Breakdown localization in RF structures

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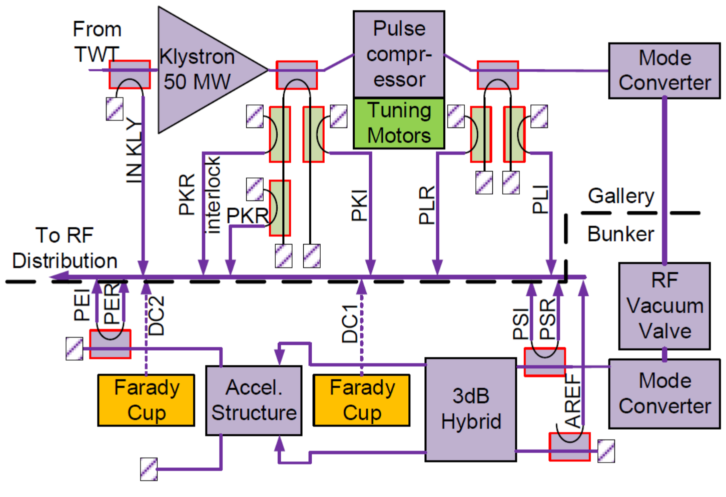
Introduction

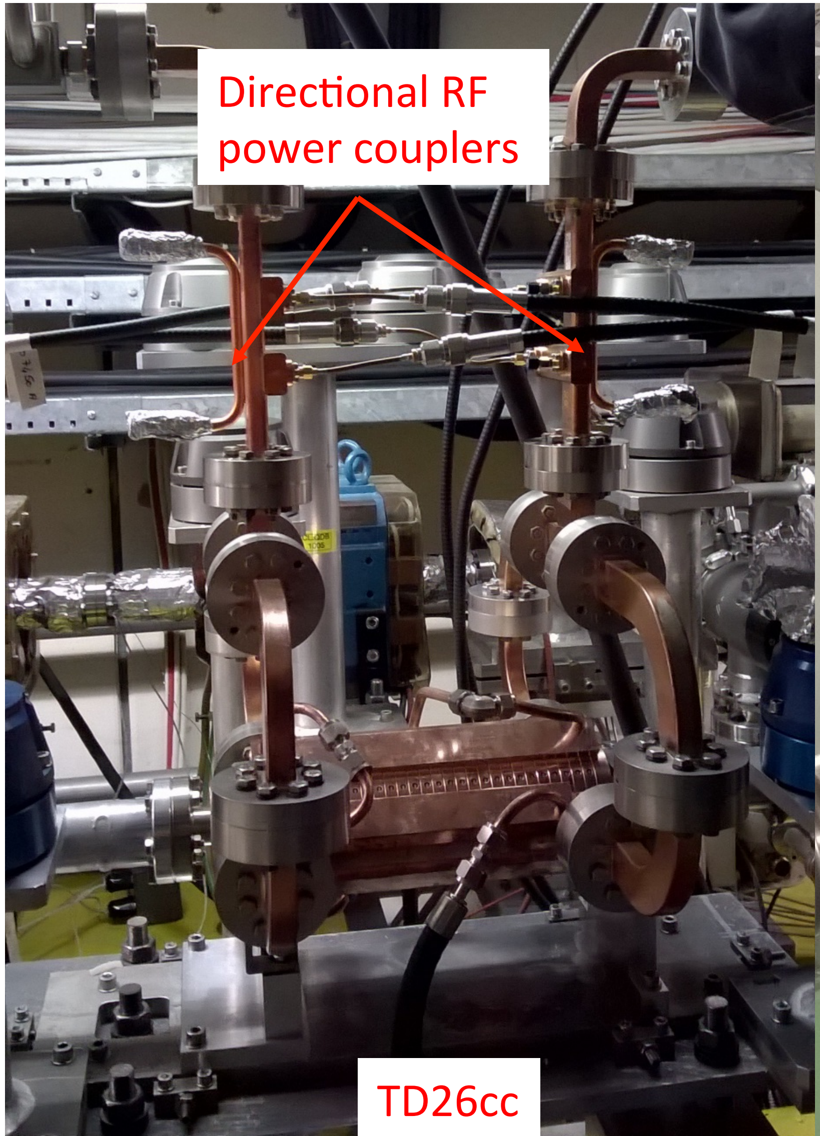
- What?
  - Localize BD in RF structures
- Why?
  - Operational diagnostics
  - Breakdown studies
- How?
  - Absorbed and reflected RF power
  - Mechanical vibrations
  - Electron emission
  - Visible light, X-rays

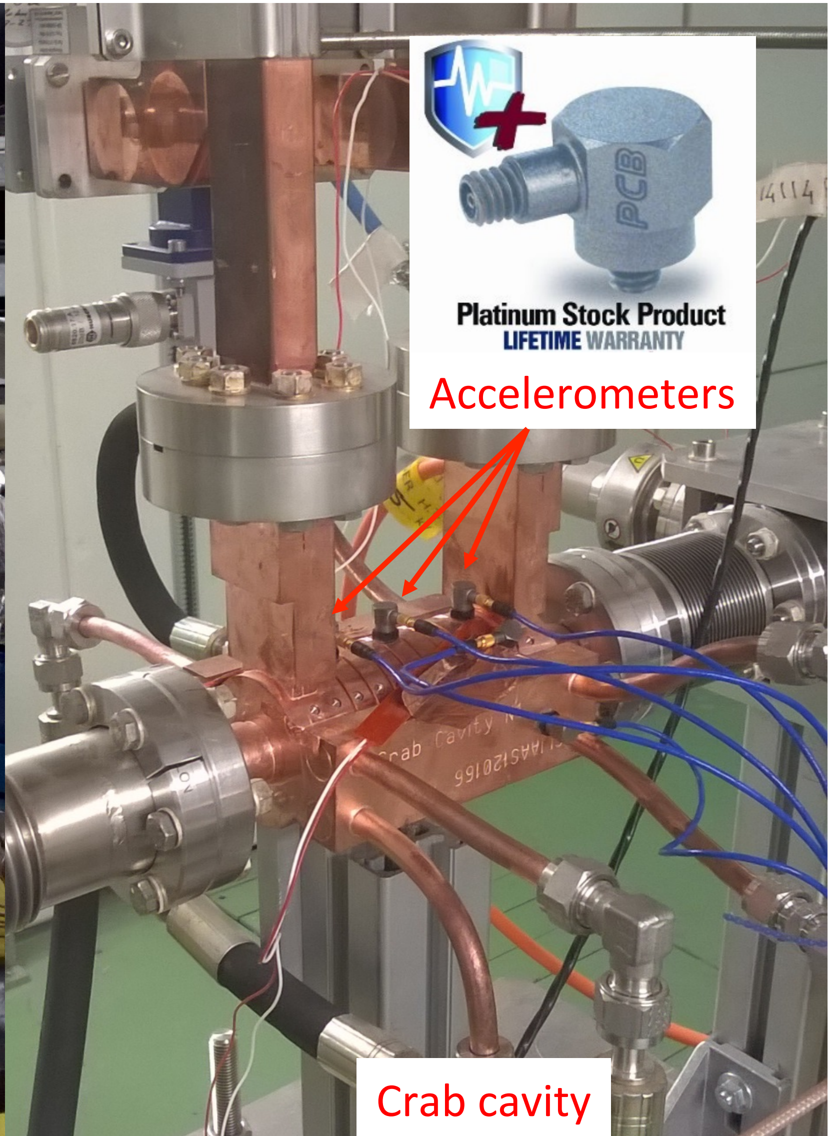
Experiments

- Two fully operational klystron based test stands at CERN for high power testing (more to come...)
  - Xbox-1:
    - TD26cc (still testing)
  - Xbox-2:
    - Crab cavity (removed)
- Both structures have accelerometers installed on their surfaces



