DARK CURRENT FLUCTUATIONS IN HIGH GRADIENT RF AND PULSED DC EXPERIMENTS

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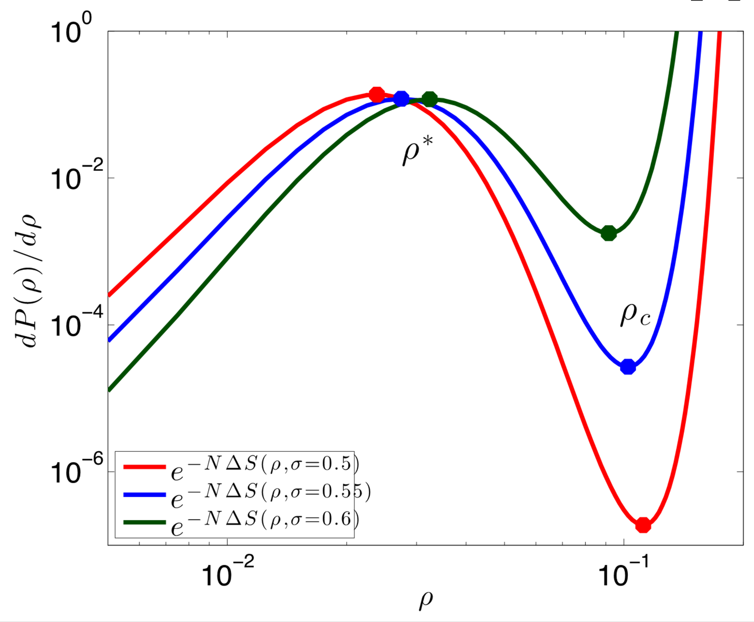
Motivation

A model for the nucleation of vacuum breakdowns via dislocation motion within metals exposed to high electric fields has been proposed [1]. It purports that the initial stages of a breakdown occur in a stepwise and stochastic manner, similar to plastic deformation on very small scales [3], and explains the observed dependence of breakdown rate on electric field of BDR ~ E^{30} [6] .

It is important to obtain direct experimental evidence of these fluctuations and characterise their behaviour in order to better understand the nucleation of breakdowns.

Measurements have been performed in high gradient RF structures and pulsed DC experiments, both of which experience vacuum breakdowns and in which field emission currents can be measured.

Dislocation dynamics under various values of surface electric field [1]:



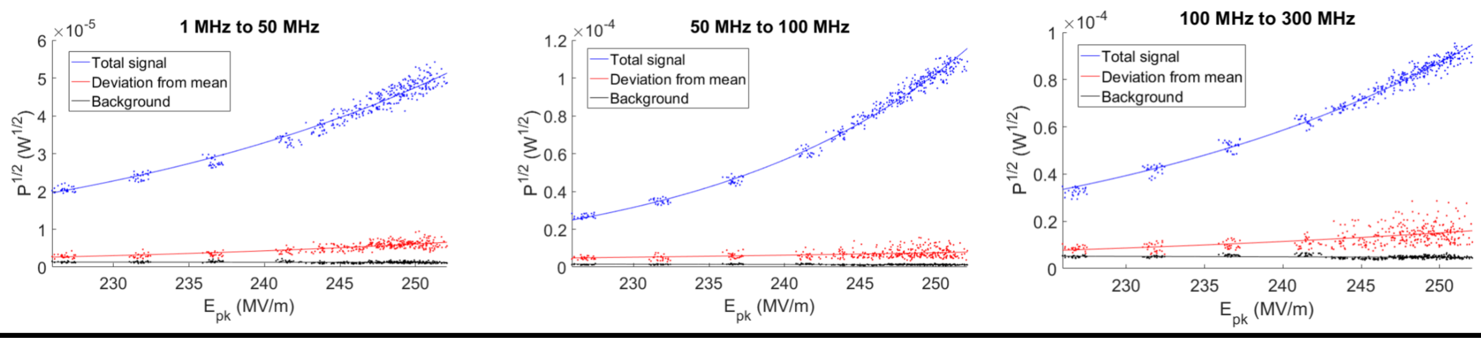
Measurements on High Gradient RF Accelerating Structures

