Radio Frequency Breakdown analysis at CERN's high gradient test stands: an ML approach

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By Paarangat Pushkarna

16 Dec, AIPC 2022

Accelerator Physics @ UoM

- Our group:
  - A/Prof Suzie Sheehy
  - Dr. Matteo Volpi
  - Dr. Jacinta Yap
  - Frank Zhang
  - Scott Williams
  - Greg Peiris
  - Adam Steinberg
  - Hannah Norman
  - Choiphy Zhao
  - Paarangat Pushkarna

Overview

- High-gradient electron acceleration (100-120MV/m)

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- RF cavity surfaces experience high fields

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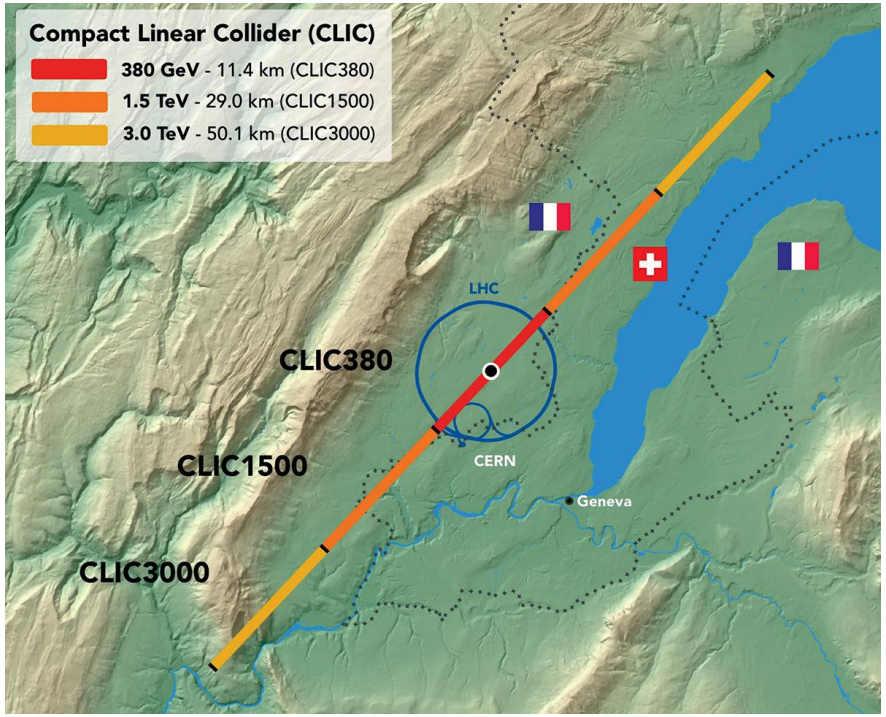
- Tension: charge emission timescales vs pressure analyses

Overview

- High-gradient electron acceleration (100-120MV/m)
- RF cavity surfaces experience high fields
- Tension: charge emission timescales vs pressure analyses
- We: address tension, postulate cause(s), identify progress

Why high gradient?

- Proposed lepton-lepton collider CLIC
- “**C**ompact **Li**near **C**ollider”



https://cerncourier.com/a/clic-beyond-a-higgs-factory/

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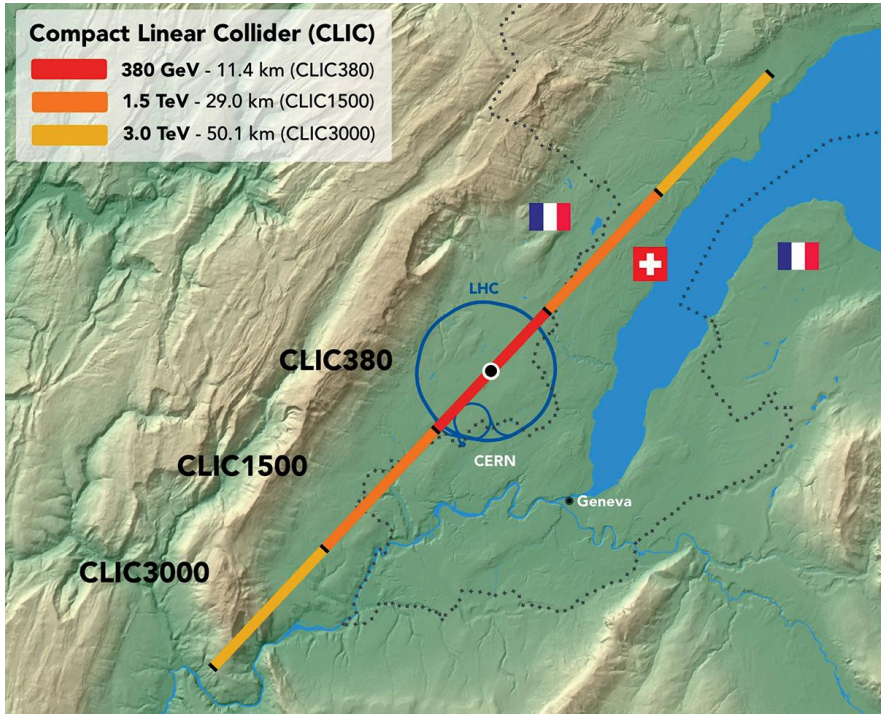
- Application for compact acceleration



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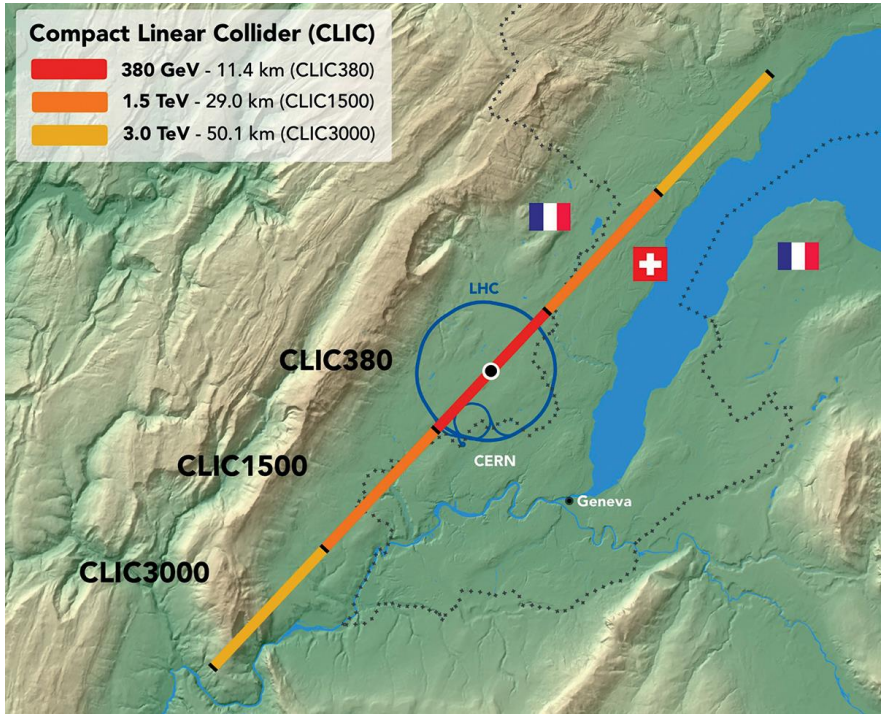
Why high gradient?

- Proposed lepton-lepton collider CLIC
- “**C**ompact **Li**near **C**ollider”
- Applications for compact acceleration
- “Breakdowns (BDs)” in structures:
  - Damage accelerator components
  - Reduce operating time



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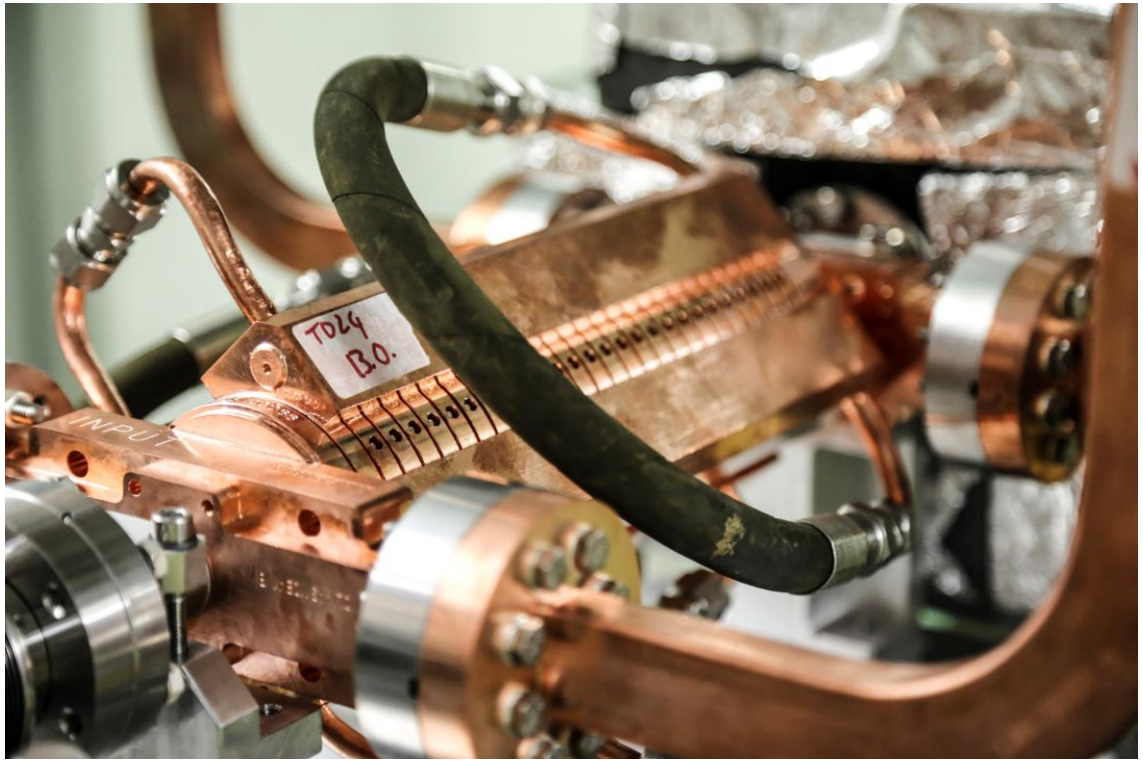
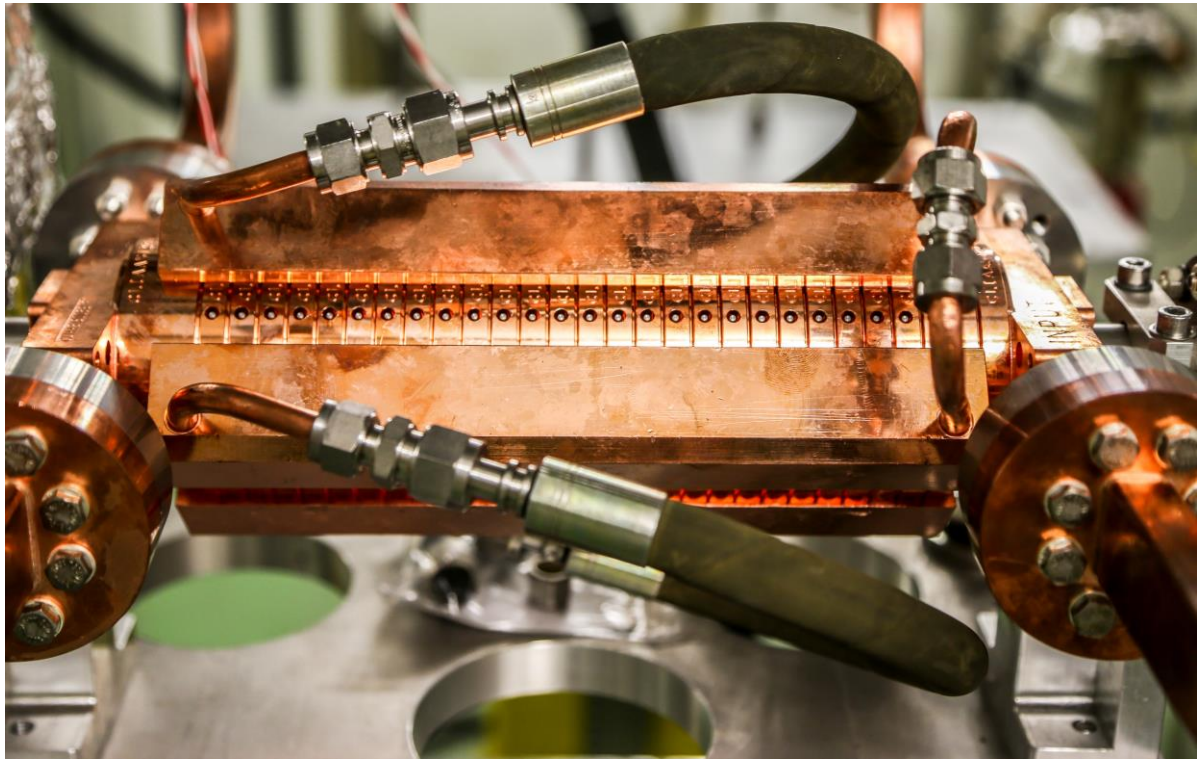
CLIC Structures (TD24)



