Breakdown measurements in the LINAC4 RFQ

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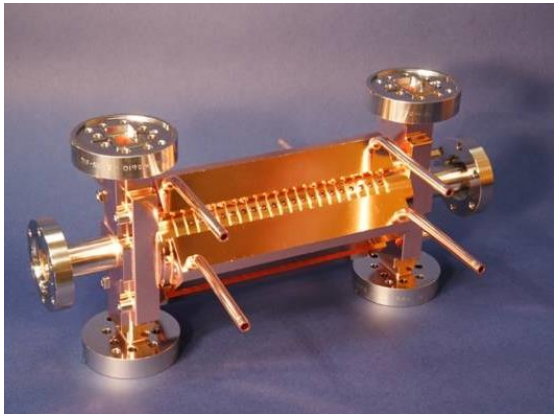
Outline

- Introduction
- Review of the 352 MHz RFQ of Linac 4, CERN
  - Technical specification of the RFQ
  - DAQ modification
- Preliminary study of Breakdown phenomenon in the RFQ
- High-gradient performance of the structure
- Conclusions and next steps

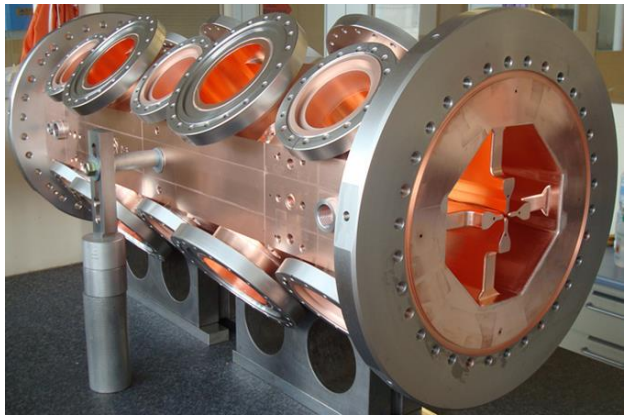
Motivation

- Transfer Knowledge from High-Gradient CLIC acceleration structure to the RFQ.



CLIC structure, **12 GHz**

180 ns, 120 MV/m



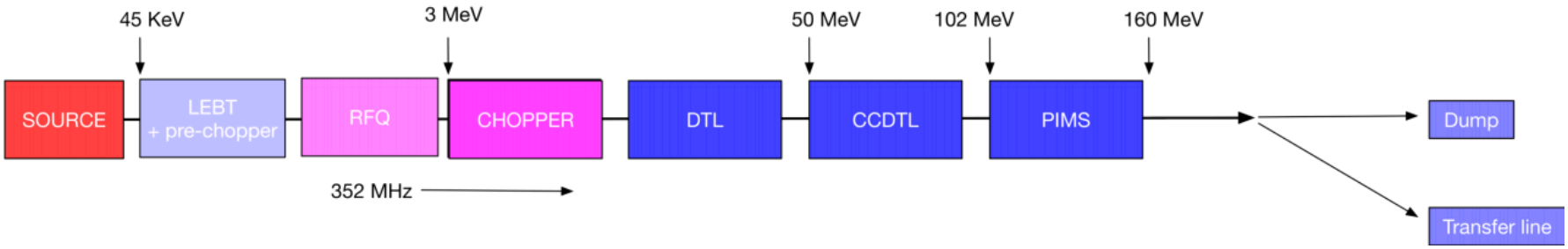
RFQ Linac 4, **352.2 MHz**

600 µs, 34 MV/m

- Investigate **high-field limits** in new parameter ranges, in particular at low frequency and a very different field profile.
- Study the **high gradient performance** of the RFQ and define limiting factors.
- Achieve a **high surface electric field** in the RFQ while minimising risk of sparking and damage.
- Use knowledge gained to optimize the design of structures.

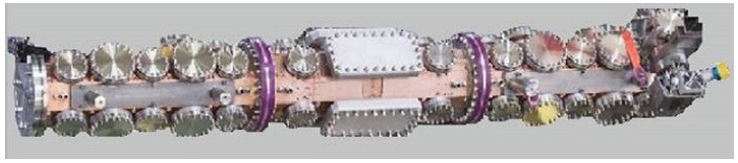
Future project: Redesign and potential build of a **Linac 4 spare RFQ on a maximum surface field** (about **50 MV/m**): 352 MHz, 600 µs pulse length H- beam.

The RFQ LINAC 4: Technical specification

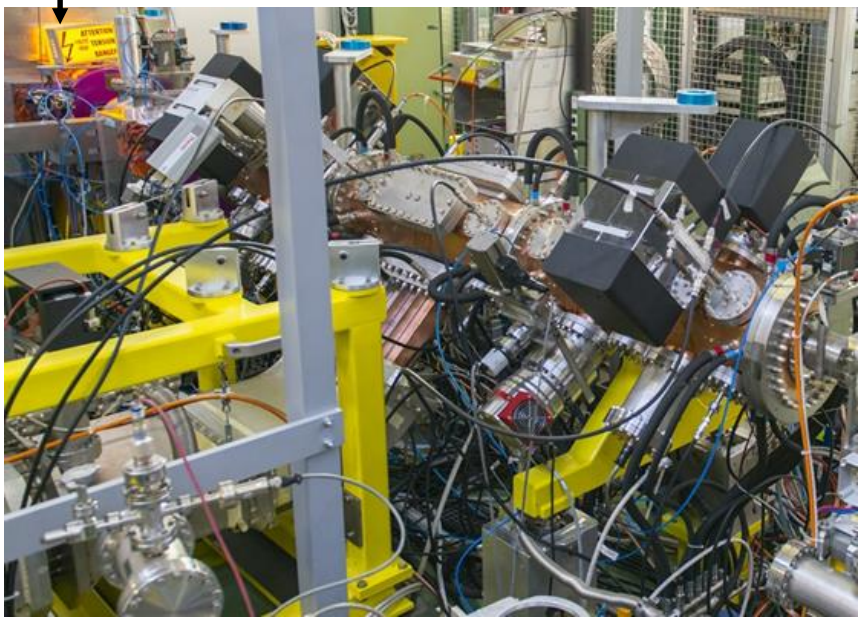


- 4-vane structure with 2 brazing steps;
- 3 elementary modules of 1 m;
- **Operation: 480 kW, 750 us, 1.2 Hz**;

Parameter	Value
Frequency	352.20 MHz
Length	3.06 m
Vane voltage	78.27 kV
Max field on pole tip	34 MV/m
RF total peak power	600 kW
Kilpatrick value	1.84
Input energy	0.045 MeV
Output energy	3.0 MeV