Searches for fast fluctuations in dark current

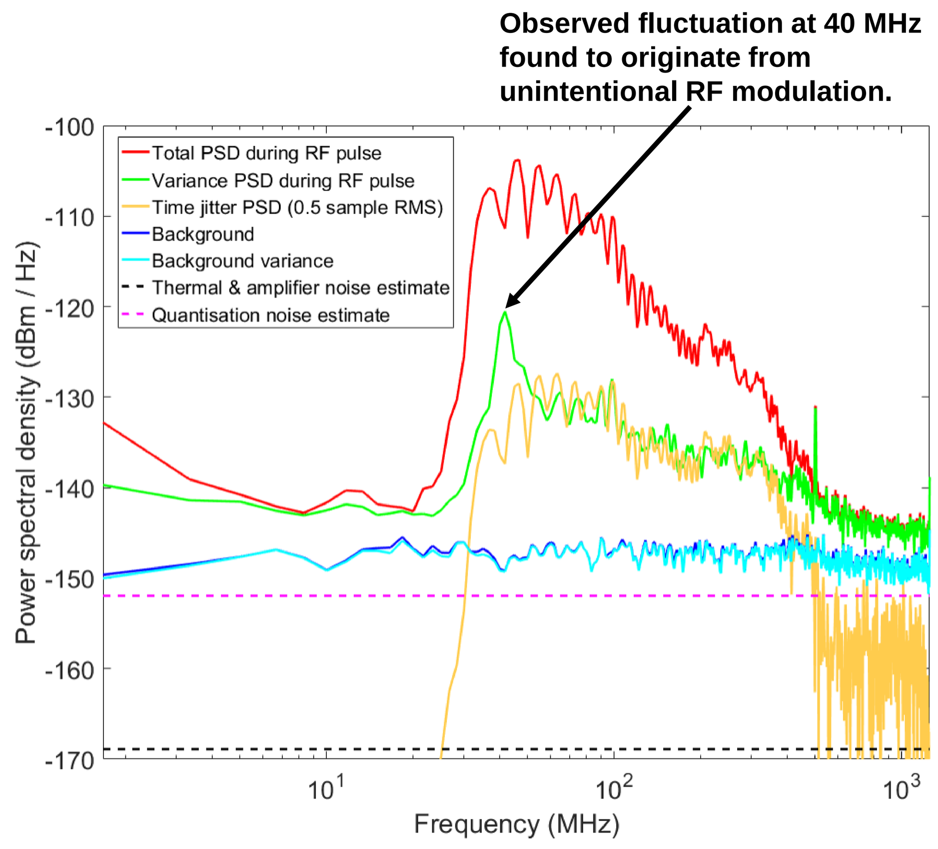
Precision measurements of dark current signals from RF structures under test in the Xbox test stands at CERN [6] were performed to search for broadband fluctuations indicative of dislocation dynamics [1]. These structures are exposed to a 12 GHz oscillating field with a peak value of around 230 MV/m in pulses of up to 200 ns [2].

A sequence of RF pulses was measured at different field levels, and the pulse to pulse variation was calculated and compared with background from external sources, jitter in the input applied electric field, and uncertainty in timing. No fluctuations larger than the experimental uncertainty were observed. There was also no change in behaviour of the dark current just before breakdown.

Dependence on surface E field:
Hypothesis predicts unstable transition at high fields before BD [1].



Frequency spectra of dark current pulses, pulse-to-pulse variation, and background:



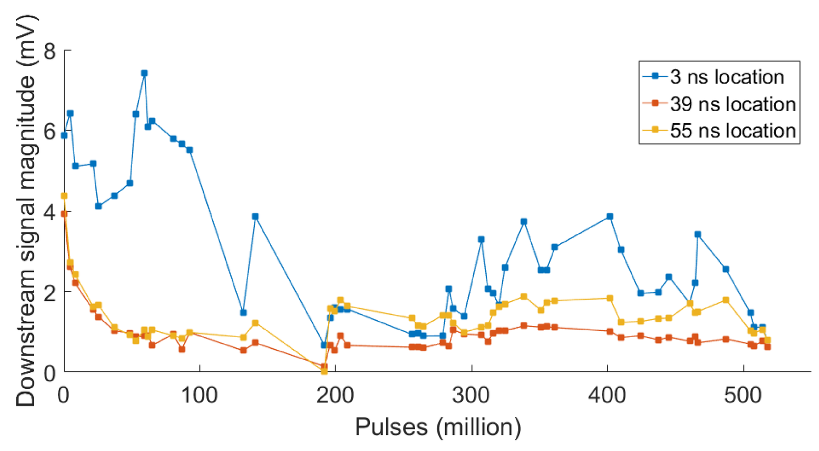
Long term measurements of dark current

Alongside dedicated searches for high-bandwidth fluctuations over a short period, measurements of dark current magnitude were also performed parasitically while conditioning the structures. Spatial resolution of the dark current emission profile was obtained by using a very short RF pulse [4]. This data was taken regularly at a consistent surface field level over the conditioning history of structure.

