High Gradient S-Band experiments at IFIC

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On behalf of the IFIC RF and Accelerators team

Special thanks to the XBOX team

HG2021
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Outline

- Introduction to the IFIC HG-RF laboratory
- Introduction to the CERN S-band BTW high-gradient accelerating structure
- Operational aspects
- BTW conditioning status
- Preliminary BD localization results
- Dark current and radiation studies work plan
- Summary

The IFIC HG-RF laboratory: layout and main parameters

Main aim:

- ❑ **High-gradient normal conducting RF cavities** research topics at **S-Band (2.9985 GHz).**

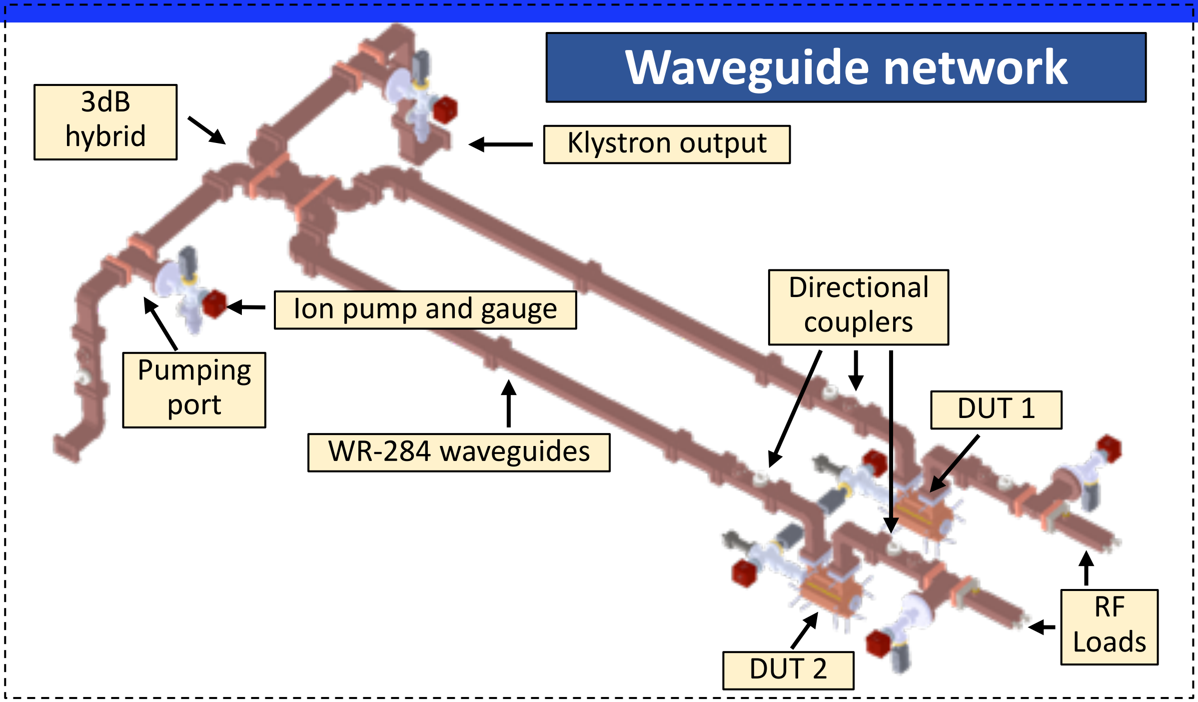
❑ Very **similar to the Xbox-3 test facility at CERN** at 12 GHz but for a central frequency of **2.9985 GHz**.

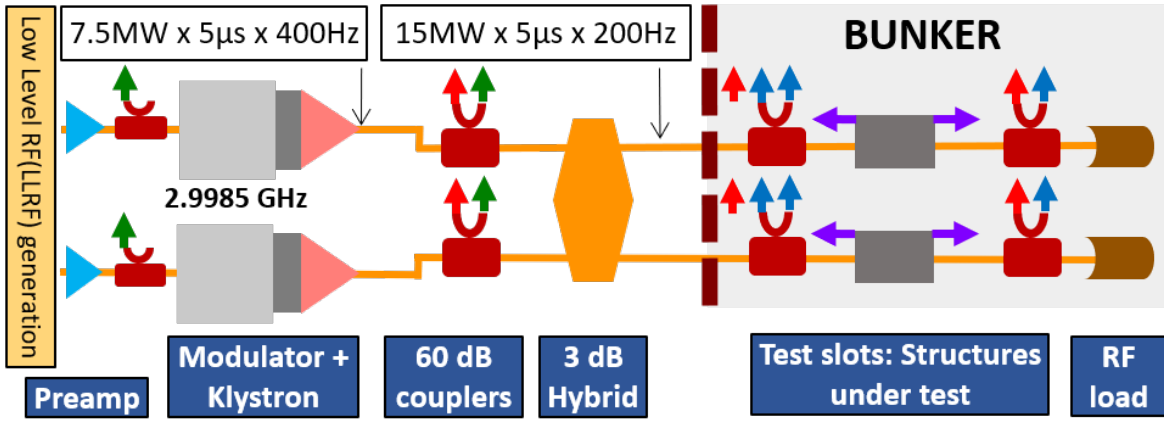
❑ **Low level RF (LLRF):** real-time control system with fast system interlock based on Ni-PXI system.

❑ **HPRF** manage the amplification and guiding of the RF to the DUT to test **2 structures at a time.**

- ❑Up to **15 MW** with **5 µs pulses** and **200 Hz repetition rate**.

- ❑ At present one DUT installed and the other line terminated with a load.





The IFIC HG-RF laboratory: objectives and progress

Current objectives of the laboratory

- ❑ **Conditioning of the Backward Travelling Wave (BTW)** structure designed and built at CERN for protons (β=0.38).

- ❑ **Explore the limitations of the accelerating gradient of the BTW in terms of BDs** and perform **dark current and radiation characterization studies.**
  - ❑ To gain operational experience and investigate the applicability of this technology for medical accelerators.

Timeline

- ❑ **Commissioning** in June 2019.

- ❑ **Started conditioning of BTW** structure in **manual operation** in October 2019.

- ❑ **In July 2020** started using the condition algorithm **(BDR limit set to $5x10^{-5}$).**

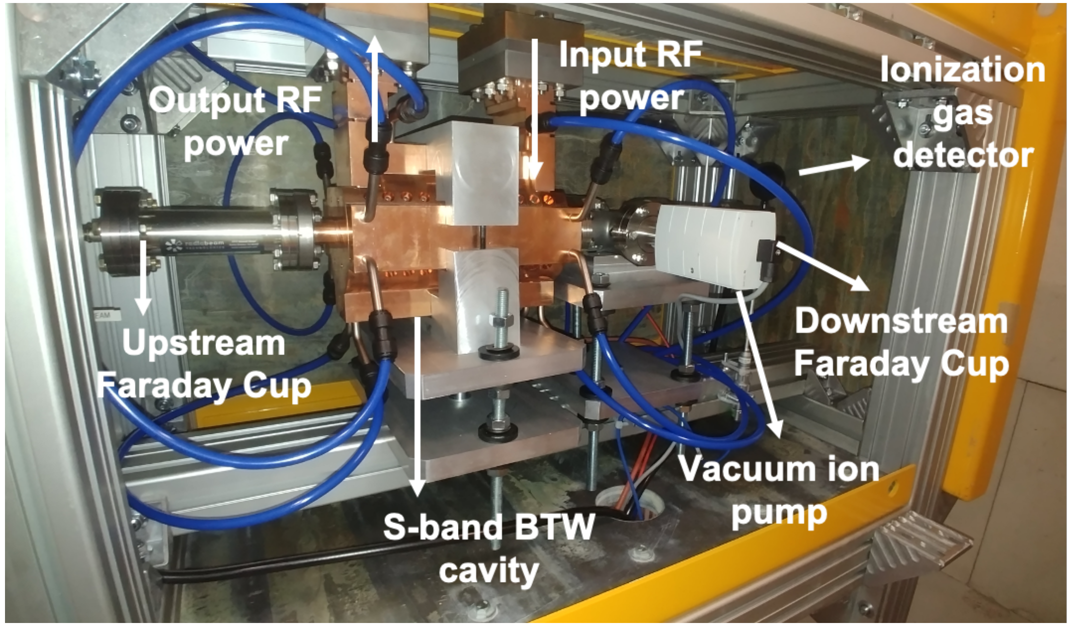
- ❑ **Running full time** from February 2021.

- ❑ **Installation of the bunker roof** in March 2021.

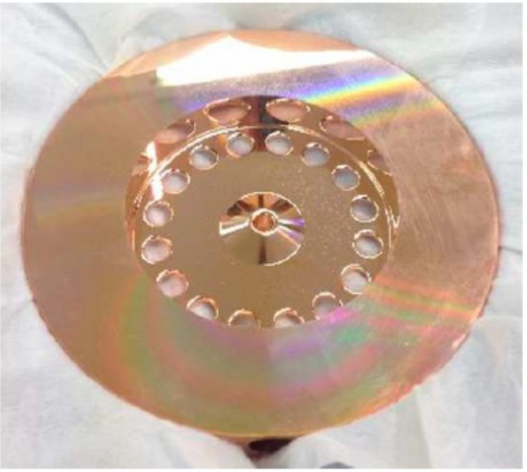
The CERN S-band BTW structure

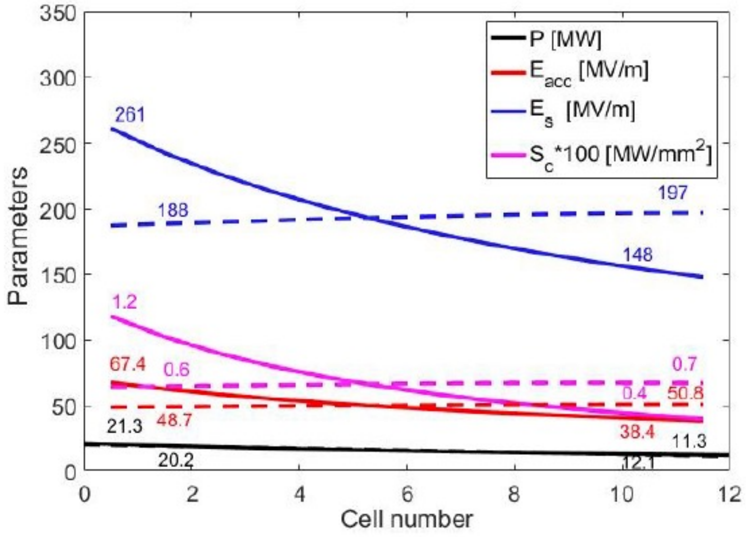
- **CERN designed and manufactured** two S-band accelerating structures **based on CLIC technology** to accelerate protons.