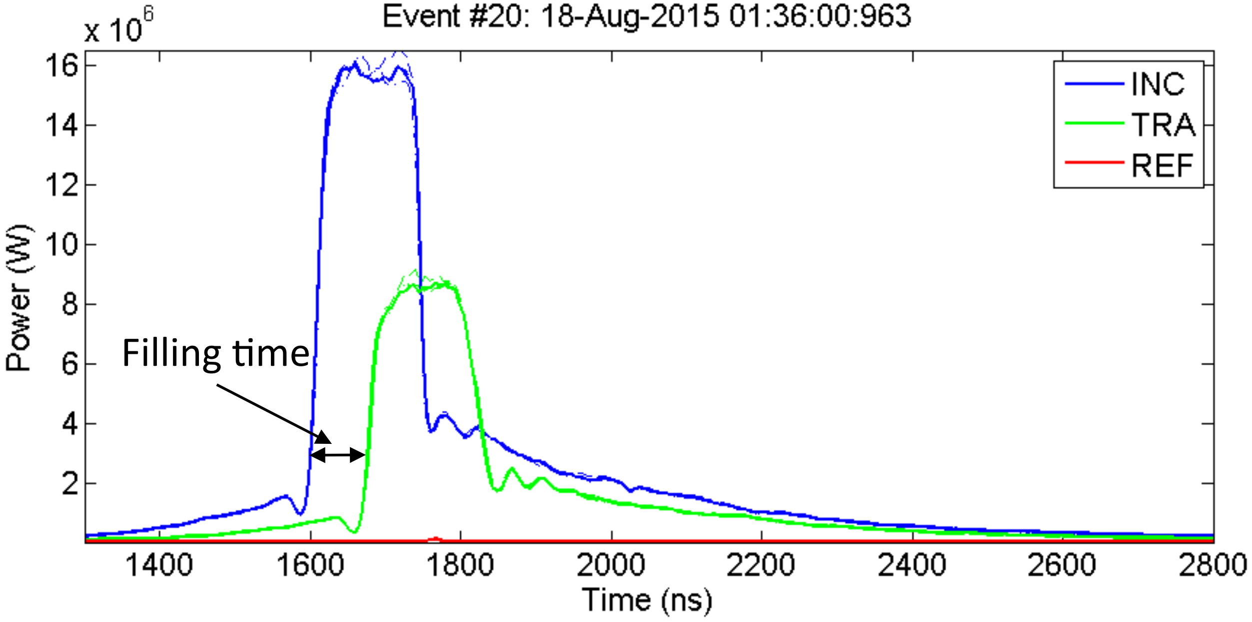
Schematic of Xbox-1 [4].



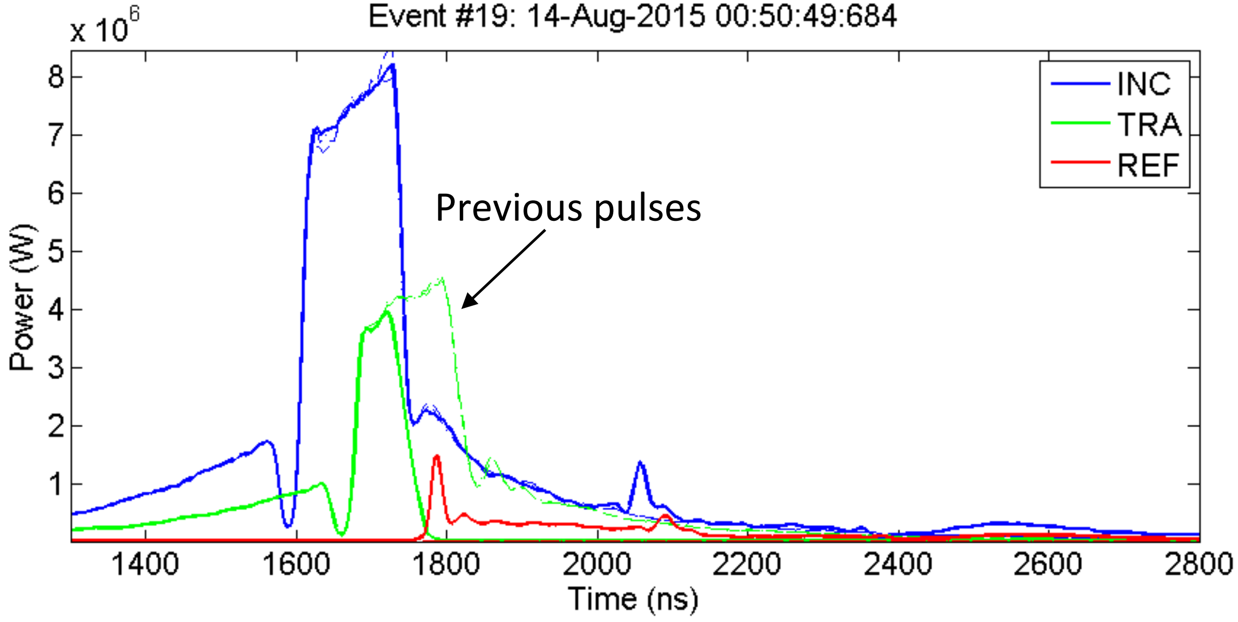


Absorbed and relfected RF power

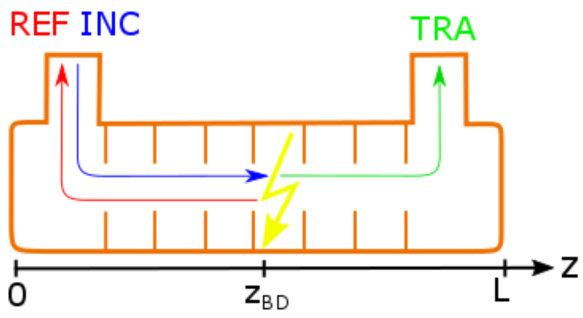
RF only (no beam)

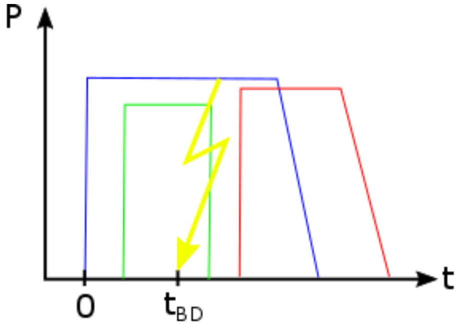


Breakdown (no beam)



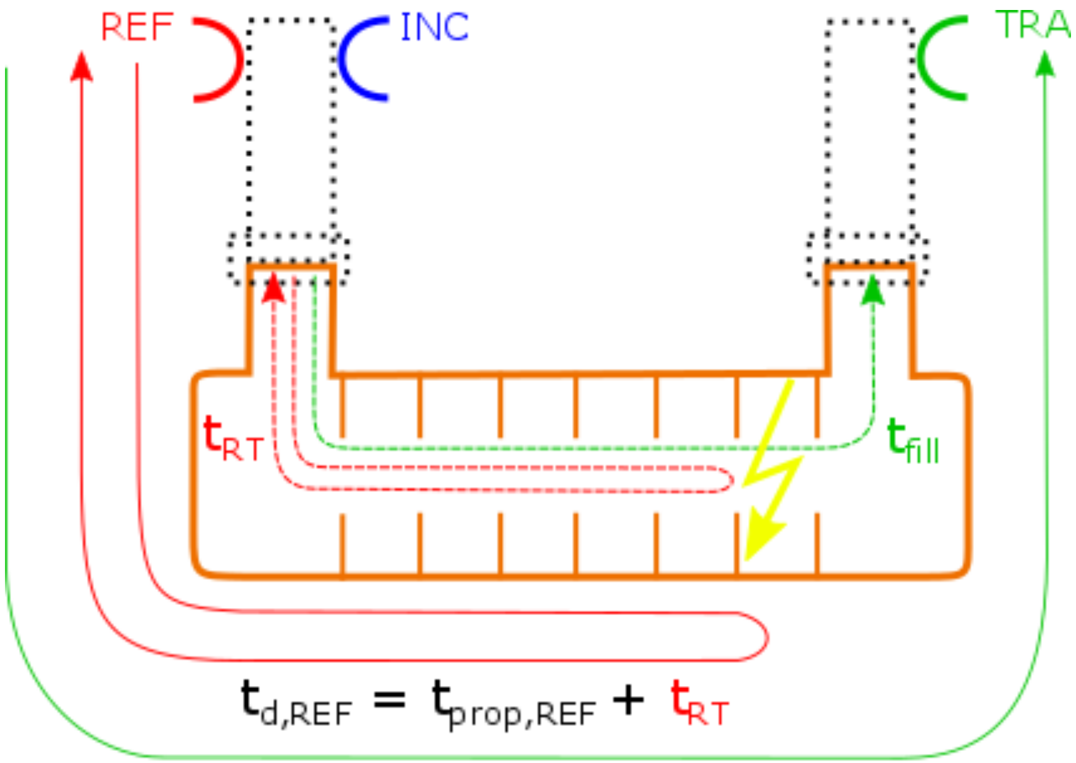
- Two methods for time delay estimation
  1. Falling edge of TRA and rising edge of REF
  2. Correlation in tails of INC and REF
- Time delay converted to cell location by knowing group velocity in structure