A slow decay of the dark current magnitude from a high initial value was observed throughout the structure as it conditioned. A small fluctuation on top of this was seen over long timescales (>10M pulses) in regions with a low breakdown rate, and large variations in regions with a high breakdown rate.

Long term evolution of dark current [4]:

Variation in current at fixed E over months



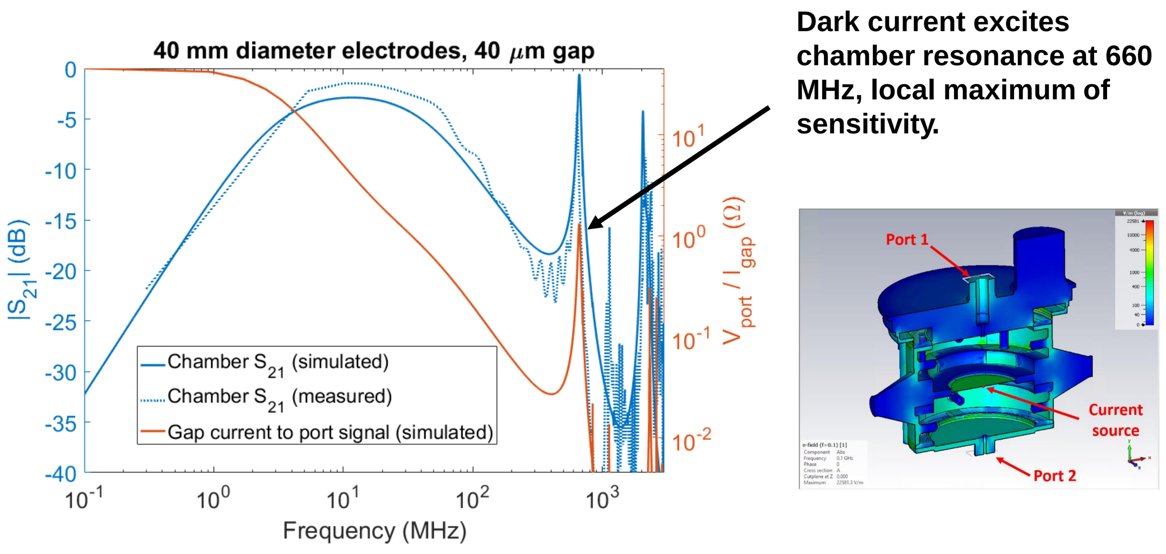
Measurements on High Voltage Pulsed DC Systems

Experimental setup in the DC systems at CERN

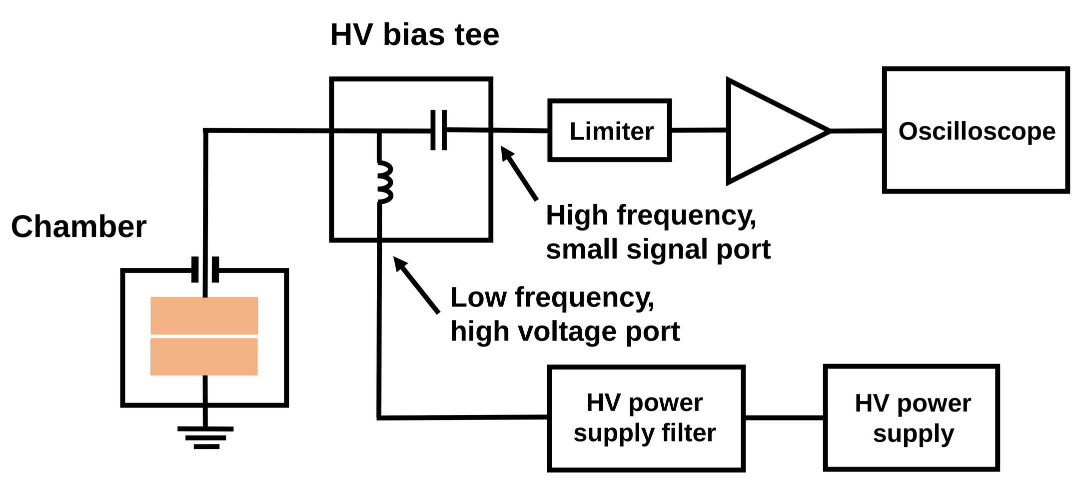
Experiments were also performed in the DC systems at CERN [7] to search for the same fluctuation phenomena under different conditions.

