Dark Current Mapping, Fluctuation and Evolution

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CLIC Workshop, CERN

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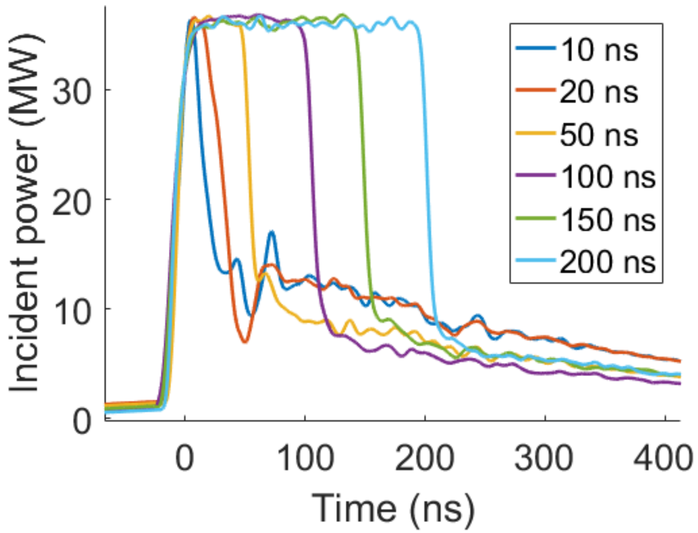
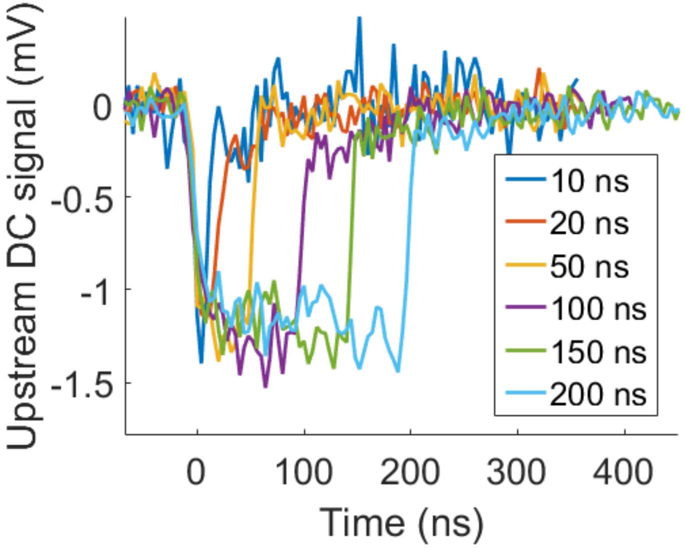
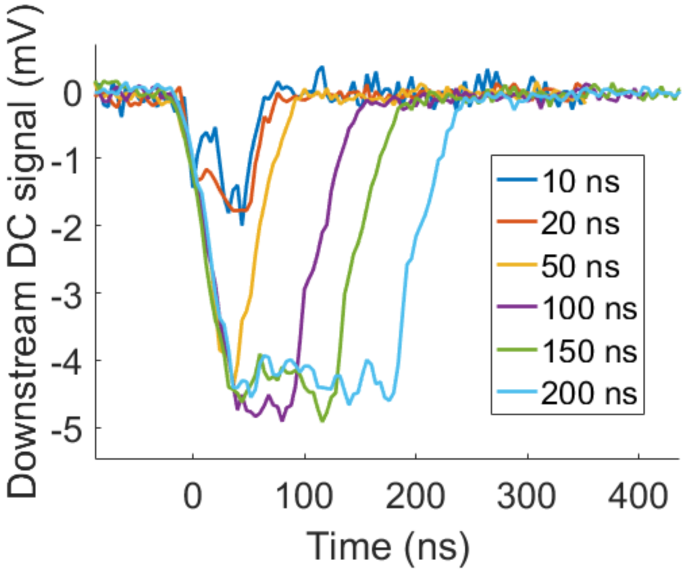
Spatial Measurements

Dark Current vs. RF Pulse Shape

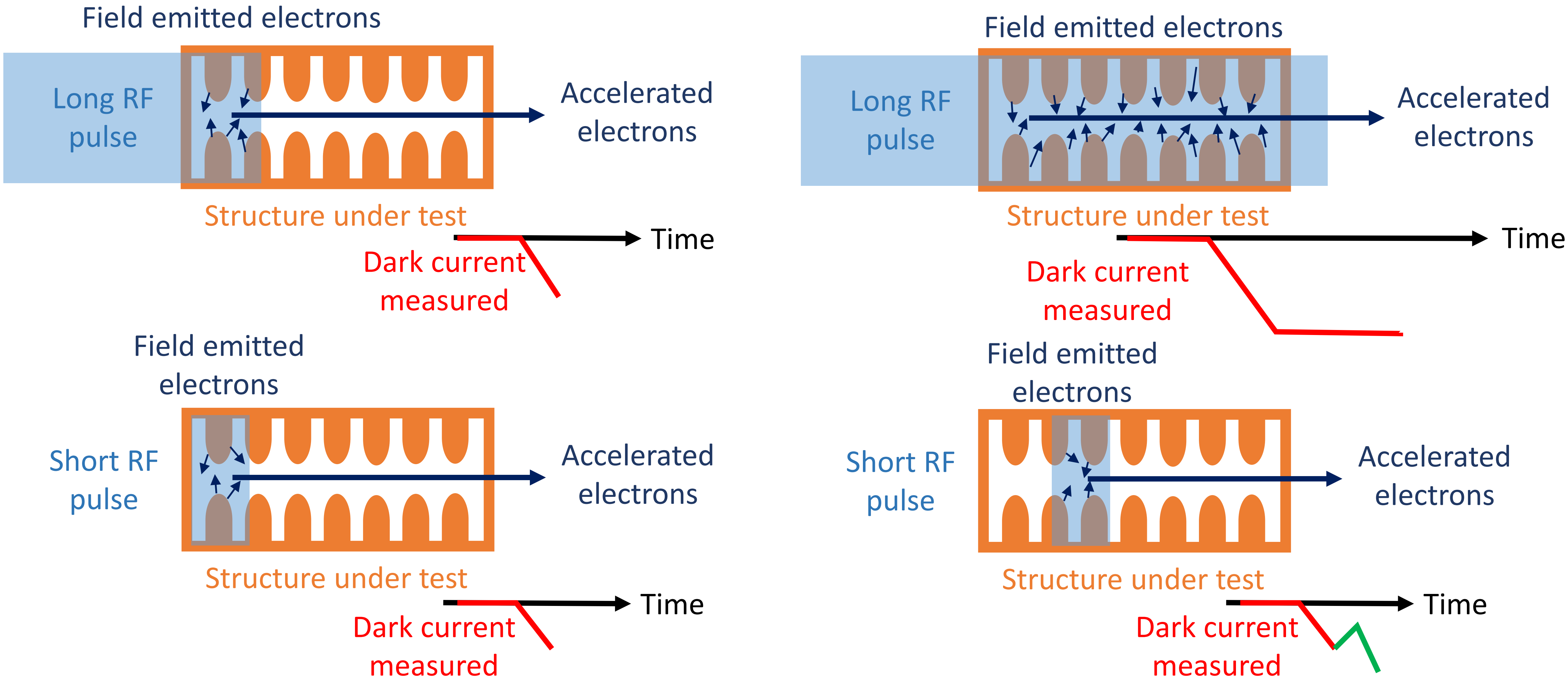






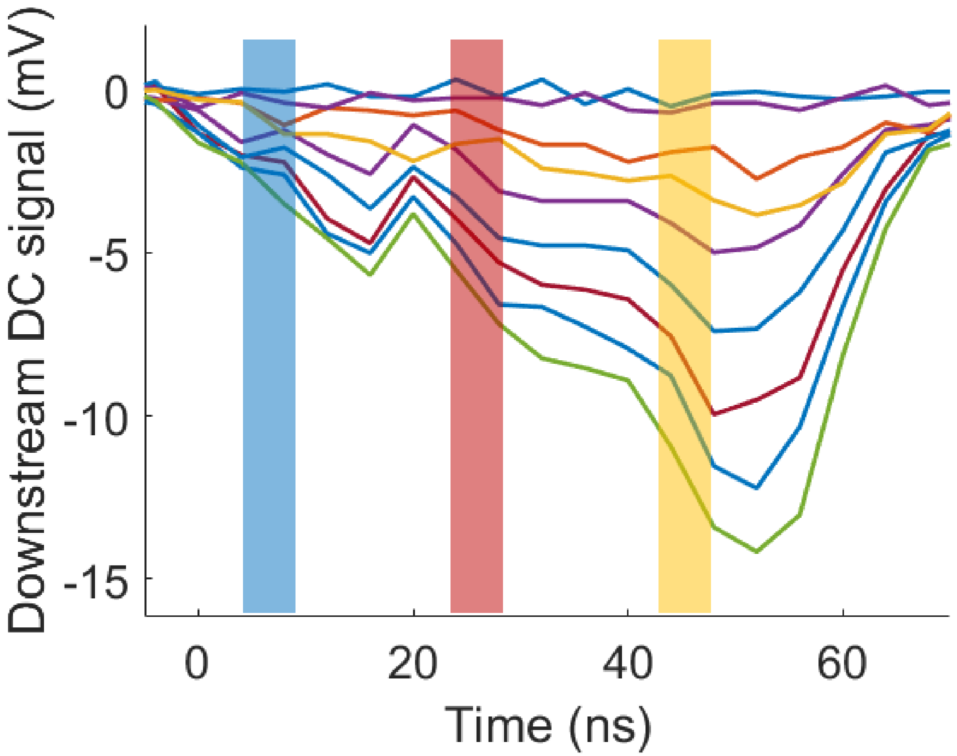
- Dark current measured rises and falls as structure fills and unfills – contains information about different parts of the structure.
- Structures have low group velocity: 0.01…0.02 c.
- Emitted electrons can become relativistic within one cell.
- With long RF pulses, the entire structure emits electrons simultaneously.
- A very short pulse allows field emission to be probed along the structure.

Separating Parts of the Structure in Time

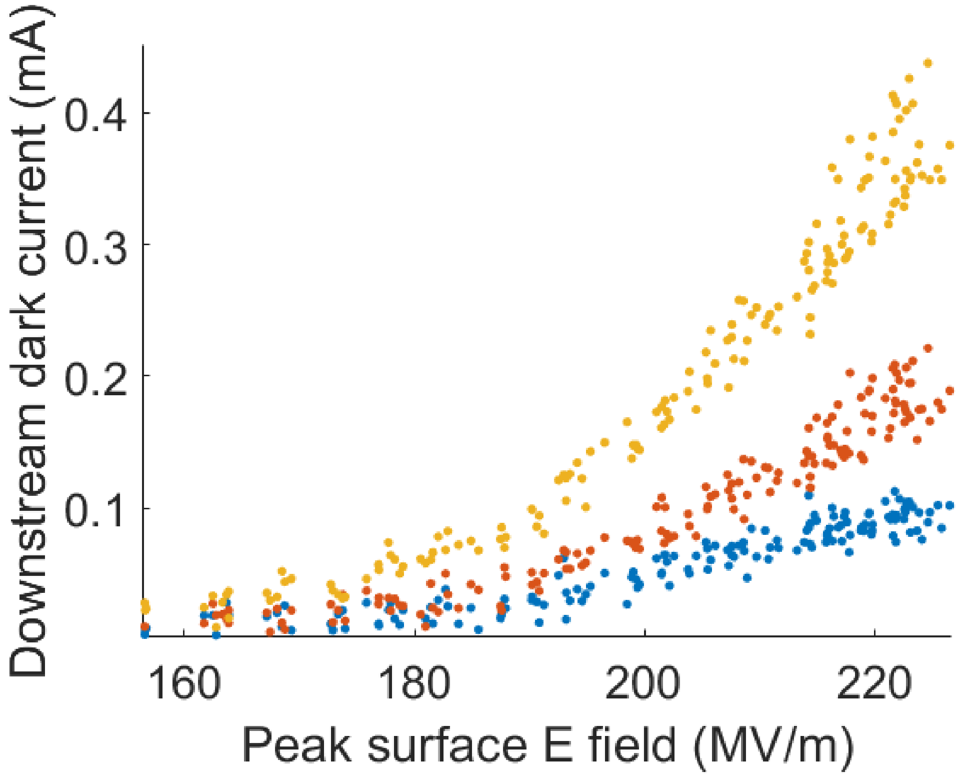


Mapping Field Emission

Dark current power scan with a 10 ns pulse length.

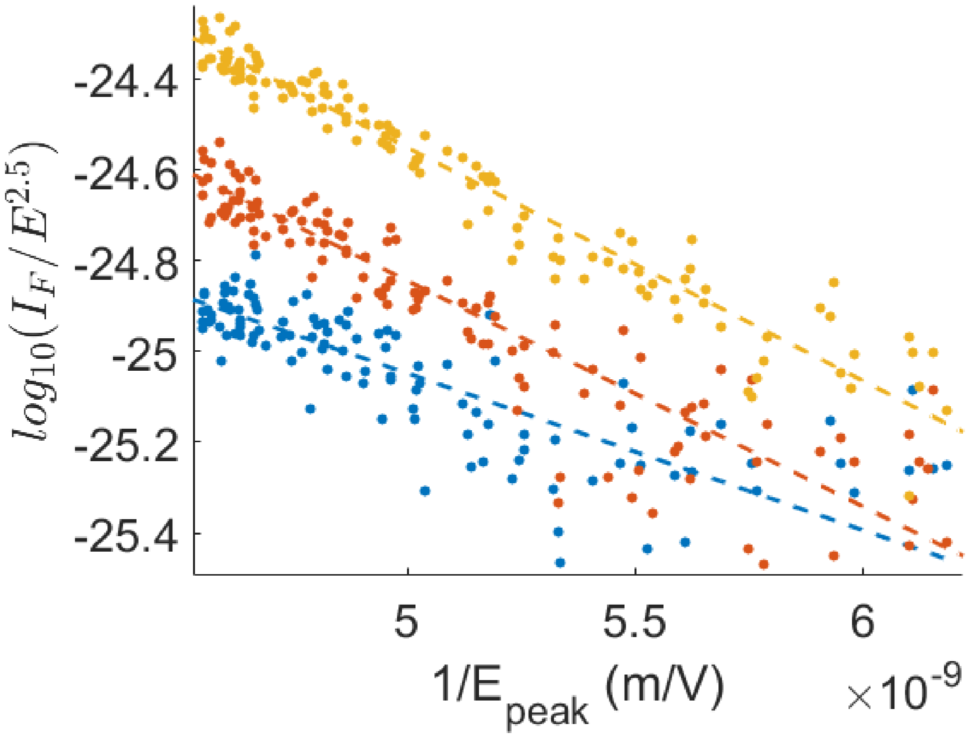


Dark current by sample as a function of surface E-field.



