Breakdown statistics: RF and DC

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CLIC and breakdown

•Vacuum electrical breakdown in the accelerating structures is a problem for CLIC. A lone breakdown anywhere along the 50 km of accelerator disrupts the beam that's currently in it:

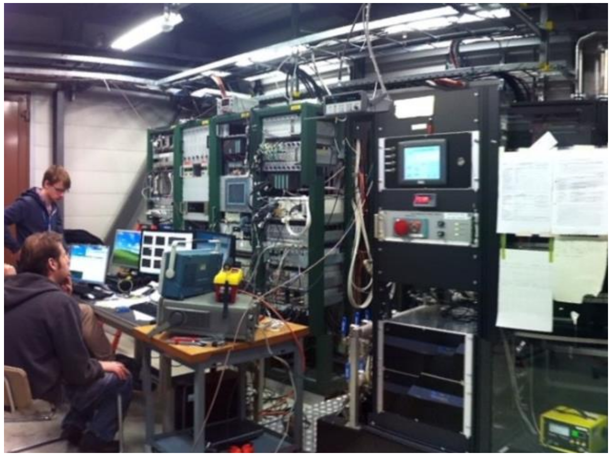
$$\xcancel{\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r}$$

•From the CLIC Conceptual Design Report:

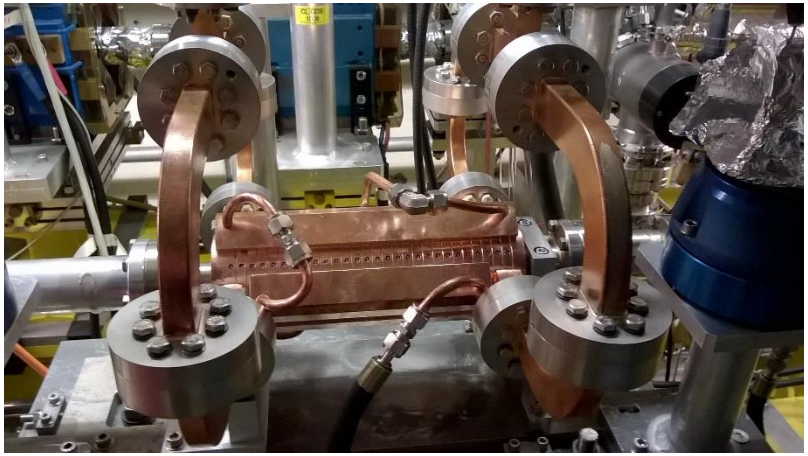
> *An accelerating structure that allows high gradient and a stable beam is essential for a cost-effective design. This requires:*
> *…*
> *-RF breakdown rate of <3×10^{-7} per pulse per metre of structure…*

Studying breakdown

•Breakdown in accelerating structures is studied at the Xbox testing facilities at CERN. Similar facilities are operated at KEK and SLAC.



Xbox-1 controls

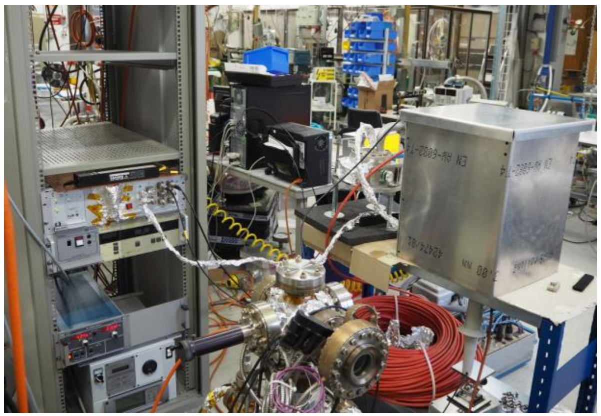


Xbox-1 test bench with structure

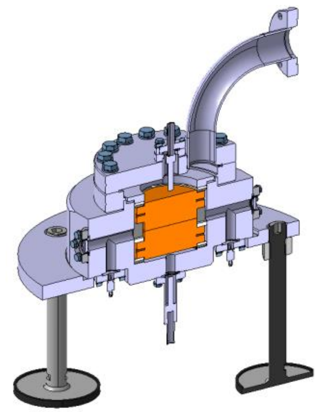
•In CLIC, a drive beam is used to produce the RF voltage pulses that power the structure with the main beam. Here, klystrons are instead used to produce the RF pulses that drive the structure, and it's run without beam in it.

