Exploring RF Breakdown and Conditioning in High-Gradient Accelerating Cavities

03.06.2025

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On behalf of CERN SY-RF-MKS, SY-RF-LIS and IFIC accelerator group

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Outline

High power conditioning and Breakdown studies:

➢ BTW cavity for medical applications:
Publication:
https://doi.org/10.1016/j.net.2024.08.033

➢ RFQ2 for Linac4 (ongoing):
Poster:
https://indico.cern.ch/event/1424597/contributions/6532647/

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NUCLEAR ENGINEERING AND TECHNOLOGY

Original Article

High-power performance studies of an S-band high-gradient accelerating cavity for medical applications☆

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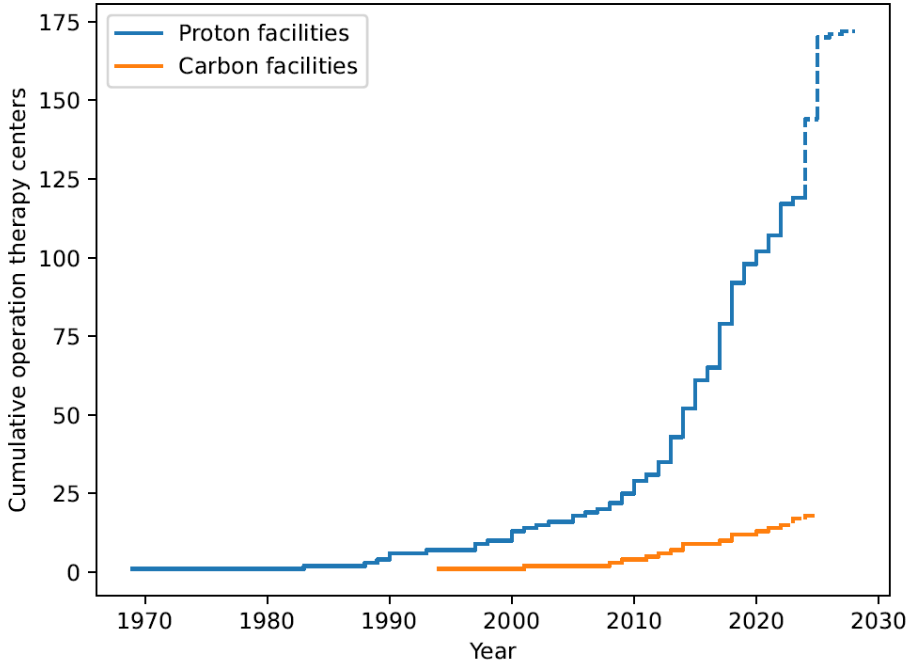
ABSTRACT

High-Gradient accelerating cavities are one of the main research lines in the development of compact linear accelerators. However, the operation of such accelerating cavities is currently limited by non-linear electromagnetic effects that are intensified at high electric fields, such as RF breakdowns, dark currents and radiation. A novel normal-conducting High Gradient S-band Backward Travelling Wave accelerating cavity for medical application (v = 0.38c) has been designed and constructed at CERN with a design gradient of 50 MV/m. In this paper, the high-power performance studies of this novel design carried out at the IFIC high-power laboratory are presented, as well as the analysis of the conditioning parameters in combination with numerical simulations.

Hadron therapy

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**

Hadron Therapy centres are growing fast, but all of them are based on circular machines



Advantages of linacs:

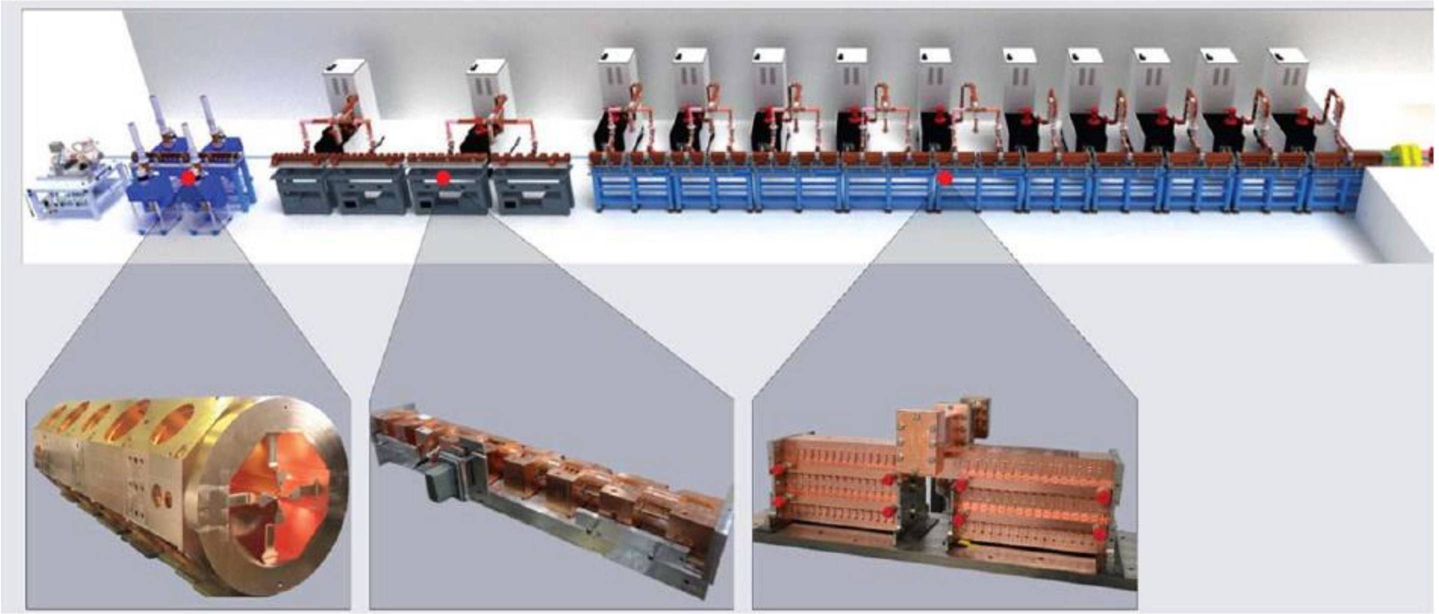
- Fast dose delivery.
- High beam quality.
- High repetition rate.
- Almost 100% of transmission: low radiation levels.

Technological challenges:

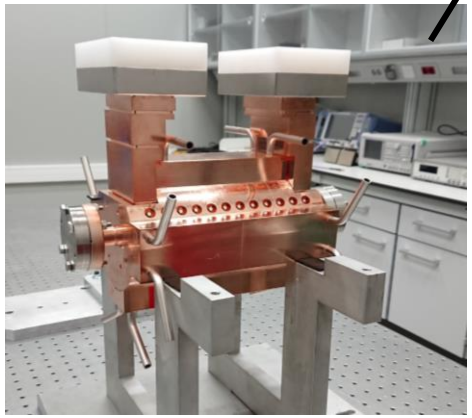
- Large machines.
- Complexity.

Linear accelerators for hadron therapy

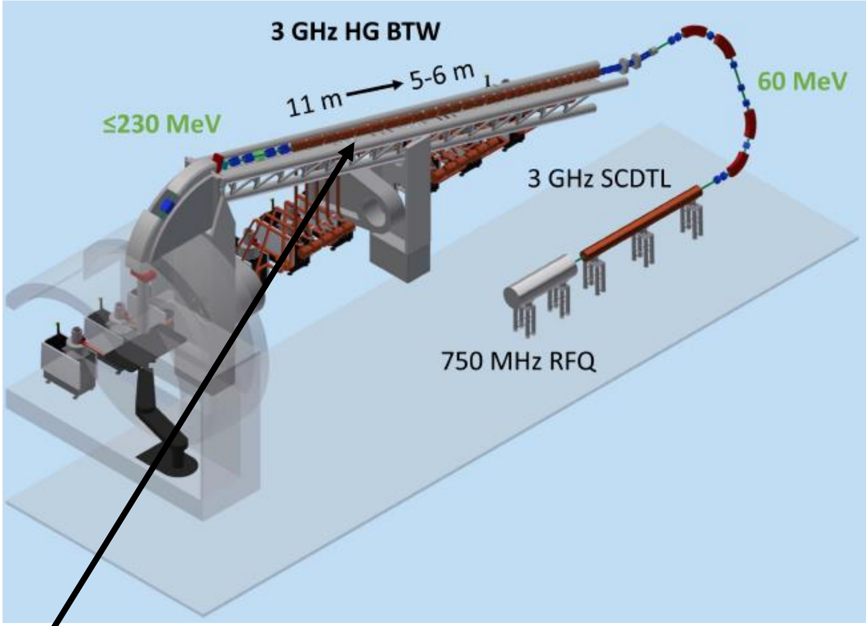
LIGHT project by A.D.A.M



- 230 MeV proton beam at 200 Hz.
  Coupled Cavity Linac:
- 18-20 MV/m.
- Total length ~28 m.

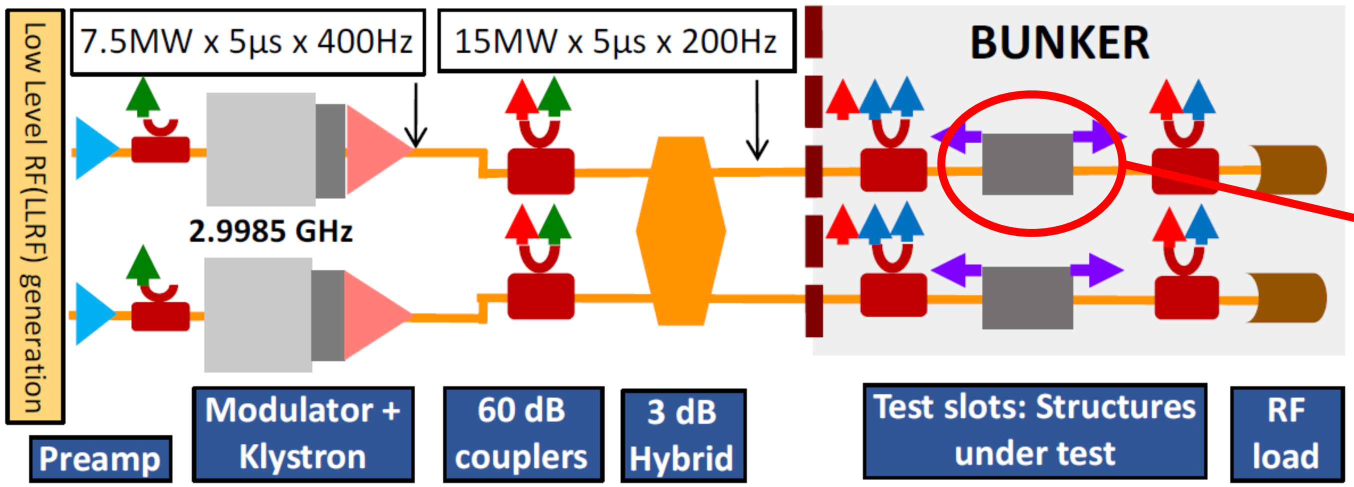


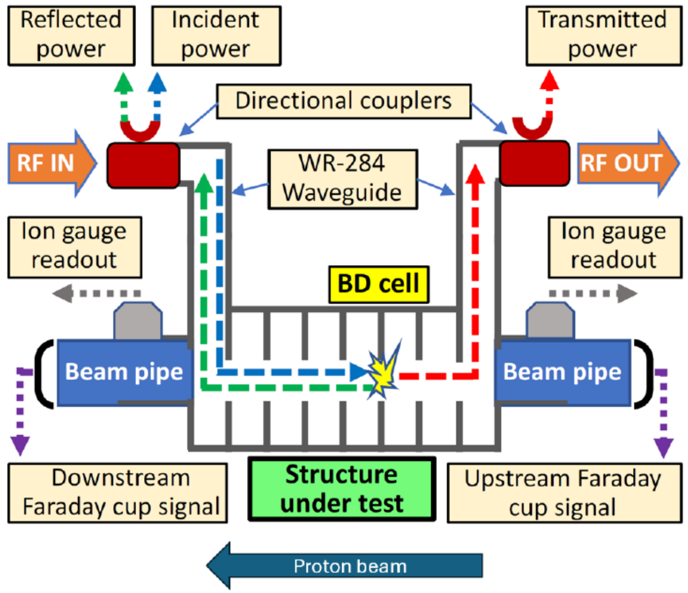
TULIP project

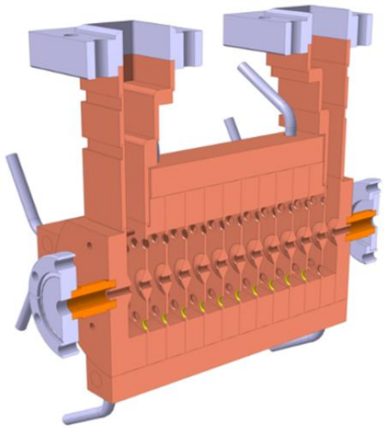


- 230 MeV proton beam at 200 Hz.
- BTW cavities: 40 MV/m.
- Length reduced by a factor 2.

IFIC High-Power S-band facility and BTW structure



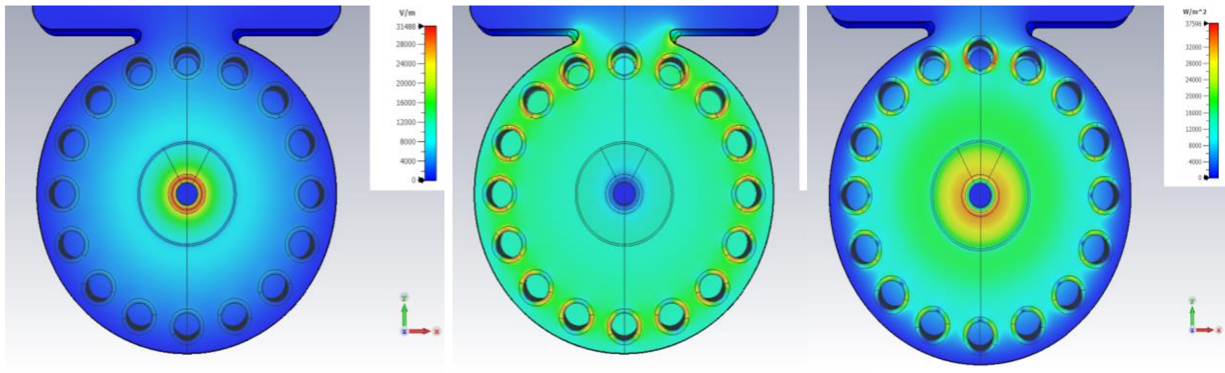




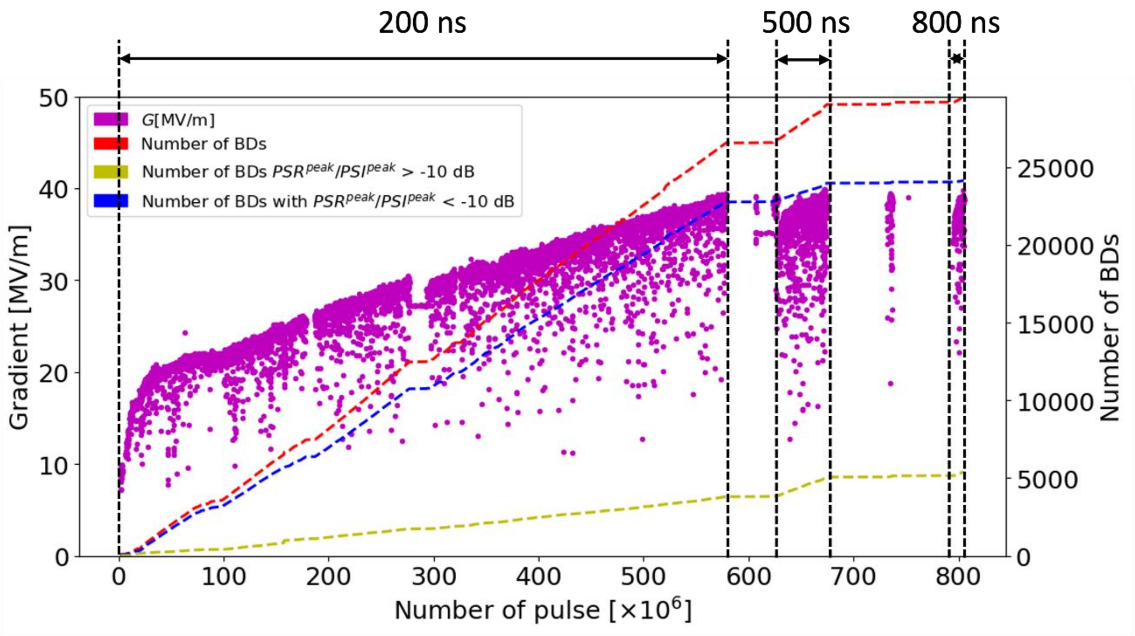
Designed at CERN for $E_a = 50$ MV/m:

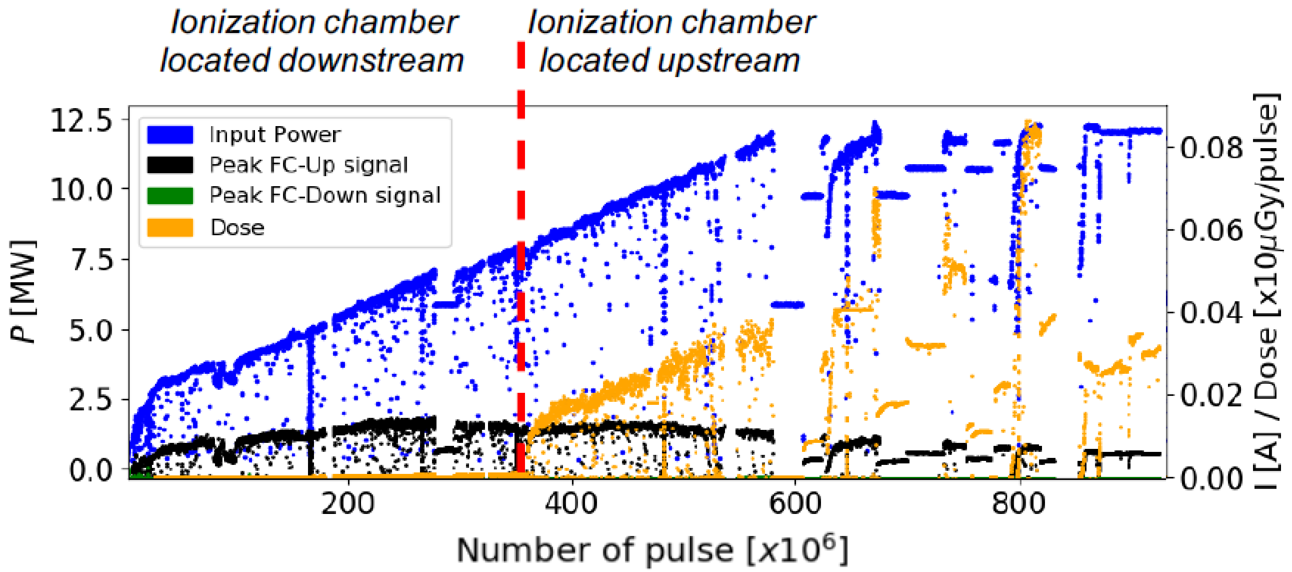
1. RF conditioning evolution
2. Breakdown localization
3. Field emission electron dynamics
4. Radiation characterization

E-field H-field S_c



RF conditioning





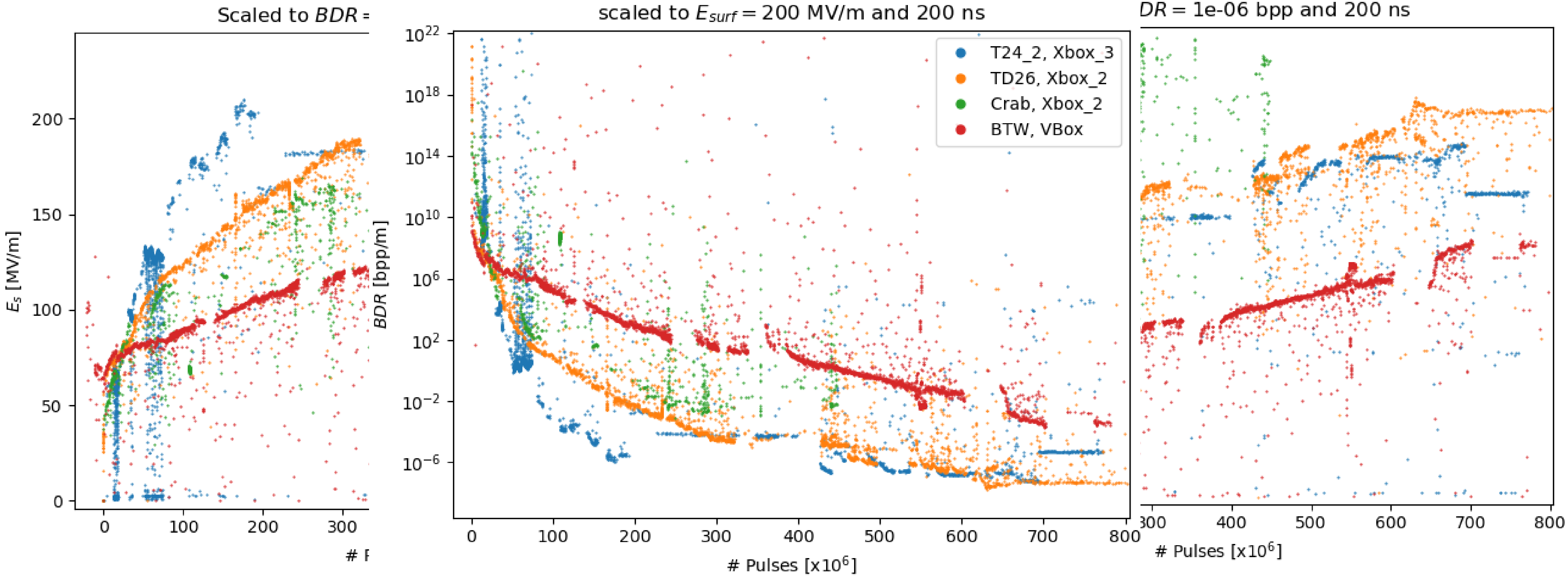
- E_a up to 39 MV/m.
- 800 M pulses.
- Over 25000 BDs.
- Limited by lab peak power.

- FC down signal ~ 0.
- FC up signal saturates.
- Dose reduced with conditioning.

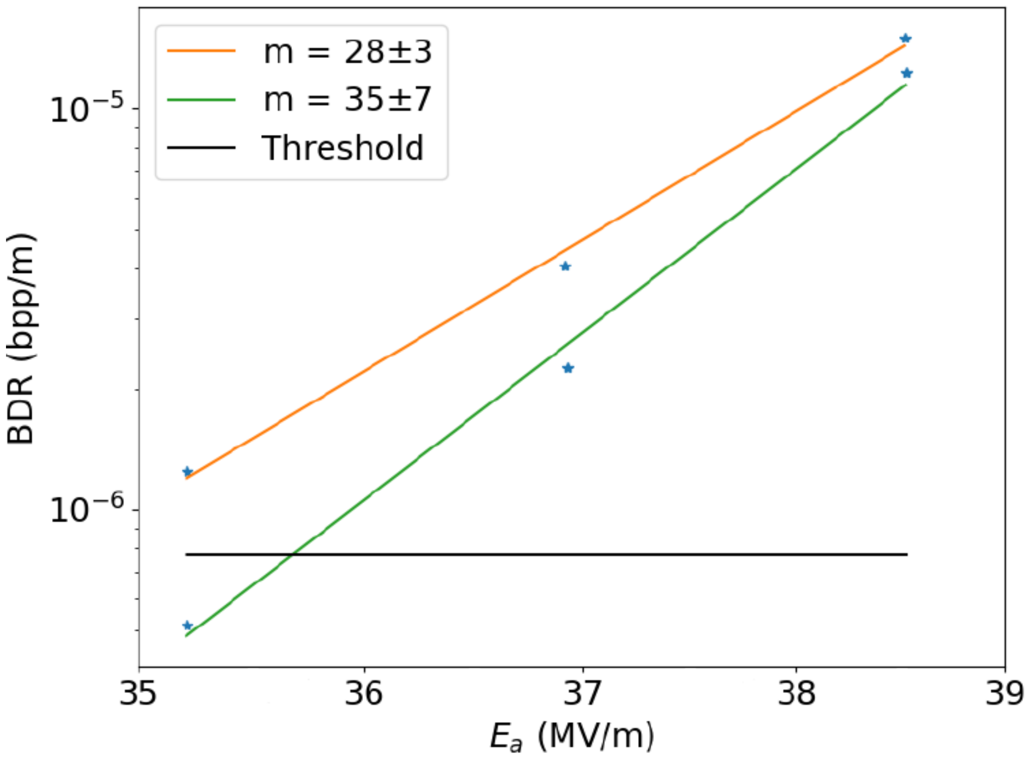
Comparison with other tests

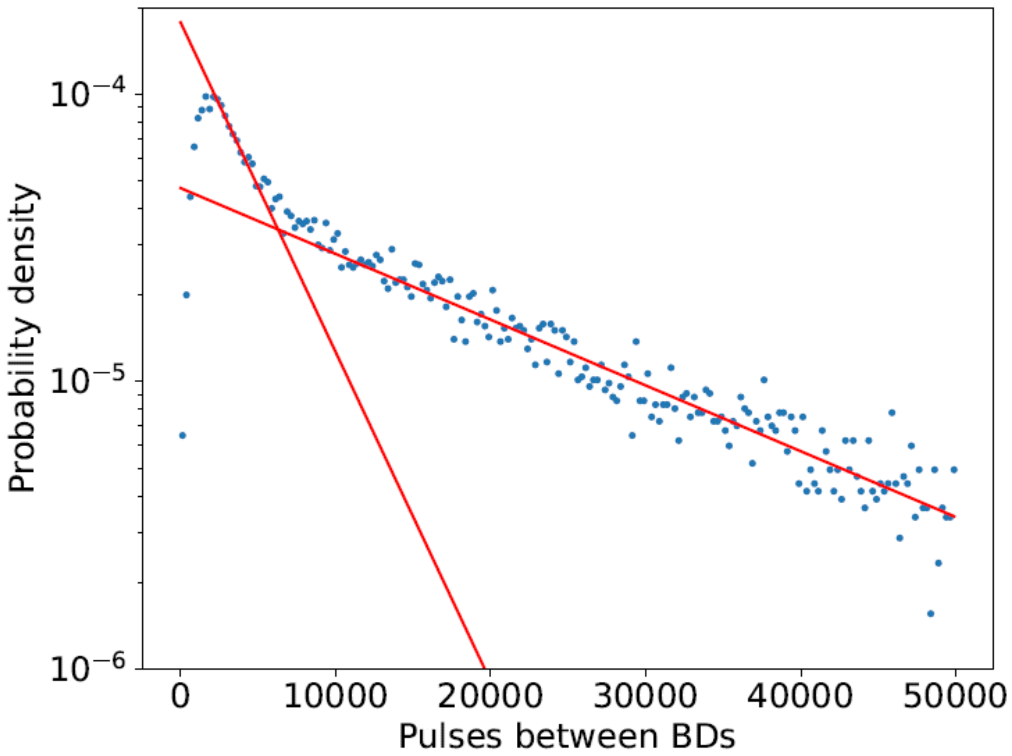
Structure	f [GHz]	Mode
TD24 N2	11.994	TM01
TD26	11.994	TM01
Crab cavity	11.994	TM11
BTW	2.9985	TM01

Normalization factor: $BDR \propto E_a^{30} \tau_p^5$



BD studies





- Good agreement with previous results: $BDR \propto E_a^{30}$
- BDR decreases after operating at constant power.