Mapping Field Emission

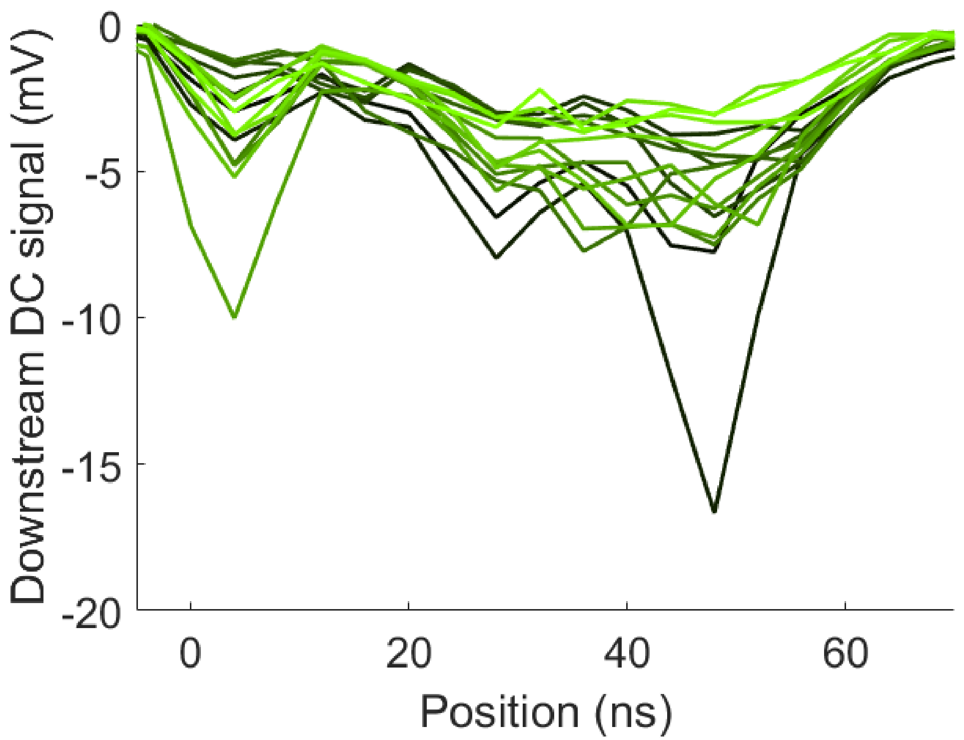
Fowler-Nordheim plot of dark current at each sample.



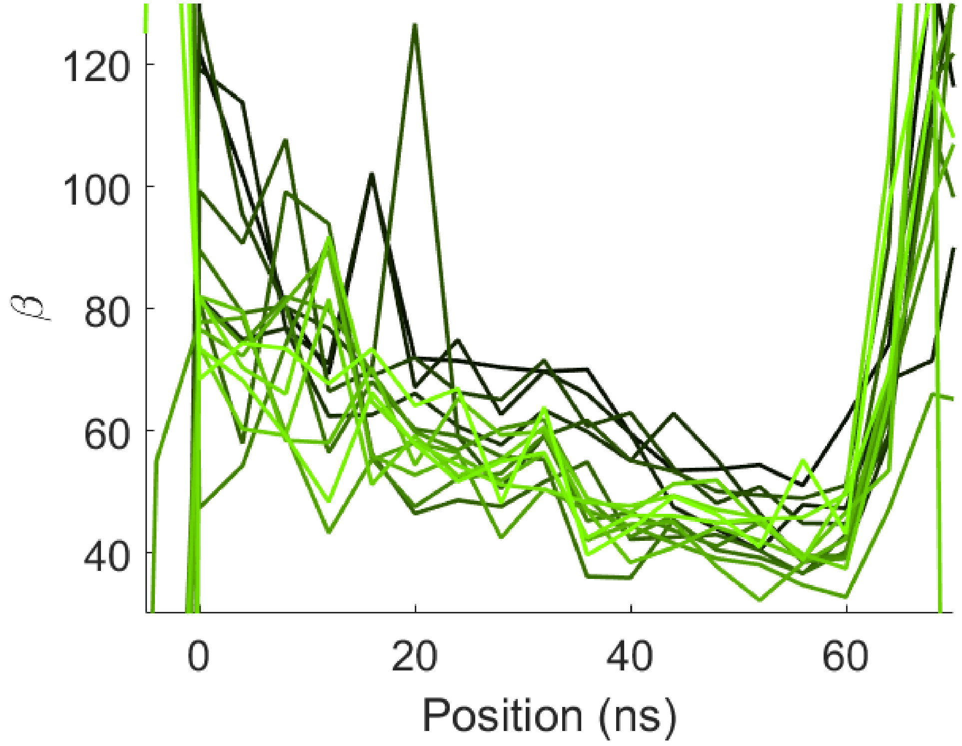
Fitted β value for each sample.

Behaviour Over Time

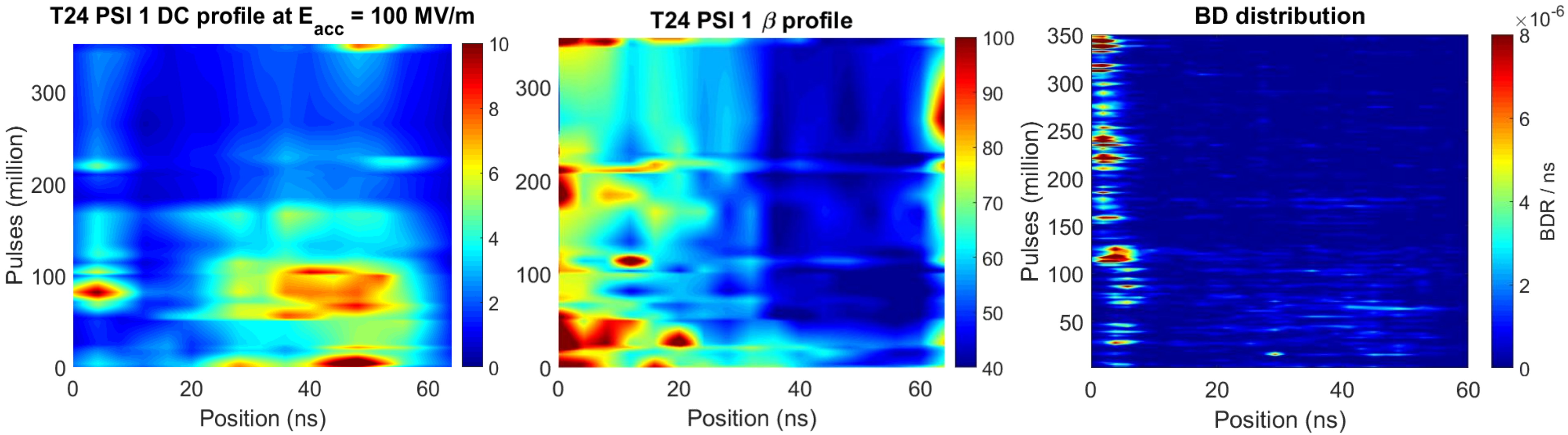
Dark current signal at E_{acc} = 100 MV/m on different days.



Fitted β value for each sample on different days.

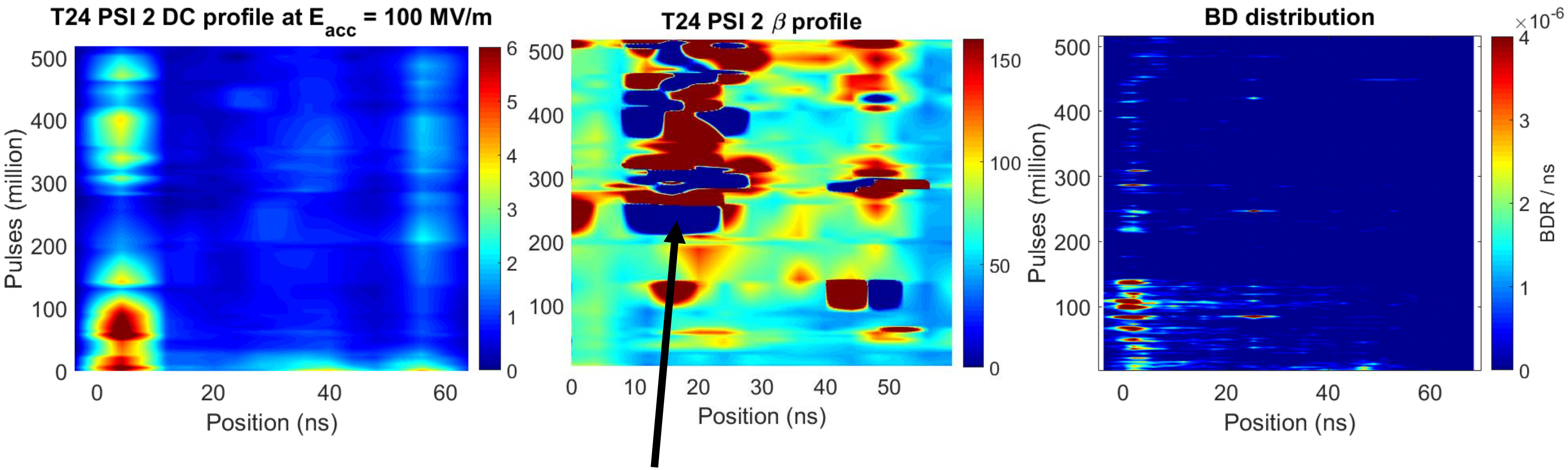


Comparison with BD position (T24 PSI 1)

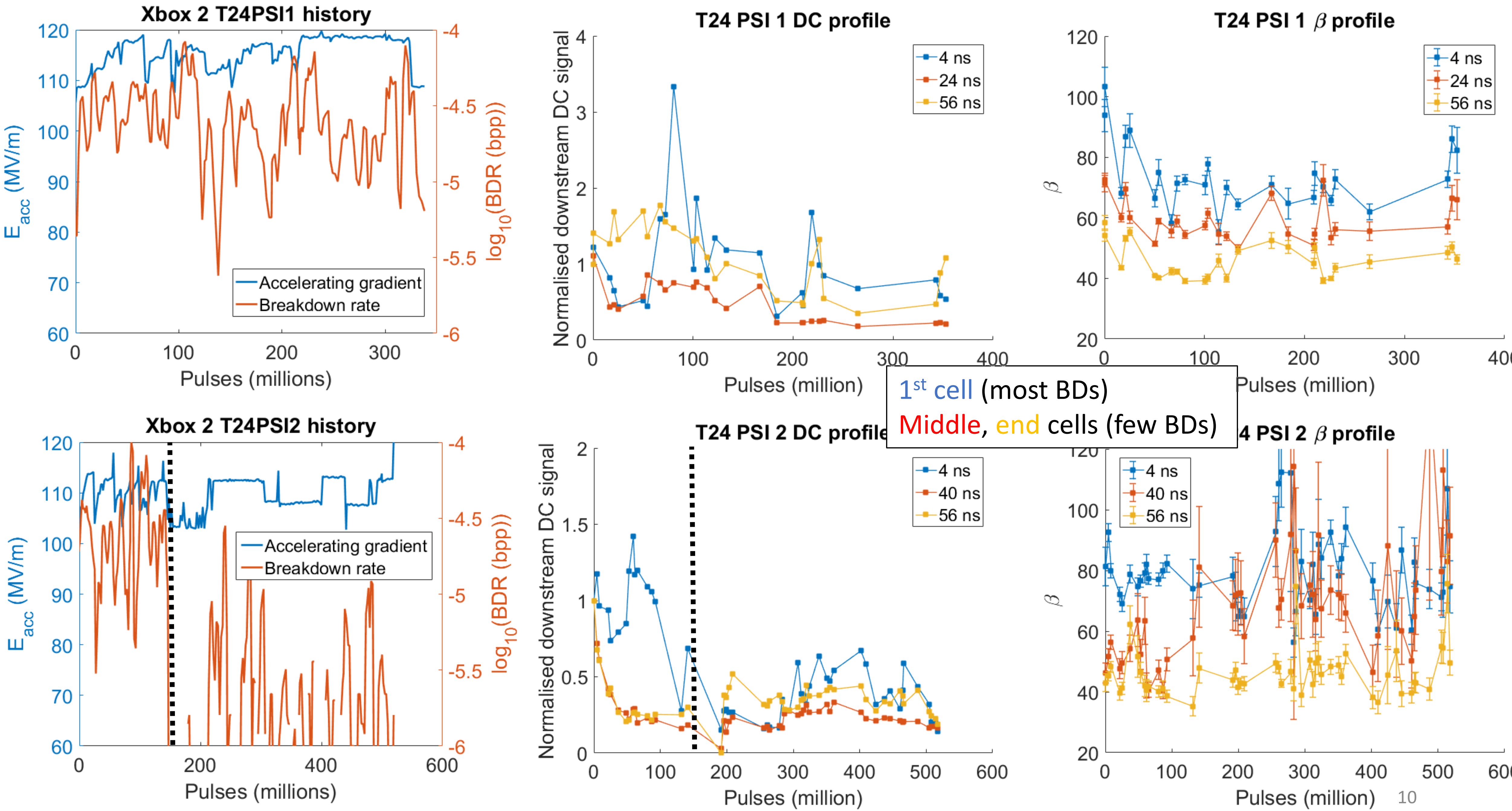


Almost all BDs during time window happened in beginning of structure.

Comparison with BD position (T24 PSI 2)

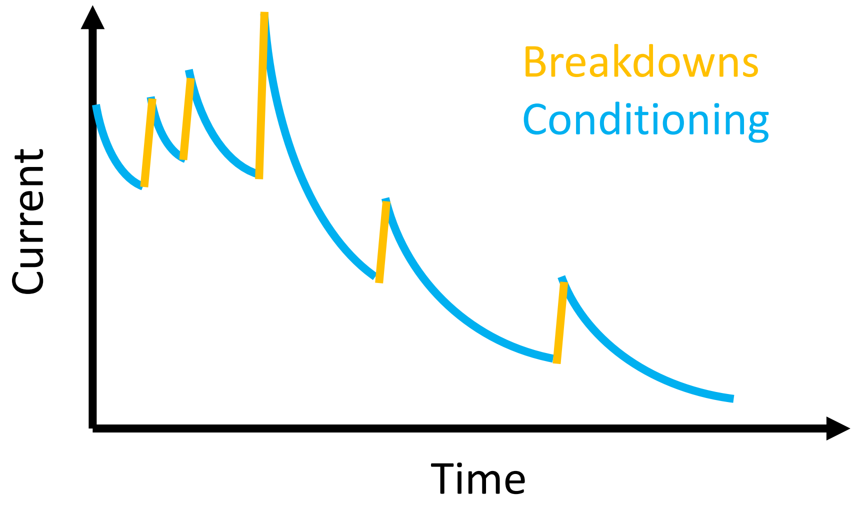


Very poor fit due to low signal to noise ratio.