Ion Source



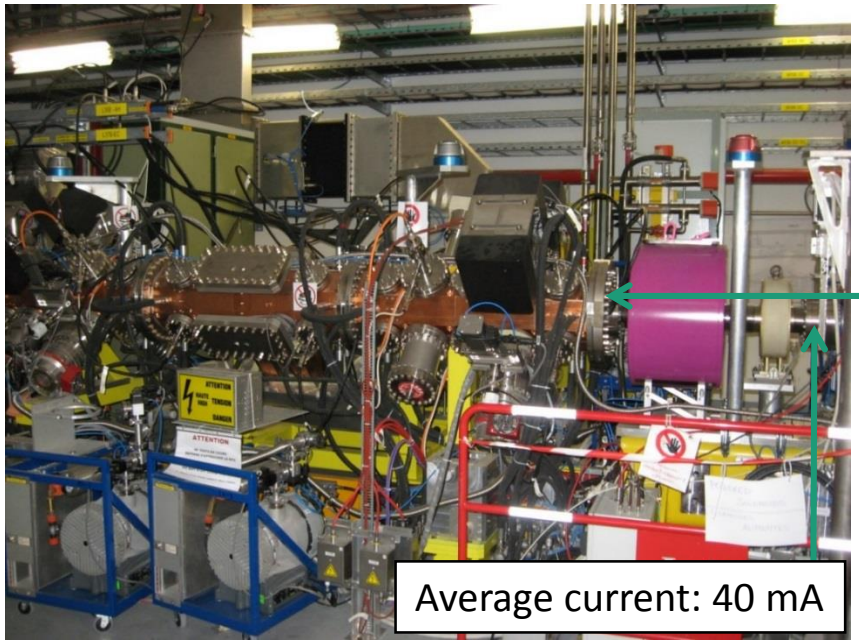
Benefits of a high field for the RFQ

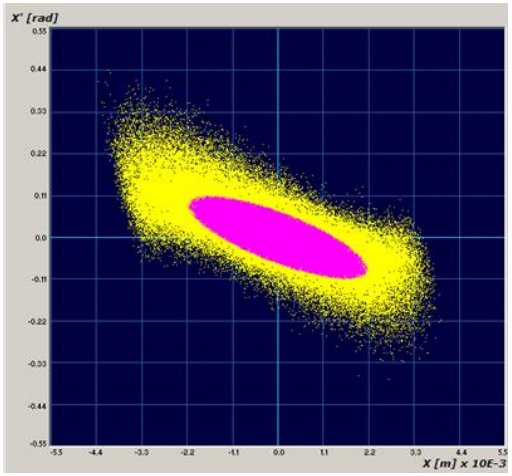
High peak fields increase the **RFQ performance** in areas of:

- ✓ Higher acceptance (larger emittance beams);
- ✓ Greater space charge capability;
- ✓ Accept heavy ions with lower charge state;
- ✓ Shorter RFQ;

but also have the effect of:

- ➢ Increased probability of sparking;
- ➢ More RF power required ;
- ➢ Tighter machining and alignment tolerances.





Comparison of **measured emittance** (yellow) and RFQ acceptance (pink).

The main problem: the expected transmission through the RFQ is 75%.

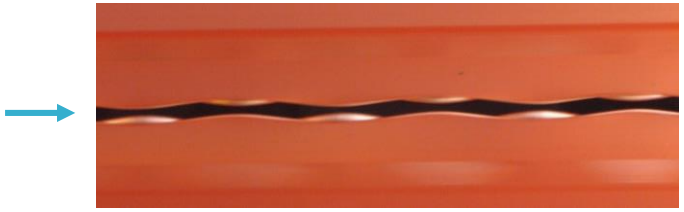
(PARMTEQ + TOUTATIS)

High gradient optimization

Solution: maximize the field on the vane-tip

- take into account the proportion between transverse acceptance and efficiency of acceleration (modulation factor);
- minimise a transverse radius of curvature.

$$E_{surf} = \frac{Voltage}{distance\ advancent\ vanes} * enhancement\ factor$$

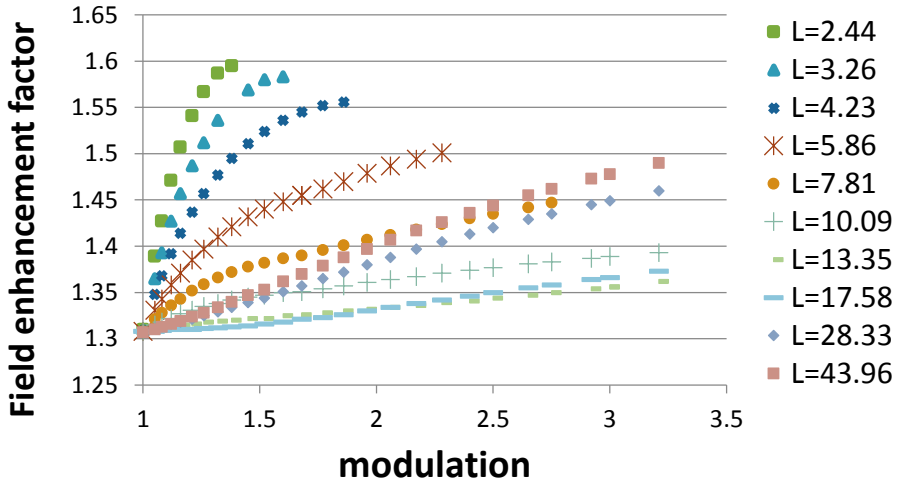


2R0 = average distance between opposite vanes

rho : Transverse radius of curvature of the vane-tip.

Field enhancement factor vs modulation

for r0=3.256 mm, pho/ro=0.89 and varying cell length L (mm)

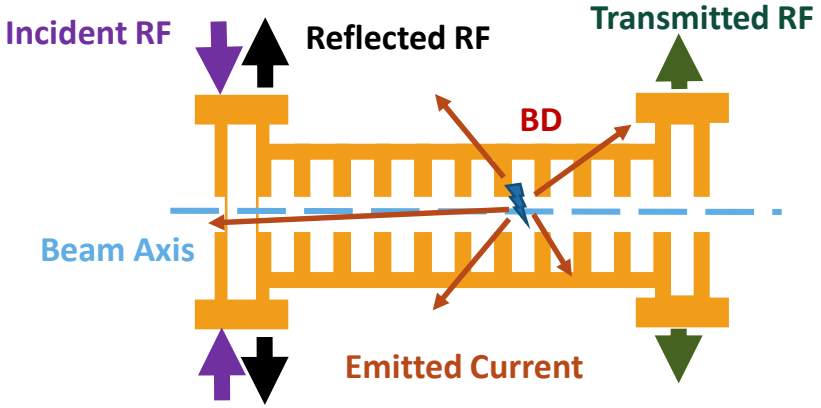


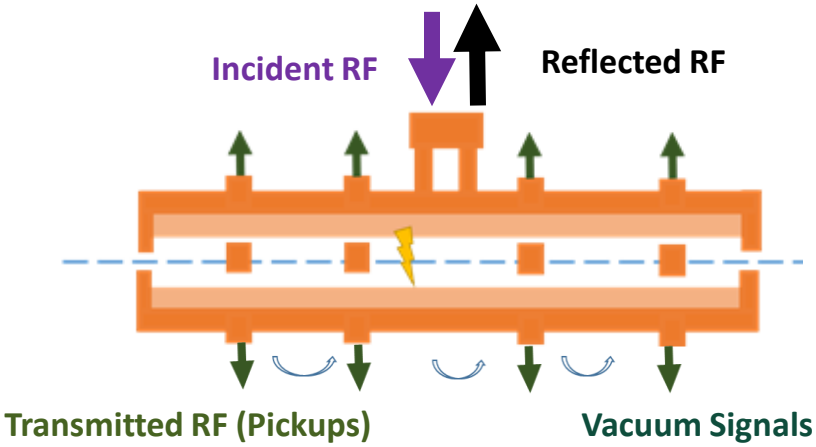
DATA from V2TERM(CHARGE3D)