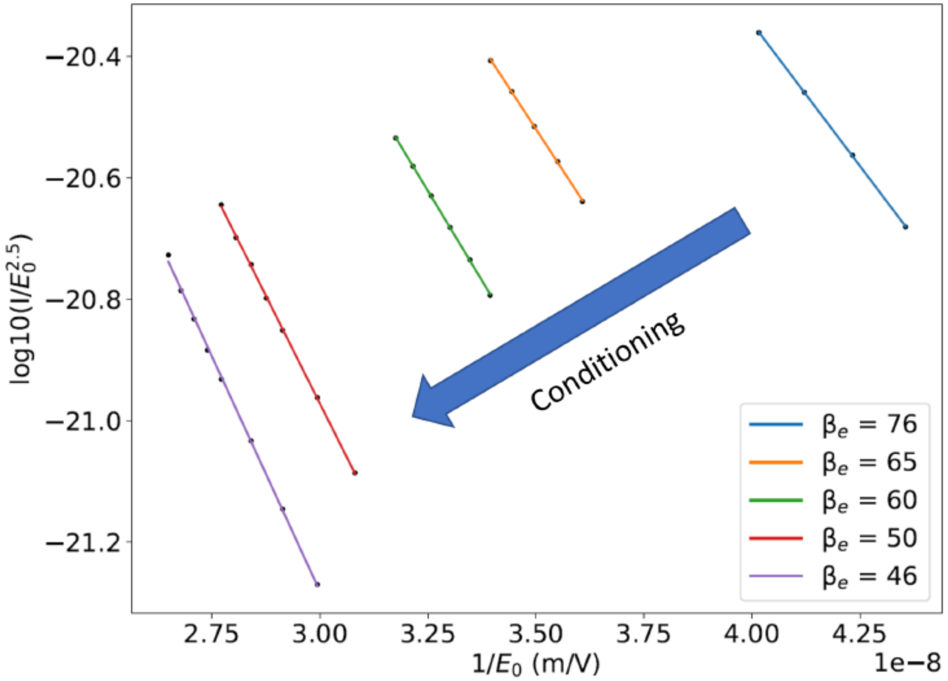
- Double exponential: tendency of BDs to produce clusters.

$$PDF = Ae^{-an} + Be^{-bn}$$

Enhancement factor evolution

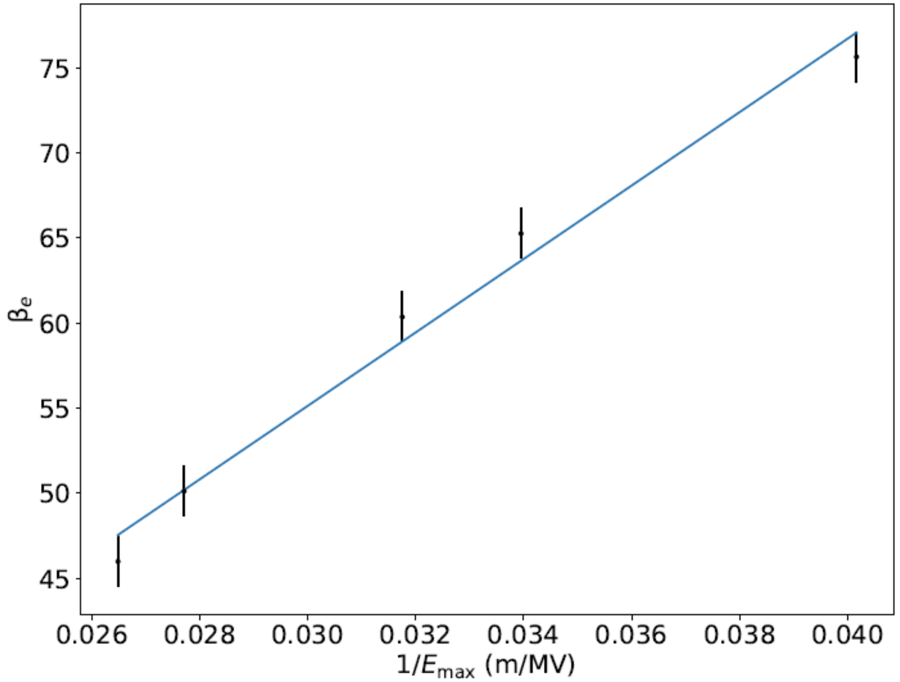
- Dark current scans were performed at different stages of conditioning.
- β_e can be fit for each scan.

$$\frac{d\log_{10}(I/E_s^{2.5})}{d(1/E_s)} = -\frac{G\phi^{3/2}}{\beta_e}$$

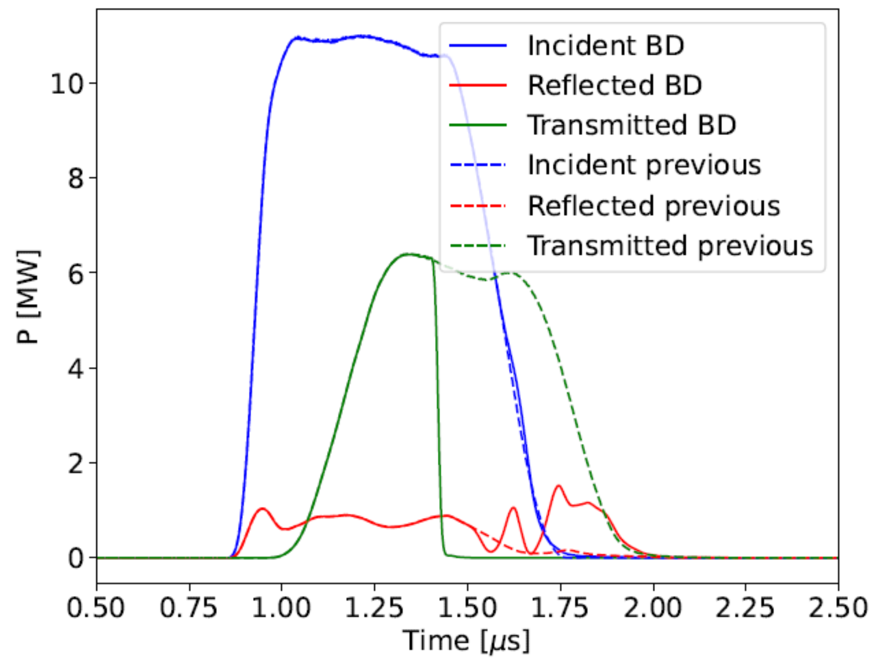


- β_e evolution during conditioning.

$$\beta_e E_{max} = \text{constant}$$



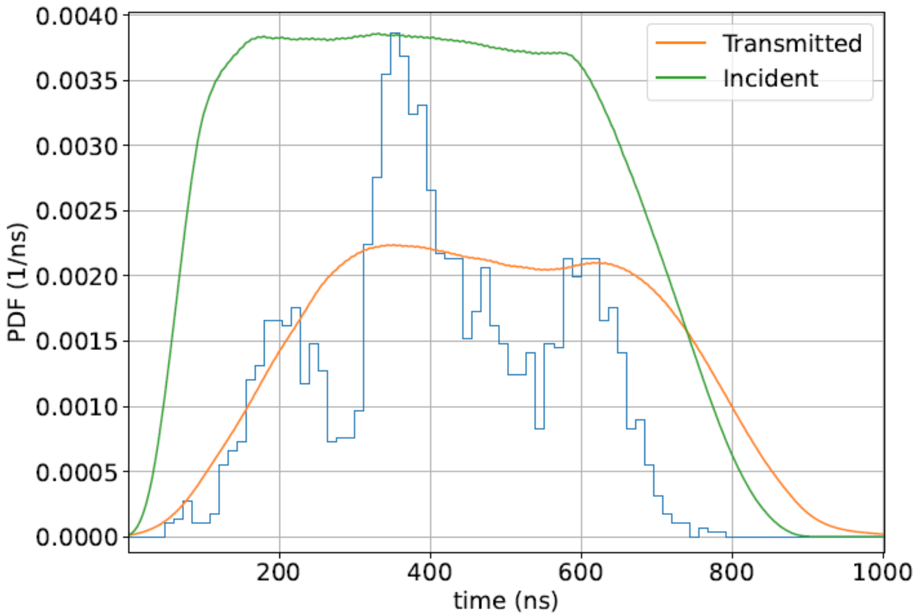
BD localization: Edge method



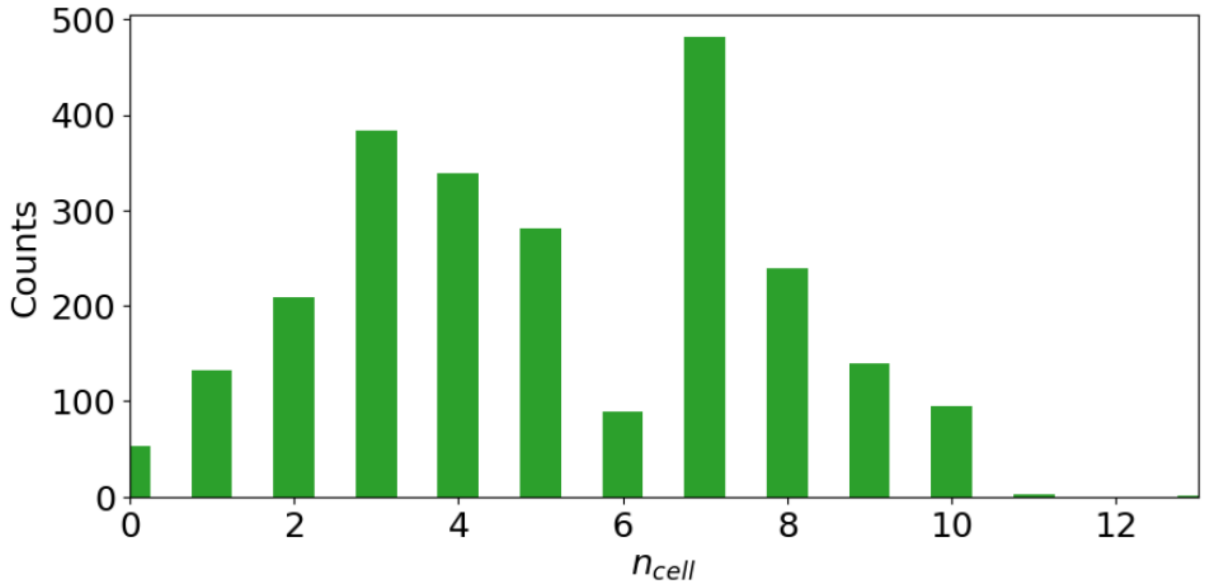
- Search of reflection rise and transmission drop.

$$t_{edge} = \frac{\Delta t_{ref} - \Delta t_{tra}}{2}$$

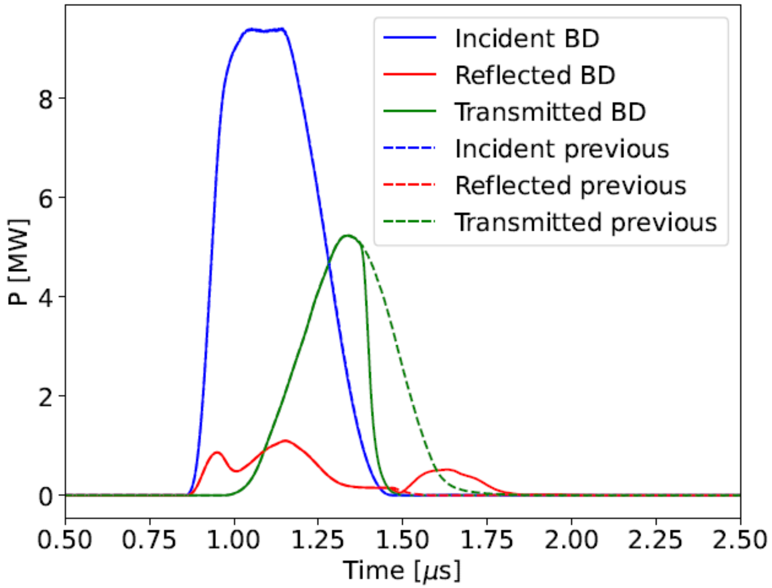
$$t_{edge} = \sum_{n=1}^{n_{BD}} \frac{L_n}{v_g(n)}$$

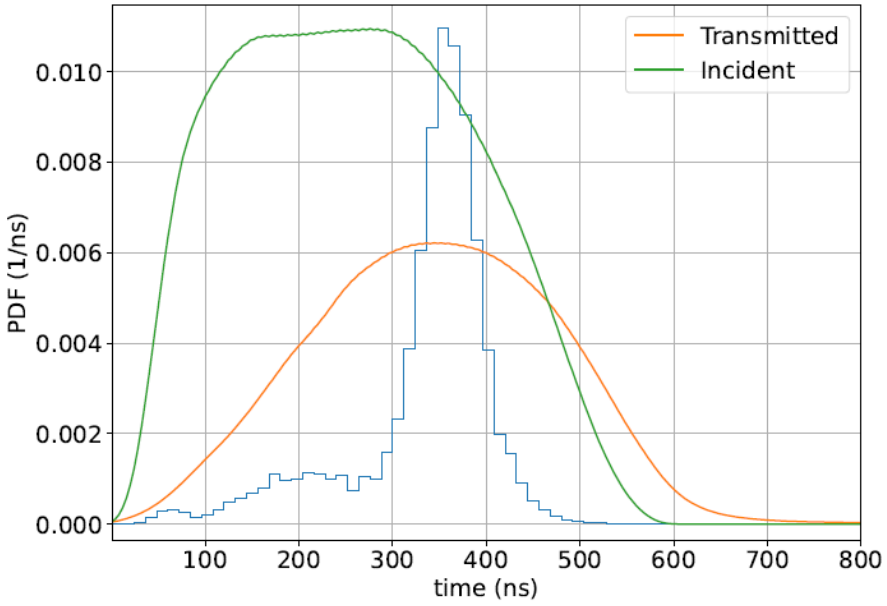


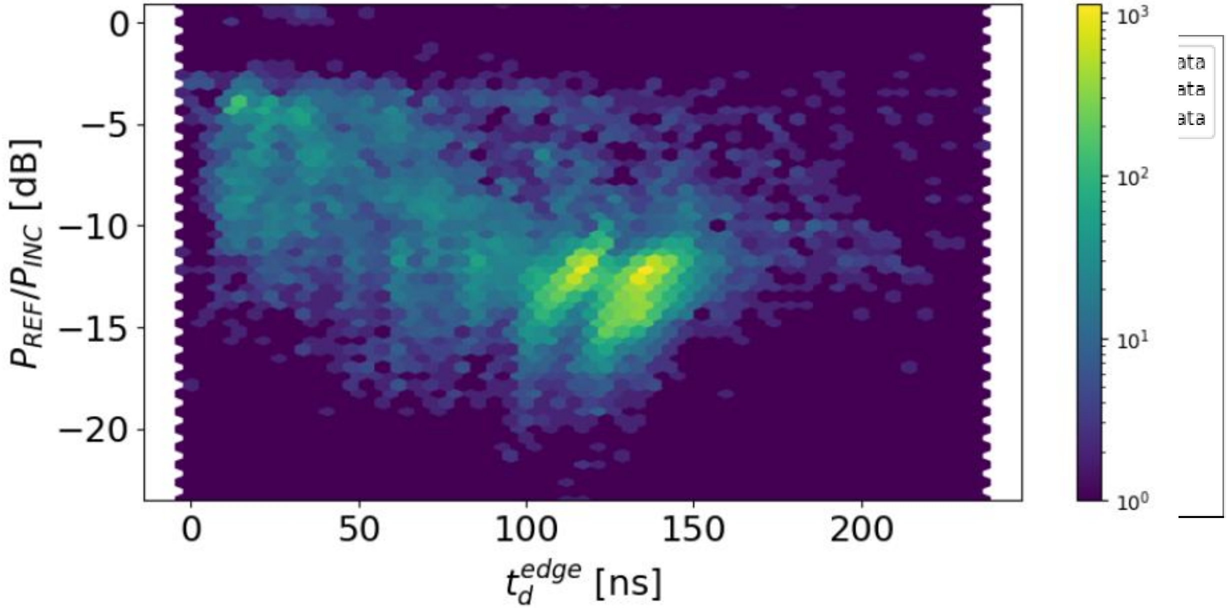
- **No hot cells detected**



BD localization: Short pulses



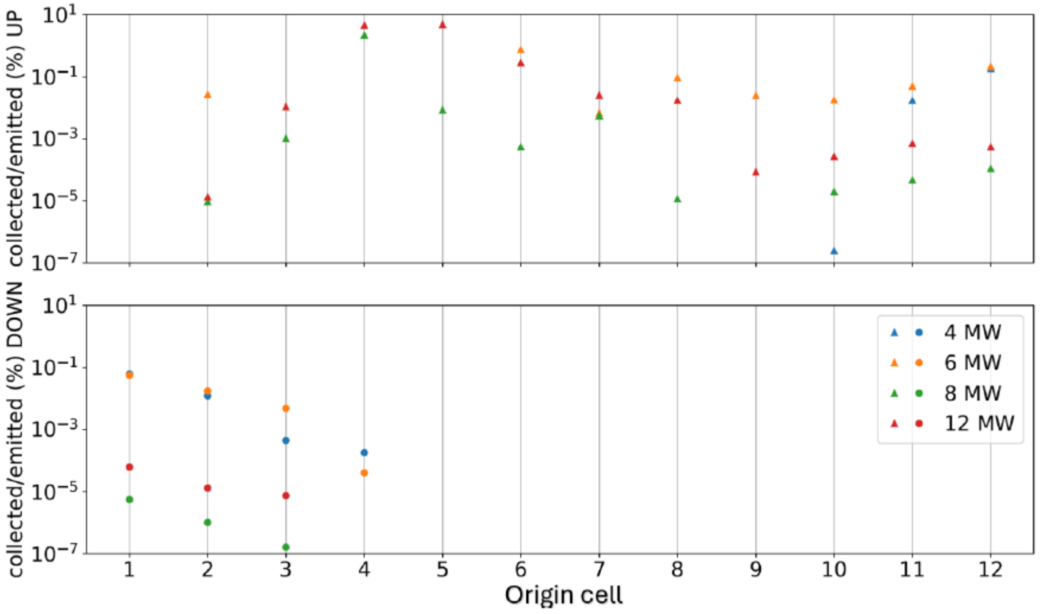


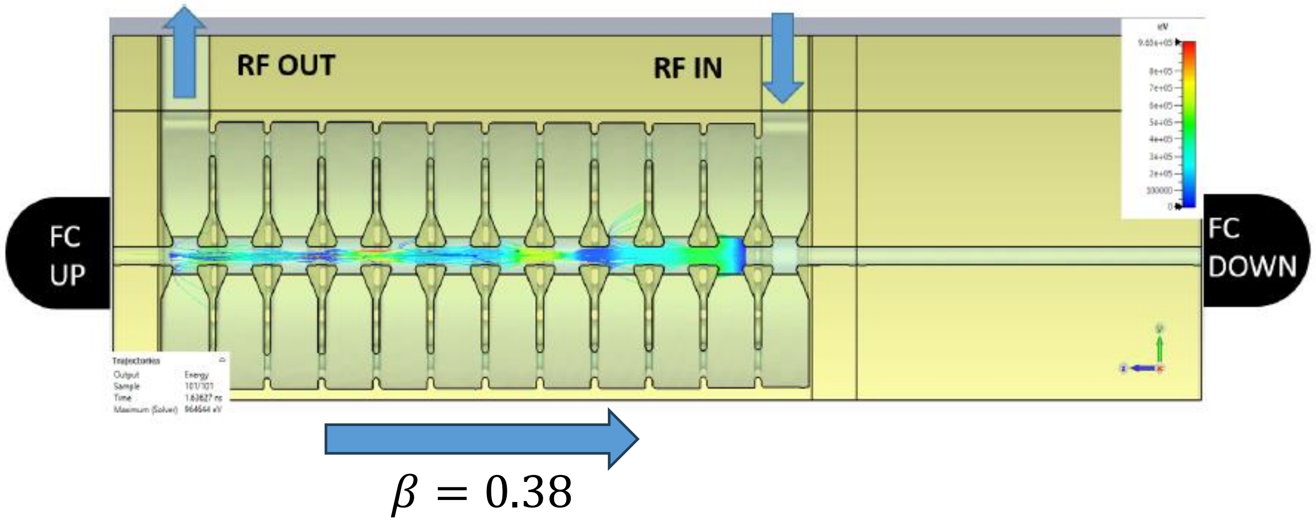


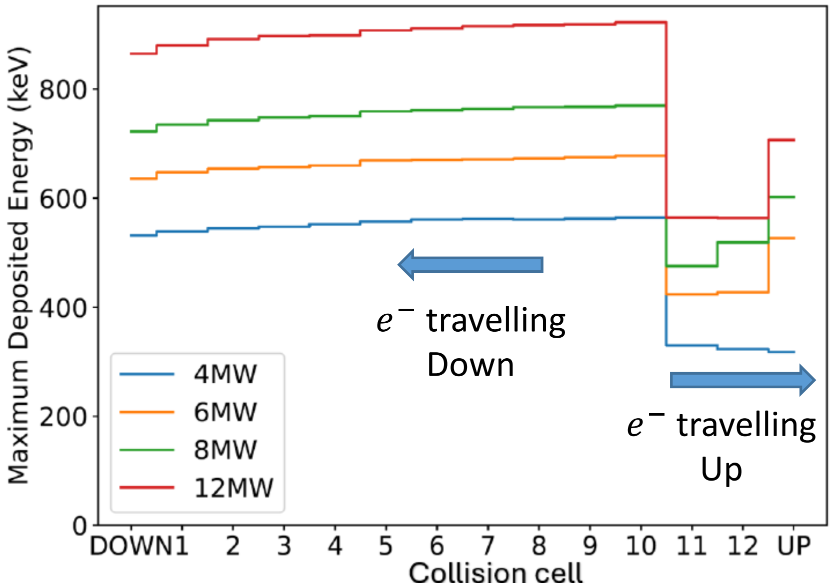
- Transmitted pulse does not show a flat top: rise time must be increased.
- High accumulation of BDs characterized by low reflection and similar t_{edge}.

Dark current dynamic simulations

- Electrodynamic simulations in CST for field emitted electrons:
  - Ratio of e^- reaching FC.
  - Energy deposited by e^-.
- Scans:
  - Emission cell.
  - Input RF power.

