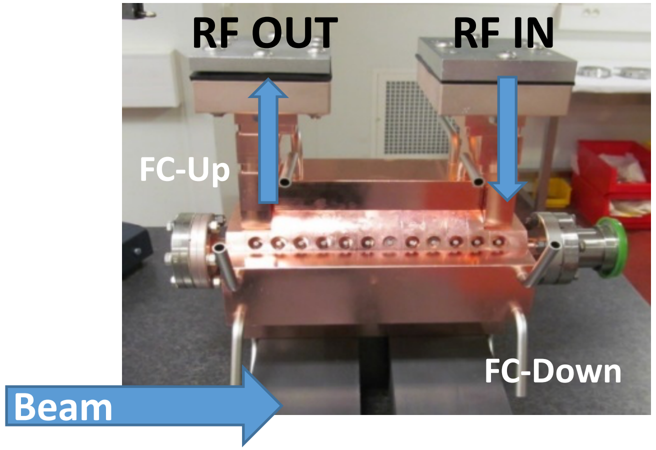
Conditioning summary

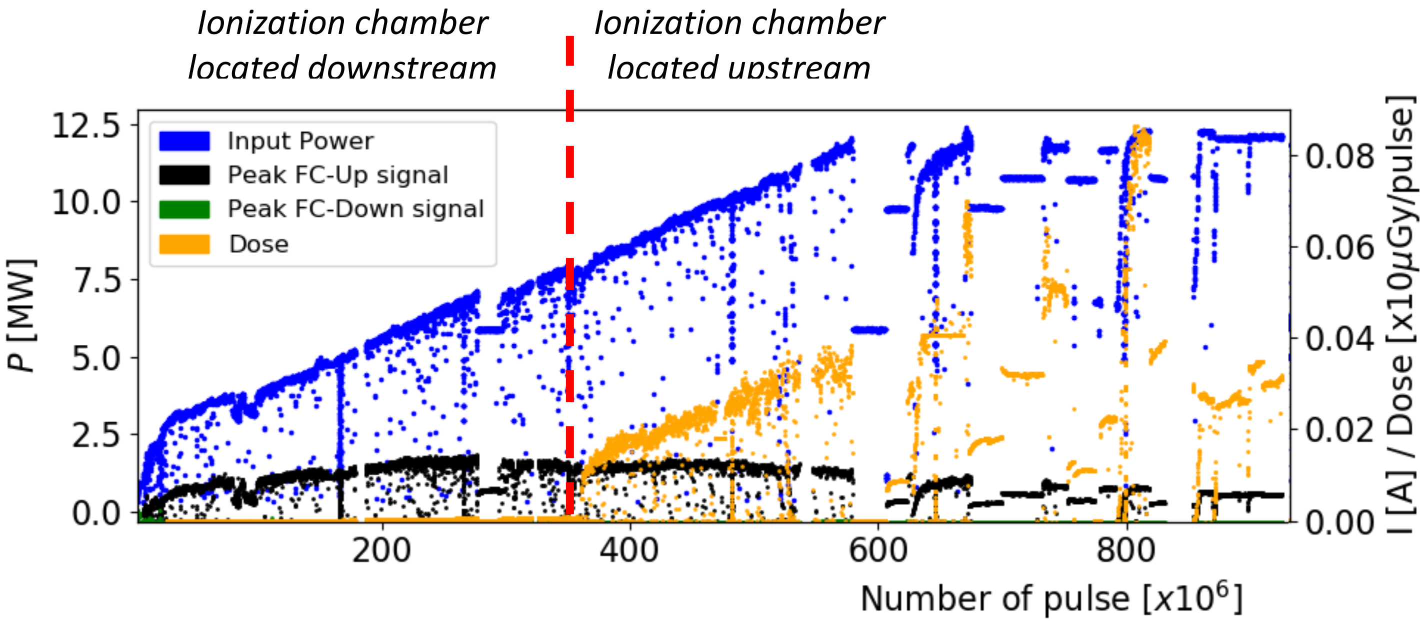
- ❑ With current set-up we reached an **accelerating gradient of ~39 MV/m**.

- ❑ **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.





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.***

$$\boxed{E = \beta E_0}$$

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

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

A, B: Constants FN model

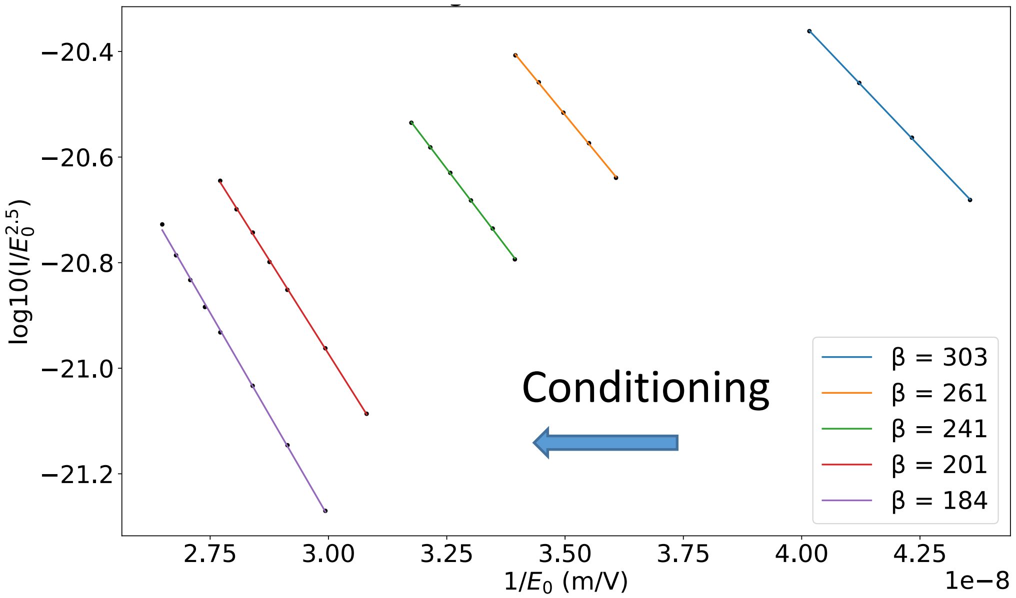
S: Emitters surface

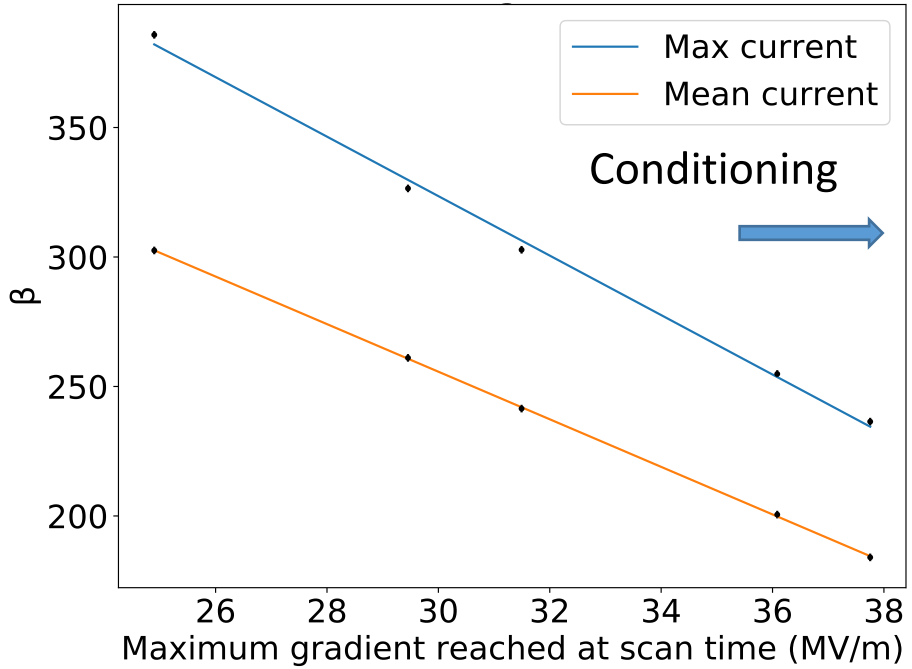
$\boldsymbol{\phi} = 4.65\ eV$ Copper work function

E : Surface electric field

$\boldsymbol{E_0}$: Acceleration gradient

$\boldsymbol{\beta}$: total enhancement factor



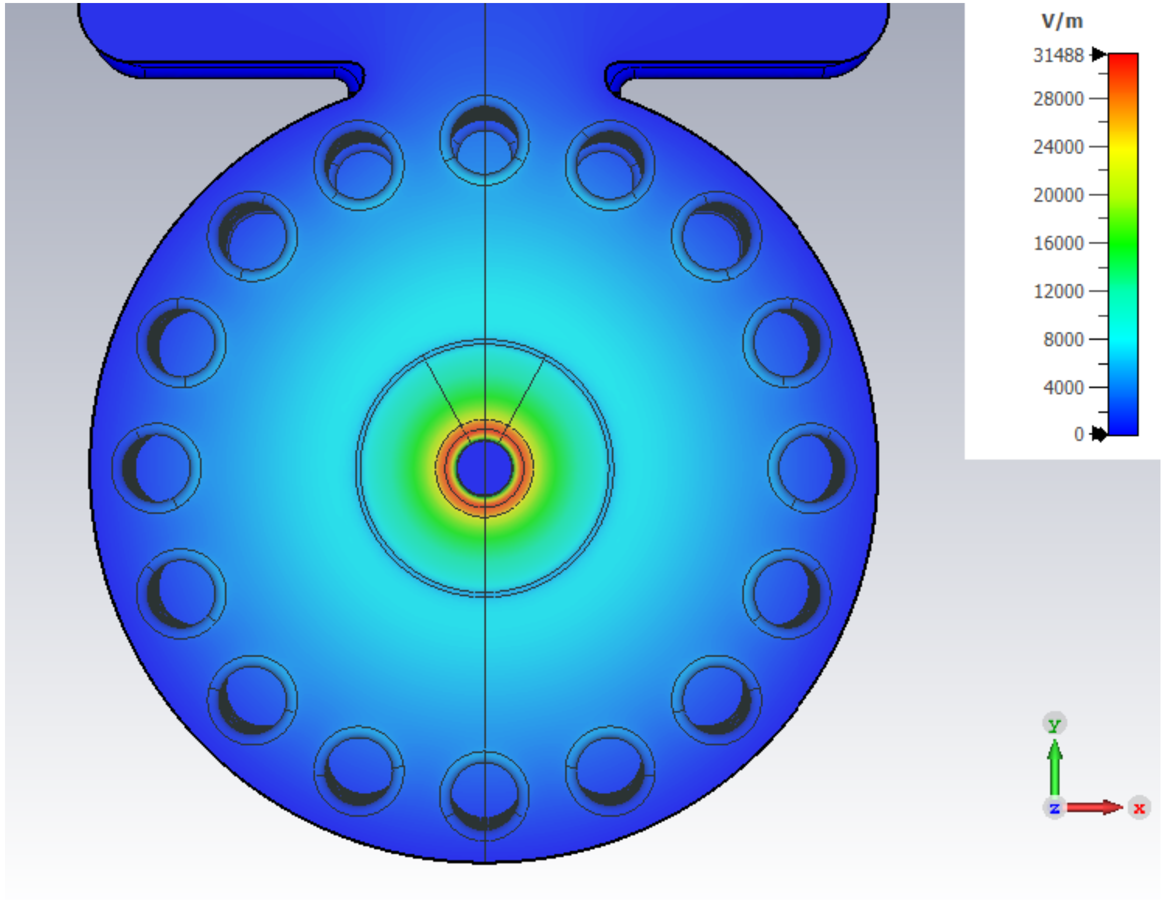


Electric and magnetic field

Electromagnetic fields can be numerically calculated using Frequency Domain Solver of CST Microwave package.

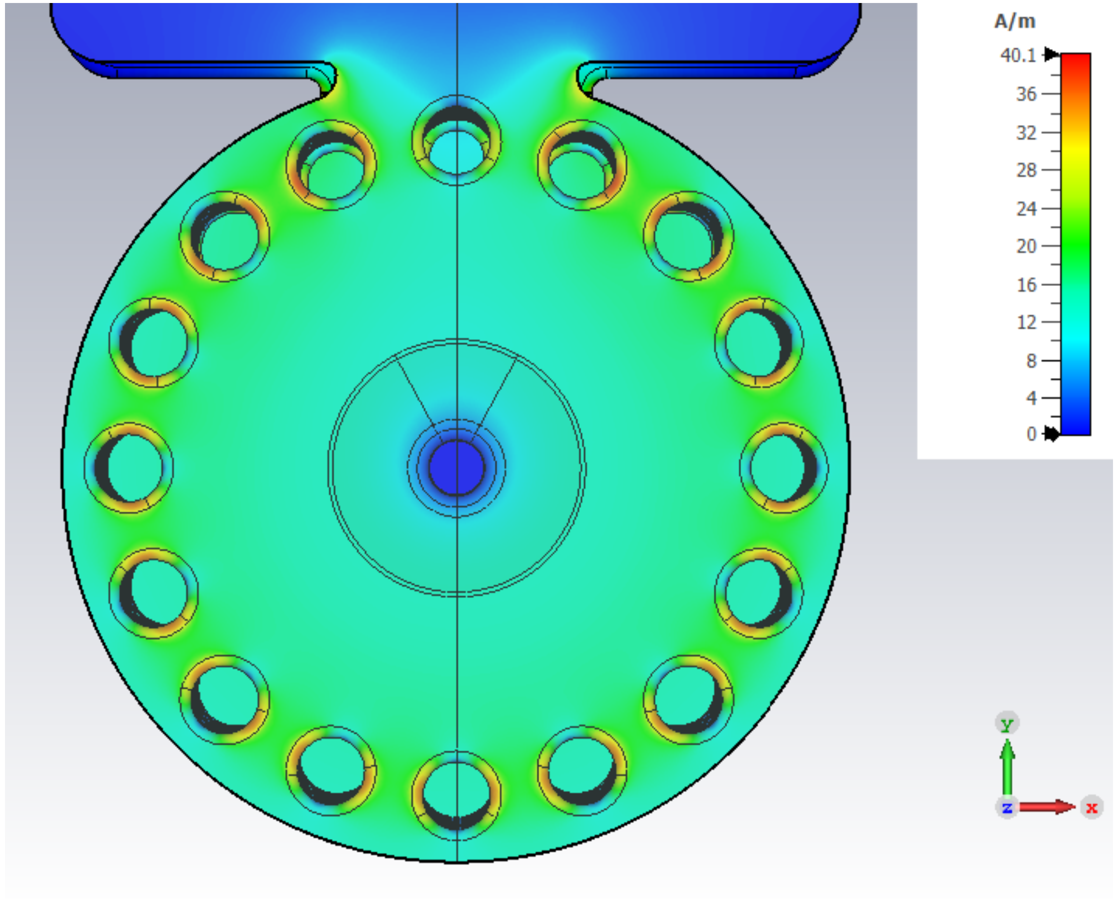
Electric field

Field emission



Magnetic field

Temperature increased

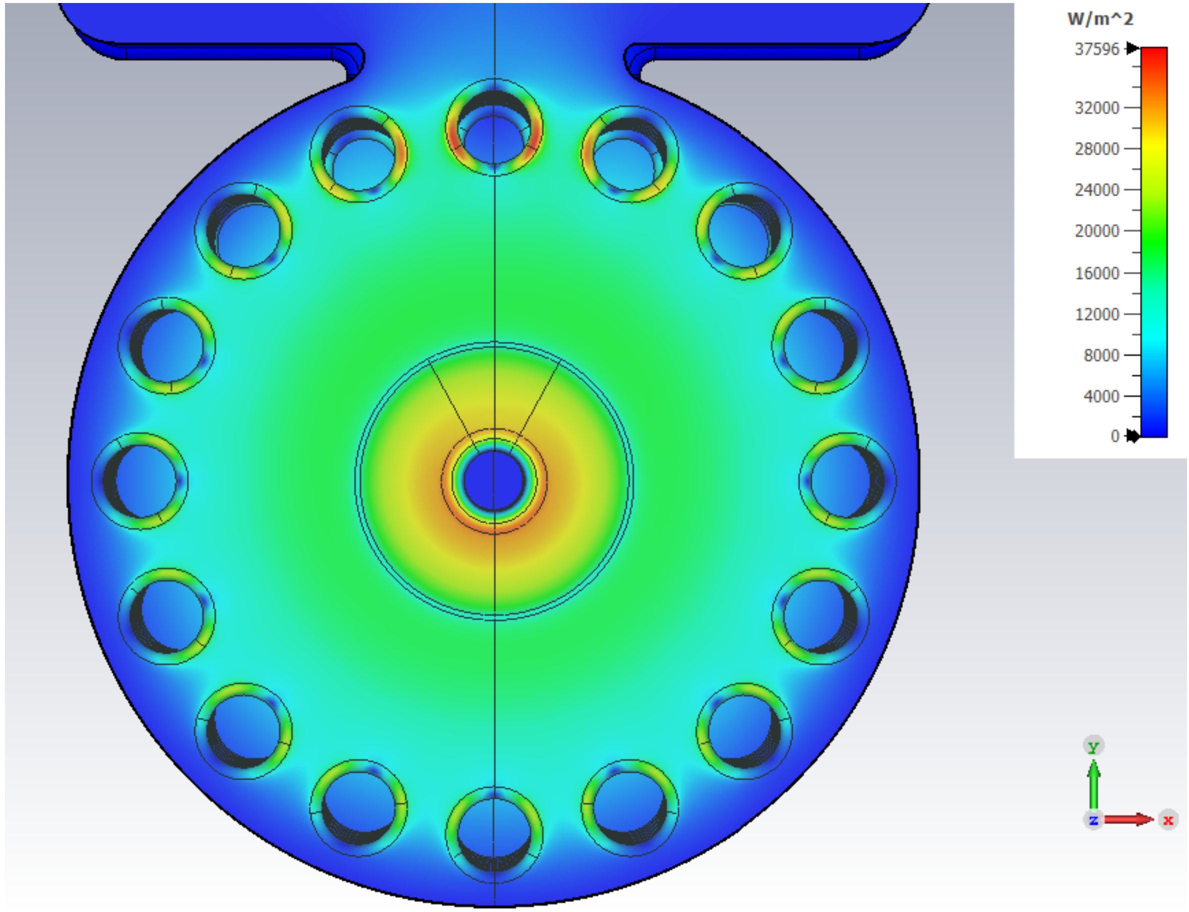


Modified Poynting vector

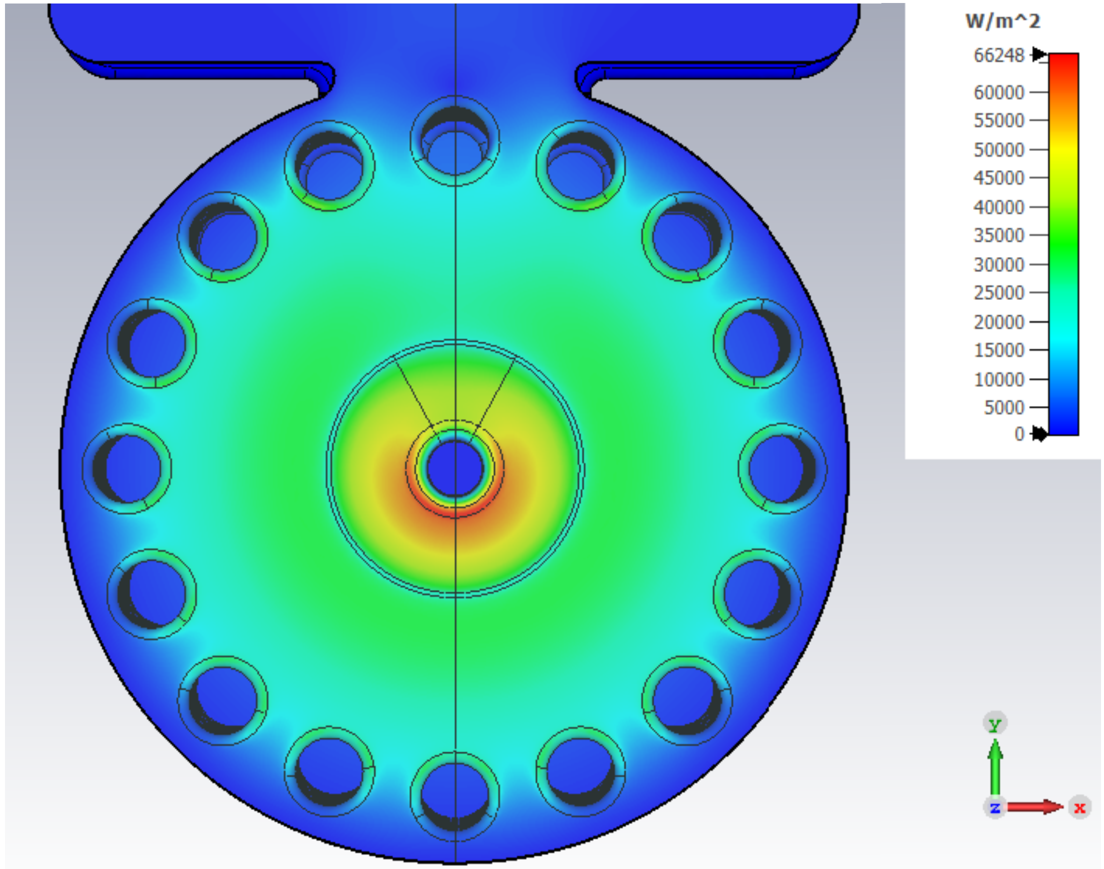
$$S_C = |Re(\boldsymbol{S})| + \frac{1}{6}|Im(\boldsymbol{S})|$$

$Re(\boldsymbol{S})$: Active power available for dark currents to exponentially increase.
$\mathrm{Im}(\boldsymbol{S})$: Reactive power available for dark currents to absorb.