The DC Spark Lab

•In addition to the Xboxes, we have at CERN a place called the DC Spark Lab, where we do breakdown experiments using lower-voltage systems:



DC Spark Lab



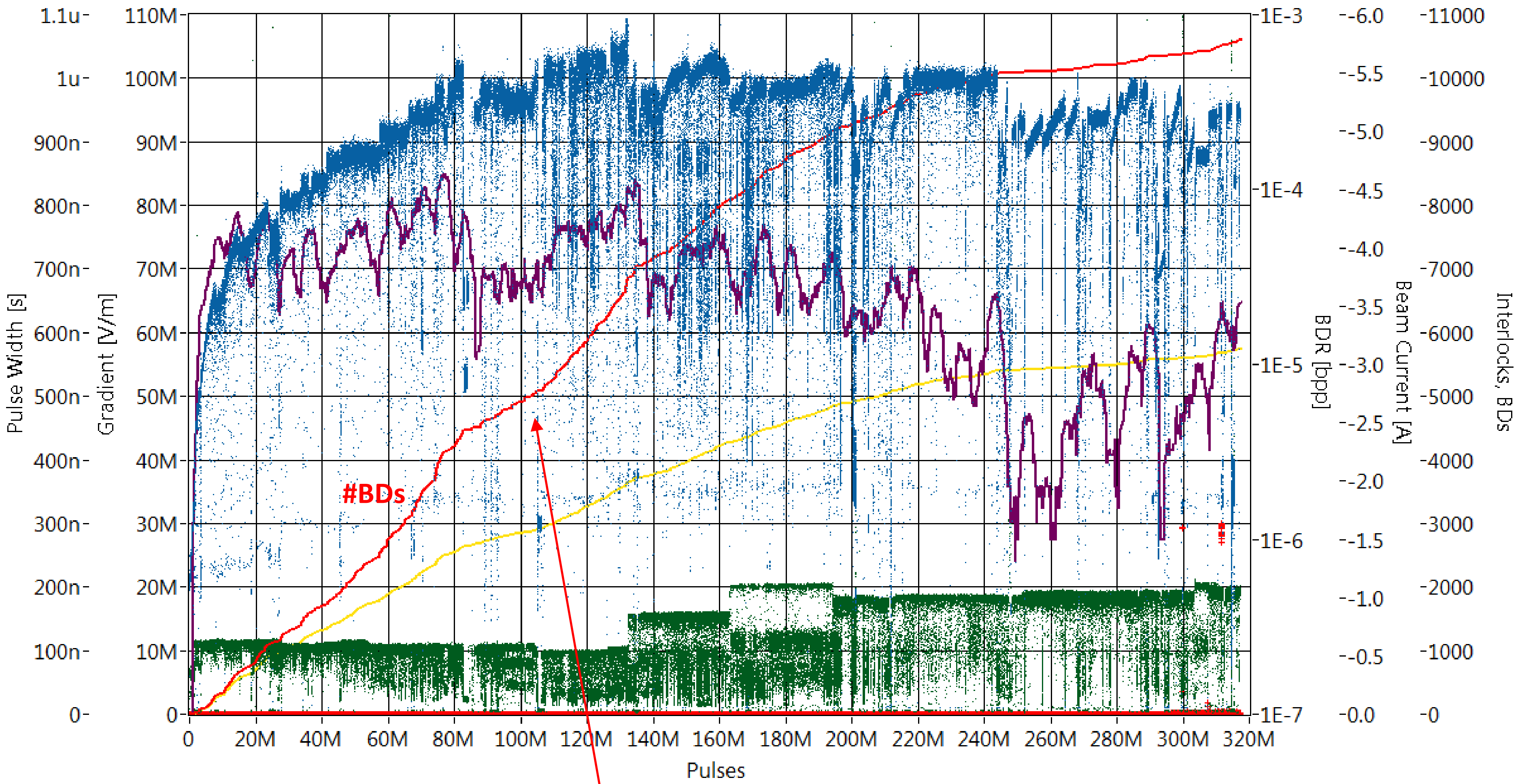
Large Electrode DC Spark System

Large Parallel-Plate Electrode used for DC spark experiments

•By applying voltages in the kV range over electrode gaps in the µm range, the electrodes are subjected to surface fields on the order of 100 MV/m, same as accelerating structures

•The advantages of these systems are low cost and fast data collection (pulsing rate of up to 1 kHz compared to 50 Hz for Xbox-1).

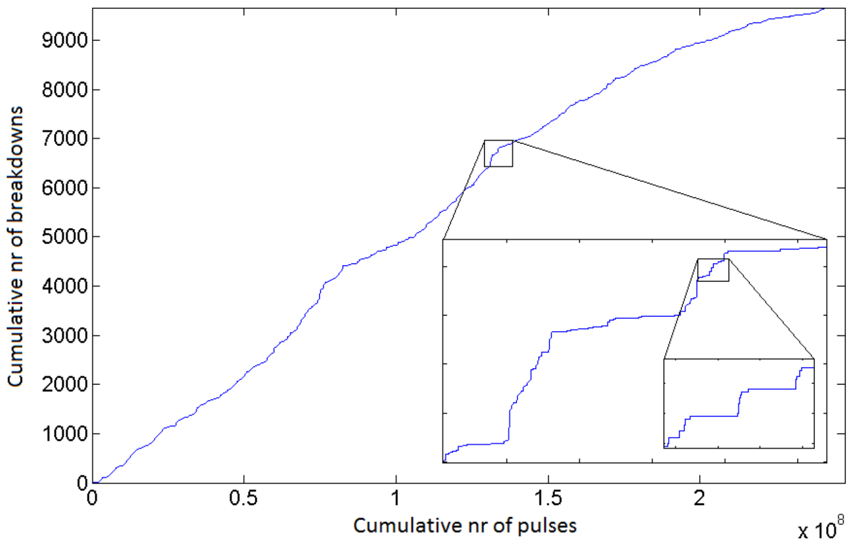
What is breakdown statistics?



- This.

What is breakdown statistics?

•The operational history of an accelerating structure tested in Xbox-1 is shown. Instead of accumulating breakdowns at a constant rate, it shows a “staircase” structure on many scales in a self-similar way.



•Hence, a single (overall) breakdown rate, i.e. $n_{breakdowns}/n_{pulses}$, is clearly insufficient to describe what’s going on. It doesn’t say anything about when breakdowns happen…

- •…in relation to the overall history
- •…in relation to each other

Why study breakdown statistics?

•Knowing what kind of breakdown behaviour to expect helps in designing CLIC and developing strategies for operation

- •The Conceptual Design Report assumes breakdown statistics to be Poissonian, which we know they are not

•The underlying material mechanics that cause breakdown are not well known, but the subject of intense modelling and simulation work.

- •Such basic research might help us find out how to build accelerators less prone to breakdown

- •Study of breakdown statistics provides these efforts an empirical reality check

Number of pulses to breakdown

•A statistical property we have investigated is *number of pulses to breakdown*, i.e. how many consecutive pulses it takes to get a breakdown, or equivalently, number of pulses between two breakdowns.