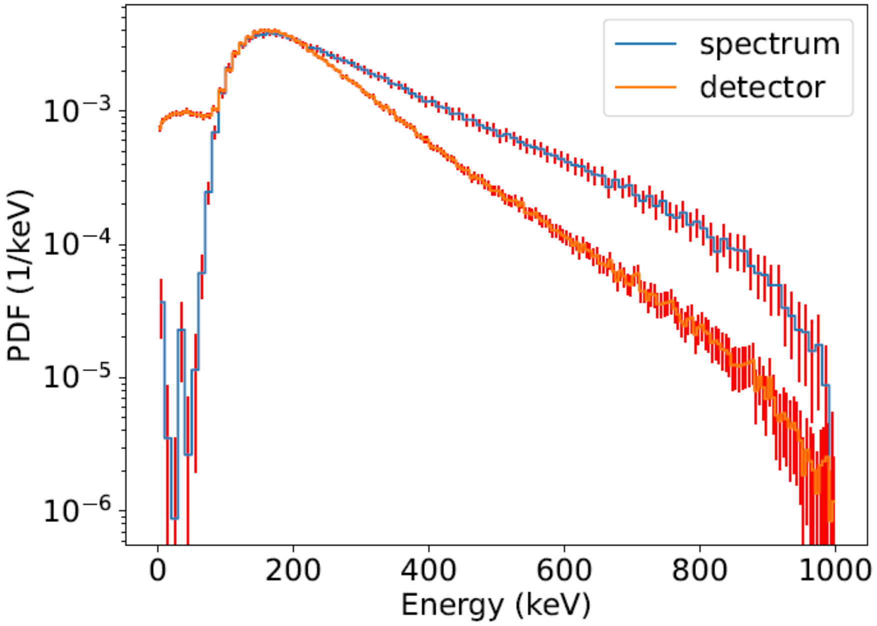






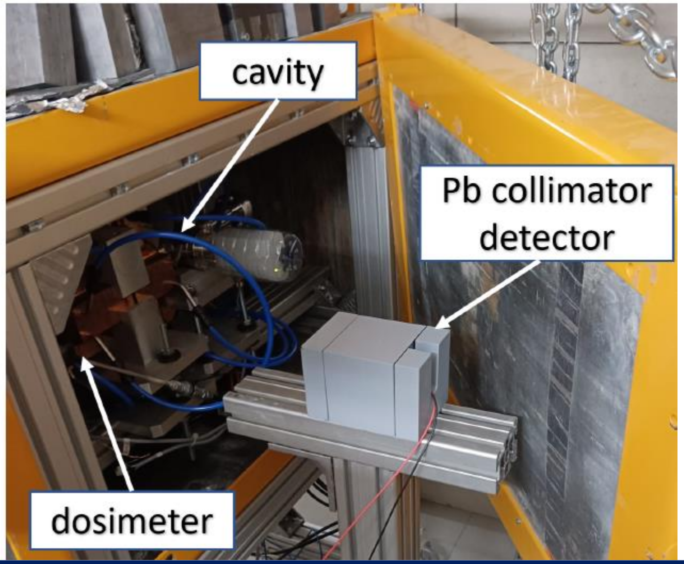
Radiation simulations and measurements

- Simulation:
  - e^- interacting with Cu wall.
  - X-rays photons produced by bremsstrahlung.
  - Spectrum decays exponentially up to maximum energy of incoming e-.

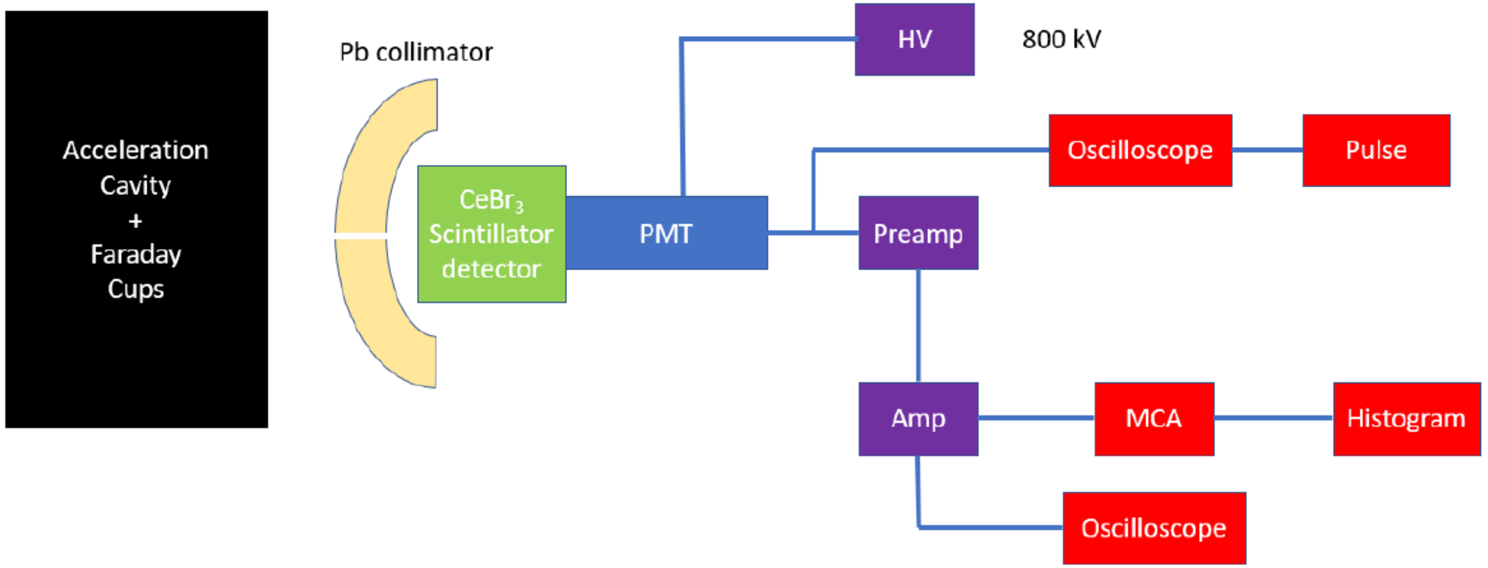


- Measurement challenge:
  - High fluence of photons during RF pulse: huge pile-up.

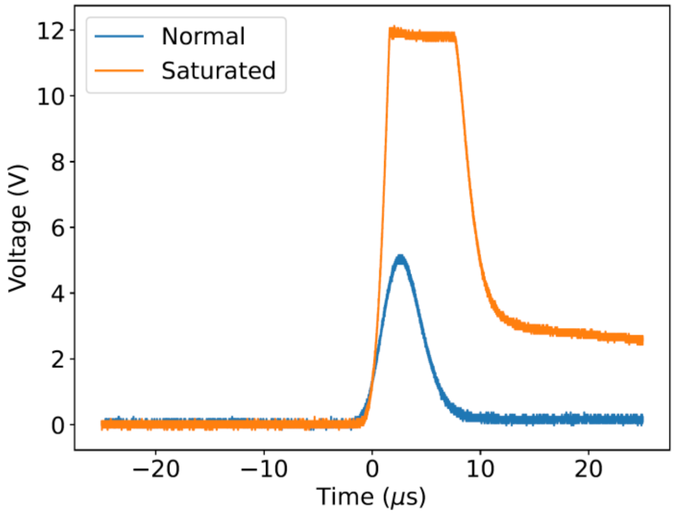
- Solution:
  - Small $CeBr_3$ scintillating crystal detector.
  - Pb collimator system: Holes of 4 and 2 mm.
  - Measurements directly from PMT.



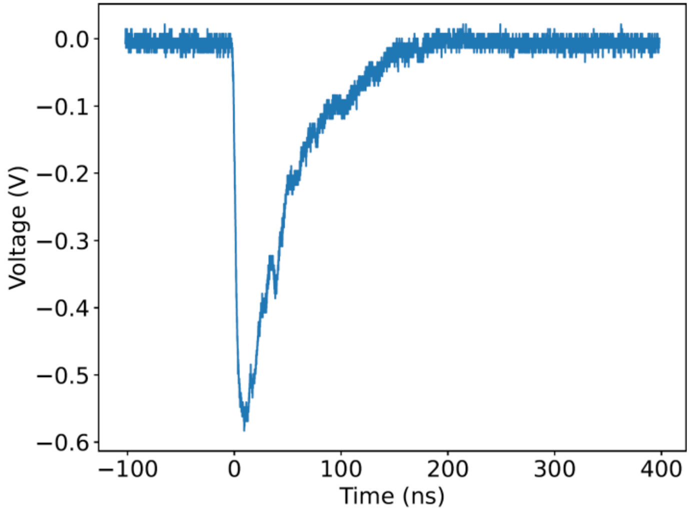
Spectrum measurement set-up



Pulse Amp

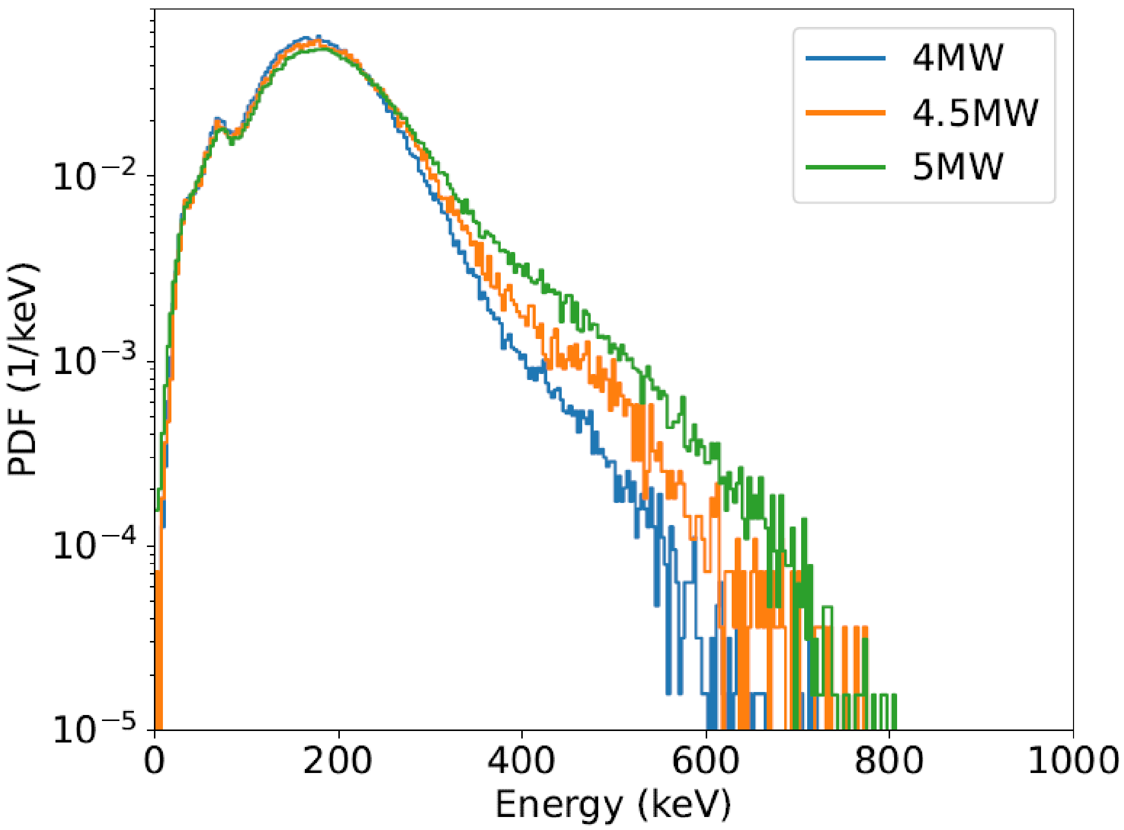


Pulse PMT

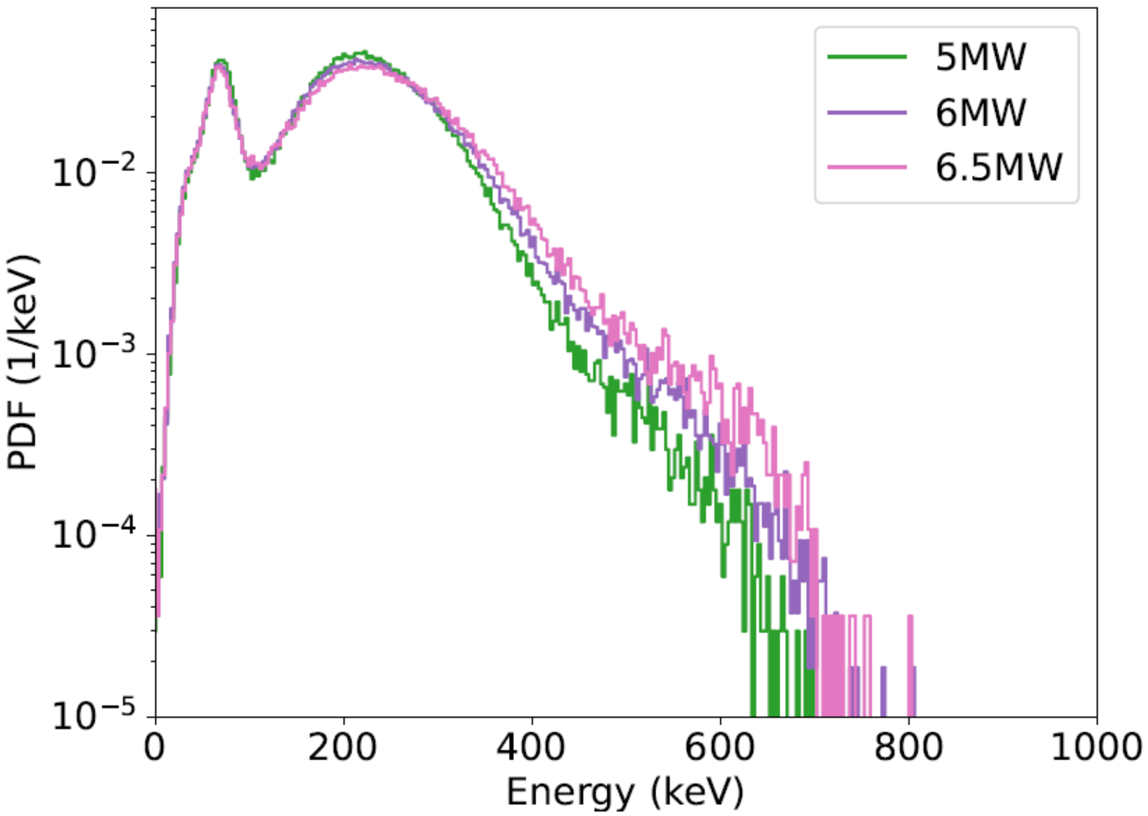


Spectrum measurements

4 mm hole



2 mm hole



- Maximum energy of photons in agreement with dark current e^- simulations.
- Measurement campaign stopped due to a klystron mulfunctioning.

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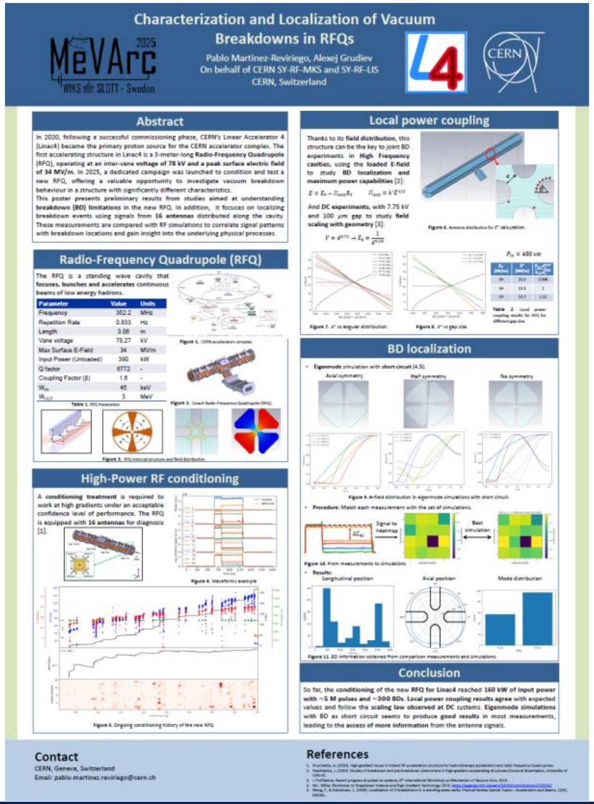
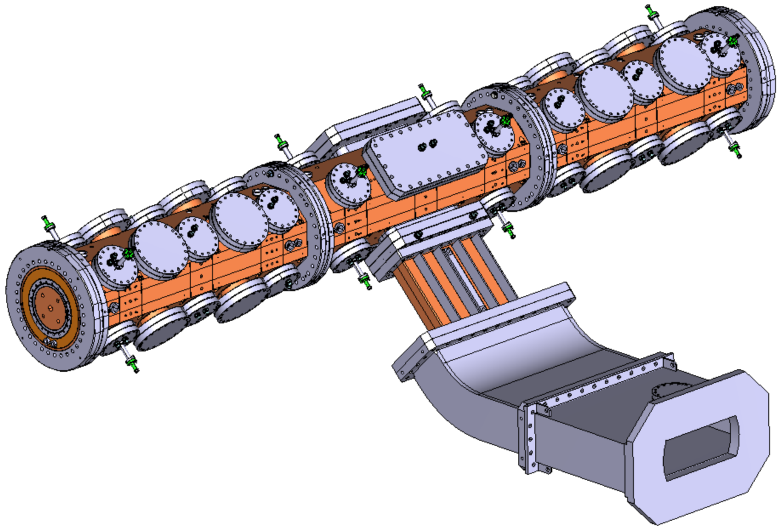
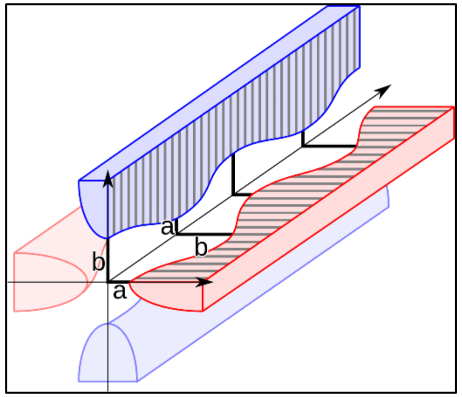
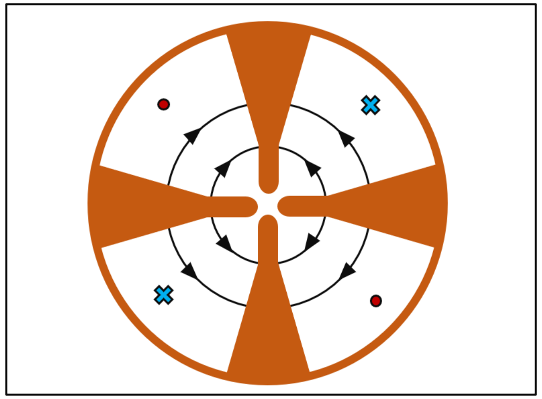


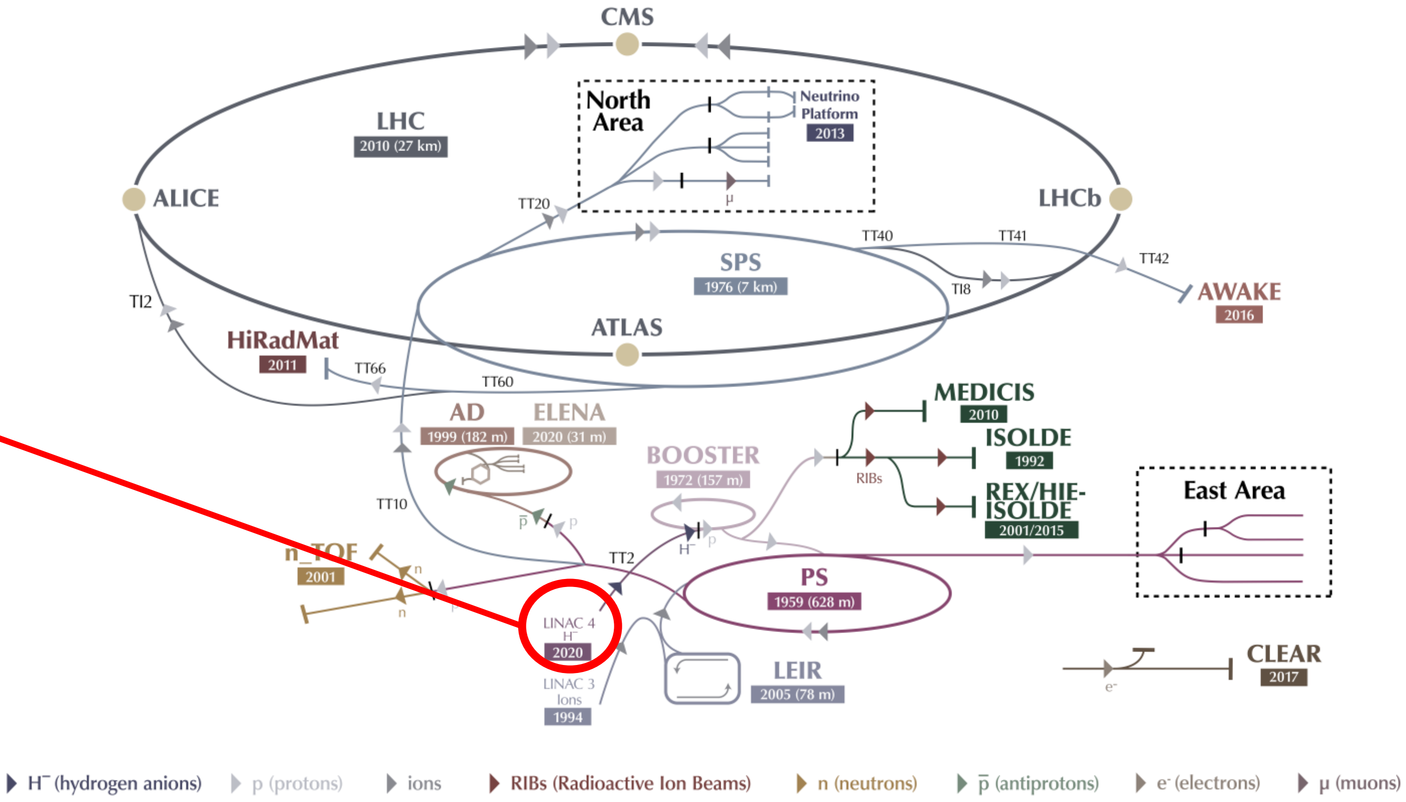
Radio Frequency Quadrupole (RFQ)

~3 m structure that **focuses, bunches and accelerates** continuous beam of low energy hadrons (few MeV)



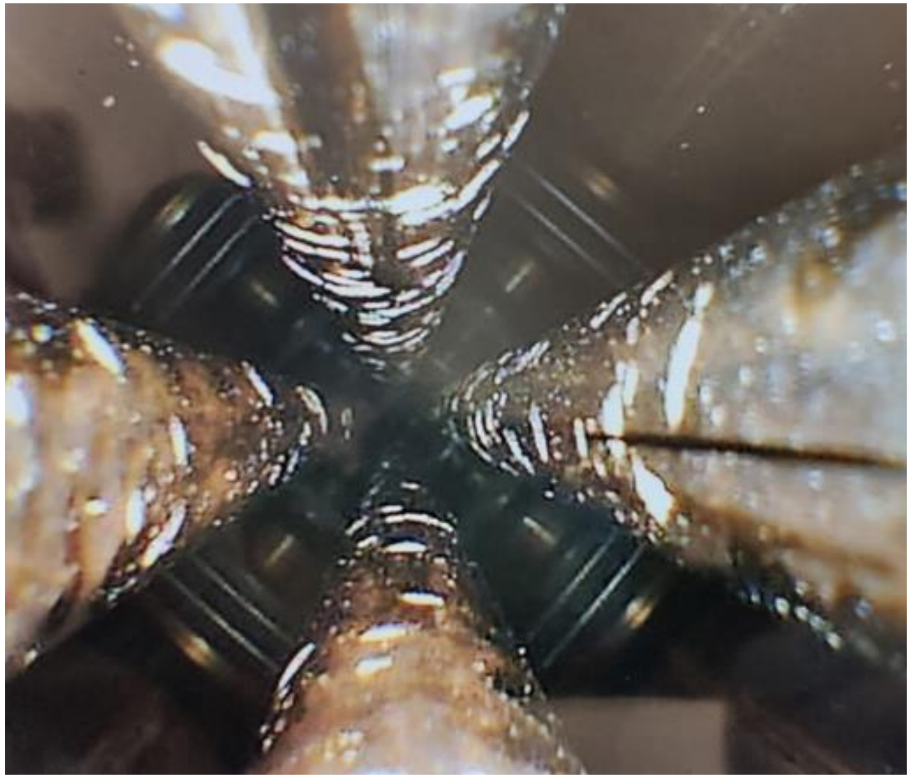






The Linac4 RFQ

Surface damage observed in Linac4 RFQ



Critical element in CERN proton chain: No spare

Hypothesis:

H^- irradiation → Degradation → More BDs

Serafim, C., Calatroni, S., Djurabekova, F., Peacock, R., Bjelland, V., Perez-Fontenla, A. T., ... & Sargsyan, E. (2025). Effects of H− low beam irradiation and high field pulsing tests in different metals. *Physical Review Accelerators and Beams*, *28*(1), 013101.

Solution:

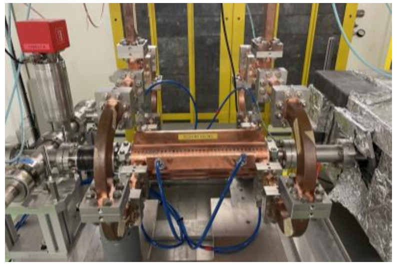
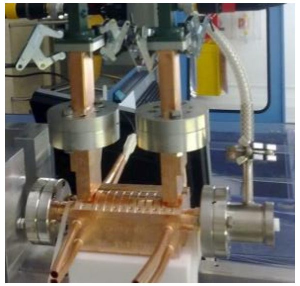
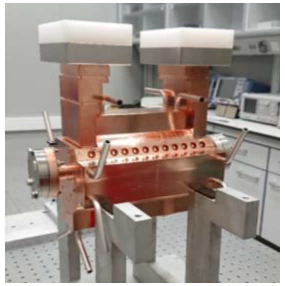
New RFQ fabrication and **conditioning**

↓

Great opportunity for BD studies!