Identification of the BD in RF accelerating structures

BD diagnostics:

- ✓ **RF signals**:
  - **Directional coupler**: incident and reflected signals
  - **Pickup**: signal of field in the RFQ cavity
  - **Oscilloscope** : additional record the signals
- ✓ **Vacuum** diagnostic signals (vacuum gauges).
- ✓ **Field-emitted current** (Faraday cups, BLMs).

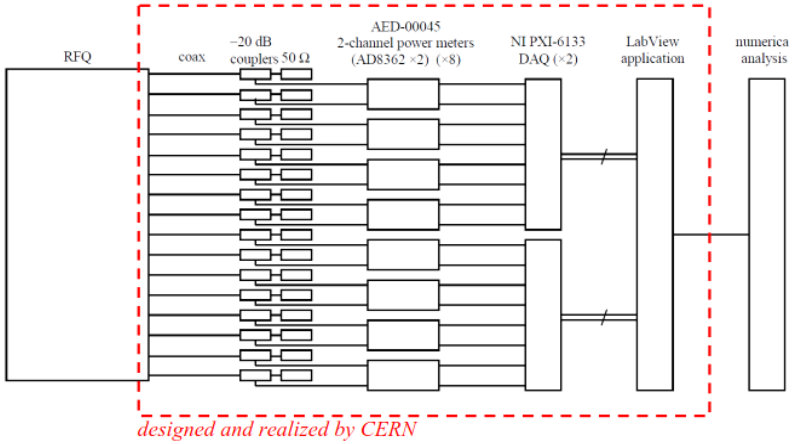




➢ BD position can be resolved using timing of RF pulses.

Acquisition system of RFQ Linac 4

1. DAQ of the RFQ based LabVIEW software:



- ✓ **16 signal from pick ups**;
- ✓ **Detect instability or BDs** (depend on pulse flatness);
- ✓ Record the **average value** of the pick up signals.

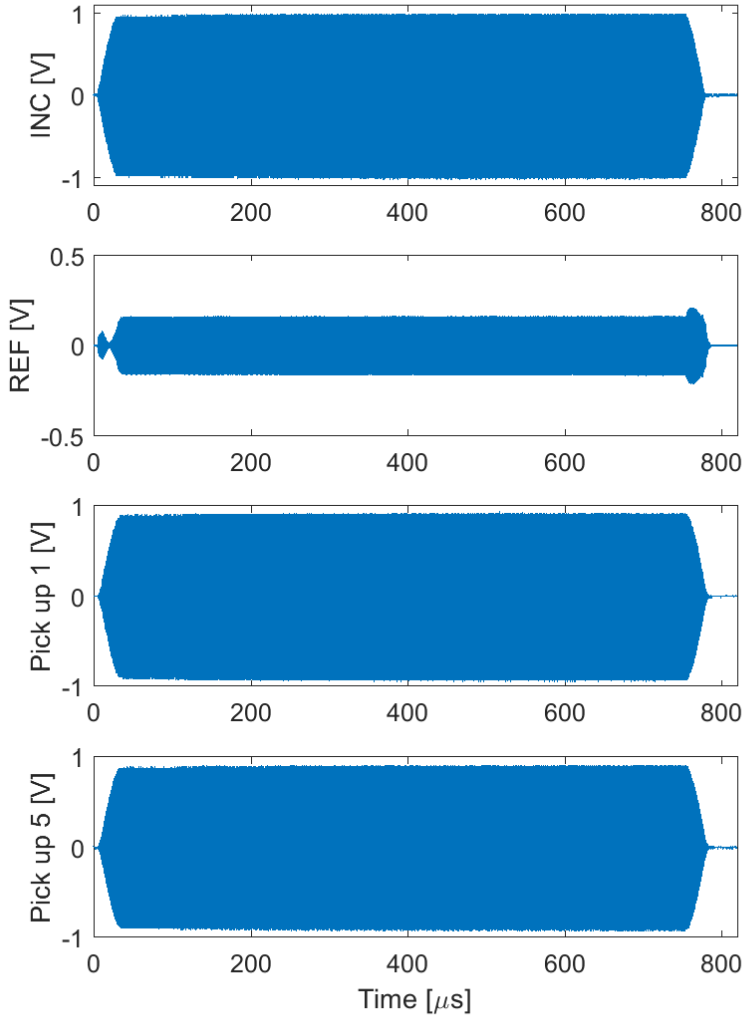
2. DAQ of LINAC 4:

- ✓ RF signals are recorded in TIMBER: **forward, reflected** (DC),
- ✓ **Vacuum signal.**

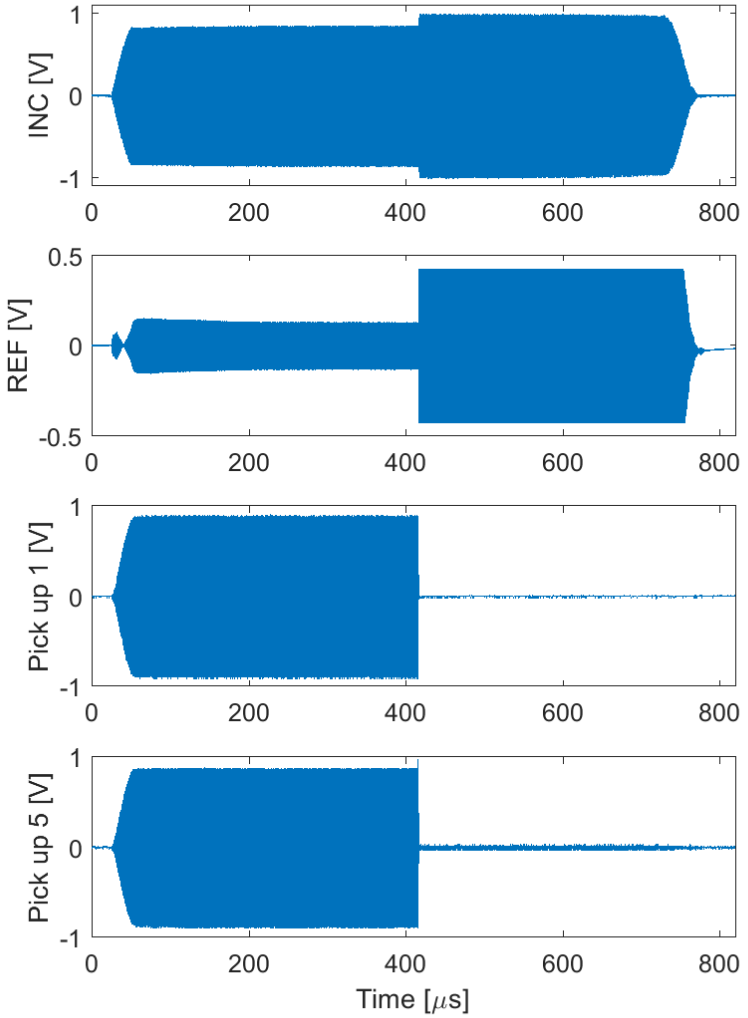
© Signals are not **synchronized** in time.

