High-field studies in the LINAC4 RFQ

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Outline

- Introduction to High-field limiting parameters
- Technical specifications of the Linac4 RFQ
- RF breakdown studies in 352 MHz Linac4 RFQ
- Conclusions

Benefits of a high field for RFQs

HG is a very important requirement for different types of accelerating structures including RFQs since **high peak fields** increase their **performance**:

- ✓ higher **acceptance** (larger emittance beams);
- ✓ acceptance of heavy ions with lower charge state;
- ✓ greater space charge capability;
- ✓ **shorter** RFQs;

but also have an impact on:

- ➢ more **RF power** is required;
- ➢ **tighter machining** and alignment tolerances;
- ➢ increased **probability of sparking or vacuum breakdown**.

RFQs have significant importance for scientific and society applications.

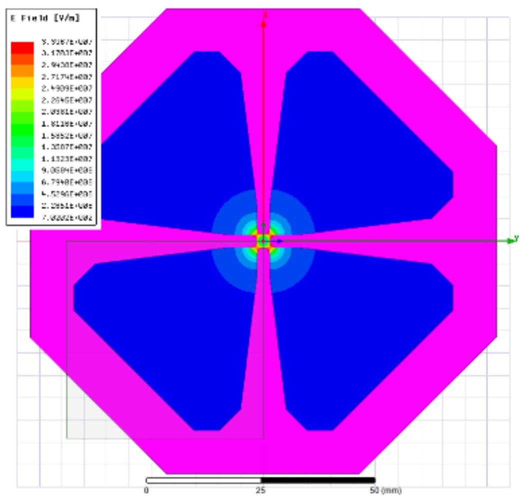
Structures	Frequency [MHz]	Energy [MeV]	Length [m]	Gradient [MeV/m]	Current [mA]
MedAustron RFQ	216.8	0.4	1.25	0.32	4
Linac4 RFQ	352.2	3	3	1	50
ADAM HF-RFQ	750	5	2	2.5	0.4

Design limiting quantities of RFQ

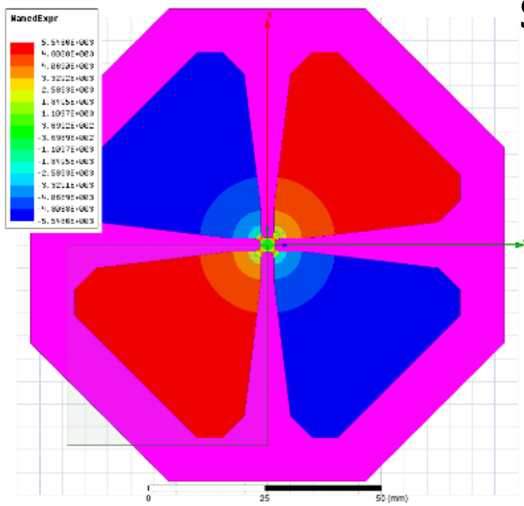
The criteria of **limit accelerating gradient** can be adapted to **RFQ:**

RFQ 750 MHz

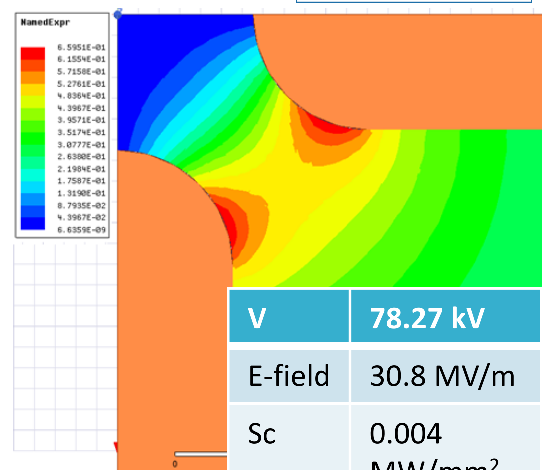
E



H



Sc



V	78.27 kV
E-field	30.8 MV/m
Sc	0.004 MW/mm^2

Courtesy of A. Grudiev

The **limit** is constrained by the **peak surface electric field** on the vane tips.

$$E_{surf} = \frac{V}{d} \; enhancement\ factor$$

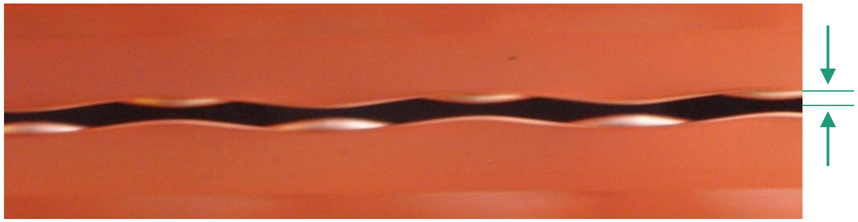
$$V_{vane} = \pm V/2 \sin(\omega t)$$

V_{vane} - voltage vane tips;

V - voltage applied to the electrodes;

d - distance between adjacent vanes;

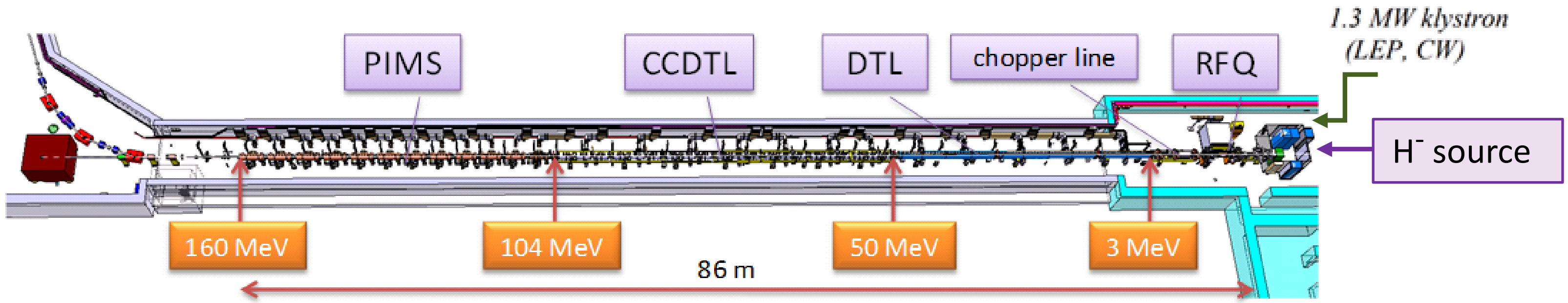
$t = 1/f$ - period of the voltage source.