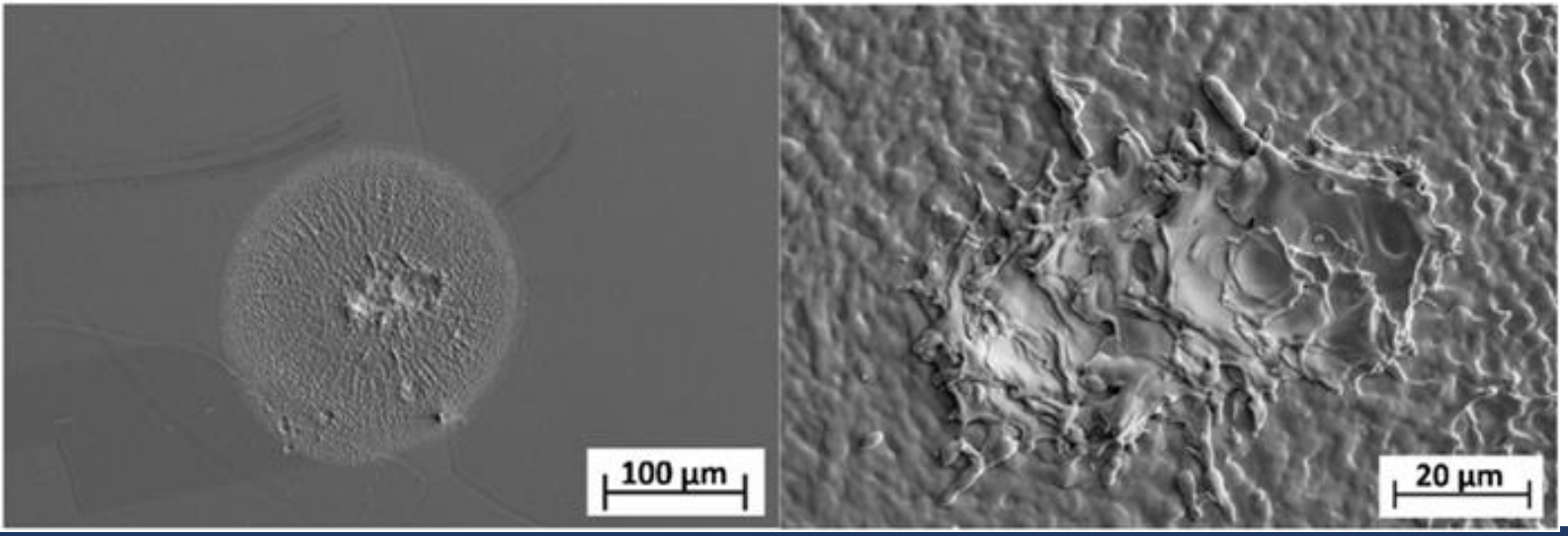


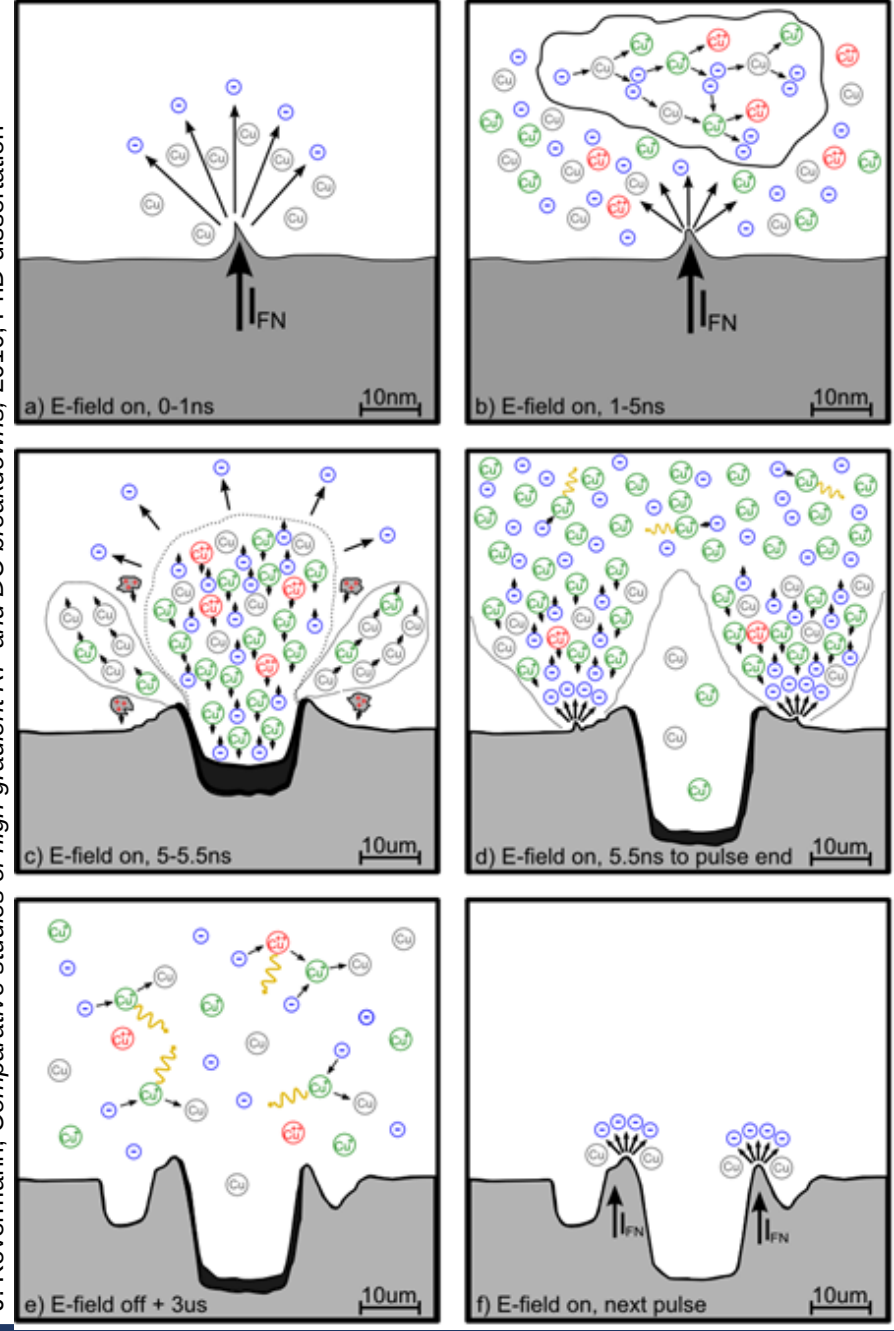
M. Volpi, TD24 type structure (‘T’-Tapered, ‘D’- Damped, 24 cells)

Breakdown theory

- Applied field narrows potential barrier
- “Dark current”
- BD timescales: μs to sub-μs

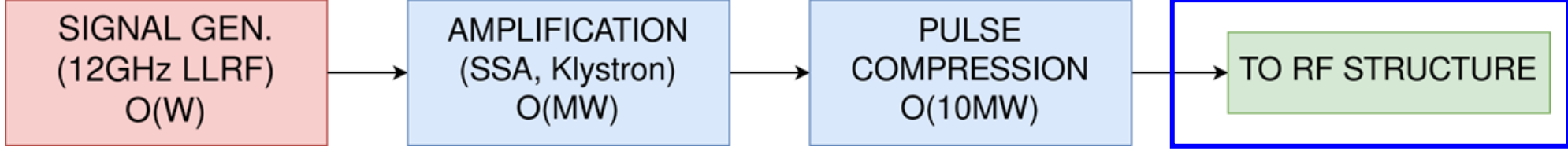
I. Profatilova et. al. *NIMA* 953 (2020)





J. Kovermann, *Comparative studies of high-gradient RF and DC breakdowns*, 2010, PhD dissertation

CERN TEST STAND LAYOUT



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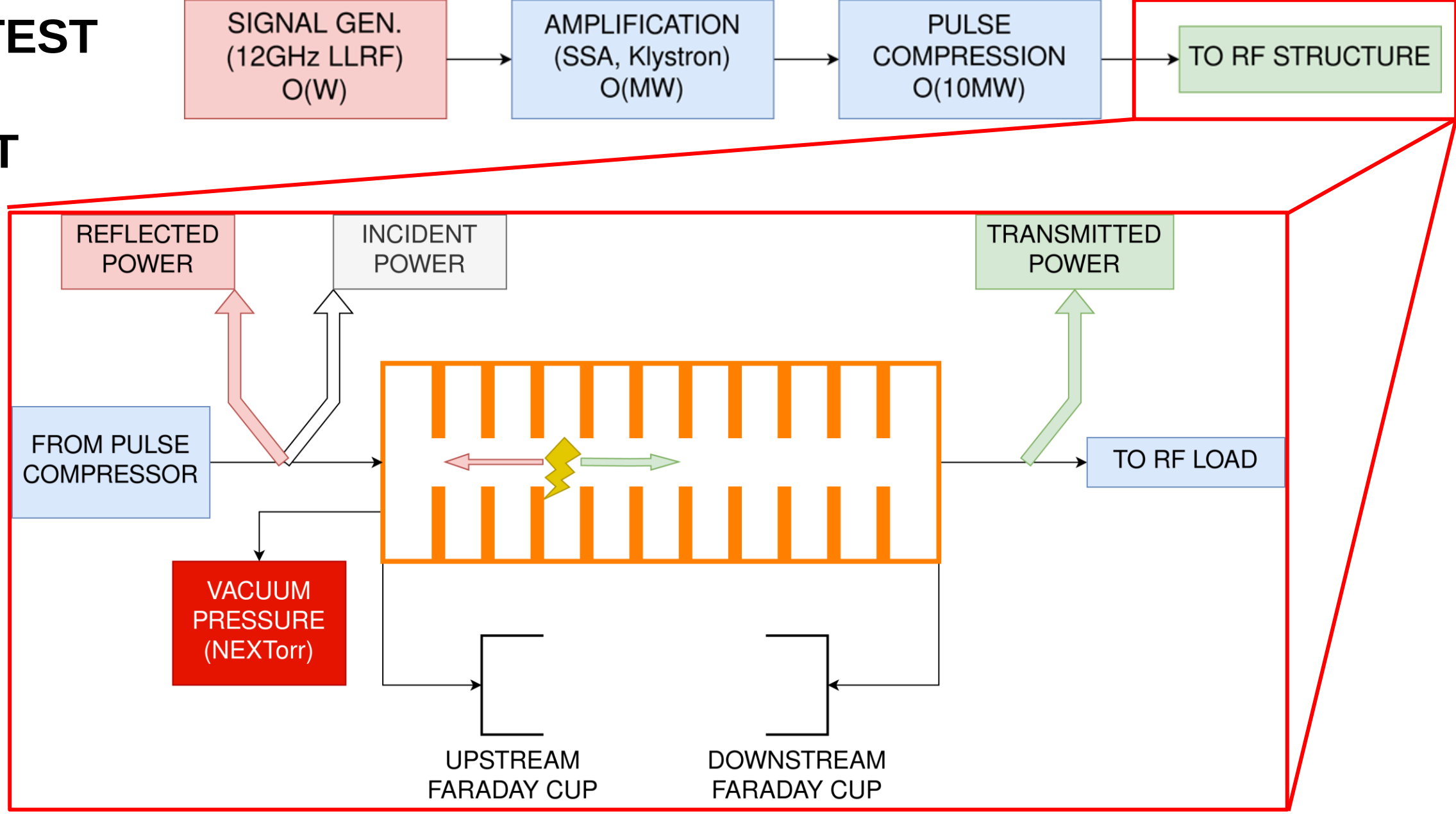
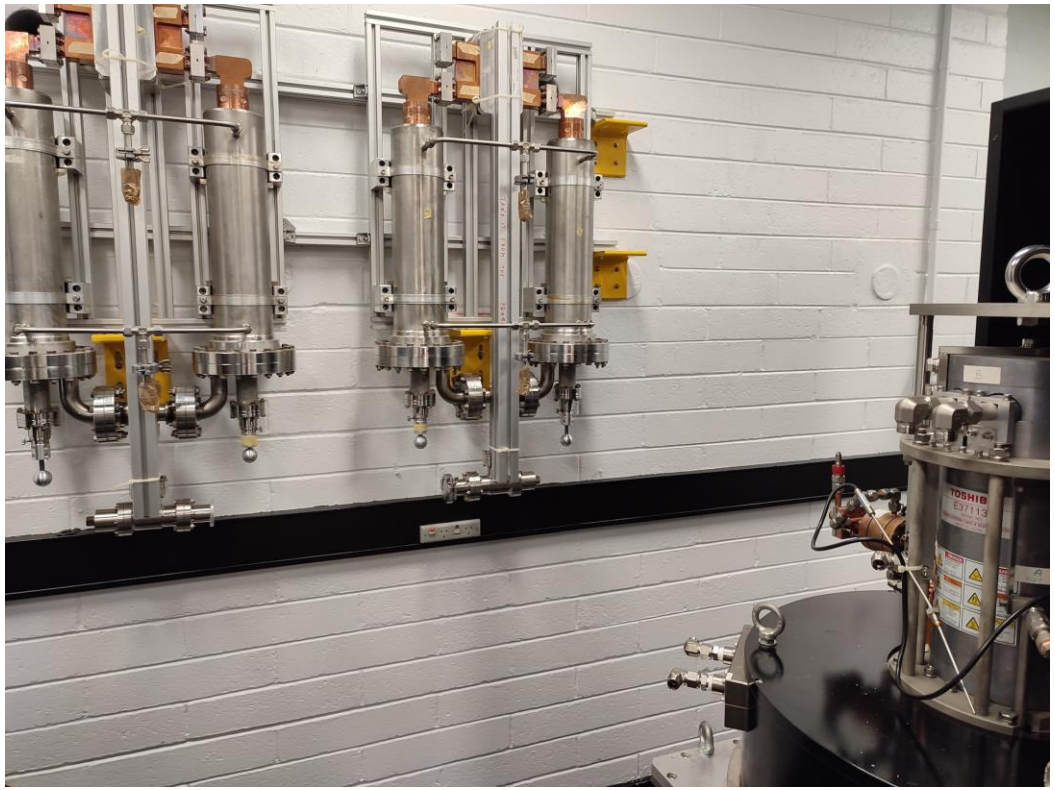


XBOX3 @ UoM, October 2022

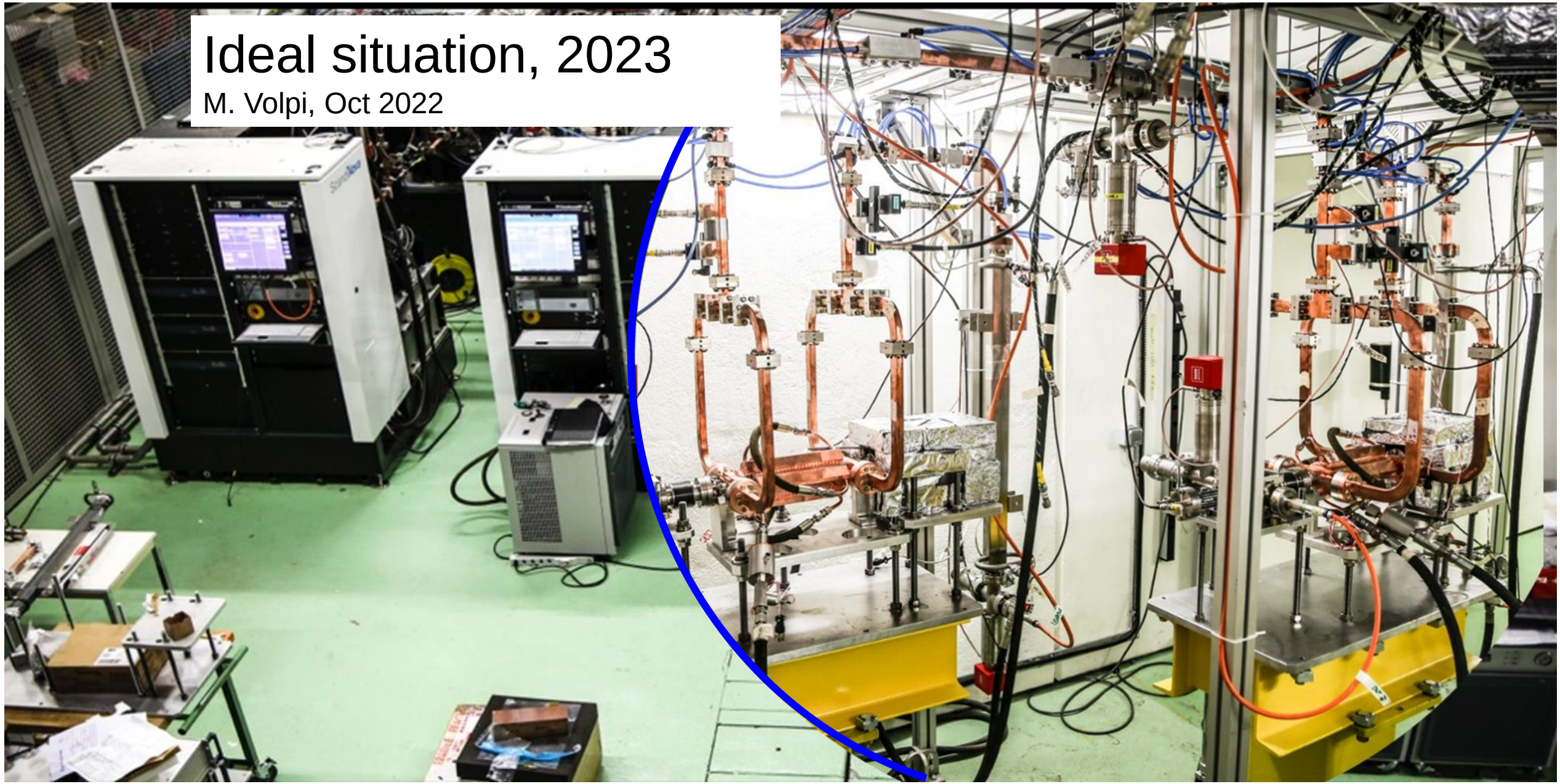
M. Volpi, Oct 2022



- Left: (From back wall to front) Pulse compressors, klystron-modulators, LLRF and Vacuum controls
- Right: Pulse compressor and klystron