RF power signals measurement:

Normal RF signals:



RF signals of BD:

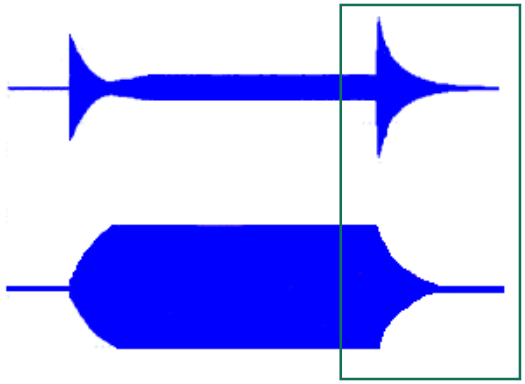


RF parameters measurement

When the RF pulse turned off, the signals decayed to 0 in the form of exponential decay.

$$V(t) = V_0 e^{-\frac{t}{\tau}} \sin(\omega_0 t + \varphi_0), \qquad \tau = 2Q_L/\omega_0$$

The RF signals:



HG18: Wenbo Ye, Tsinghua Univ.

$$V_{-}(t) = V_{ref} + V_{rad}$$

The **effective reflected** voltage:

1) the **direct-reflected wave** from the **coupler,**

2) the **radiated wave** from the cavity.

- Measured REF signal is overcoupled:
  power rise time is about 20 us
  filling time is about 10 us

QL calculates by the slope of the decay of the cavity power when the pulse is over.

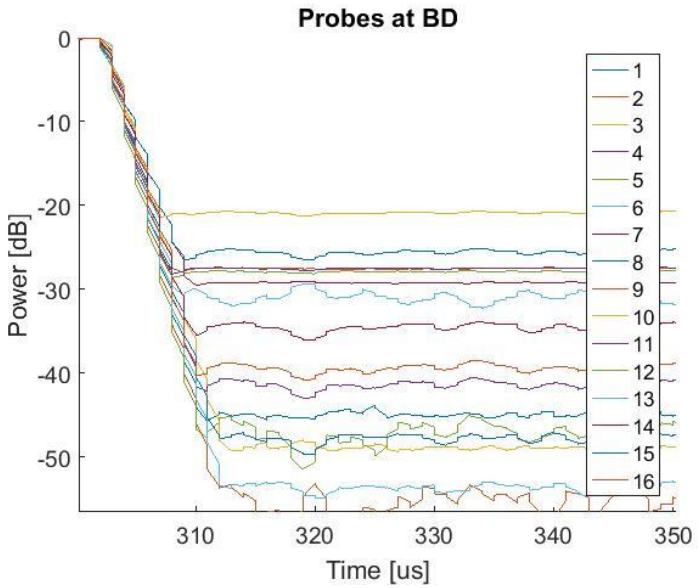
QL = −ω0/2k, where the slope **k = −1/ τ**

$$\boldsymbol{Q_0 = (1+\beta)Q_L}$$

RF parameters measurement

Normal pulses (theoretical value):

f = 352.2 MHz **β = 1.5926** Unloaded Q-factor ≈ **6772**



- **BD pulse:**

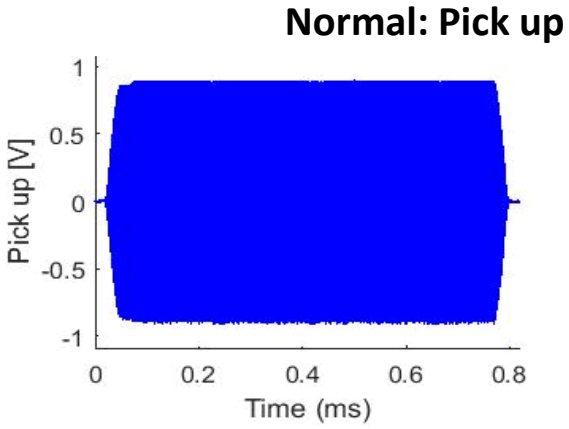
  τ = 1 – 2 us,

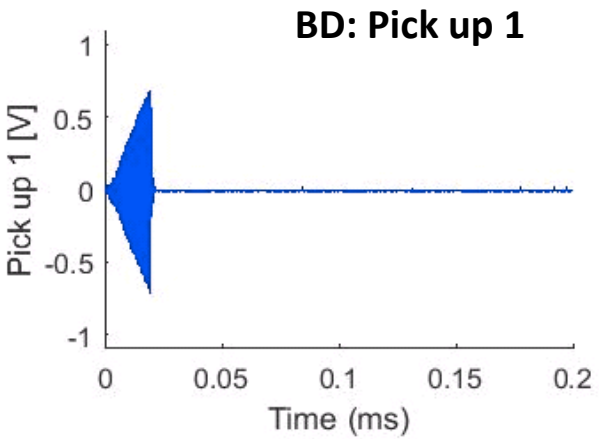
  Loaded Q-factor ≈ 1100 – 3085

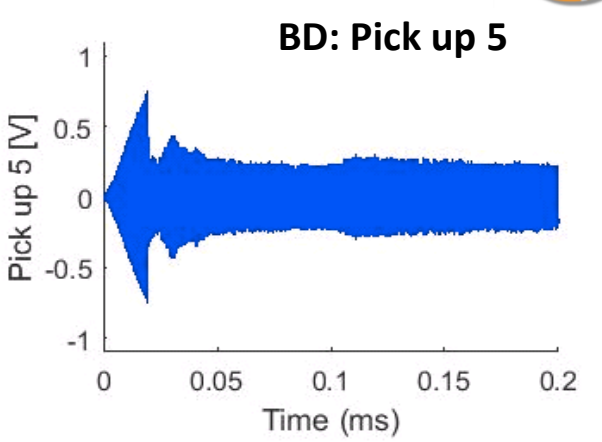
  => **Q-factor = 2850 - 5700**

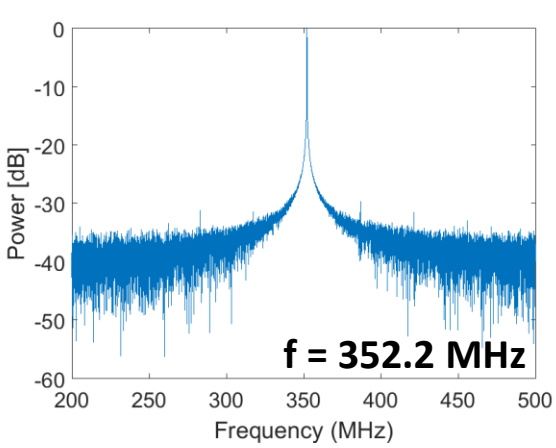
- ✓ Decay time of the stored energy varied from event to event
- ✓ Quality factor of the structure at BD is twice smaller compare to normal operating regime.