Designed direction



Reversed



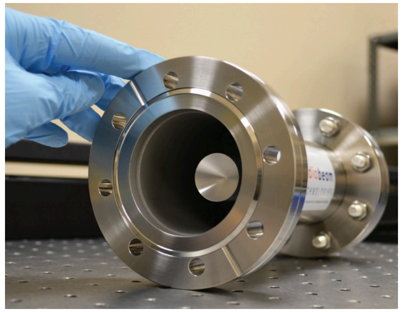
Dark current dynamics studies

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.
- ❑ Tracking of emitted electrons.



Faraday Cup (FC): Particle beam electric current measurement device

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

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

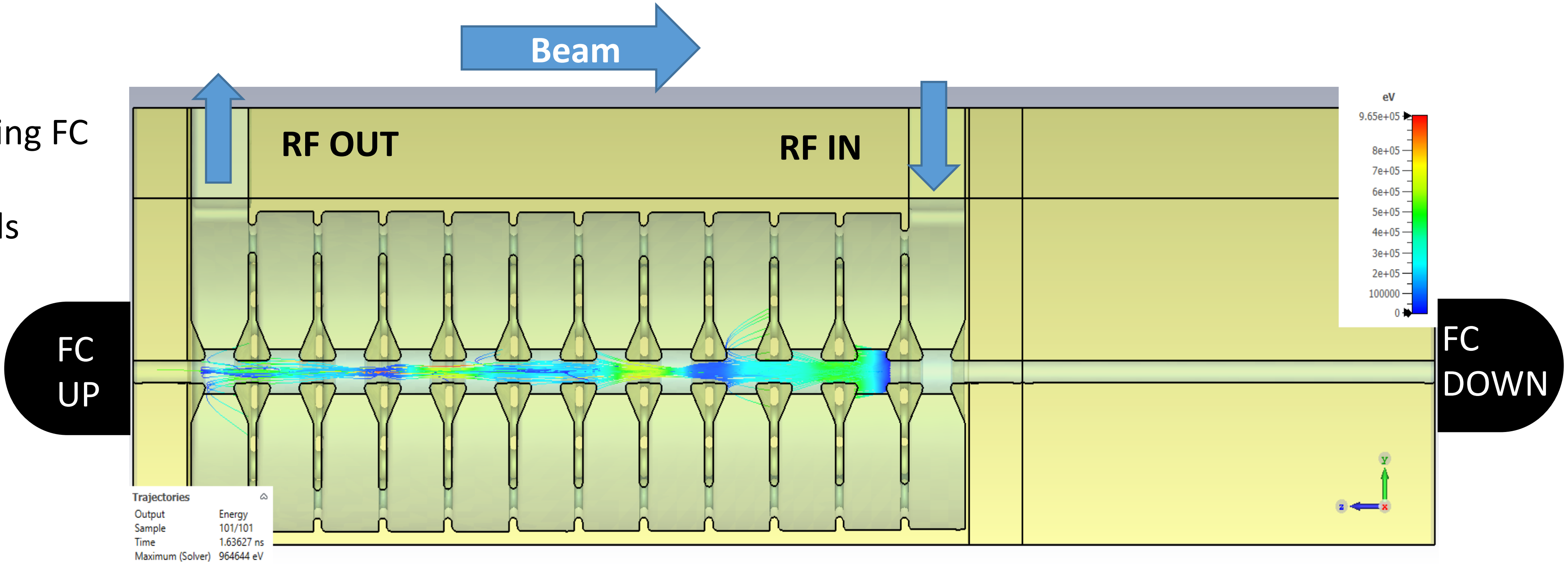
$\boldsymbol{E}$: Surface electric field
$\boldsymbol{E_0}$: Acceleration gradient
$\boldsymbol{\beta}$: Enhancement factor

Studies:

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

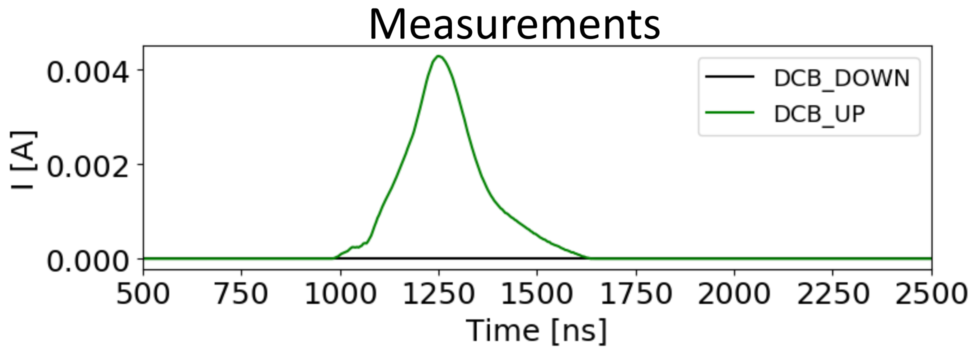
Scans:

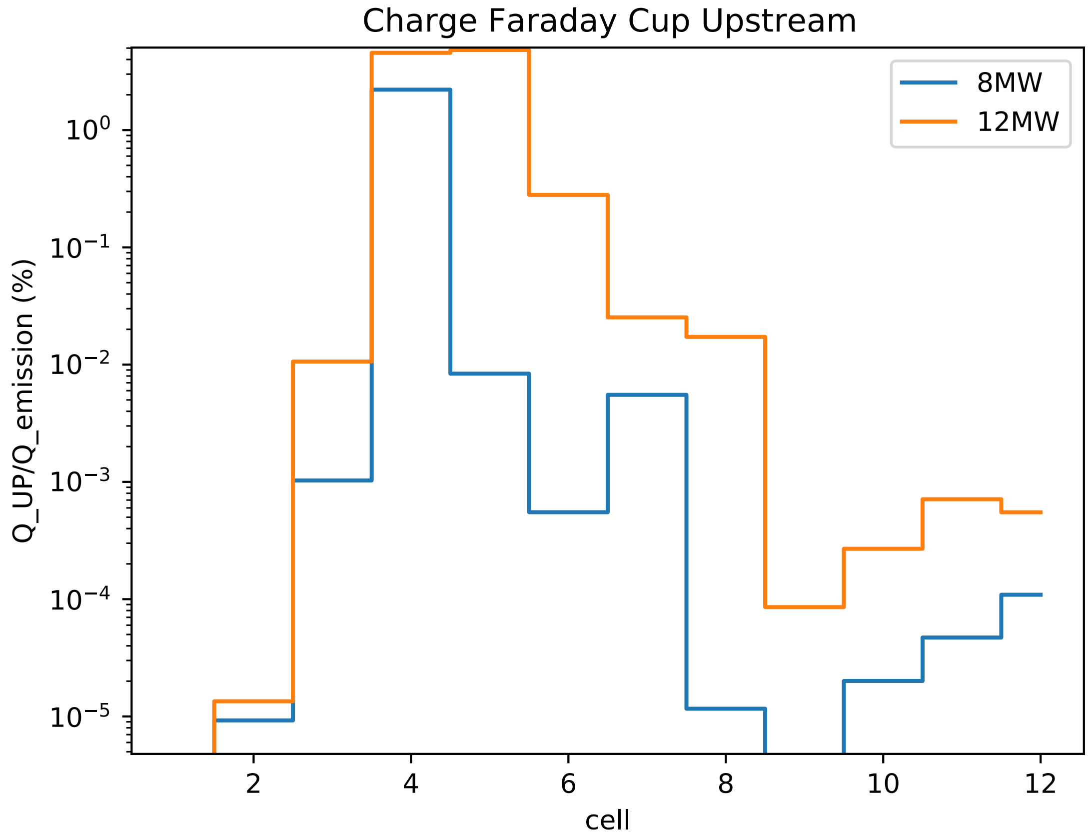
- ❑ Emission cell
- ❑ RF power

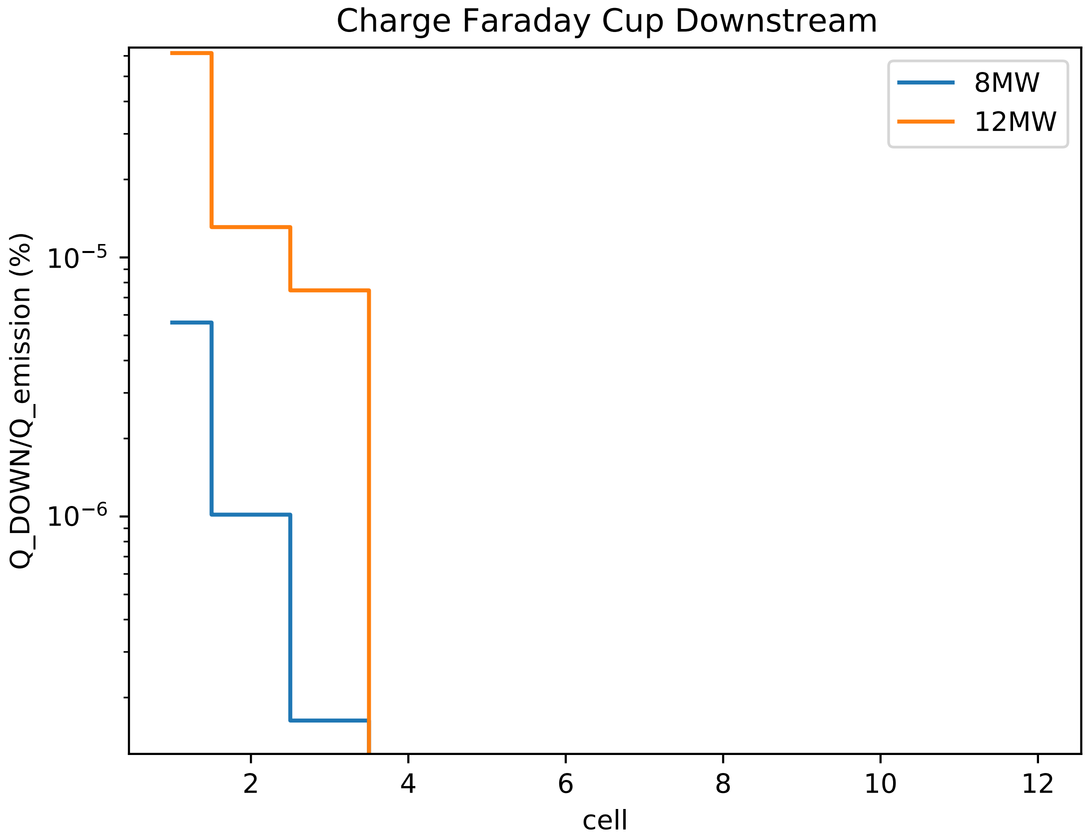


Charge collected by Faraday Cups

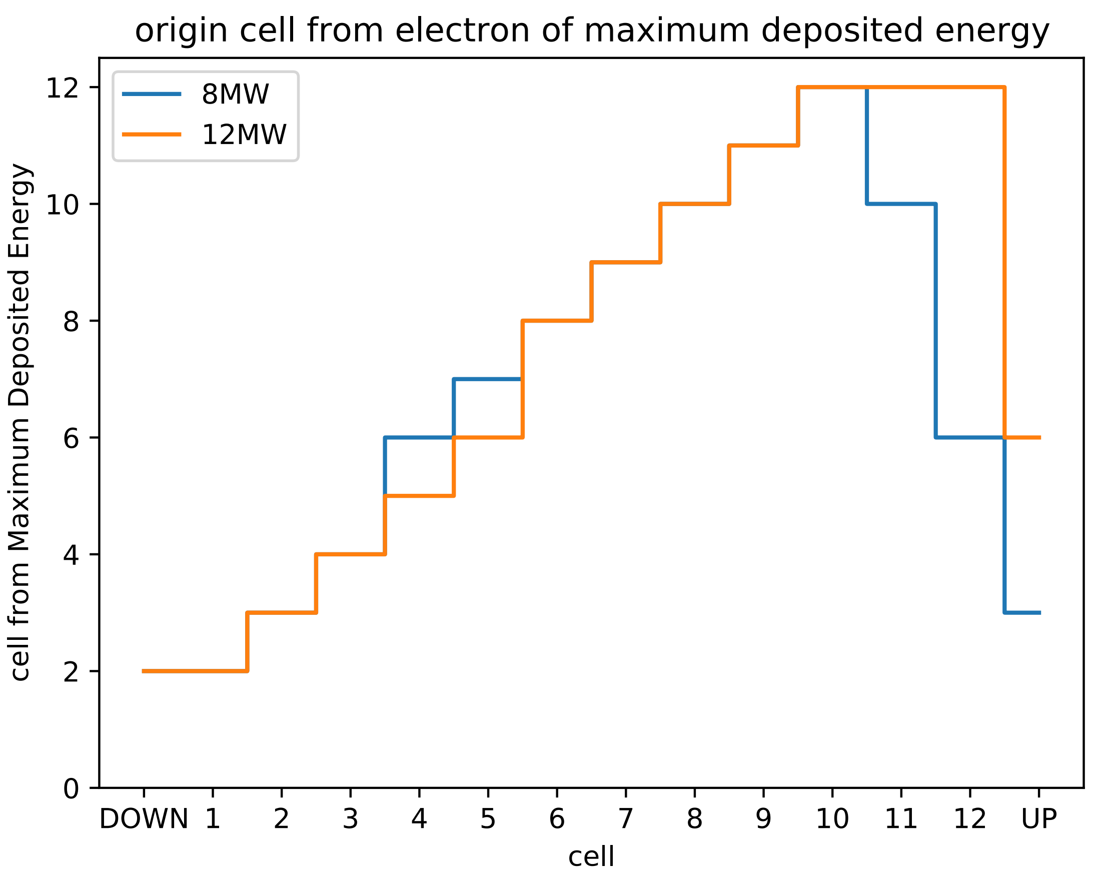
Power (MW)	Q UPSTREAM/Q EMISSION (%)	Q DOWNSTREAM/Q EMISSION (%)
8	9.14×10^{-3}	2.25×10^{-8}
12	6.60×10^{-2}	5.28×10^{-7}

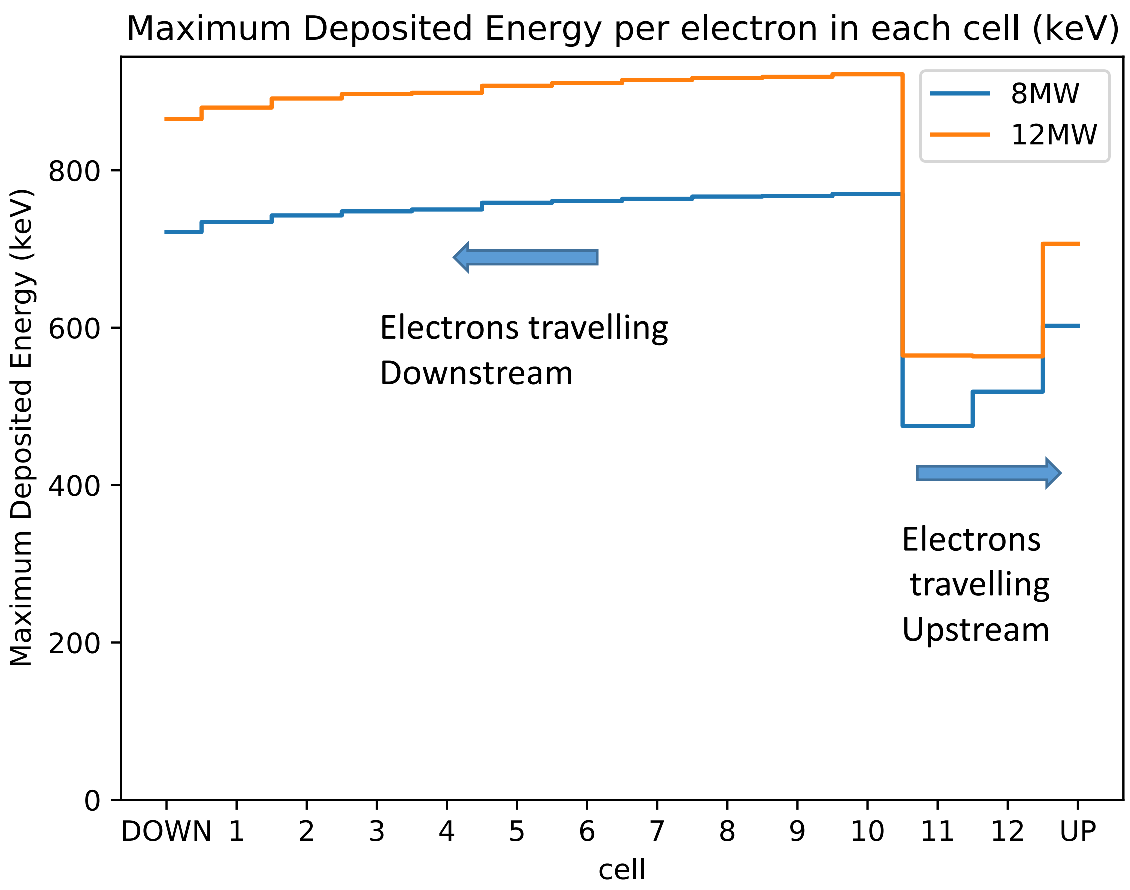






Maximum energy of electrons colliding inside the cavity





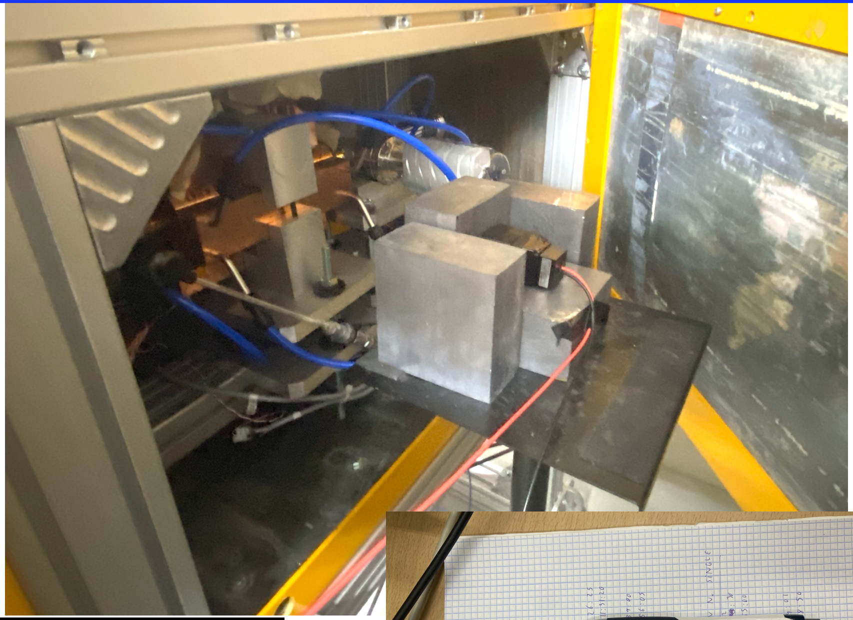
Observations:

- ❑ 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).