- S-band BTW structure (2.9985 GHz at 32°C)
- 12 cells with Δϕ=150°
- Filling time: 224 ns
- Structure length: 189.9 mm
- Group velocity: 0.39/0.21 %c



Beam





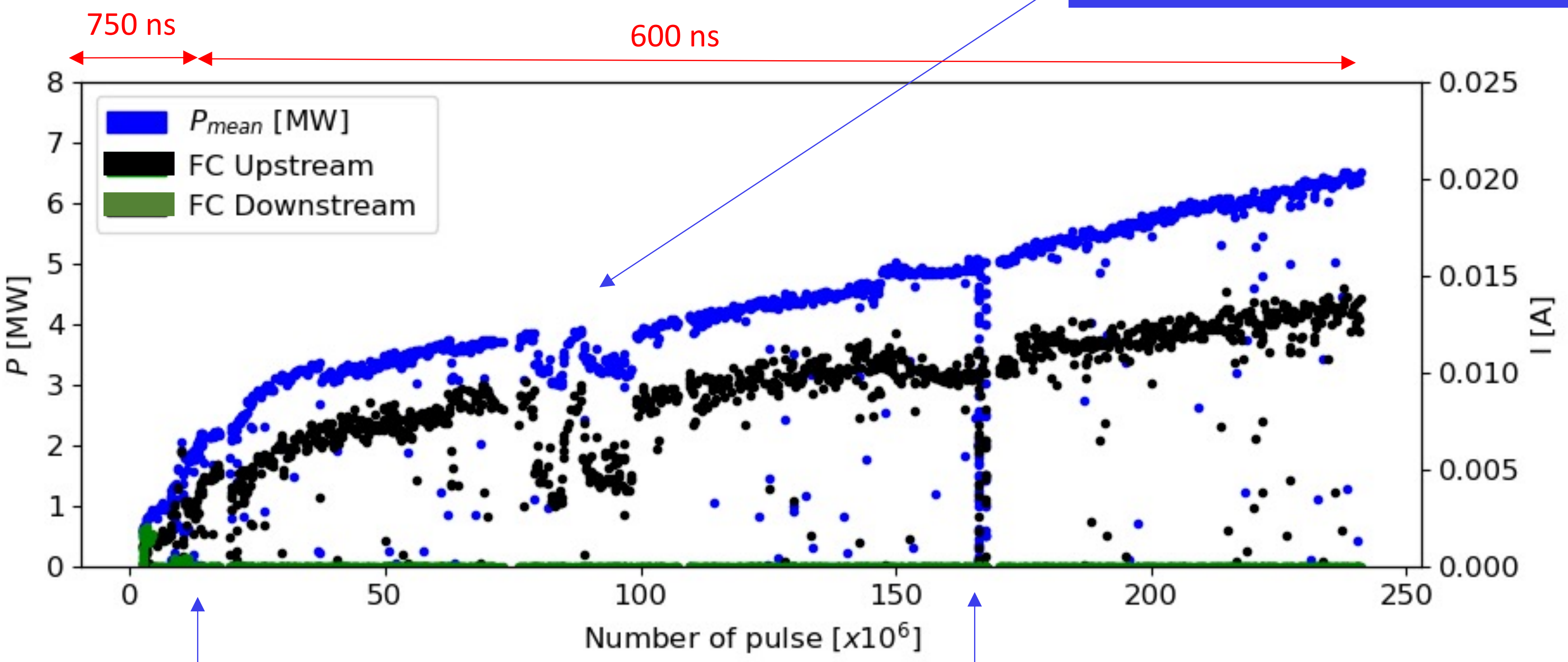
A. Vnuchenko et al., High-gradient testing of an S-band, normal-conducting low phase velocity accelerating structure, Phys. Rev. Accel. Beams, 8 23 084801. 13 p, year = "2020", http://cds.cern.ch/record/2730215

- Design accelerating gradient of 50 MV/m
  - Surface electric field >200 MV/m.
  - S_c maximum not only in the noses but also on the holes.

Operation parameters overview 2019-2021

- **Repetition rate**: 50 Hz-100 Hz
  - Ongoing software development to operate at 200 Hz.
  - New operation mode in which all pulses are sent to the structure under test allowing to go up to 400 Hz.
- **Vacuum:** Below ~1x10^{-8} mbar
- **Temp. structure**: 22-23°C

Second weekend running full time in remote
Problem with PID settings of ramp up power



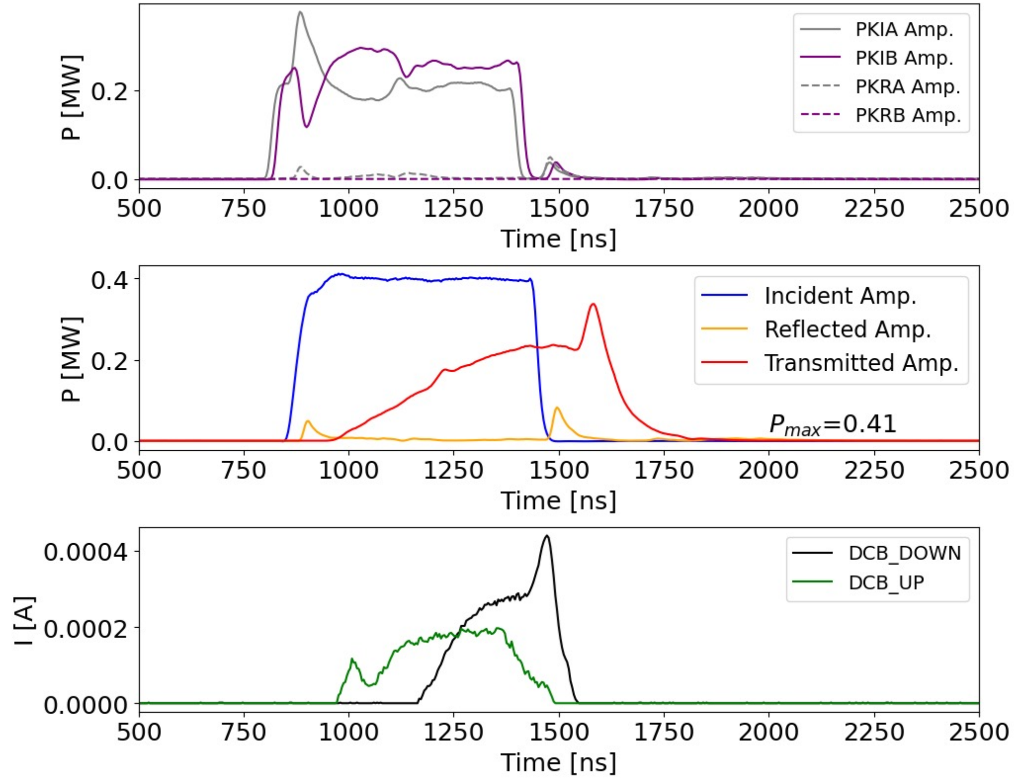
Dark current observed in the downstream FC only on the first days.

Dedicated dose studies

Normal pulse main signals

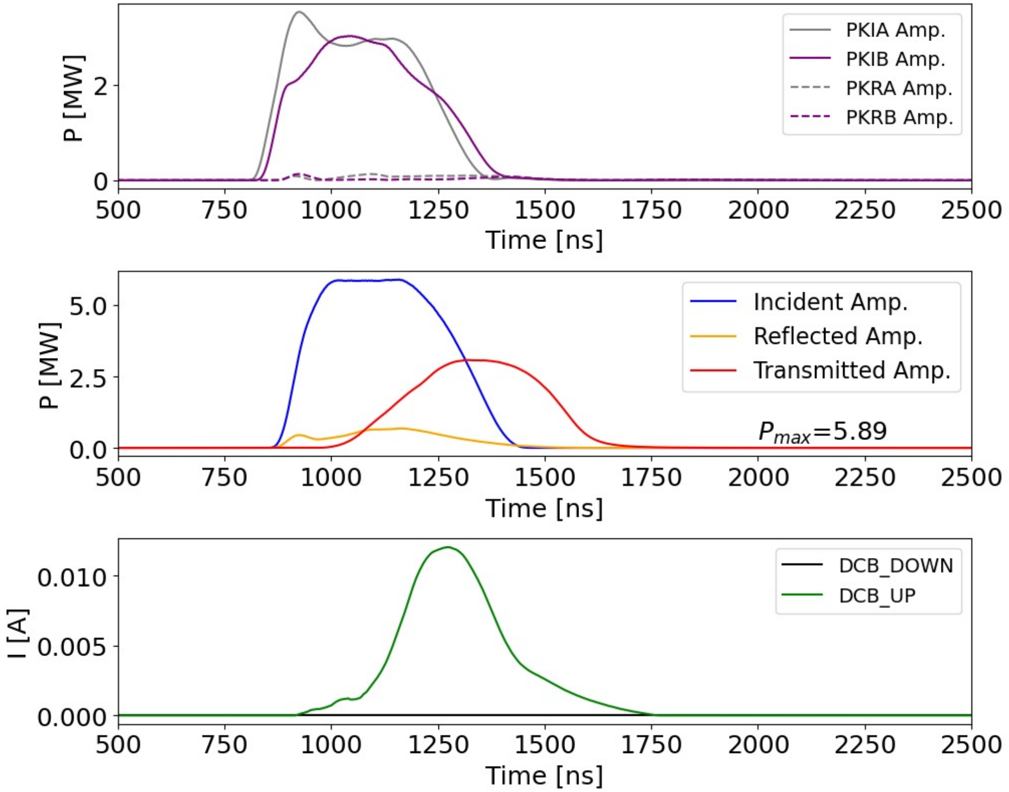
2019:

- ❑ **Pulse length:** 550 ns (flat top) + 100 ns (up)+ 100 (down)



2021:

- ❑ **Pulse length:** 200 ns (flat top) + 100 ns (up) + 300 ns (down)
  - ❑ Reduce reflected and smoothen the transmitted signals.



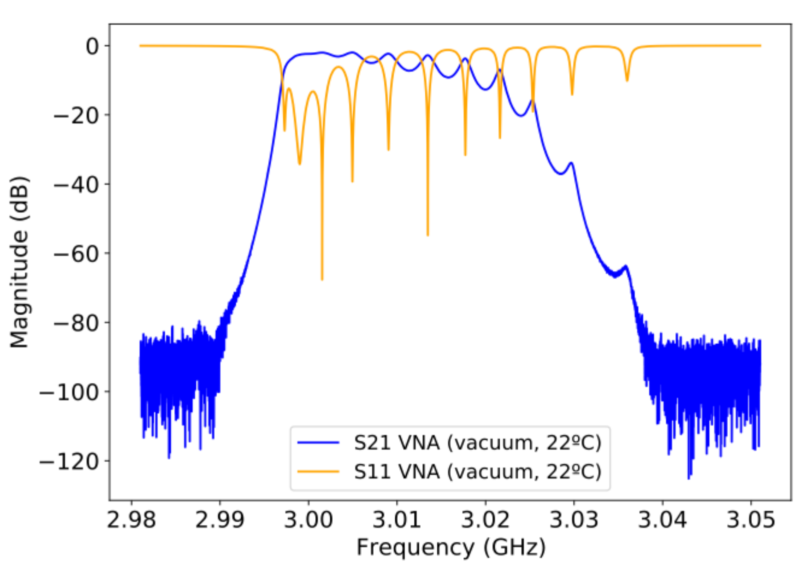
- ❑ Transmitted pulse shape is deformed. Asymmetric rise and drop of the signal.
- ❑ In 2019 the reflected signal at the klystron (PKR) was recorded as the reflected from the structure (wrong cabling).

Simulated pulse

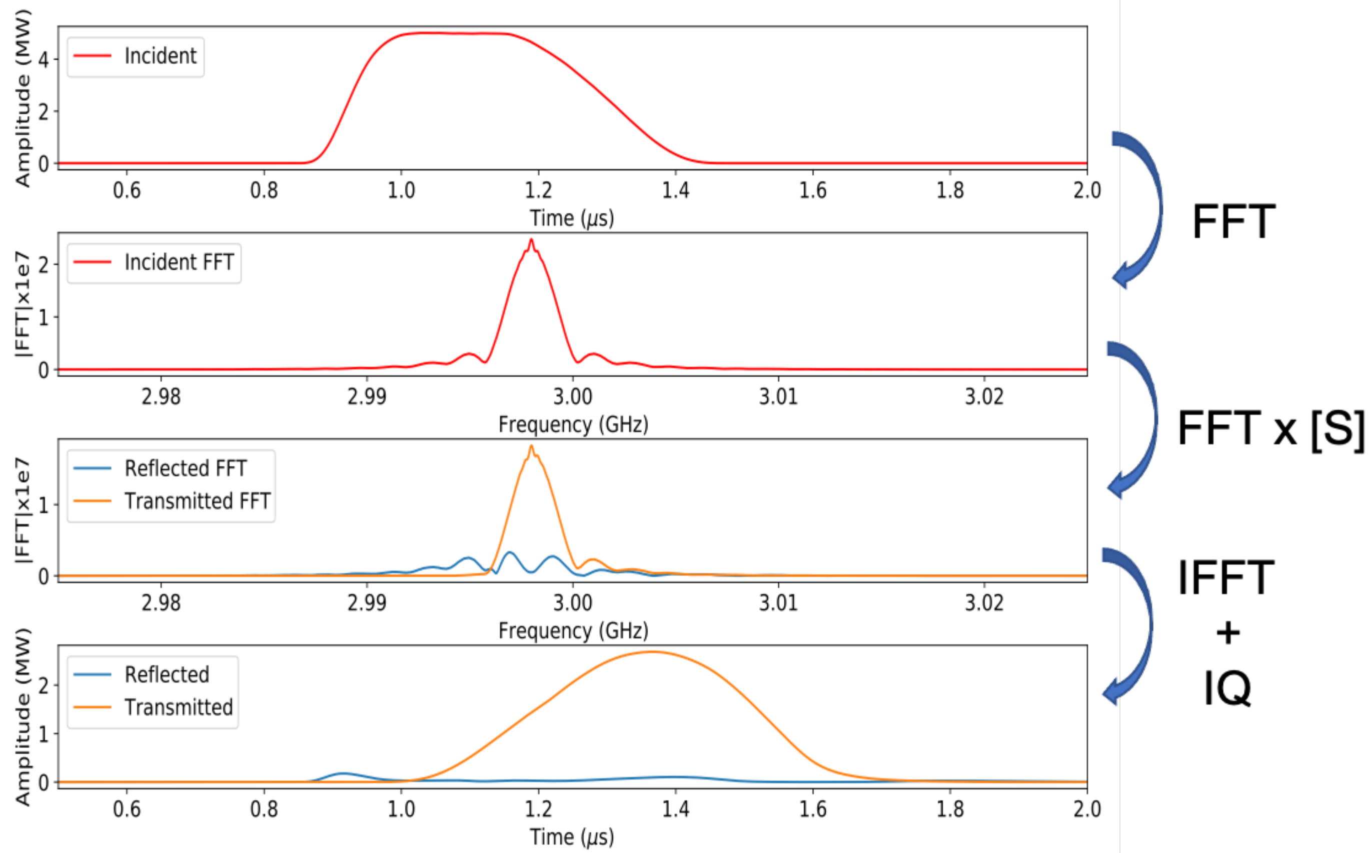
- $S_{11}(\omega)$, and $S_{21}(\omega)$ have been **measured with a VNA**.
- **Incident pulse model** based on measured signal with the experimental set-up.
- **Fast Fourier Transform** (FFT) of the full incident pulse ($f_0 = 2.9990$ GHz) computed using numpy.fft library in python.
- **Reflected and transmitted** pulses in the Fourier space:

$$R(\omega) = S_{11}(\omega) \times I(\omega)$$
$$T(\omega) = S_{21}(\omega) \times I(\omega)$$

- **Inverse Fast Fourier Transform** (IFFT) Computed.
- **Amplitude and phase signals** obtained from IQ demodulation.



Thanks to P. Martínez

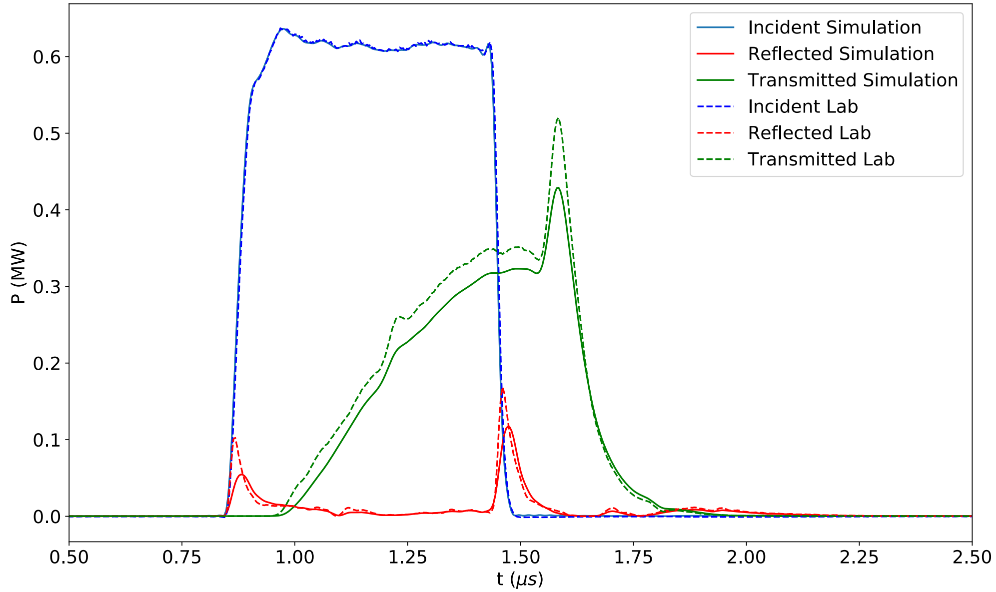


Simulated vs measured pulse examples

2019

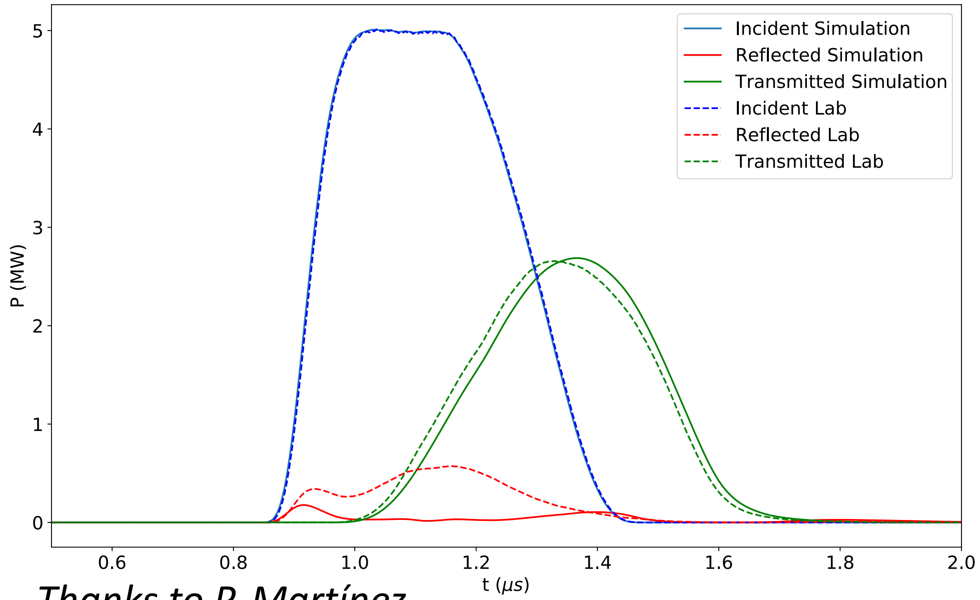
- ❑ Pulse width: 750 ns
- ❑ Rise time: 100 ns
- ❑ Fall time: 100 ns
- ❑ **RF: 2.9985 GHz (for 22 °C)**

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.



Thanks to P. Martínez

Frequency scan

- **Measurements of the reflected and transmitted signals** were performed with a power meter connected to the corresponding directional couplers as a function of the frequency (2.9960-3.002 GHz).

- **Good agreement on the transmitted S21** amplitude but not on S11.

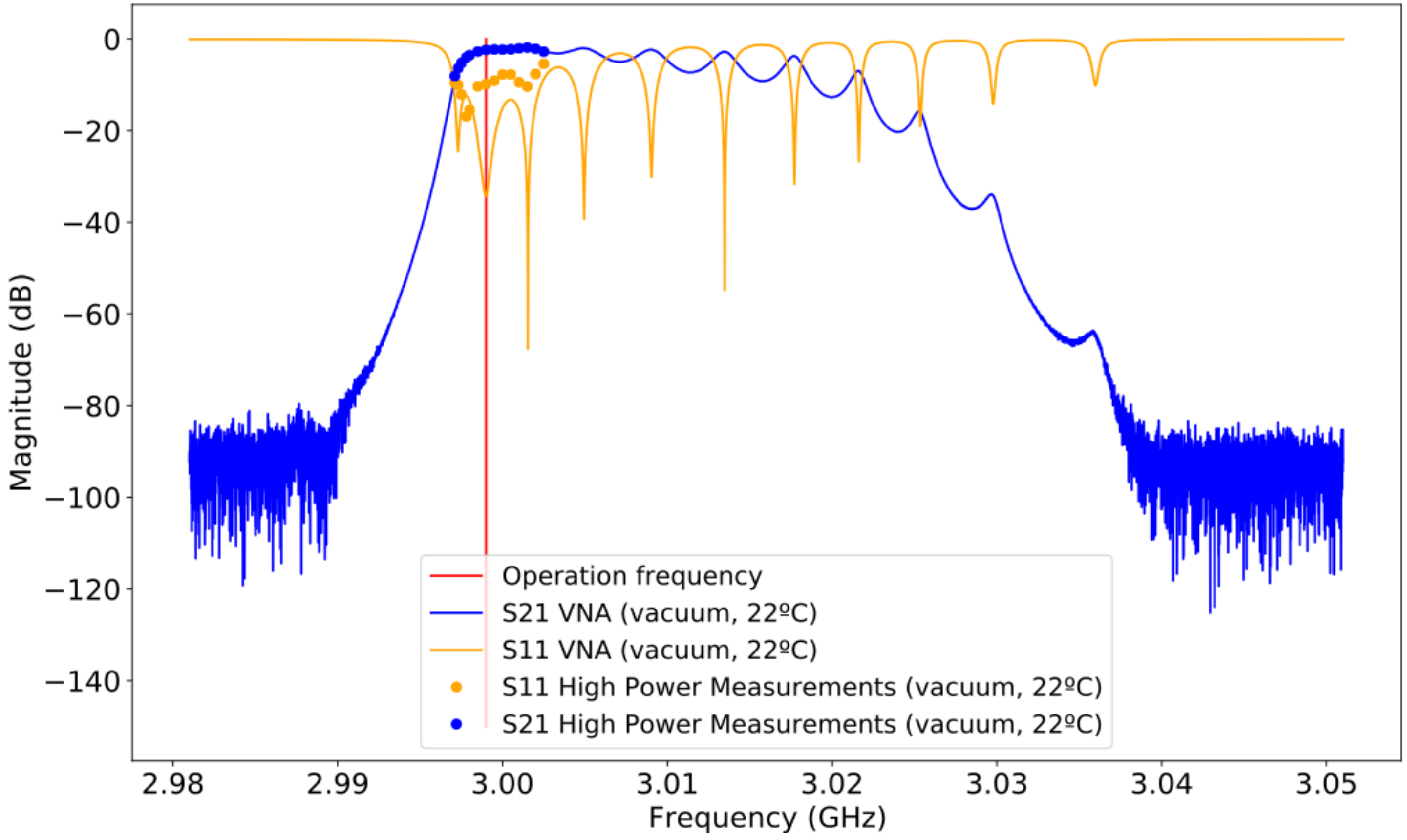
- Reflected signal higher than expected.

  - This issue is not fully understood.

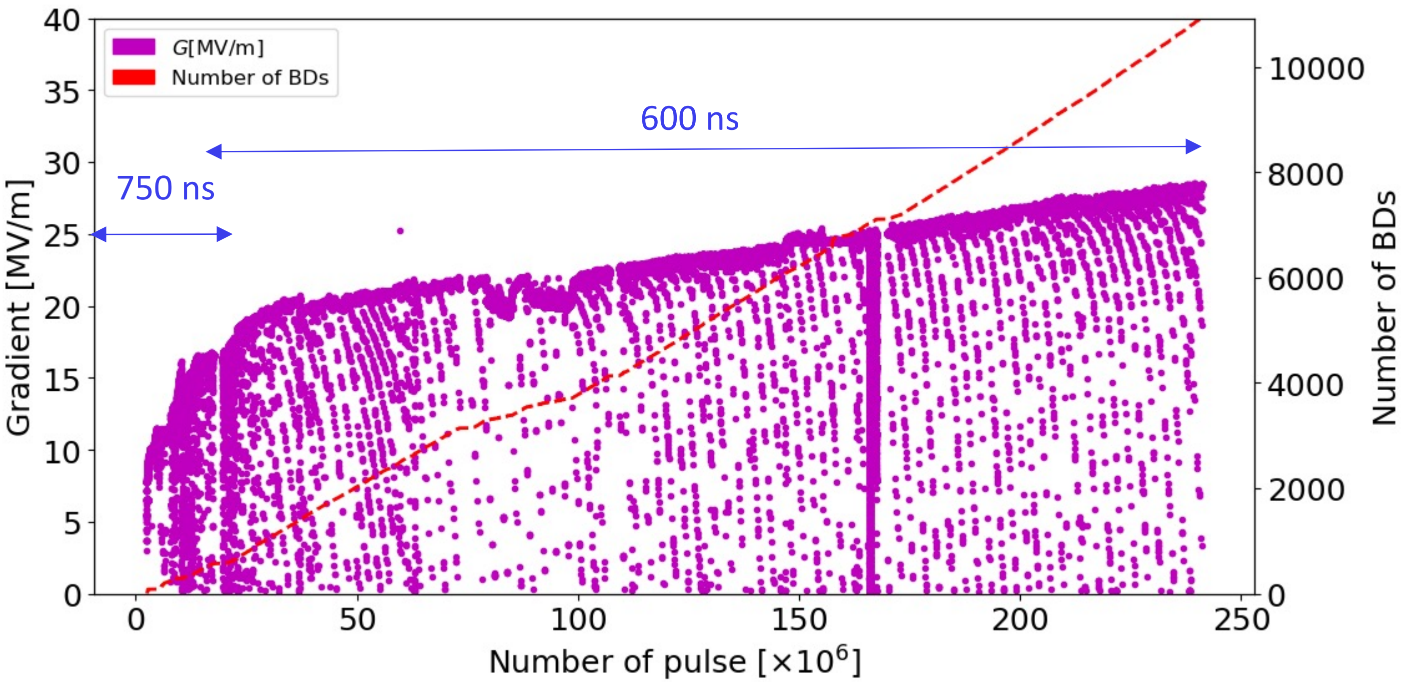
  - Expected different sensitivity of the VNA and power meter.