Limitation: New RFQ must survive the conditioning

A very different structure

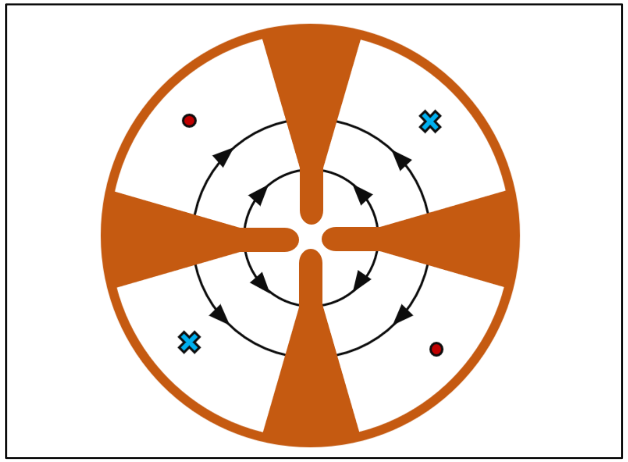





Parameter	CLIC T24	Crab cavity	BTW (hypothetical)	RFQ
Type	Travelling wave	Travelling wave	Travelling wave	Standing wave
Mode	TM01	TM11	TM01	TE210
f [GHz]	11.994	11.994	2.9985	0.352
Length [m]	0.2	0.24	0.190	3.06
Repetition Rate [Hz]	20 - 200	50	20 - 200	0.833
Pulse length [μs]	0.2	0.2	2.5	1000
P_{in} [MW]	42.4	40	33	0.4
Max. E-field [MV/m]	220	154	281	34
Max. H-field [kA/m]	410	505	319	5.17
Max. S_c [$\mathrm{MW/mm^2}$]	3.4	5.48	5.13	0.01
E^* [MV/m]	123	105	115	**?**

Paszkiewicz, J. (2020). Studies of breakdown and pre-breakdown phenomena in high-gradient accelerating structures (Doctoral dissertation, University of Oxford).

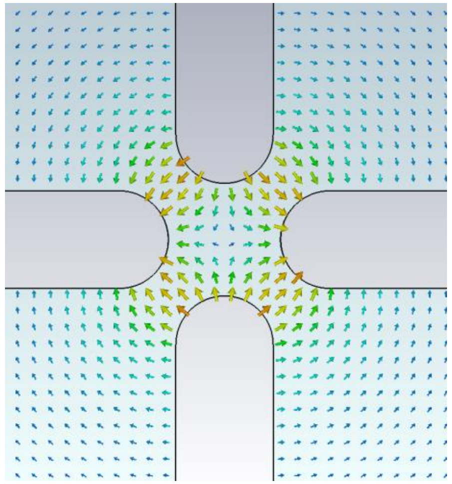
Field distribution

RFQ cross section:
TE210 mode

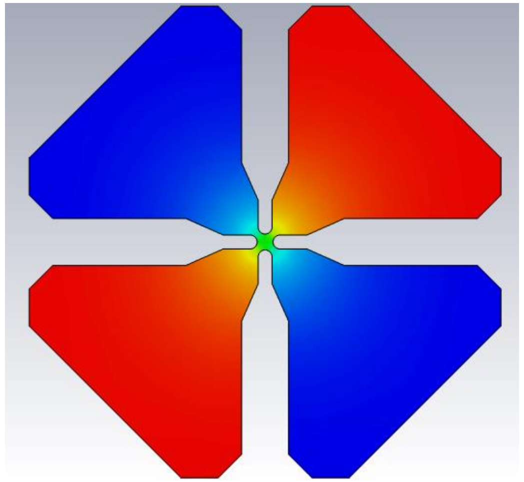


Large separation between electric and magnetic field

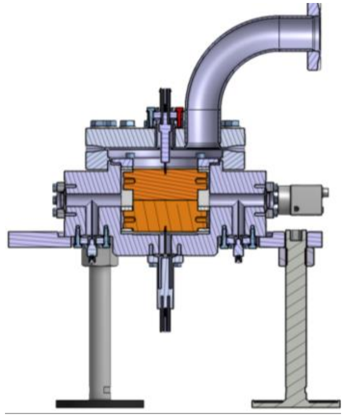
E-field



H-field



Large Electrode System (LES)



$$V_0 \propto d^{0.72}$$

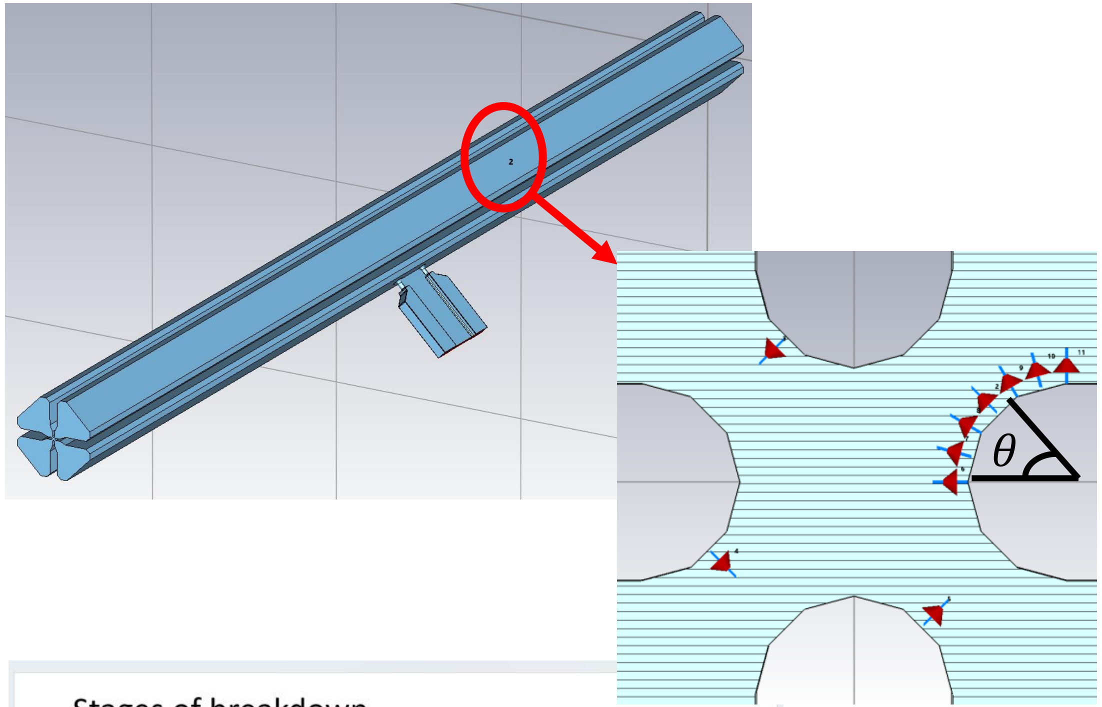
$$E_0 \propto \frac{1}{d^{0.28}}$$

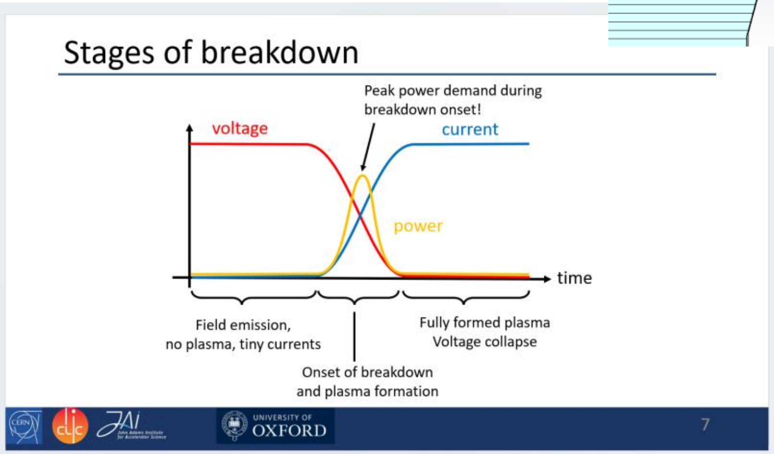
I. Profilatova, Recent progress at pulsed dc systems, 8th International Workshop on Mechanism of Vacuum Arcs, 2019.

Parameter	RFQ	LES
f [MHz]	352	0
Repetition Rate [Hz]	0.833	1 - 6000
Pulse length [μs]	1000	1 - 1000
Gap [mm]	2.3	0.1
Voltage [kV]	78	7.75
Max. E-field [MV/m]	34	77.5

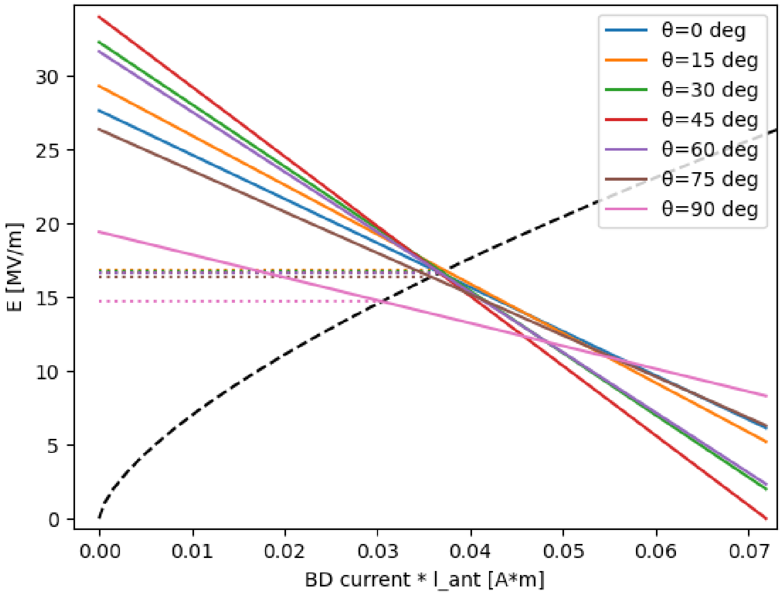
RFQ might be a key to connect High Frequency and DC

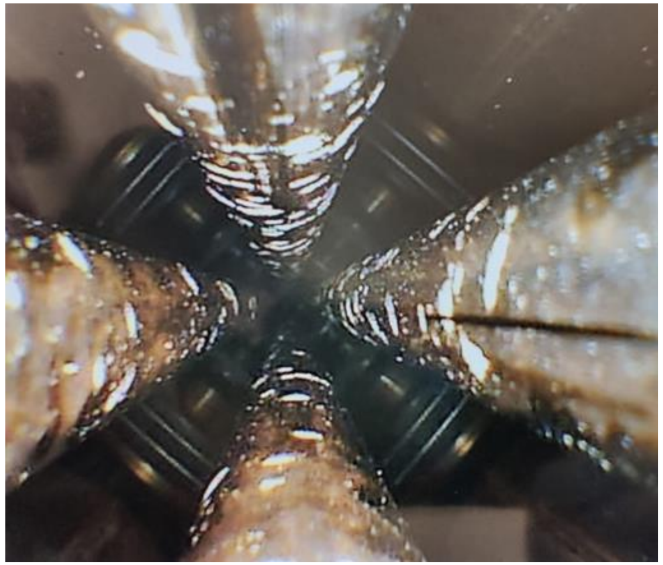
Local power coupling simulation





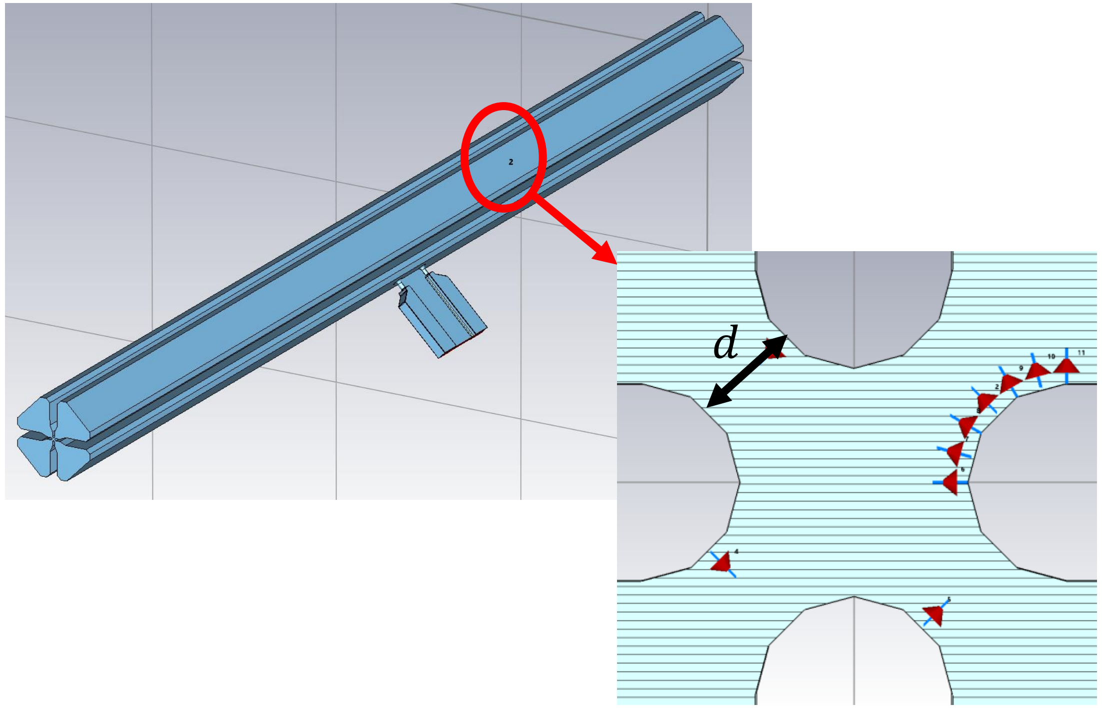
Angular dependence





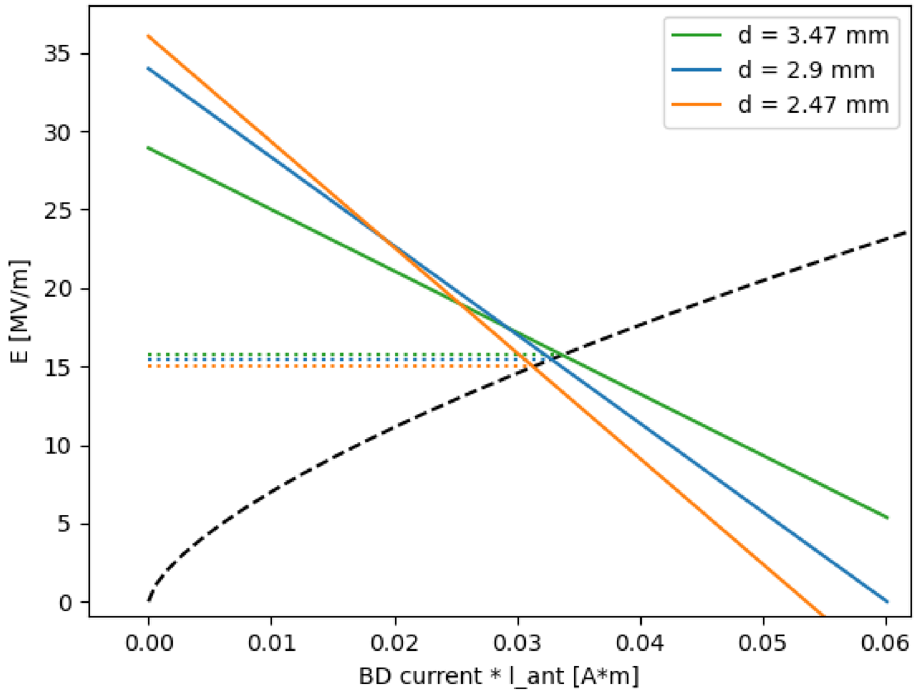
Paszkiewicz, J. Local power coupling as a predictor of high-gradient breakdown performance. High Gradient Workshop 2021.

Local power coupling simulation



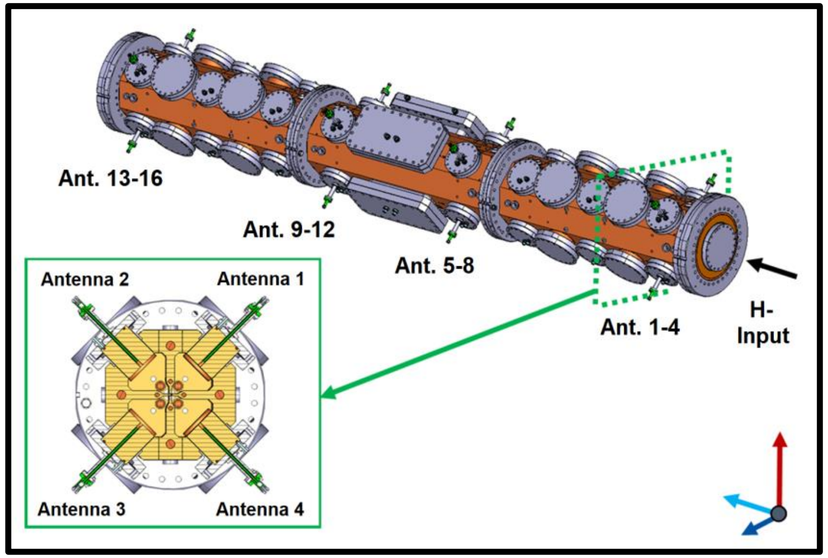
- $d\downarrow\ \rightarrow\ C\uparrow\ \rightarrow f\downarrow$
- $d\downarrow\ \rightarrow\ E_0\uparrow$
- $d\downarrow\ \rightarrow\ R_0\downarrow$

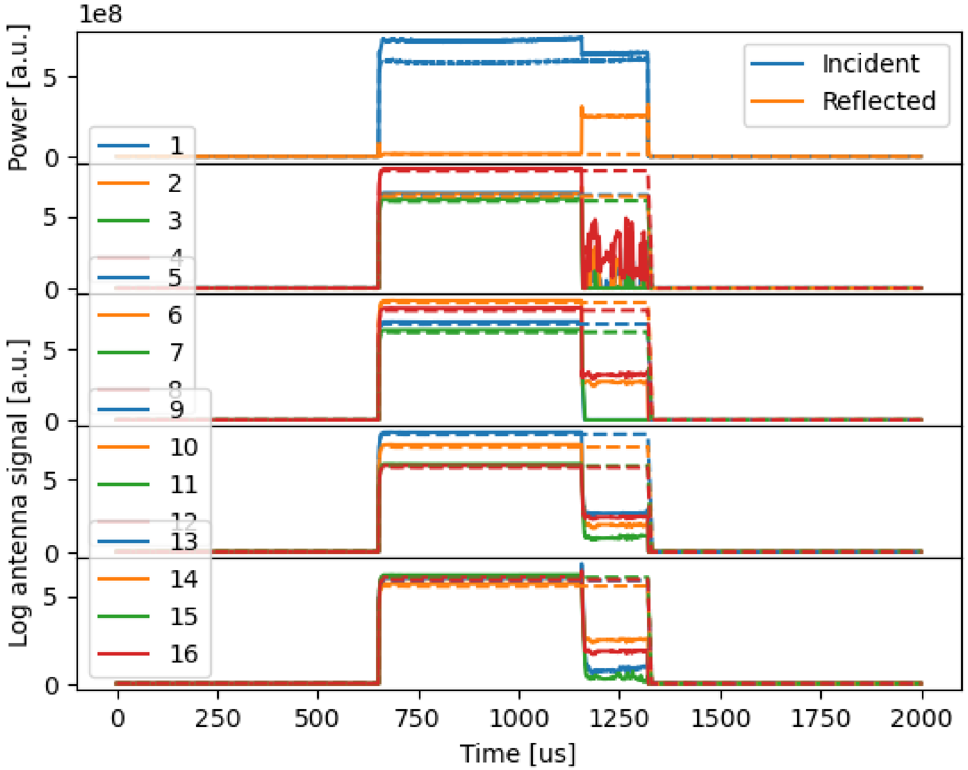
Gap dependence At $P_{in} = 400$ kW



d [mm]	E_0 [MV/m]	E^* [MV/m]	$\frac{E_{0,1}d_1^{0.28}}{E_{0,2}d_2^{0.28}}$
2.47	36	15.0	0.986
2.9	34	15.5	1
3.47	29	15.7	1.12

RFQ measurements

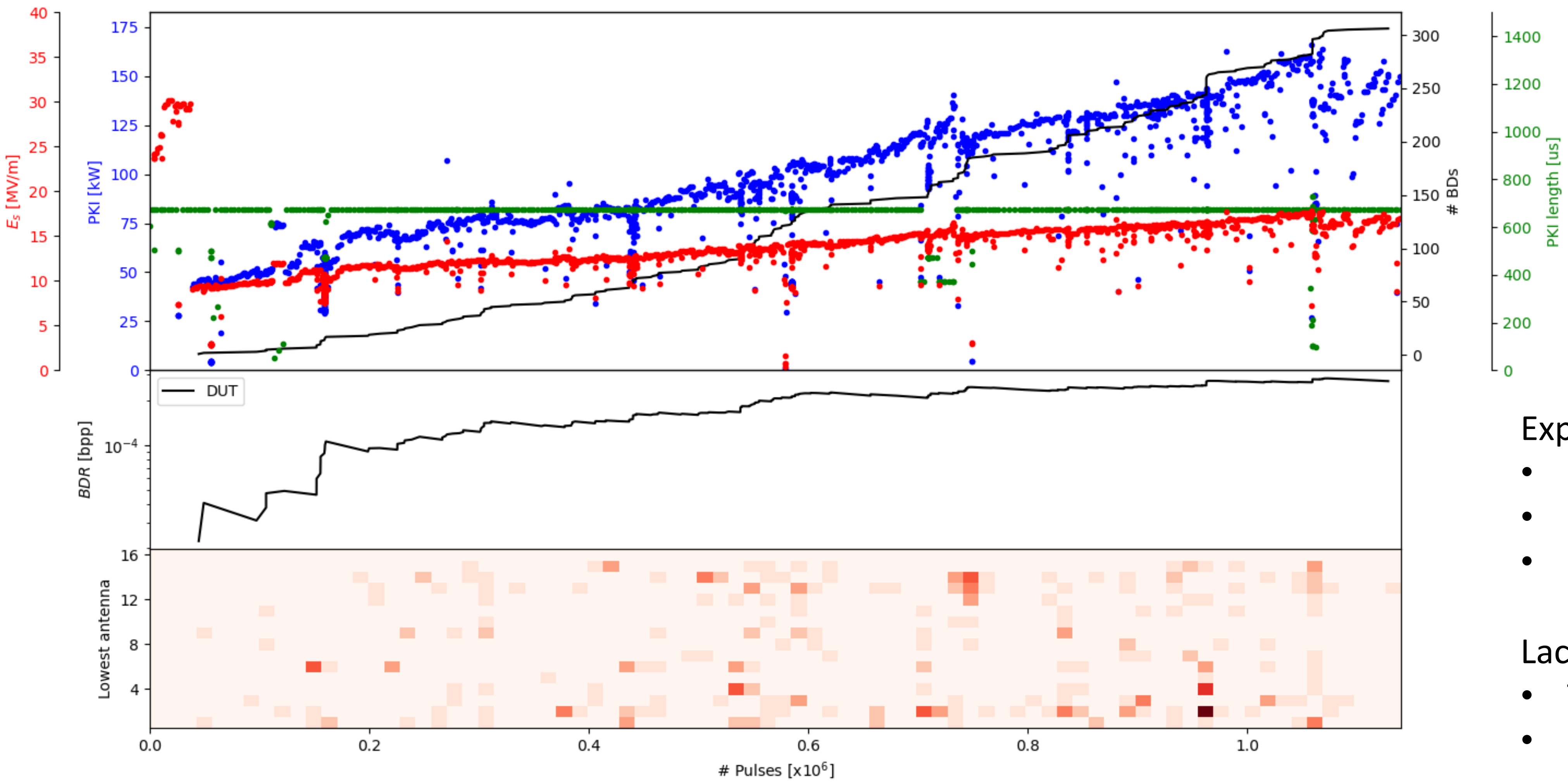




- Reflected power increases: Different coupling
- Antennas show different behavior: BD localization

Vnuchenko, A. (2020). High-gradient issues in S-band RF acceleration structure for hadrontherapy accelerators and radio frequency Quadrupoles

RFQ conditioning (ongoing work)



Experimental set-up:

- Incident power
- Reflected power
- 16 antenna signals

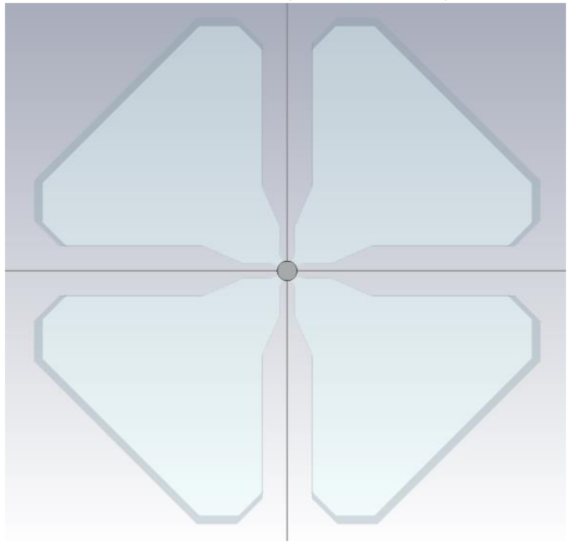
Lack of:

- Transmitted power
- Dark current

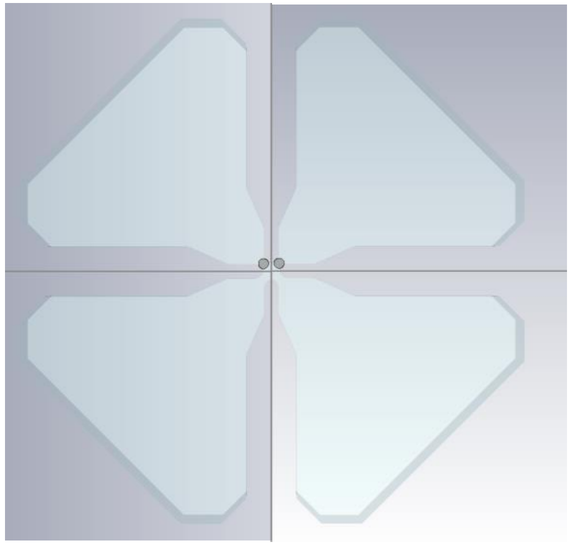
How can we localize BDs?