Adjacent vanes (looking in from the RF port)

Specifications of the Linac4 RFQ

The **Linac4 RFQ is part of the new injector complex** of the **LHC**.



LINAC 4: schematic layout

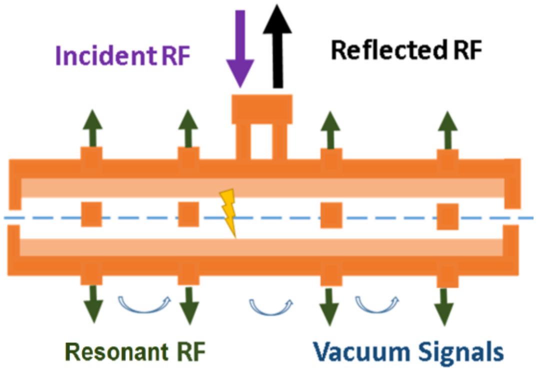
RFQ parameters	
Frequency	**352.2 MHz**
Length	3.06 m
Vane voltage	78.27 kV
Max field on pole tip	34 MV/m
RF total peak power	600 kW
Beam Input Energy	45 keV
Beam Output Energy	3.0 MeV
Coupling coefficient	1.59
Quality factory	6800

- Linac4 RFQ is a 4-vane structure consisting of 3 elementary modules.
- Operation: **480 kW, 750 µs, 0.83 Hz**

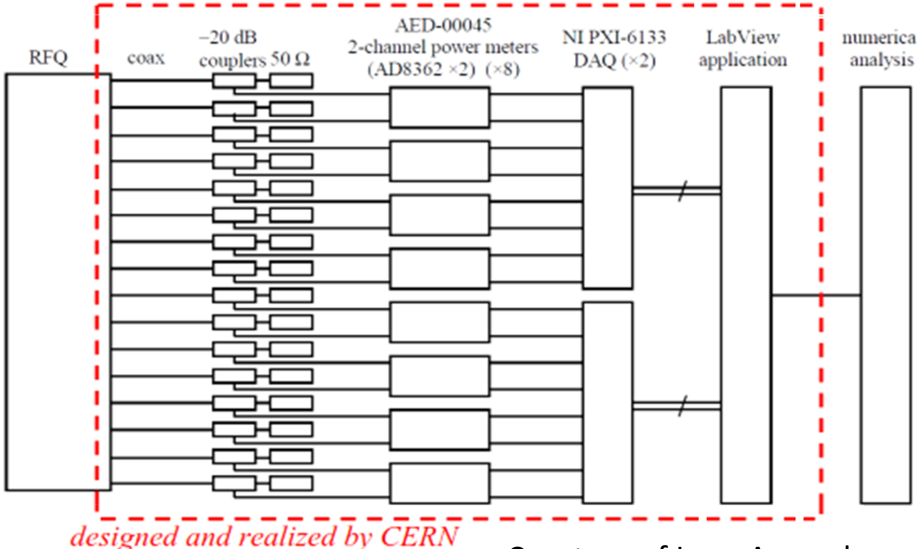
Data acquisition system of the Linac4 RFQ

- **The available signals** that can be **used to determine BDs** are:
  - **Forward** and **reflected** RF signals (directional coupler)
    - average value of signals saved to TIMBER database;
  - **signal of the field** in the RFQ (pickups (antennas))
    - 4 signal monitored by TESA ;
  - **vacuum** signals (vacuum gauges):

    normal operation - below 1e-07 mbar,
    during BD event - up to 5e-07 mbar.



- The **initial DAQ** of the Linac4 RFQ makes possible to measure and record signals from **16 pickup (antenna)** base on LabVIEW software.



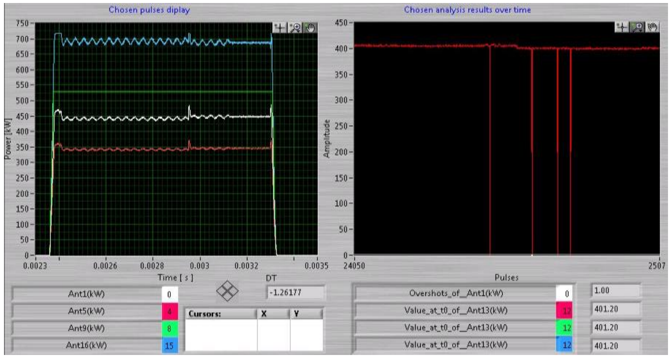
Courtesy of Luca Arnaudon

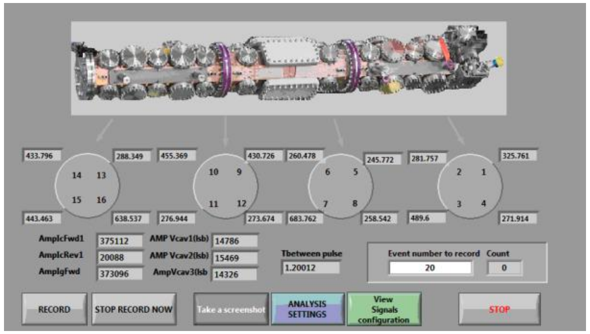
- In order to perform the BDs study, the **existing DAQ** has been updated as part of this work.