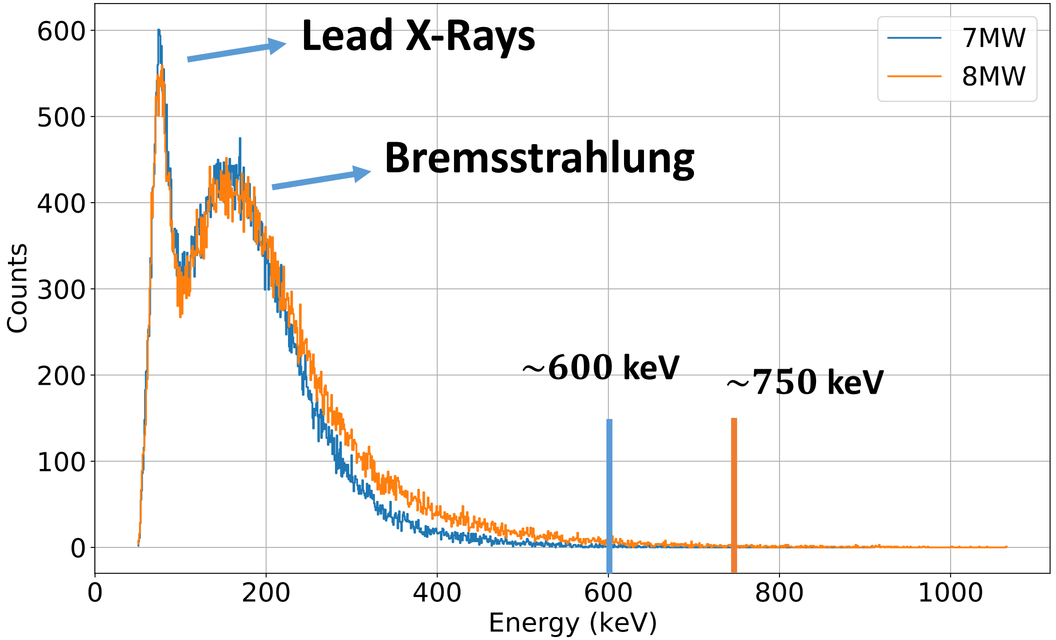
Radiation measurements

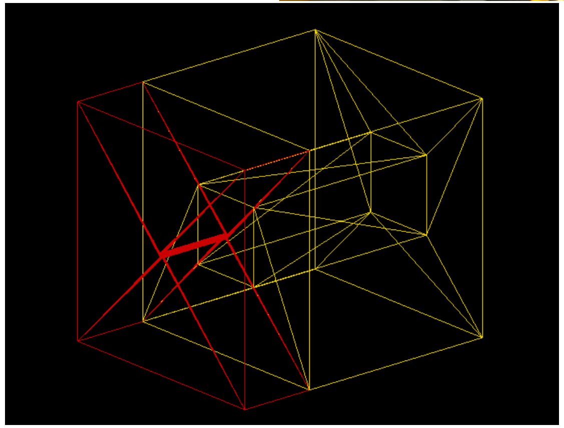
Measurements to:
- ❑ Validate the EM model.
- ❑ Estimate the impact of the radiation produced.

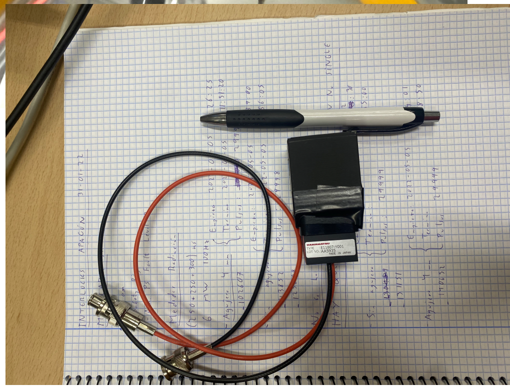
Energy spectrum of photons coming out of the structure.
- New set-up with smaller crystal of CeBr3, reading the pulses from an oscilloscope and dedicated collimator: **Faster and more flexible**



Preliminary

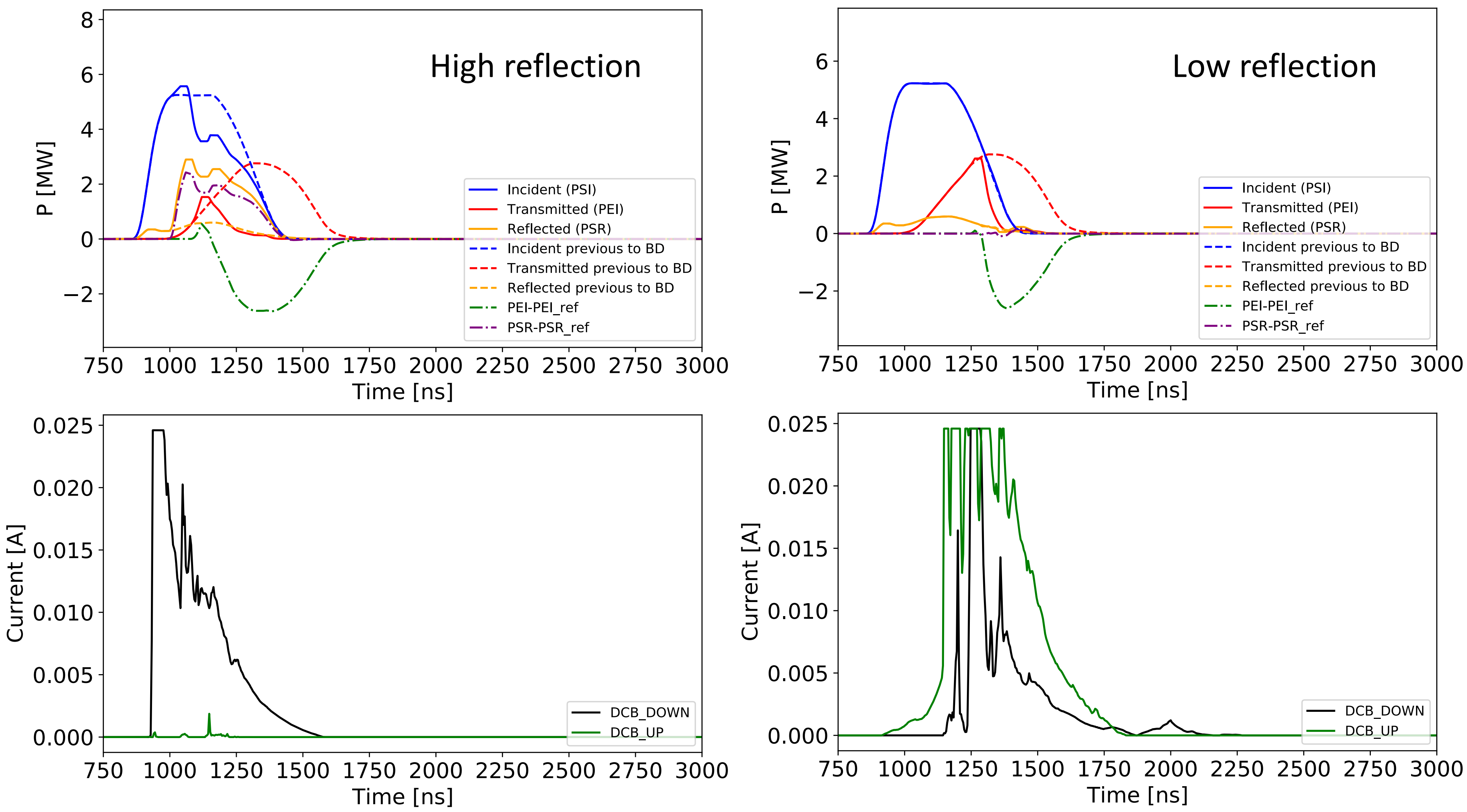






- ❑ Combine measured energy spectrum and dose with Geant4 simulations to estimate **the flux of photons**.

RF Breakdown phenomena



RF Breakdowns are characterized by:

- ❑ Explosive Dark Currents signals
- ❑ Drop of Transmitted signal
- ❑ Rise of Reflected signal

Where does the energy go in a low reflection BD?

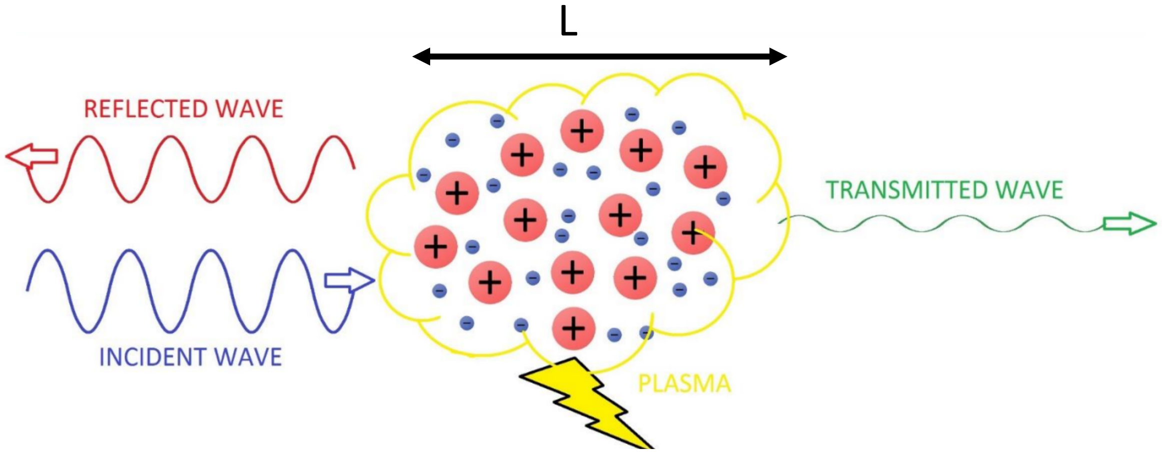
Dark current dynamics studies

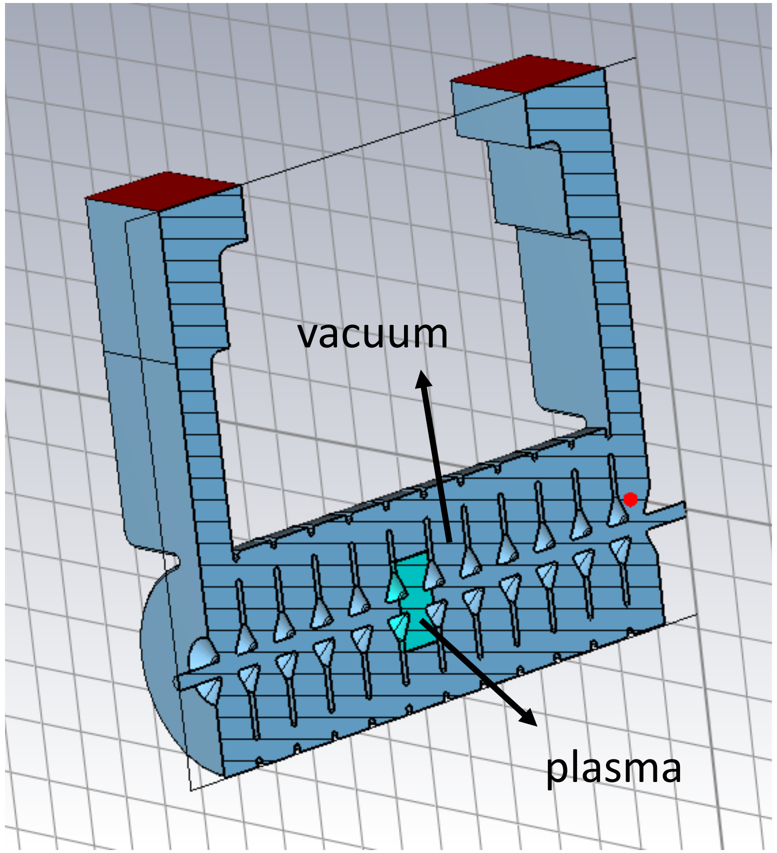
Motivation:

- ❑ Model and characterize the reflections and transmission phenomena in plasmas.

Procedure:

- ❑ Study the analytical reflection and transmission in plasmas
- ❑ Fill one cell of the acceleration cavity with plasma-equivalent material.





Studies:

- ❑ Reflection and transmission coefficient in plasma, with and without losses.
- ❑ Reflection and transmission coefficient in cavity, with and without losses

Scans:

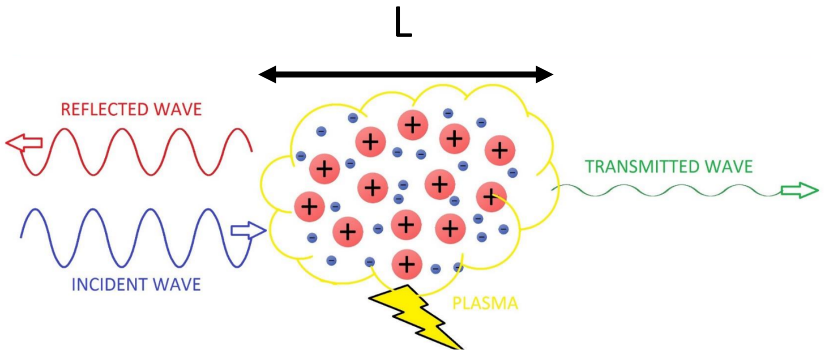
- ❑ Relative electric permittivity (ε_r)
- ❑ Losses ($\tan\,\delta$)

Reflection and transmission in plasma with no losses

Plasma electric permittivity $\epsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu)}$

Plasma frequency $\omega_p^2 = \frac{ne^2}{\epsilon_0 m}$

$\boldsymbol{n}$: electron density
$\boldsymbol{e}$: electron charge
$\boldsymbol{m}$: electron mass
$\boldsymbol{\nu}$: collision frequency

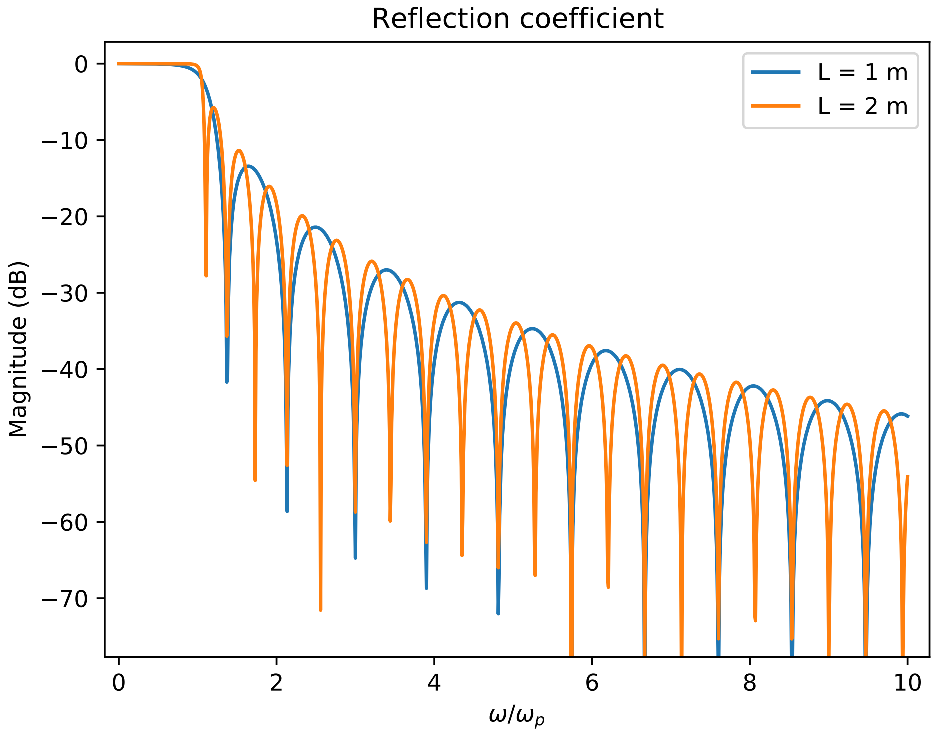


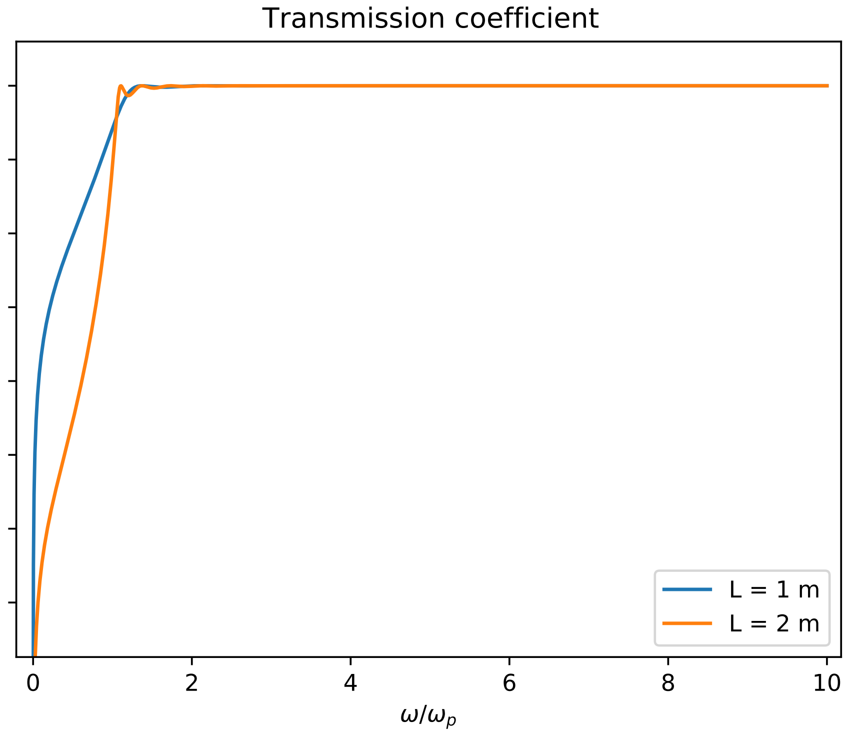
No losses: $\nu = 0$

$$\boxed{\epsilon_p = 1 - \frac{\omega_p^2}{\omega^2}}$$

Dispersion function $\boxed{k^2 = \omega^2 \mu_0 \epsilon_0 \epsilon_p = \mu_0 \epsilon_0 (\omega^2 - \omega_p^2)}$

$$\begin{cases} \omega > \omega_p \rightarrow & \text{Propagative} \\ \omega < \omega_p \rightarrow & \text{Evanescent} \end{cases}$$





Without losses:

- ❑ Transmission falls quickly below cut-off frequency.
- ❑ Reflexion increases as fast as transmission decreases.