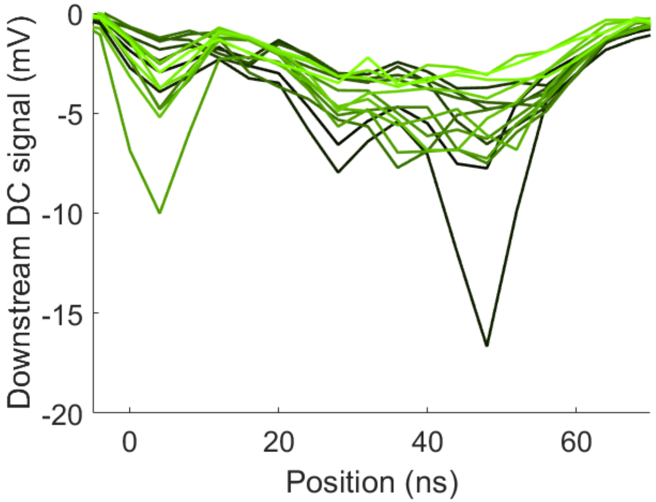

Xbox 2 T24PSI1 history
Eacc (MV/m)
log10(BDR (bpp))
Accelerating gradient
Breakdown rate
Pulses (millions)
T24 PSI 1 DC profile
Normalised downstream DC signal
4 ns
24 ns
56 ns
Pulses (million)
T24 PSI 1 β profile
β
4 ns
24 ns
56 ns
Pulses (million)
1st cell (most BDs)
Middle, end cells (few BDs)
Xbox 2 T24PSI2 history
Eacc (MV/m)
log10(BDR (bpp))
Accelerating gradient
Breakdown rate
Pulses (millions)
T24 PSI 2 DC profile
Normalised downstream DC signal
4 ns
40 ns
56 ns
Pulses (million)
4 PSI 2 β profile
β
4 ns
40 ns
56 ns
Pulses (million)

Proposed Interpretation

- Field emitted current decayed in regions with few BDs.
- Fluctuated at start of structure, where most BDs occurred.
- Change in behaviour between ramping and flat run.
- Breakdown craters cause changes in geometry: fluctuations in β and current density
- Decay in field emission = self-healing / conditioning behaviour?
- I.e.: too aggressive conditioning damages the surface faster than it can heal?

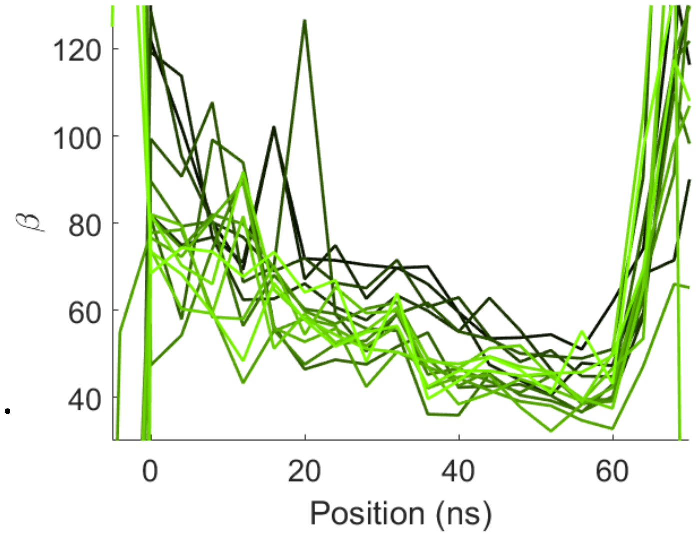


Dispersion and Tapering

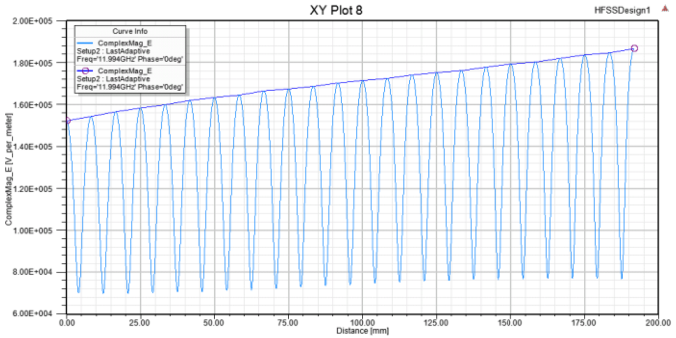


Observed more current from end of structure than beginning.

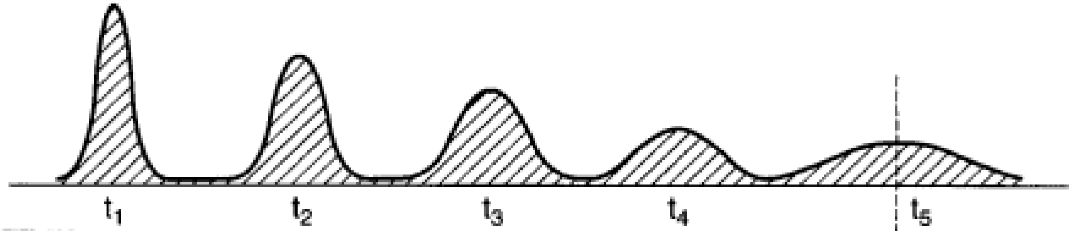
Fitted β lower at end of structure. Suggests that peak E field decreases towards the end.



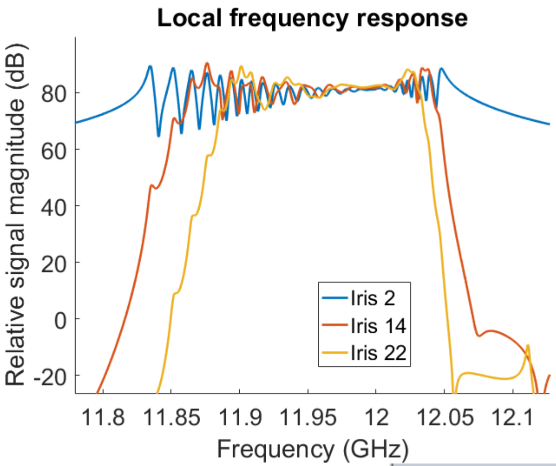
Design gradient as a function of position at 11.994 GHz – **implies opposite effect!**

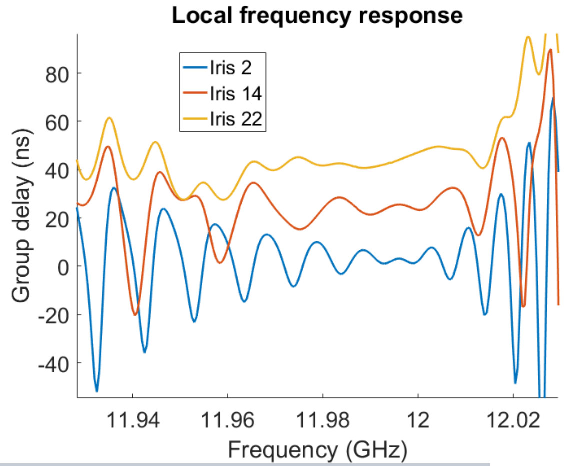


Dispersion of the pulse? Causes pulse to spread in time due to varying group velocity with frequency.

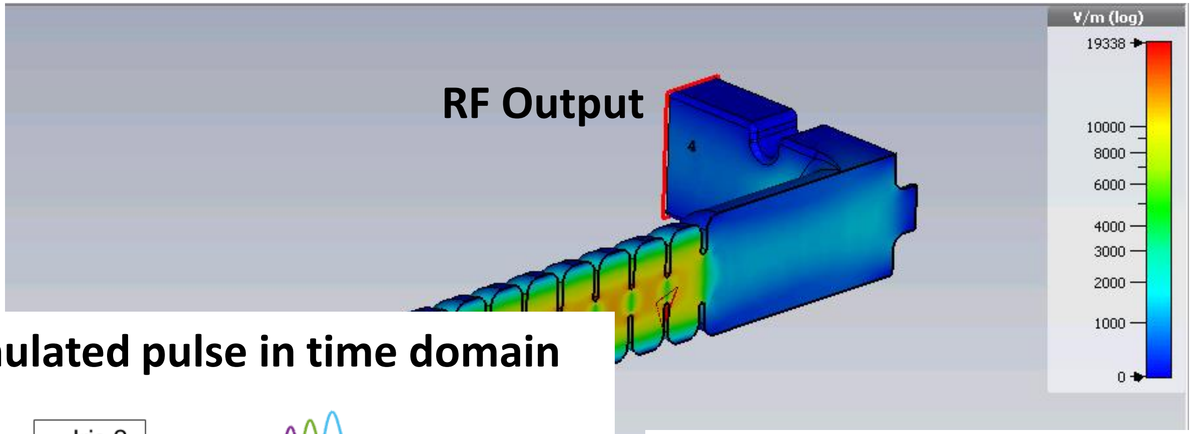


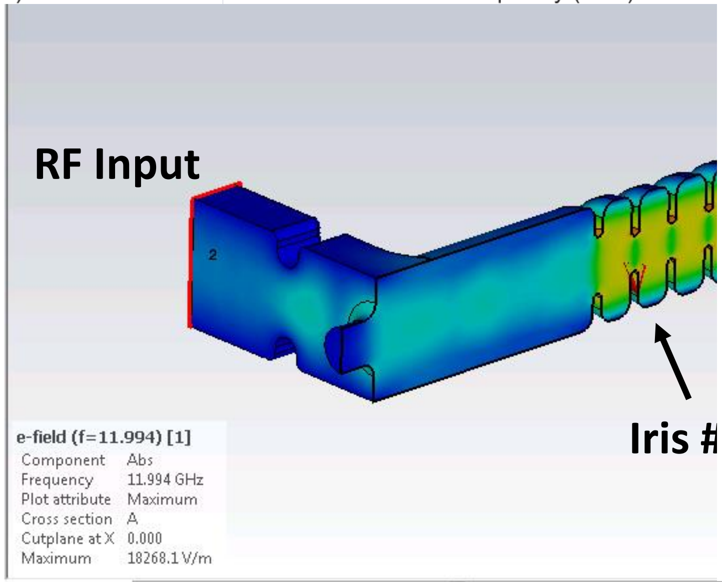
Dispersion Simulation



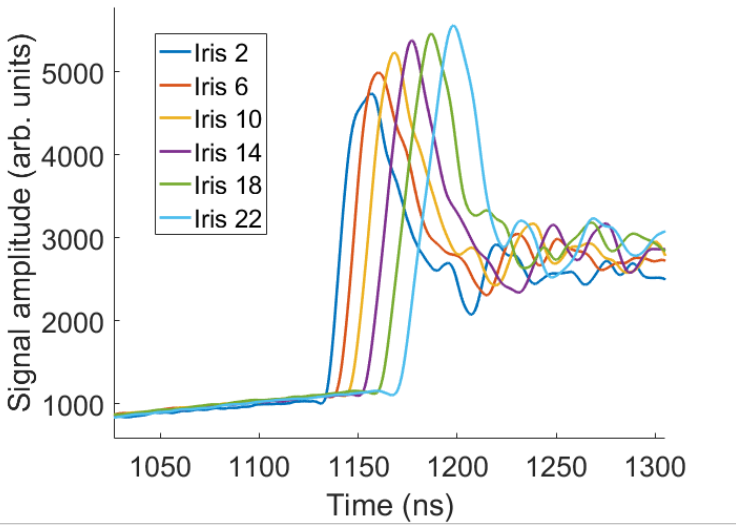


T24 PSI structure, E field complex magnitude





Simulated pulse in time domain

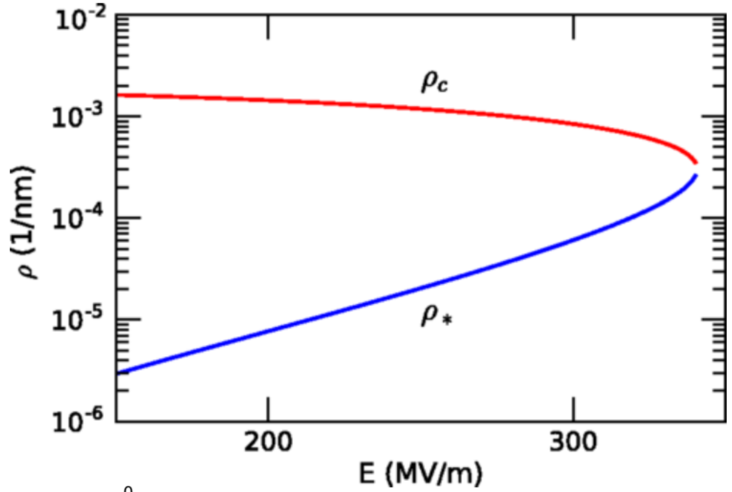


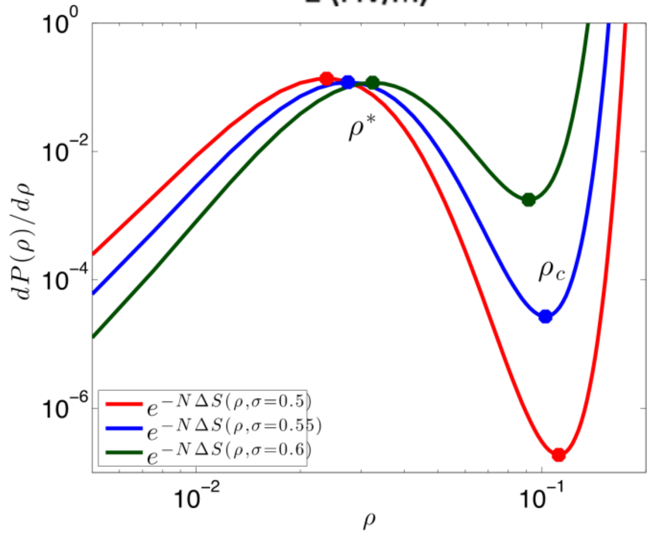
Tapering much more significant than dispersion. Effect must be caused by something else, e.g. electron dynamics.