The novel DAQ for BD detection of the Linac4 RFQ

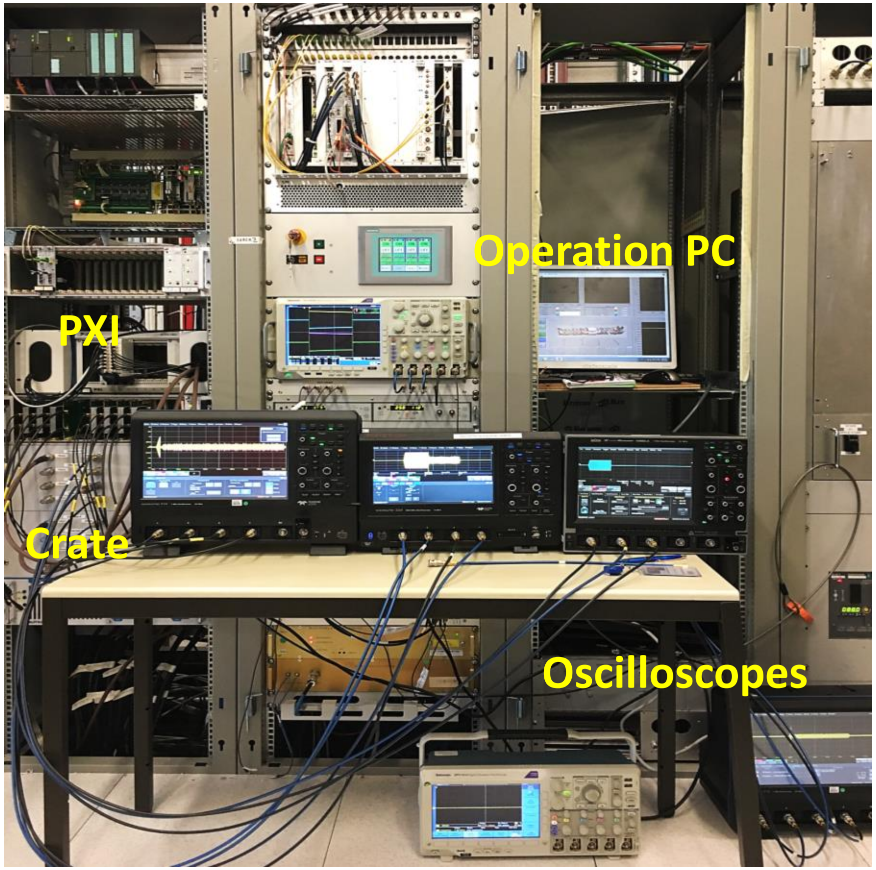
✓ The upgraded DAQ: **monitor** and **logging RF signals** (from pickups) in the case of BD events.

❑ **Time domain signals** record based on initial software





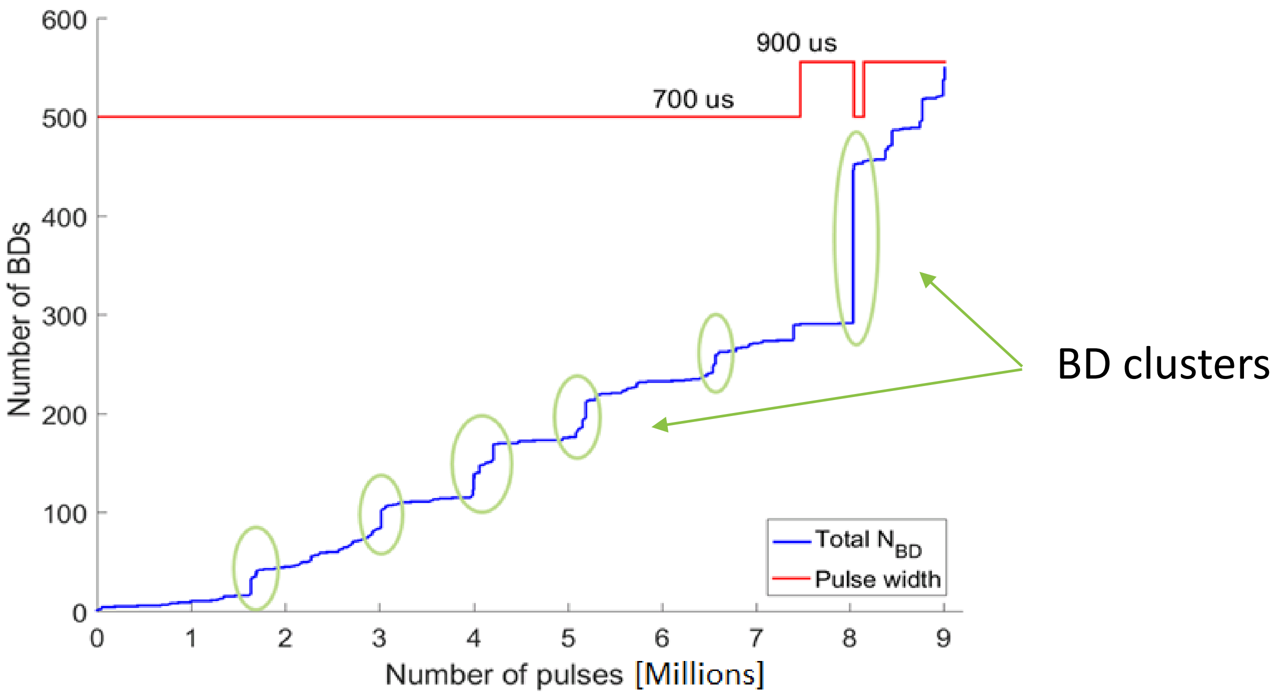
❑ **Frequency domain signals** record using 'oscilloscope readers'



❑ **Forward and reflected** RF signals was added to TIMBER (LHC Data Storage)

Operation history of the Linac4 RFQ

- Measurement of BDs in the Linac4 RFQ have been performed during strong variation of operation conditions (beam commissioning) from **September to December 2018.**
- The history plot of the Linac4 RFQ operating with beam at about **440 kW** forward power:



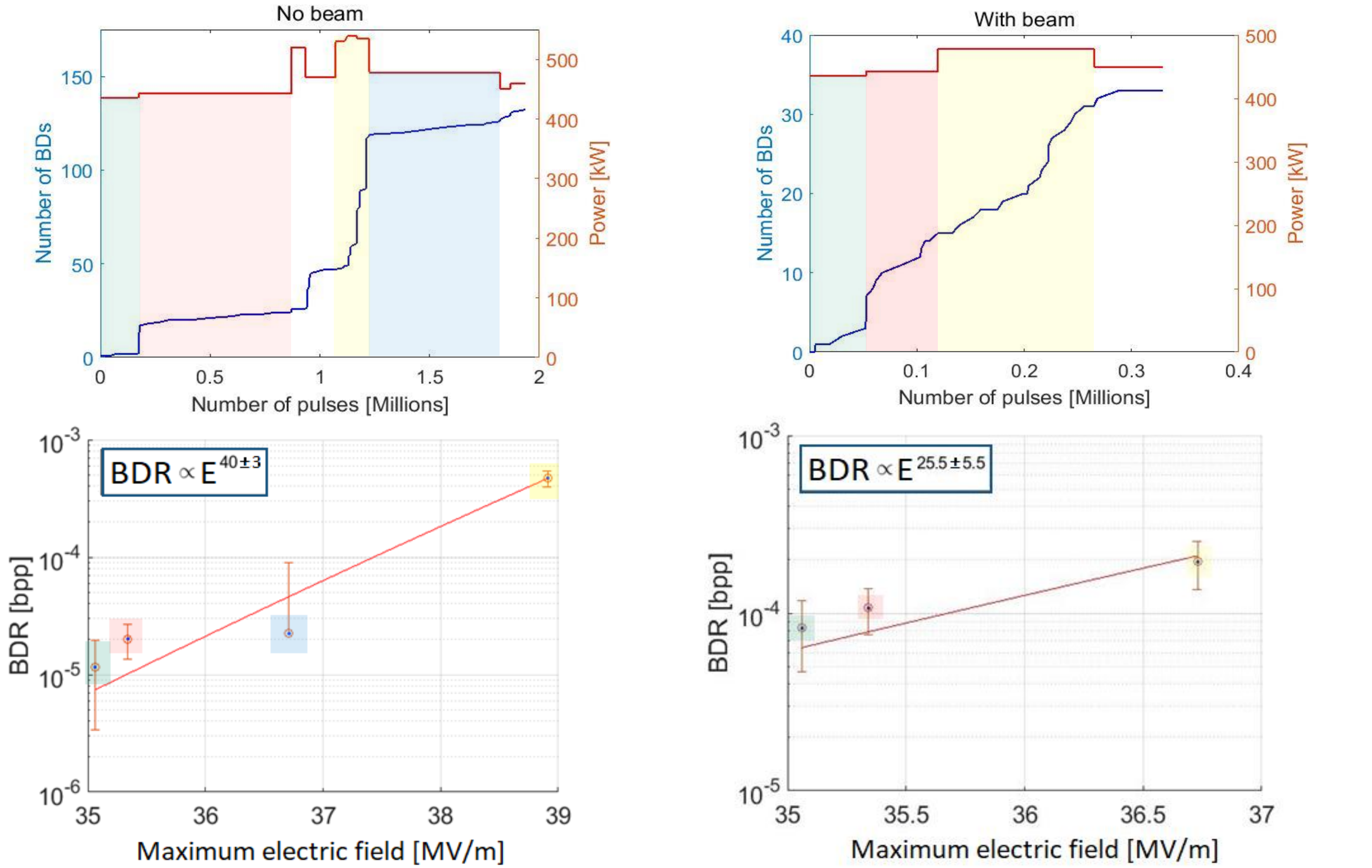
- A **non linearly** increasing number of BDs indicates **the appearance of BD clusters**.

The measured **BDR** as function of RF pulse length: **3.85 x 10^{-5}** [1/pulse] for **700 µs**

6.22 x 10^{-5} [1/pulse] for **900 µs**

Effect of beam loading on BDR of the Linac4 RFQ

- Measurement of the BDs was continued in **April 2019**, when the Linac4 RFQ has been operated with **forward power from 440 to 540 kW** at **900 µs** RF pulse length

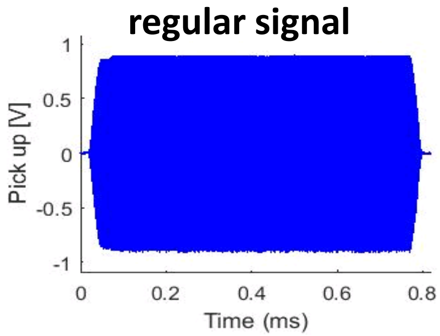


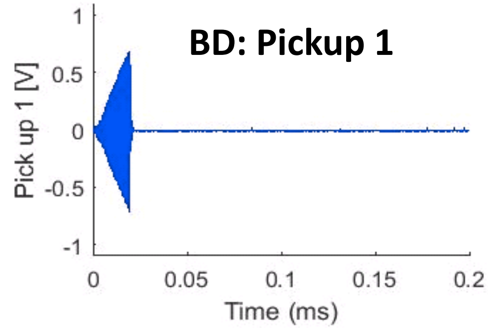
For forward power **440 kW, unloaded** BDR = **1.1 x 10^{-5}** 1/pulse;   **loaded**   BDR = **8.2 x 10^{-5}** 1/pulse.

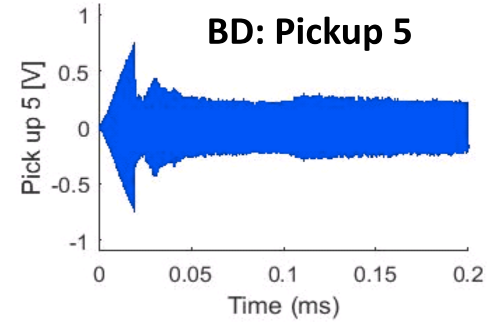
✓ BDR has increased during operation of Linac4 RFQ with beam.

Preliminary technique to localize BD in the RFQ

- ❑ During a **BD event**, there is a **drop in the voltage** of the signals from the pickups.

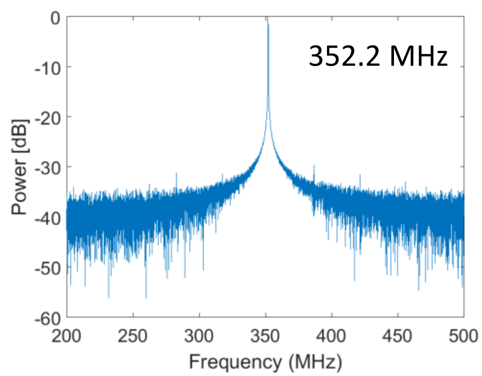


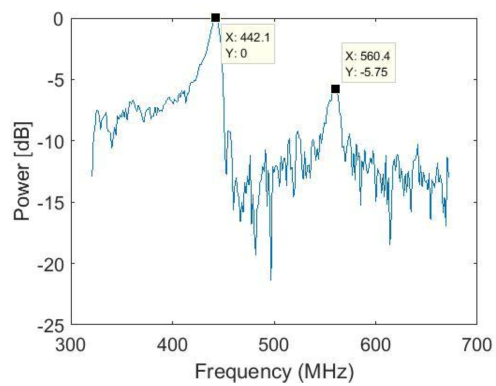


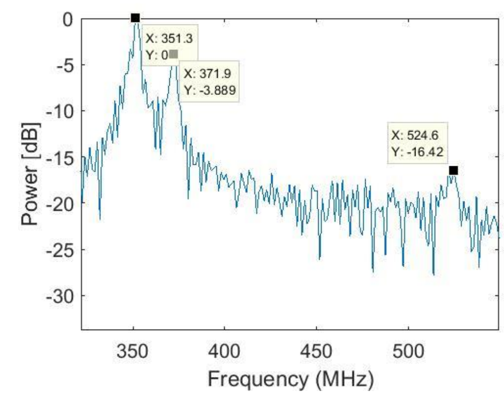


✓ When RF BDs occur, **the cavity is divided in two sections**: the power continue flow to the section where power coupler is located and radiative value is visible on other section.