Reflection and transmission in plasma with losses

L = 1 m

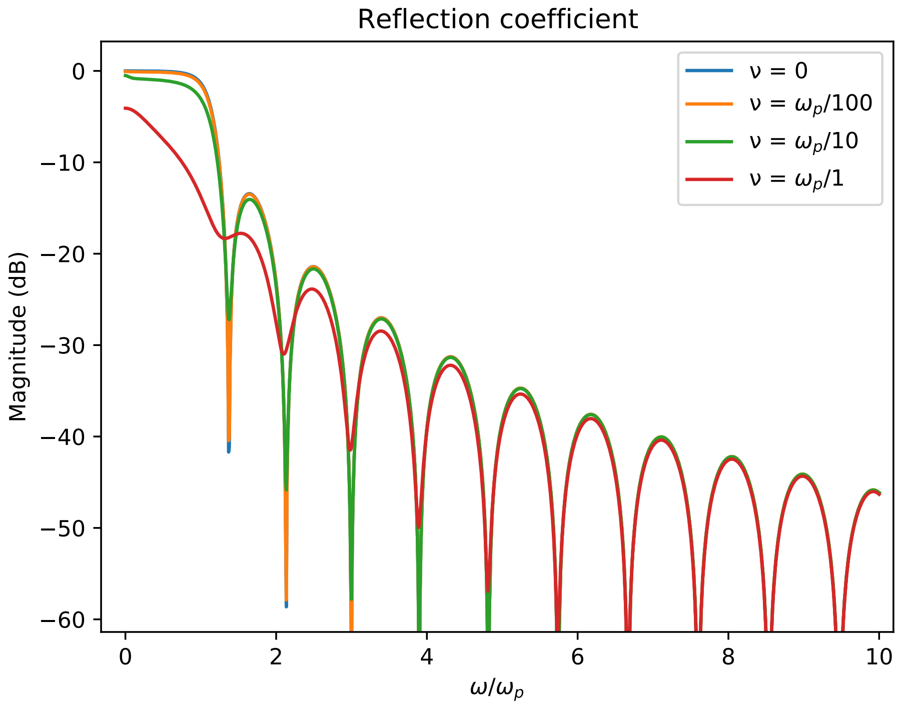
$\boxed{\text{With losses: } \nu \neq 0}$

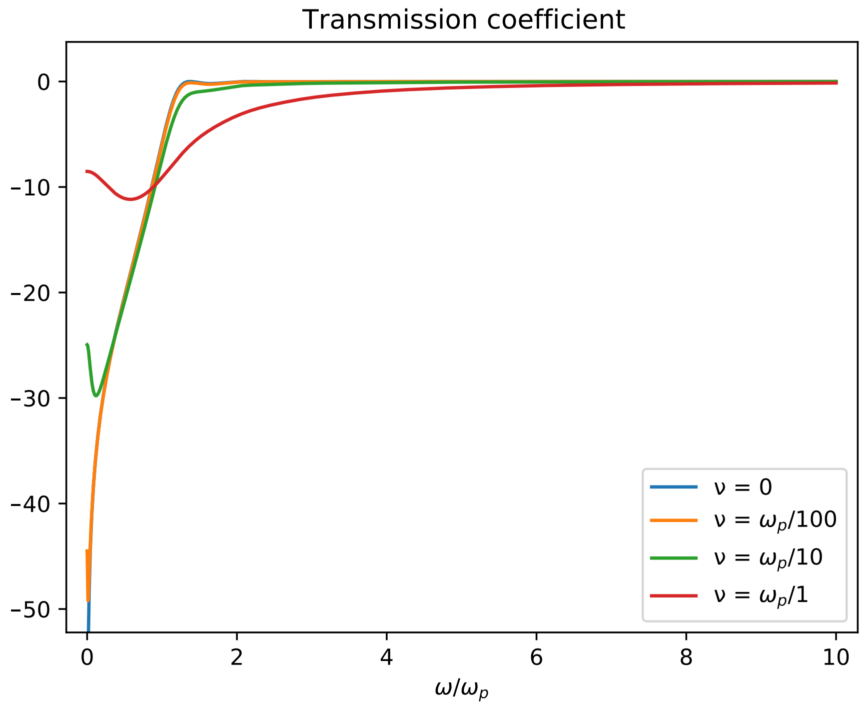
$$\epsilon = \epsilon' - j\epsilon''$$

$$\epsilon' = 1 - \frac{\omega_p^2}{\omega^2 + \nu^2}$$

$$\epsilon'' = \frac{\omega_p^2 \nu}{\omega(\omega^2 + \nu^2)}$$

$$\tan\delta = \frac{\epsilon''}{\epsilon'} = \frac{\omega_p^2 \nu}{\omega\left(\omega^2 + \nu^2 - \omega_p^2\right)}$$



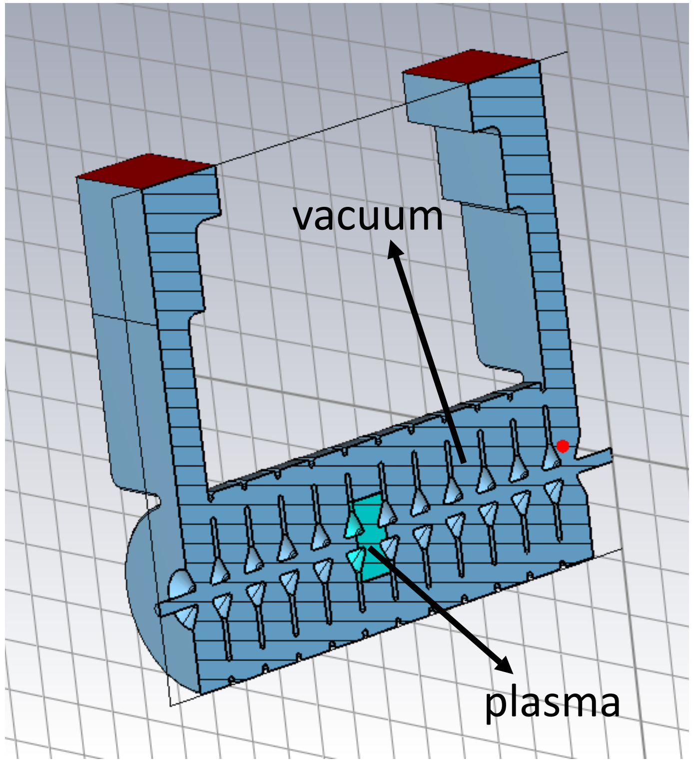


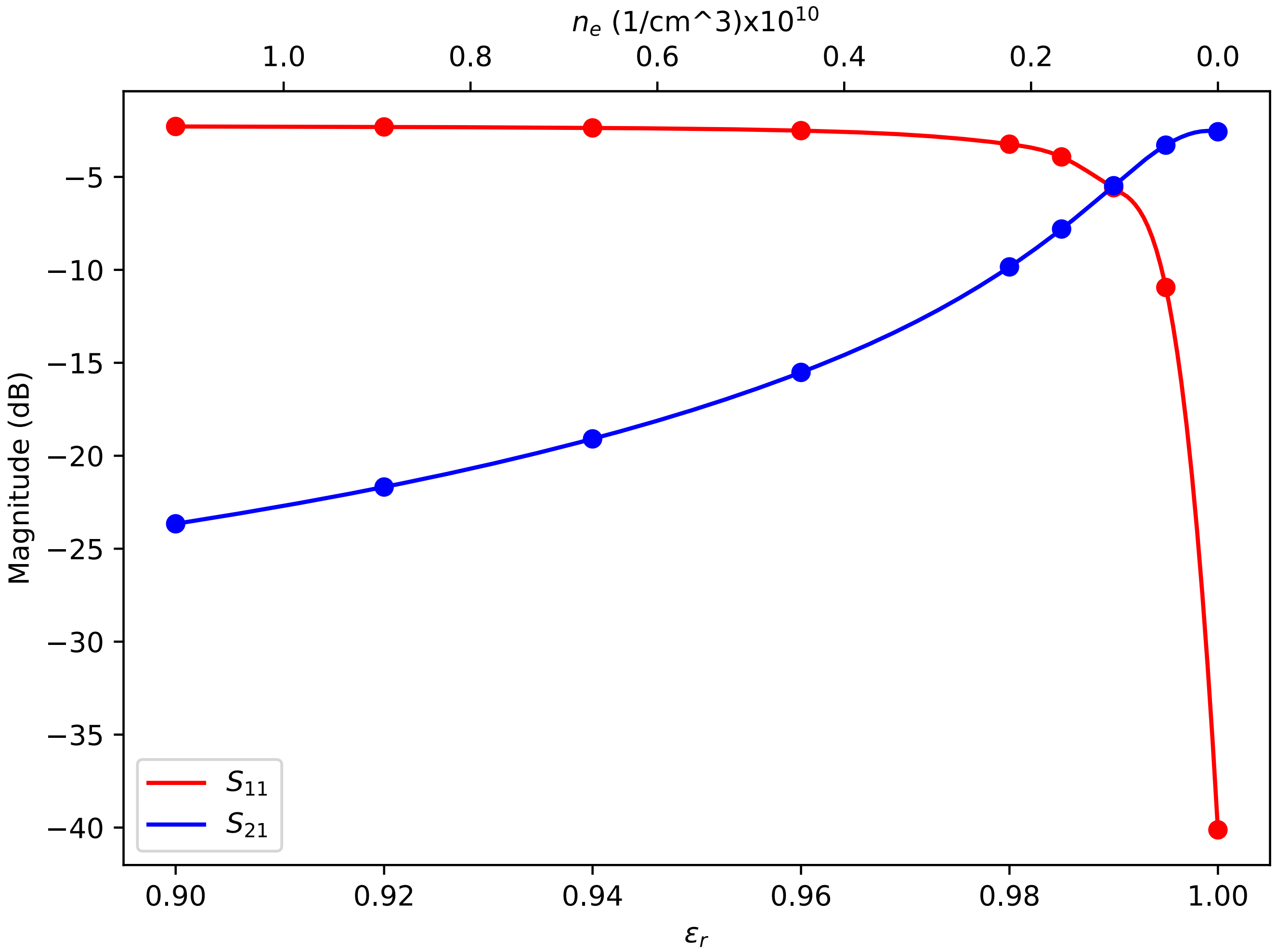
With losses:

- Transmission reachs a local minimum that varies with ν and ω.
- Reflexion increases is slower as ν gets larger values.

Reflection and transmission BTW cavity

No losses @ 2.9985 GHz

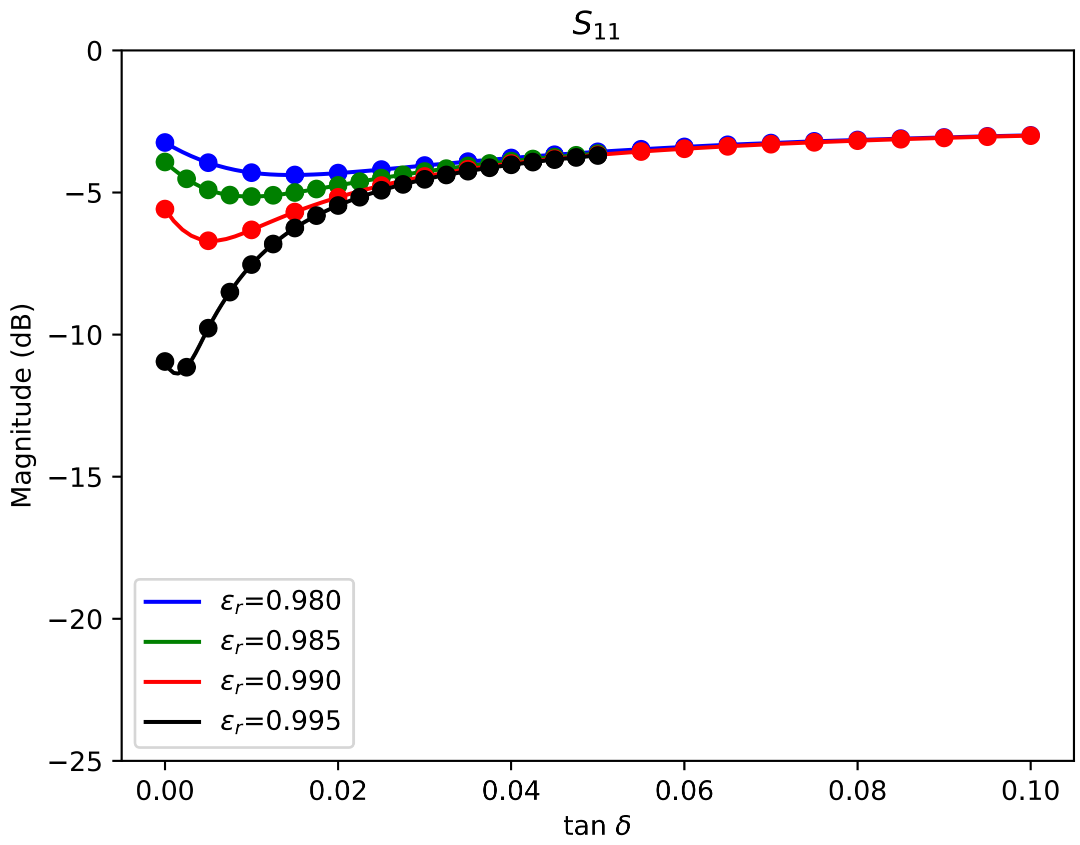


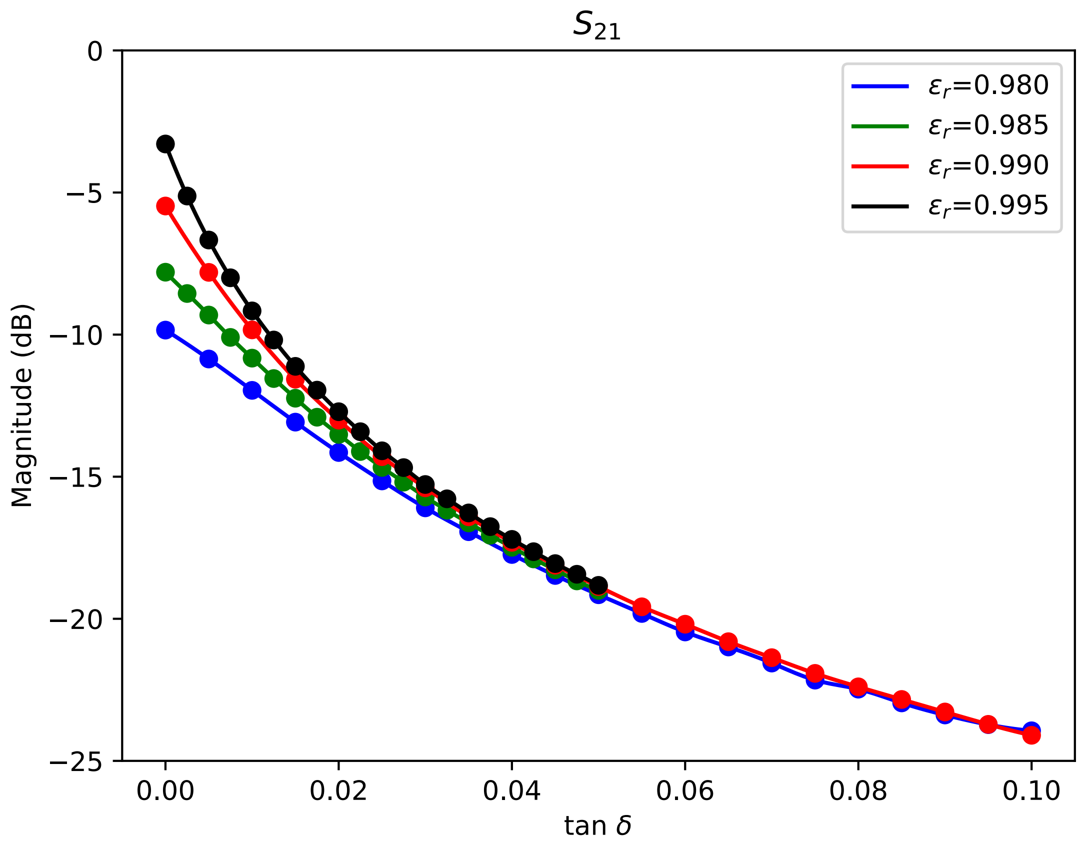


Without losses:

- ❑ Transmission falls quickly as electric permittivity differs from vacuum
- ❑ Reflexion increases as transmission decreases.

Reflection and transmission BTW cavity





Observations:

- ❑ Without losses, a high density of electrons must produce the reflection of the incident signal.
- ❑ With losses, the presence of a local minimum in S_{11} can explain signals of low reflected signal where the power is absorbed by the plasma.

Conclusions

- ❑ 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).

- ❑ Modelled the RF breakdown as a plasma with losses could explain low reflection BDs.

<u>Future plans</u>

- ❑ Continue Dark current dynamics for higher input power.

- ❑ Study behaviour of coupling holes filled with plasmas.

- ❑ Study the behaviour of different cells filled with plasmas.

Thank you very much for your attention!

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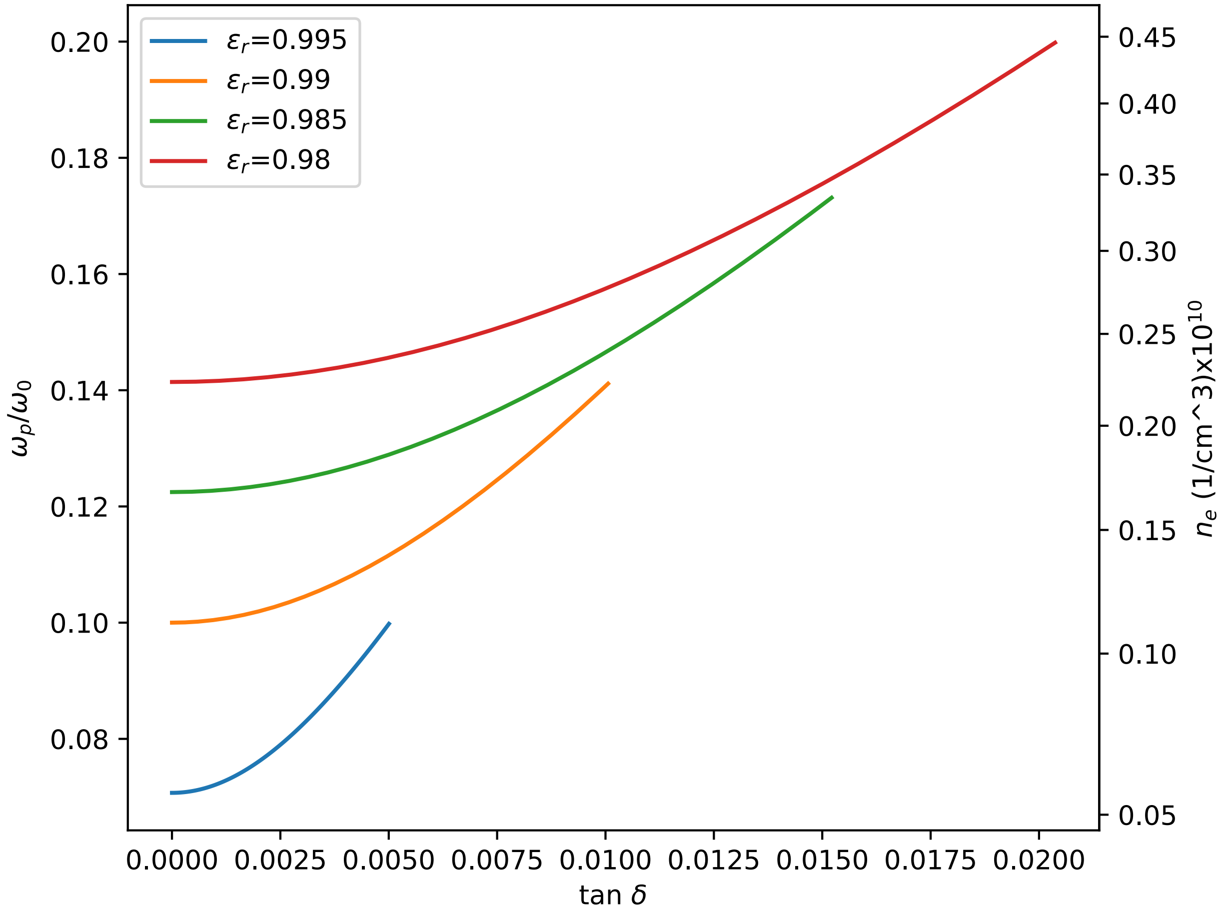
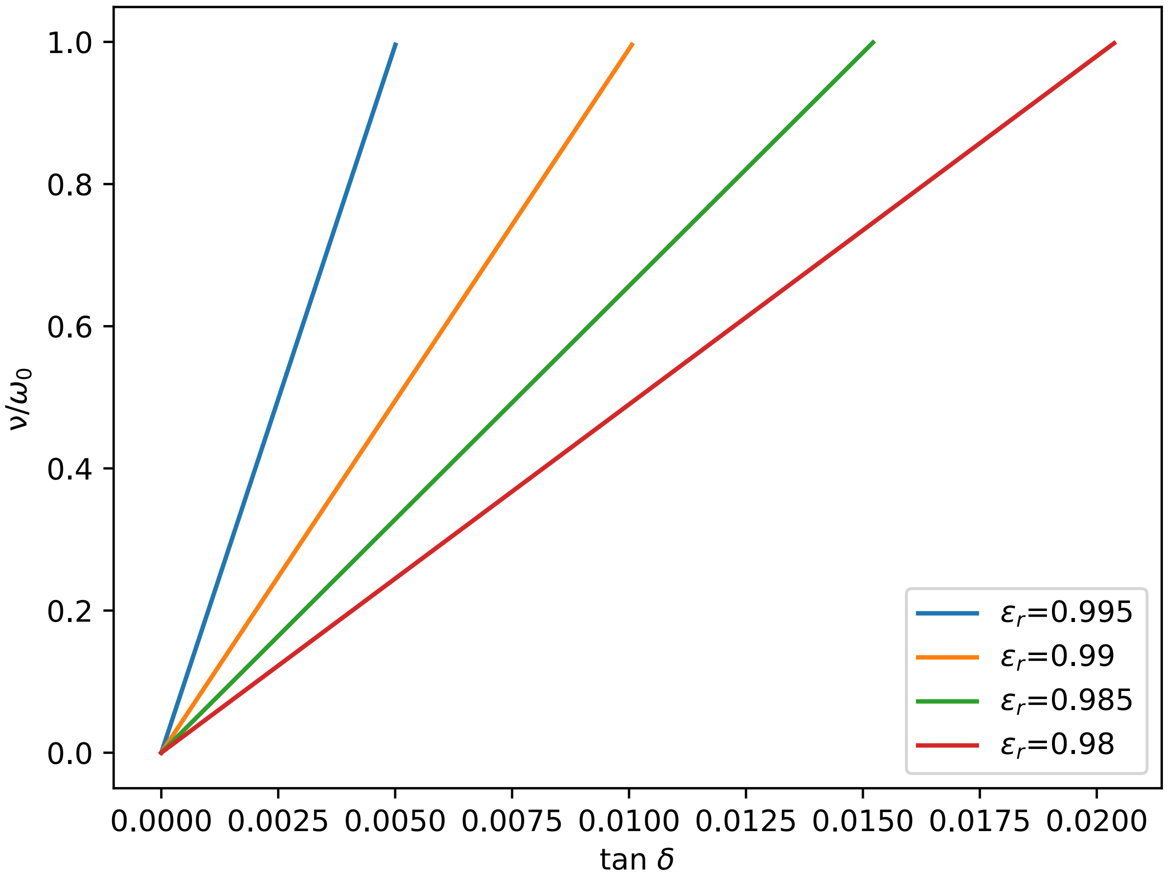
Back-up