Ideal situation, 2023

M. Volpi, Oct 2022



Ideal situation, 2023

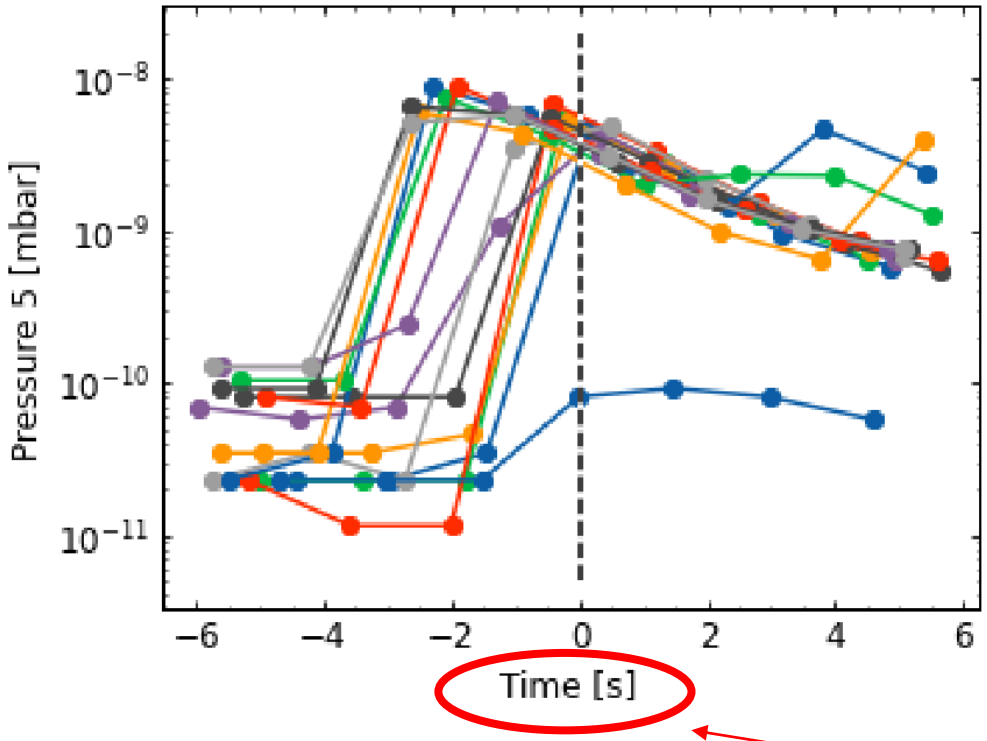
M. Volpi, Oct 2022

Melbourne, Oct ‘22

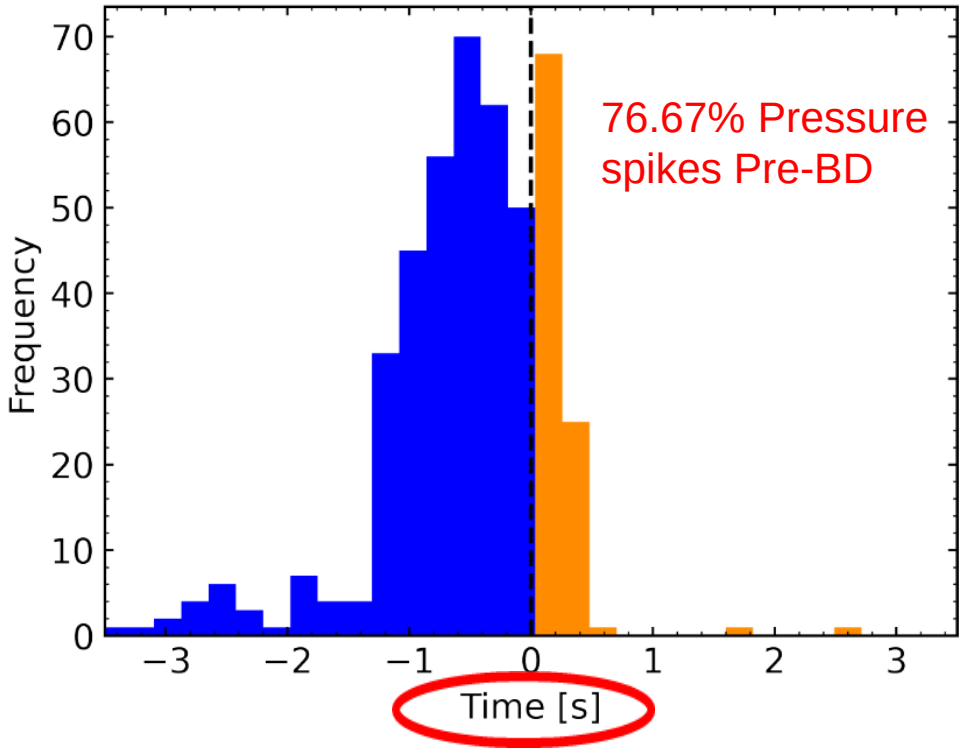
Previous analysis – Obermair et. al. 2022

- Using CNNs and XAI (Explainable AI) to predict breakdowns:
  - CLAIM: Pressure spikes precede breakdown by several seconds?

Pressure signals around BD, Obermair et. al.

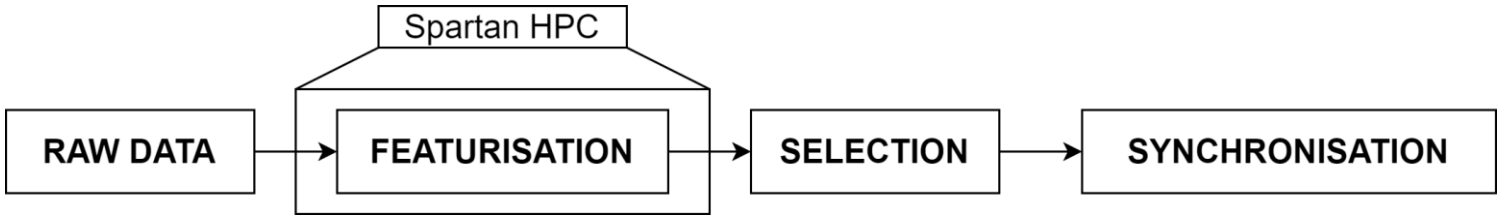


Pressure spike position relative to BD posn.



Time relative to BD position

Data processing pipeline



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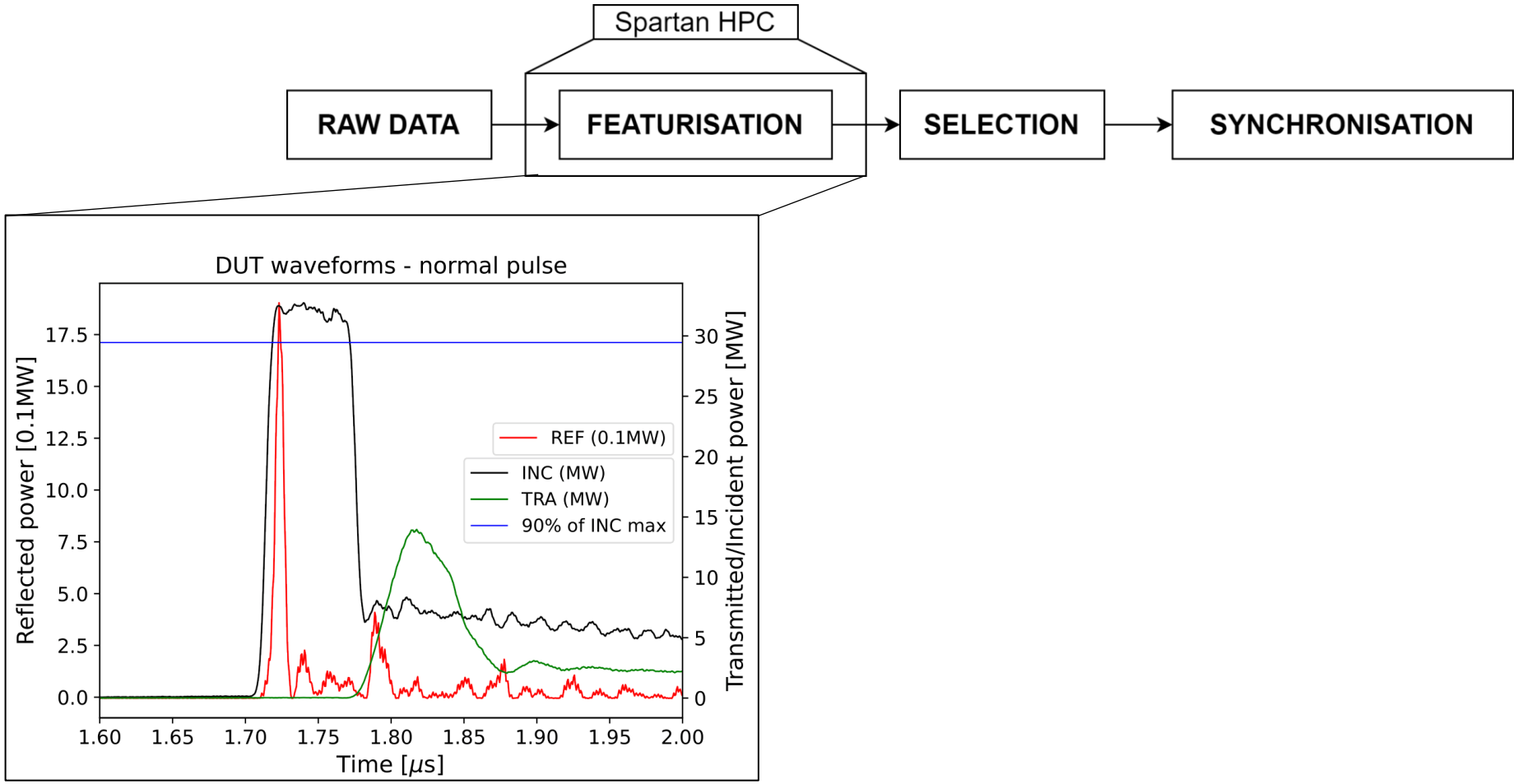

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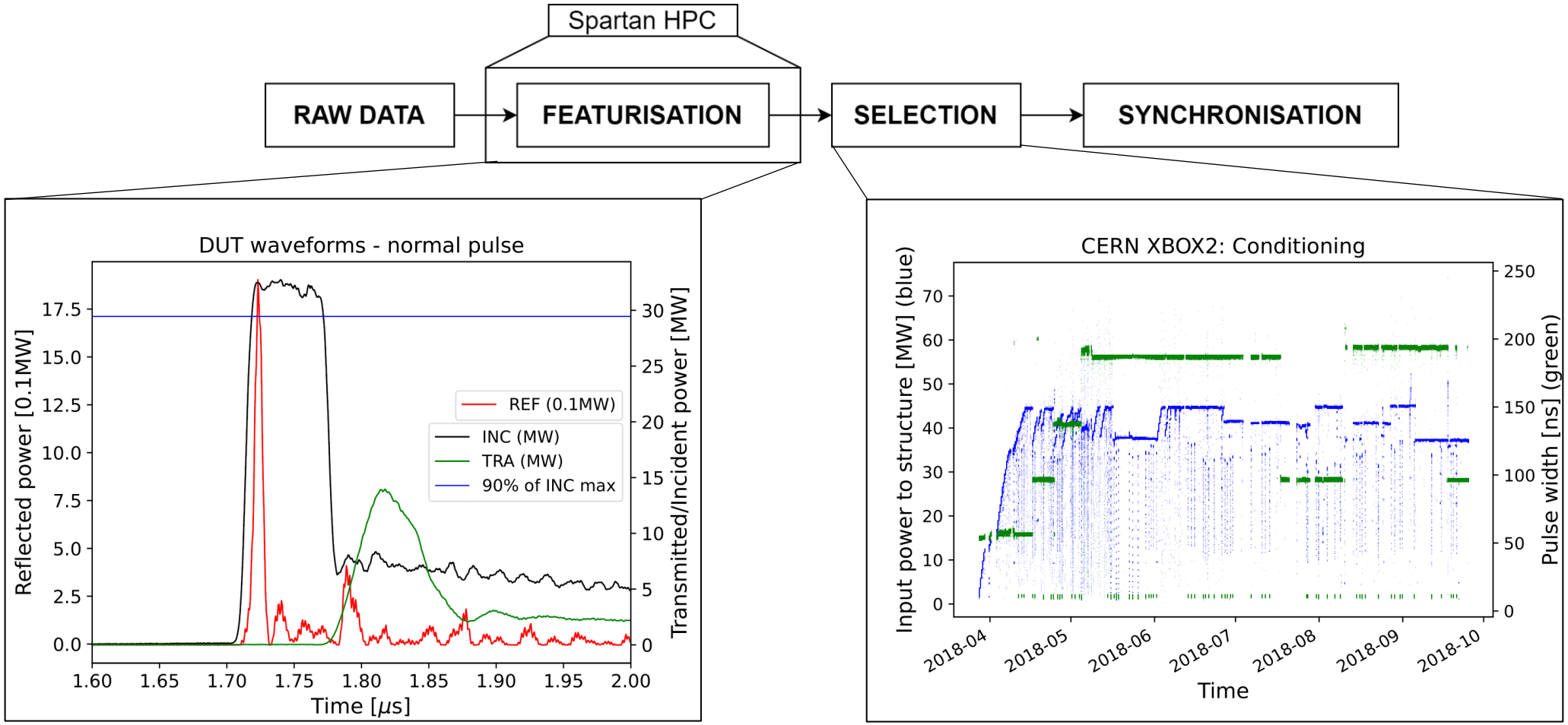
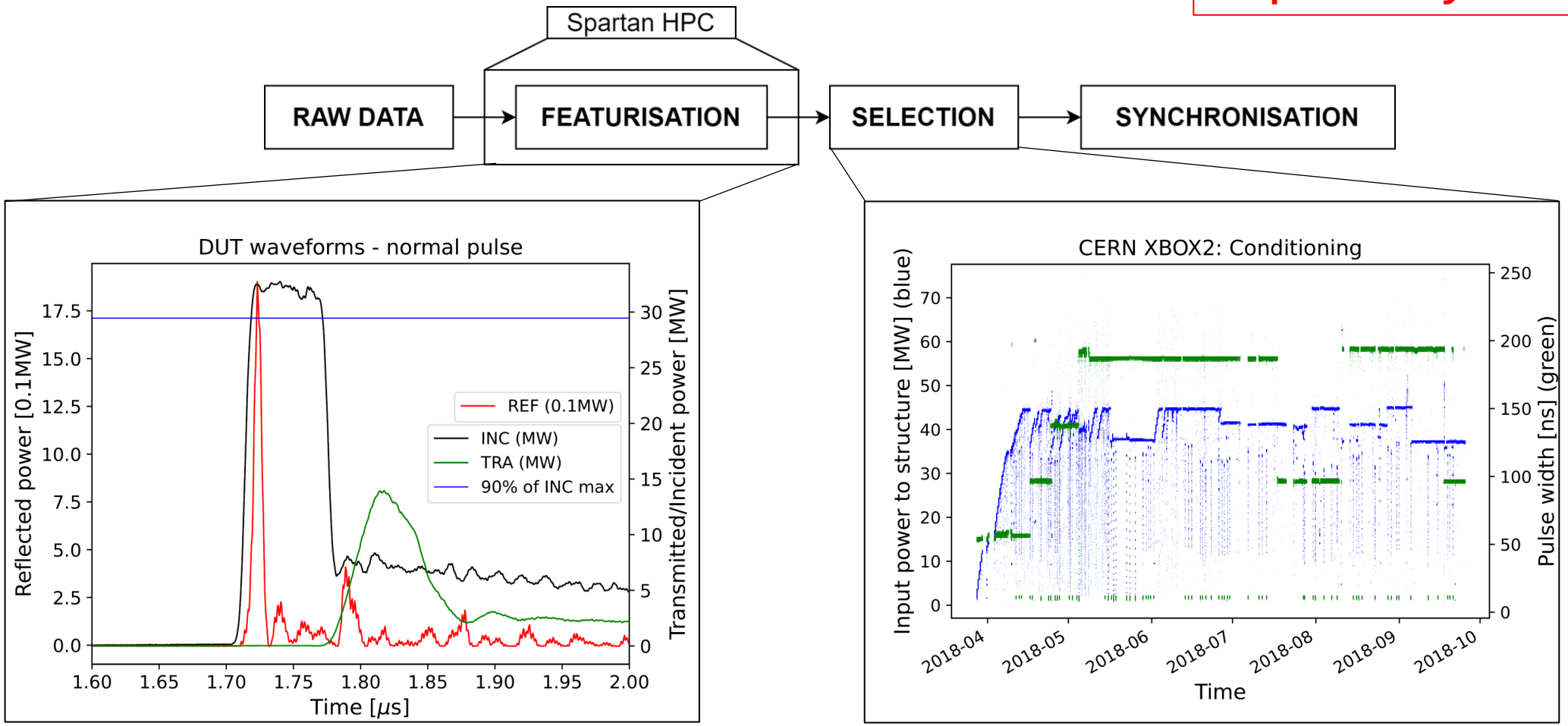
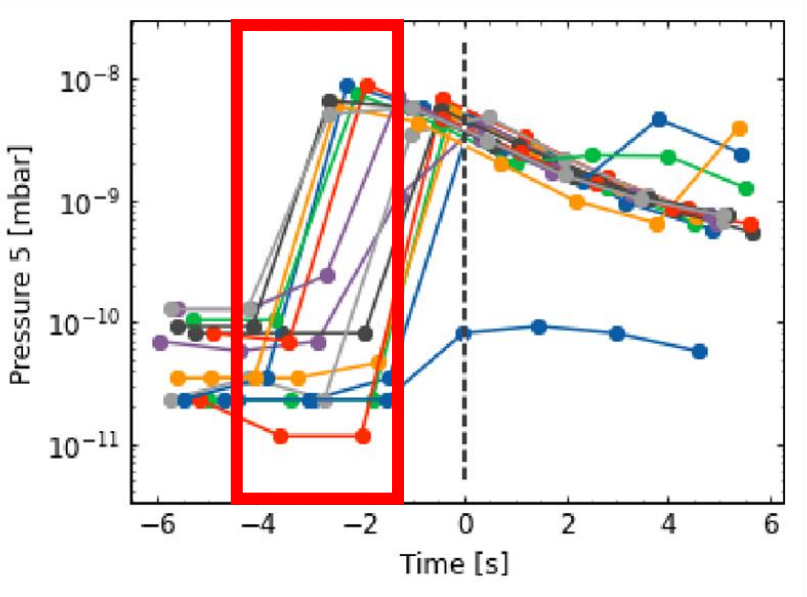