Fluctuation Measurements

Dark Current Fluctuations in RF Structures

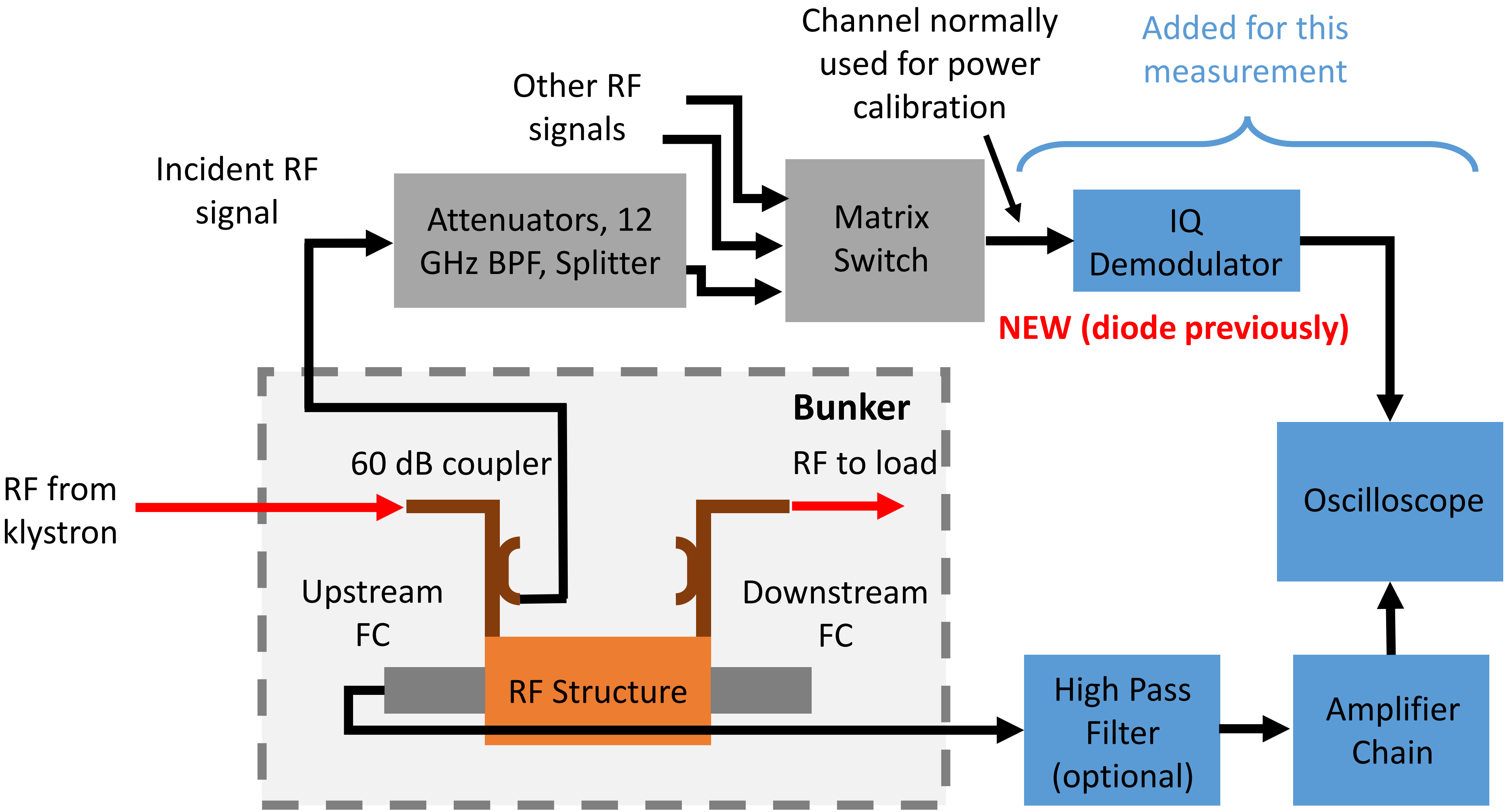
- Stochastic model of breakdown nucleation has been proposed by Ashkenazy et.al.
- Fluctuations in dark current could give insight into dislocation dynamics inside copper.
- Breakdown corresponds to bifurcation point in dislocation dynamics – stable fixed point disappears.
- Warning signs before breakdown might be observable.





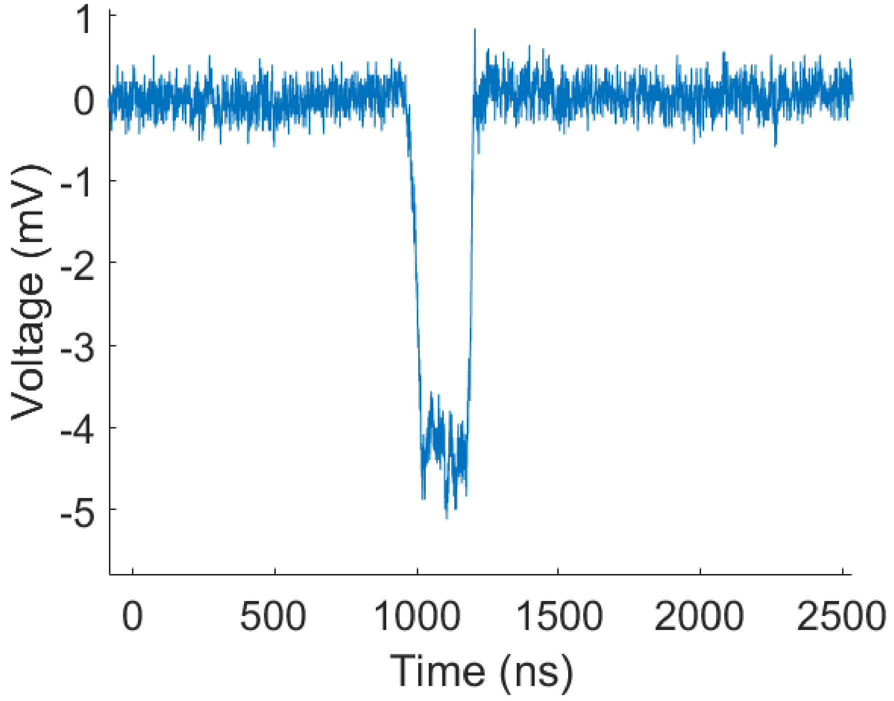
E. Engelberg, Y. Ashkenazy, M. Assaf

Experimental Setup

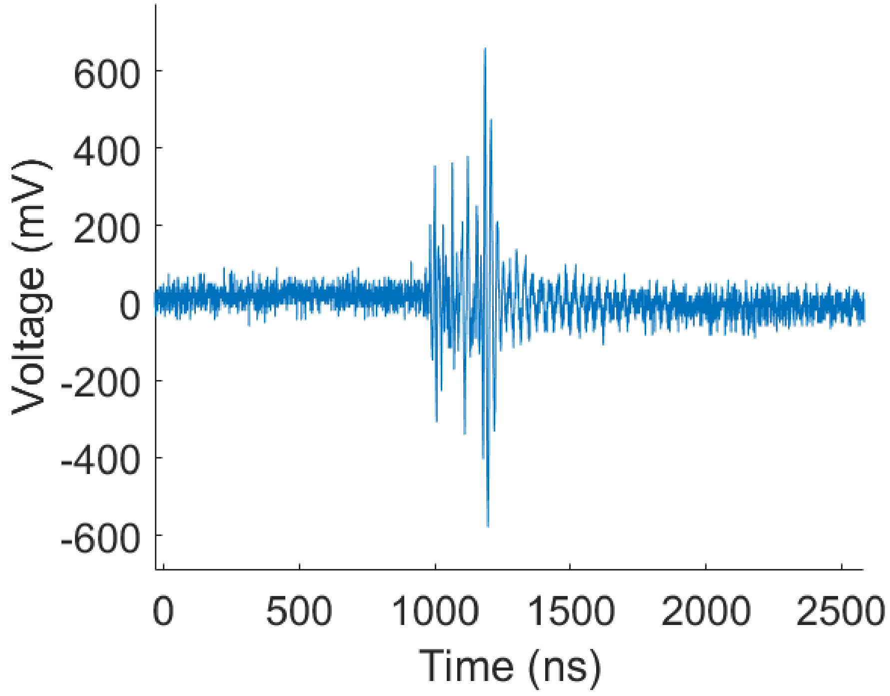


Example Dark Current Pulses

Raw upstream dark current



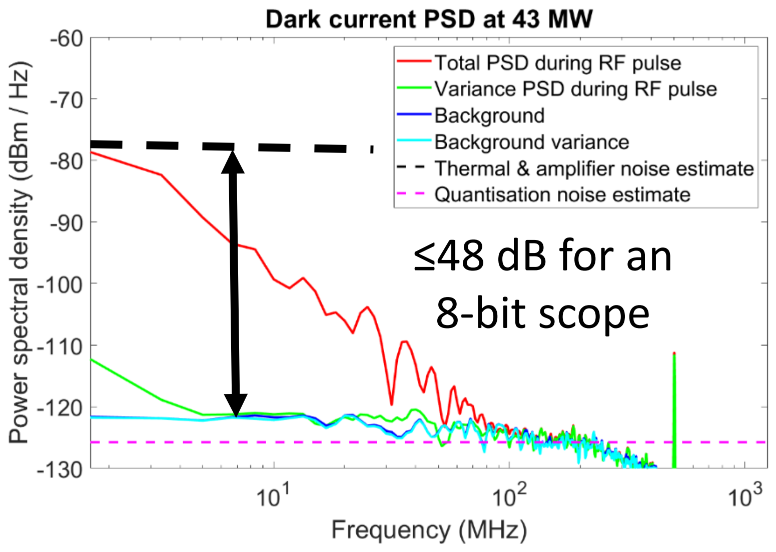
Dark current with high pass filter and amplifiers



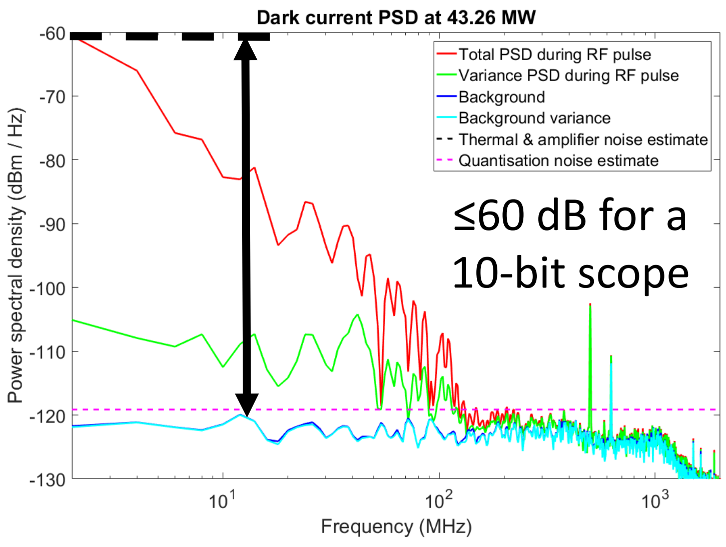
Improvements to Measurement

- Higher dynamic range oscilloscope: (8 bits: 48 dB, 10 bits: 60 dB)
- Higher sample rate and bandwidth (10 GS/s, 1 GHz)
- Running much closer to breakdown.
- Replaced diode detector with IQ demodulator.

Previously:



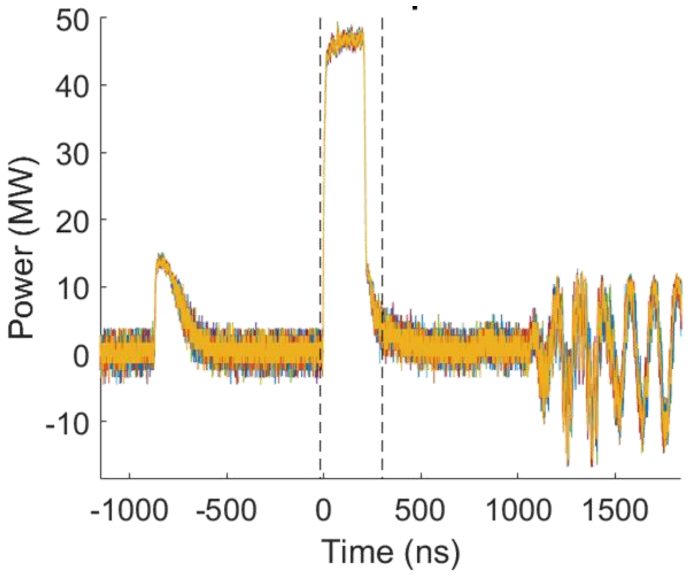
Now:



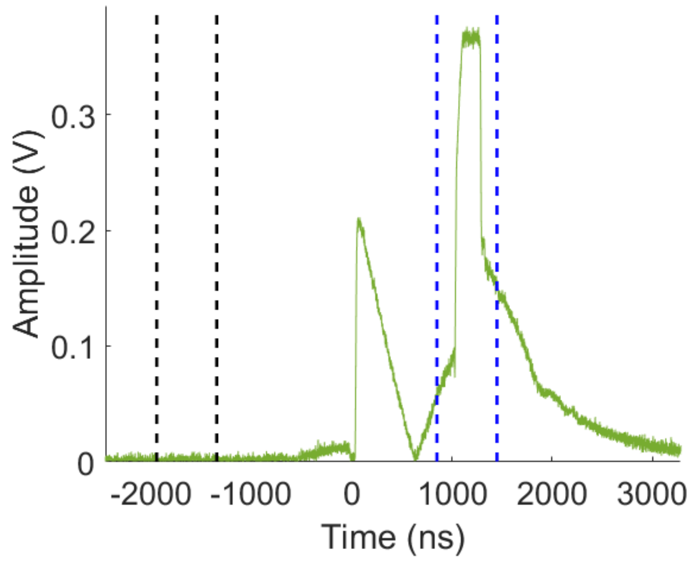
IQ Demodulator

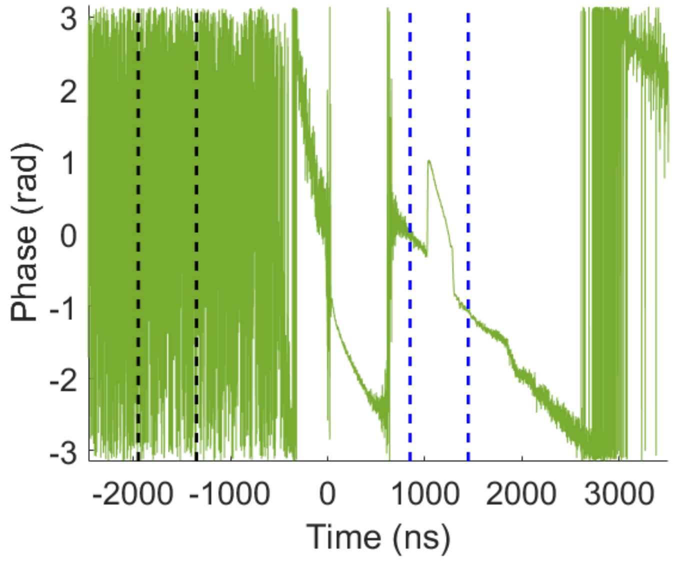
- Previously, concluded that incident RF had to be measured more accurately to take into account RF fluctuations.
- IQ demodulator is linear and gives phase information – allows full reconstruction of original waveform in time domain.
- Very fast, high resolution, synchronised sampling of RF and dark current (built in acquisition has jitter and lower resolution)