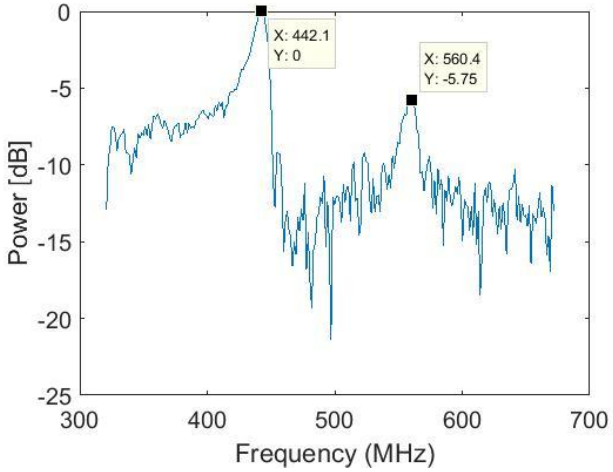
RF parameters measurement

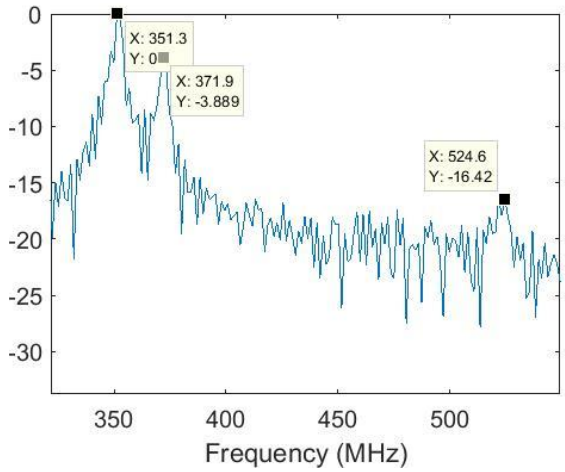






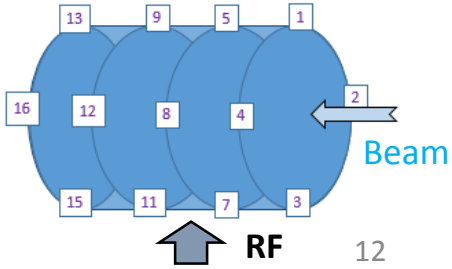




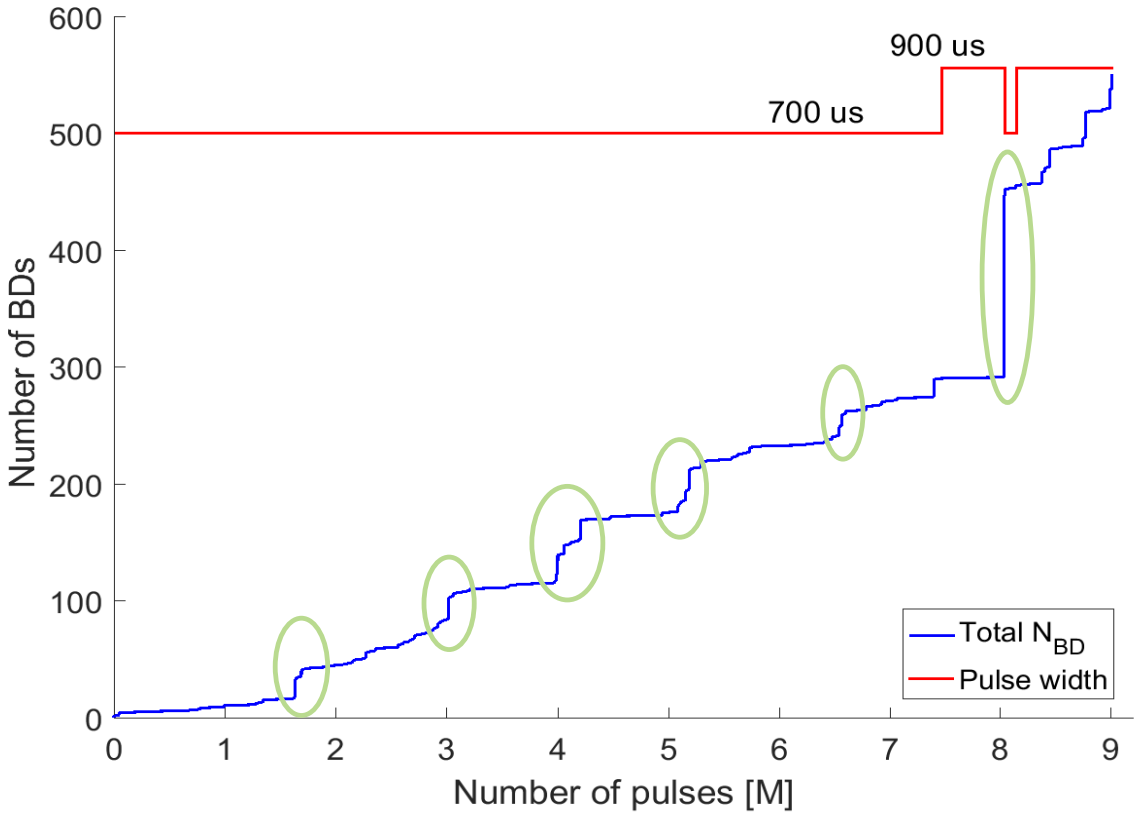


- Non Resonant frequencies appear during BD
- Radiative value is driving with BD present

Pick up 1 and 5 located at the same vane, E field direction from 5 to 1: BD occurred in front of the structure (beam direction)