Data processing pipeline

Pressure and BD data stored separately!



Pressure signals around BD, Obermair et. al.

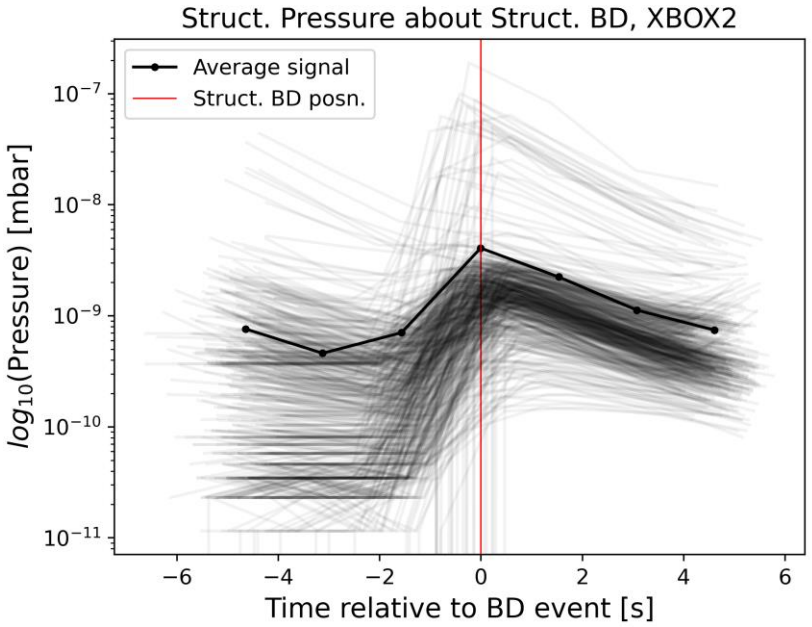


Obermair

Contradiction

Our results

No pressure rise @ -4s!



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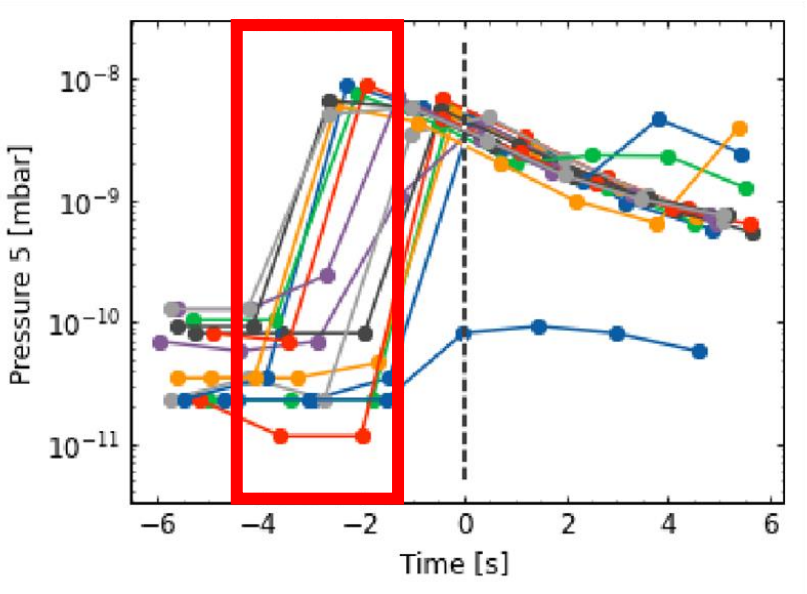

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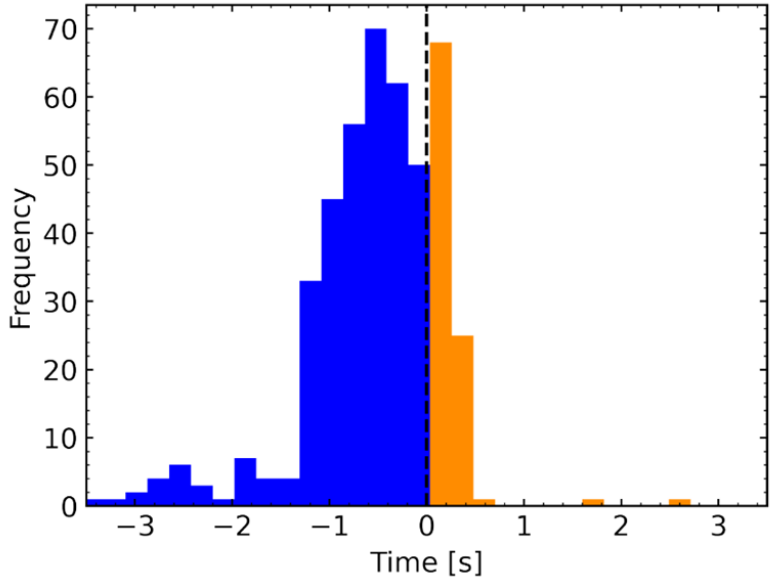
Pressure spike position relative to BD posn.



76.7% Pre-BD Spikes!

Our results

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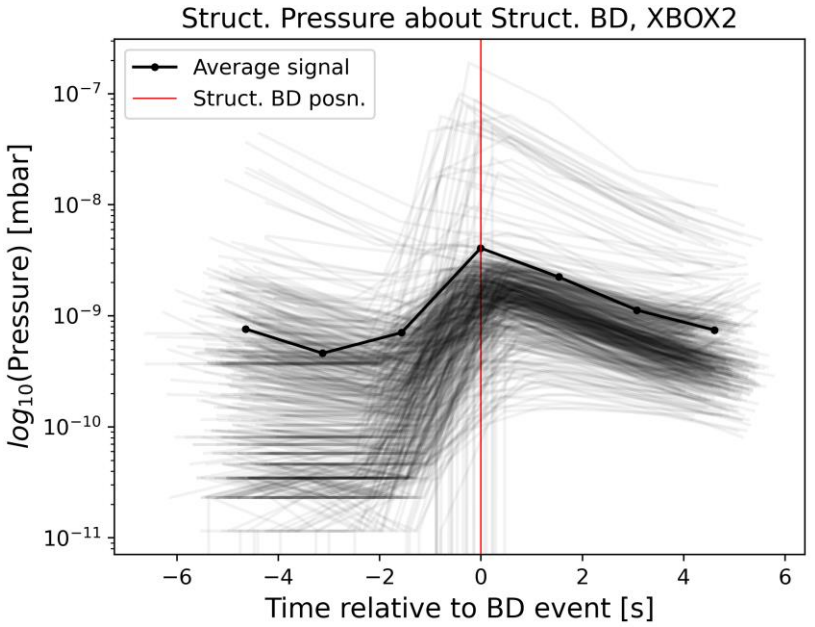
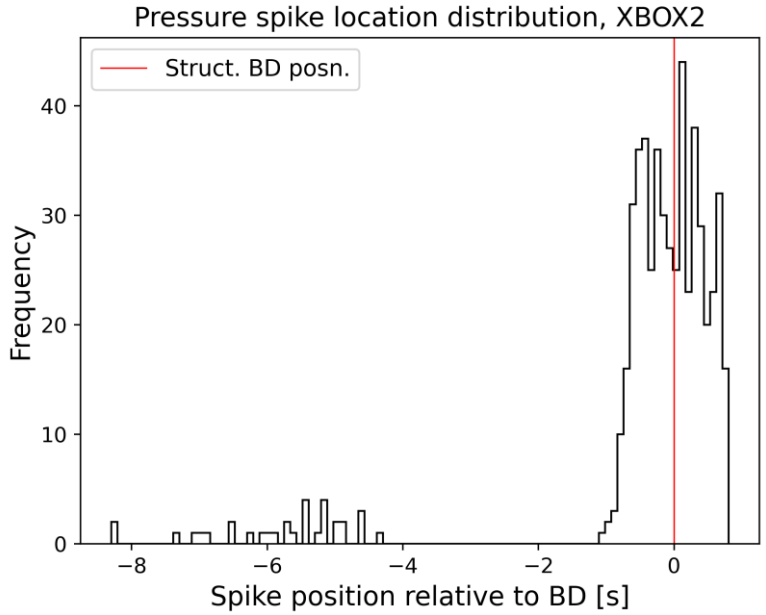
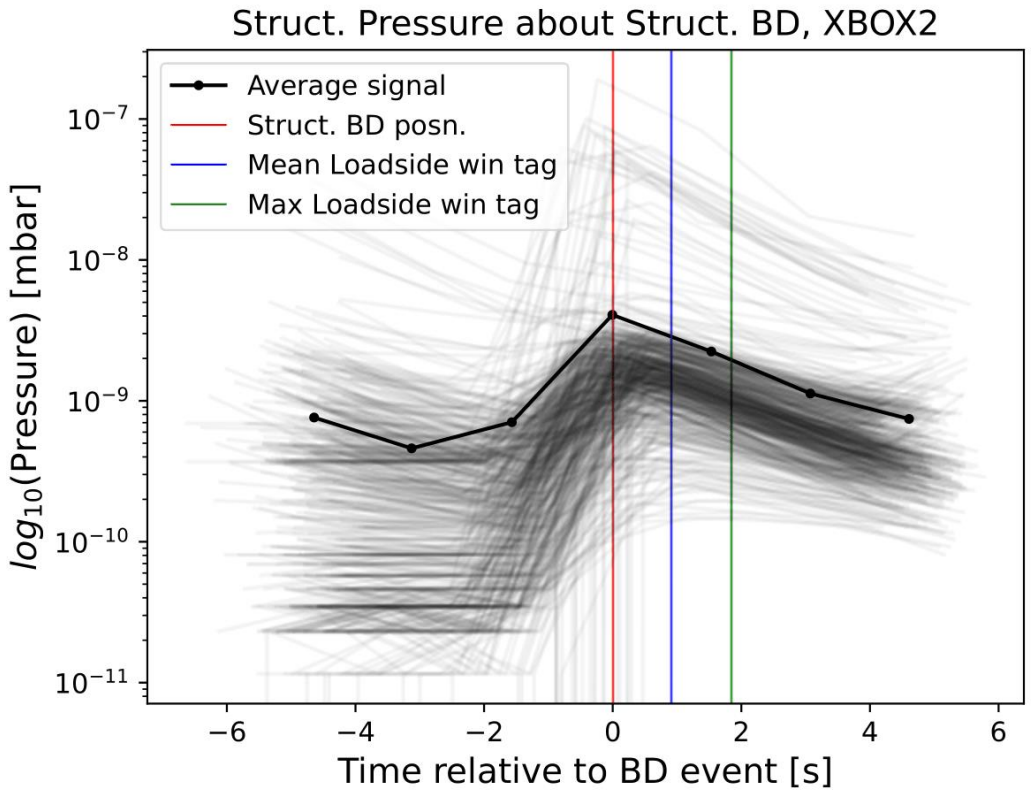


51.7% Pre-BD Spikes!



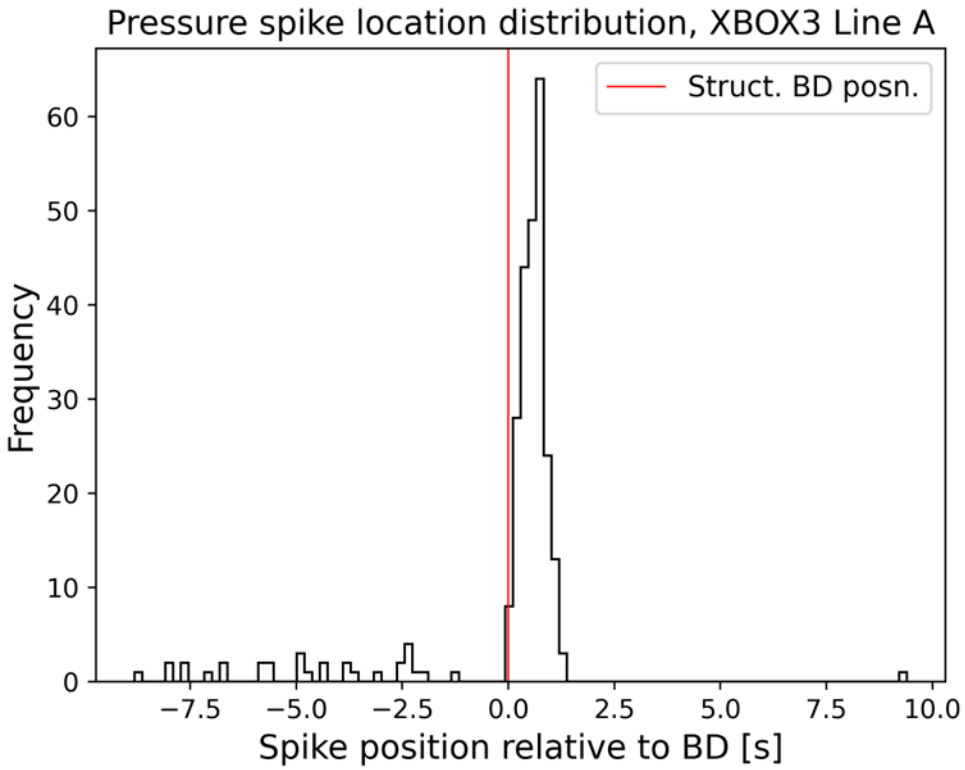
Beware asynchronous acquisition!