Reflection and transmission BTW cavity

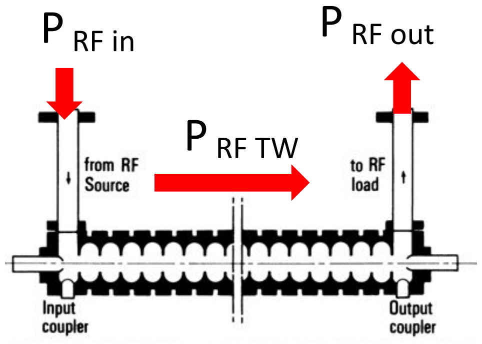
$$\epsilon' = 1 - \frac{\omega_p^2}{\omega^2 + \nu^2}$$

$$\tan\delta = \frac{\epsilon''}{\epsilon'} = \frac{\omega_p^2 \nu}{\omega\left(\omega^2 + \nu^2 - \omega_p^2\right)}$$

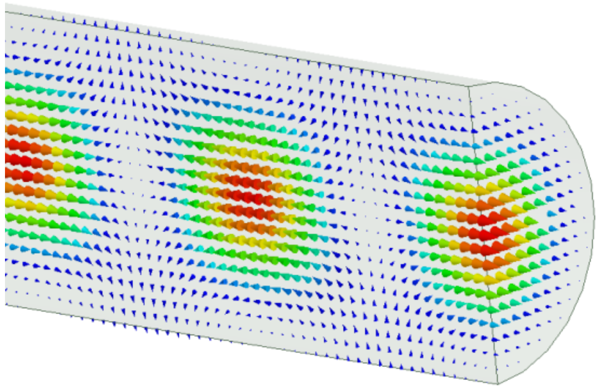




Travelling Wave Acceleration Cavities

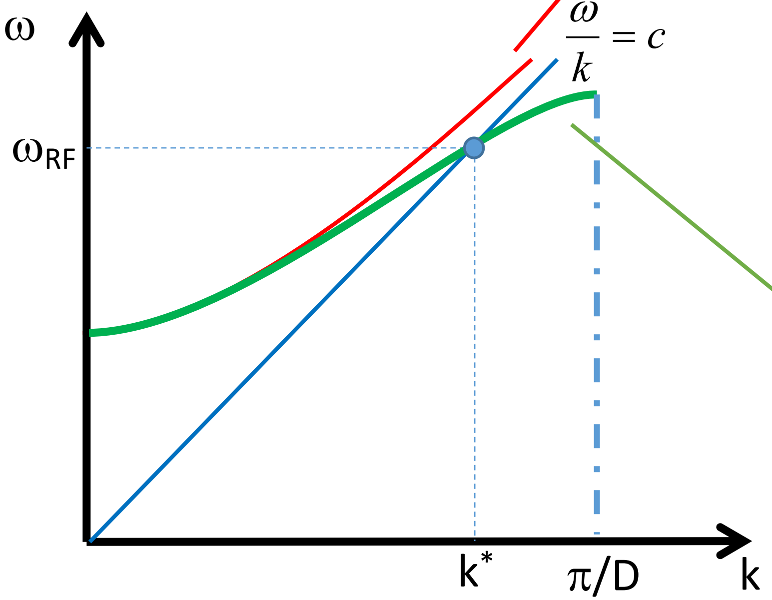


CIRCULAR WAVEGUIDE $v_{ph} > c$

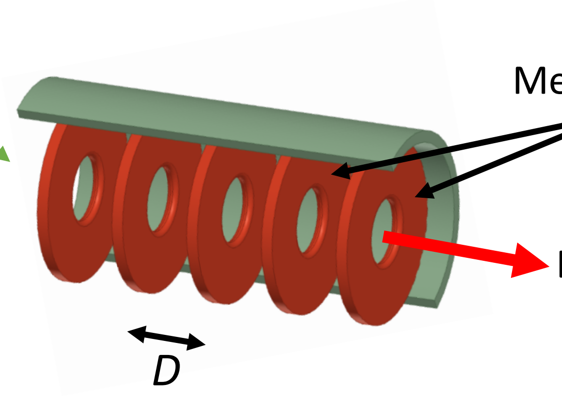


MODE TM_{01}

Dispersion curve

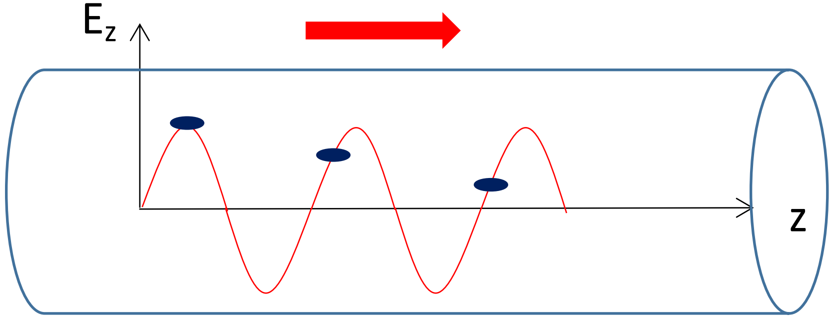


IRIS LOADED STRUCTURE $v_{ph} < c$

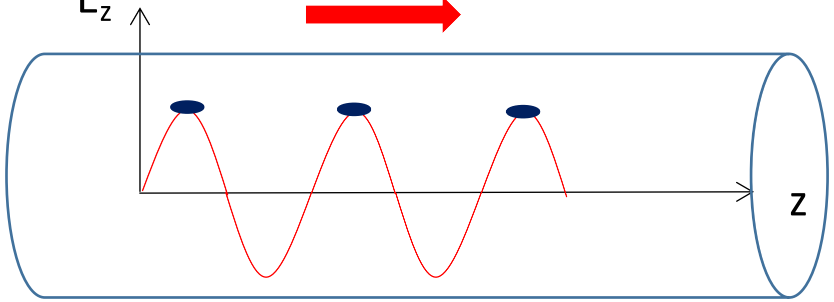


MODE TM_{01}-like

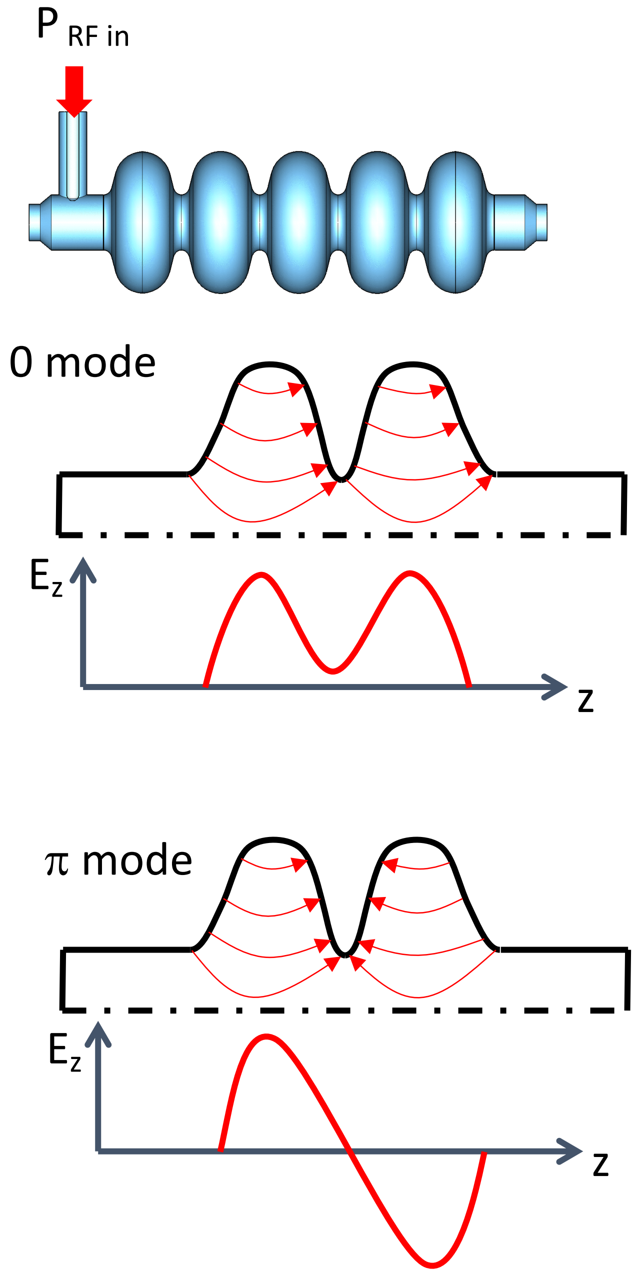
Particle velocity < phase velocity



Particle velocity = phase velocity

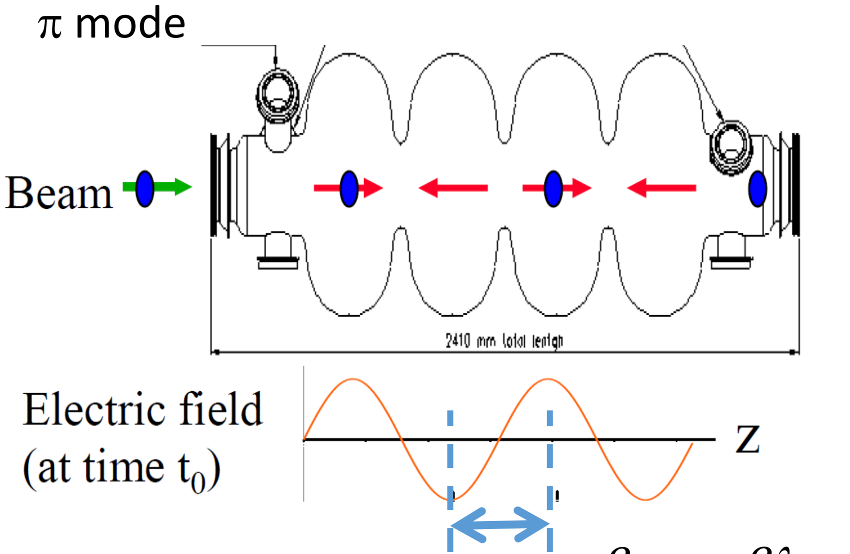


Standing Wave Acceleration Cavities



Cylindrical single (or multiple cavities) working on the **TM_{010}-like** mode are used

Synchronization condition



$$d = \frac{\beta c}{2 f_{RF}} = \frac{\beta \lambda_{RF}}{2}$$

β: particle velocity
d: distance between cells
f_{RF}: RF frequency
c: speed of light in vacuum

The **performance** is defined by:

- ❑ Shunt impedance: efficiency of the acceleration mode.

$$\boxed{R = \frac{\hat{V}_{acc}^2}{P_{diss}} \ [\Omega]}$$

NC cavity R~1MΩ SC cavity R~1TΩ

- ❑ Quality factor: efficiency to store RF energy .

$$\boxed{Q = \omega_{RF} \frac{W}{P_{diss}}}$$

NC cavity Q~10^4 SC cavity Q~10^{10}

- ❑ R/Q: pure geometric qualification factor.

$$\boxed{\frac{R}{Q} = \frac{\hat{V}_{acc}^2}{\omega_{RF} W}} \sim 100\ \Omega$$

Non Linear effects

Field Emission

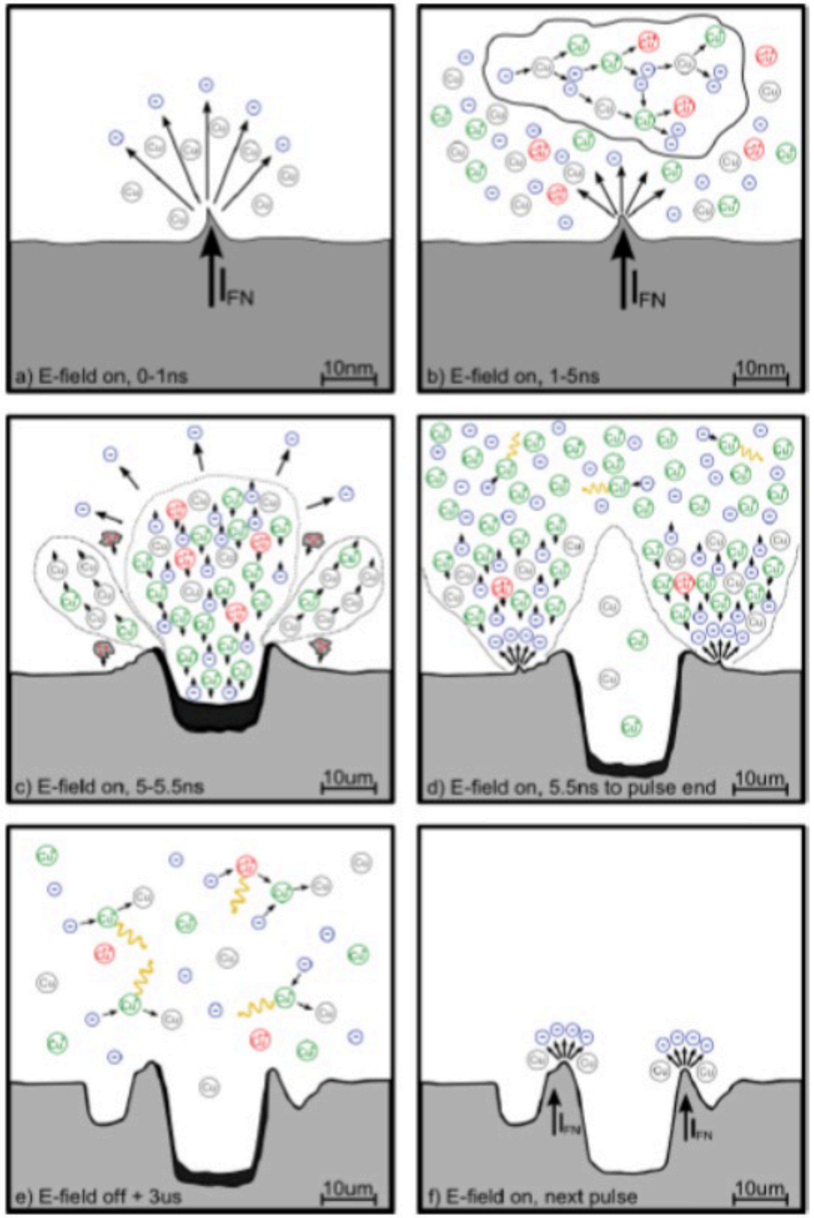
- ❑ Electrons are emitted by **tunneling** due to **High surface electric fields** following **Fowler-Nordheim equation**.

RF Breakdown

- ❑ Electron currents burn protrusions **evaporating ion atoms**.
- ❑ Ions and electron cloud interact with electromagnetic fields prouducing **reflection effects**.

Radiation

- ❑ Electrons interaction with walls translates into high radiation dose due to **bremsstrahlung photon emission**.

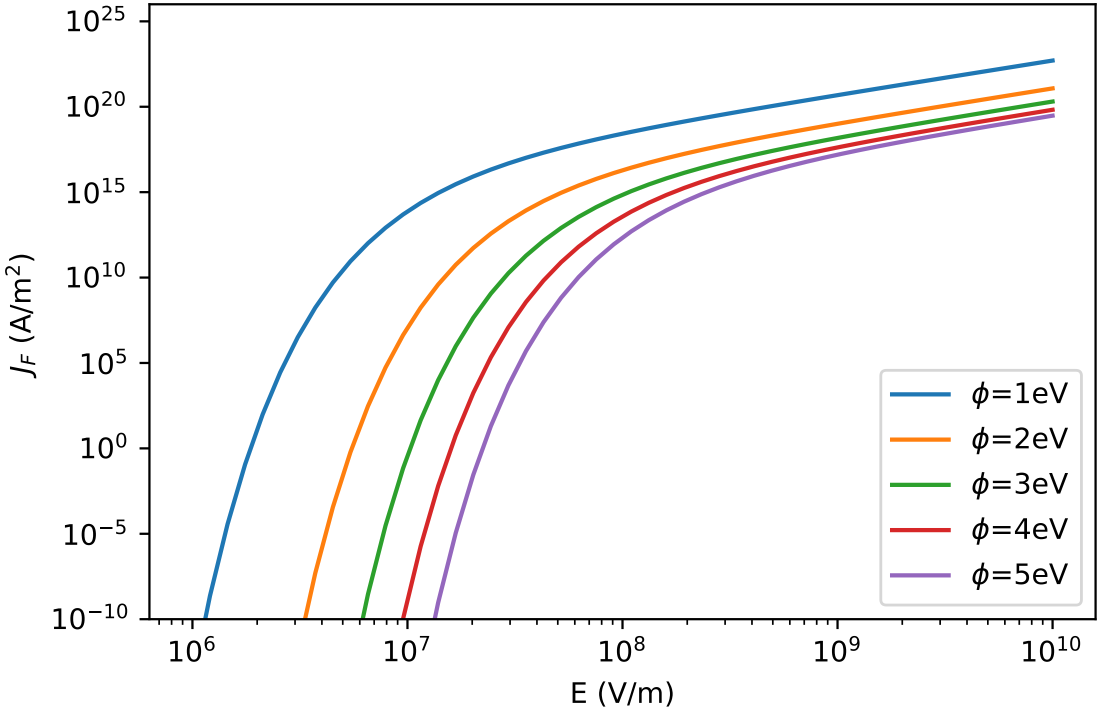


Field emission and RF conditioning

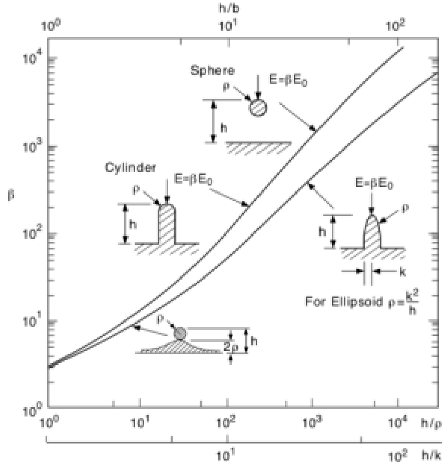
Fowler-Nordheim equation: Electrons are emitted through tunneling due to **high surface electric field**.

$$j_F = \frac{1.54\times10^{-6}\times10^{4.52\phi^{-0.5}}E^2}{\phi}\exp\left[-\frac{6.53\times10^{9}\phi^{1.5}}{E}\right]\ \mathrm{A/m^2}$$

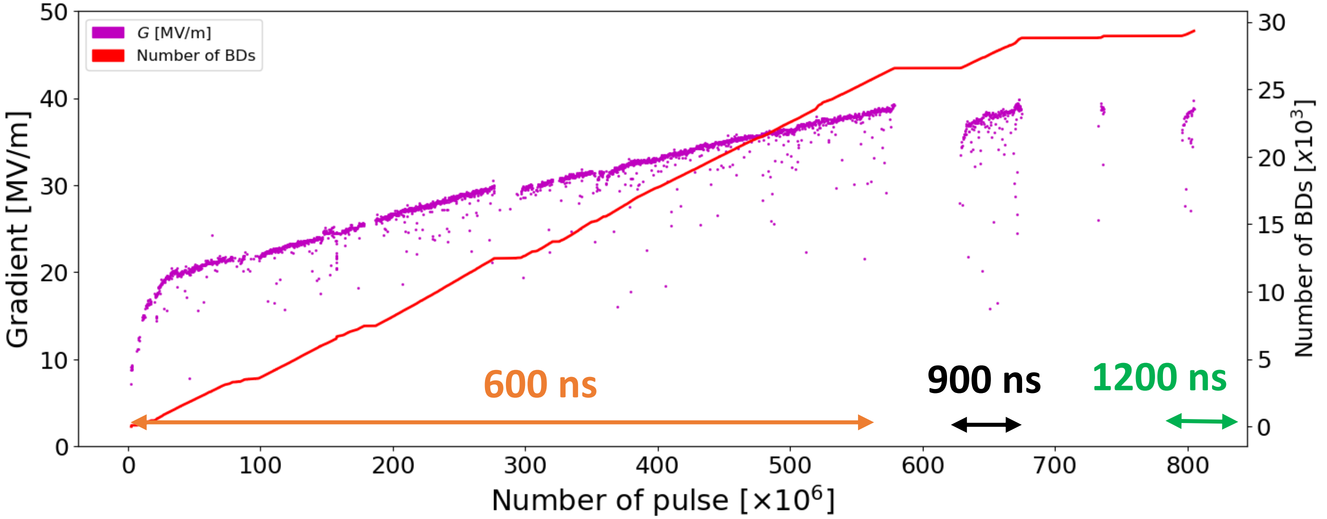
- Work function ϕ: depends on material and geometry.