BD simulation

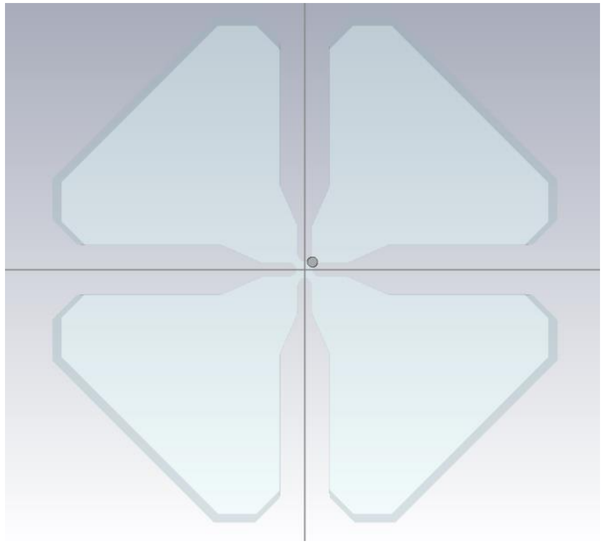
Axial symmetry

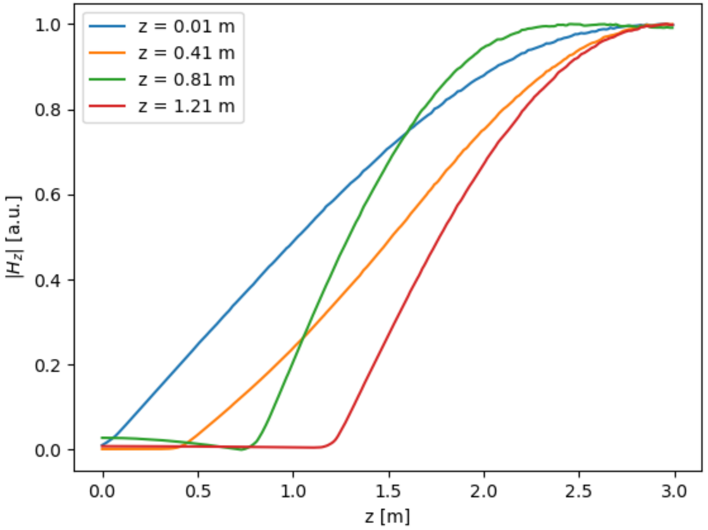


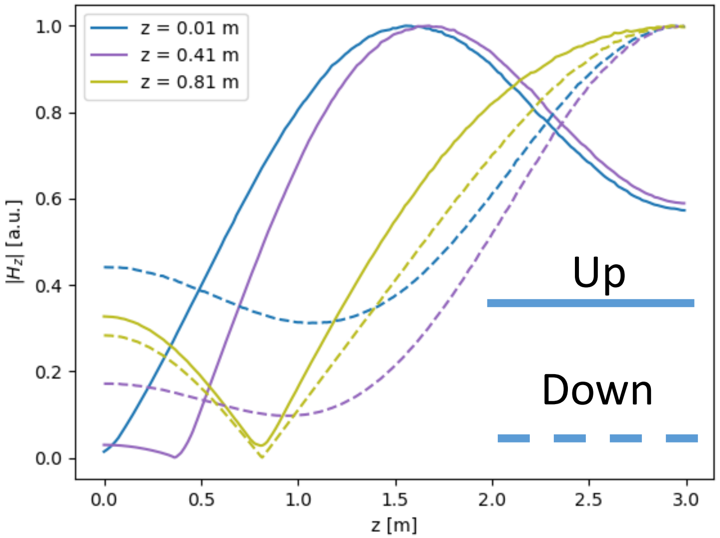
Half symmetry

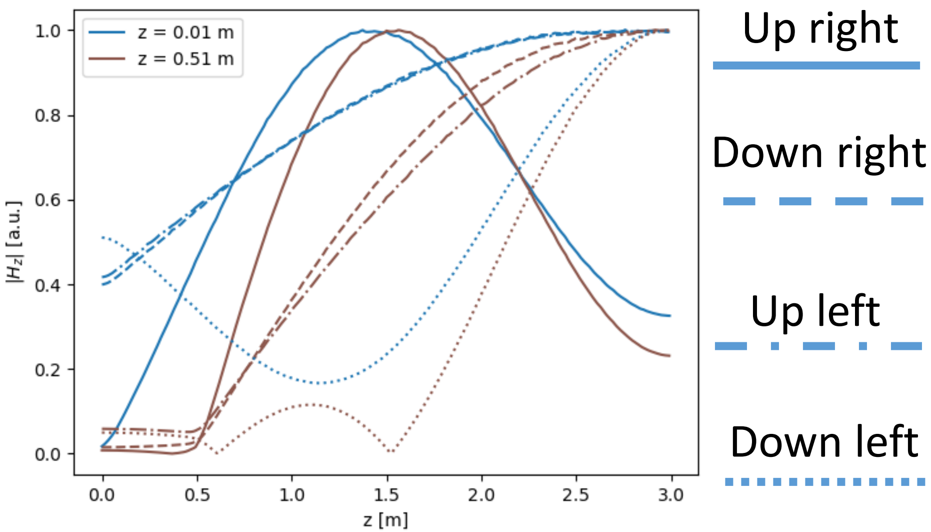


No symmetry



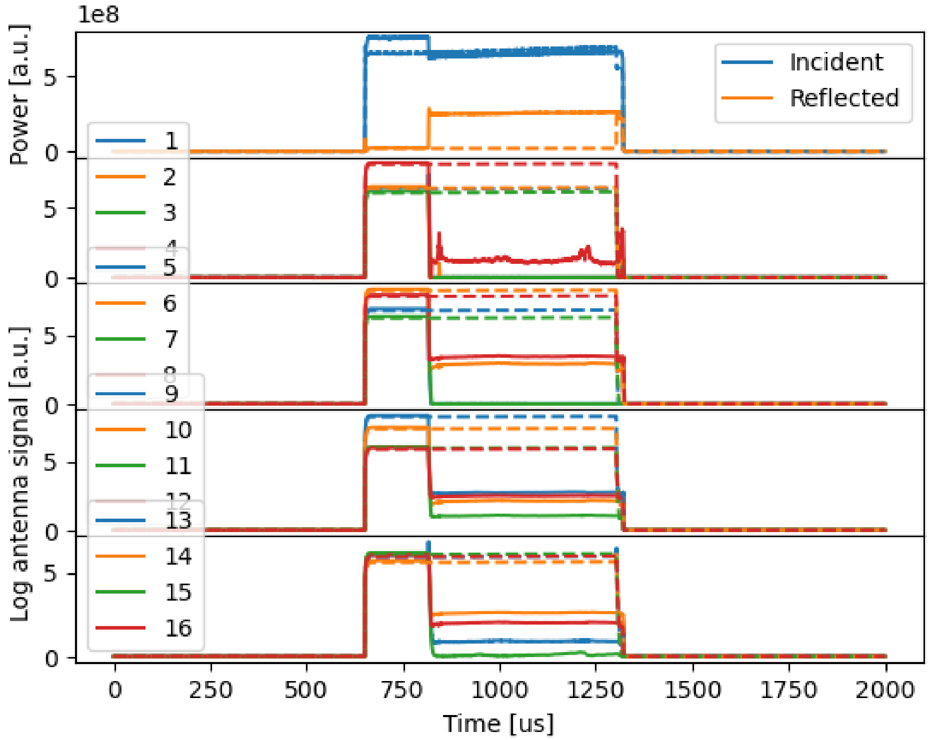


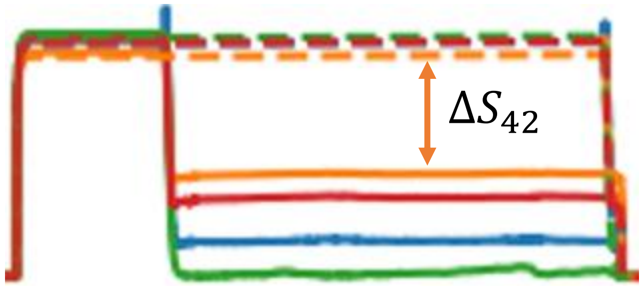




Wang, F., & Adolphsen, C. (2009). Localization of rf breakdowns in a standing wave cavity. Physical Review Special Topics—Accelerators and Beams, 12(4), 042001

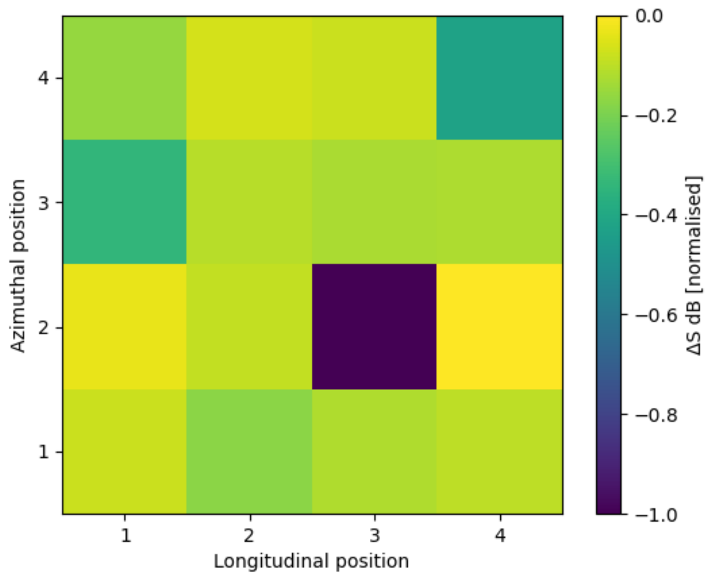
From measurement to simulation



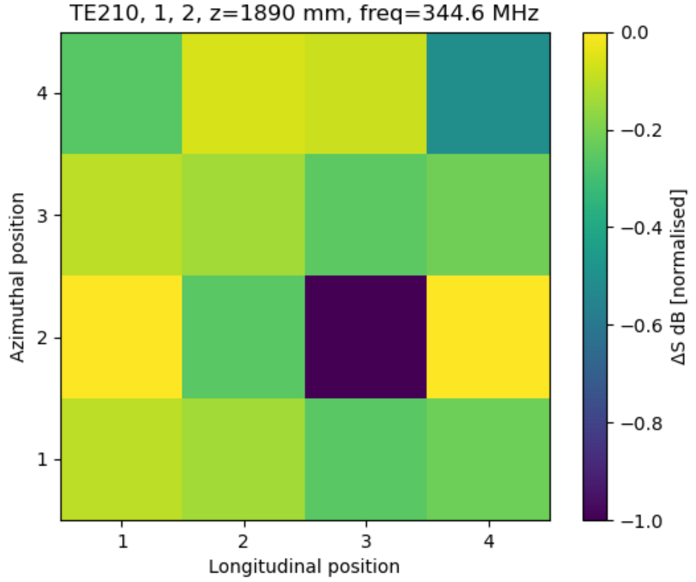


Normalization:

$$\Delta S_{ij} = \frac{\Delta S_{ij} - \Delta S_{min}}{\Delta S_{max} - \Delta S_{min}}$$



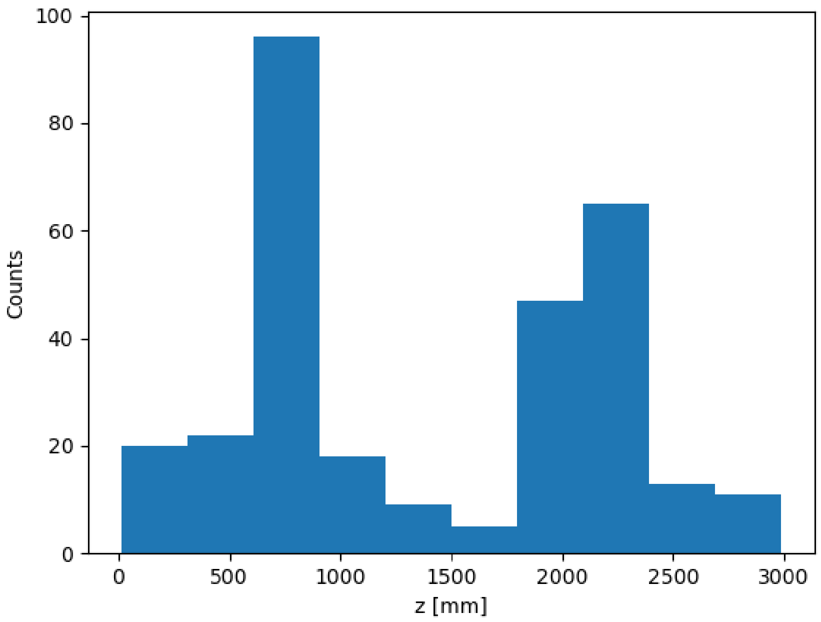
Most similar simulation



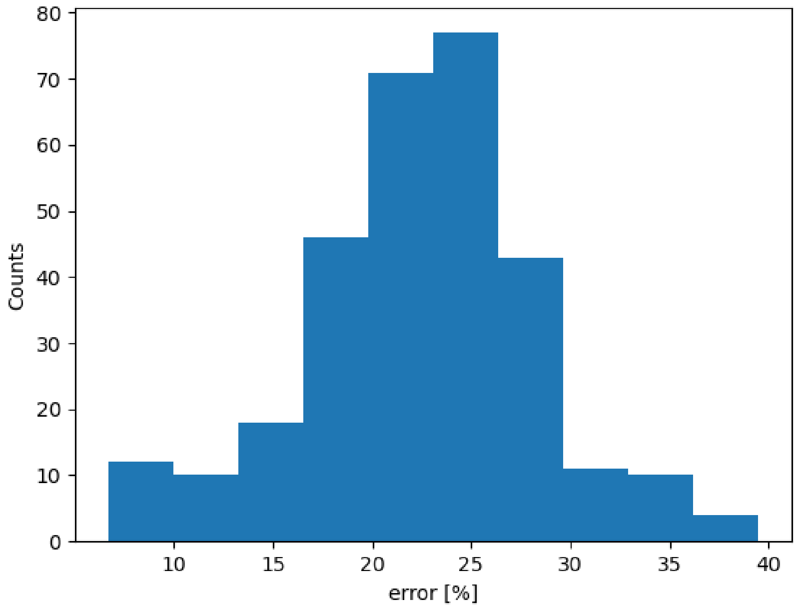
W.L. Millar. Workshop on Breakdown Science and High Gradient Technology 2023, https://agenda.infn.it/event/34253/contributions/210153/

What information can be obtained?

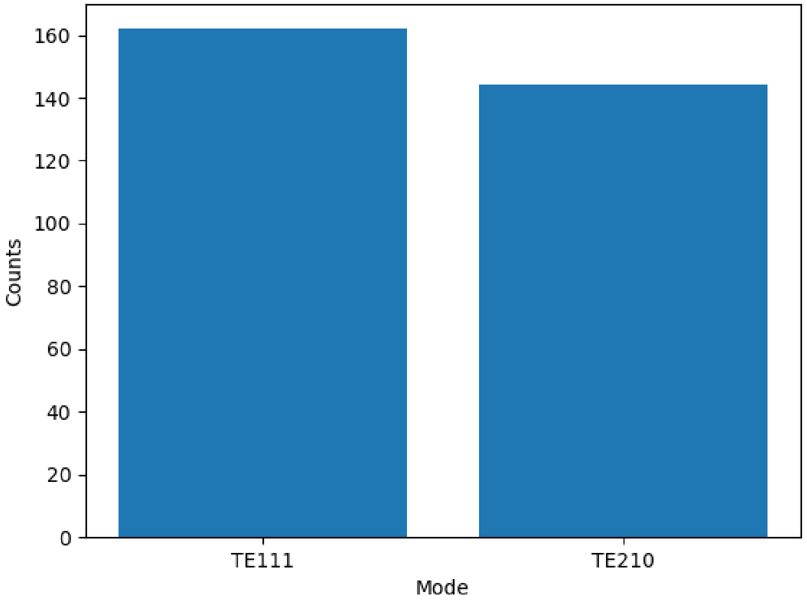
- BD longitudinal position



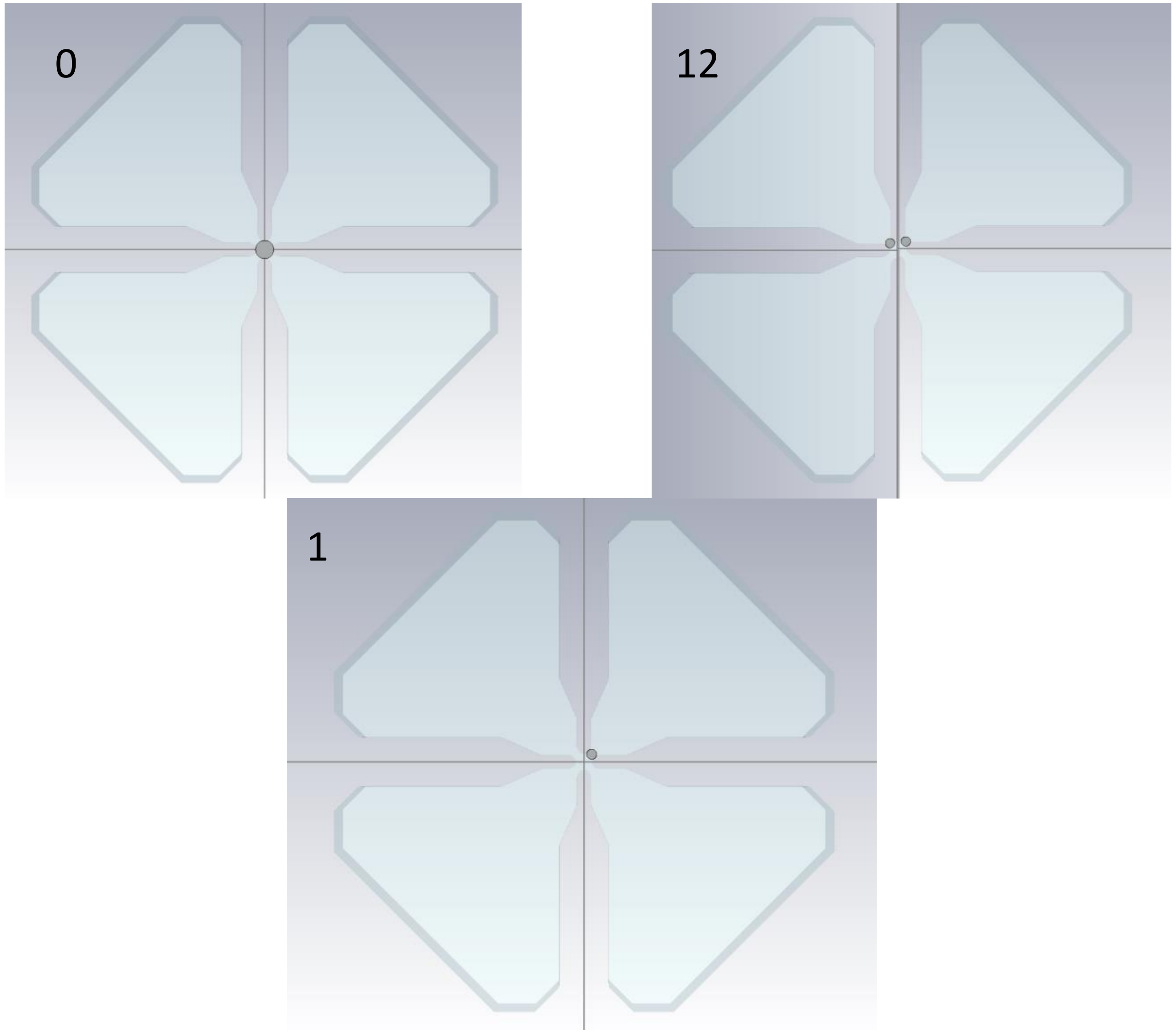
- Measurement and simulation agreement



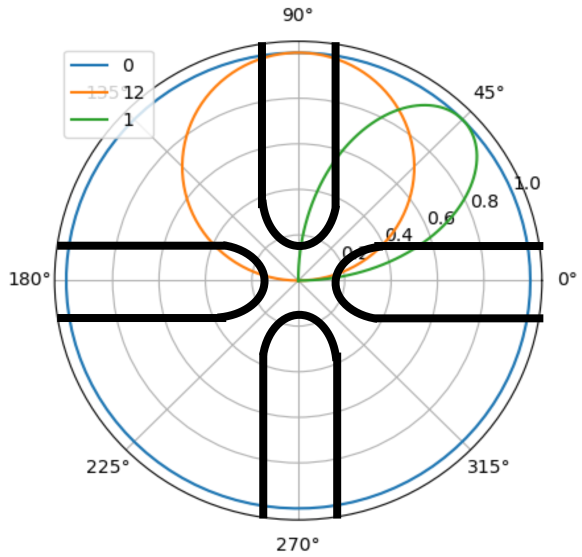
- Most similar mode distribution



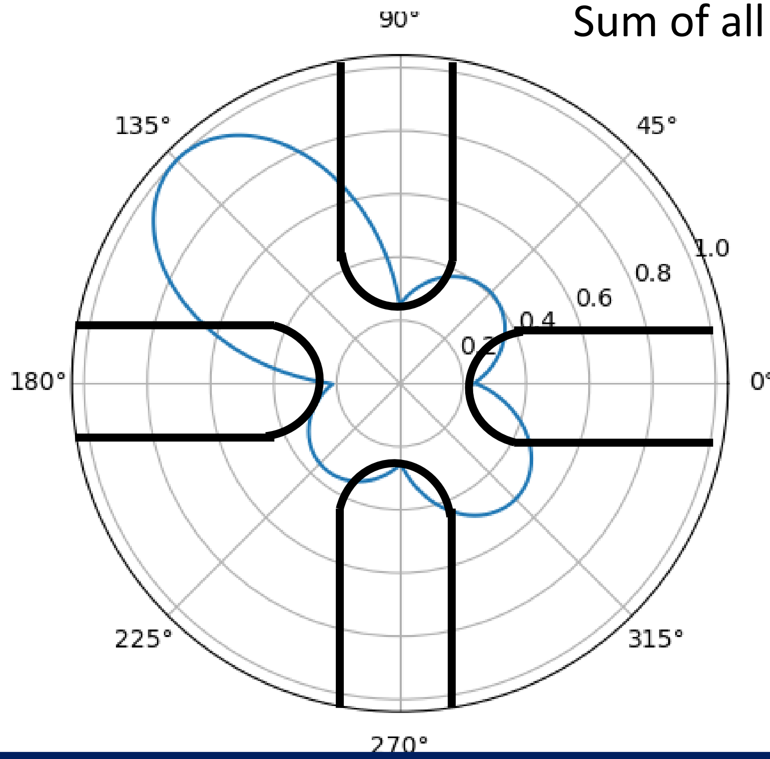
Axial position

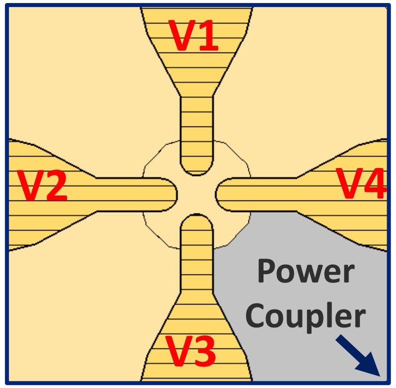


12 and 1 type BD can be rotated by integers of $\pi/4$



Sum of all BDs





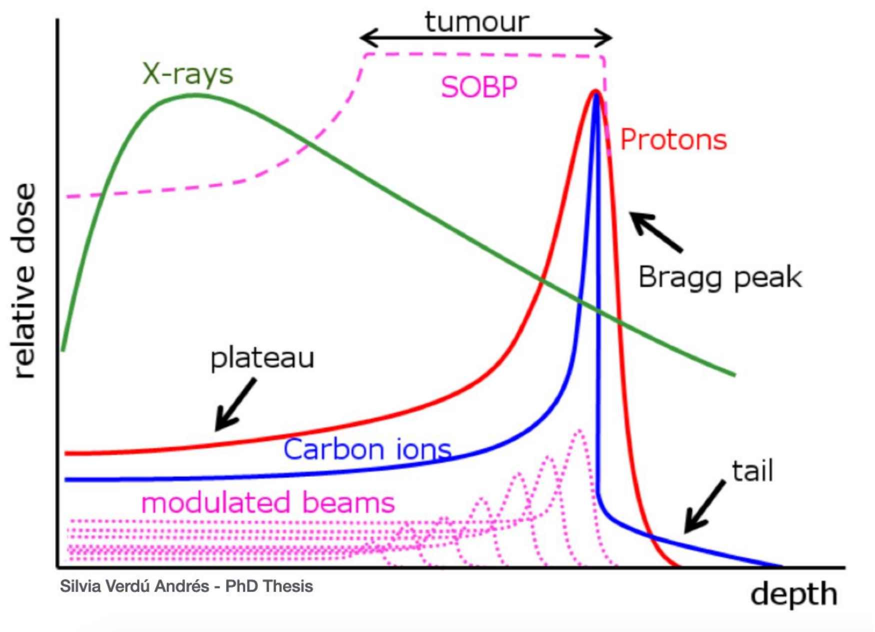
Conclusions

- BTW structure:
  - A maximum gradient of 39 MV/m was achieved with 800 ns pulses without saturation.
  - No hot cells detected.
  - Dark current simulations show good agreement with experimental observations.
  - Spectroscopy measurements showed good results. Klystron malfunction stopped measurements campaign.
  - Dose decreases with conditioning. HG linacs produce high radioactive dose, requiring shielding.
- Radio-Frequency Quadrupole:
  - Local power coupling simulations agree with BD location and field gap dependence in DC.
  - First conditioning curve for an RFQ structure (ongoing).
  - Testing of method to compare antenna signals and BD localization simulation.