- Obermair BD timestamp lags BD
- Spikes seem as if prior to BD
- Engineered correlation
- Explains ML performance
  - Suspend deployment!



Outlook

- Improved time resolution
  - Experiments planned at CERN
- Timescale of pressure response?
- Dark current?
  - Faster response
  - No syncing required
  - Underway at CERN (watch this space!)
  - Jitter alignment, pre-processing techniques



Takeaways

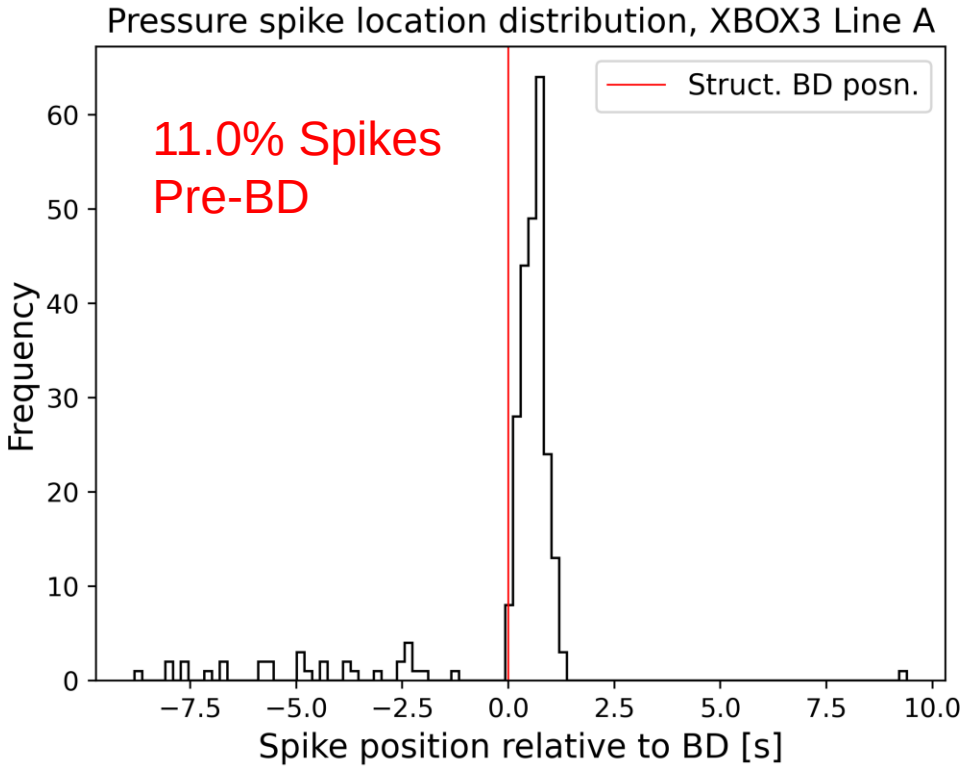
- Asynchronous data acquisition discouraged (where possible)
- Diligent synchronisation
- Systematic errors in data preparation
- Hindrance to deployment of ML routines
- Lively intersection of disciplines! Watch this space

- Thank you to Geoff, Matteo, Scott, Rebecca and Suzie!

Bonus slides

Implications of result

- Pressure still an important BD observable
- Awaits improved time resolution
  - Microsecond resolution for plasma evolution
  - Previously unexplored
- Timescales of pressure response to BD?
- Machine Learning a fickle friend!
- Future investigations benefit

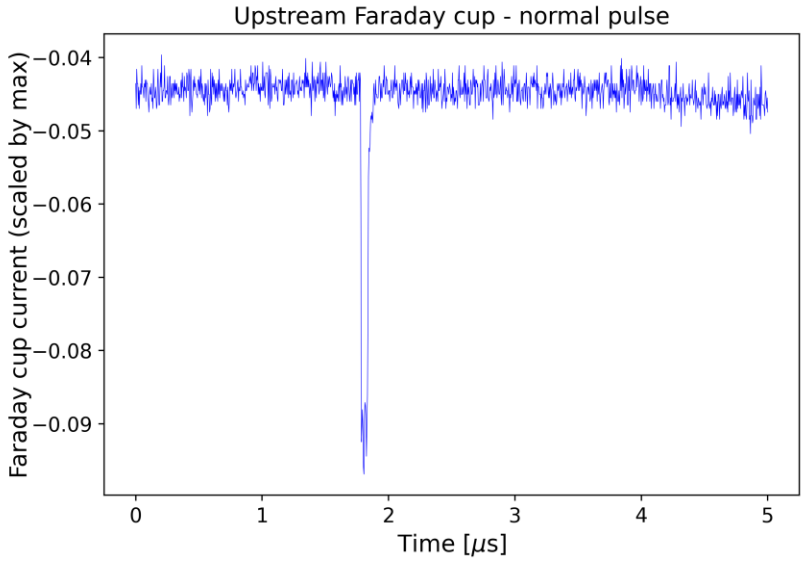


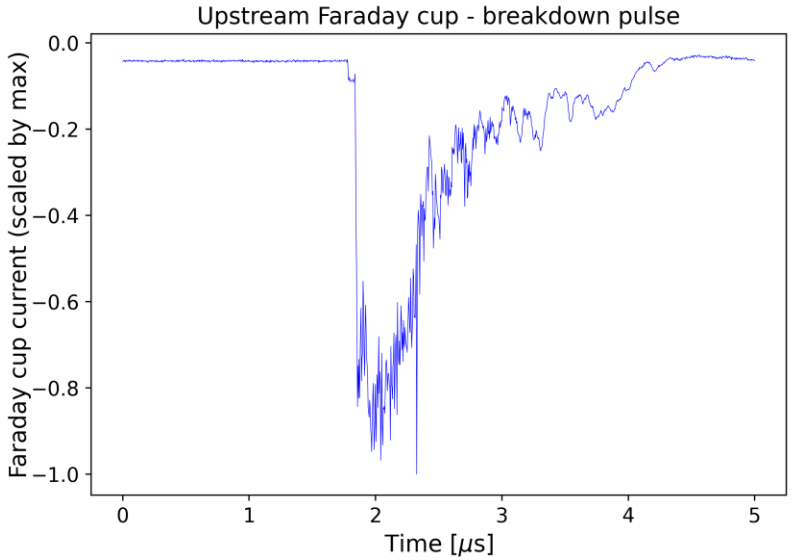
Dark current studies – future work

- Syncing problems absent in dark current based analysis
- CNN performance still poor on prediction with dark current
- Possible improvements
  - Use of physics informed, domain-specific pre-processing
  - Oscilloscope jitter reduction, signal smoothing
  - Focus on dark current signals, reduce dimensionality
- Leveraging ADC acquisition imperfection (< 20ms)
- Dark current preferred due to faster response timescales

Breakdown detection

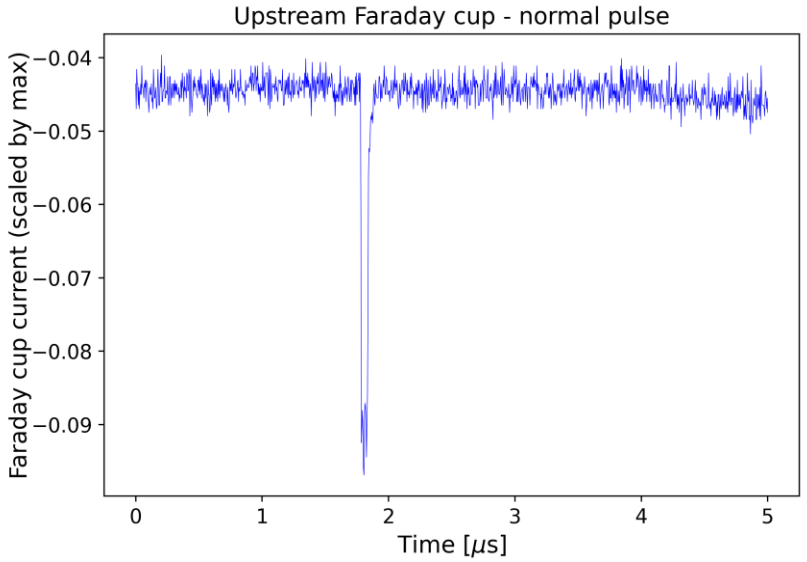
- Magnitude of reflected power

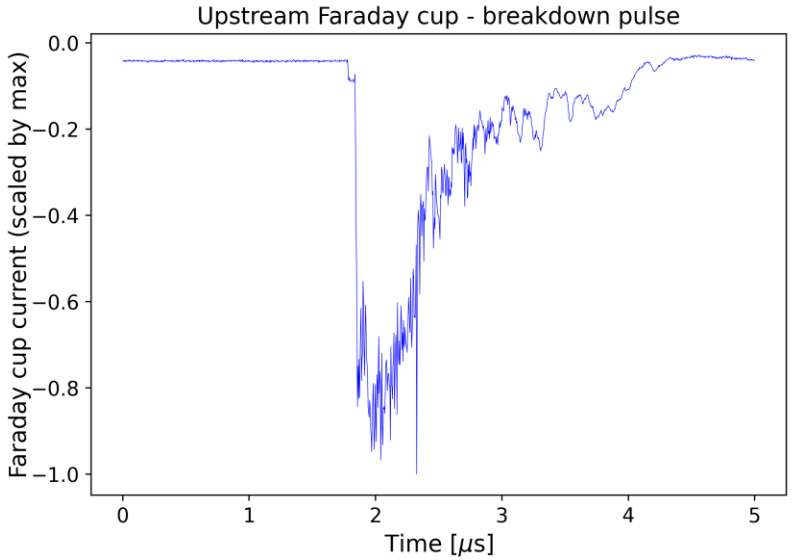




Breakdown detection

- Magnitude of reflected power
- Dark current emission
  - Emission always present
  - Pronounced for BD events





Breakdown detection

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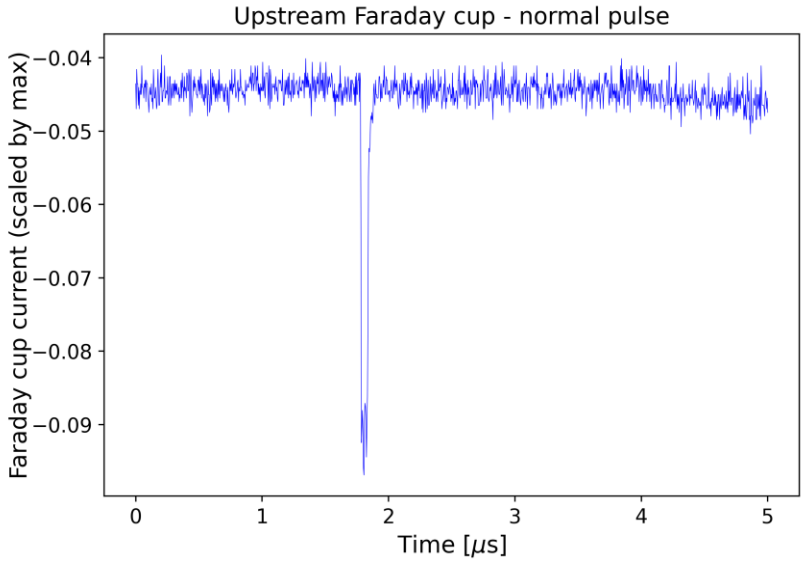
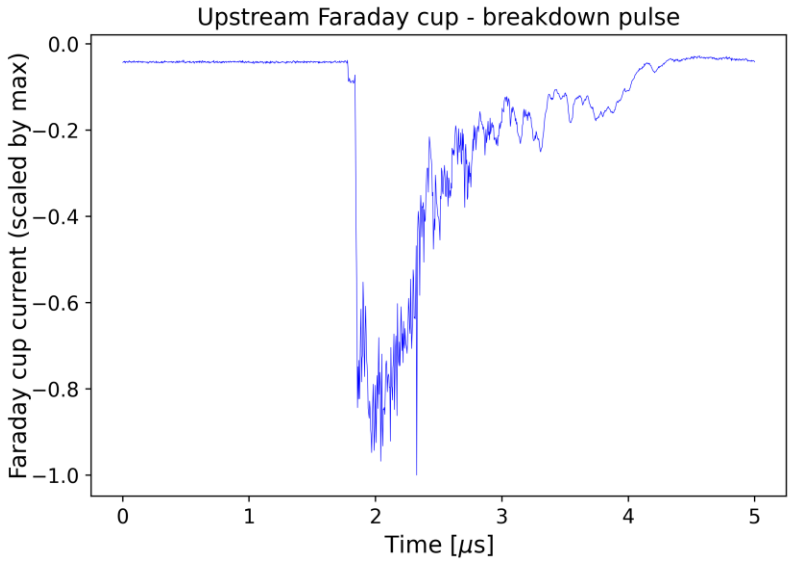
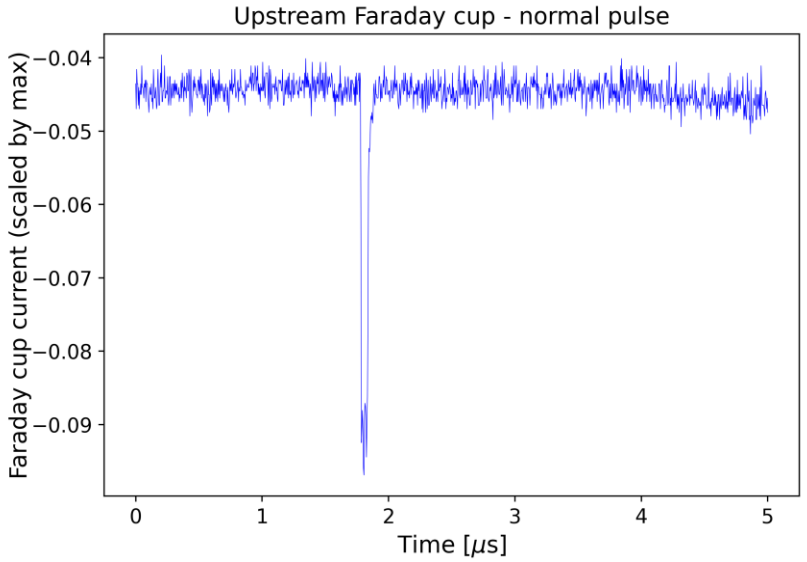
- Pressure thresholds (10^{-5} ,10^{-7} mbar)