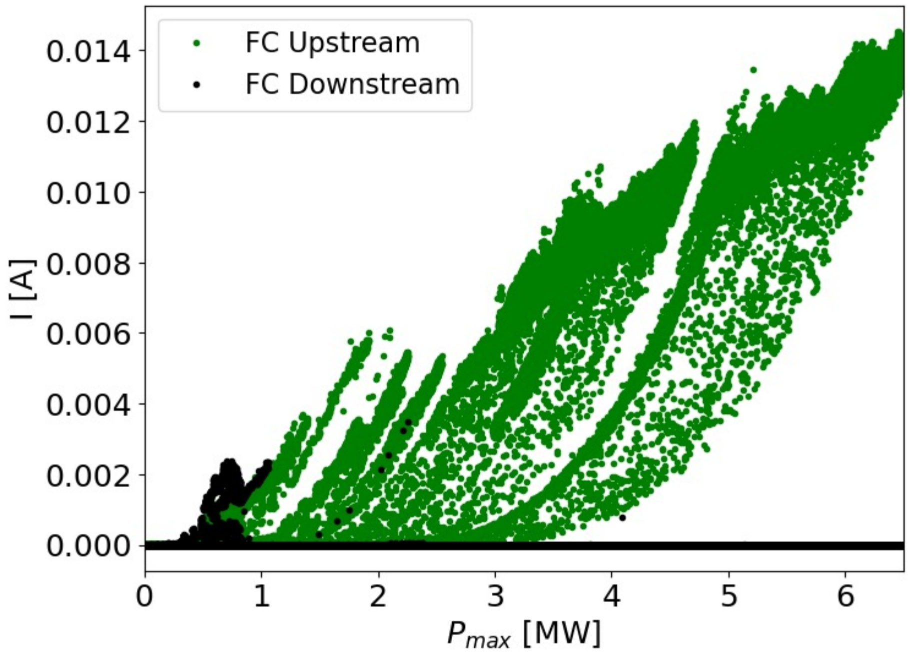
  - Could be due to a problem of directivity of the directional coupler.

Thanks to P. Martínez



BTW conditioning status 2019-2021





- ❑ **Conditioning period**: ~56 days (day time) 48 days (full time)
- ❑ **~10000 BDs and >225M pulses** reaching a gradient of **~27.3 MV/m**
  - ❑ For the same number of pulses with 350 μs pulse length reached 50 MV/m with the structure installed backward *(S. Benedetti. High-gradient and high-efficiency linear accelerators for hadron therapy. Thèse 8246, École Polytechnique fédérale de Lausanne)*
  - ❑ The conditioning process seems much slower than for the BTW structure tested at CERN.

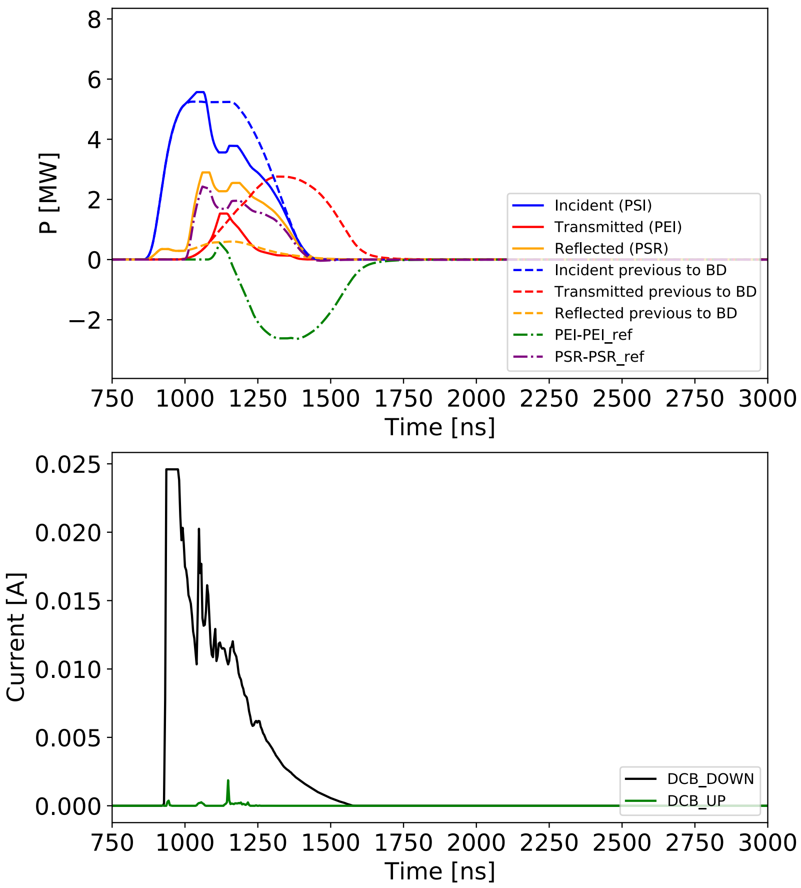
$$G\left[\frac{MV}{m}\right] = 50[MV/m]\sqrt{\frac{INC\_P[MW]}{20.16[MW]}}$$

With current set-up we could go up to 43 MV/m
A pulse compressor will be installed along 2021

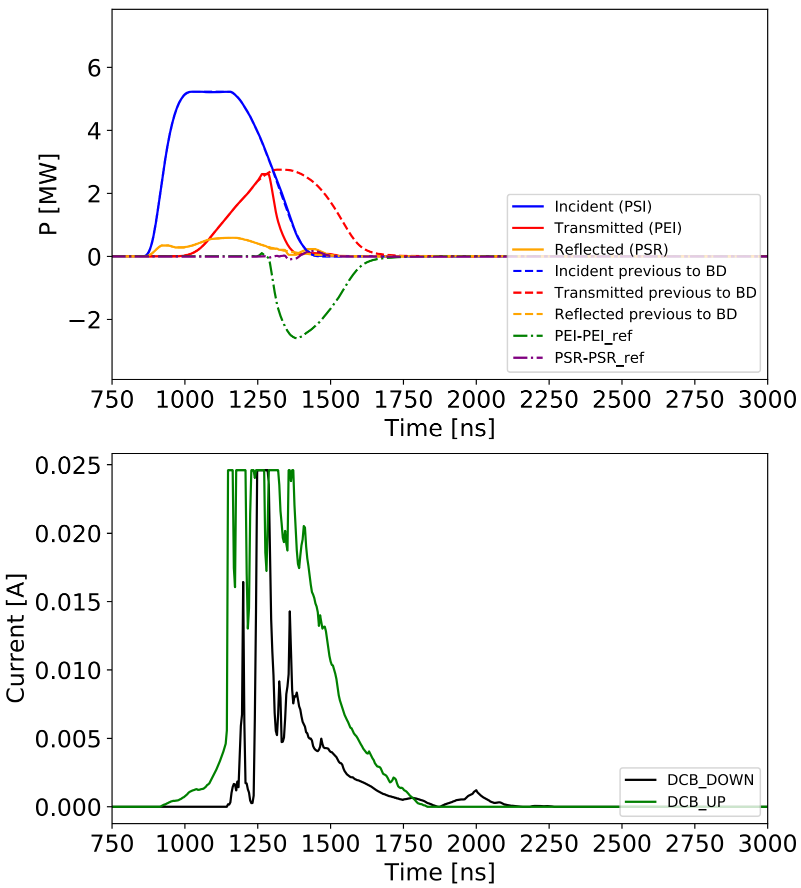
Typical observed BD events examples

2021 data, 600 ns total pulse length

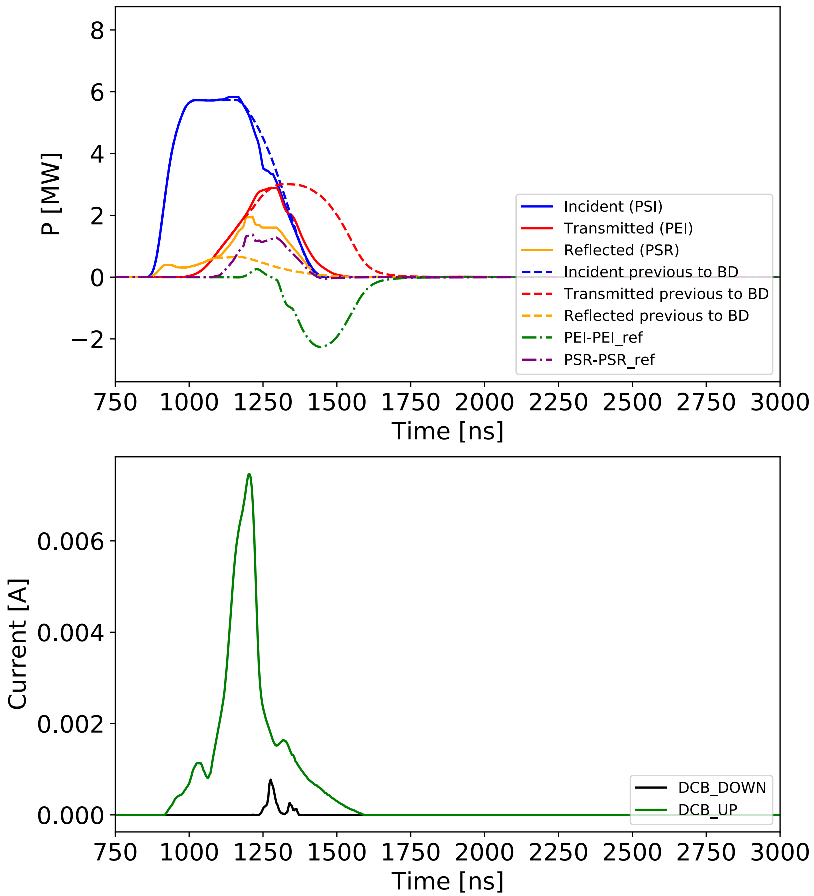
High REF. signal and dark current



Low REF. signal and high dark current



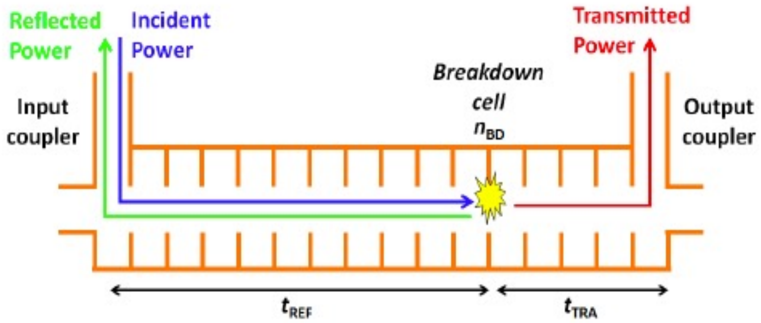
High REF. signal and low dark current

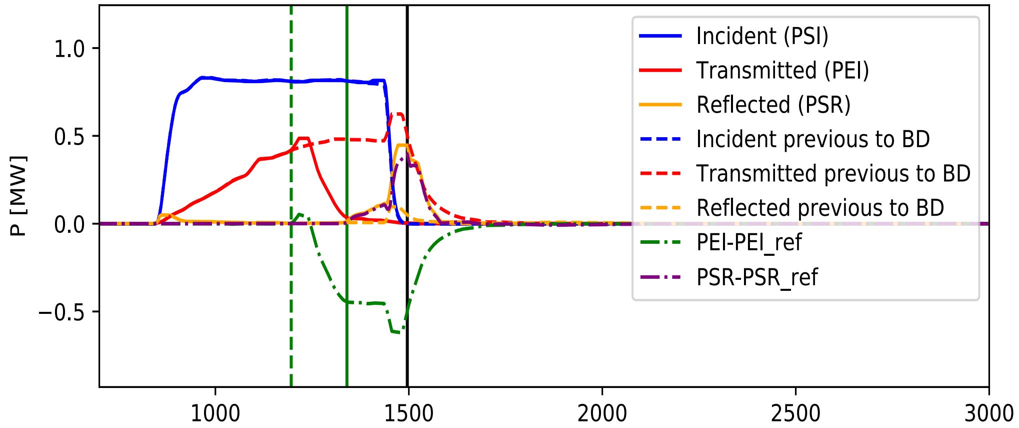


- ❑ The most abundant breakdown signature that we observed is the one characterized by very low reflection and high dark current signals.