Converting time delay into cell

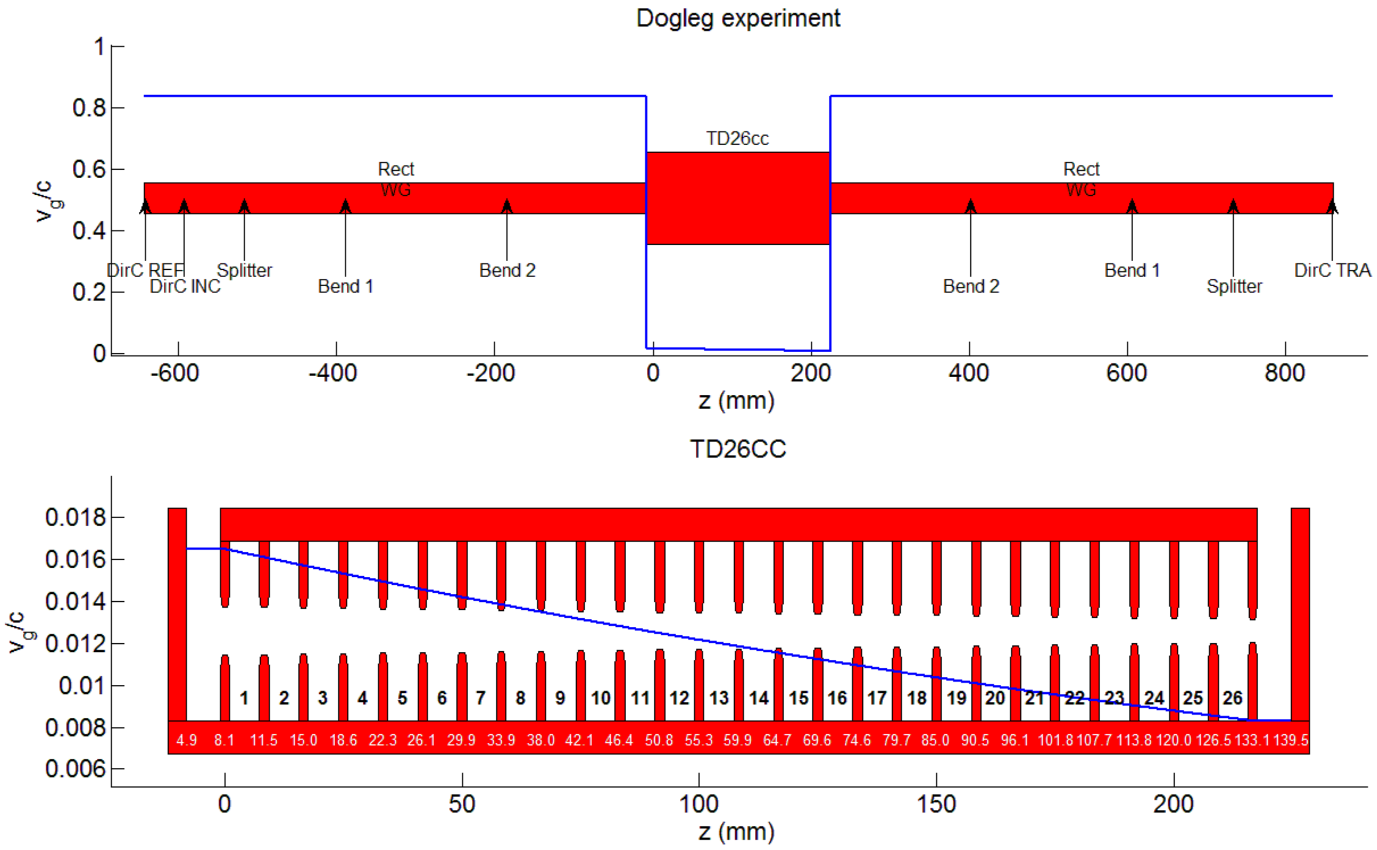
<u>Measured time delays</u>



$$t_{d,REF} = t_{prop,REF} + t_{RT}$$

$$t_{d,TRA} = t_{prop,TRA} + t_{fill}$$

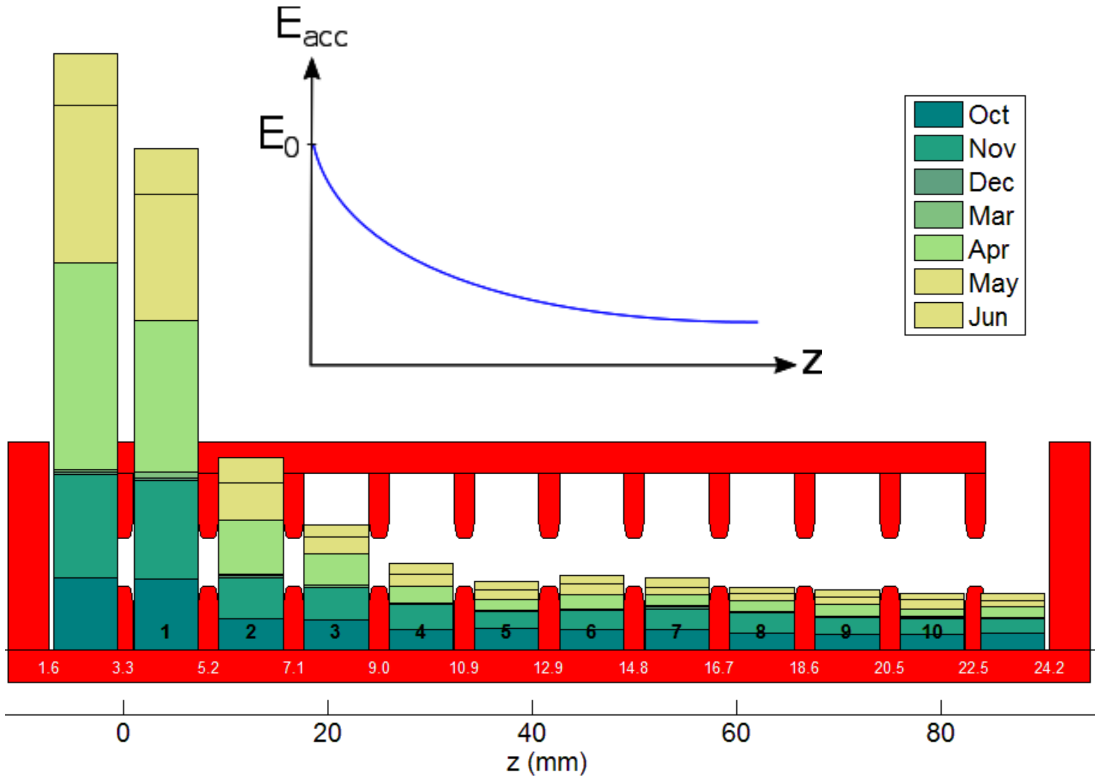
<u>Group velocity profile of TD26cc</u>



Breakdown cell distribution