Signal from diode detector

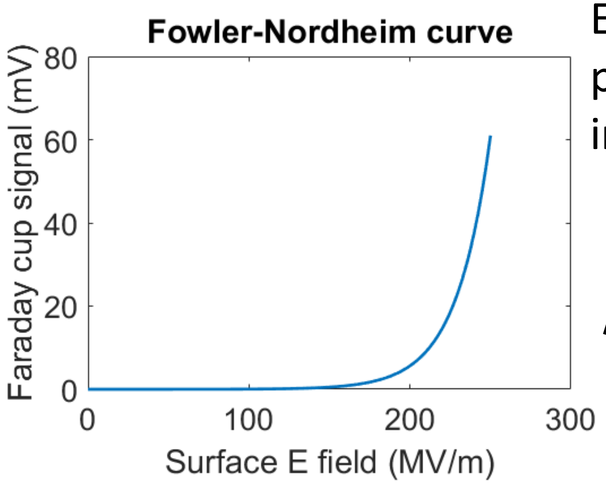


Signals from IQ demodulator

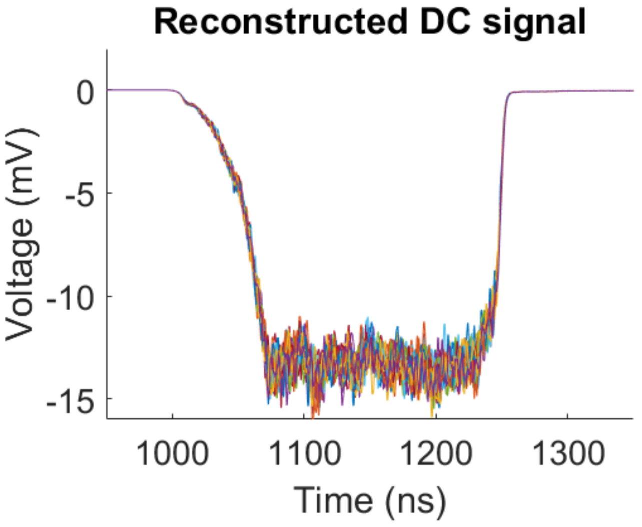


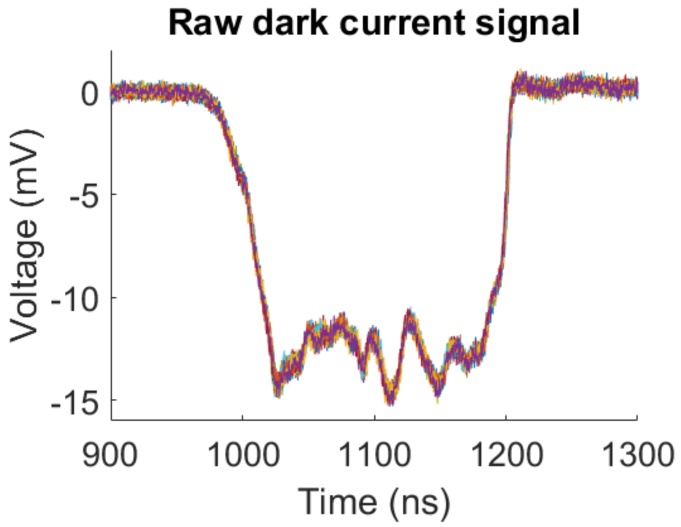


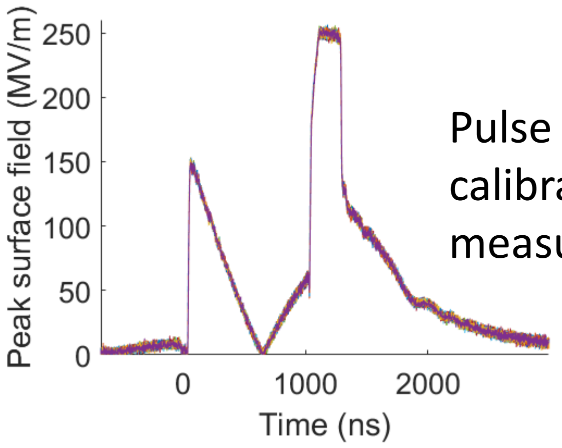
Reconstruction of DC pulse



Empirically obtained from previous power scan. No BDs in between measurements.



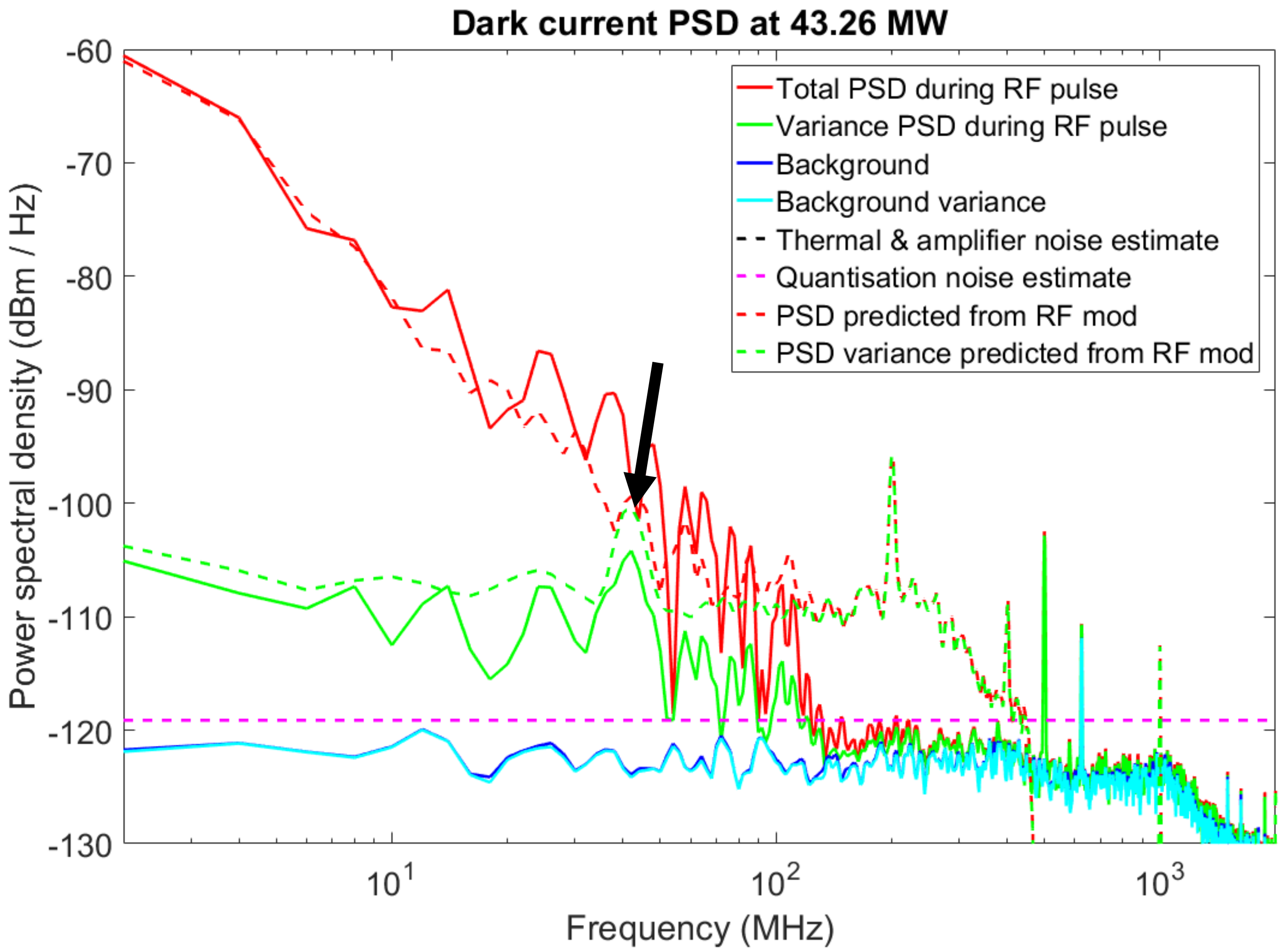




Pulse by pulse, calibrated E field measurement.

General pulse shape and signal level is correct, but some higher frequency deterministic phenomena not recreated. (Electron capture & transport)

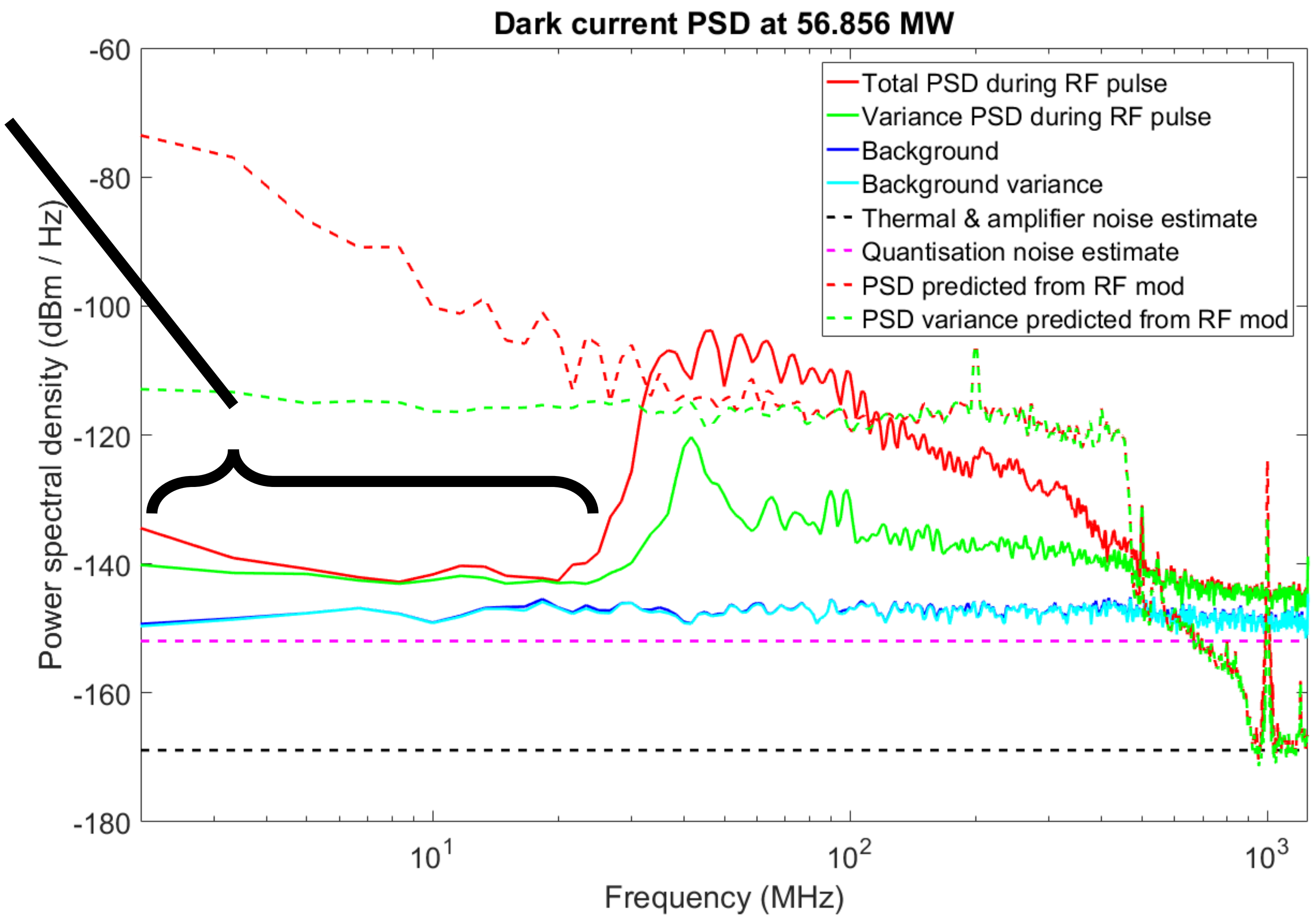
Reconstruction of DC pulse



Measured DC fluctuations still lower than limits set by static field emitter with known RF fluctuations.