The vacuum chamber was connected to a non-pulsed high voltage supply along with a specialised setup designed to measure high frequency signals originating from the inter-electrode gap with high bandwidth (up to 1.5 GHz) and maximum sensitivity. A study in CST Microwave Studio [5] was also performed to estimate the coupling of high frequency signals from the gap to the feedthroughs of the chamber.

EM simulation for predicting measurement sensitivity:

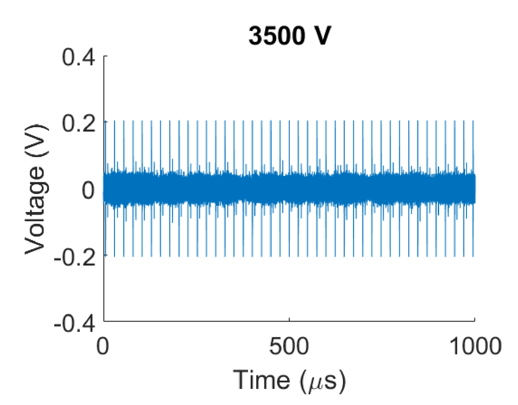


Block diagram of electronics hardware:

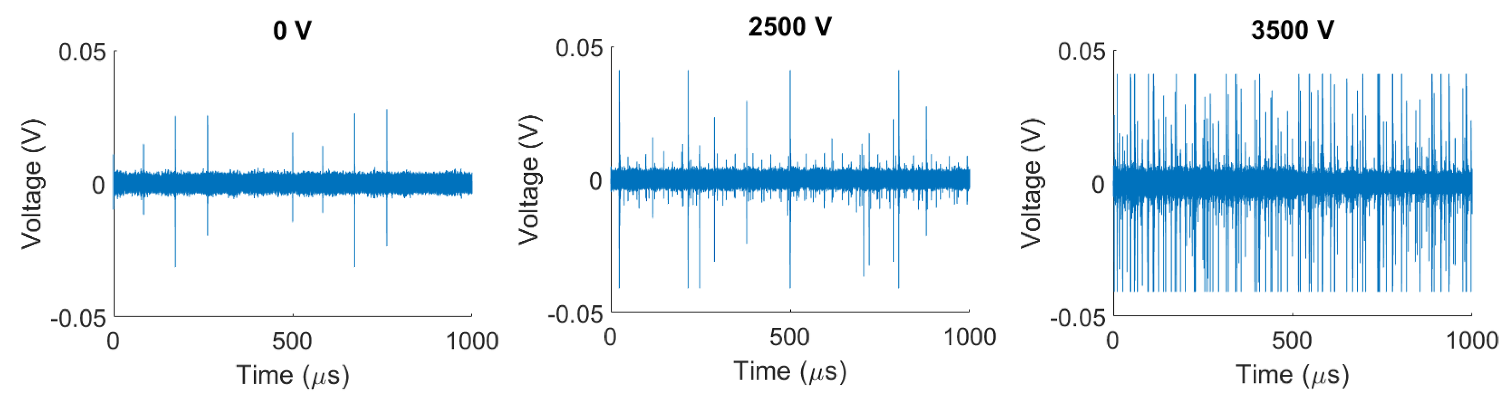


Current bursts during field emission experiments

Signal with resistive load:
Regular current spikes



Measured signals with electrodes under high field:
Current spikes randomly distributed, increasing frequency with voltage