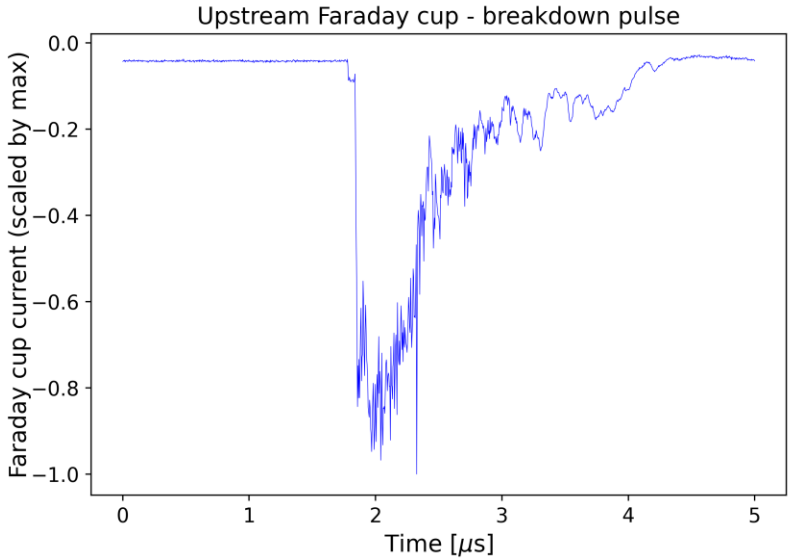


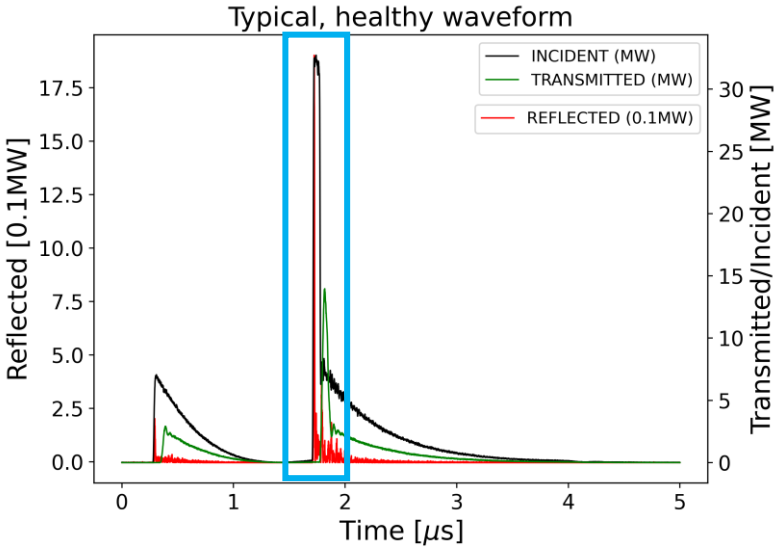


Breakdown detection

- Magnitude of reflected power
- Dark current emission
  - Emission always present
  - Pronounced for BD events
- Pressure thresholds (10^{-5} ,10^{-7} mbar)
- Test stand interlocking
- Response timescales

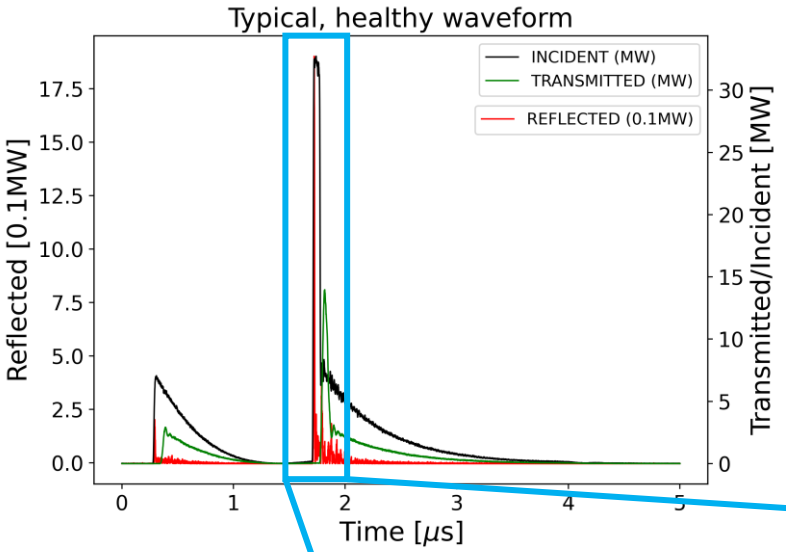


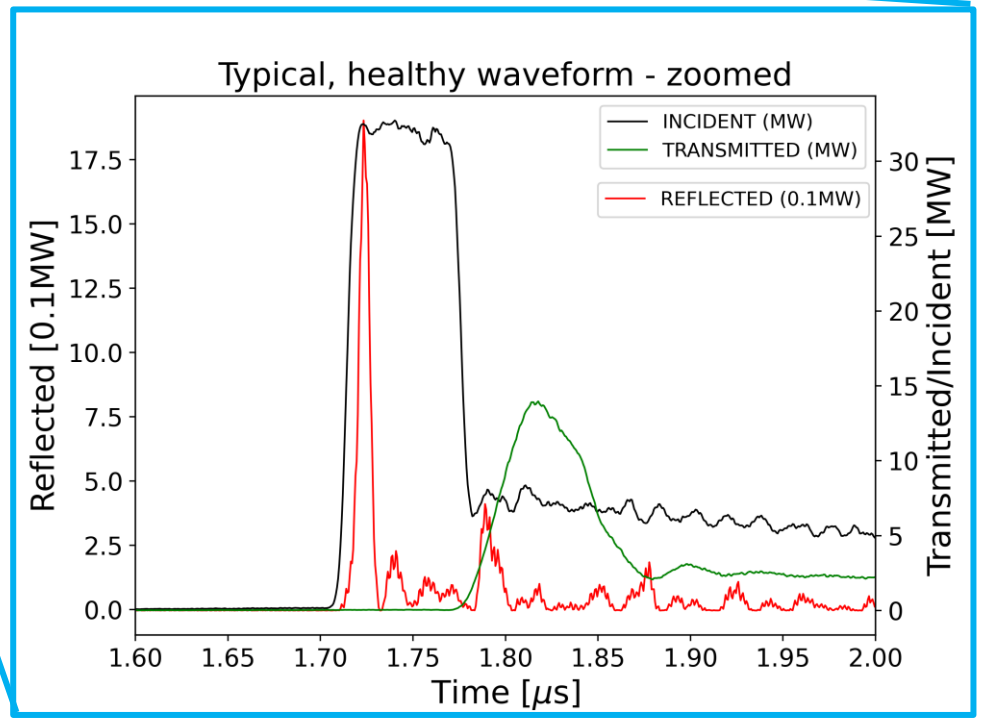




Test stand data output, RF waveforms

- 0.625ns sampling, 12-bit resolution
- Plasma, short-circuit, reflection
- Useful for filtration of breakdown data





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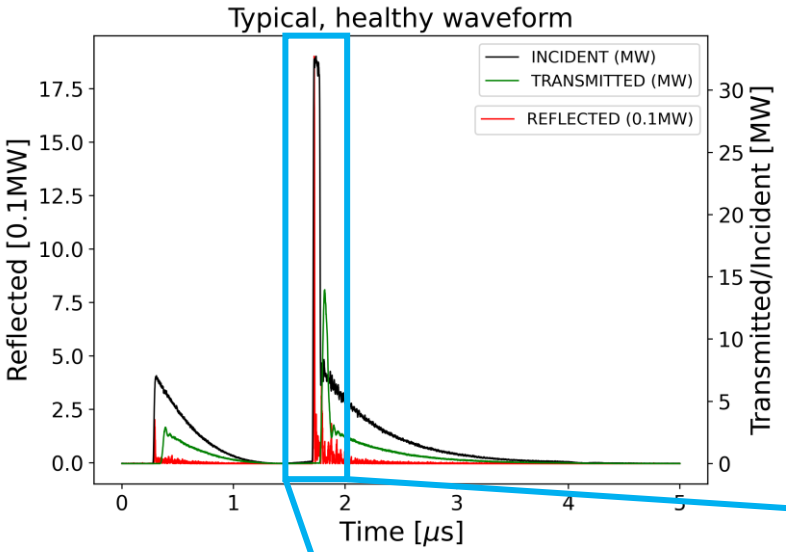
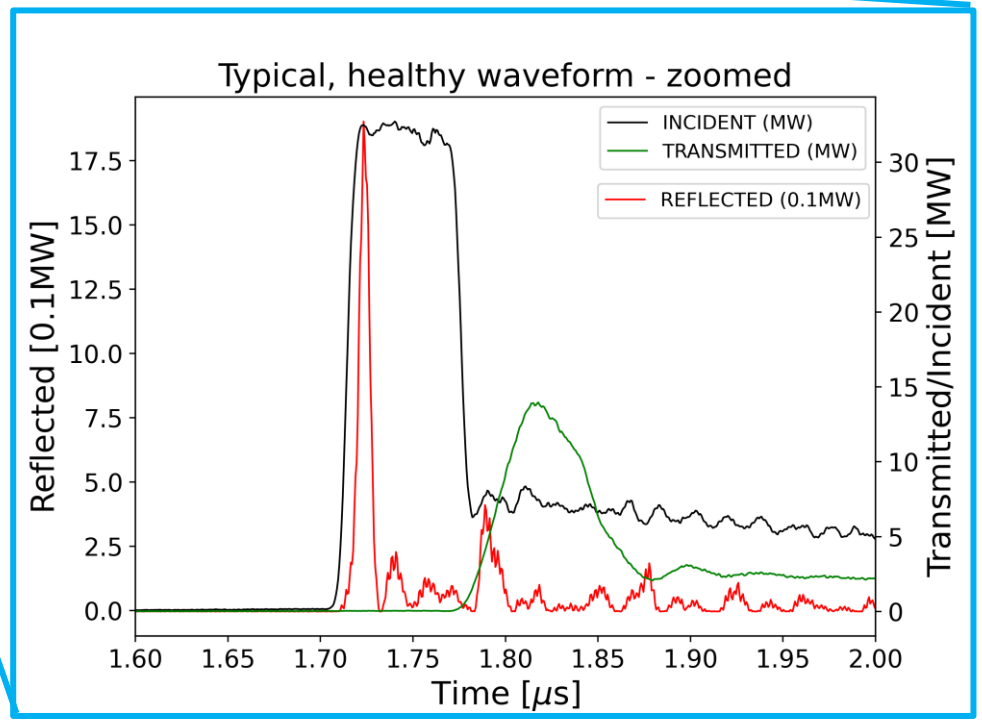
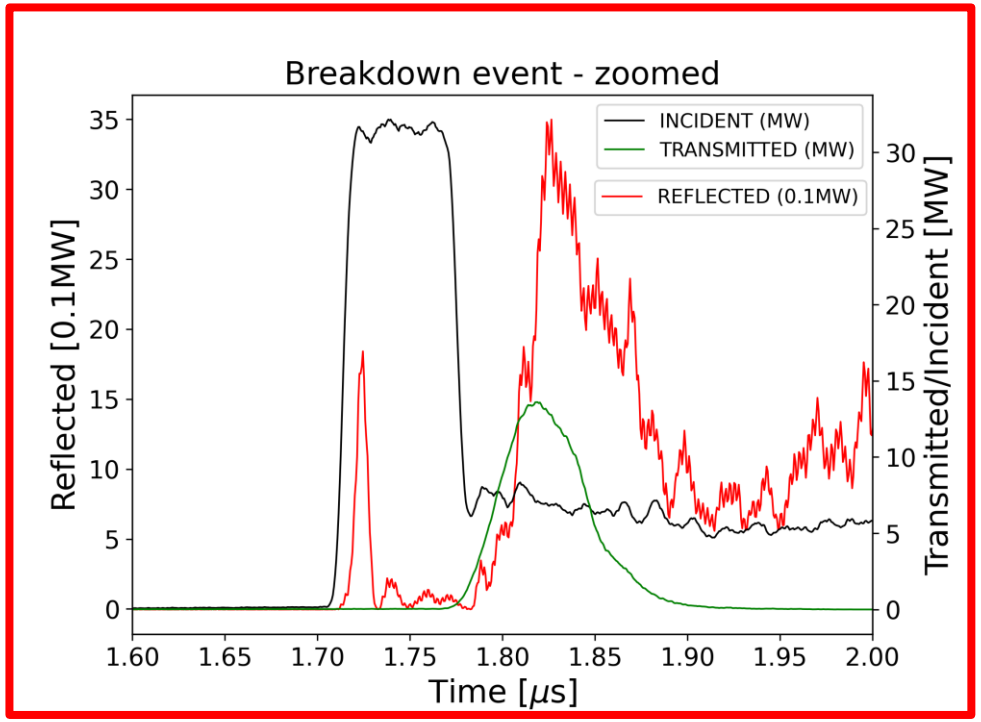
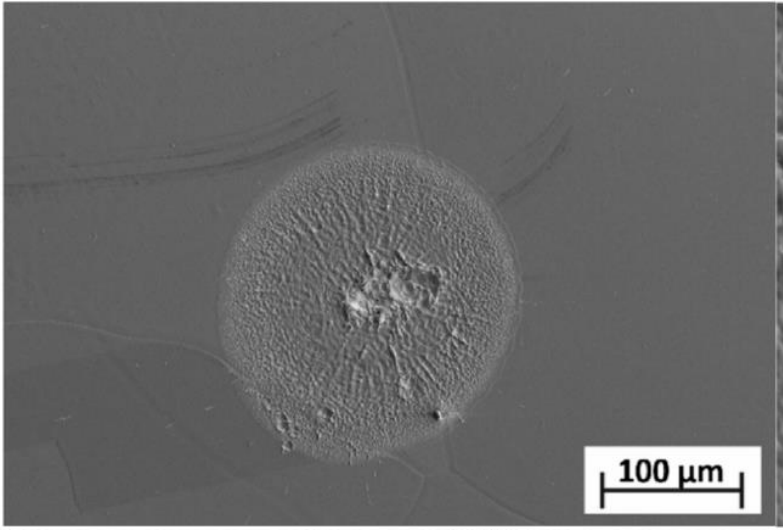
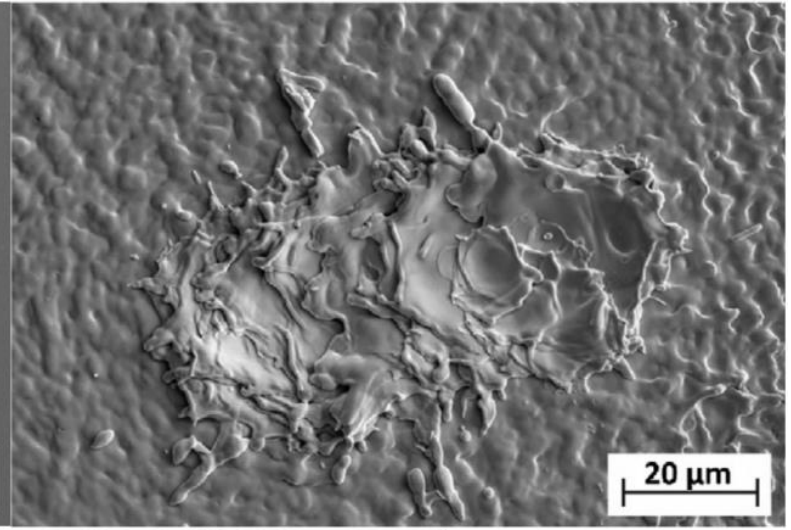