Surface roughness:
Local enhacement factor β for different geometries of idealized metallic microprotusions: $E_{id} = \beta \cdot E$



Conditioning process necessary

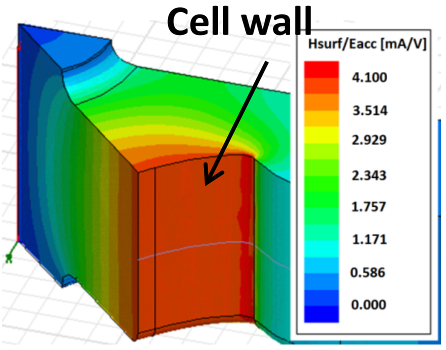


High-Gradient limitation

❑ Surface magnetic field

Pulsed surface heating produced material fatigue -> cracks.

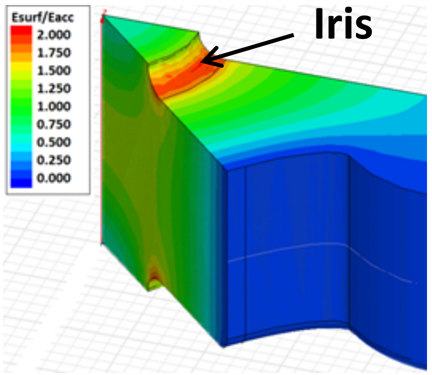
$$\Delta T \propto H_s^2 \sqrt{t_p},$$
$$\boldsymbol{\Delta T_{\max}} = \mathbf{50^oC}$$



❑ Field emission due to surface electric field

- RF breakdowns; Electron emission initiates vacuum arcs. The exact mechanism is still unclear.
- Breakdown rate (BD/pulse.m) -> Operation efficiency;
- Local plasma triggered by field emission -> Erosion of surface;
- Dark current capture -> Efficiency reduction, detector backgrounds.

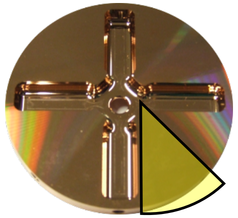
$$E_s = 200 \frac{MV}{m}$$



*[W. Wuensch et al. Phys. Rev. ST Accel. Beams **12**, 102001 (2009)]*

❑ RF power flow

RF power flow and/or iris aperture has a strong impact on achievable E_{acc} and on surface erosion.



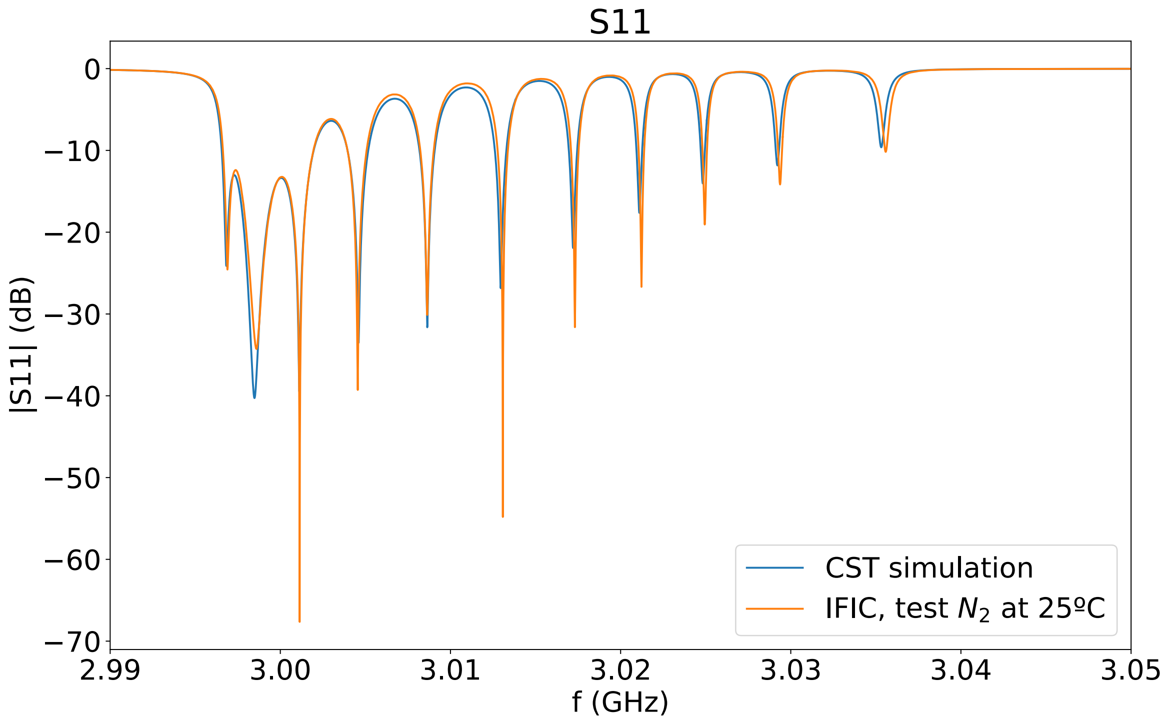
Modified Poynting vector:

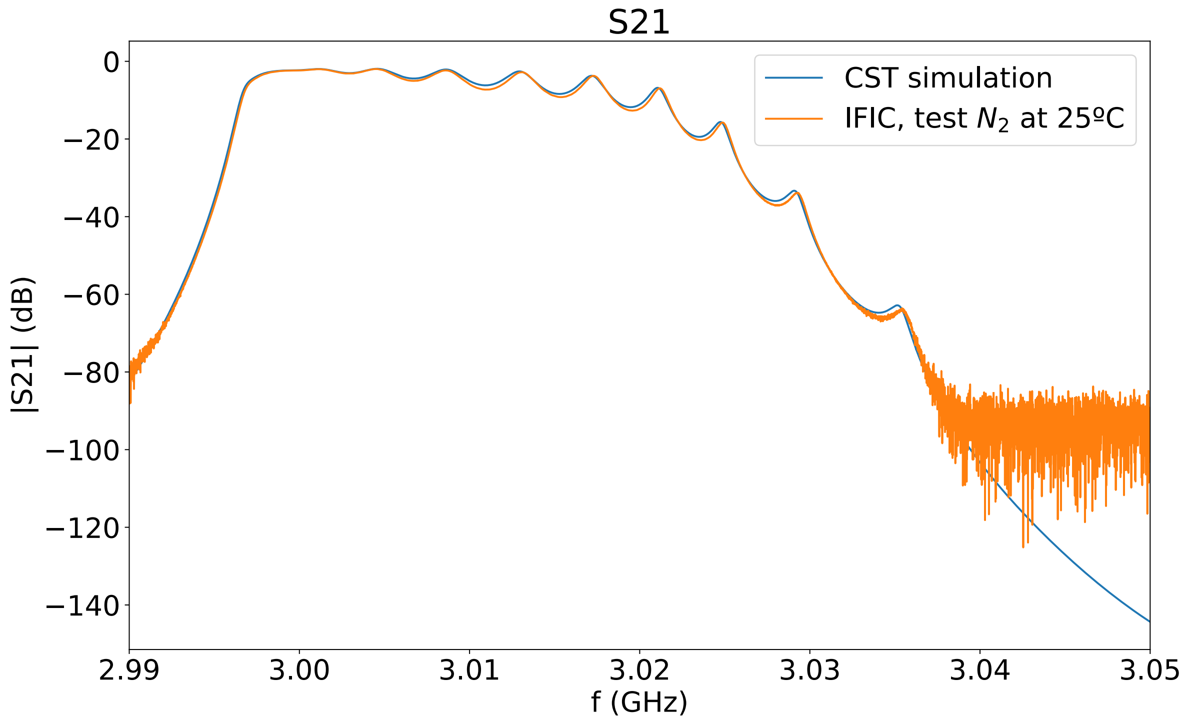
$$S_c = |Re(\vec{S})| + \frac{1}{6}|Im(\vec{S})|$$
$$5\ MW/mm^2$$

S-parameters

First, we study the electromagnetic behaviour of the S-Band BTW cavity and compared simulations with measurements.

- S-parameters of the cavity were measured using a Vector Network Analyzer (VNA).
- Numerical results were obtained using the Frequency domain solver of CST Studio Microwave package.

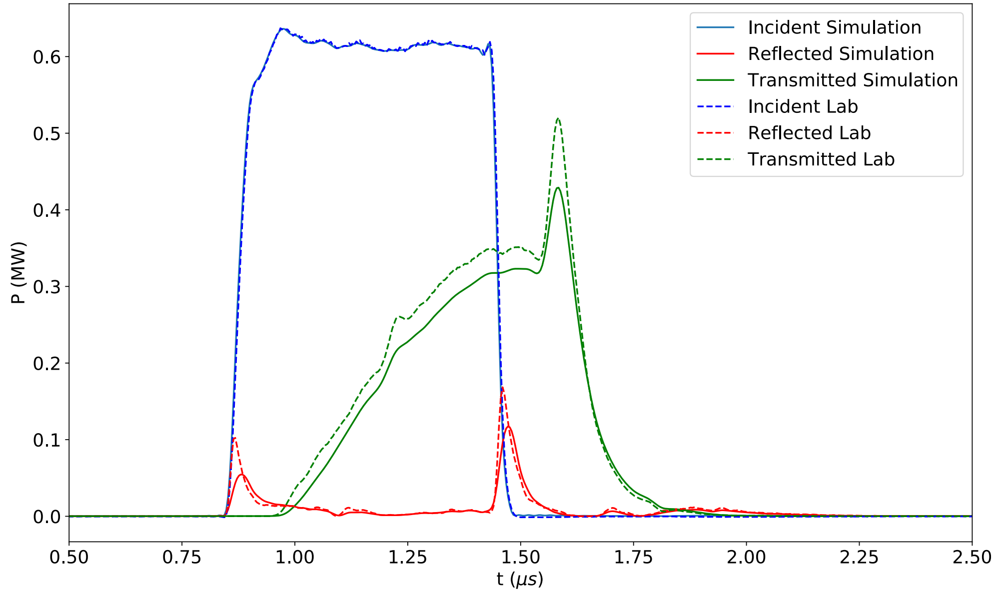




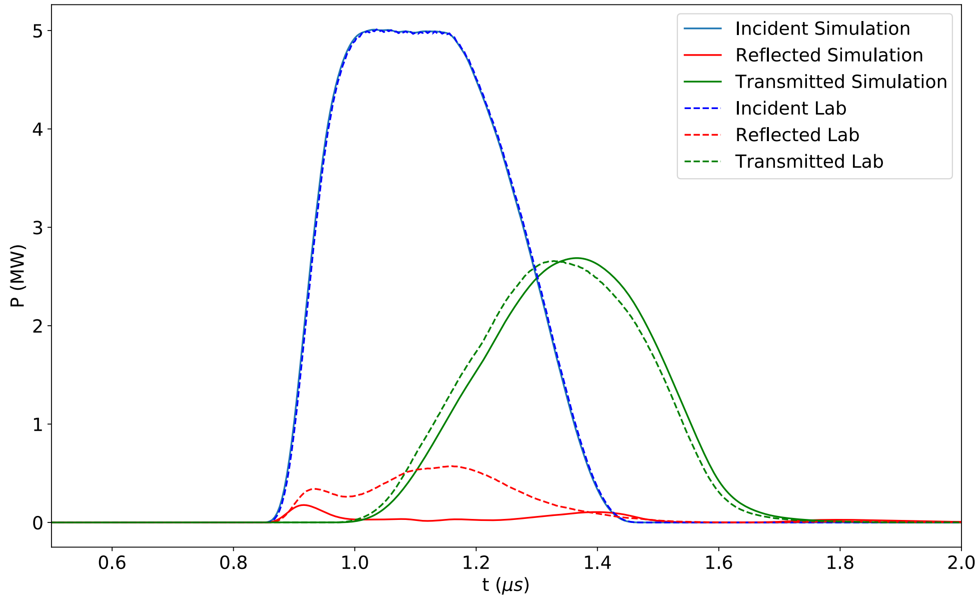
Simulated vs measured pulse examples

2019
- ❑ Pulse width: 750 ns
- ❑ Rise time: 100 ns
- ❑ Fall time: 100 ns
- ❑ **RF: 2.9985 GHz (for 32 °C)**

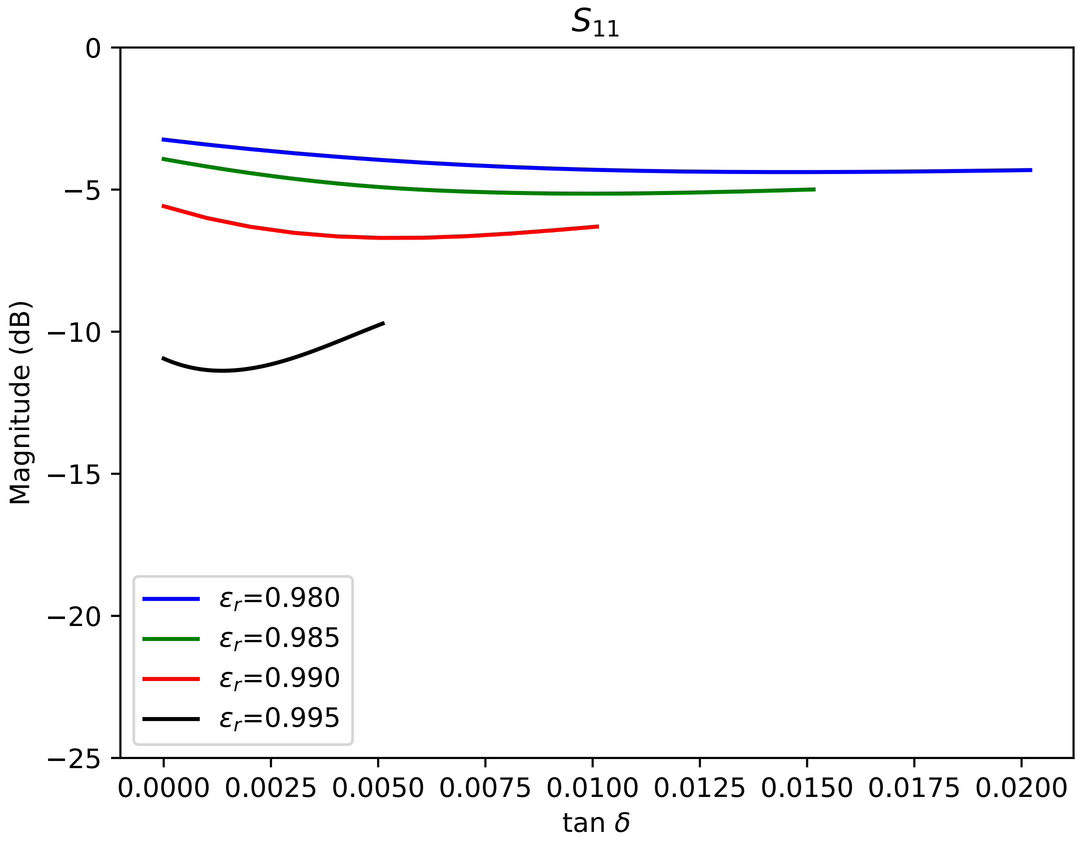
Note: Measured reflected signal is not to the structure but back to the klystrons (wrong cabling).

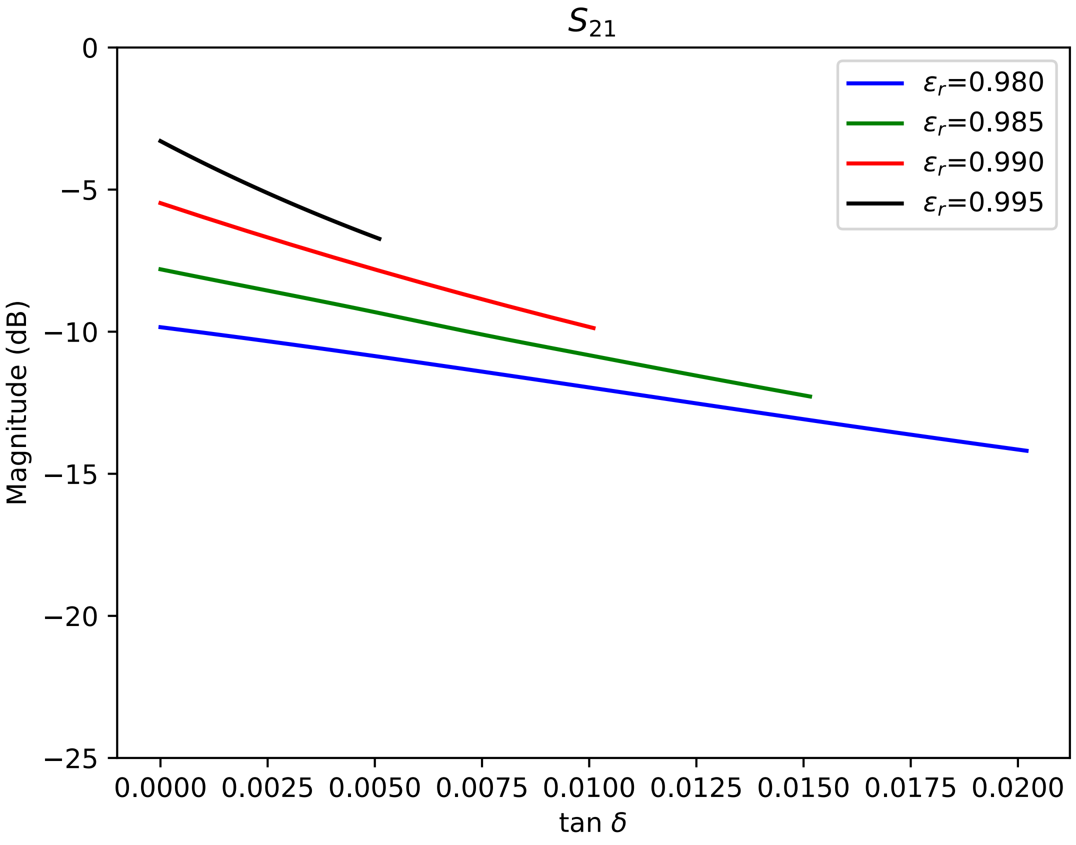


2021
- ❑ Pulse width: 600 ns
- ❑ Rise time: 100 ns
- ❑ Fall time: 300 ns
- ❑ **RF: 2.9990 GHz (for 22 °C)**
  - ❑ The structure was tunned at operating T=32°C at 2.9985 GHz.