- ❑ **The Fourier Transform (FT)** of the RF power measured with pickups show the appearance of **non resonant frequencies** during BD, that depends on how far the BD event occur.





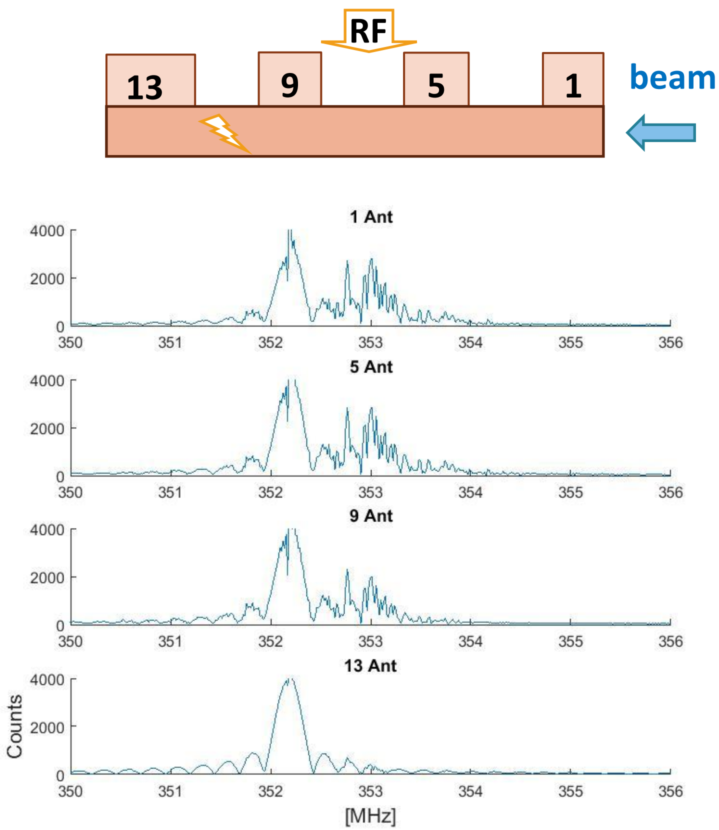


During BD, the energy is **partitioned into more than one mode**, there is a beating pattern as the energy decays.

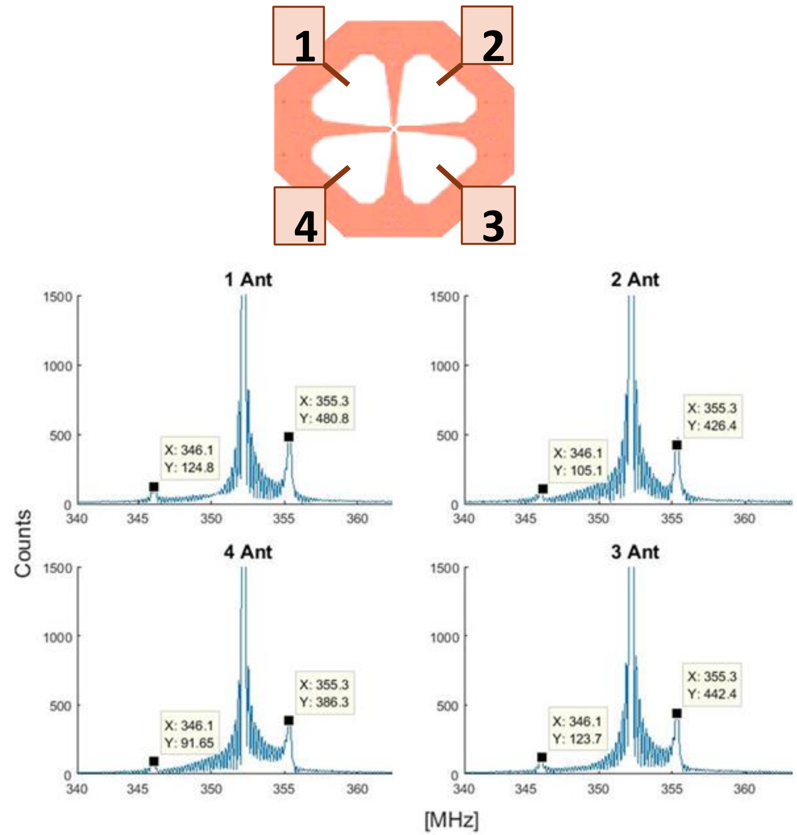
Study of RF signals of the Linac4 RFQ during BD

Observation of the **longitudinal** and **transverse behaviour** of the signals from antennas, located on one **vane** and one **plane section** respectively, have been performed during BD.

Longitudinal analysis



Transverse analysis



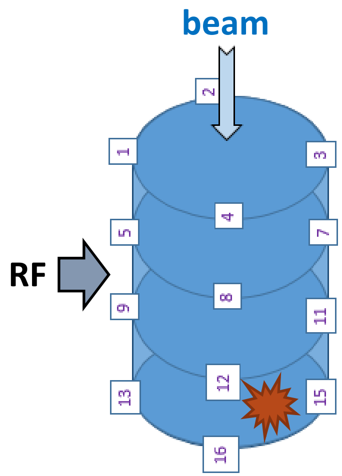
- ✓ BD divide volume in two areas: with minimal frequency variation and with a large frequency range that depends on how far the BD occur.
- ✓ 4 signals show the **same frequencies** of 346.1 MHz and 355.3 MHz at each antennas of the same plane.