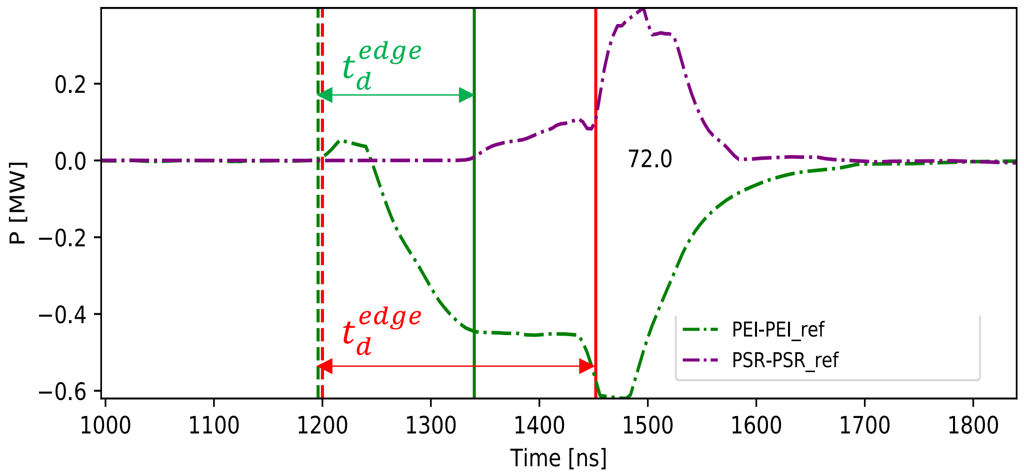
BD localization analysis: “edge method"

- We are interested in finding the regions which could limit the overall performance of the structure.





Edge method: compares the time of detection in which the reflected power rises and the transmitted drops.



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

Edge method criteria for rise and fall time calculation:

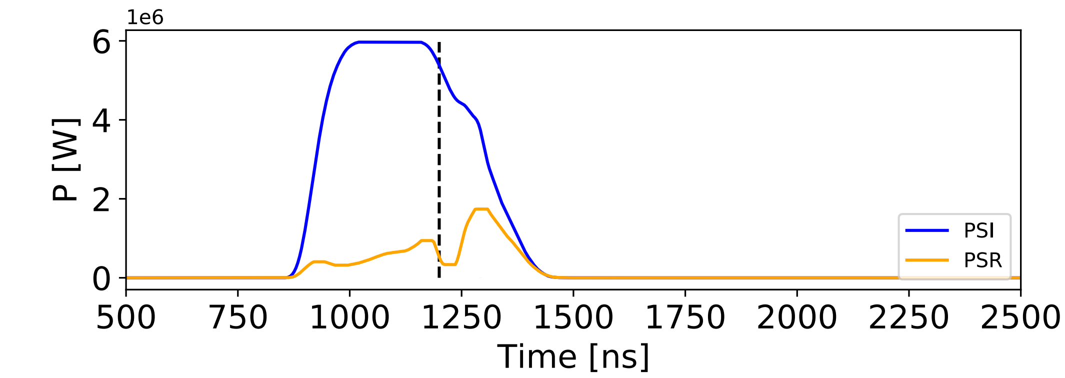
1. $\text{Threshold} = \bar{b} + n * \sigma$ n = 6, 20, 30
2. Threshold =25%*PSR peak increase of PSR and 25%*PEI peak decrease of PEI

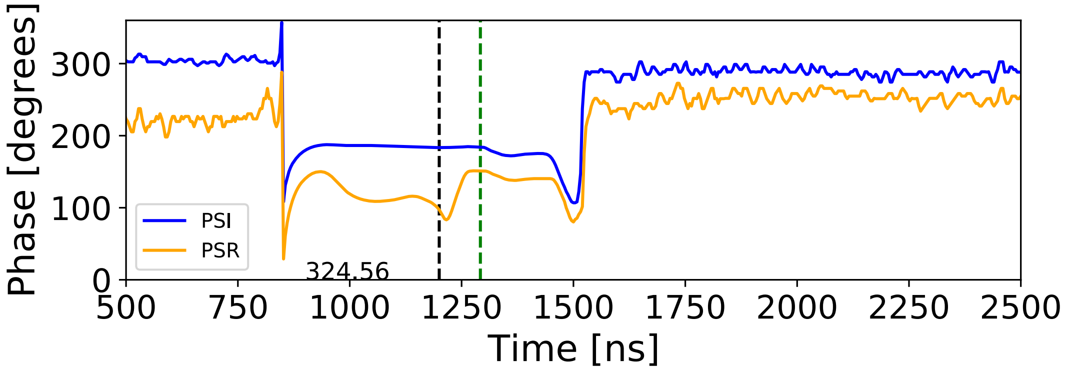
BD localization analysis: "phase method"

Phase method: compares the phase of the incident signal which is constant along the pulse with the reflected phase signals.

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

$$\phi_{BD} = 2 \sum_{n_{cell}=1}^{n_{BD}} (\Delta\varphi(n_{cell})) + \phi_0 = 2\Delta\varphi \cdot n_{BD} + \phi_0$$



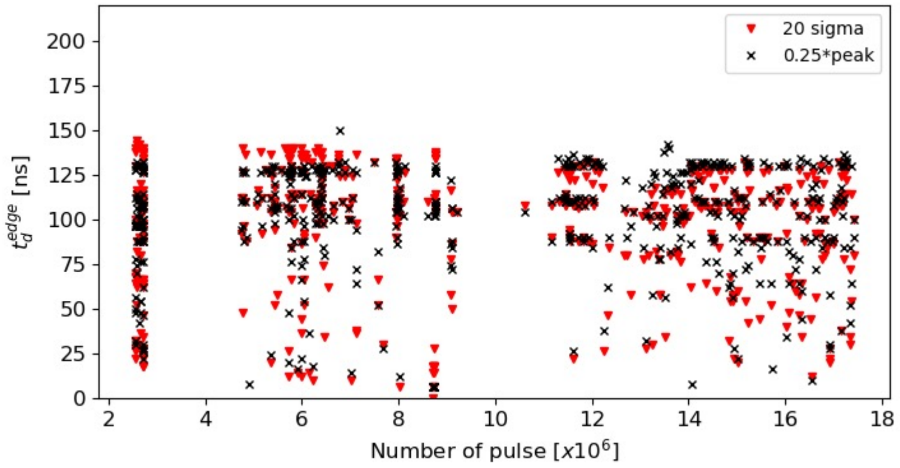


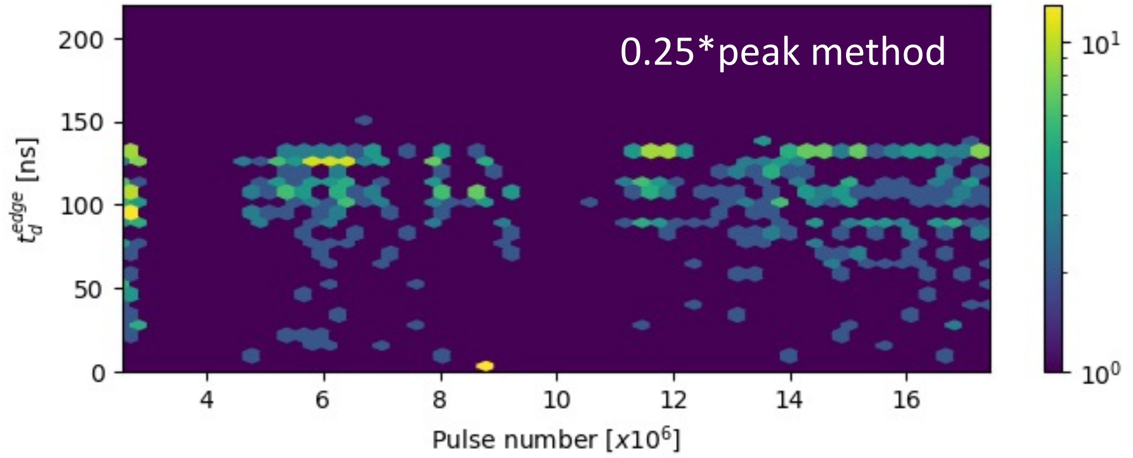
- ❑ **Distribution observed of ϕ_{BD} very noisy**
  - ❑ Preliminary results are presented but a deeper analysis is in progress to better filtering the data.

- ❑ We take the phase signal averaged in 16 ns windows with the minimum standard deviation around the PSR peak (in a window of 80 ns).
  - ❑ Reject pulses with a variation with respect to the next ±4 points larger than 10%.

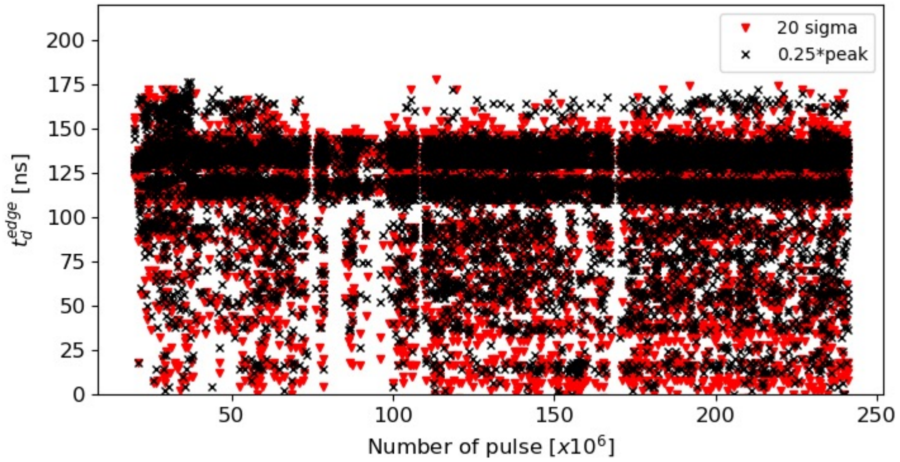
BD localization preliminary results: “edge method”