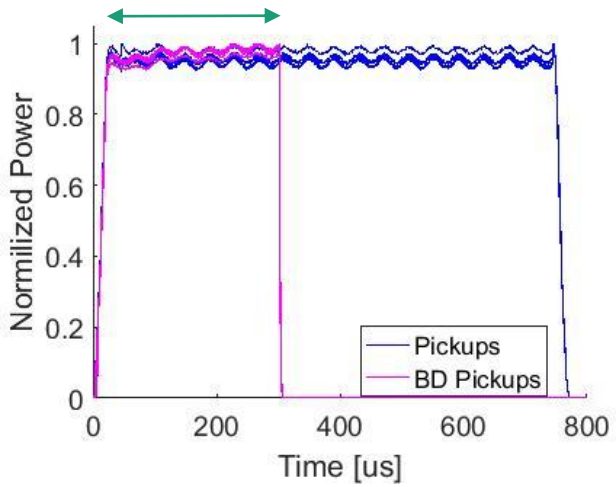
Operation history plot of the RFQ at LINAC 4

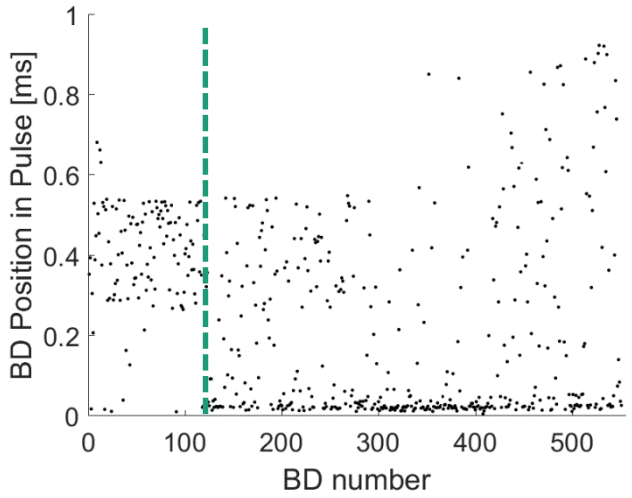


Cumulative number of BDs as a function of cumulative number of rf power pulses

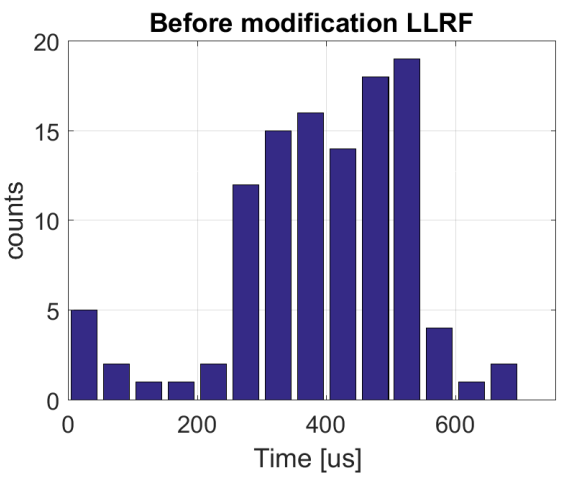
- Non linear increasing number on BD (clusters): for **t = 700 us, BDR = 3.85 E-5 bpp**

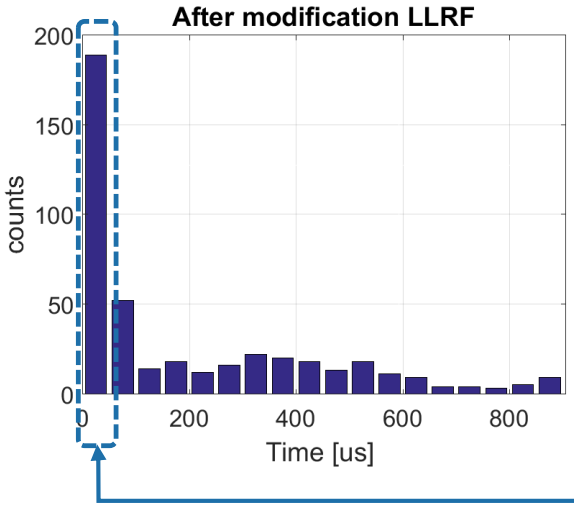
BD positioning in pulse

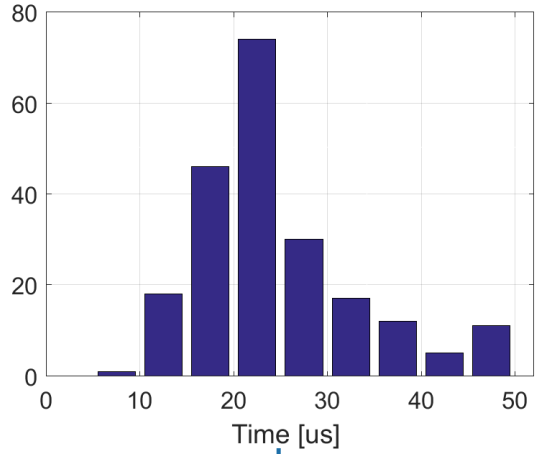




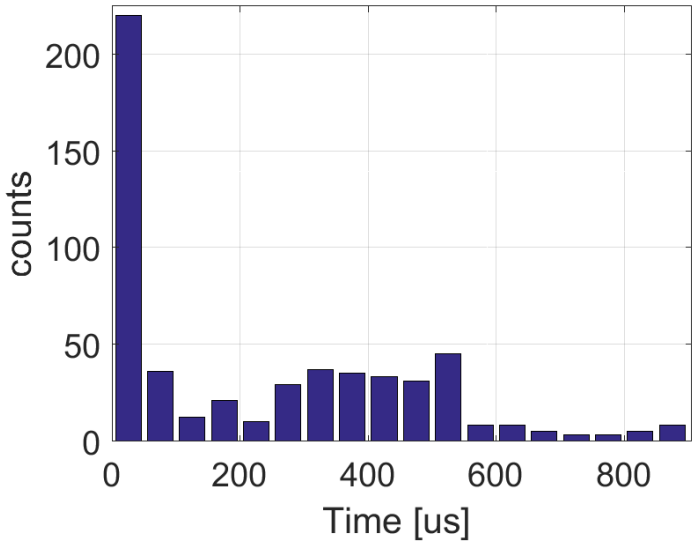
LLRF changes:
RF immediately come back to previous value after BD