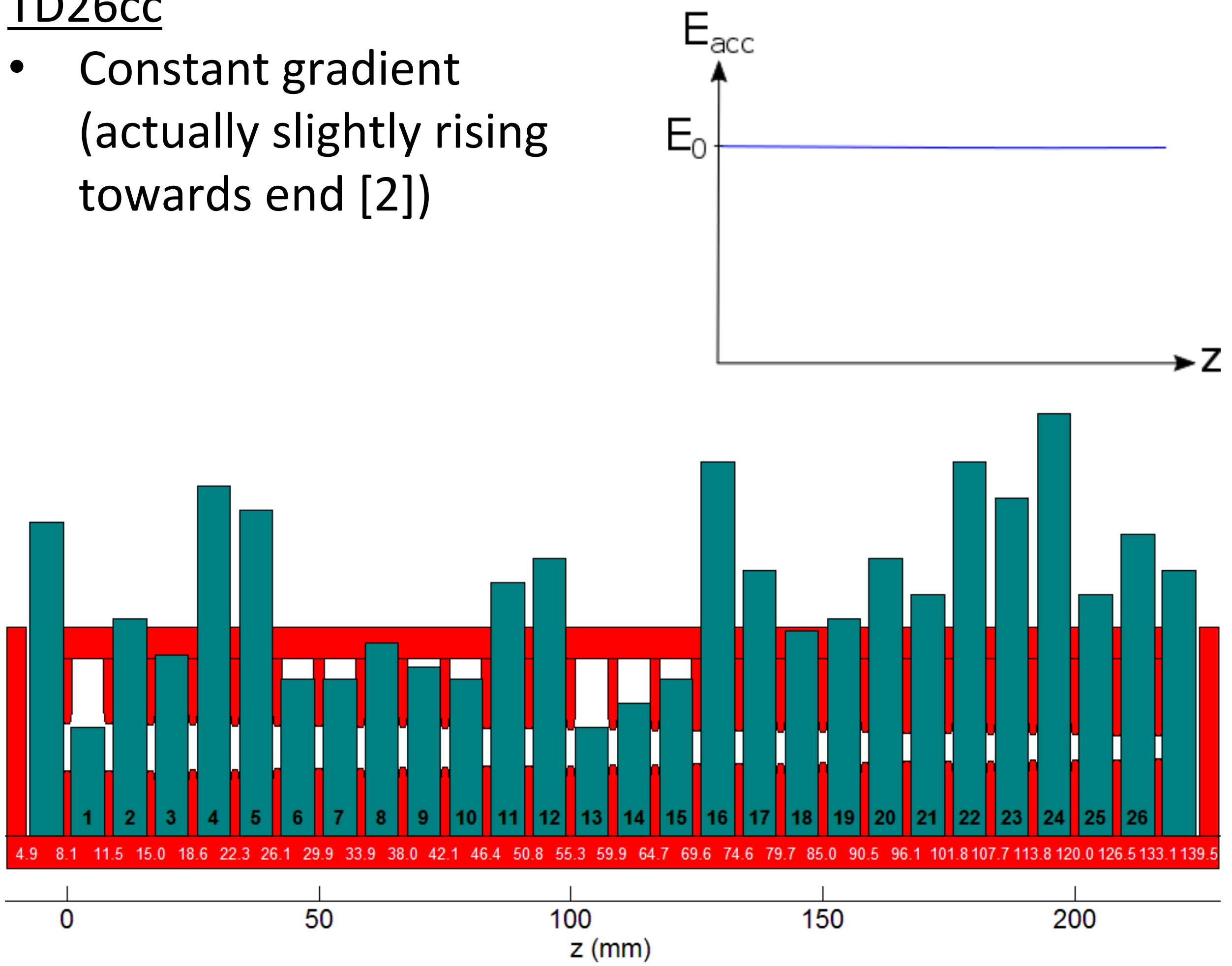
Crab cavity

- Constant impedance -> Exponentially decreasing gradient [3]



TD26cc

- Constant gradient (actually slightly rising towards end [2])



$$BDR \propto E^{30} \,?$$

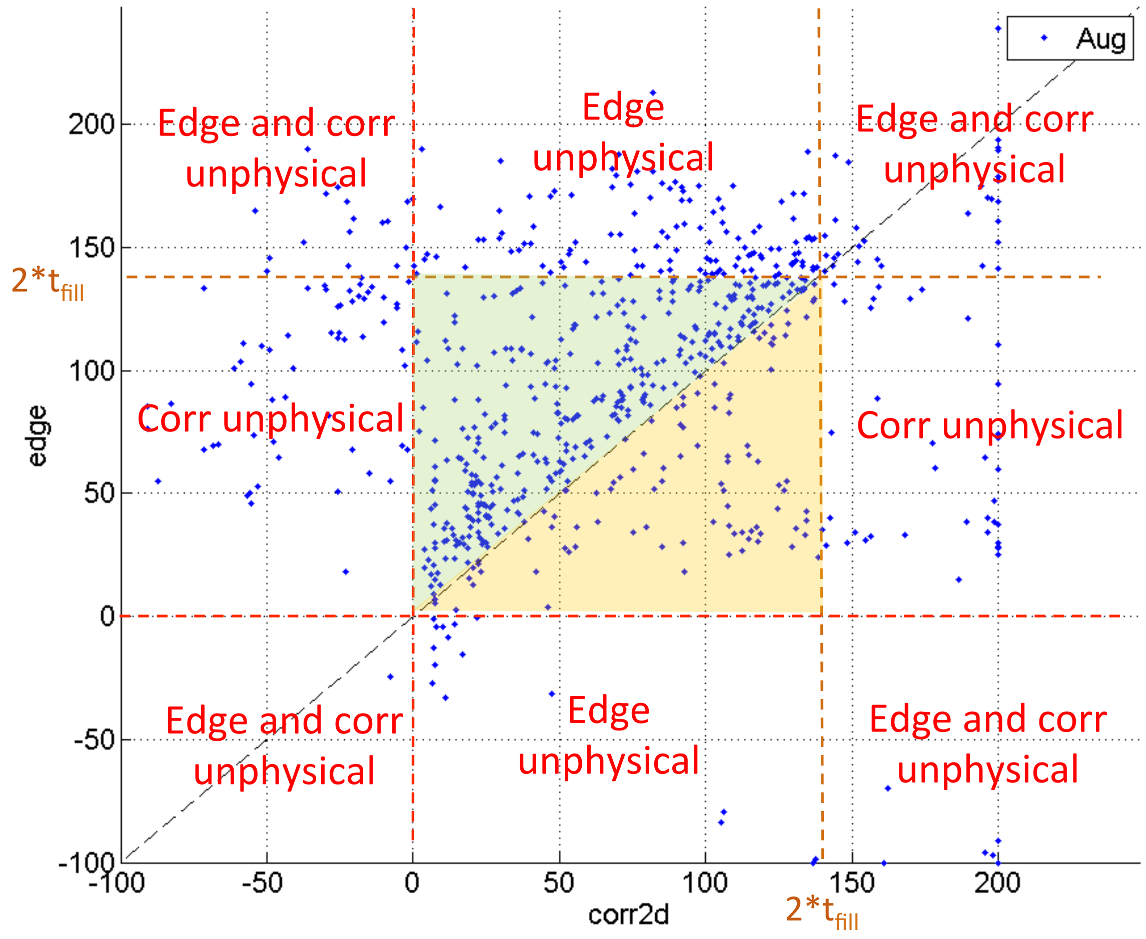
See also [5].