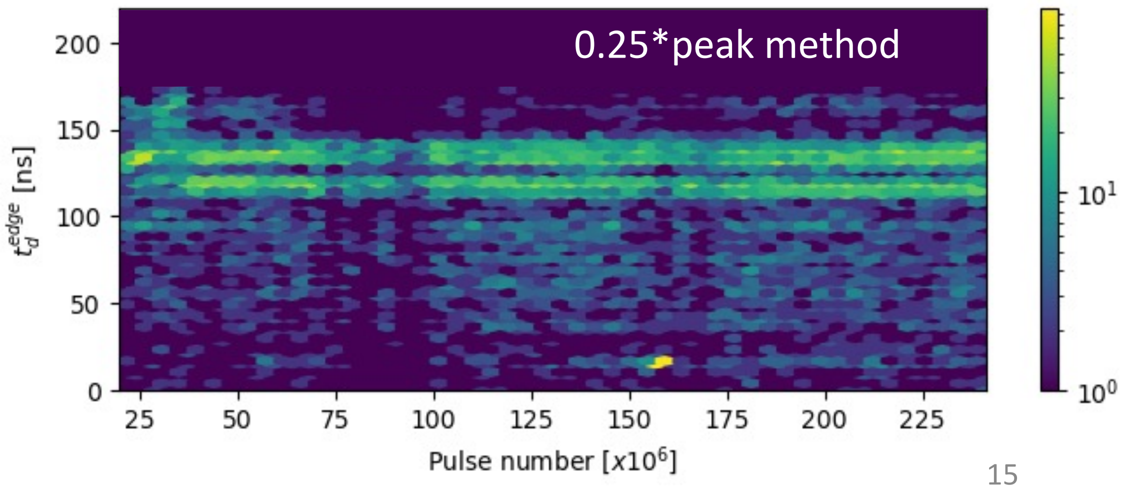
2019-2020
L_p= 550-400 ns (flat top) + 200 ns (up/down)
Frequency: 2.9985 GHz (22 °C)





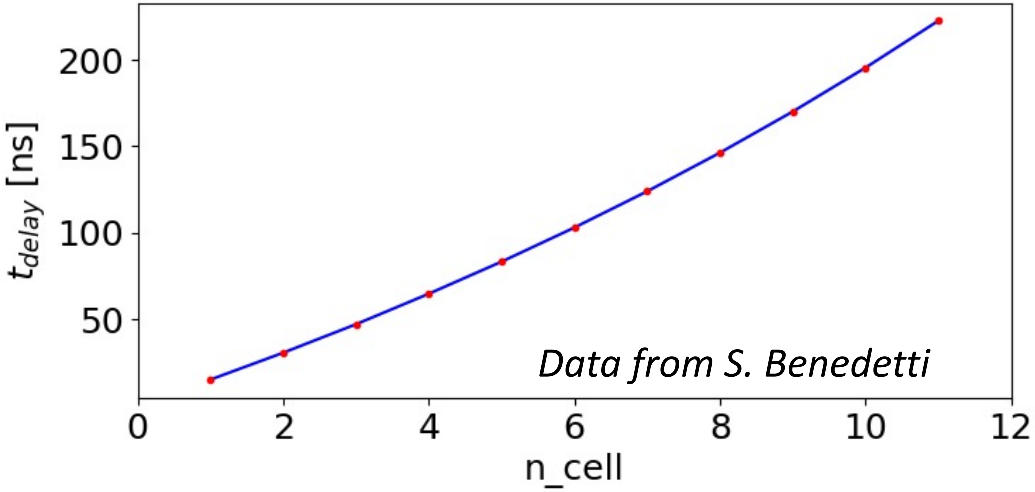
2021
L_p= 200 ns (flat top) + 100 ns (up)+ 300 ns (down)
Frequency: 2.9990 GHz (22 °C)





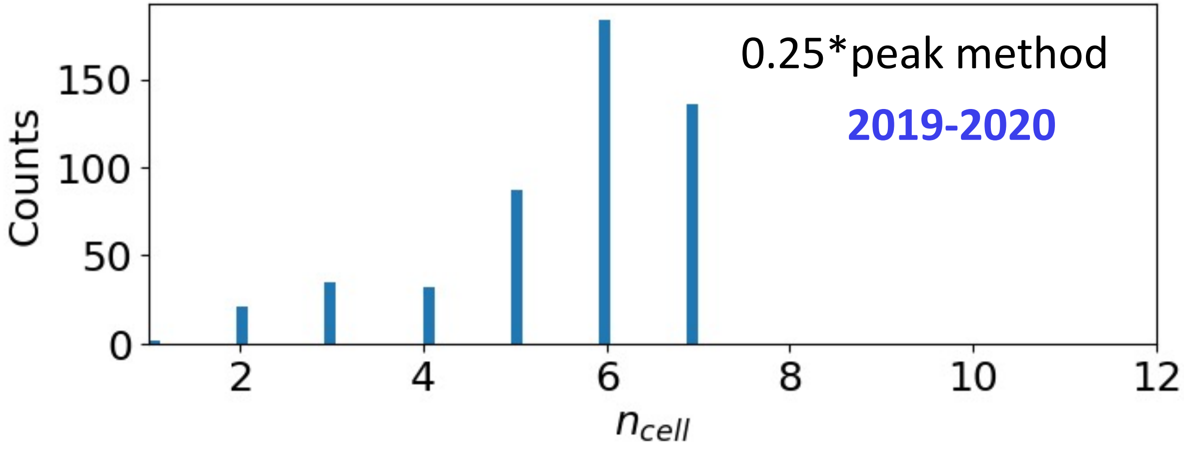
BD localization preliminary results 2019-2021

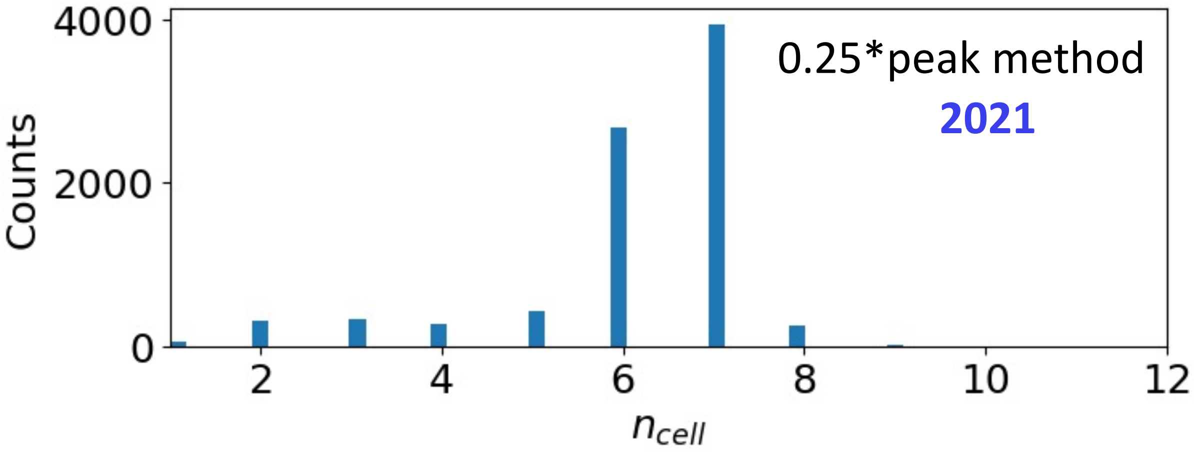
- Using the v_g **profile** the delay expected for each cell can be computed.



S. Benedetti. High-gradient and high-efficiency linear accelerators for hadron therapy. Thèse 8246, École Polytechnique fédérale de Lausanne.

- The BD delays calculated correspond to cell 1 to 9.
- Apparently more BDs observed in cells 6 and 7.
  - Ongoing deeper analysis to better understand the observations is real or there is a type of BD for which the localization method fails.
  - Verify with other methods.

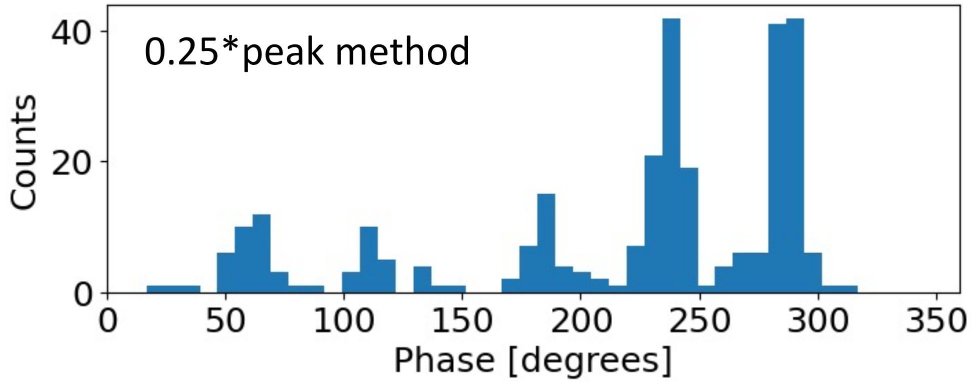


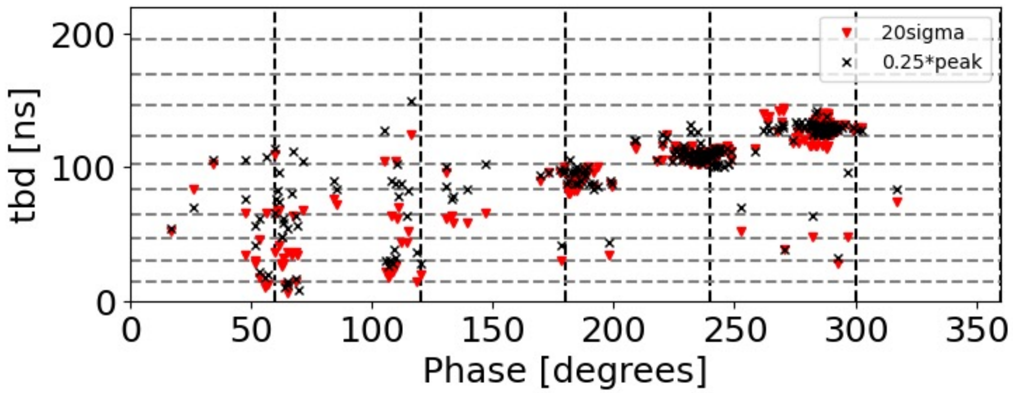


BD localization preliminary results: “phase method”

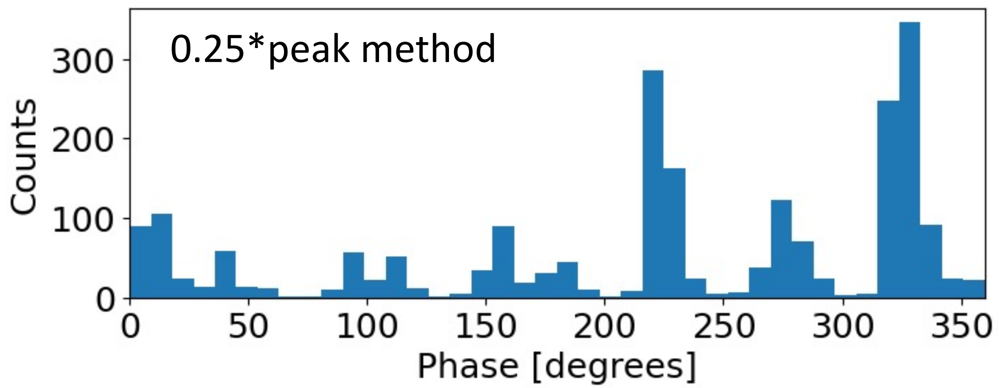
- For the BTW $\Delta\phi$=150° we expect the ϕ_{BD} to be distributed in 6 peaks separated 60° $\phi_{BD} = \langle \phi_{REF}(t + t_d) - \phi_{INC}(t) \rangle$