THANK YOU!

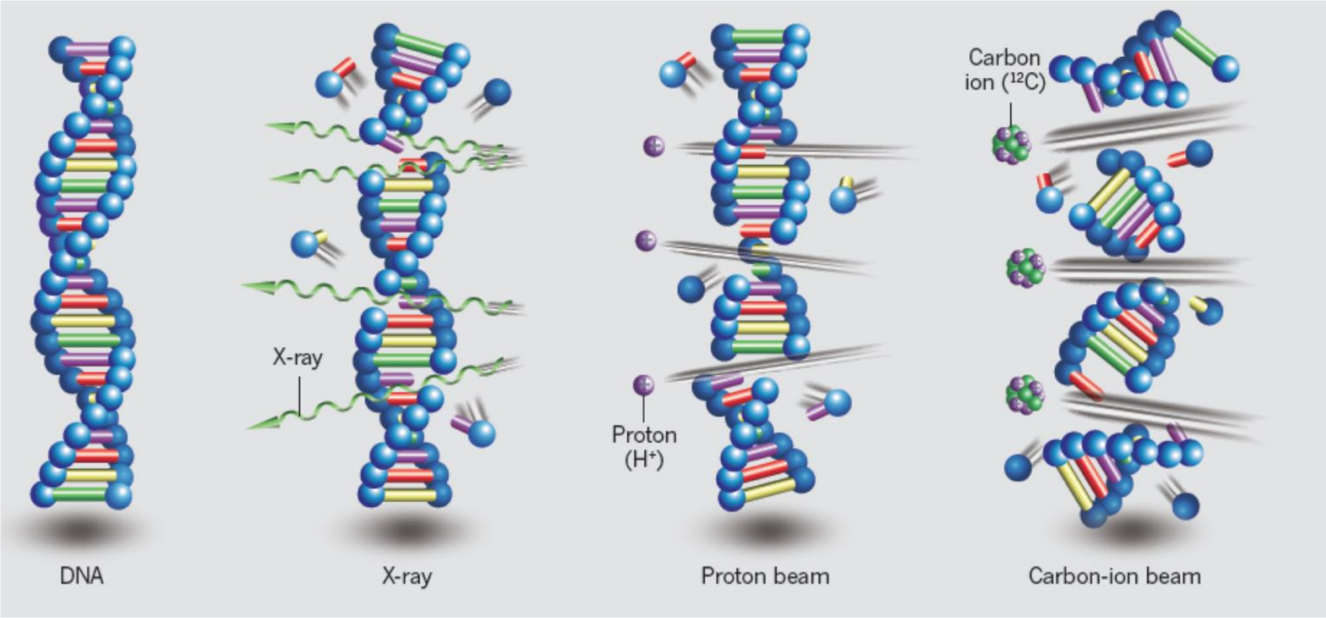
Back up

Hadron therapy



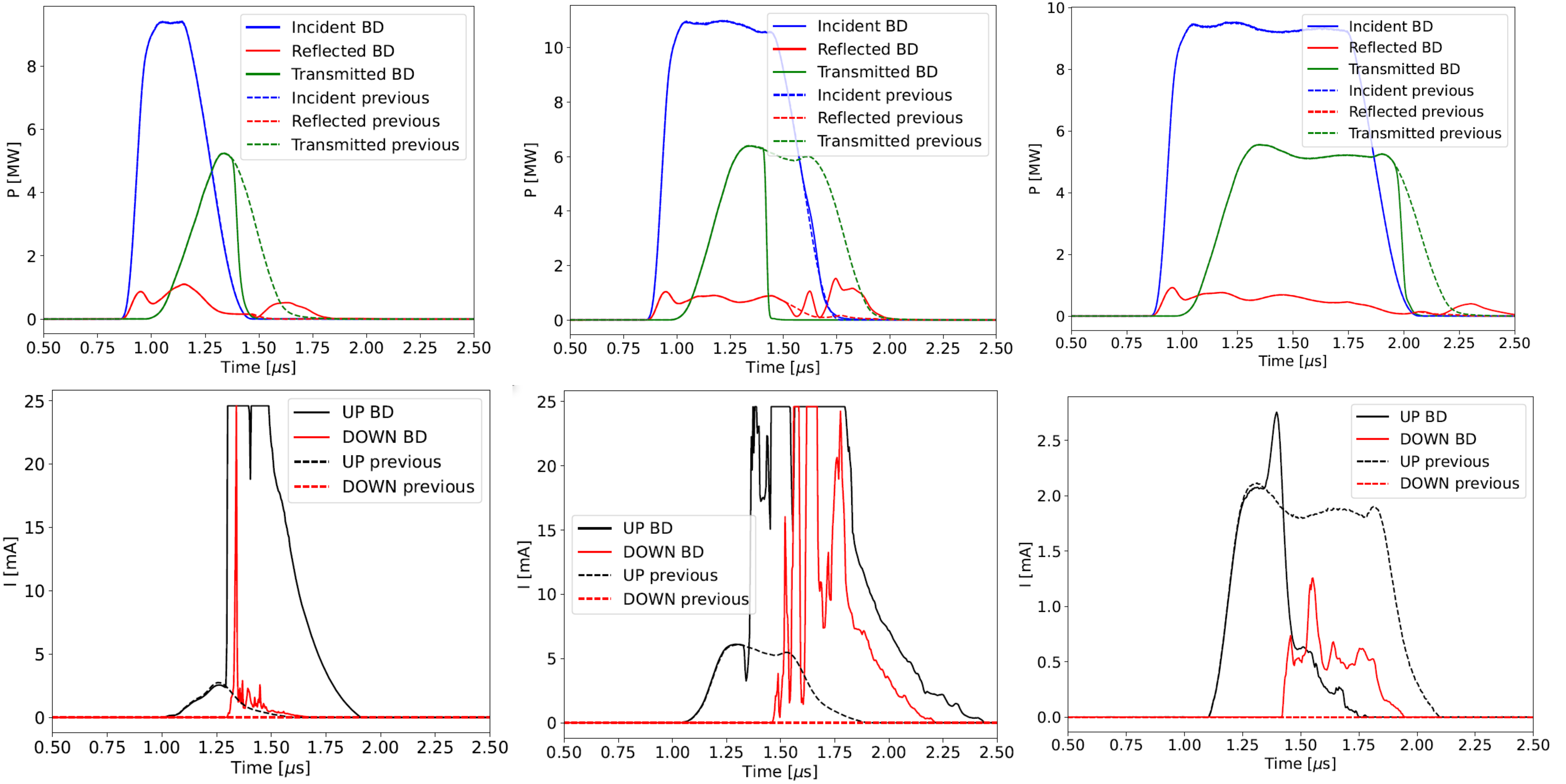
Accelerator	Beam always present during treatment?	Energy variation by electronic means?	Time needed for varying the energy
Cyclotron	Yes	No	80-100 ms (*)
Synchrotron	No	Yes	1-2 s
Linac	Yes	Yes	1-2 ms

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



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

Some pulses



Incident BD
Reflected BD
Transmitted BD
Incident previous
Reflected previous
Transmitted previous
P [MW]
Time [μs]
0
2
4
6
8
10
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
UP BD
DOWN BD
UP previous
DOWN previous
I [mA]
0
5
10
15
20
25
0.0
0.5
1.0
1.5
2.0
2.5

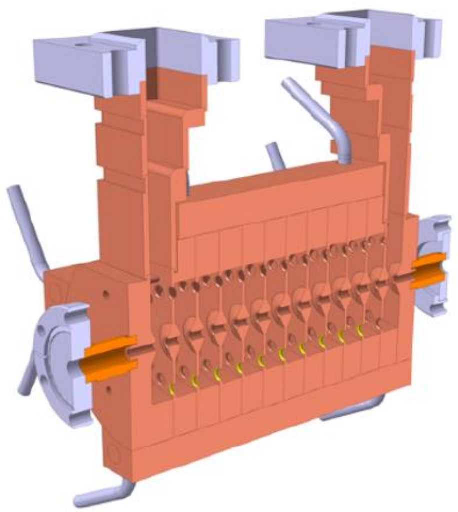
The S-band BTW structure

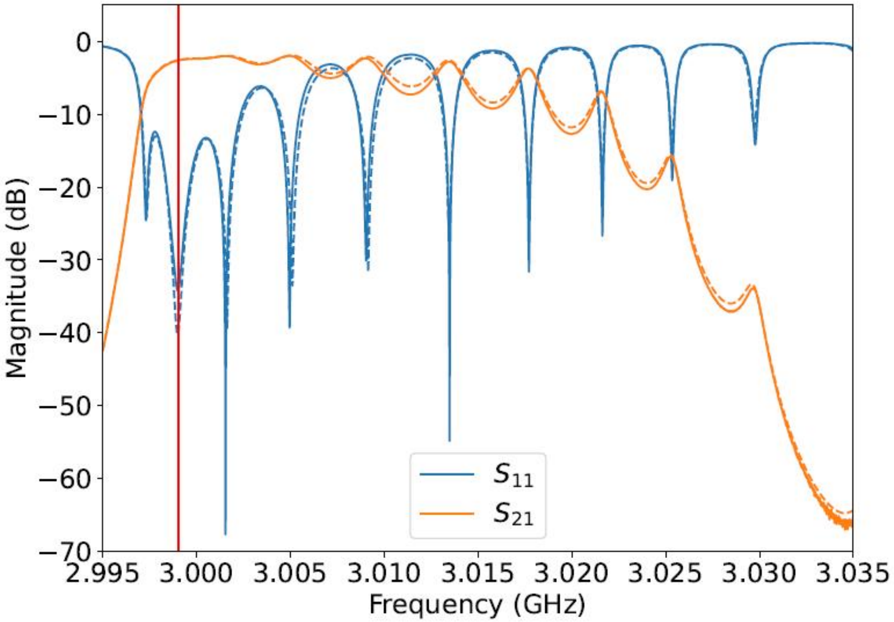
- Transfer function:

$$E_a[\text{MV/m}] = 50[\text{MV/m}]\sqrt{\frac{P_{in}[\text{MW}]}{20.16[\text{MW}]}}$$

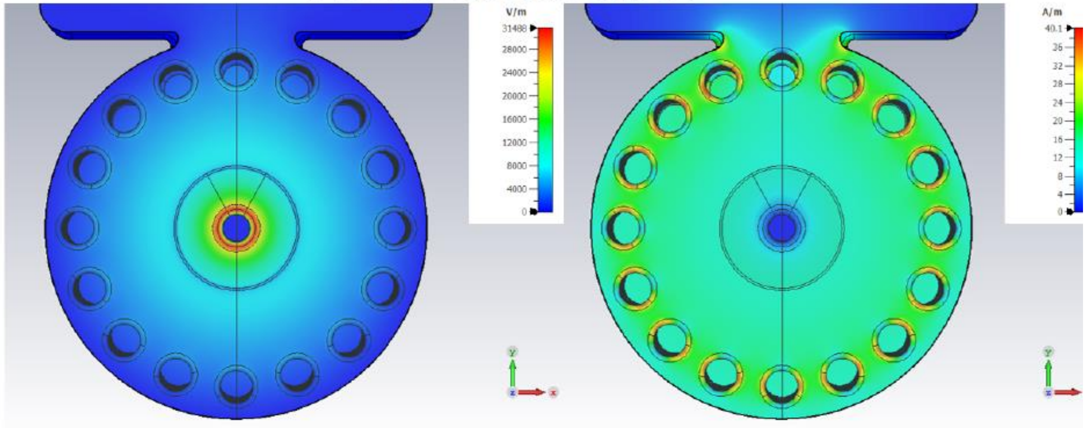
- Tapered 12 cells with $\Delta\phi = 150^o$.
- Magnetic coupling.
- Band-pass filter.

Internal structure



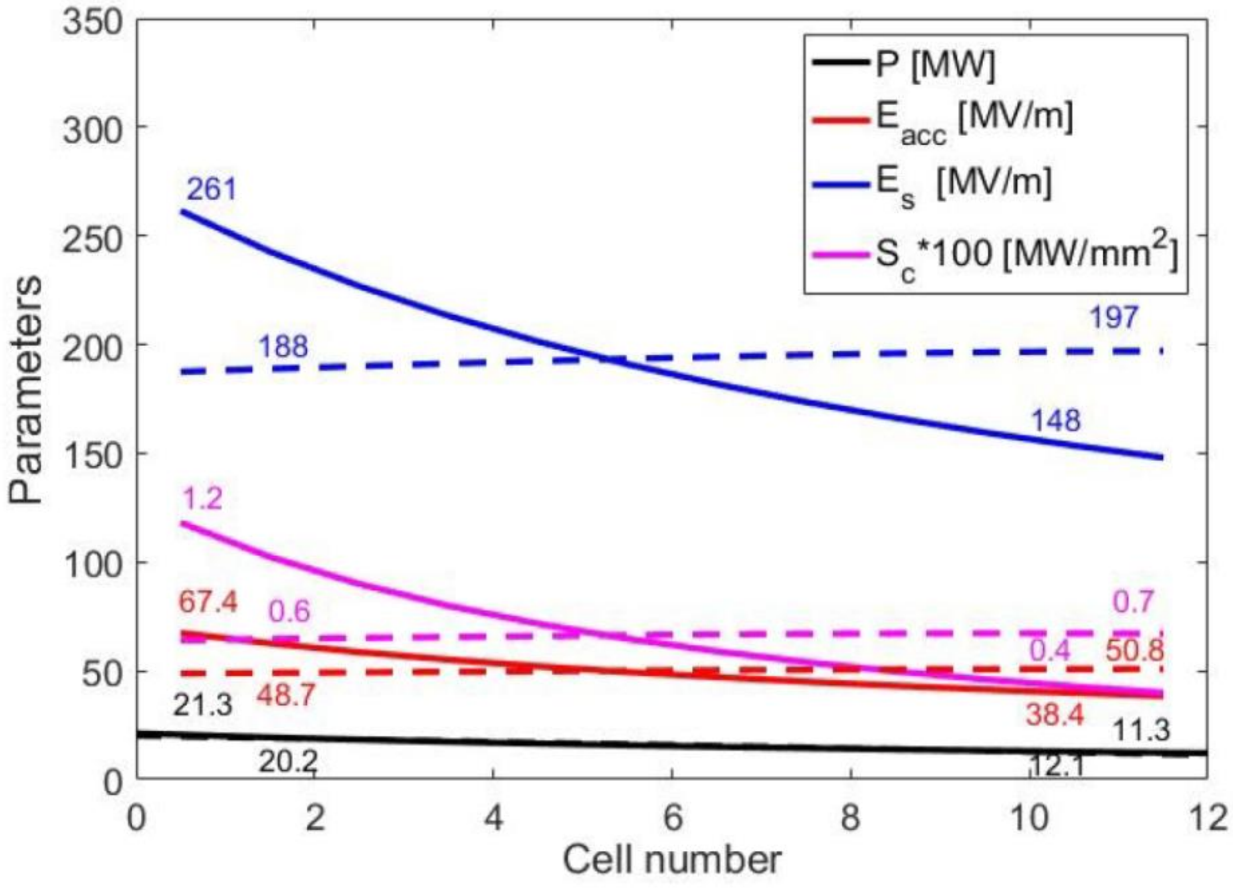


Fields distribution

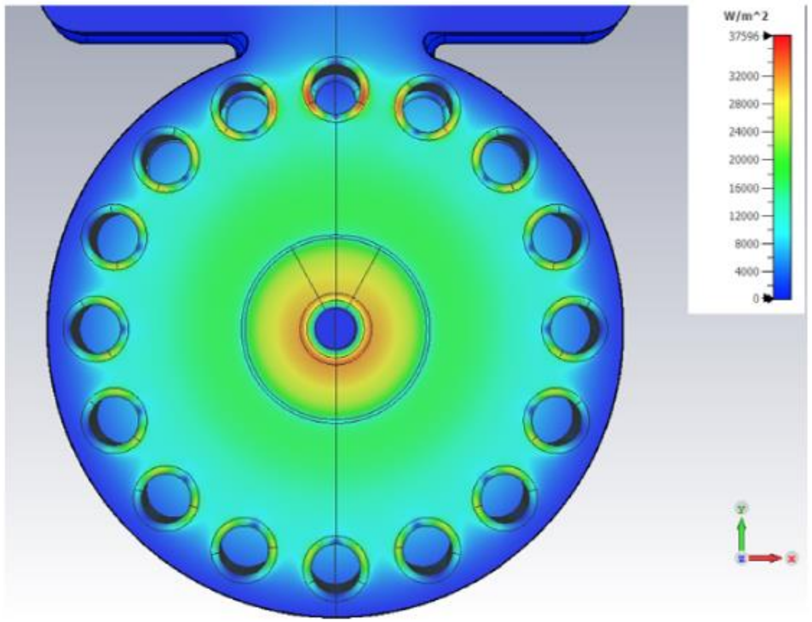


Tapering

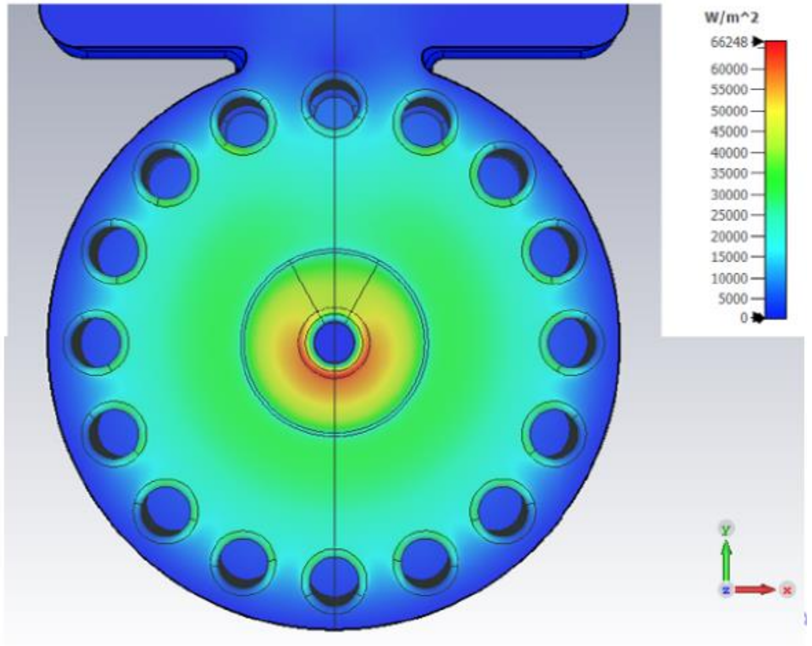
The tapering makes the structure asymmetrical in the longitudinal direction



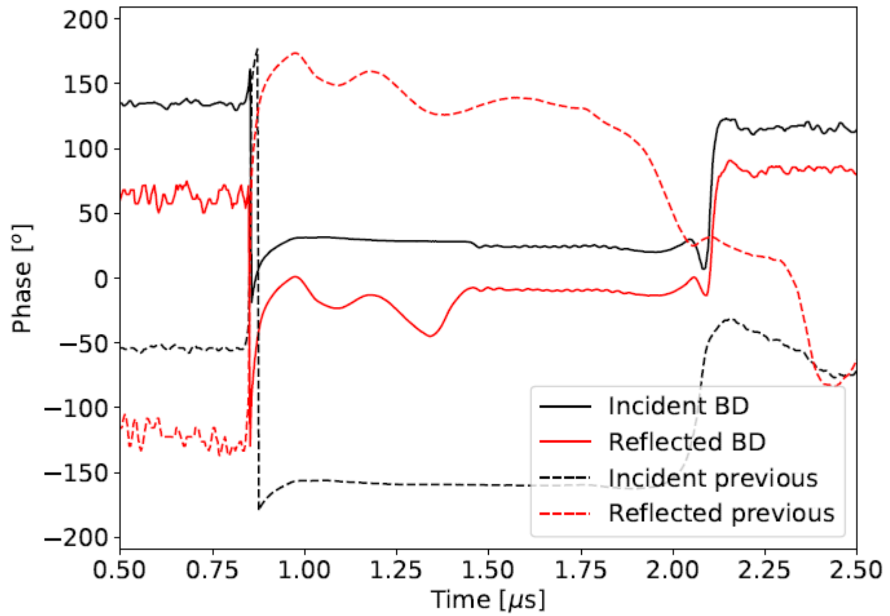
Design direction



Opposite direction



BD localization: Phase method



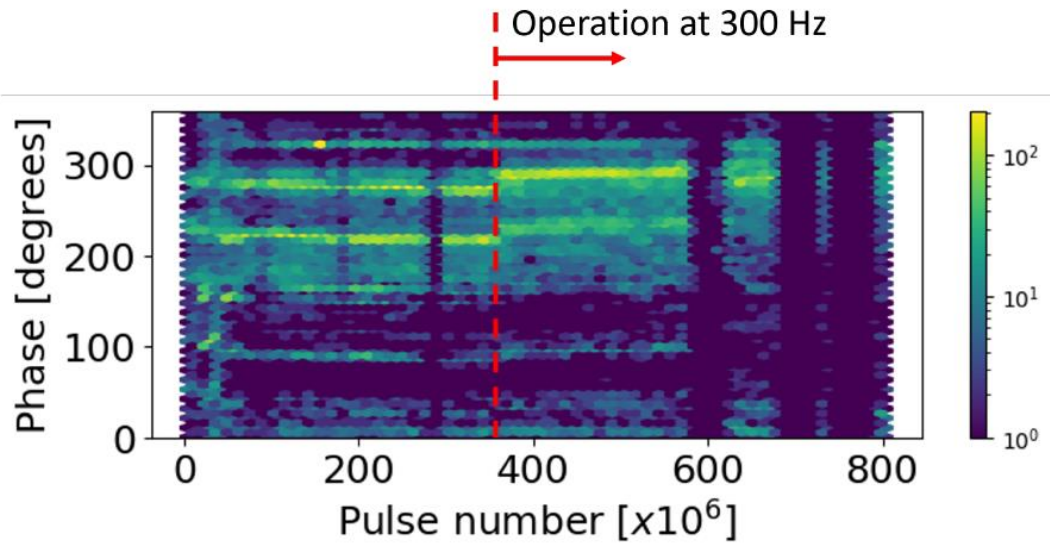
- Search for BD phase.

$$\phi_{BD} = \phi_{REF}(t + t_d) - \phi_{INC}(t)$$

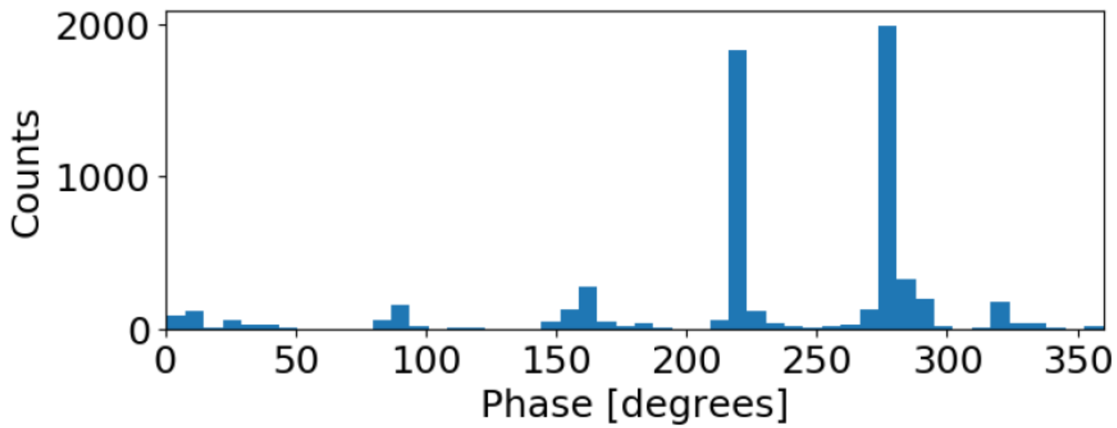
- Cell localization.