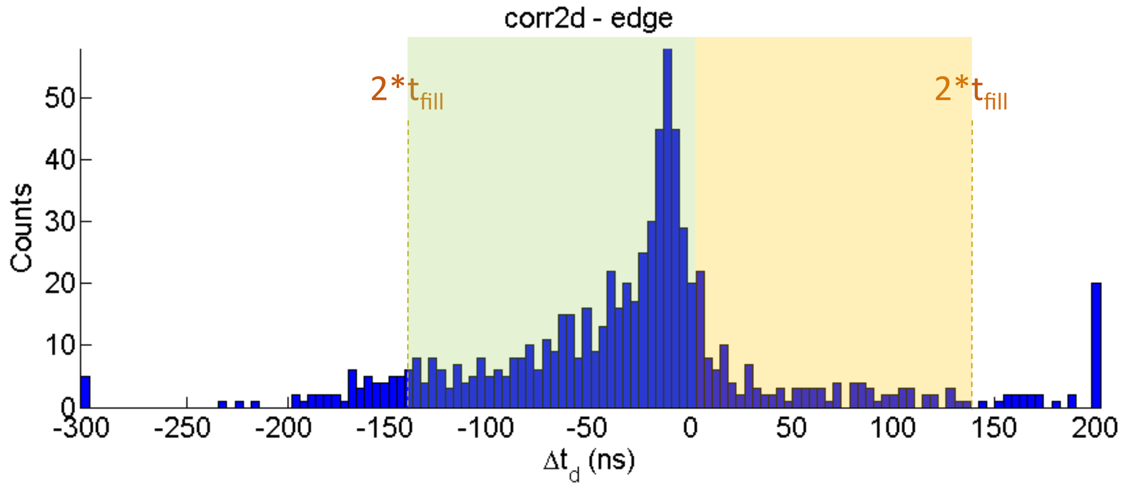
Breakdown migration?

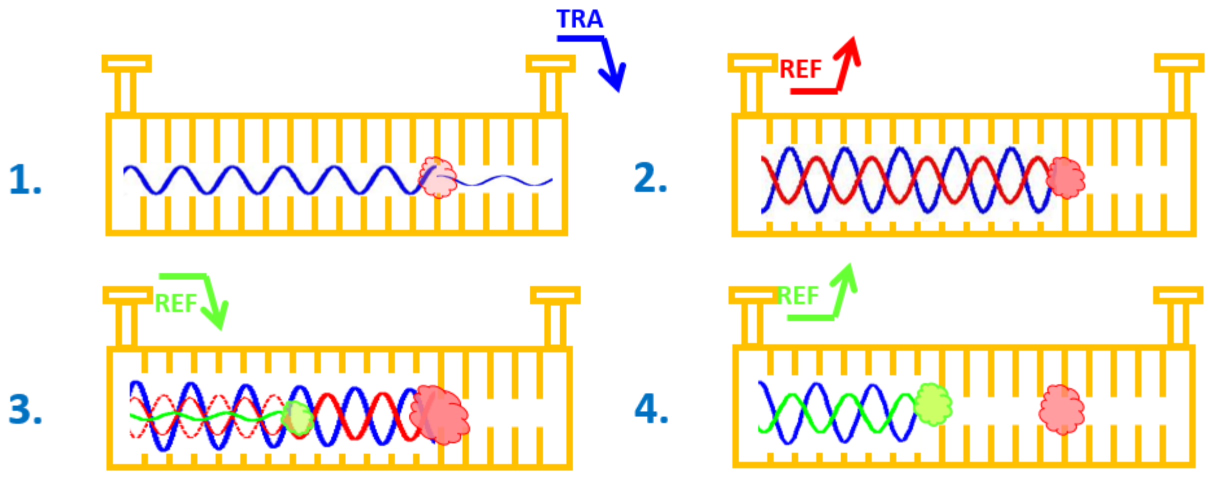
The correlation of tail (corr2d) method consistently finds more BDs towards the input of the structure in comparison to the TRA falling - REF rising (edge) method. Is this BD migration or estimator bias?