BD event in the last section of the Linac4 RFQ

Analysis of 16 pickup signals

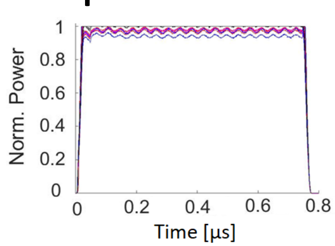
Example 1:

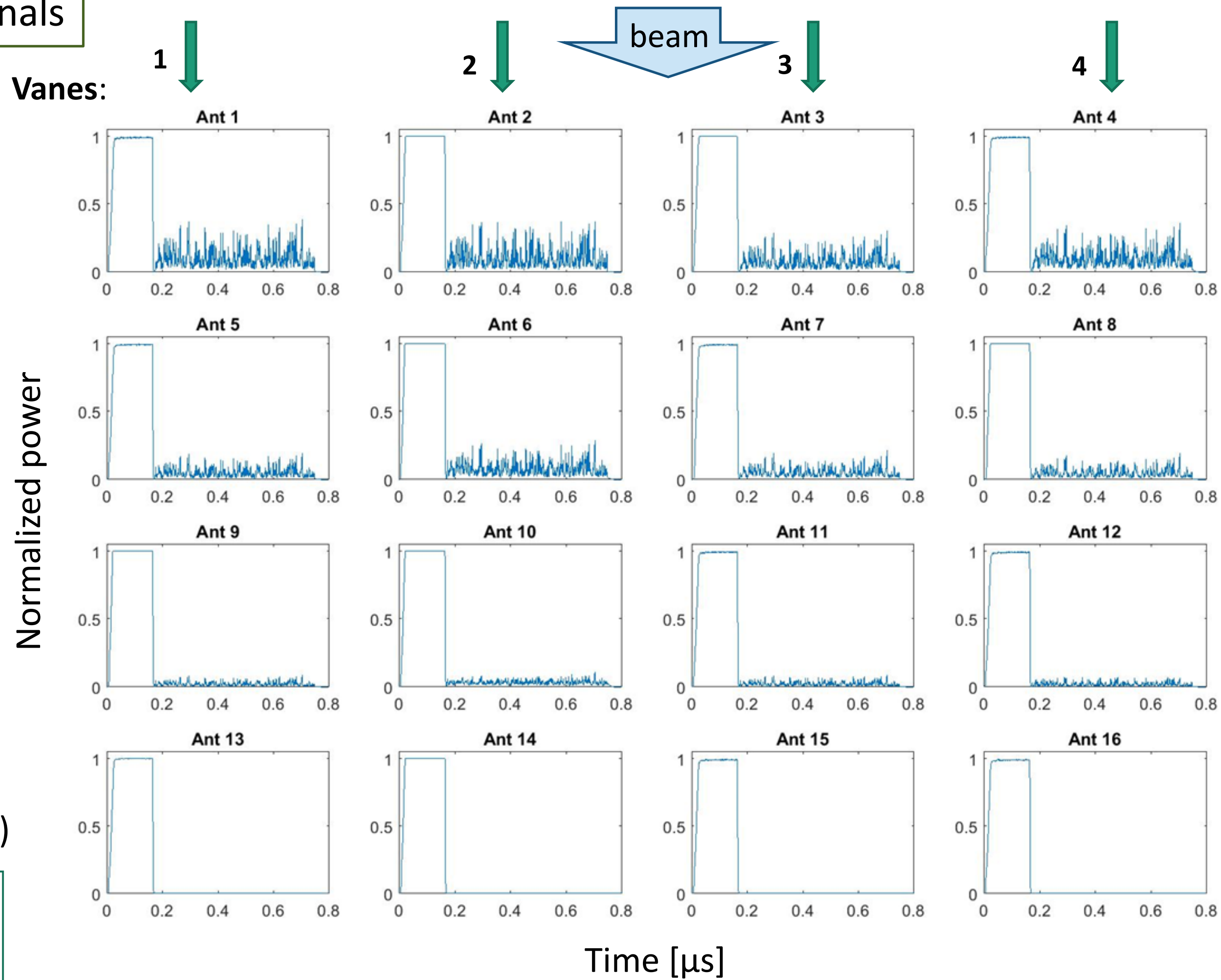
The predominant form of BD event in LINAC4 RFQ (60 % of the cases)



Location of 16 pickups (antennas: Ant 1 … Ant 16)

Normal pulse





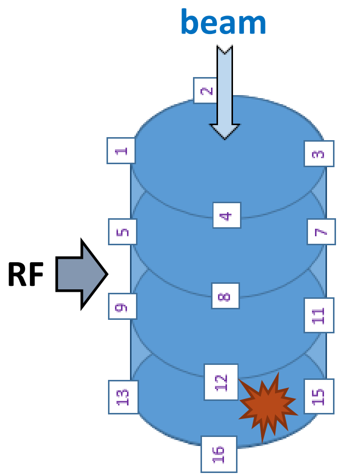
- ✓ BD occur at the end of the cavity, zone of the high-energy beam.
- ✓ Forward power continue flows into one section after BD, and disappears in another.