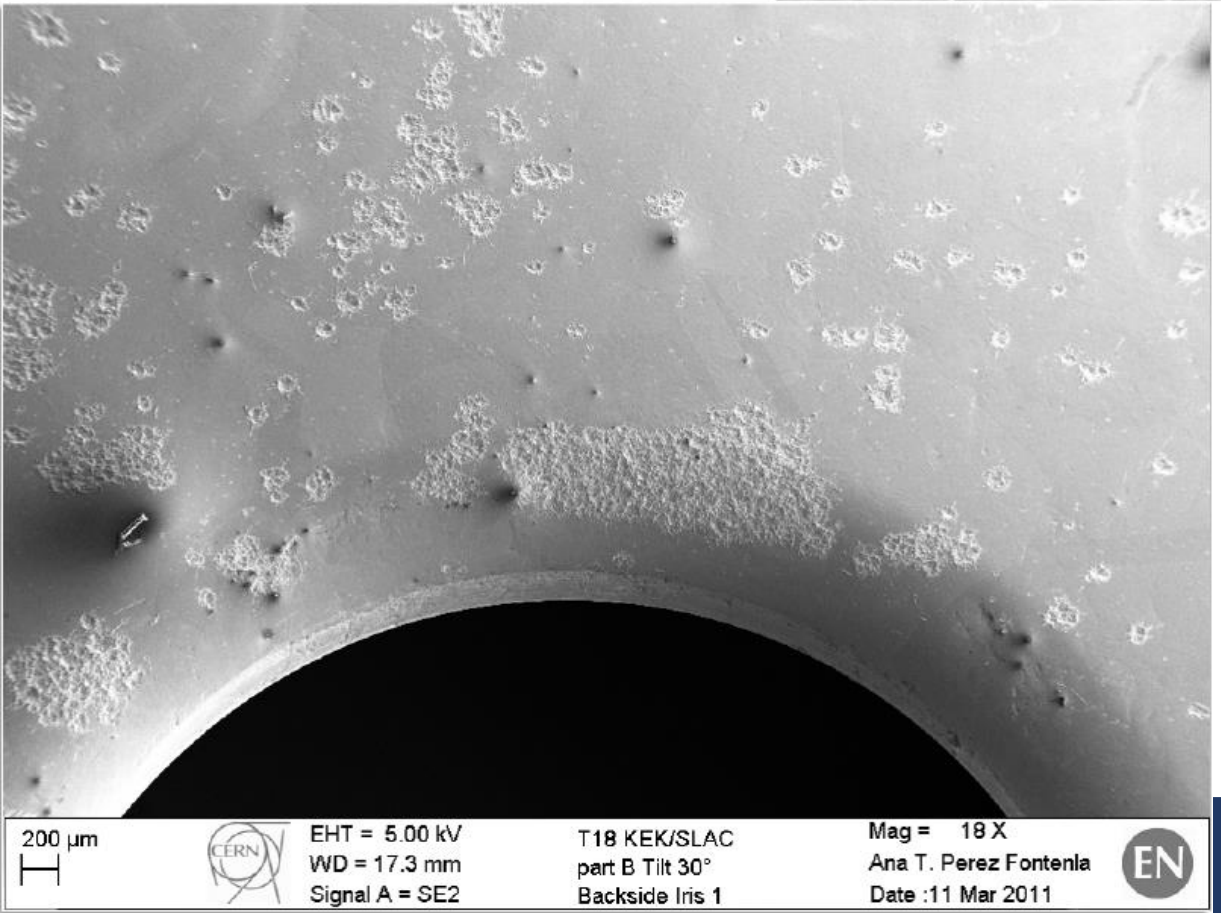
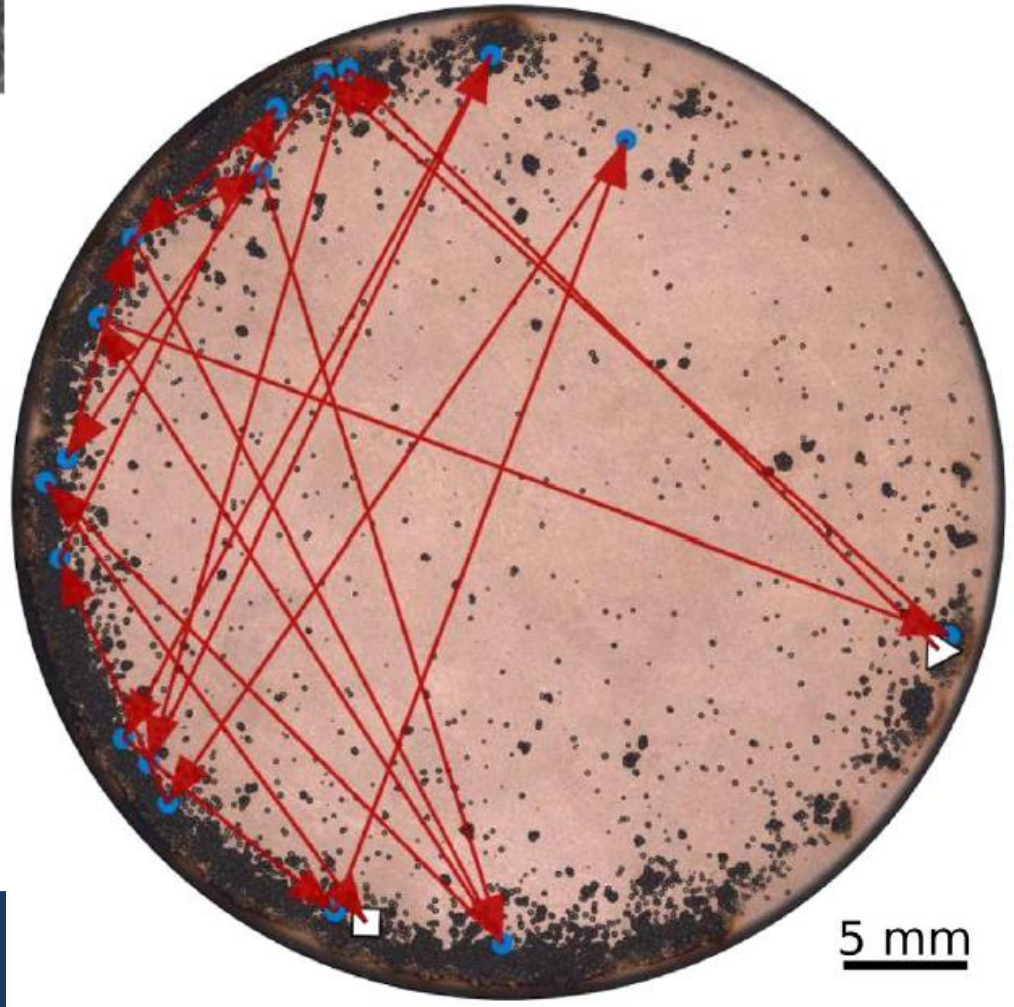
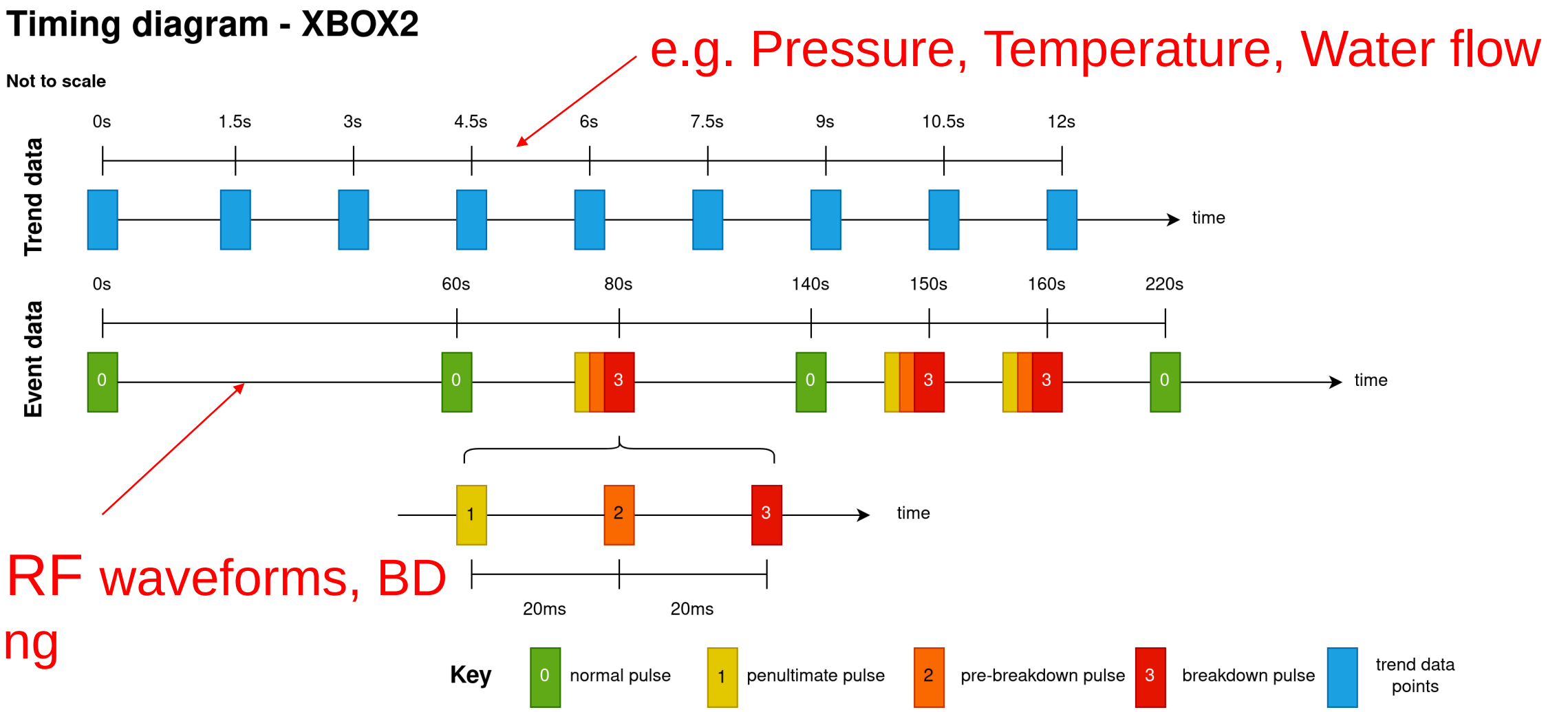


Image attribution: (anti-clockwise from top)

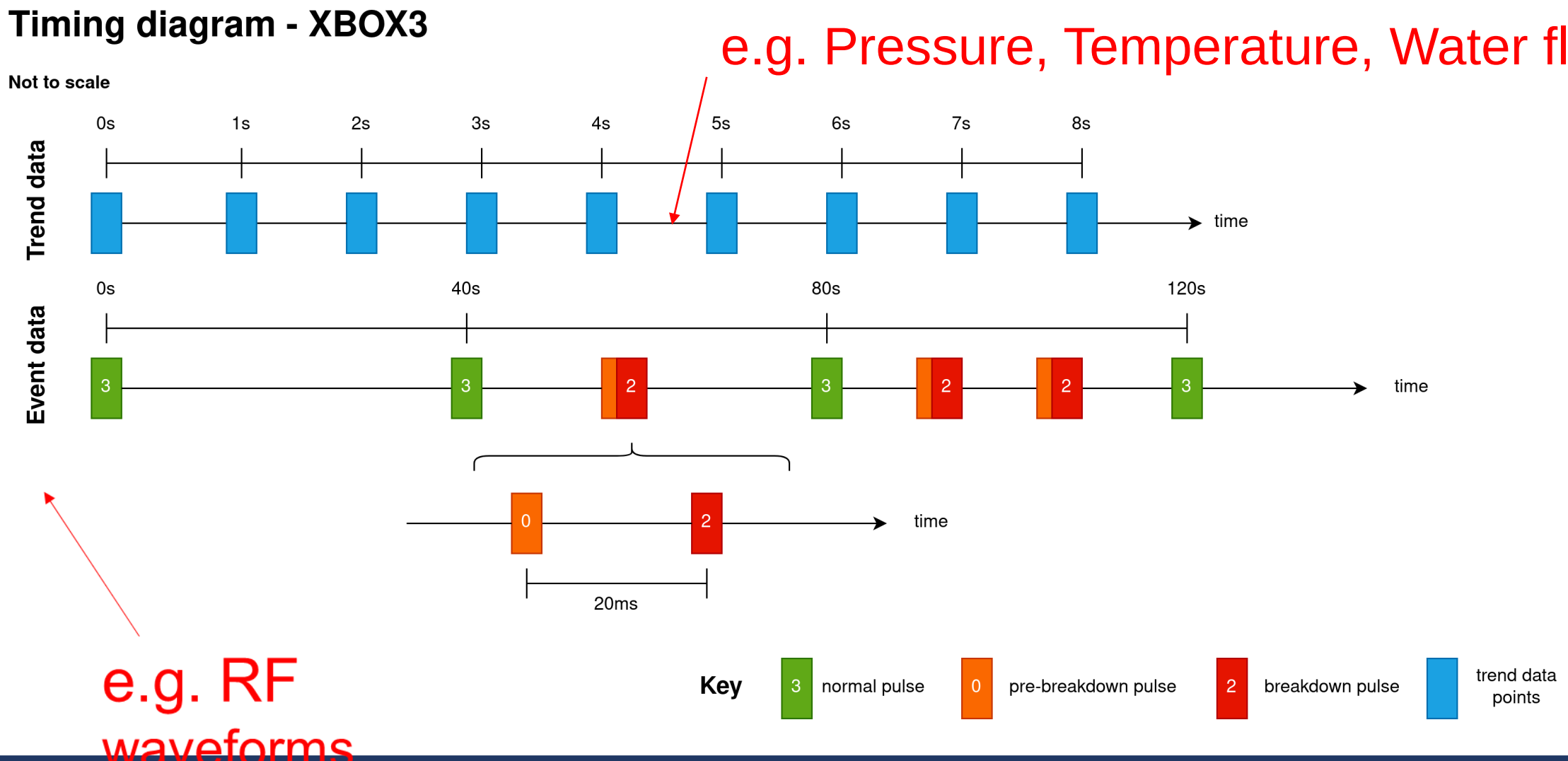
- I. Profatilova et. al. *NIMA* 953 (2020)
- A. P. Fontenla, *CLIC Workshop Geneva* (2015)
- A. Saressalo et. al. *PRAB* 23, 023101 (2020)