Region consistent with migration hypothesis

Region inconsistent with migration hypothesis

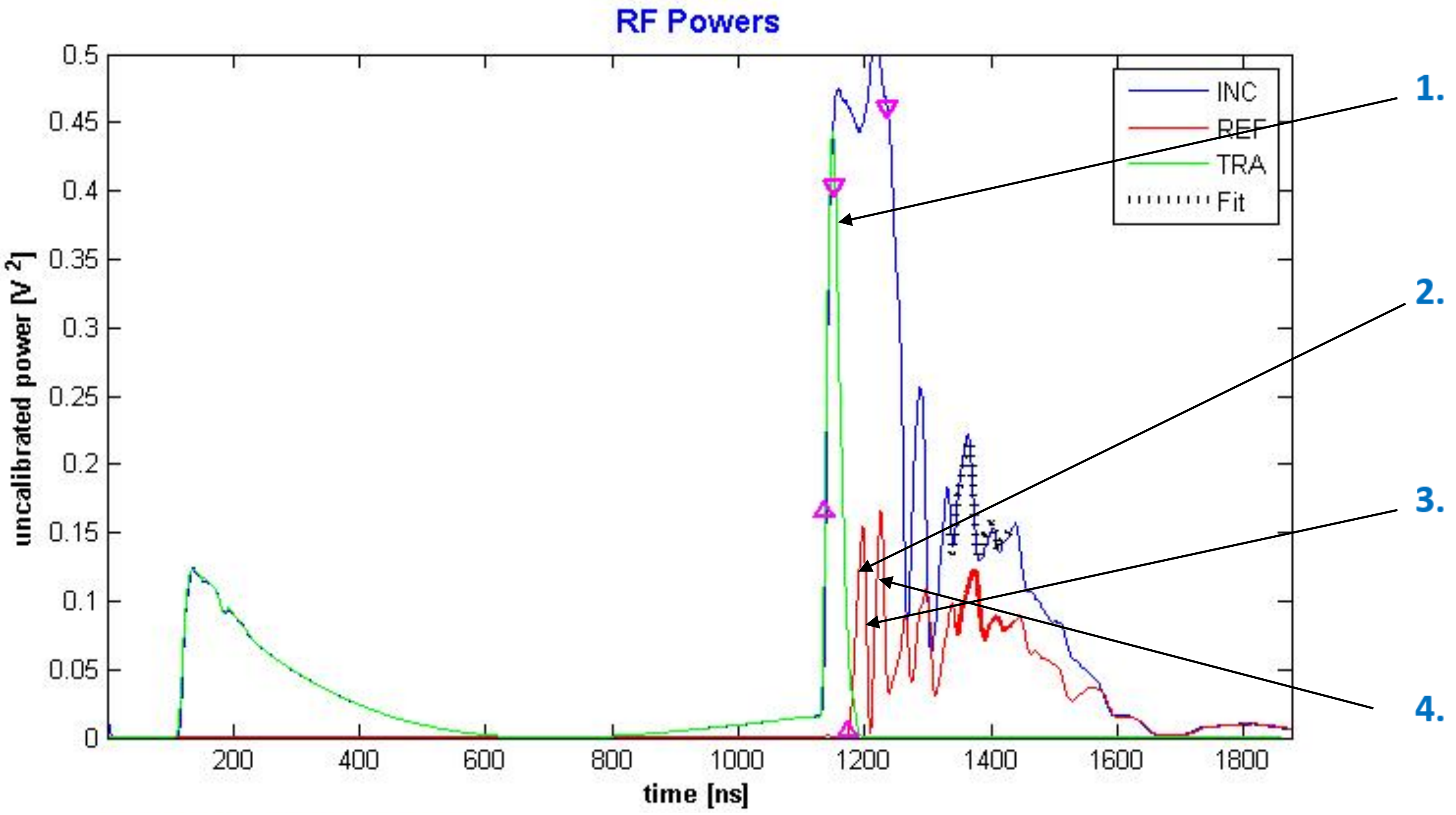


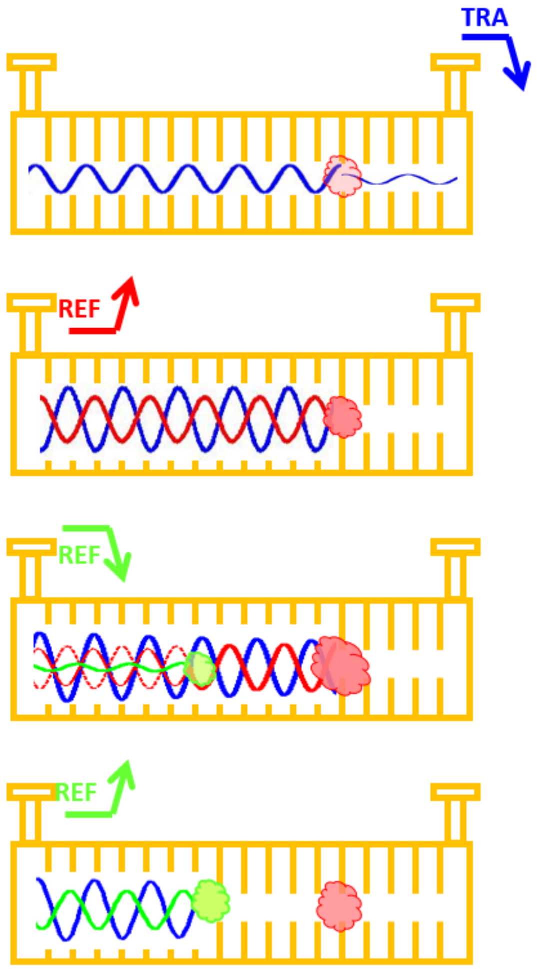




A possible scenario of breakdown migration [1].

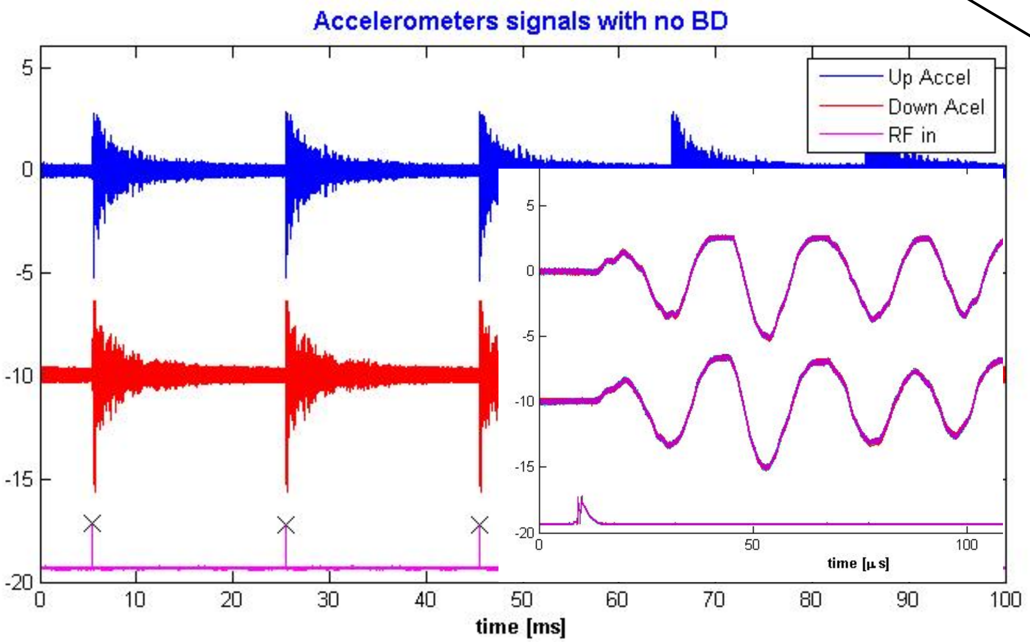
Possible breakdown migration feature [1]





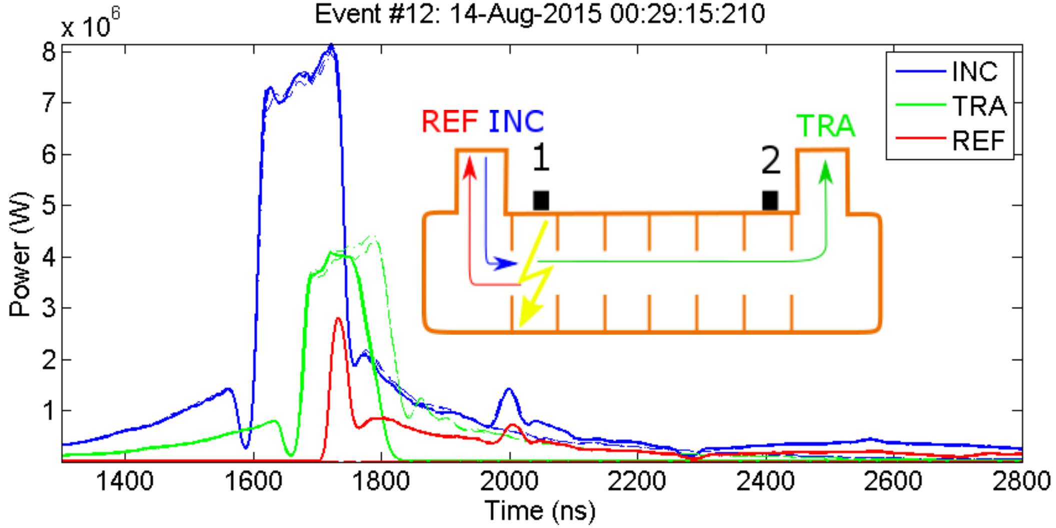
Mechanical vibrations

- RF causes mechanical ringing
  - Thermal expansion due to ohmic losses
  - $a=\mathcal{O}(10\ g)$
  - $f=\mathcal{O}(10\ kHz)$
- Breakdown causes even higher ringing

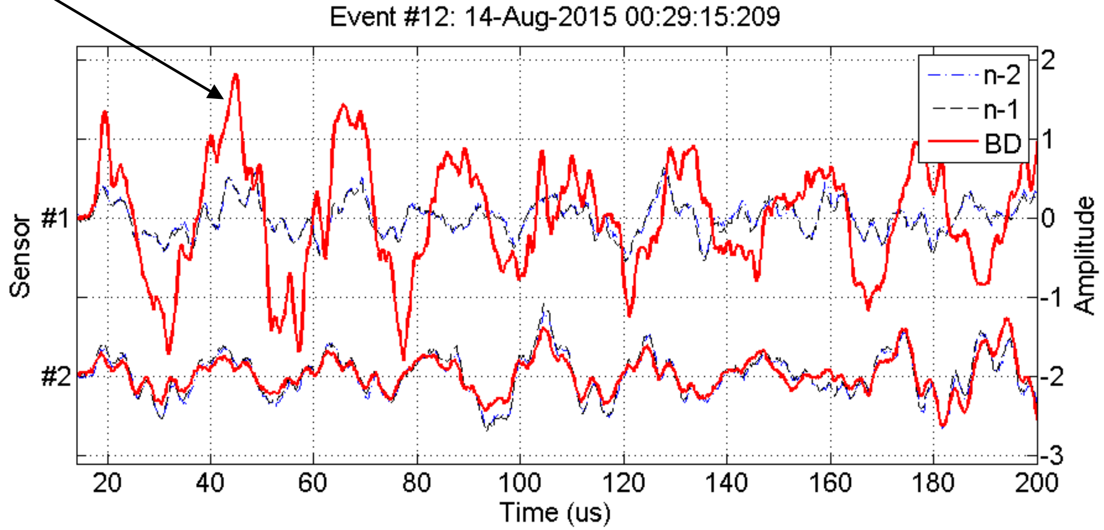


RF and acoustic waveforms [1]. Observe the very different time scales.