BD event in the middle section of the Linac4 RFQ

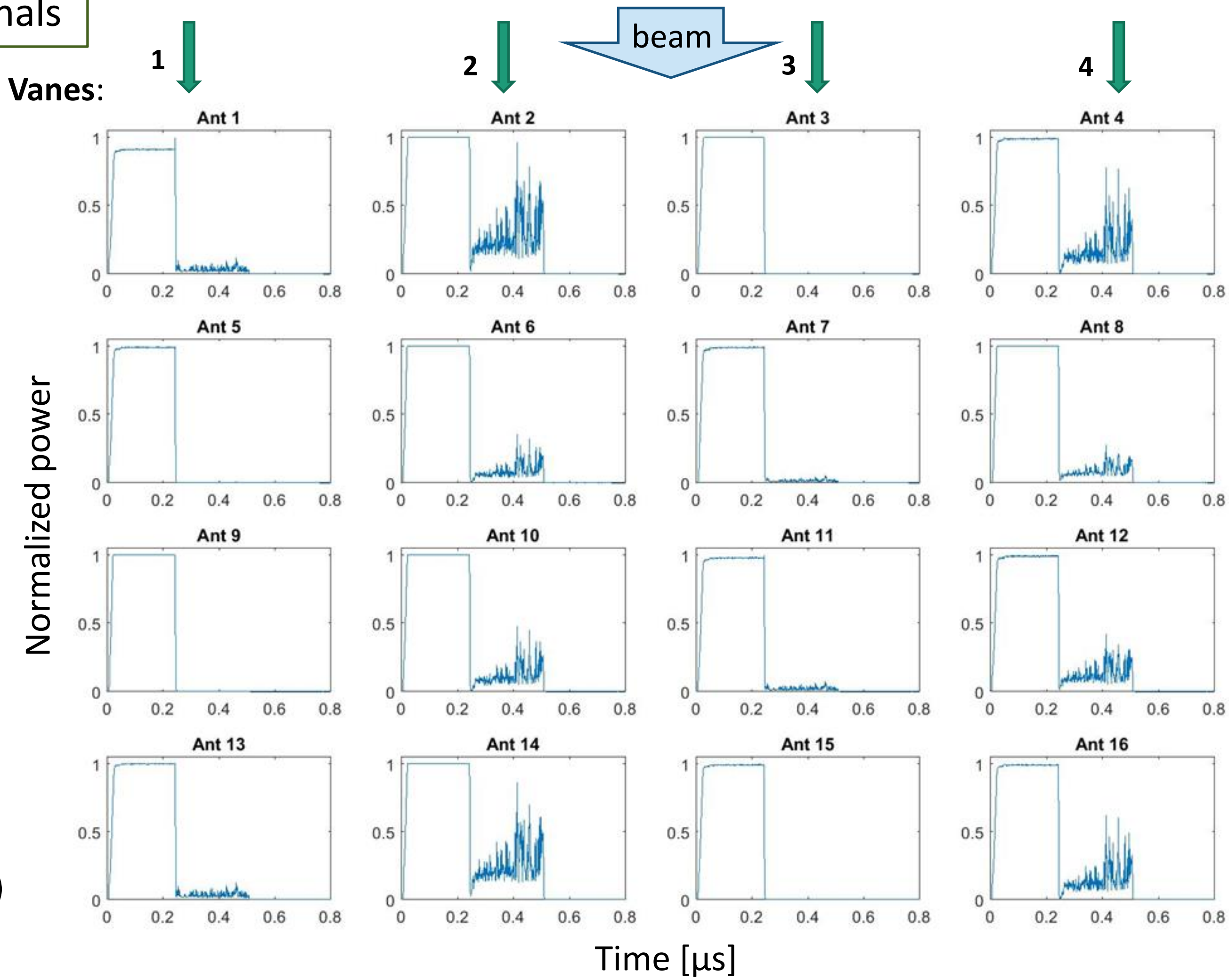
Analysis of 16 pickup signals

Example 2:

This type of BD event occurs in 20 % of the cases.



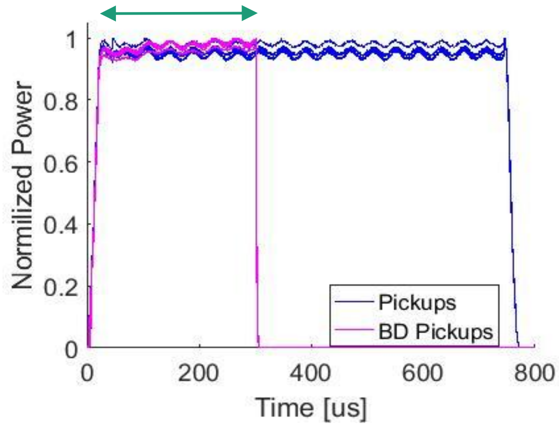
Location of 16 pickups (antennas: Ant 1 … Ant 16)

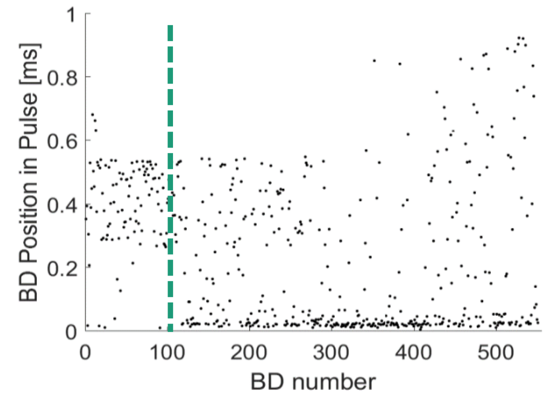


- ✓ The BD occurs in the middle of the RFQ, between antennas 5 and 9 (zone of the power coupler).
- ➢ As hypothesis, a small mismatch in the power flow could lead to high surface field that causes the BD.

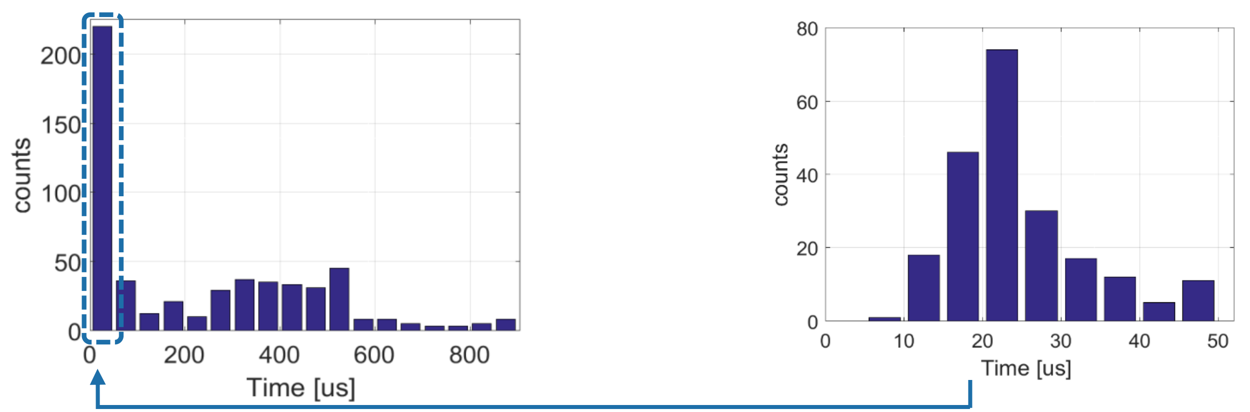
BD positioning in RF pulse of the LINAC4 RFQ

The high BD activity could be caused by external factors.





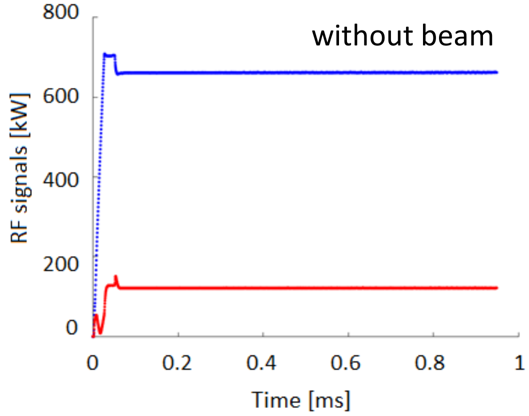
LLRF: RF immediately come back to previous value after BD.