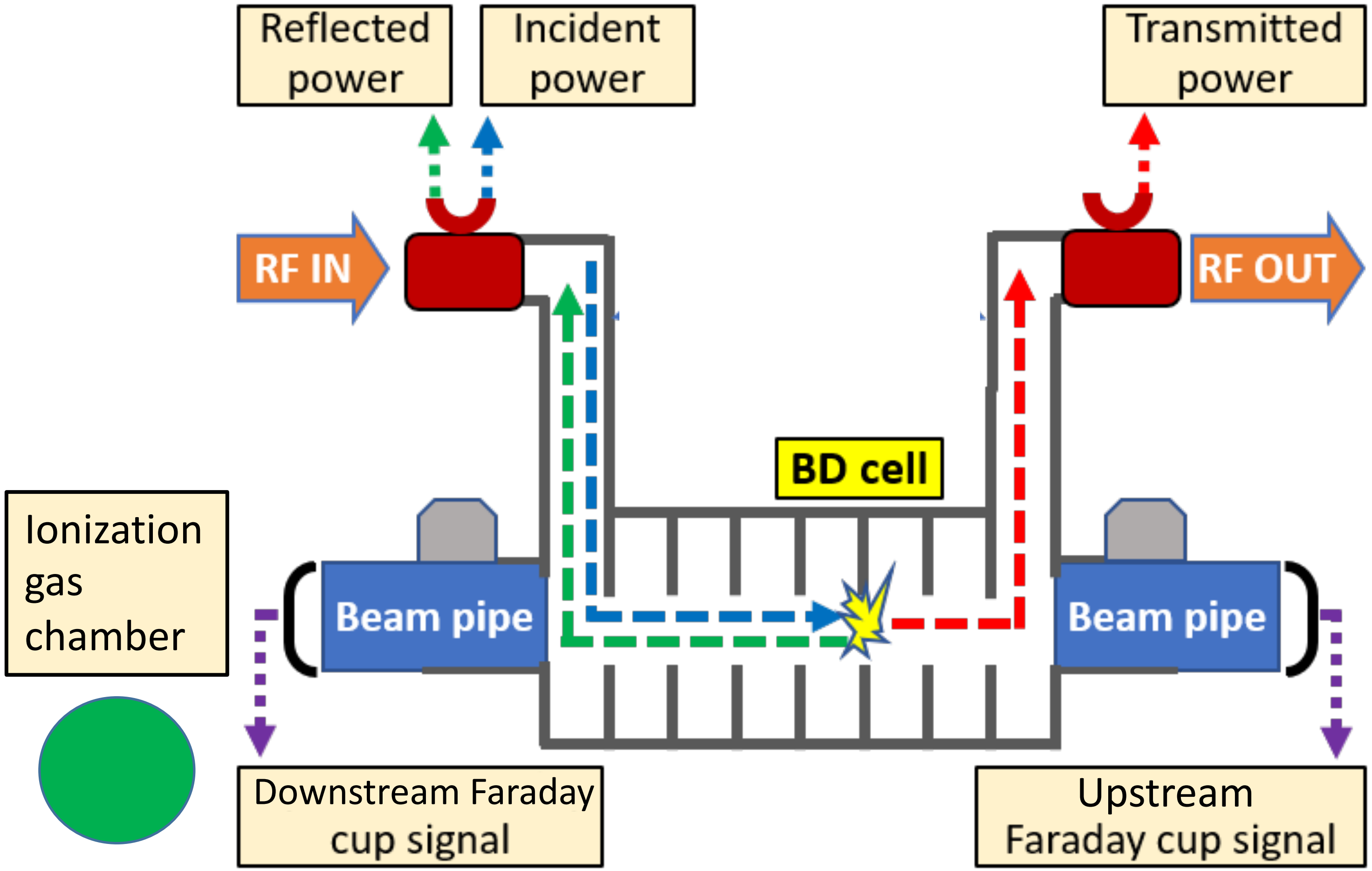


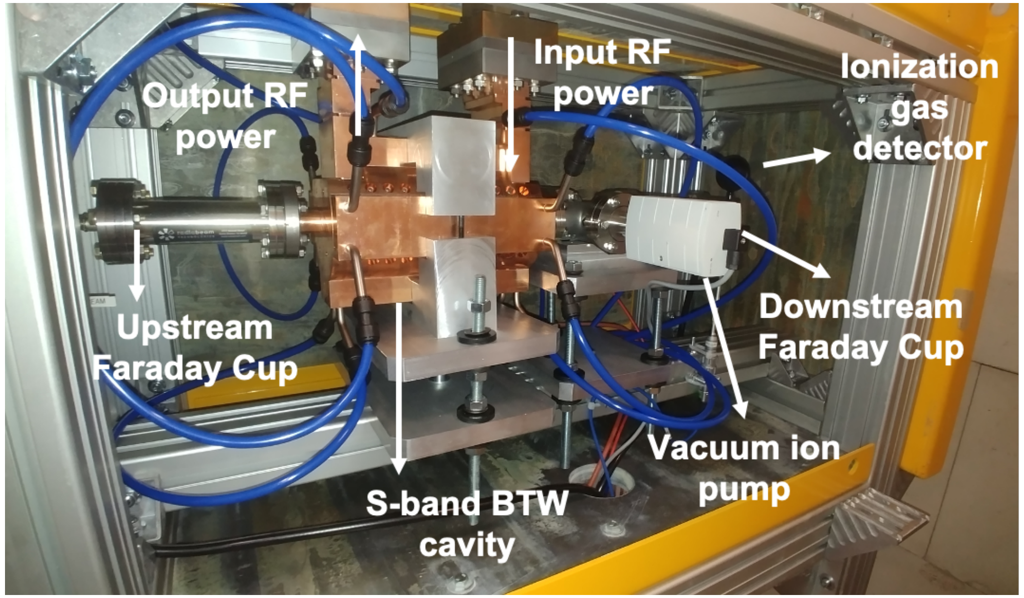
Reflection and transmission BTW cavity

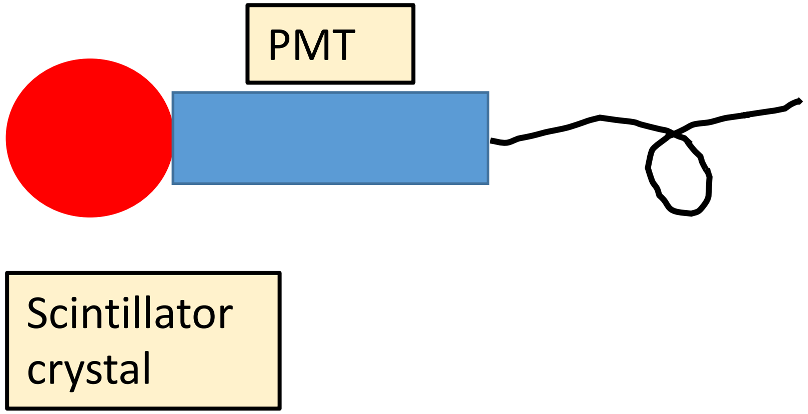




Experimental set up



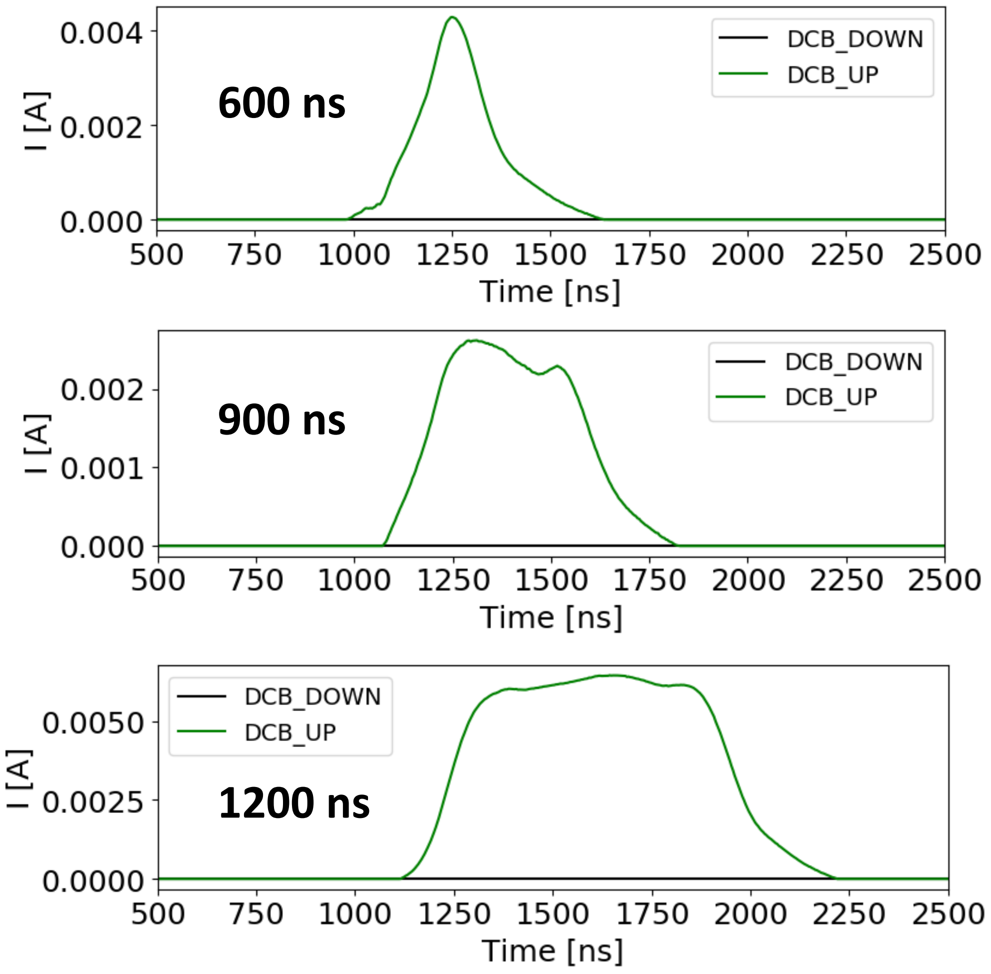




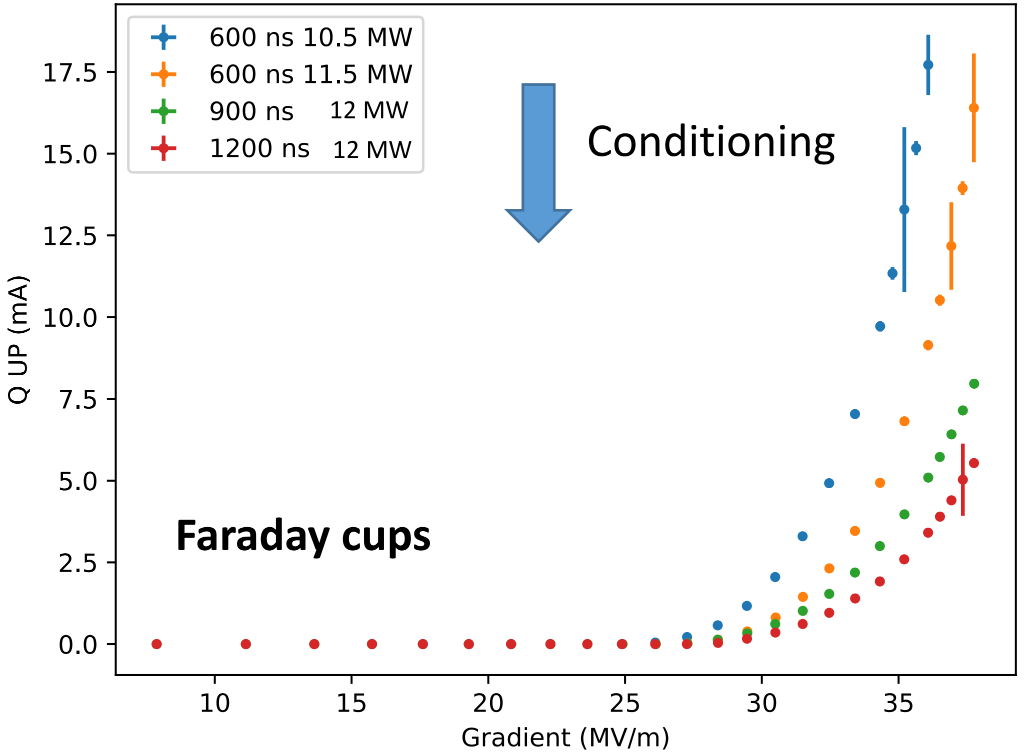
PROTON BEAM CONVENTION FOR FARADAY CUPS

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.



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



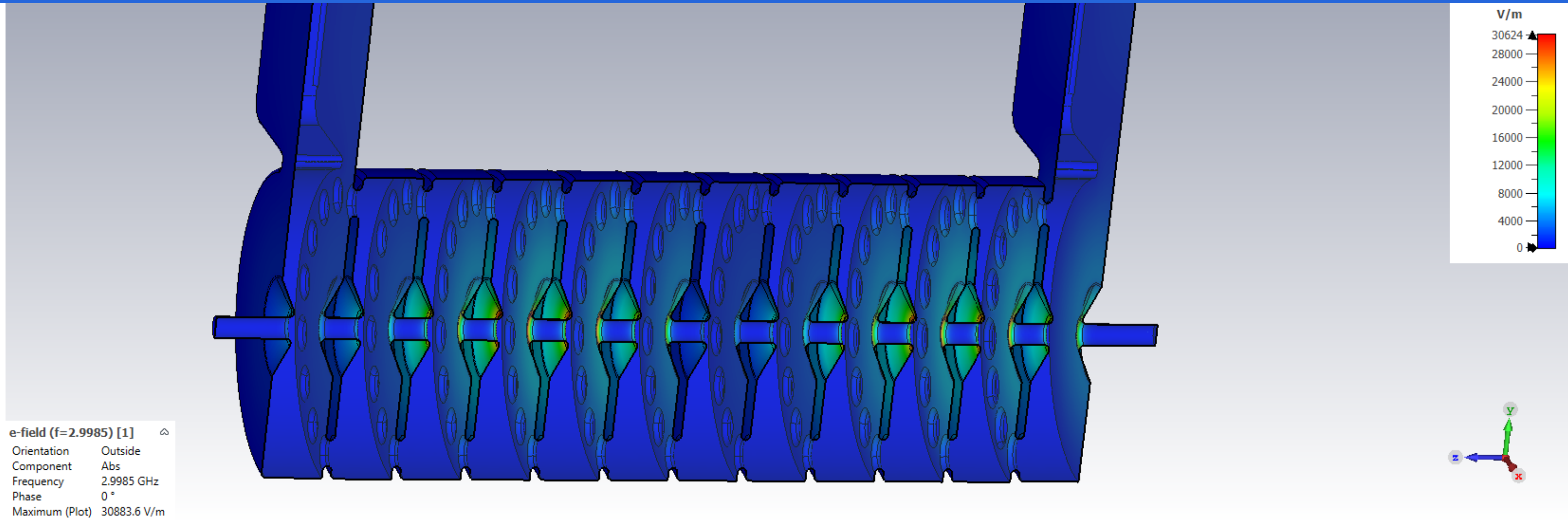
BTW High-Gradient Cavity: Electromagnetic studies

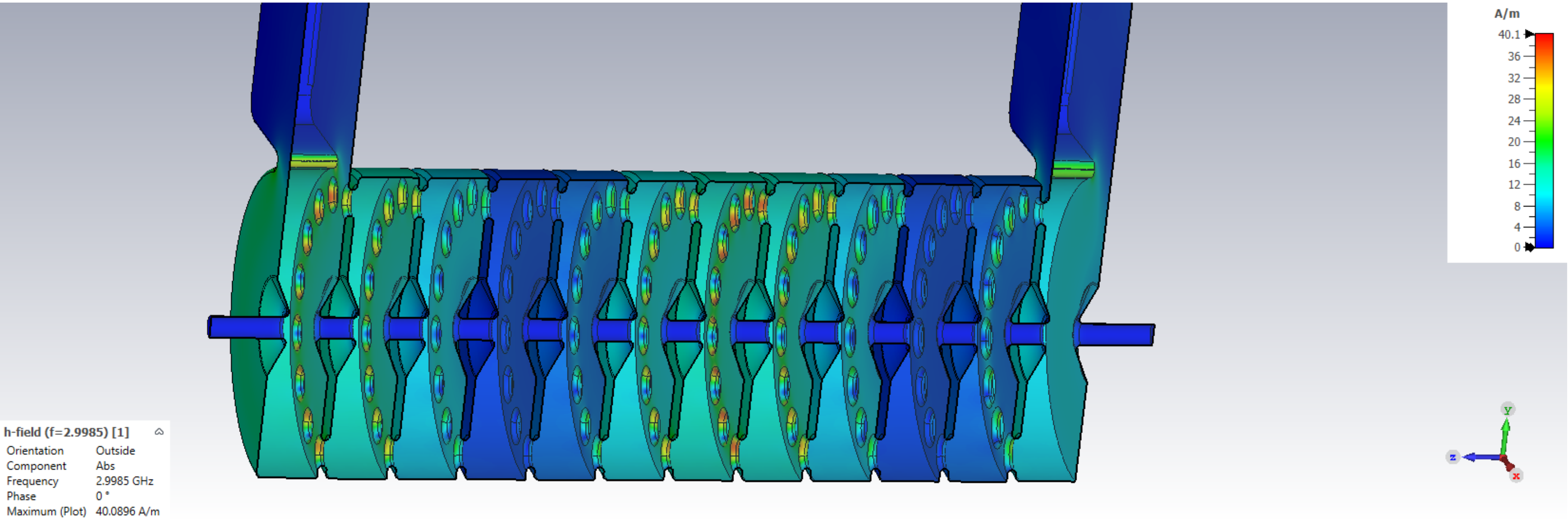
Electric field intensifies in the irises:

- ❑ Dark current in the irises

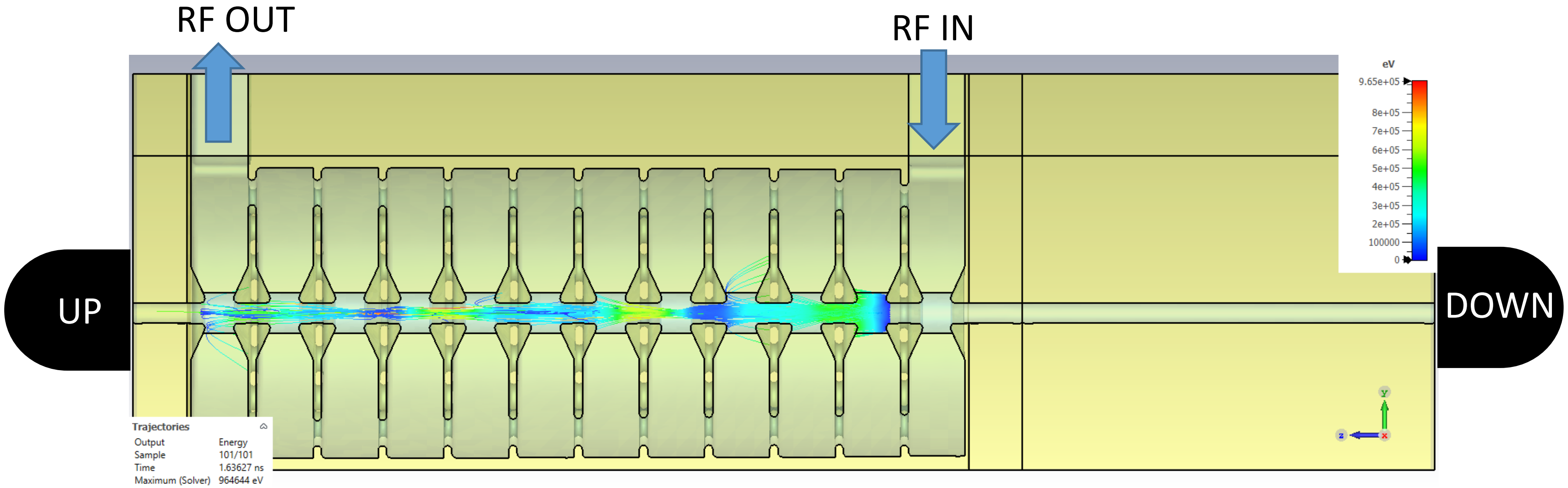
Magnetic field intensifies in the holes:

- ❑ Power travels through the holes.





Dark currents tracking with CST



Procedure:

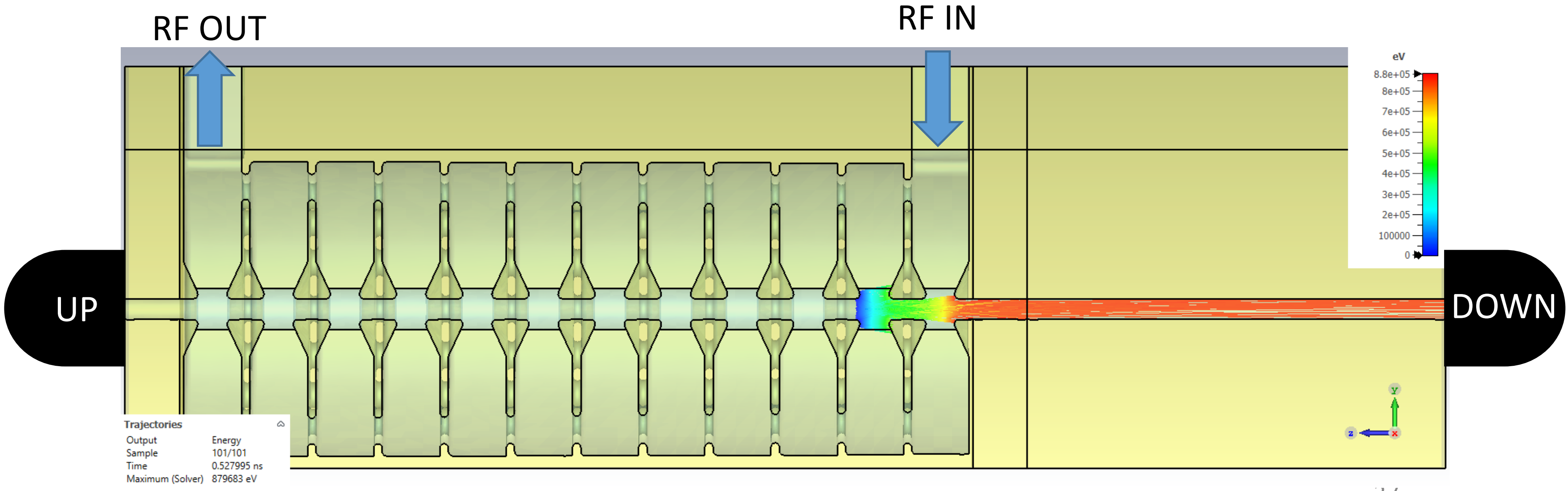
- ❑ Field emission from a certain cell.