$$\phi_{BD} = 2\Delta\phi n_{BD} + \phi_0$$

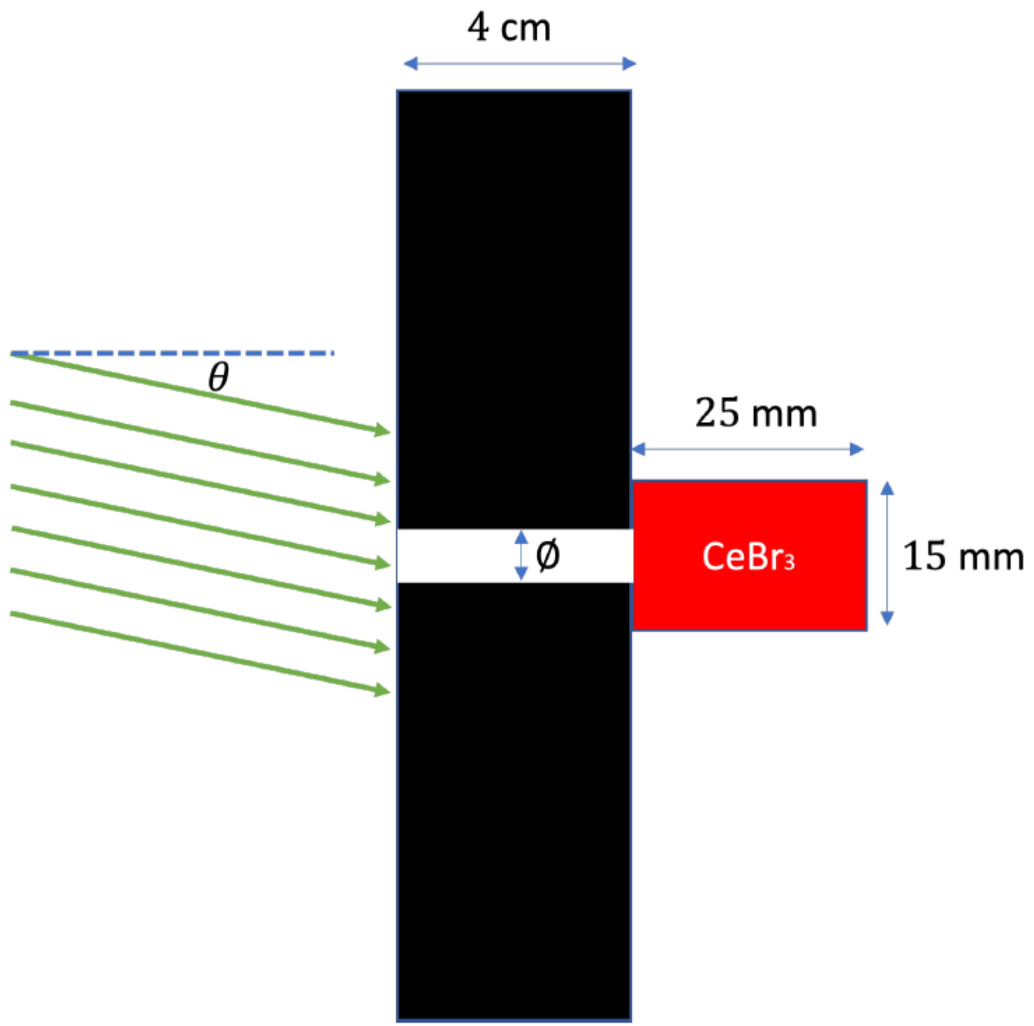
- $\Delta\phi$ is highly affected by ΔT



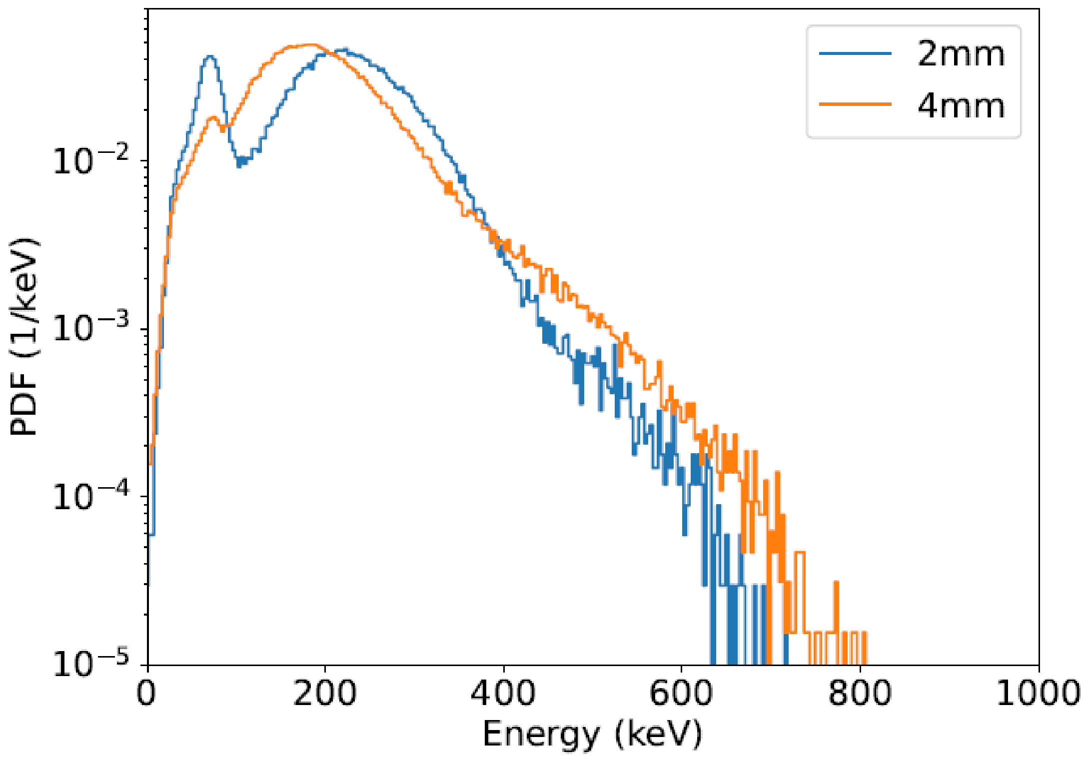
- Accumulation of BDs in agreement with short pulses



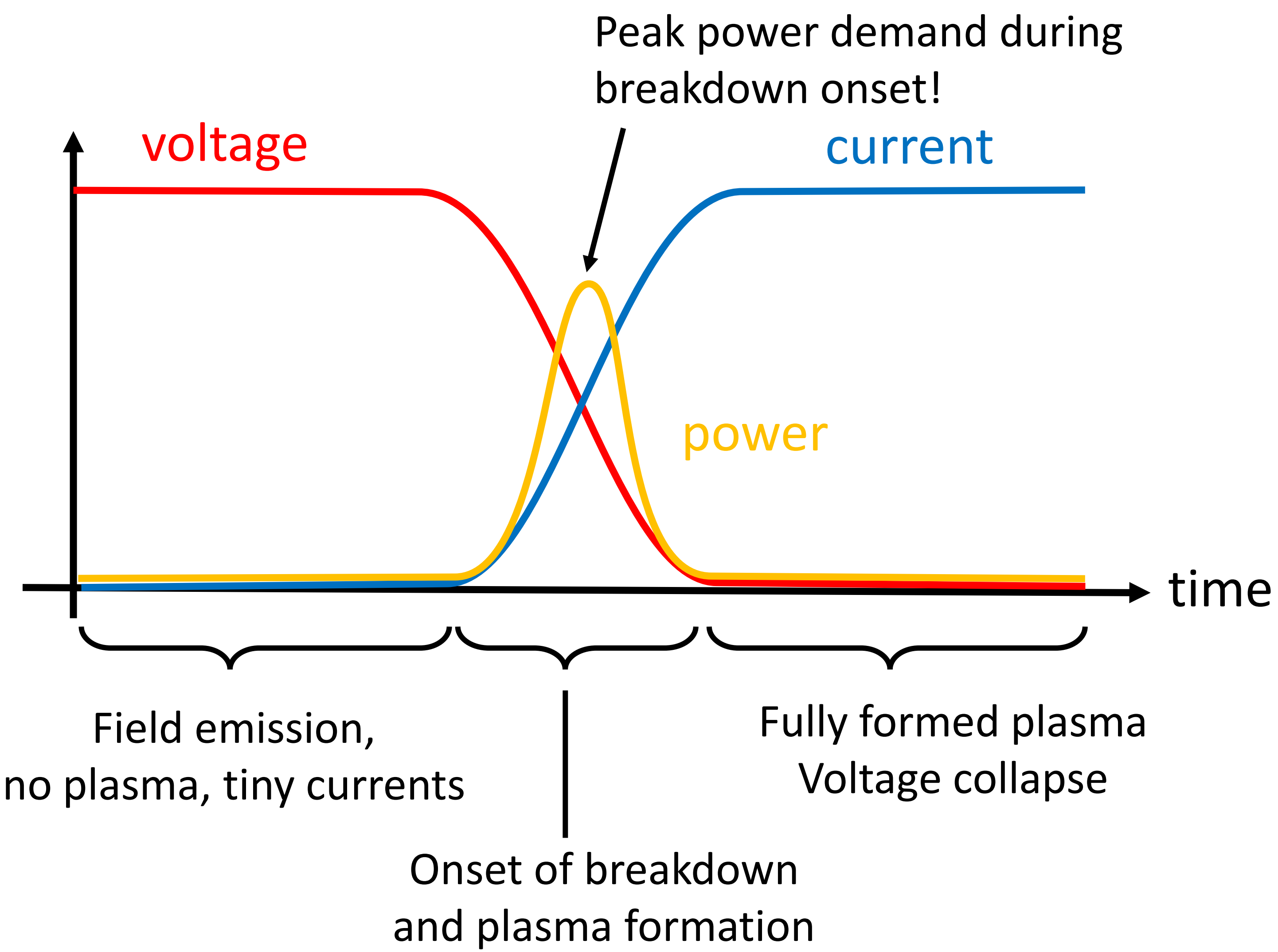
Hole size impact

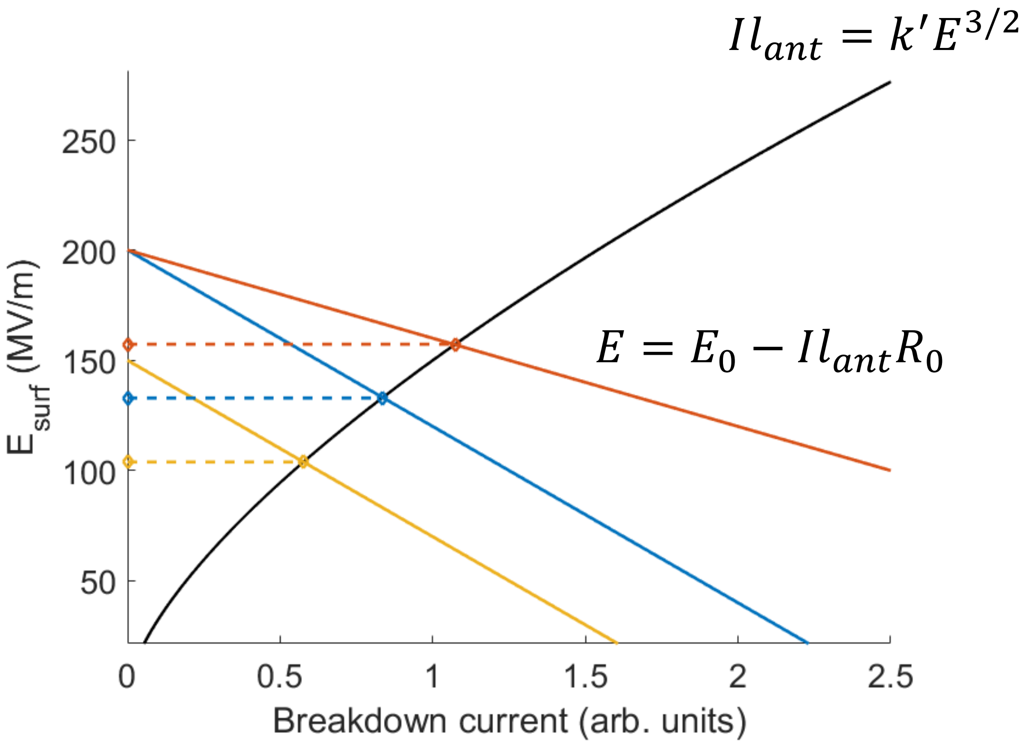


- Small hole: Photons must pass through small Pb region. Attenuation is higher for photons of lower energy.
- Big hole: Photons can reach directly to the detector.



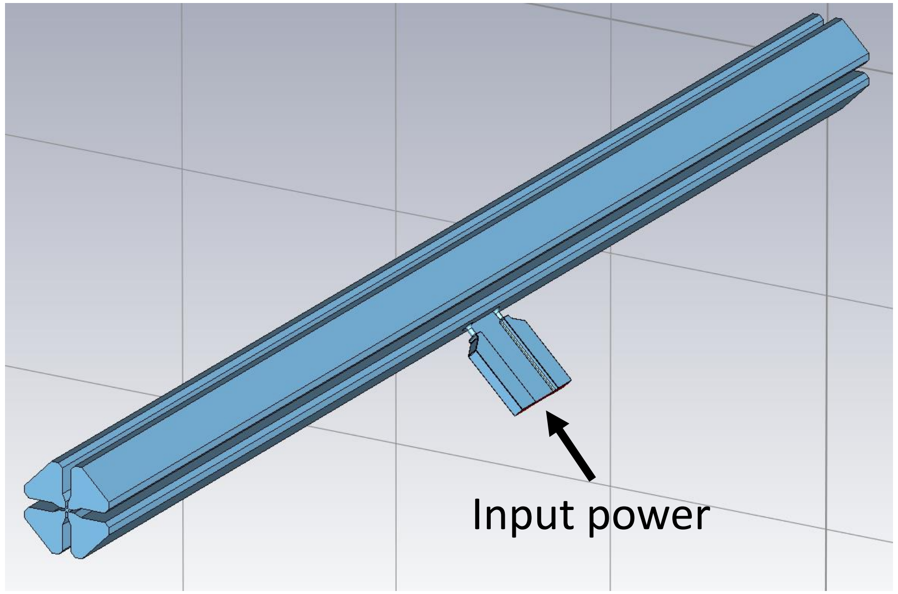
Local power coupling

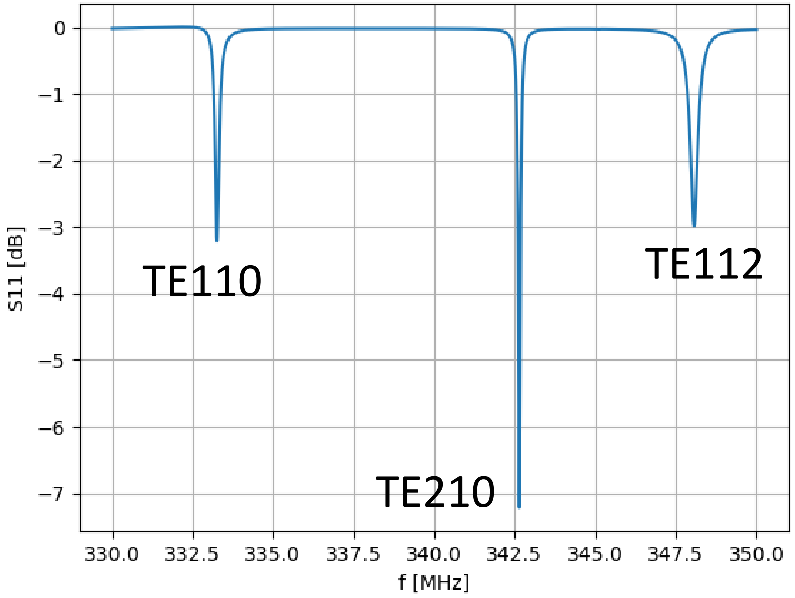




$$k'R_0E^{*3/2} + E^* - E_0 = 0$$

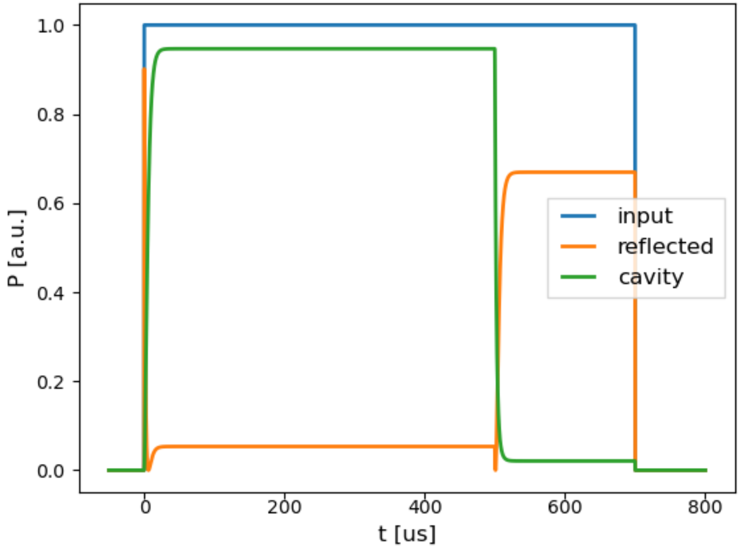
BD simulation

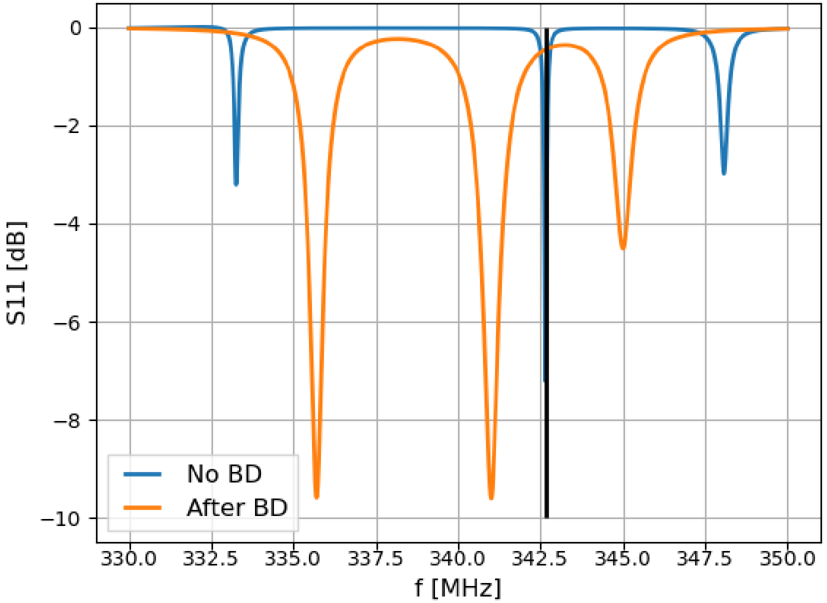




Before BD:

- Mostly TE210 is excited
- Close to critical coupling

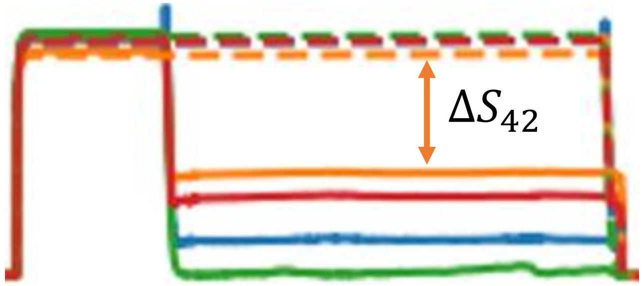


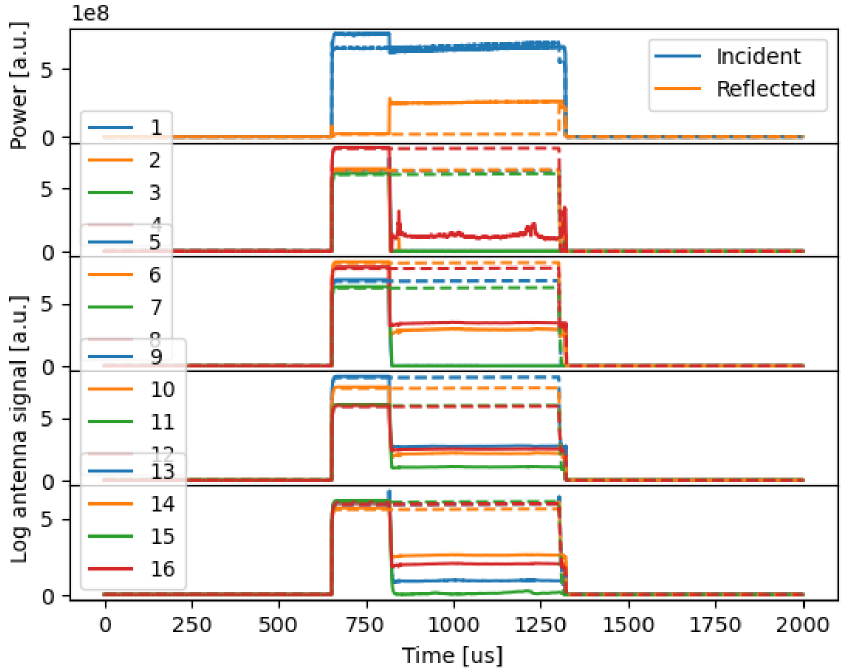


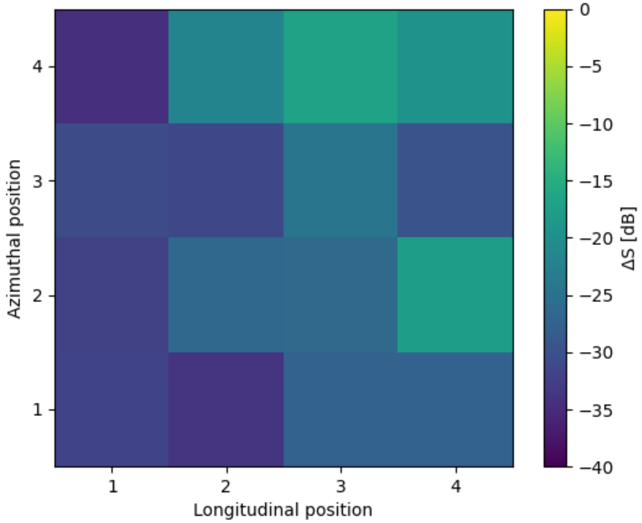
After BD:

- Different eigenmode f, Q_0, Q_{ext}
- New field distribution

Measurement normalization

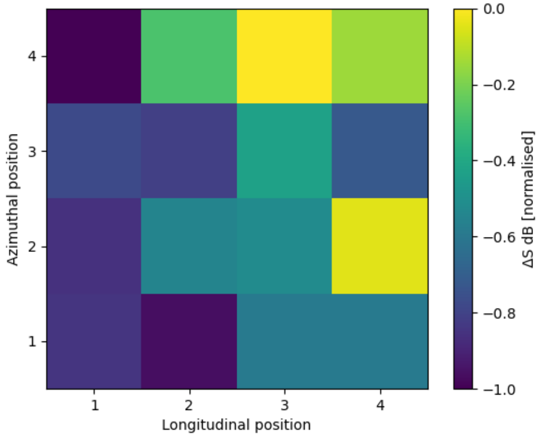






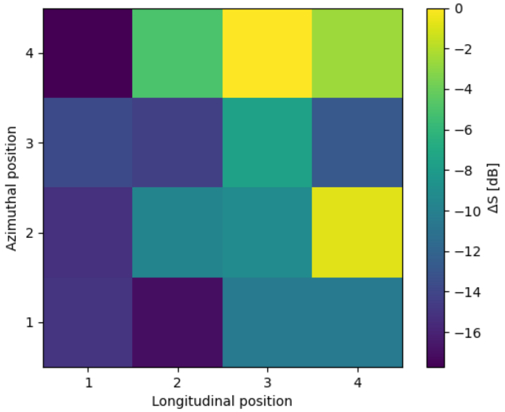
Normalization 1:

$$\Delta S_{ij} = \frac{\Delta S_{ij} - \Delta S_{min}}{\Delta S_{max} - \Delta S_{min}}$$

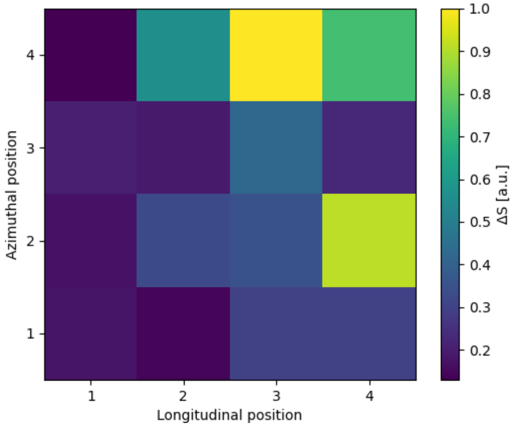


Normalization 2:

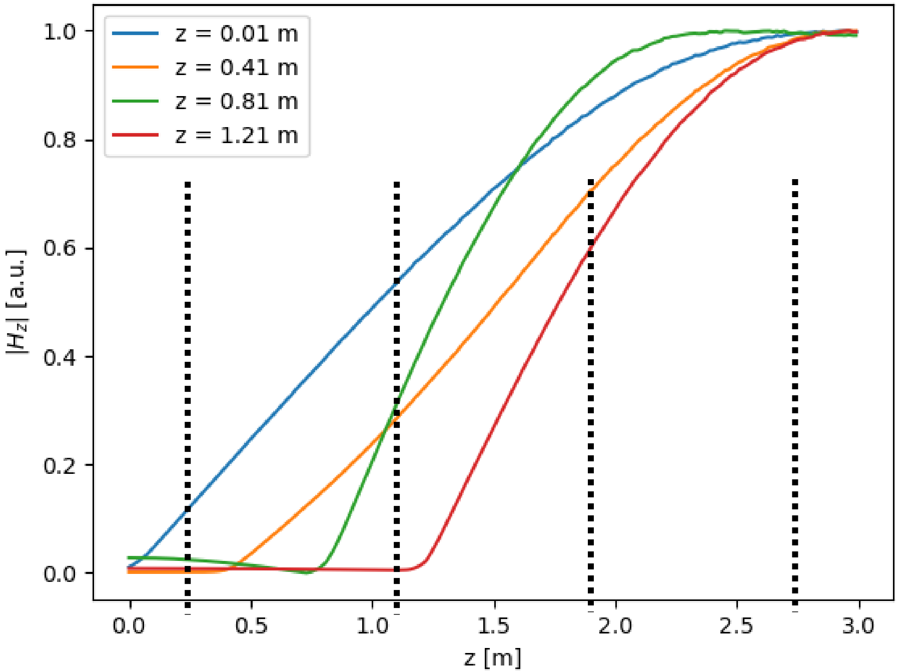
$$\Delta S_{ij} = \Delta S_{ij} - \Delta S_{min}$$