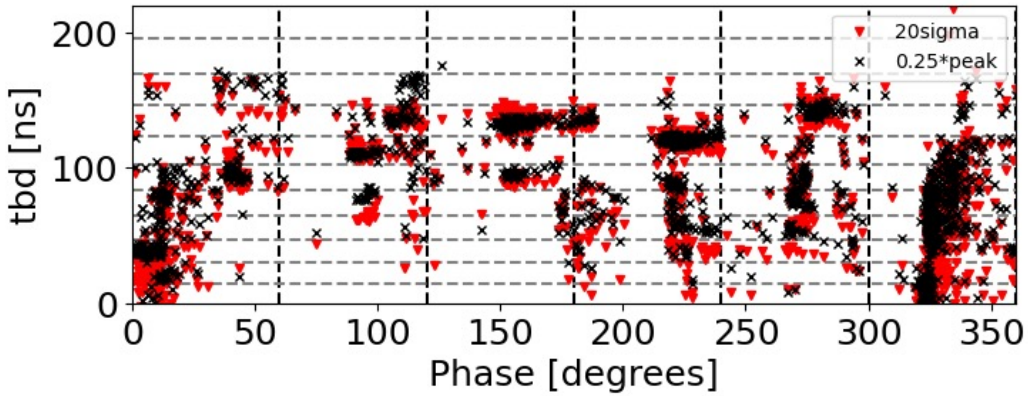
2019-2020





2021

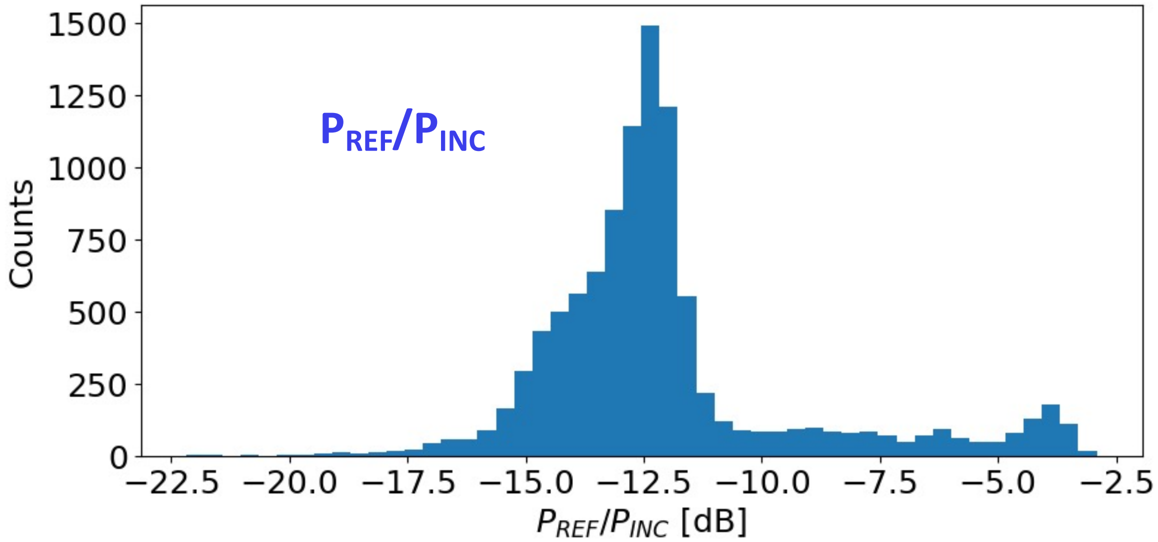


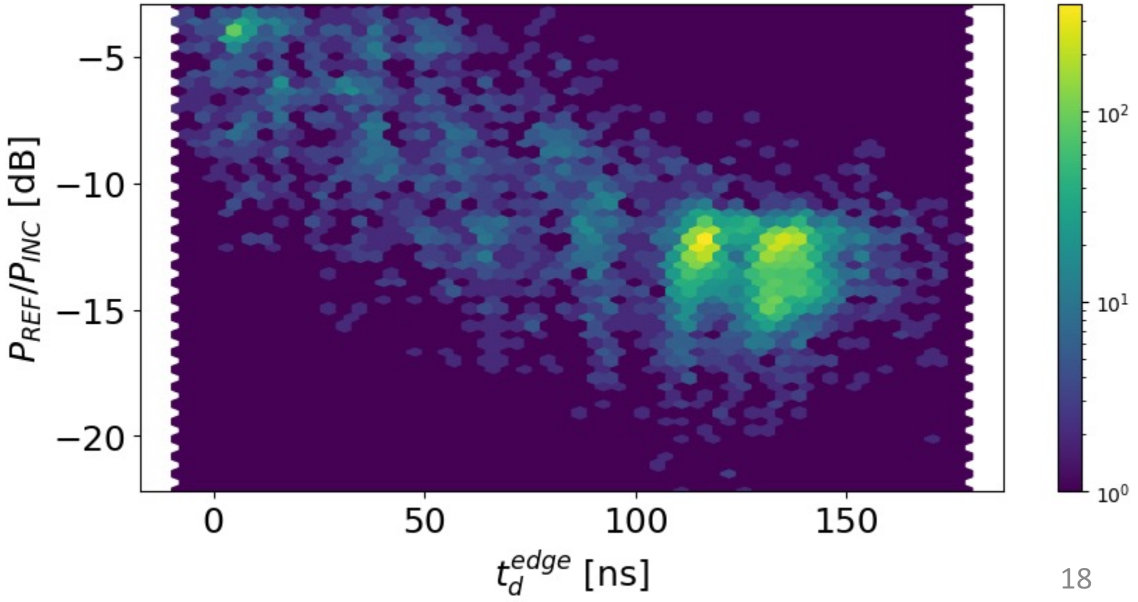


- Not clear correlation between phase and delay time.
- This analysis needs further investigation.

BD reflected power signatures

- BDs reflected power statistics.
- Only considering 2021 data.
- Most of the BDs detected have a quite low reflected power.
- Larger reflected signal observed only for lower delay times.





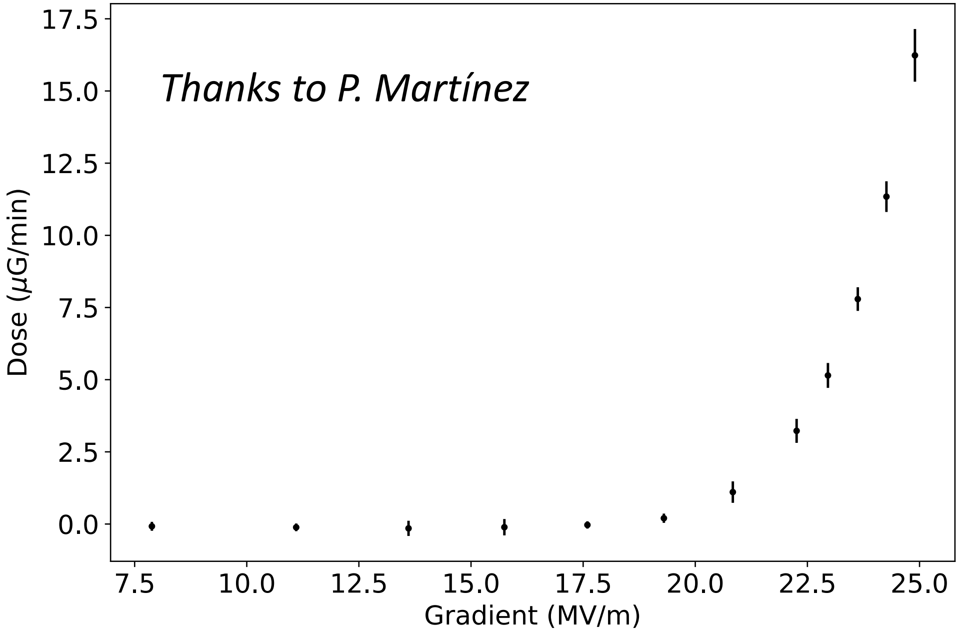
Dark current and radiation studies work plan

Motivation:

- ❑ Characterize the dynamics and impact of the dark currents.

Dosimeter:

- ❑ Placed next to Faraday Cup Downstream.
- ❑ Spherical ionization chamber.
- ❑ Energy range: 25 keV – 50 MeV.



Future plans:

- ❑ Measure energy spectrum of the photons emitted using scintillator detectors (collaboration with IFIC Nuclear Physics Team).
- ❑ Compare measurements and simulations.
- ❑ Dark current electron dynamics simulation (PIC code).
- ❑ Compute electron-walls interactions and secondary photons emission simulations (Geant4).

Summary

- **The conditioning of the second S-band BTW structure is in progress at the IFIC HG laboratory.**
  - An accelerating gradient **of ~27.3 MV/m** has been reached **in 240M pulses** with **more than 10000 BDs** detected.
  - The effect of the **conditioning process is visible on the dark current data**.
  - **Preliminary breakdown localization analysis** indicates that we have two cells that accumulate more BDs than the others for the current conditioning status.
    - However, a deeper understanding on the analysis results and procedure is required.

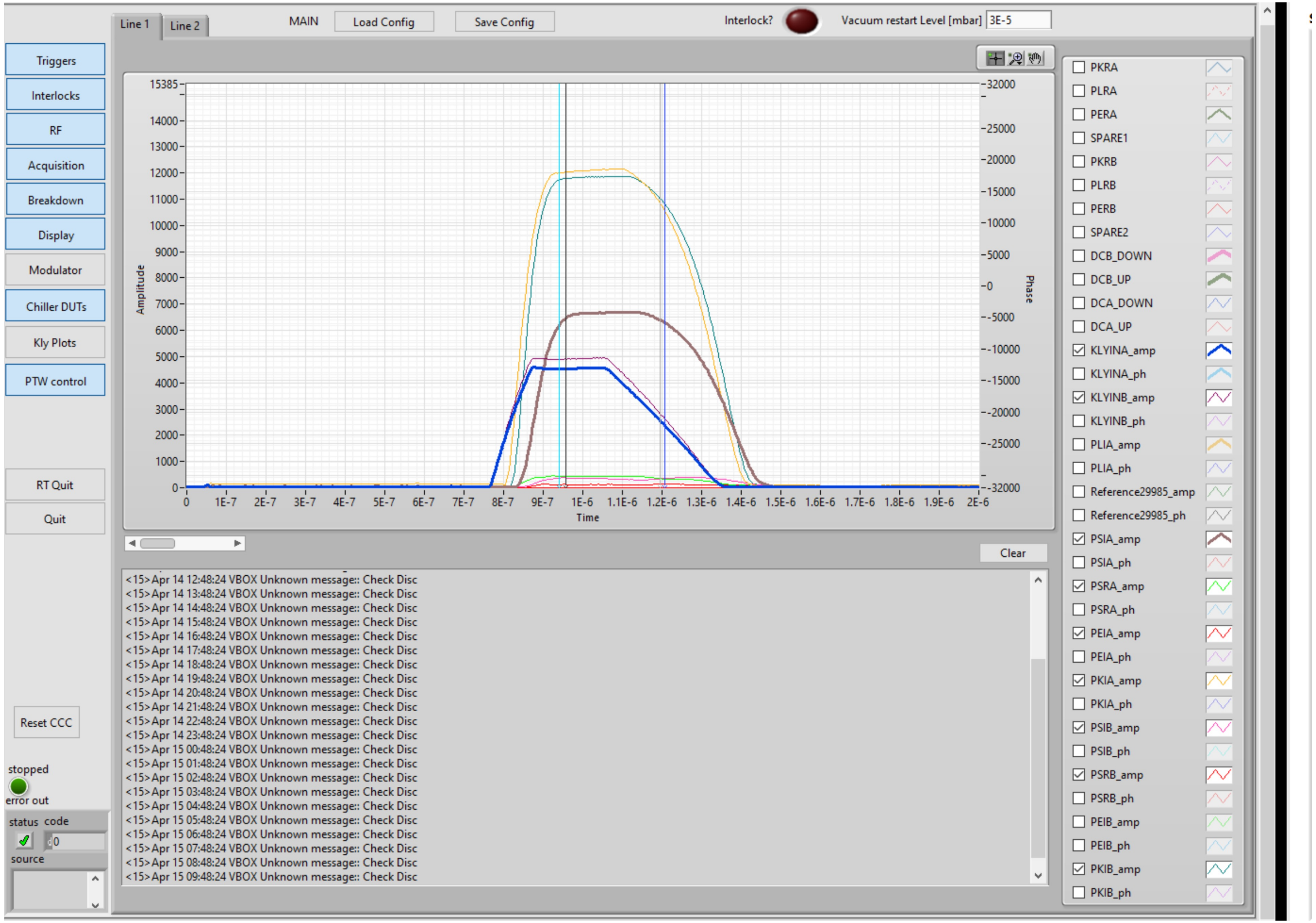
Next steps:

- Continue the conditioning of the BTW structure to higher gradients.
  - Pulse compressor installation in 2021.