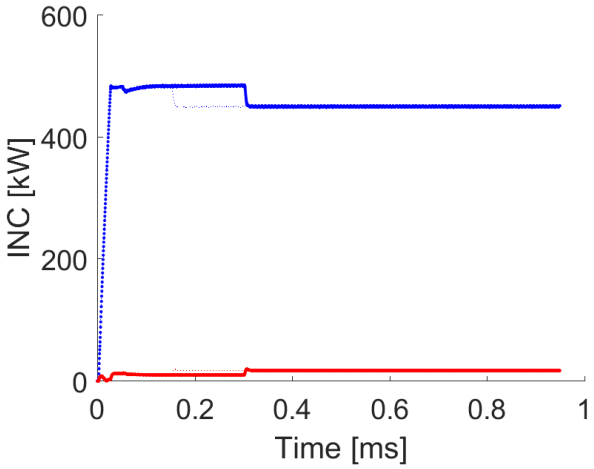


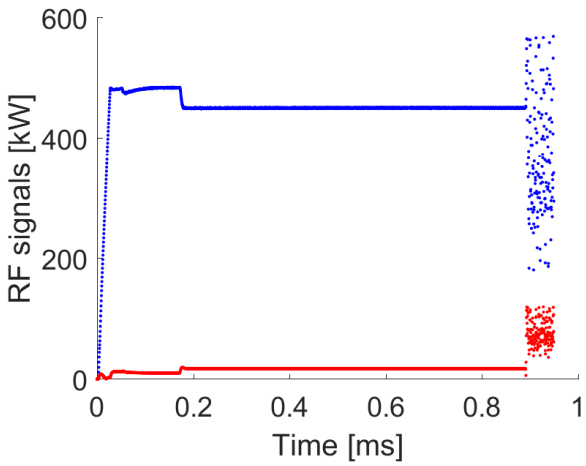


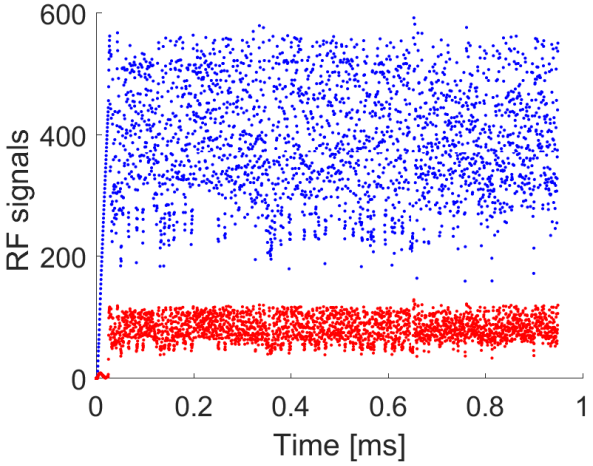


BD positioning in pulse





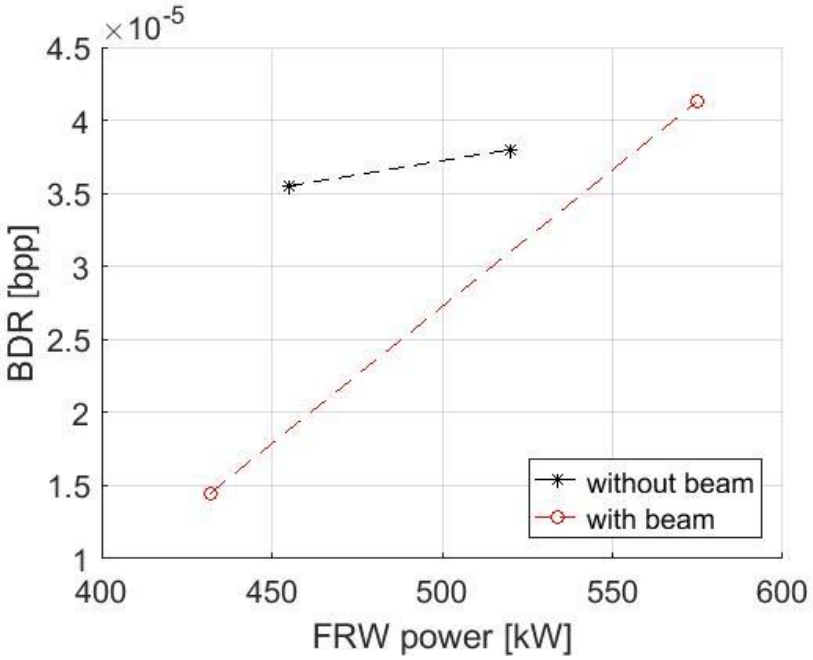




- 53% all BDs happened at over ramped part of pulse

BD rate analysis

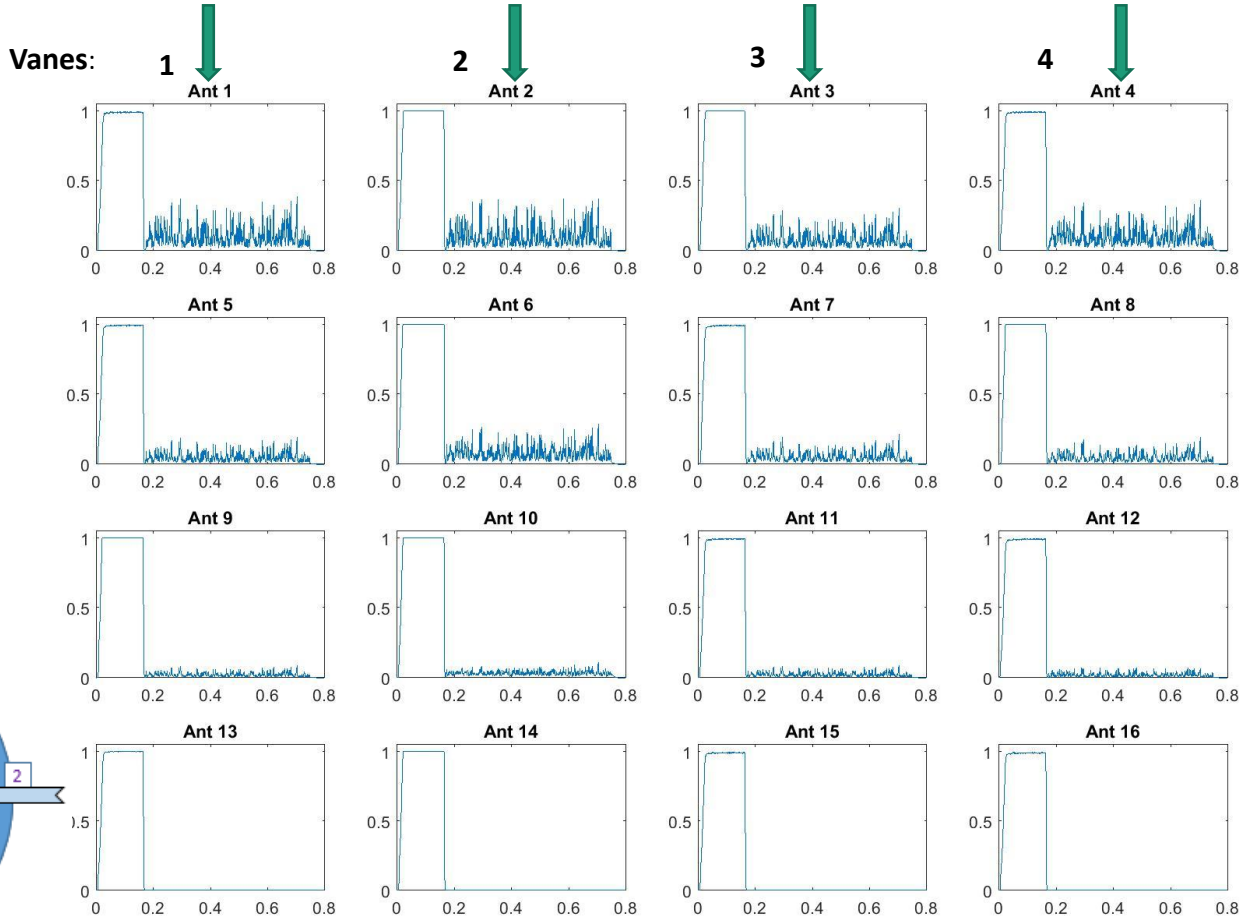
- BDR used to predict the behaviour of the structure and the determine nominal operating parameters.