RF

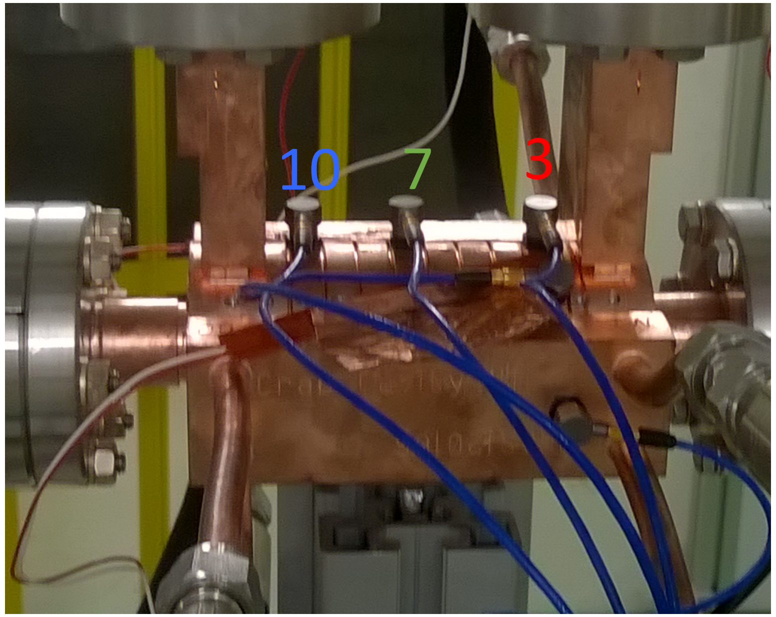


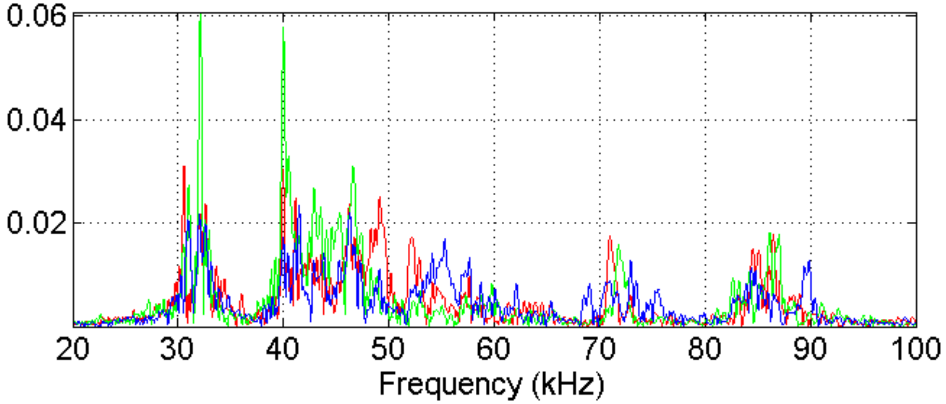
Accelerometer



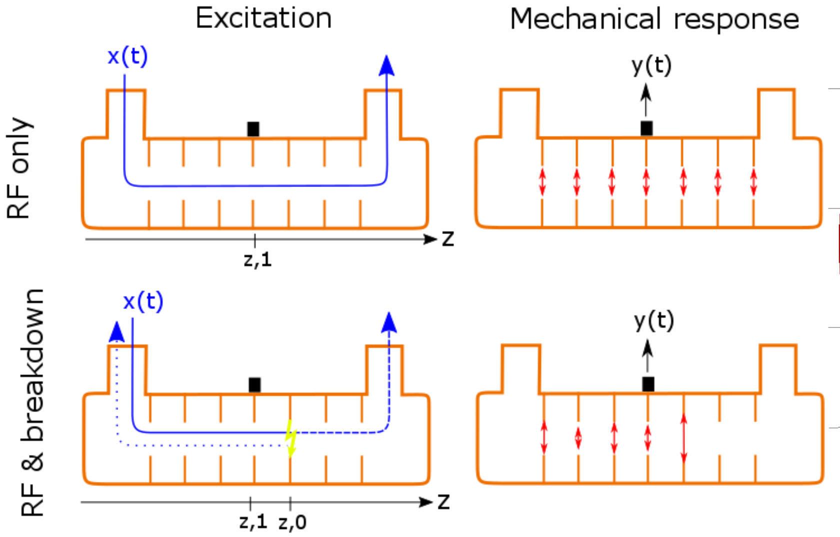
Mechanical excitation by RF

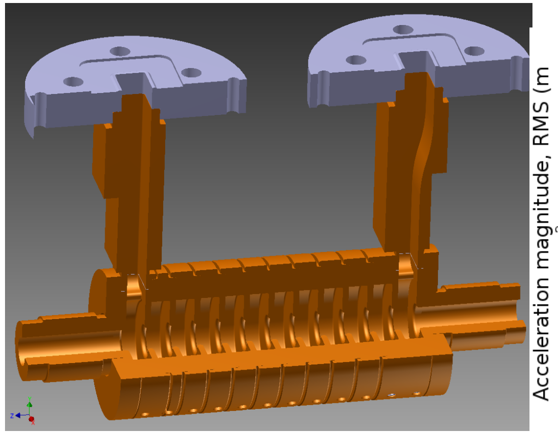
Measurement



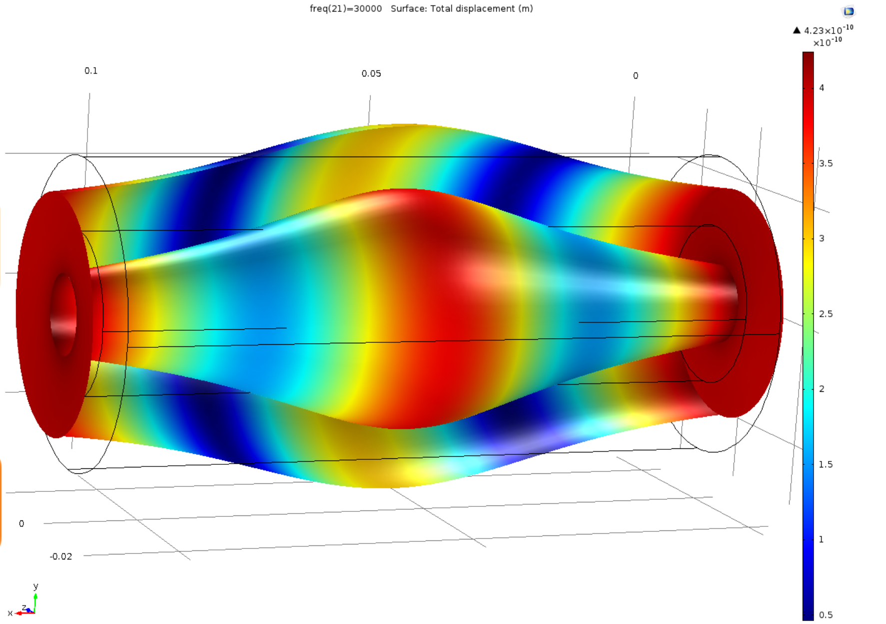


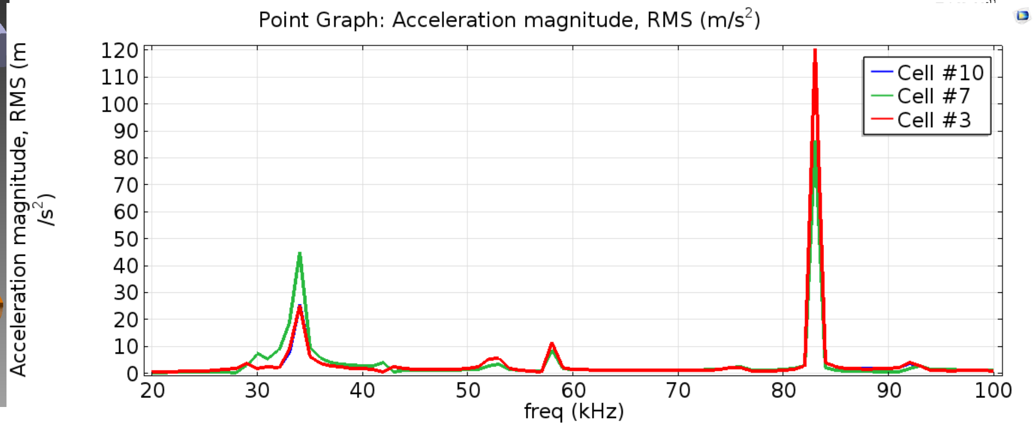
Model





Simulation



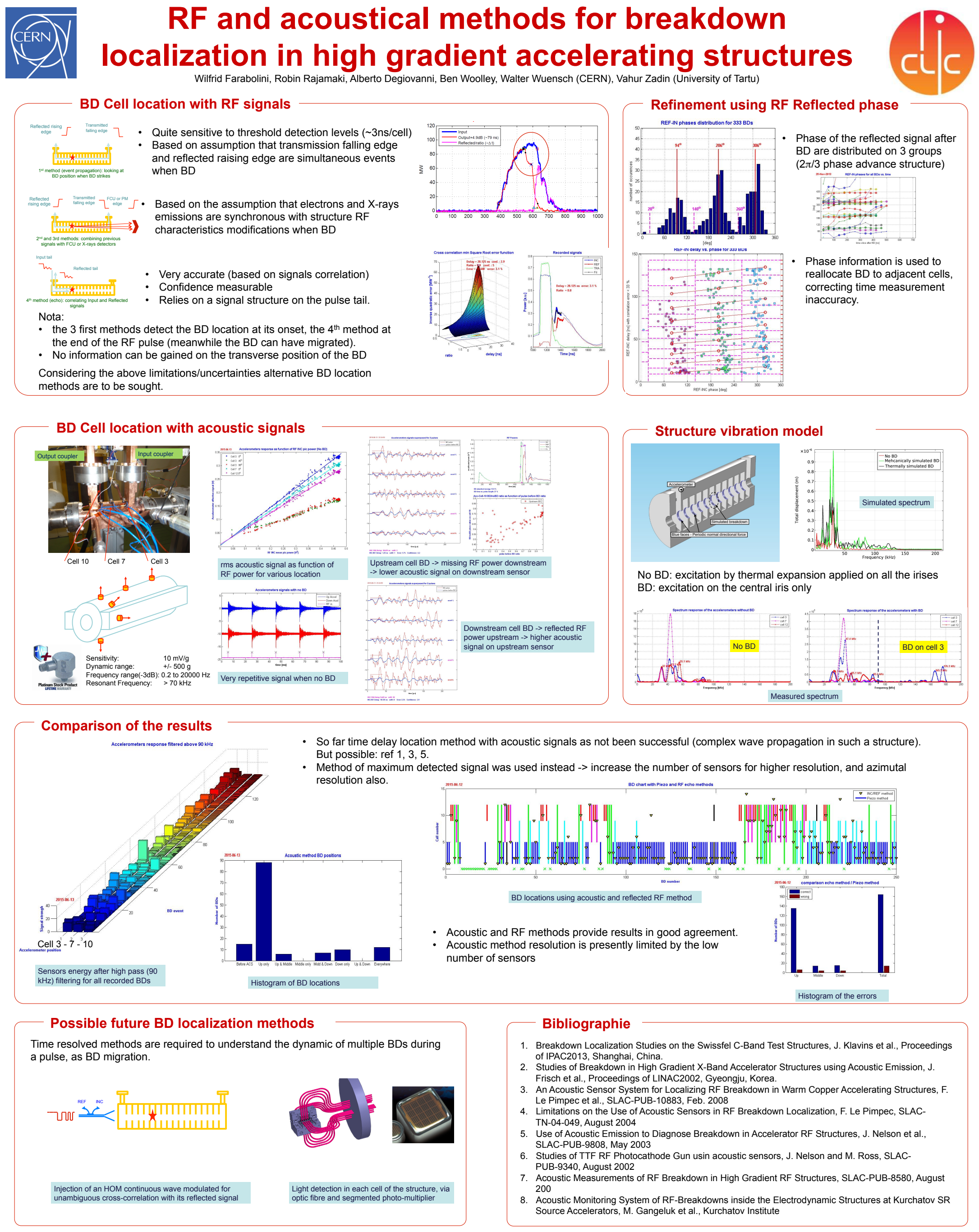


Conclusions

- Breakdowns can be localized in RF structures using
  - The absorbed and reflected RF power
    1. Edge method: Falling edge of transmitted power and rising edge of reflected power
    2. Correlation method: correlation of incident and reflected power in signal tails
  - Accelerometers picking up the mechanical shock caused by the breakdown
    - Good agreement with RF methods [1]
- Measured cell distributions do not seem to follow empirical breakdown rate power law
- Discrepancy between the two RF power based methods might be evidence of breakdown migration

References

- [1] Farabolini, W. – *BD analysis in Crab Cavity using RF and piezo signals*, Presentation, July 2015
- [2] Grudiev, A. - *TD26_vg1.8_R05_CC, 12WDSDVG1.8R05_CC, CLIC_G_r05 at 12 GHz with compact couplers*, June 2010
- [3] Wangler, T. P. - *RF Linear Accelerators*, 2008
- [4] Catalan-Lasheras, N. et al - *Experience operating an X-band high-power test stand at CERN*, 2014
- [5] Shi, J. et al - *Recent X-band activities in Tsinghua University*, CLIC workshop, 2015


RF and acoustical methods for breakdown localization in high gradient accelerating structures

Wilfrid Farabolini, Robin Rajamaki, Alberto Degiovanni, Ben Woolley, Walter Wuensch (CERN), Vahur Zadin (University of Tartu)

BD Cell location with RF signals

- Quite sensitive to threshold detection levels (~3ns/cell)
- Based on assumption that transmission falling edge and reflected raising edge are simultaneous events when BD
- Based on the assumption that electrons and X-rays emissions are synchronous with structure RF characteristics modifications when BD
- Very accurate (based on signals correlation)
- Confidence measurable
- Relies on a signal structure on the pulse tail.

Nota:
- the 3 first methods detect the BD location at its onset, the 4th method at the end of the RF pulse (meanwhile the BD can have migrated).
- No information can be gained on the transverse position of the BD

Considering the above limitations/uncertainties alternative BD location methods are to be sought.

Refinement using RF Reflected phase