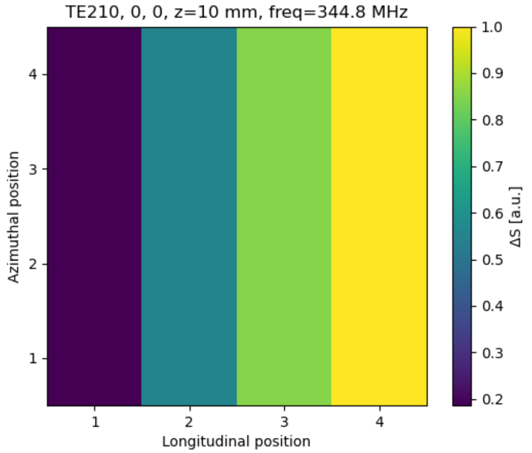
Normalization 3:
Linear



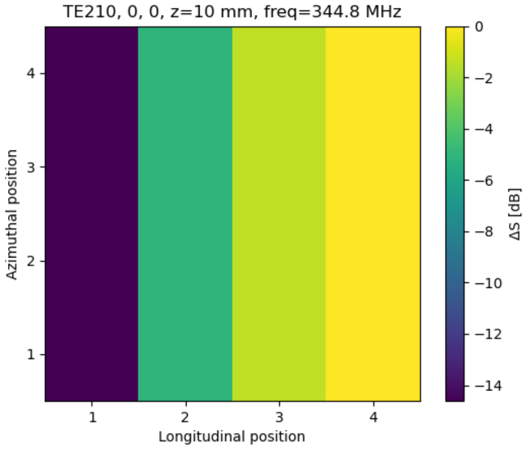
Simulation normalization



Linear (Normalization 3)

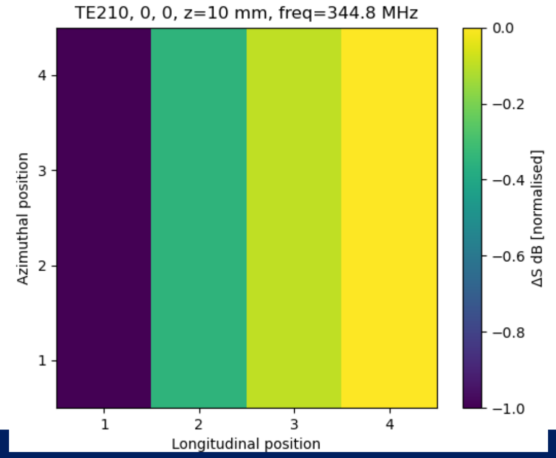


To dB (Normalization 2)



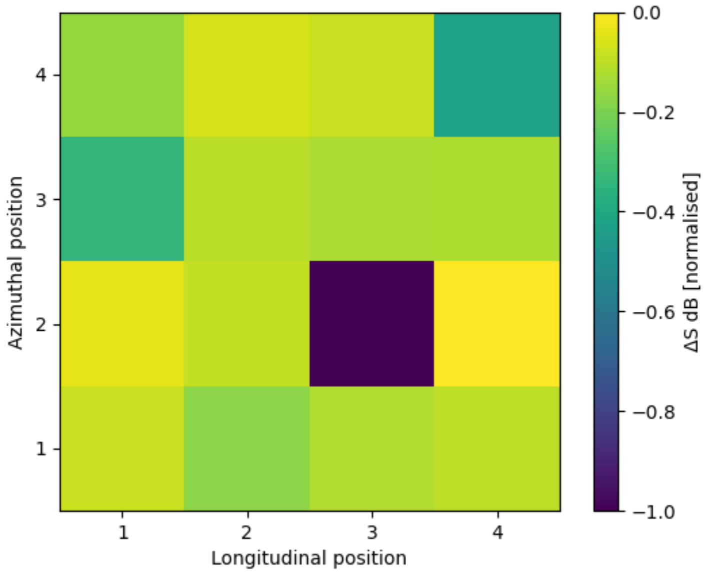
Normalization 1:

$$\Delta S_{ij} = \frac{\Delta S_{ij} - \Delta S_{min}}{\Delta S_{max} - \Delta S_{min}}$$

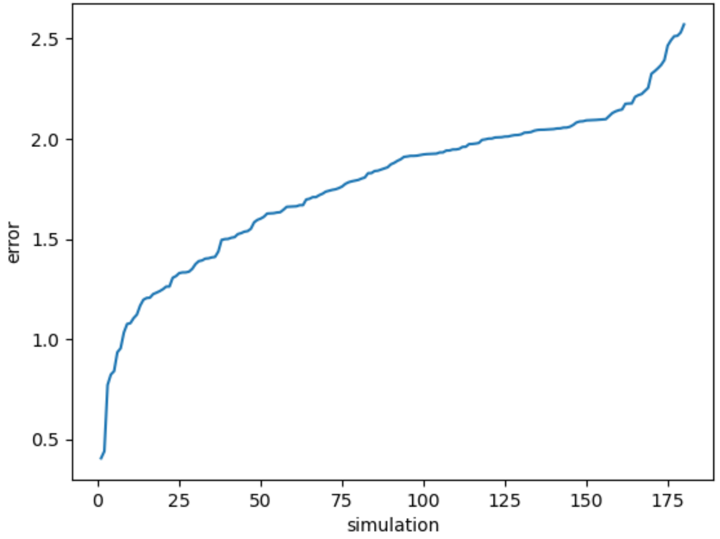


Error minimization

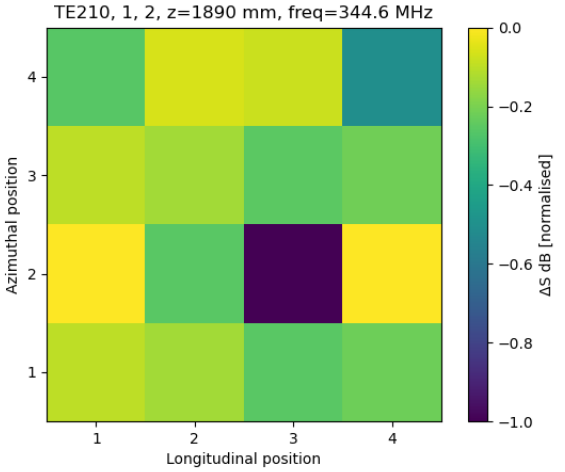
Measurement



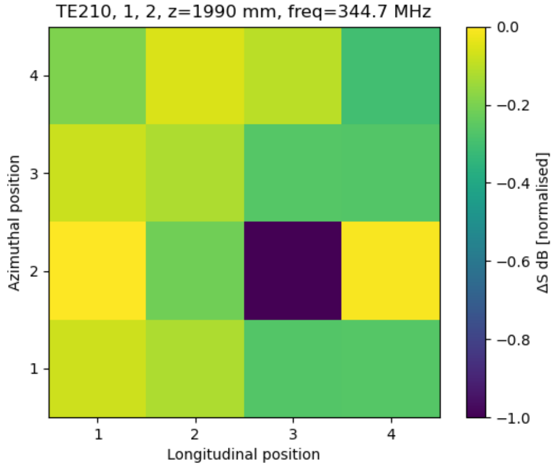
$$\text{error} = \sqrt{\sum_{i=1}^{16}\left(\Delta S_i^{sim} - \Delta S_i^{meas}\right)^2}$$



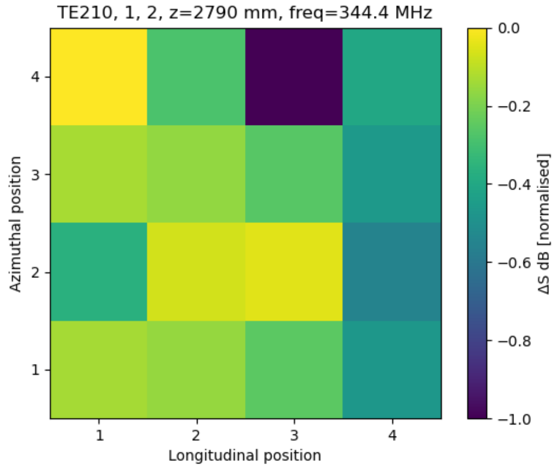
1



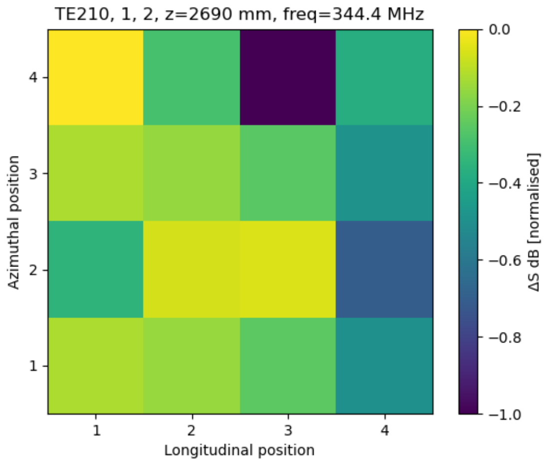
2



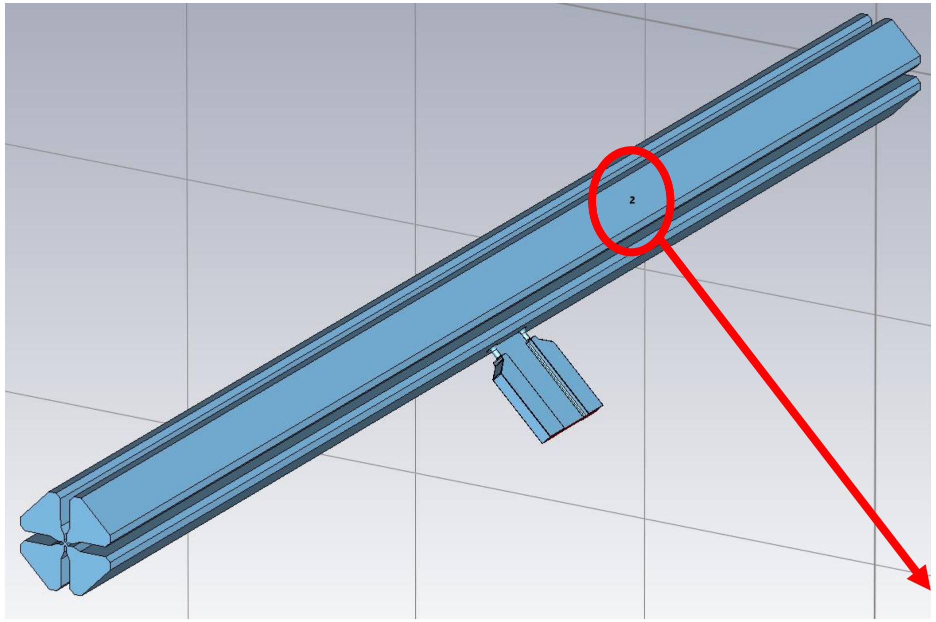
3



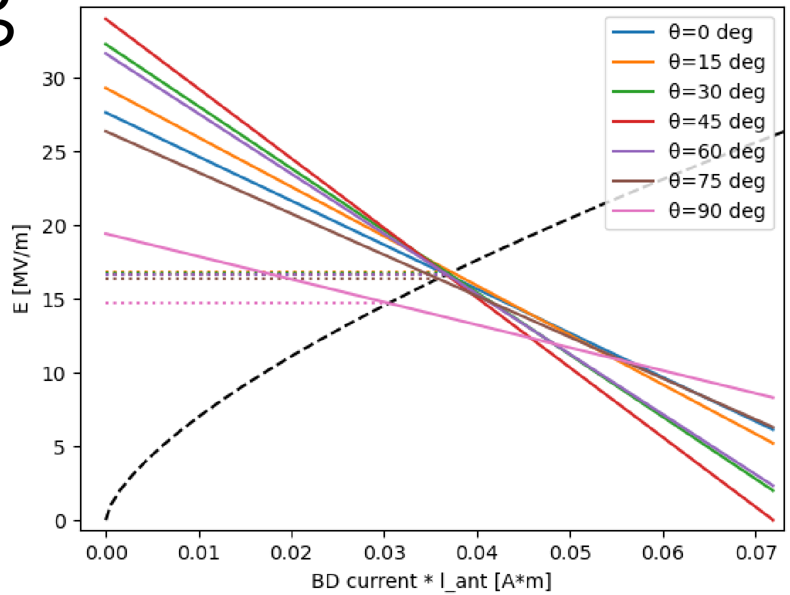
4



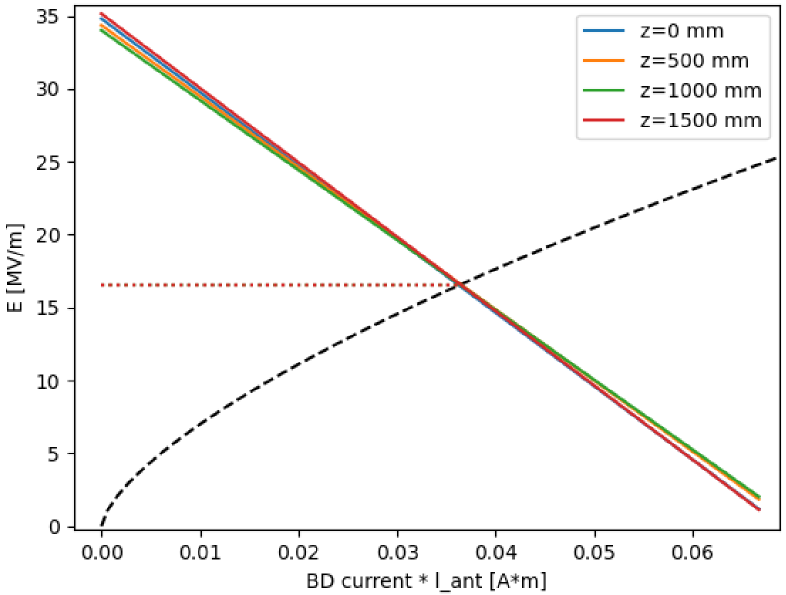
Local power coupling



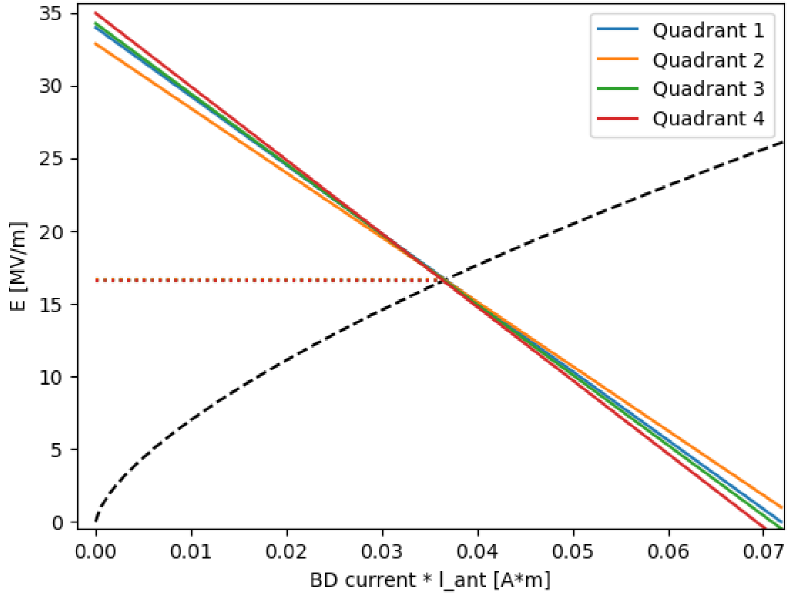
Angular dependence



Longitudinal dependence

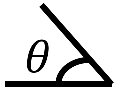


Quadrant dependence

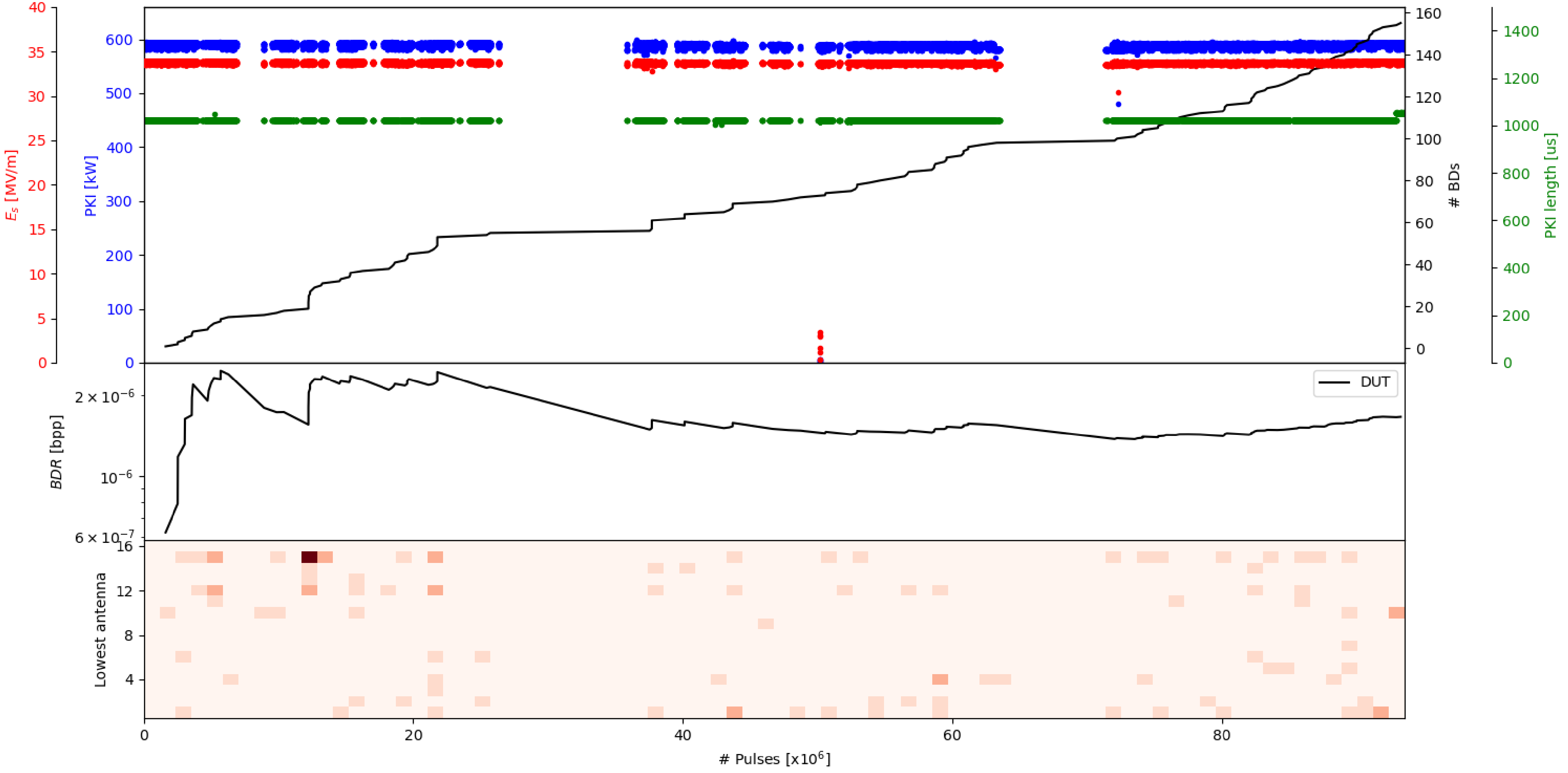


- Antenna length: 1 mm
- $k_l = 5.4 \times 10^{-9}\ \mathrm{Am}^{3/2}\mathrm{V}^{-3/2}$

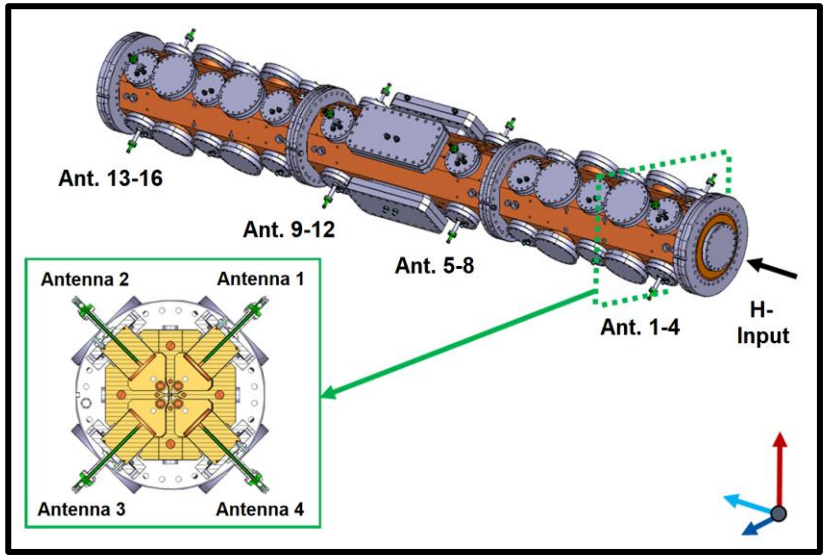
- Antenna length: 1 mm
- $k_l = 5.4 \times 10^{-9}\ \mathrm{Am}^{3/2}\mathrm{V}^{-3/2}$

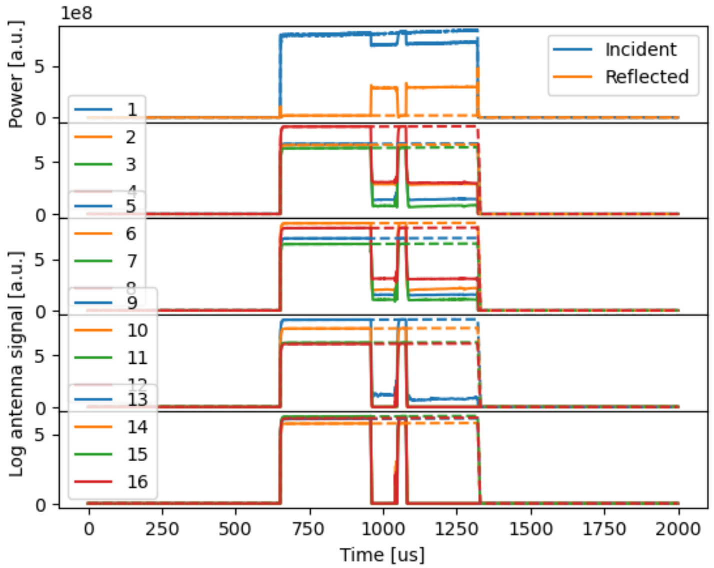


BD distribution RFQ1

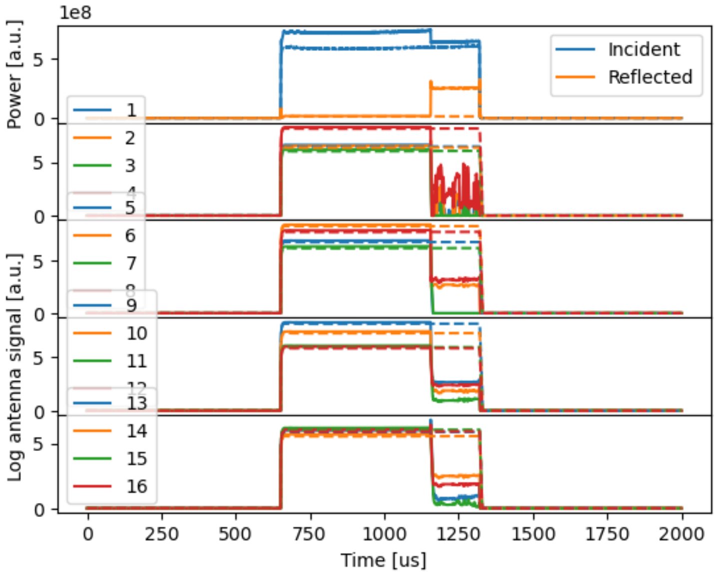


RFQ measurements

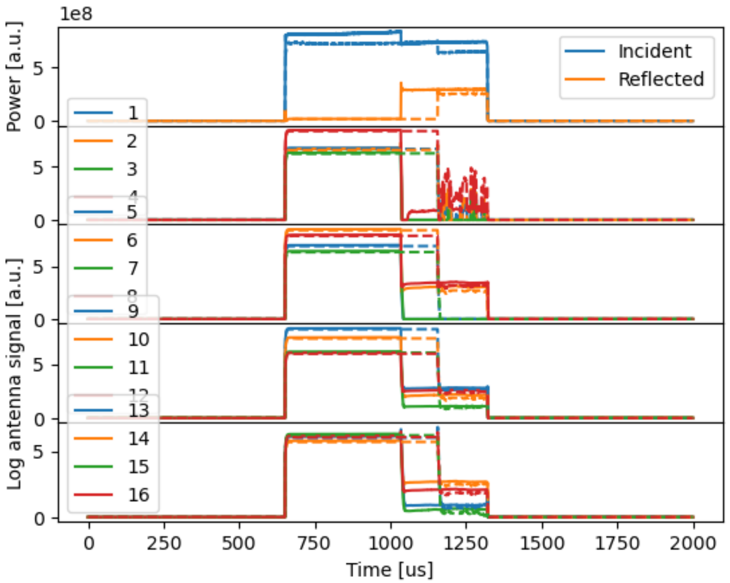




BD recovery and soon activation with the same antenna pattern



- Reflected power increases: Different coupling
- Antennas show different behavior: BD localization



Consecutive BDs (1 s separation) with the same antenna pattern

Vnuchenko, A. (2020). High-gradient issues in S-band RF acceleration structure for hadrontherapy accelerators and radio frequency Quadrupoles