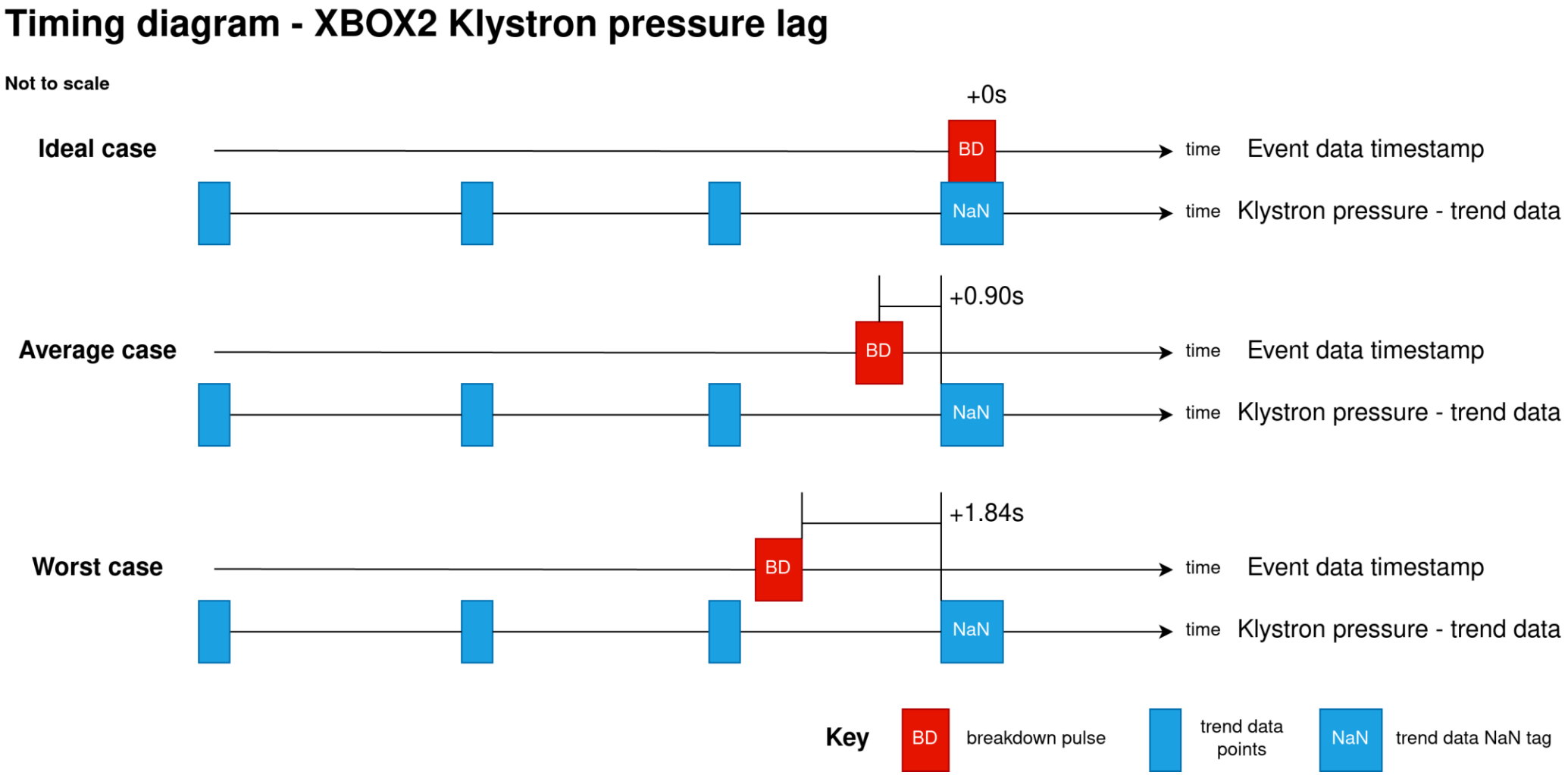
Breakdown data acquisition, XBOX2



Bonus slide -- Breakdown data acquisition, XBOX3

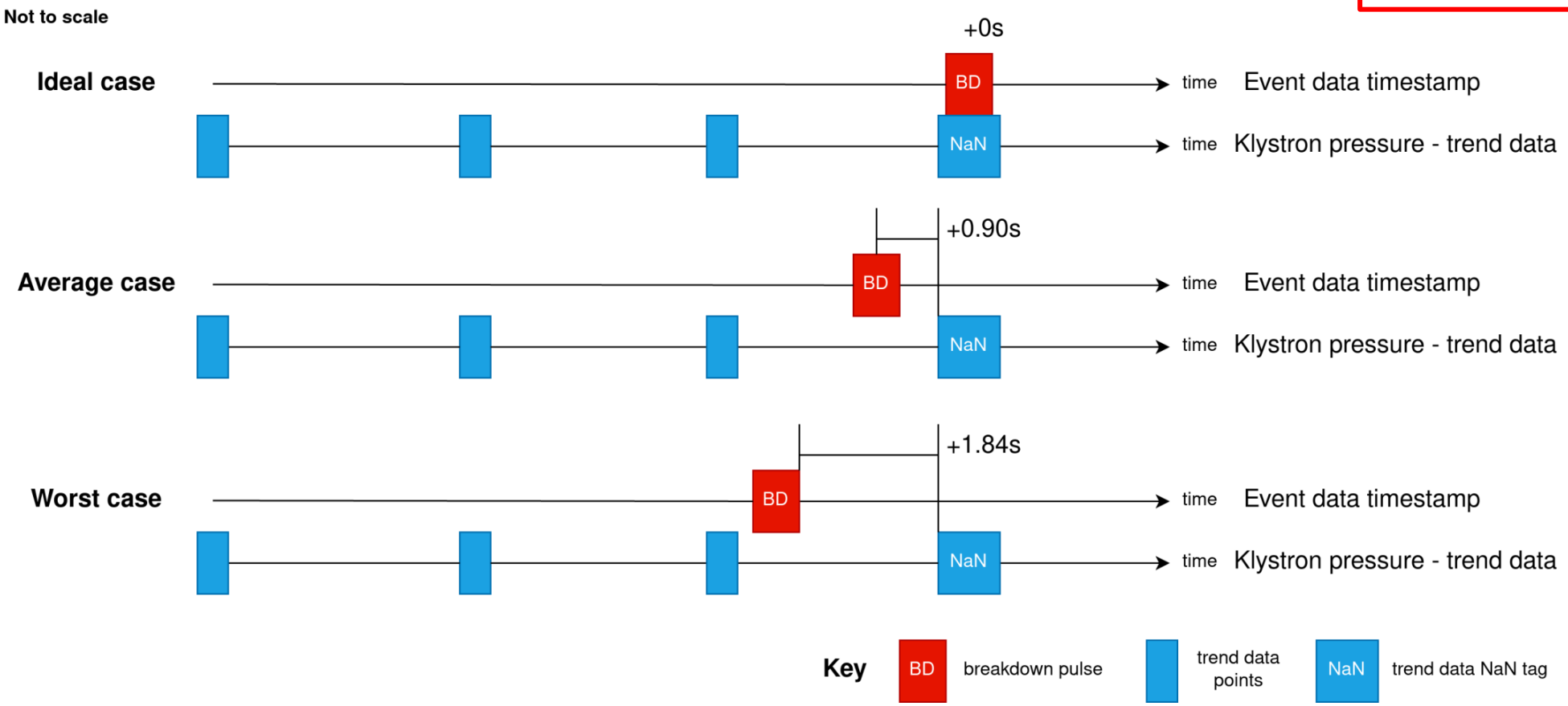


Reasons for Obermair contradiction



Reasons for Obermair contradiction

- Additional bug: np.searchsorted()
  - Opaque synchronisation method
  - Off-by-one error
  - Read documentation!

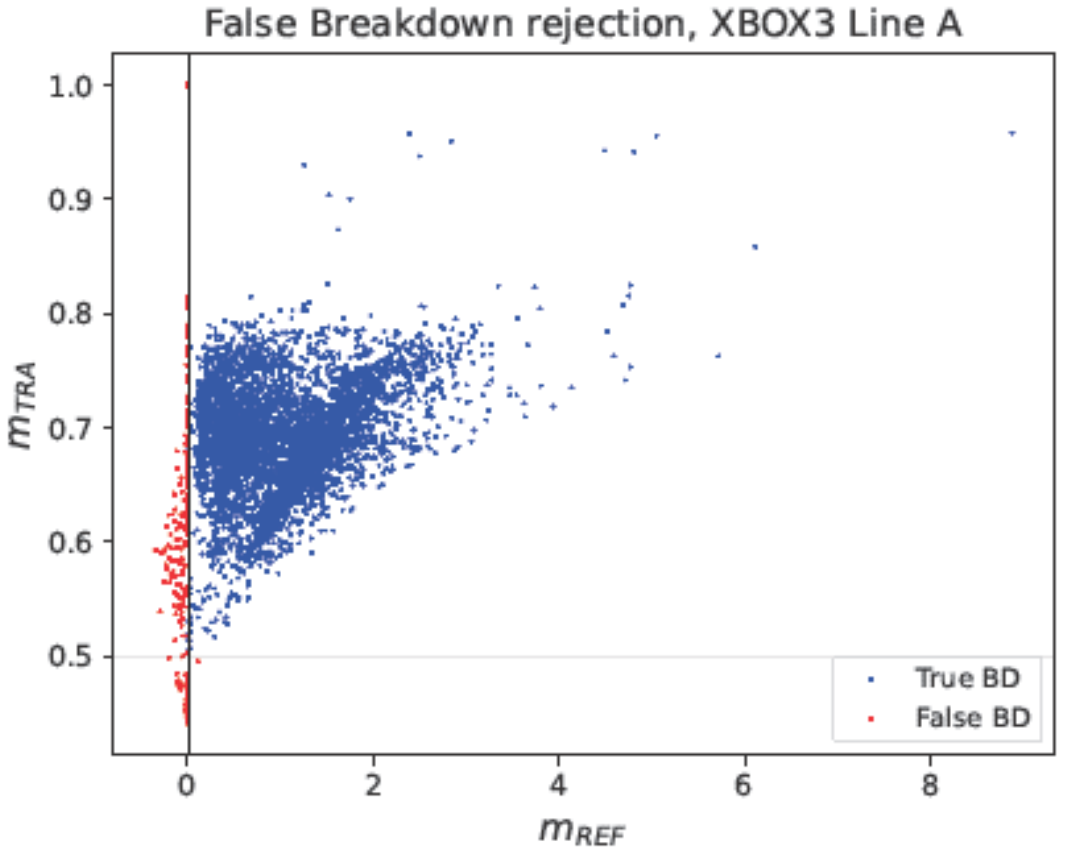


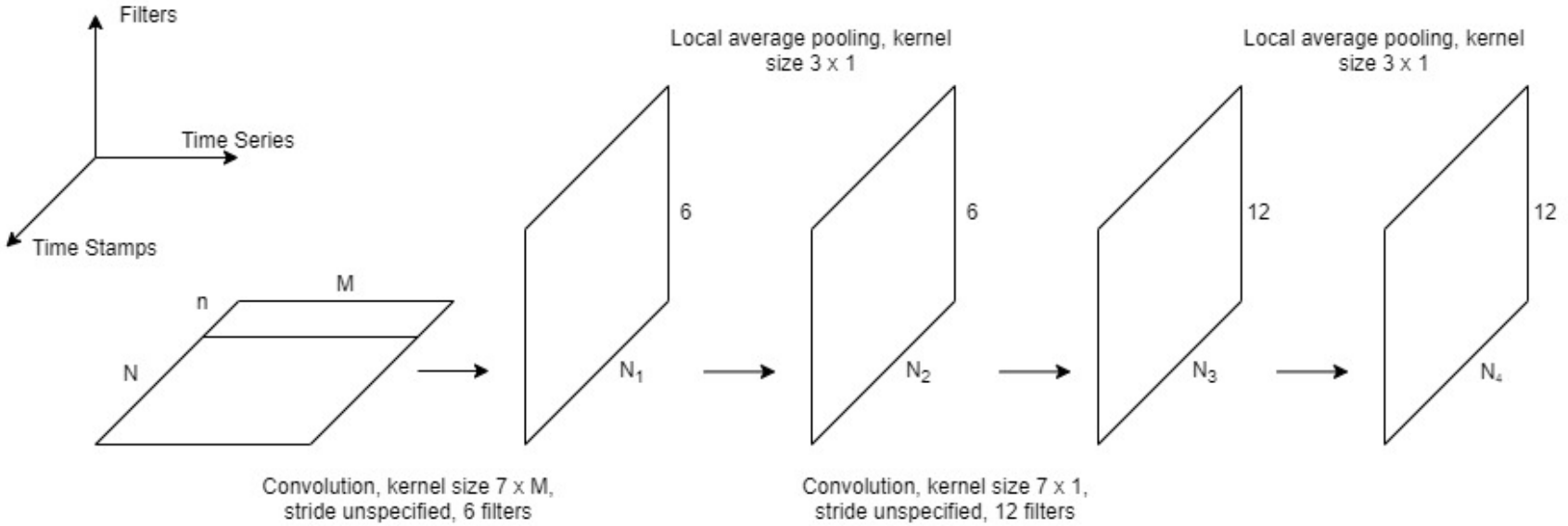
Bonus slide – probing pressure at high res.

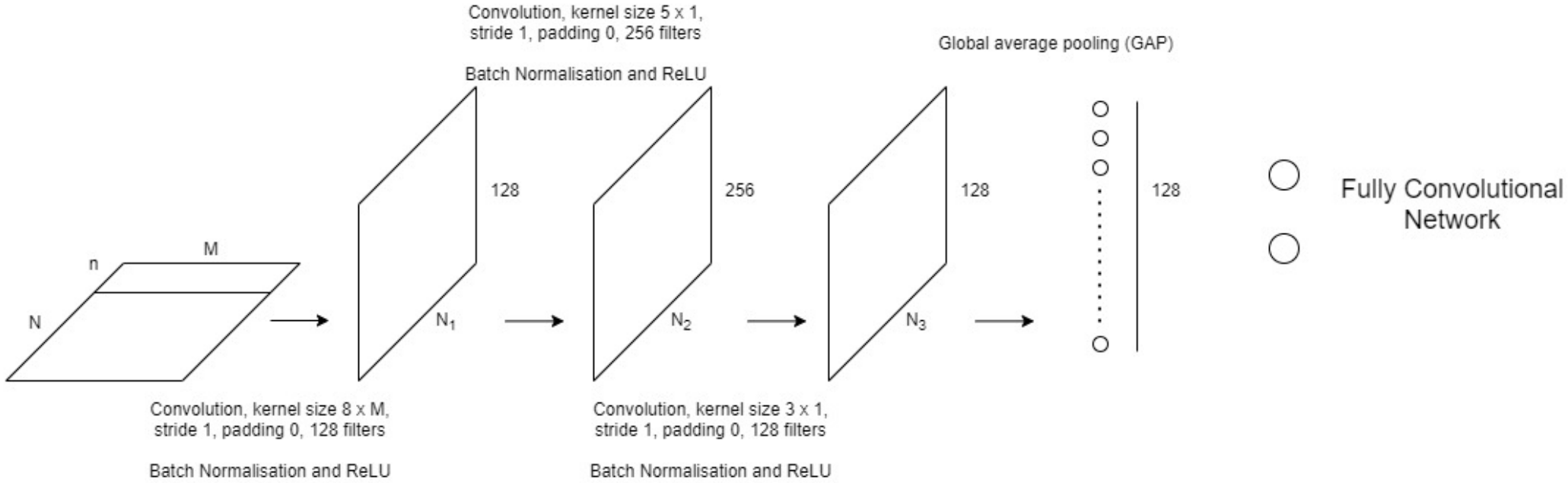
- Higher resolution for pressure analyses enabled by:
  - National Instruments PXIe-6363 X-series DAQ
  - 32 analogue signals each at 16-bit resolution
  - 1 MSPS ➔ Microsecond resolution
- One-off experiment, not for interlocking or control
- Redirecting electronics to high resolution oscilloscope
- Re-calibrating Reflected power signal
- Dark current spectrometer
- Residual Gas Analyser (RGA)

Bonus slide – False BD rejection

- $m_{TRA} = \frac{U_{INC}-U_{TRA}}{U_{INC}+U_{TRA}} \rightarrow 0$ for non-BD events
- $m_{REF} = \frac{U_{INC}+U_{REF}}{U_{INC}-U_{REF}} - 1 \rightarrow 0$ for non-BD events
- Can apply cuts to m_{TRA} and m_{REF} accordingly
- Discard non-BD events using "missing energy" approach




Filters
Time Series
Time Stamps
n
M
N
Local average pooling, kernel size 3 x 1
Local average pooling, kernel size 3 x 1
6
6
12
12
N_1
N_2
N_3
N_4
Convolution, kernel size 7 x M, stride unspecified, 6 filters
Convolution, kernel size 7 x 1, stride unspecified, 12 filters
Time-CNN


Convolution, kernel size 5 x 1, stride 1, padding 0, 256 filters
Batch Normalisation and ReLU
Global average pooling (GAP)
n
M
N
128
256
128
128
N_1
N_2
N_3
Convolution, kernel size 8 x M, stride 1, padding 0, 128 filters
Batch Normalisation and ReLU
Convolution, kernel size 3 x 1, stride 1, padding 0, 128 filters
Batch Normalisation and ReLU
Fully Convolutional Network

Bonus slide -- XAI (Explainable AI)

- Feature importance values
- To make CNNs more transparent
- “SHAP” (SHapley Additive exPlanation) values
- Each neuron assigned a “contribution score”
- Updated on each backpropagation step to inputs
- Inputs assessed on relative “importance”
- Pressure, dark current

Bonus slide – Stochastic protrusion model

- Birth-Death process for dislocation population
- Dislocation (line defects) (mobile vs sessile)
- Critical transition beyond a certain dislocation density defines breakdown onset
- Biased random walker simulations (Kinetic Monte Carlo)
- First passage time to reach critical density
- 100-150ns to protrusion formation