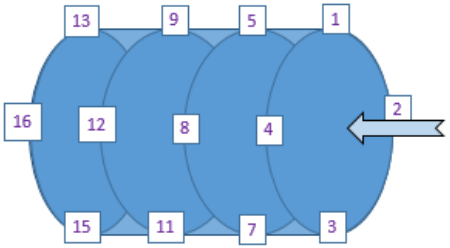


- There are lower power at the cavity during operation with beam.
- **No big difference without beam at higher power**.
- Not enough **statistics** to made conclusions.

BD study of RFQ L4

Example 1: The predominant form of breakdown in the structure (60 %)





RFQ with 16 probes

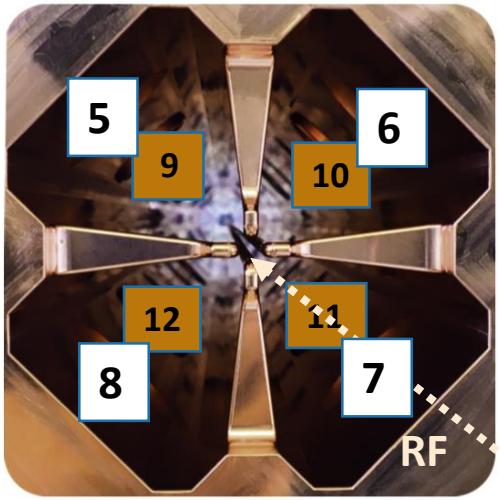
Signals from 16 pickups

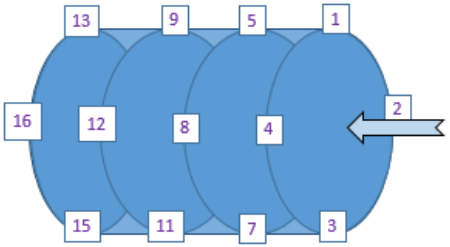
Faya Wang, Chris Adolphsen,
Phys. Rev. ST Accel. Beams 12, 2009

When RF BDs occur, the cavity divided to 2 sections: power continue to flow into section with coupler.

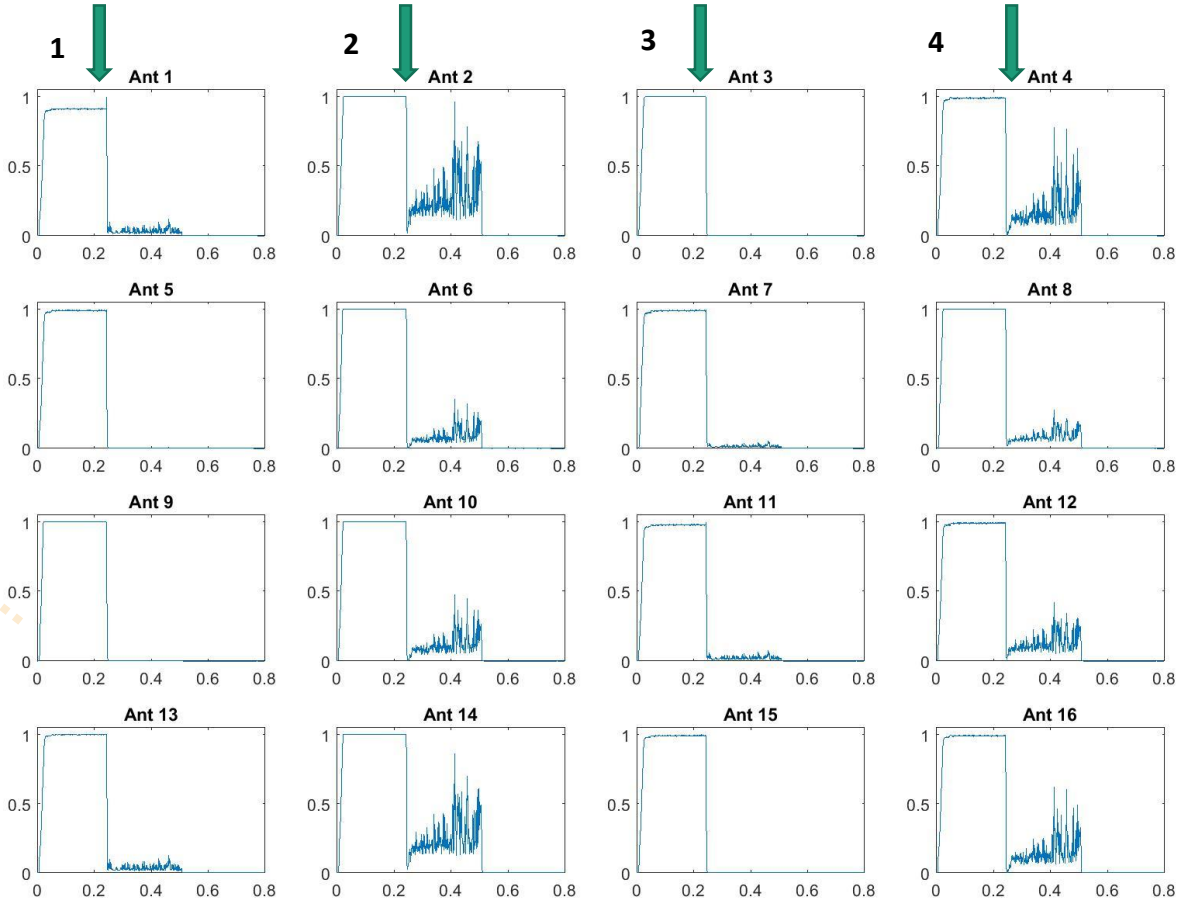
BD study of RFQ L4

Example 2: High Radiative wave at 2 and 4 vane (20%)





RFQ with 16 probes



Signals from 16 pickups

- BD occurred in central part of the structure: front of the RF port

Conclusions:

- The high gradient experience of CLIC cannot directly scale to the RFQ because the operating regime is completely different: *pulse length, repetition frequency and way of filling* (standing wave structure + ion source).
- The first study of BD phenomena was performed in the RFQ Linac 4.
  - Q-factor at BD is lower compared to the value during normal operation.
  - Non resonant frequency occurred at BD.
- Preliminary analyse show that the main number of BD happened after full filling of the cavity.

Future work:

- Continue breakdown location analysis.
- Implement CLIC conditioning algorithm to the new RFQs.

Thank you for your attention!