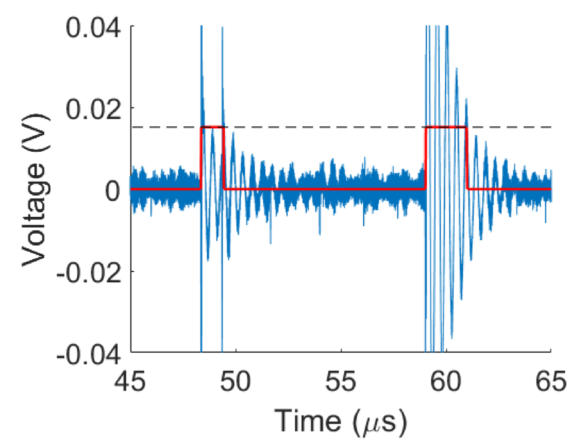
Measurements on the DC spark systems with a high voltage bias tee reveal voltage spikes and subsequent ringing. The ringing is believed to be caused by the dynamic response of the reactive elements in the high voltage power supply to an impulse of current.

Noticeably different behaviour has been observed when the power supply is loaded by a resistor and by the DC system. With the DC system, the impulses appear to be randomly distributed in time and rapidly increase in median frequency as the voltage is increased. This suggests the presence of stochastic phenomena at play in with field emission, which are not present with a resistive load. This, along with the voltage dependence of the time between impulses, strongly suggests that these are not external interference but related to field emission.

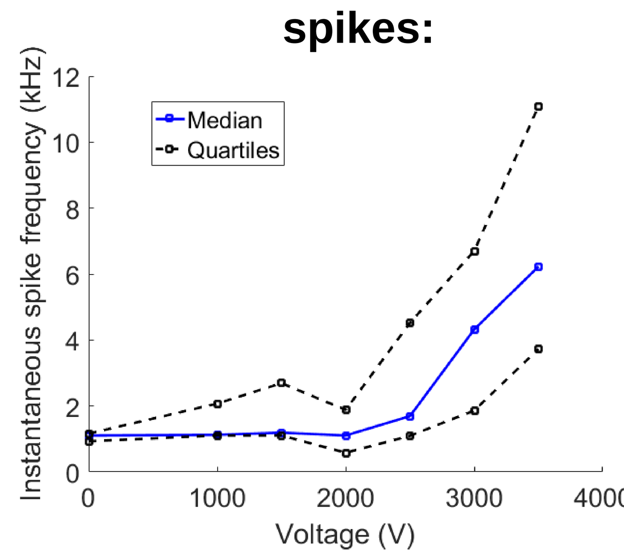
Due to a resonance of the vacuum chamber at 660 MHz, a local maximum of sensitivity to dark current signals at this frequency was expected. However, no evidence of a signal at this frequency has been found. (i.e. no difference between high voltage on and off.)

The experimental evidence gathered so far suggests that the constant, broadband fluctuations expected to arise from a large population dislocations moving randomly cannot be measured via dark current. However, the presence of randomly distributed current spikes implies stochastic behaviour in some form and should be investigated further. It should be noted that the typical time between these spikes (10 - 100 μs) greatly exceeds the duration of RF pulses within the accelerating structures (up to 200 ns), which may explain the lack of measureable signal in the RF experiments.

Detailed view of current spikes:



Time distribution of current spikes:



[1] E. Z. Engelberg, Y. Ashkenazy, and M. Assaf, "Stochastic Model of Breakdown Nucleation under Intense Electric Fields," Physical Review Letters, vol. 120, no. 12, p. 124 801, Mar. 2018. doi: 10.1103/PhysRevLett.120.124801.
[2] A. Grudiev, W. Wuensch, and G. Switzerland, "Design of the CLIC Main Linac Accelerating Structure for CLIC Conceptual Design Report,"
[3] D. M. Dimiduk, C. Woodward, R. LeSar, and M. D. Uchic, "Scale-Free Intermittent Flow in Crystal Plasticity," Science, vol. 312, no. 5777, pp. 1188{1190, May 2006, issn: 0036-8075. doi: 10.1126/SCIENCE.1123889.
[4] J. Paszkiewicz, P. N. Burrows, and W. Wuensch, "Spatially Resolved Dark Current in High Gradient Travelling Wave Structures", 2019, in 10th International Particle Accelerator Conference (IPAC2019), doi: 0.18429/JACoW-IPAC2019-WEPRB062
[5] CST Microwave Studio, https://www.cst.com/products/cstmws
[6] See talk and poster by L. Millar.
[7] See talk and poster by I. Profatilova.