- Phase of the reflected signal after BD are distributed on 3 groups (2π/3 phase advance structure)
- Phase information is used to reallocate BD to adjacent cells, correcting time measurement inaccuracy.

BD Cell location with acoustic signals

Output coupler | Input coupler | Cell 10 | Cell 7 | Cell 3

Sensitivity: 10 mV/g
Dynamic range: +/- 500 g
Frequency range(-3dB): 0.2 to 20000 Hz
Resonant Frequency: > 70 kHz

rms acoustic signal as function of RF power for various location

Very repetitive signal when no BD

Upstream cell BD -> missing RF power downstream -> lower acoustic signal on downstream sensor

Downstream cell BD -> reflected RF power upstream -> higher acoustic signal on upstream sensor

Structure vibration model

Simulated spectrum

No BD: excitation by thermal expansion applied on all the irises
BD: excitation on the central iris only

No BD | BD on cell 3

Measured spectrum

Comparison of the results

- So far time delay location method with acoustic signals as not been successful (complex wave propagation in such a structure). But possible: ref 1, 3, 5.
- Method of maximum detected signal was used instead -> increase the number of sensors for higher resolution, and azimutal resolution also.

Cell 3 - 7 - 10

Sensors energy after high pass (90 kHz) filtering for all recorded BDs

Histogram of BD locations

BD locations using acoustic and reflected RF method

- Acoustic and RF methods provide results in good agreement.
- Acoustic method resolution is presently limited by the low number of sensors

Histogram of the errors

Possible future BD localization methods

Time resolved methods are required to understand the dynamic of multiple BDs during a pulse, as BD migration.

Injection of an HOM continuous wave modulated for unambiguous cross-correlation with its reflected signal

Light detection in each cell of the structure, via optic fibre and segmented photo-multiplier

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2. Studies of Breakdown in High Gradient X-Band Accelerator Structures using Acoustic Emission, J. Frisch et al., Proceedings of LINAC2002, Gyeongju, Korea.
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8. Acoustic Monitoring System of RF-Breakdowns inside the Electrodynamic Structures at Kurchatov SR Source Accelerators, M. Gangeluk et al., Kurchatov Institute

Kiitos *[Kee-toss]*

See Wilfrid Farabolini's (not pictured above) poster for more details and results!