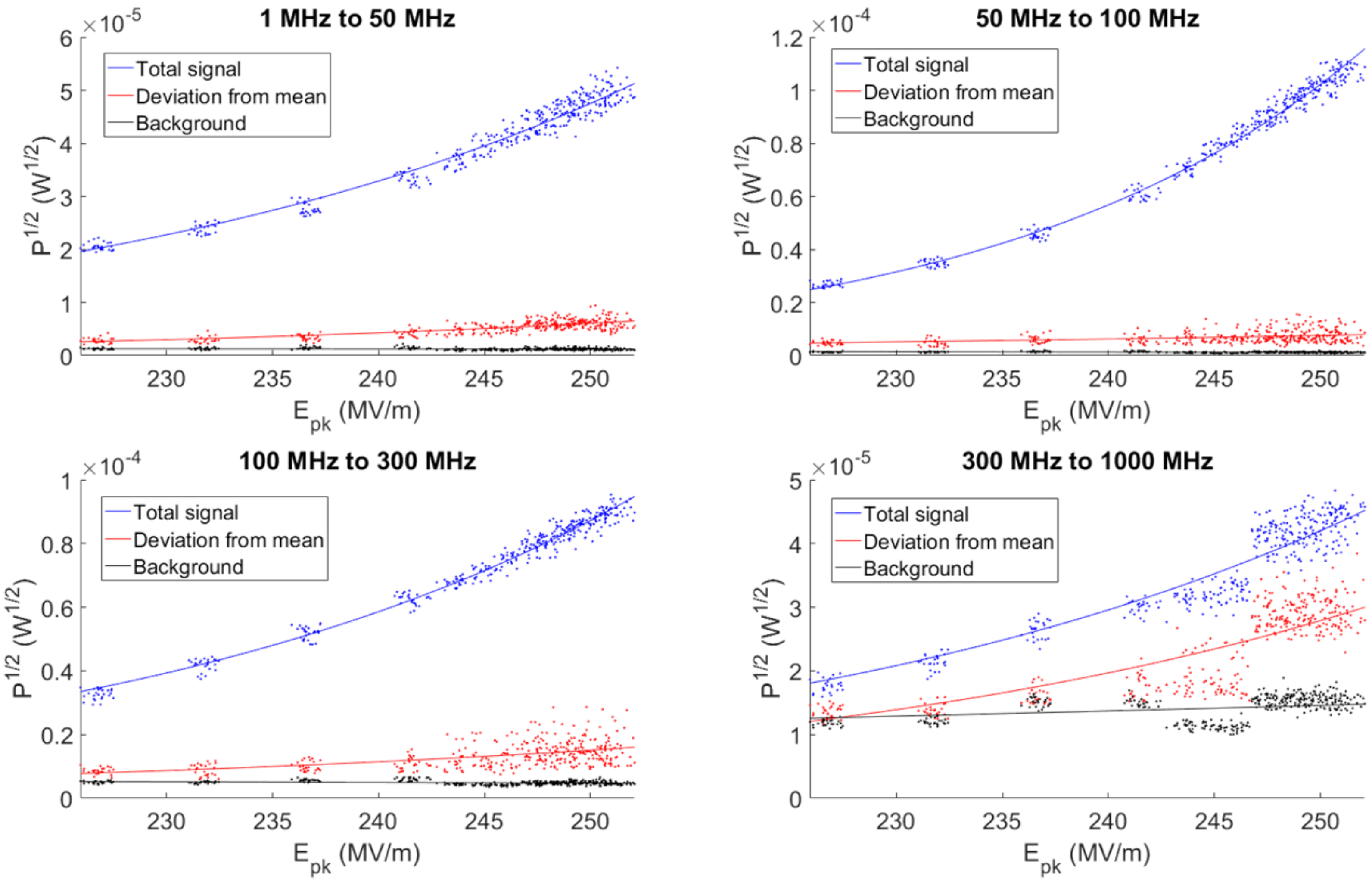
Measurements with High Pass Filter

Low frequency components with low fluctuation removed to allow more amplifier gain and lower noise floor.



CERN clic JAI John Adams Institute for Accelerator Science UNIVERSITY OF OXFORD

Measurements with High Pass Filter

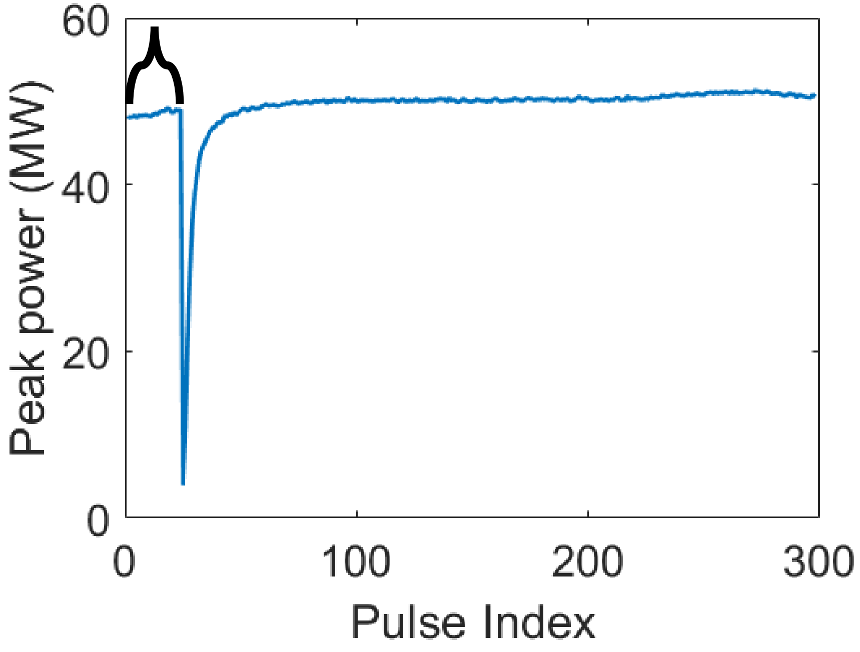


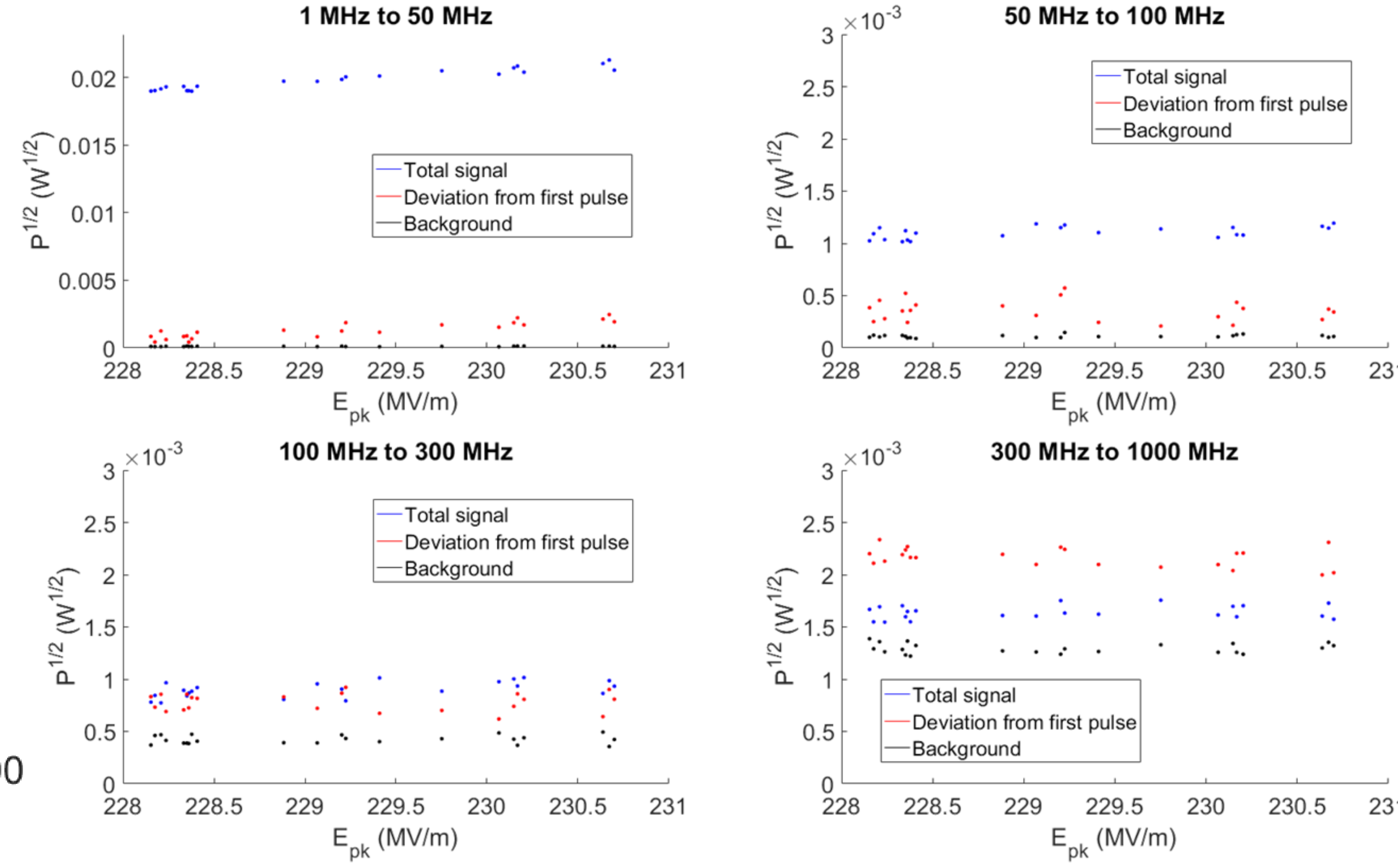
Data shown for power values up to **55.2 MW**.
BD occurred at **55.5 MW**.

Getting Even Closer to Breakdown

No power scans. Let system run at high power and wait for breakdown. Saved 1 in every 15 pulses.

Data shown for this range.

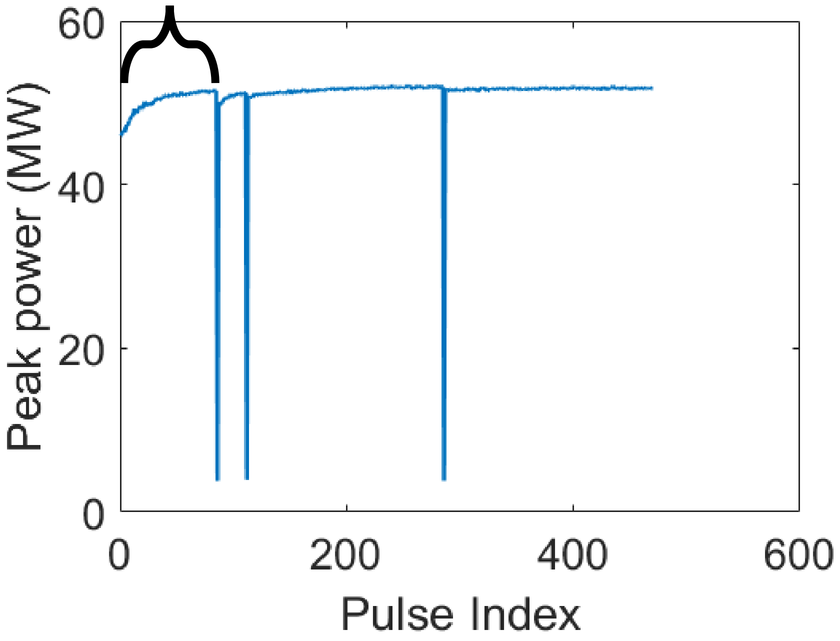


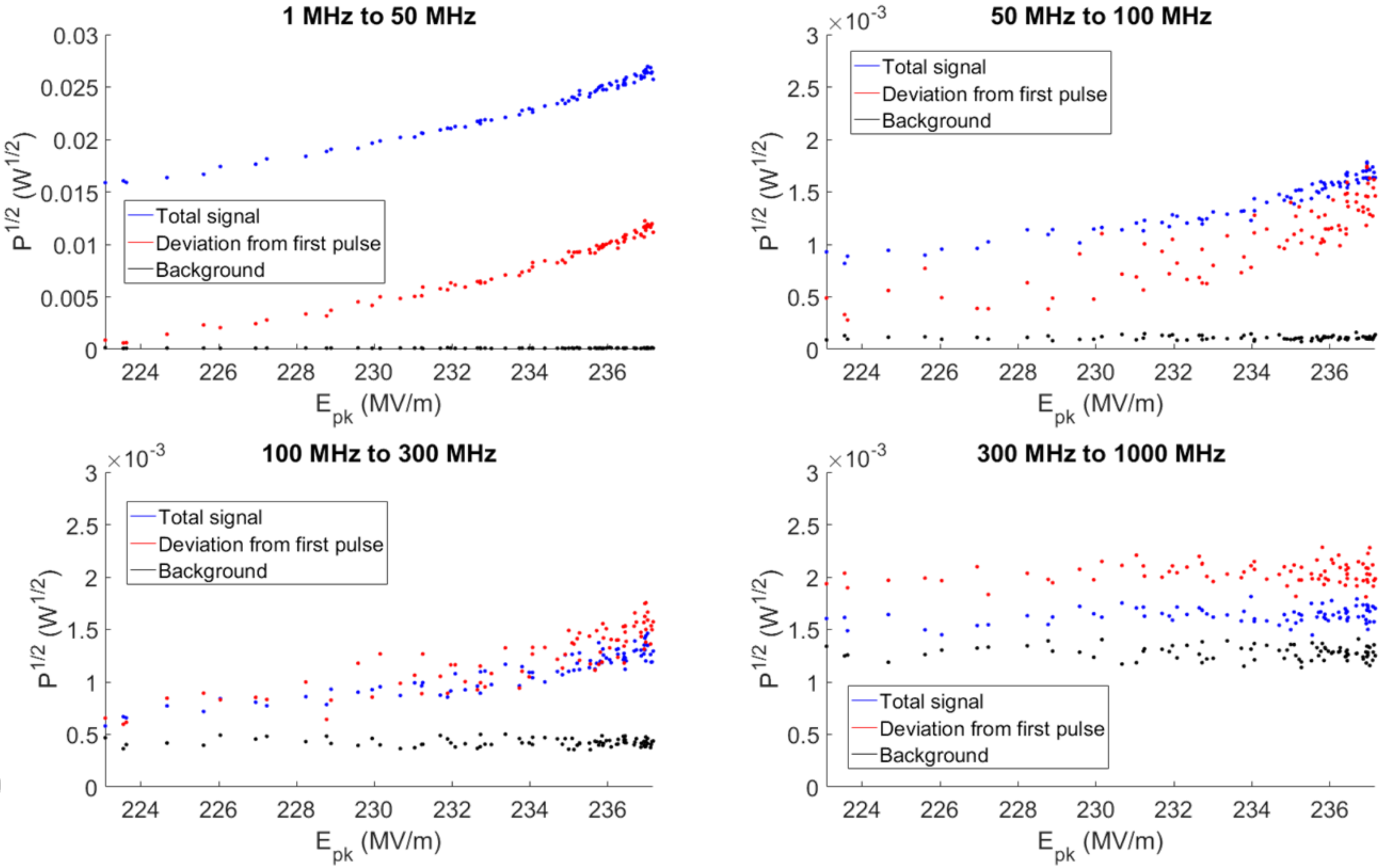


Getting Even Closer to Breakdown

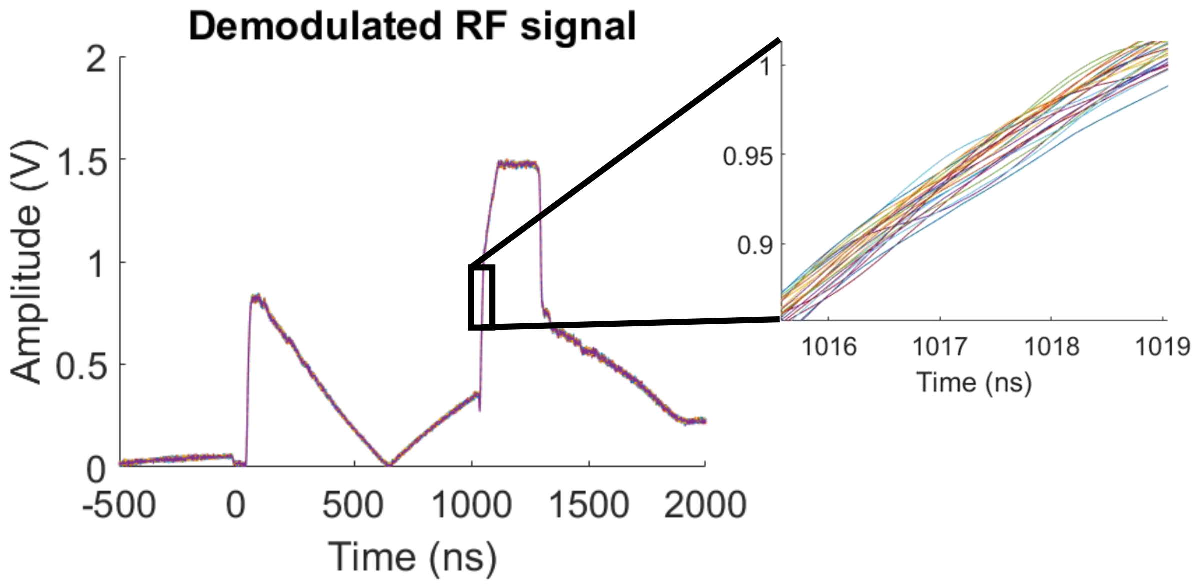
Saved 1 in every 20 pulses.