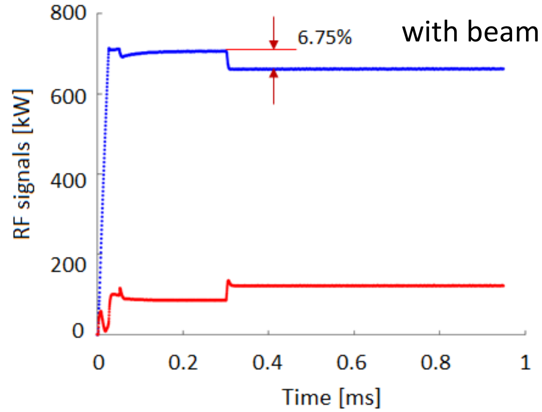


✓ 53% BDs happened at over ramped part of pulse after full filling of the cavity.

BD occurrence in of the LINAC4 RFQ

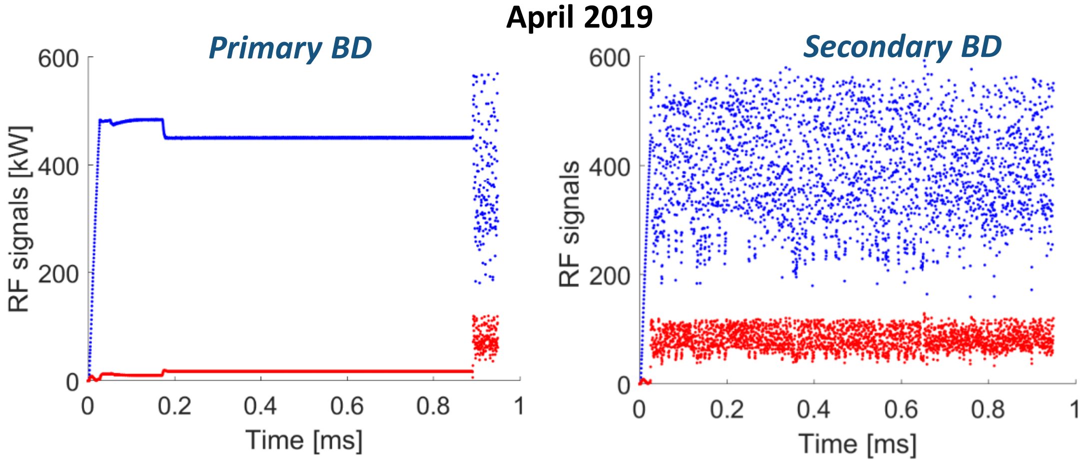
- The beam passes the structure immediately after feeling of the RF power and causes an overshoot in the power. A power **increase of 7 %** is observed in the **presence of beam**. This can cause the BD.

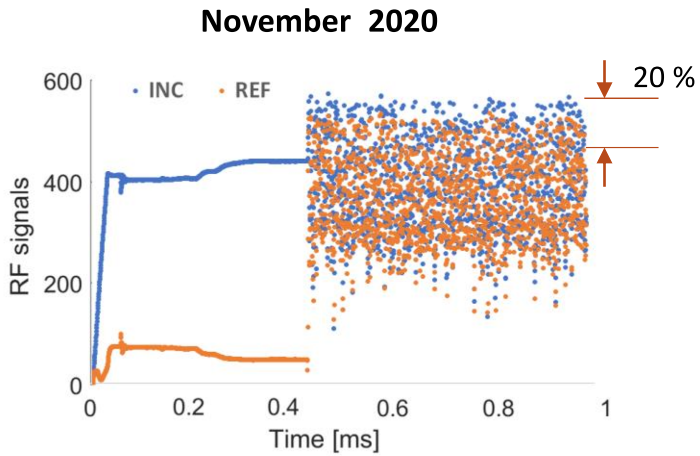




FWD and RFL signals of the regular pulse without beam (left) and with beam (right).

- The **feedback** of LLRF causing an increase of power during breakdown:





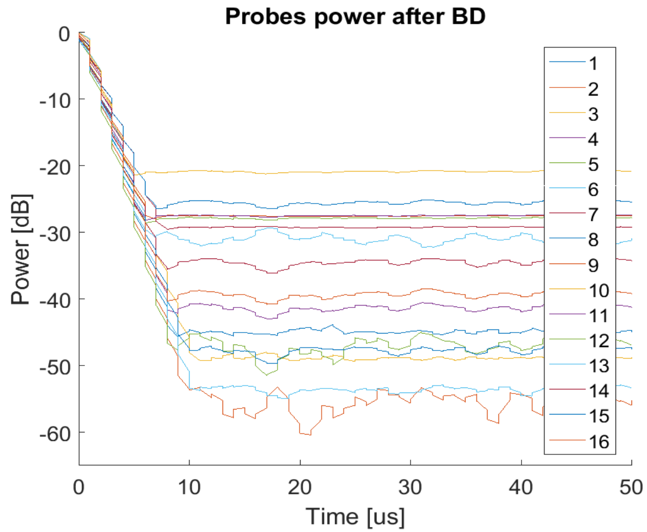
Quality factor measurements of the Linac4 RFQ

- The evolution of **stored energy (Q-factor)** have been measured to characterise the cavity during BD. Simulated Q-factor due to losses in copper is about **6880**.
- **Rise time or time domain method** is used for evaluating attenuation through the structure.

Loaded Q-factor calculates by the slope of the decay of the cavity power:

$$Q_L = w_0/(2\,k), \qquad Q = (1+\beta_c)\,Q_L$$

where k - slope, β_c - coupling factor.



Pickup signals of Linac4 RFQ during BD event.

- In general, the Q_{BD}- factor during BD of the Linac4 RFQ has been in the range from 2800 to 5700 during BD events.

- The Q-factor is reduced by 1.5 - 3 times during BD that can correspond to the RF power absorbed by field emission currents.

Conclusions of the study

- ✓ This is the **first time** that a **systematic measurements** of the BDs behaviour have been carried out in RFQ.

- ✓ **High-power tests** are critical to achieve the best **performance** of the RF structures and RFQs. **Dedicated test benches** are mandatory for HG studies.

- ✓ **The upgraded data acquisition system** opens the possibility to measure RF signals directly from RFQ during operation and record BDs.

- ✓ A high **BDR** have been observed in Linac4 RFQ operated at **34 MV/m** with different pulse length:

  for **700 μs:** **3.85×10^{-5}** 1/pulse;

  for **900 μs:** **6.22×10^{-5}** 1/pulse;

- ✓ **A preliminary technique** has been developed for **determining the BD** distribution in the Linac4 RFQ:

  1st module: 10%, 2nd module: 20%, **3rd module: 60%**, Unclear: 10%.

Thank you for your attention!

Also, thank you to all collaborators & contributors to the work presented today:

CLIC RF team:

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