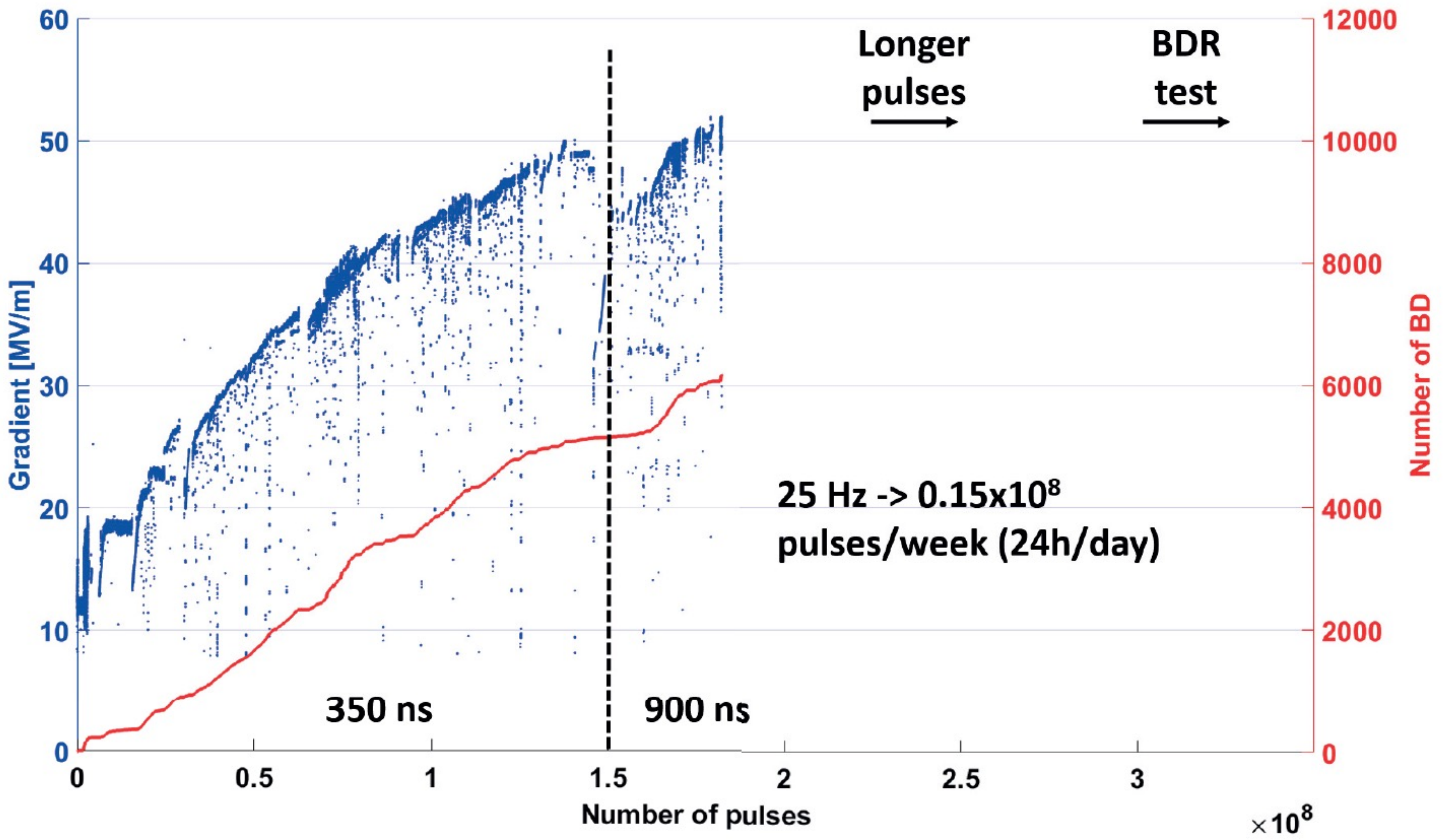
- Energy spectrum measurements of radiation generated by dark currents.

Thank you very much for your attention!

Line A main signals

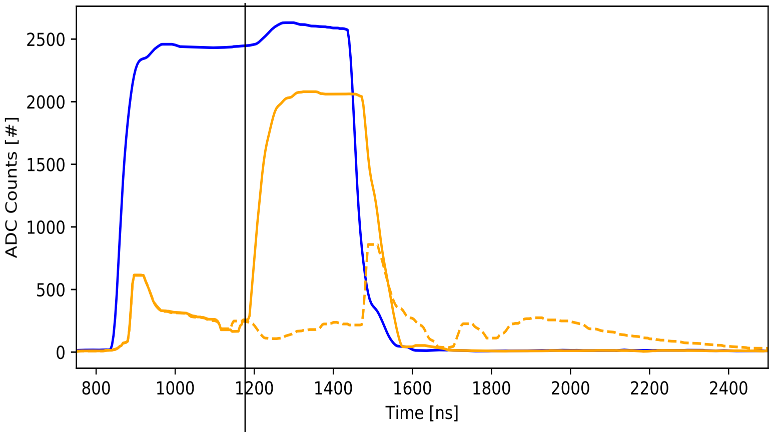


CERN BTW conditioning

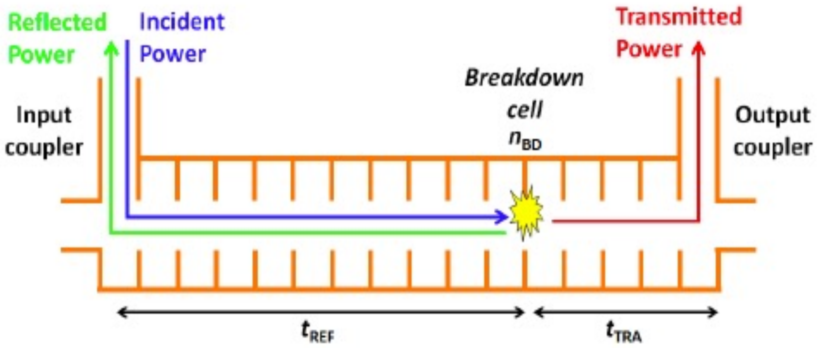


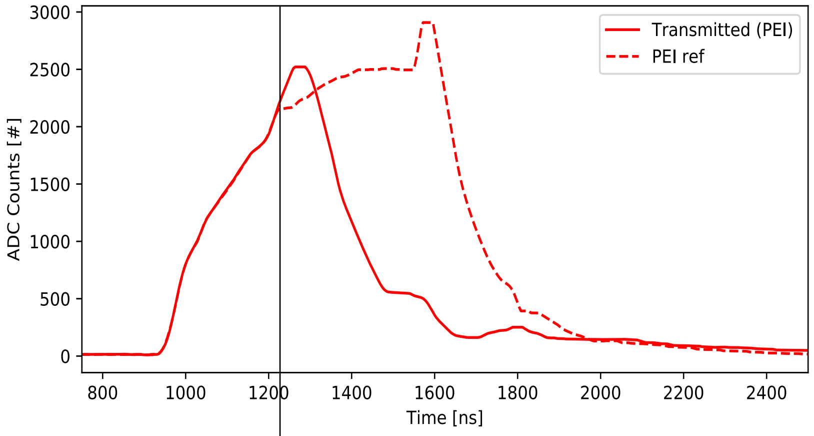
BD localization preliminary results no filtering

- Assuming that the signals are temporally aligned.
- Assuming that the rise and drop of signal for the reflected and transmitted signals occur at the same time.



t_{REF}





t_{TRA}

$$t_d^{edge}[ns] = t_{REF} - t_{TRA} + tfill$$

$$t_d^{edge}[ns] = \sum_{n_{cell}}^{n_{BD}} \frac{L_{cell}}{v_g(n_{cell})} - \sum_{n_{BD}}^{n_N} \frac{L_{cell}}{v_g(n_{cell})} + t_{fill}$$

- A t_{fill} has to be added in order to ensure the same time origin of the signals as one is measured at the entrance and the other at the exit of the structure.

Preliminary summary of BD analysis localization

1

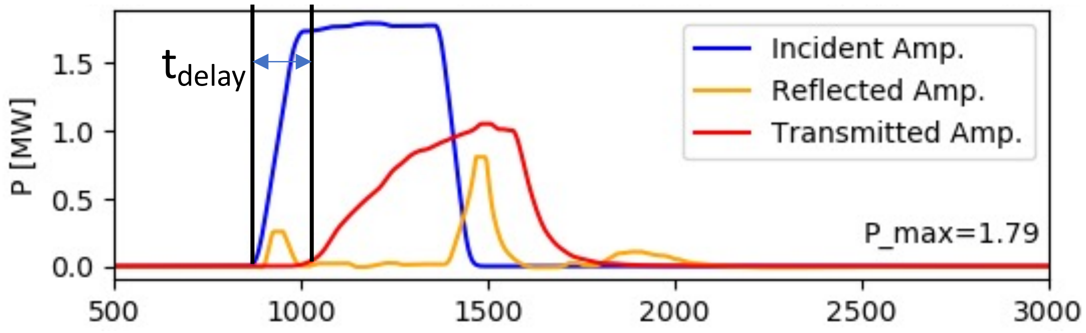
$$t_d^{edge}[ns] = \frac{\Delta t_{REF} - \Delta t_{TRA}}{2}$$

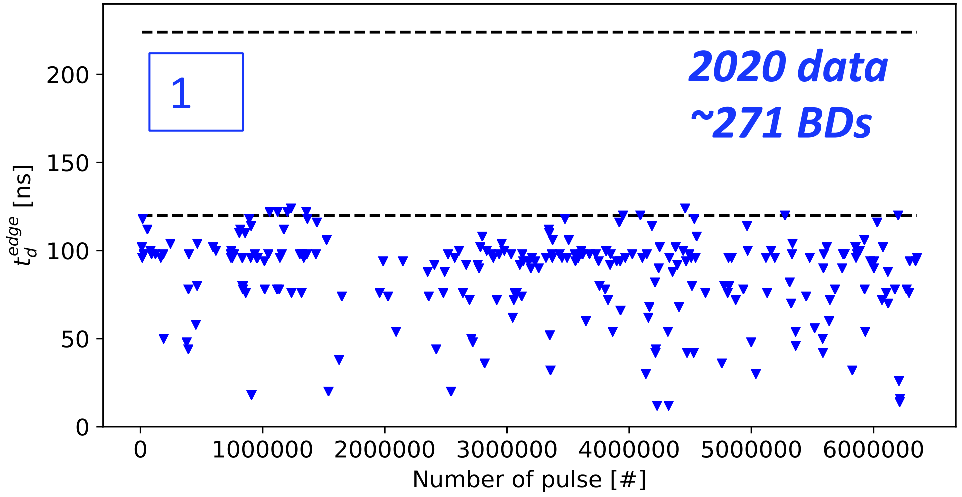
Using the typical formula with the absolute values of rising reflected signal and drop of transmitted signal.

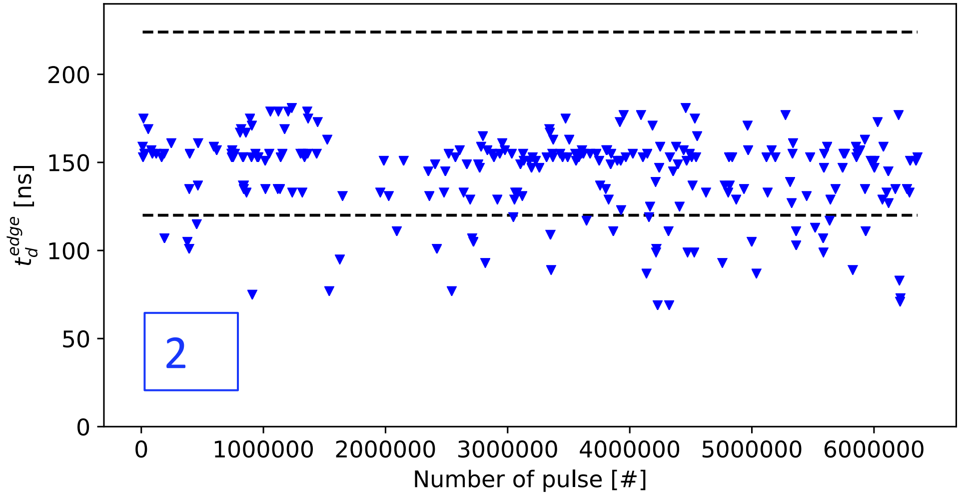
2

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

- Expressions 1 and 2 should be equivalent if $t_{fill} = t_{delay}$?







- The applicability of the method 1 and how to apply it is under investigation as well as finding a way to measure the filling time from the measured signals.

BD localization preliminary results no filtering

- We expect 6 peaks separated 60°