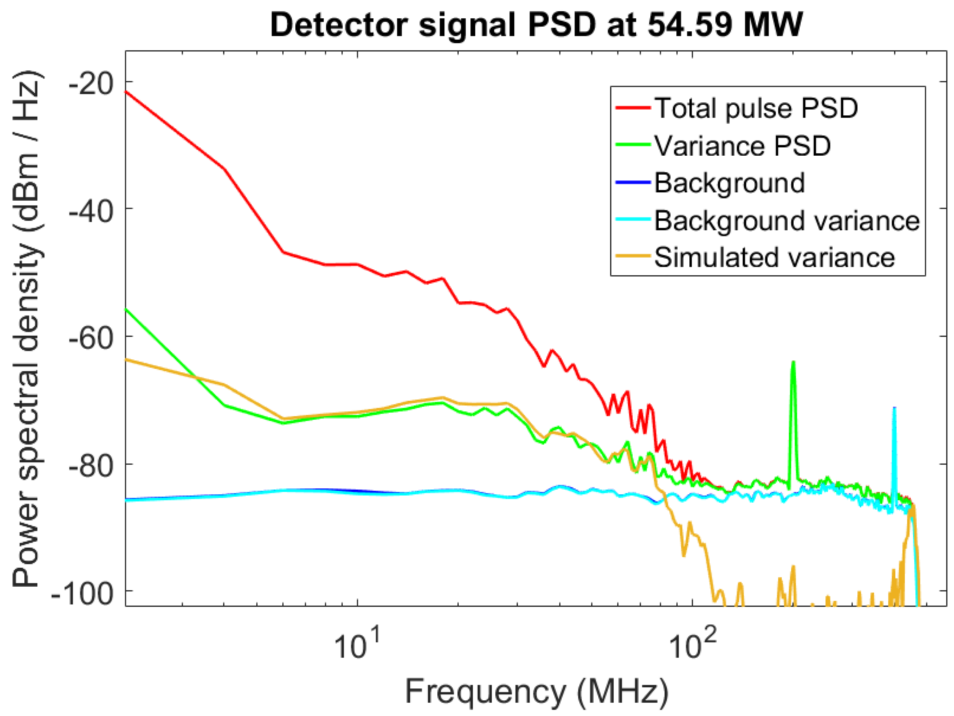
Data shown for this range.





Time Alignment Limitations

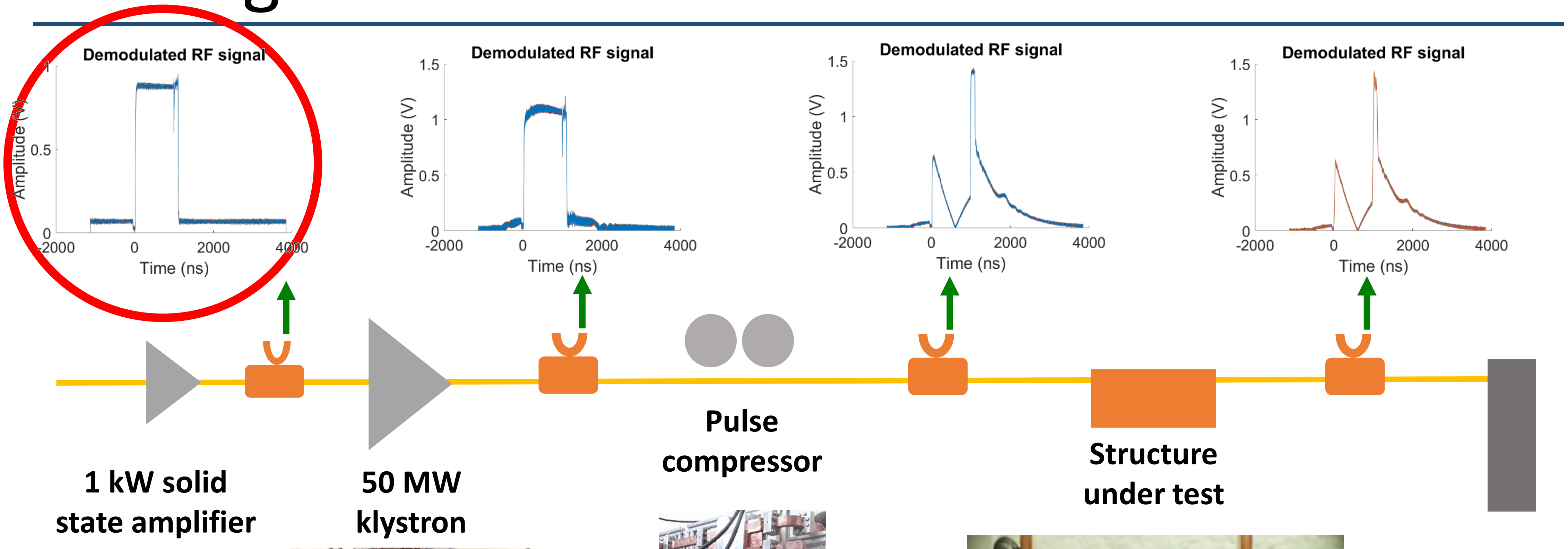




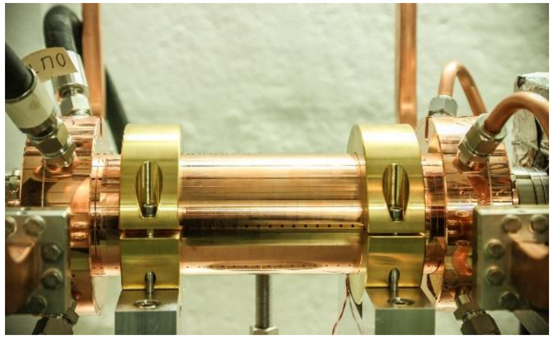
- Misalignment of pulses in time looks like fluctuation, proportional to time difference / rise time.
- Not possible to align perfectly. Tried various forms of threshold crossing and cross-correlation for alignment.
- Ultimate limit of jitter is time resolution of the oscilloscope.
- Puts a limit on smallest measureable fluctuation in RF and dark current.

Simulated apparent fluctuation PSD caused by a shift of 2 samples (200 ps)

Tracing RF Fluctuations

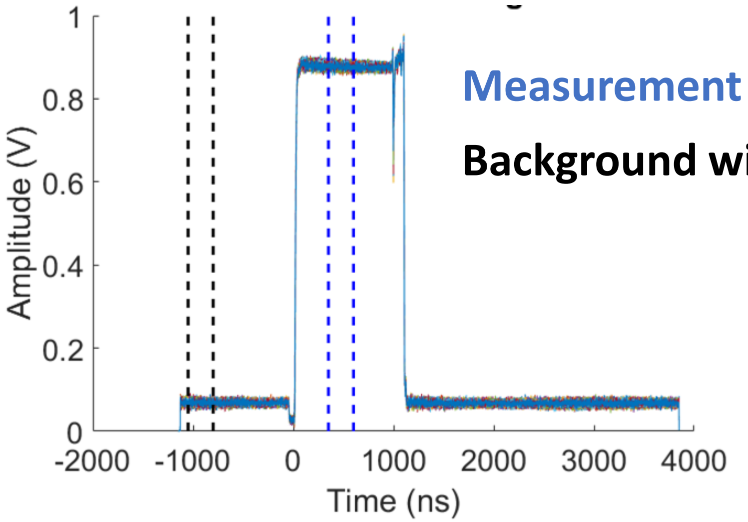


RF Load



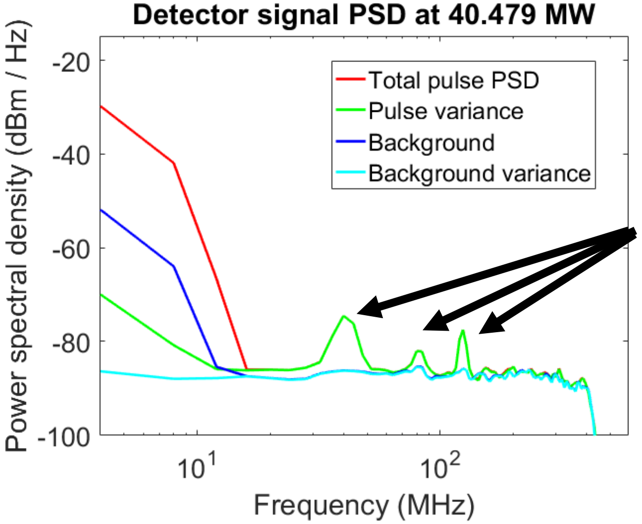
Signal amplitude at each stage is relative.

Noise at Klystron Input

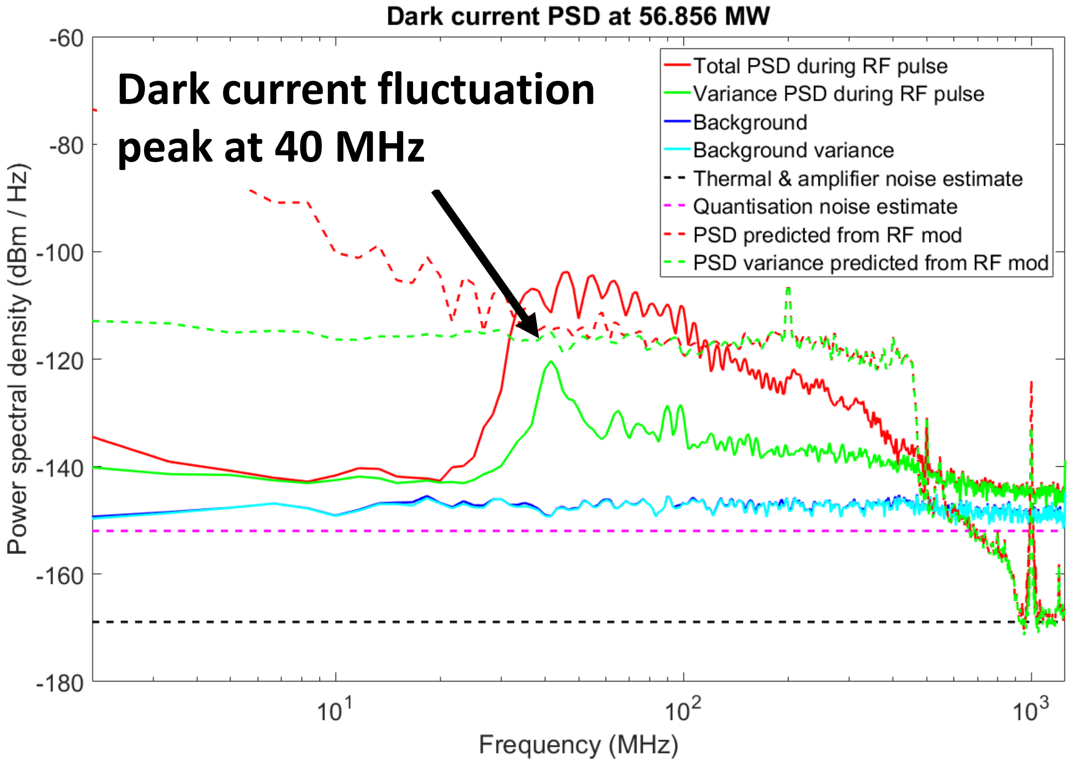


Measurement window

Background window



Peaks at 40, 80, 120 MHz



Dark current fluctuation peak at 40 MHz

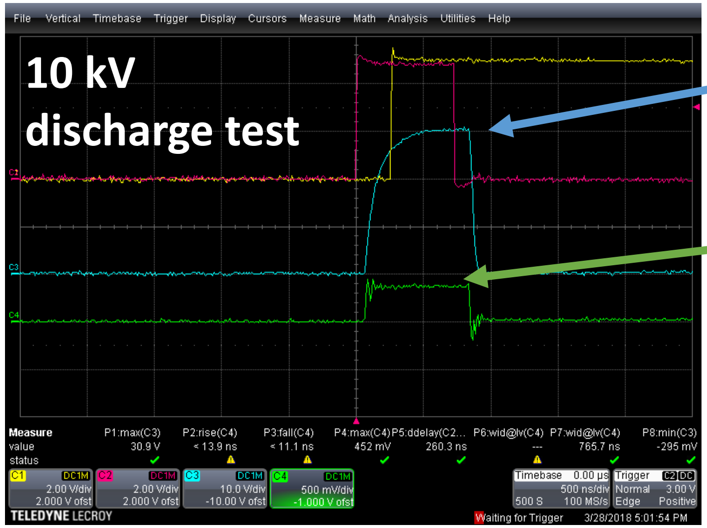
Fluctuations in DC Experiments

Developed a broadband, high voltage bias tee to act as a probe to measure small currents in the DC system.