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

- ❑ Tracking of emitted electrons.

We can study:

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



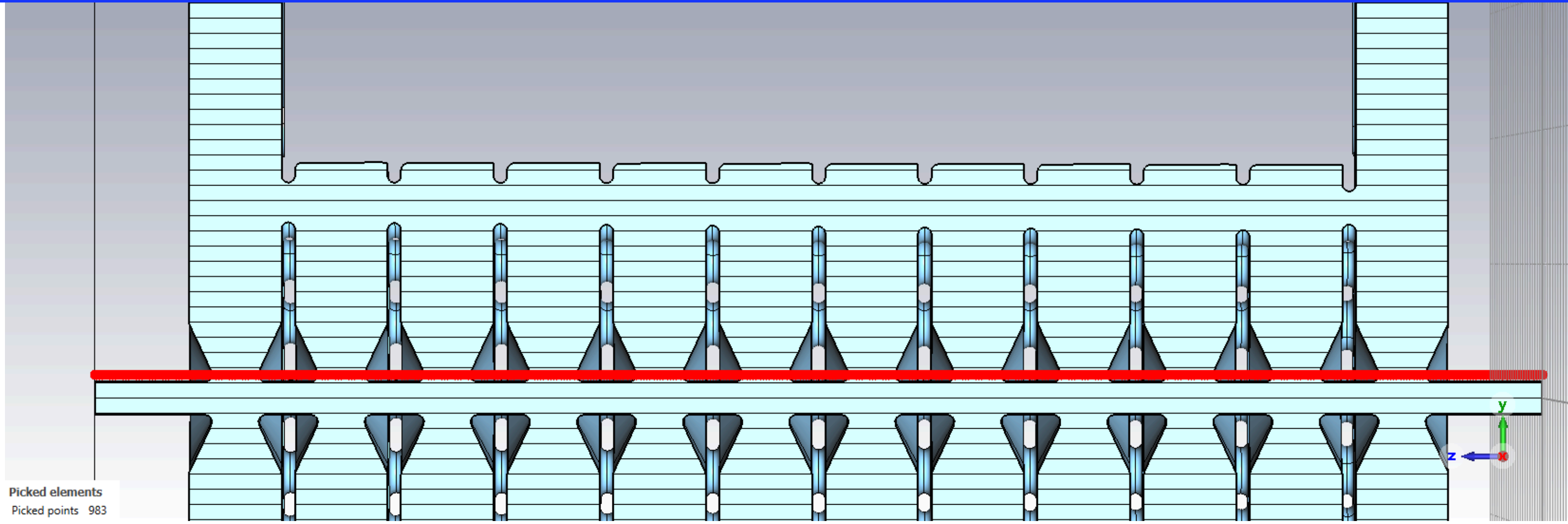
Scans:

- ❑ Emission cell
- ❑ RF power

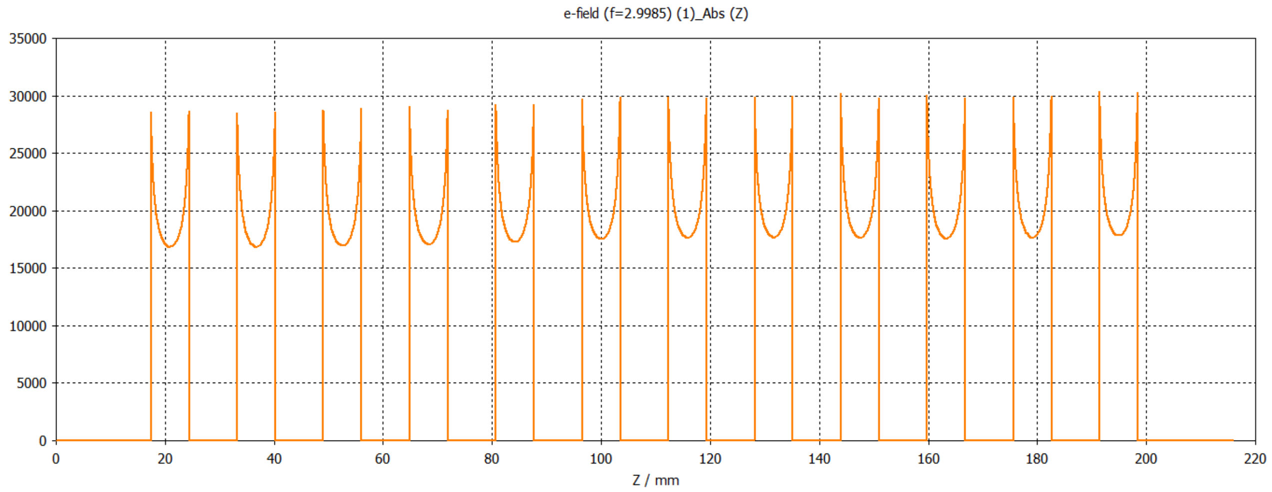
Electromagnetic studies with CST

We have to use 2 different solvers in CST

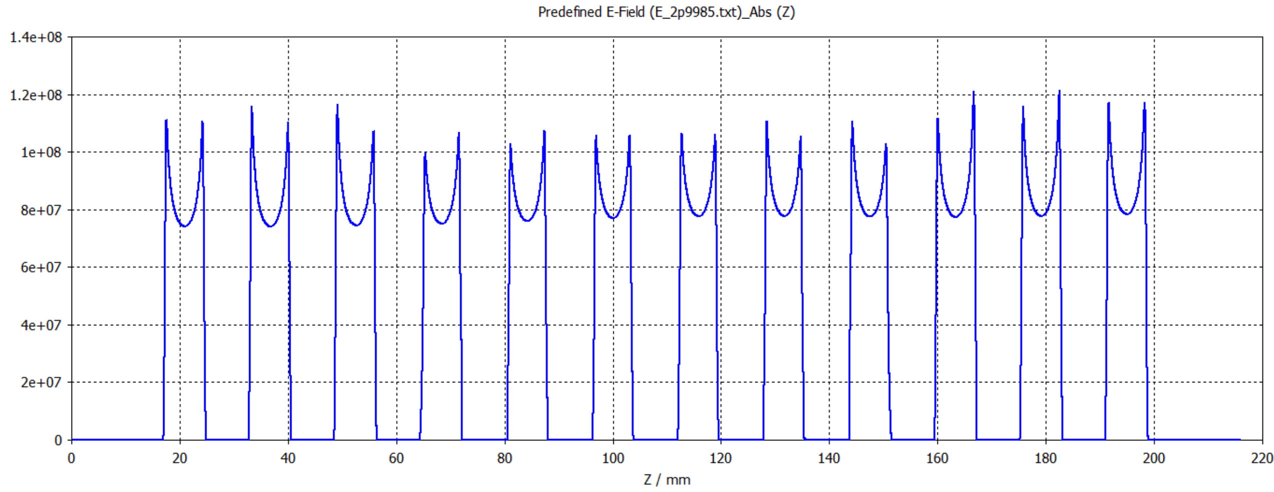
- ❑ First we compute and export electromagnetic fields using Microwave solver.
- ❑ Then we import the fields in Tracking solver to compute electron dynamics.



Microwave simulation



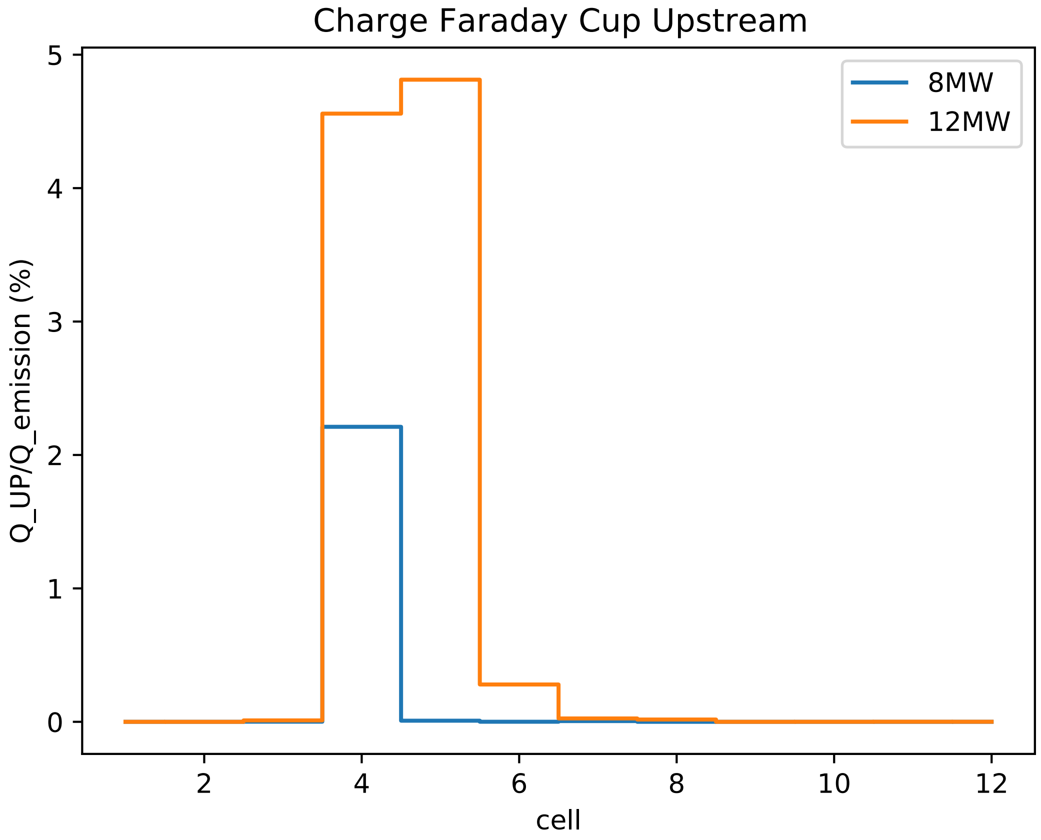
Tracking simulation

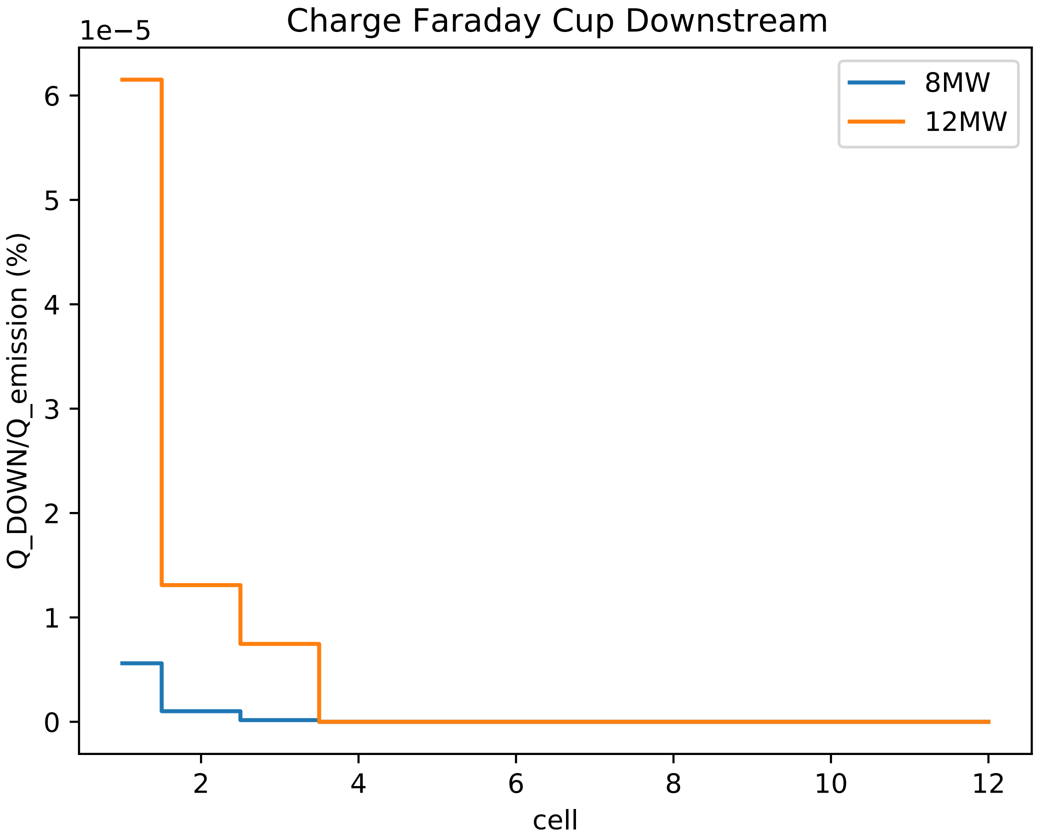


The extreme behaviour of Fowler-Nordheim emission will cause large differences in the emission current for the tracking

Charge collected by Faraday Cups

Power (MW)	Q UPSTREAM/Q EMISSION (%)	Q DOWNSTREAM/Q EMISSION (%)
8	9.14×10^{-3}	2.25×10^{-8}
12	6.60×10^{-2}	5.28×10^{-7}





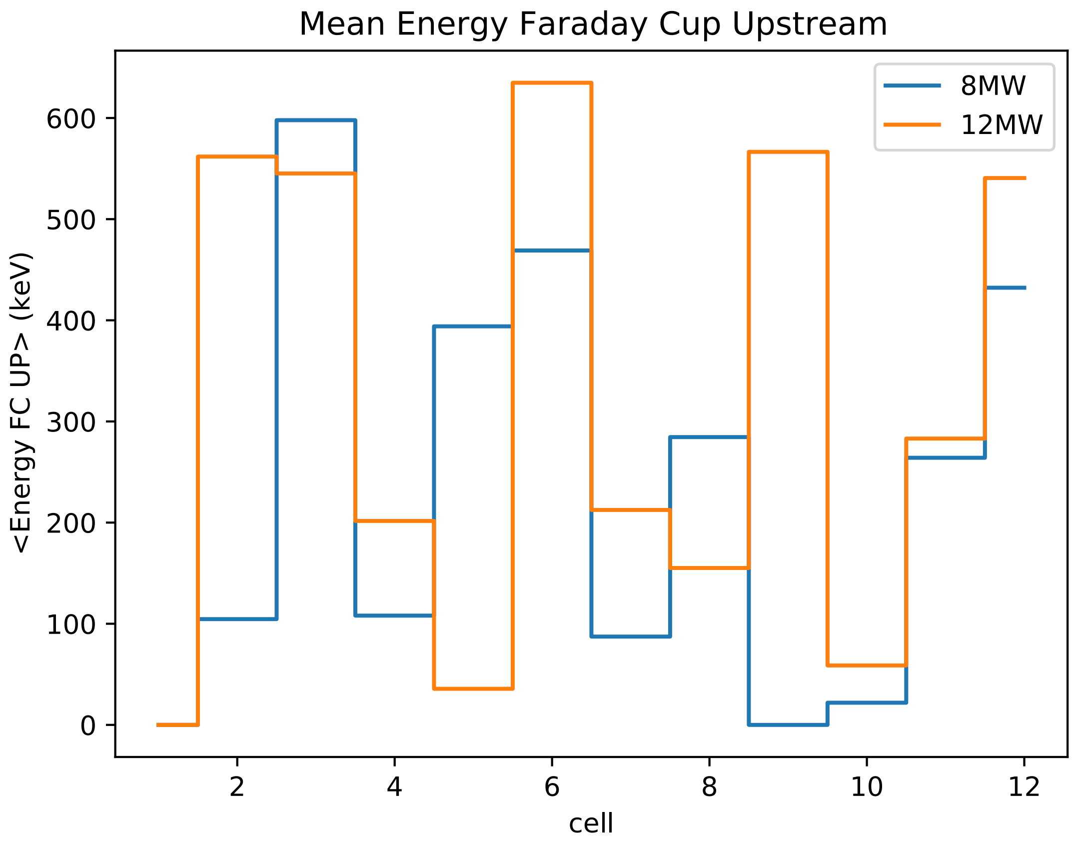
Mean Energy of electrons collected by Faraday Cups

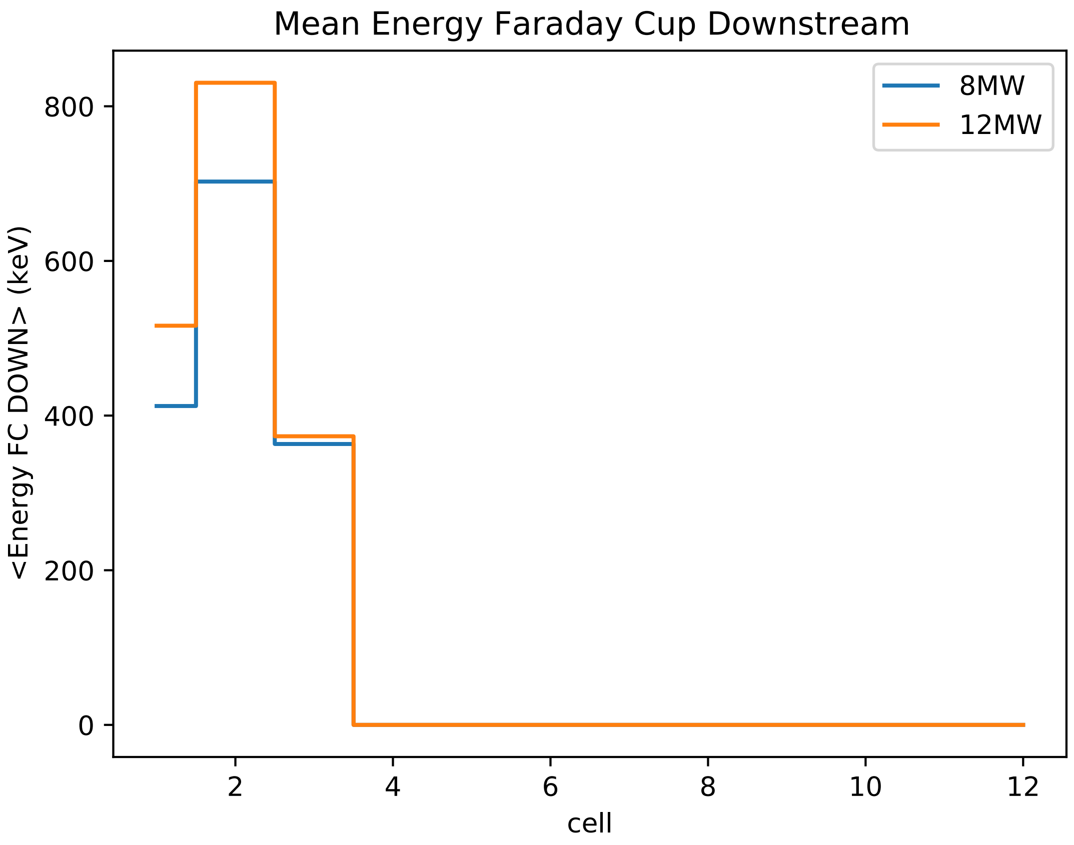
$$< E_{cell}^{FC} >= \frac{\sum_i w_i E_{cell_i}}{\sum_i wi}$$

i: macroparticles reaching FC emitted from cell i

$w_i = Q_i$: macroparticle charge

E_{cell_i}: macroparticle energy





Simulations results

$$< E_j >= \frac{\sum_i w_i < E_i >}{\sum_i wi}$$

i: emission cell

j: Deposited energy cell

$w_i = \frac{Q_i^{cell}}{Q_{emission}^{cell}}$: macroparticle charge normalized

$< E >_i$: Mean electron energy emitted from cell i deposited in cell j