Protects sensitive equipment from high voltage and BD currents.

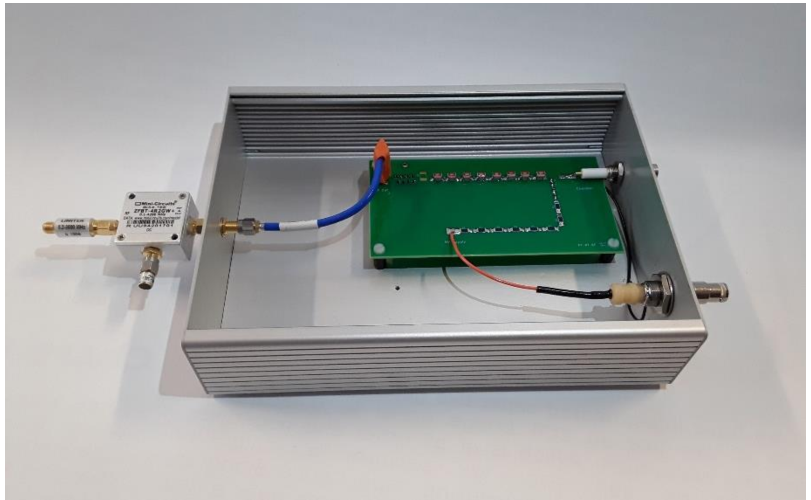
Can measure fast phenomena (< 250 ps risetime).

Currently limited by switching noise in HV power supply (work in progress)

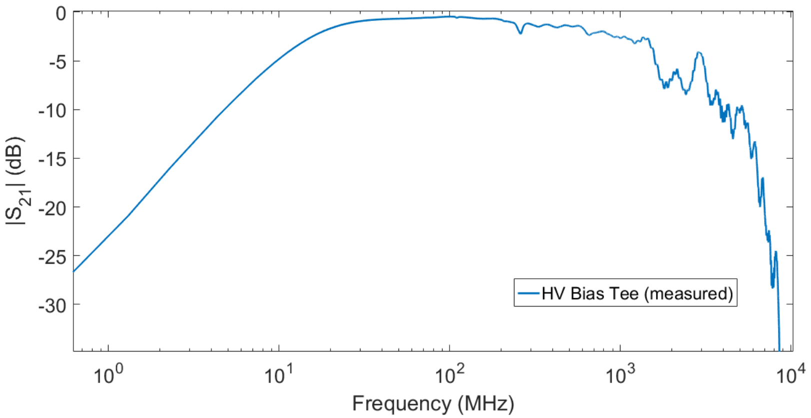


30 A discharge

Output clamped to 40 V.



Small-signal bandwidth measurement

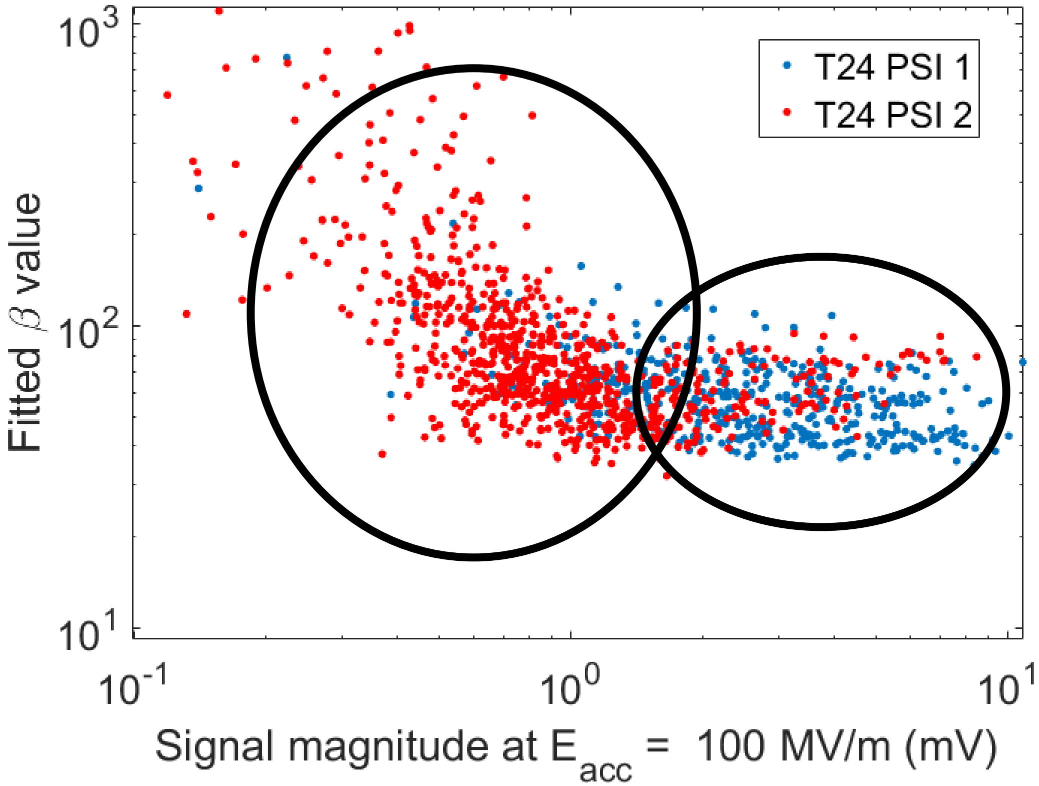


Thank you!

Any questions?

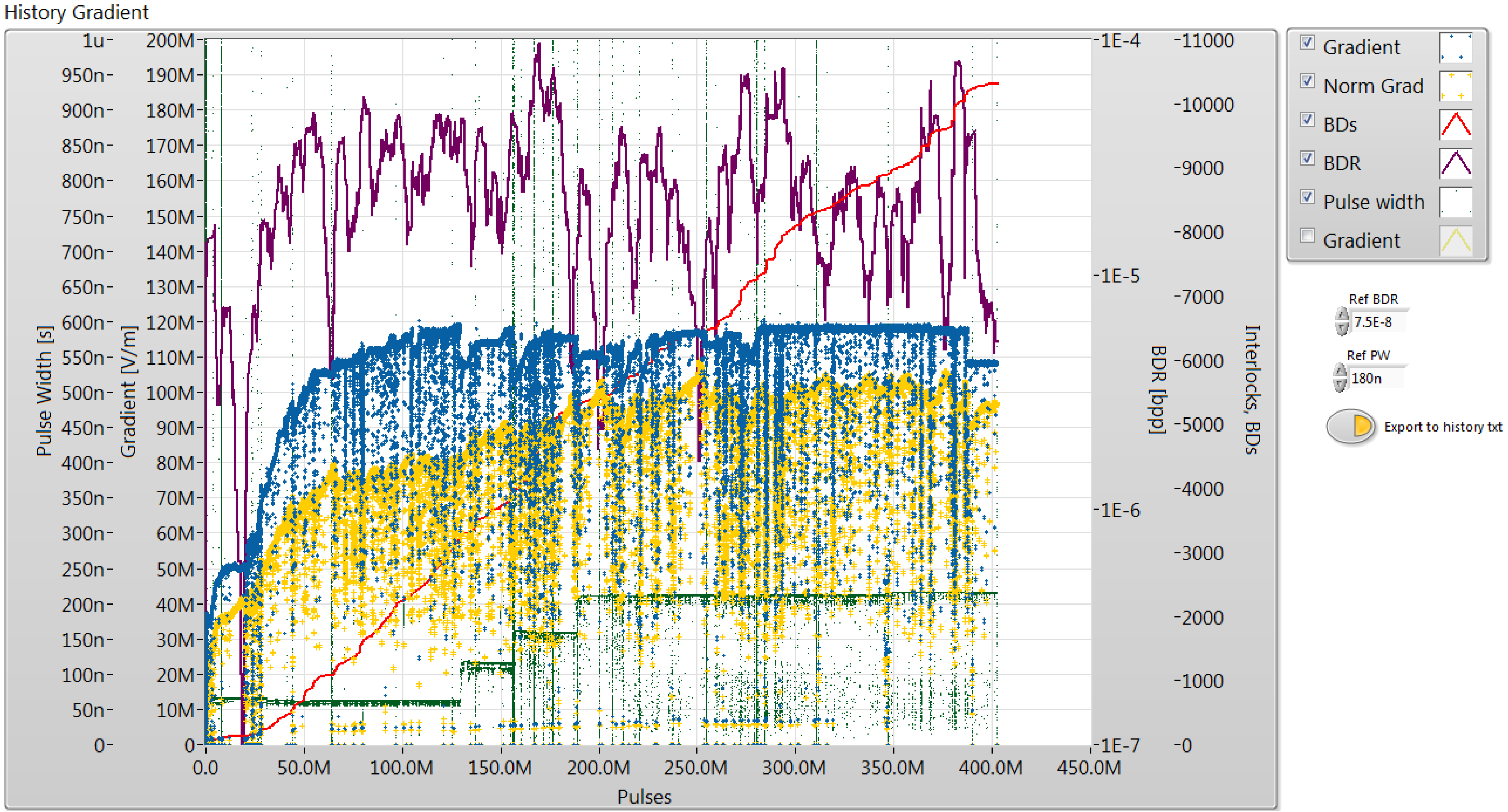
Noise and Beta Fit

Random noise gives very large β values. Small signal = low SNR = higher β than expected.

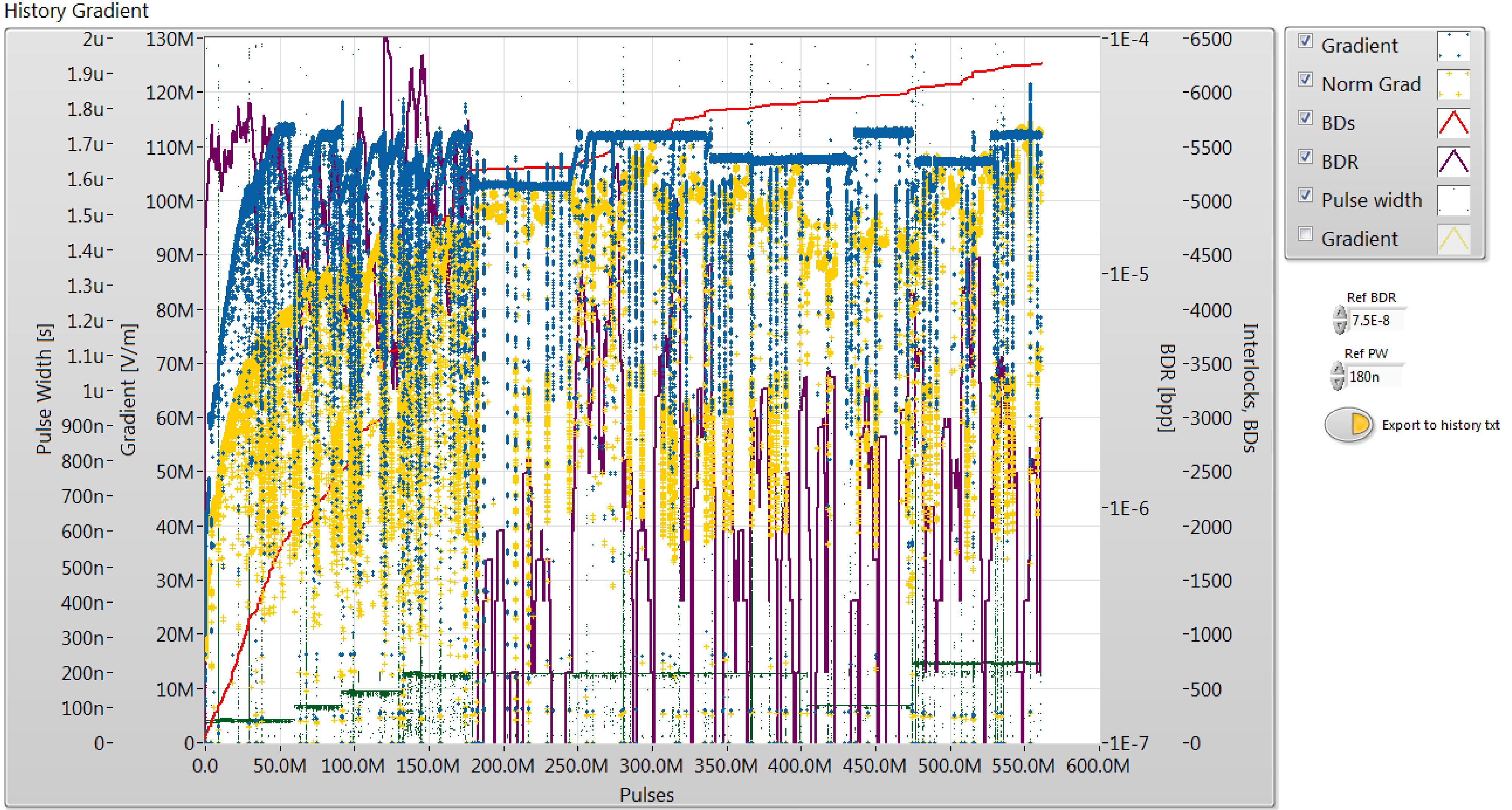


Sufficiently large SNR: no systematic error due to signal magnitude.

History of T24PSI1 in XBox 2



History of T24PSI2 in XBox 2



PSD of Pulse to Pulse Fluctuations

Measurement of pulsed dark current signal:

Measured signal → $v_i(t) = d(t) + r_i(t)$

Deterministic component

Random component: different for every pulse

Averaging in time domain first removes random component:

$$FT[\langle v_i(t)\rangle] \cdot FT[\langle v_i(t)\rangle]^* = D(\omega)D^*(\omega)$$

← PSD of deterministic component

Ensemble average of PSDs includes random component:

$$\langle FT[v_i(t)] \cdot FT[v_i(t)]^* \rangle = \left\langle \big(D(\omega) + R_i(\omega)\big)\big(D(\omega) + R_i(\omega)\big)^* \right\rangle =$$

$$D(\omega)D^*(\omega) + \langle R_i(\omega)R_i(\omega)^* \rangle$$

← PSD of random component – not zero due to square term. (Effectively variance of random distribution)

Taking the difference between the two leave PSD of random component only.