•To visualize, imagine a structure is pulsed, each pulse either causes or doesn't cause a breakdown. We get an operational history that looks something like this:

□: non-breakdown pulse, ■: breakdown pulse

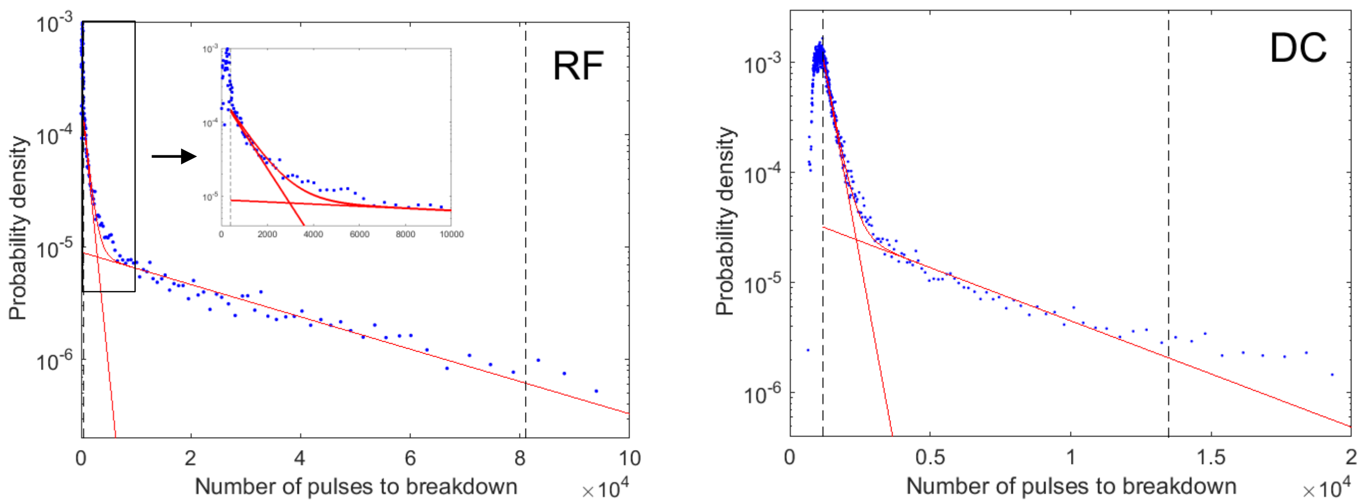
□□□□■□■□□□□□□■□□□■□□□□□□□□□■□□■■□□□□□□□□□■□■□□■■□□

5 2 7 4 10 3 1 10 2 3 1

•The numbers below the white and red squares are samples of *number of pulses to breakdown.* We have conducted a number of breakdown measurement runs to collect statistics to find out the distribution of this value.

Pulses to breakdown, statistics

•In both RF and DC, and under several different sets of experimental conditions and input parameters, we get distributions for number of pulses to breakdown like this:



•When plotted with a log-y-axis, all distributions show a kinked-line shape. A straight line in log-y is an exponential decrease. With the exception of some data far out on the upper tail of the distribution, a fit of a sum of two exponentials fits the data well in each case. This, despite the fact that the actual parameters of the fits and other properties of the distributions are orders of magnitude apart!

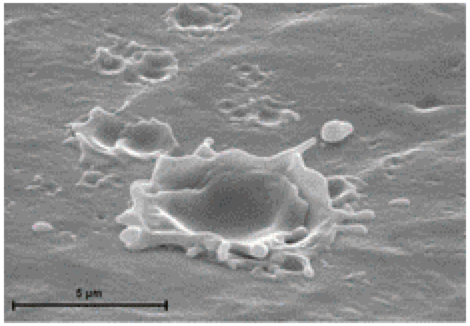
Two-Rate Statistics

•An exponentially decreasing probability distribution signifies Poisson statistics, with the slope on the log-y plot being the event (BD) rate

•A distribution shaped like a sum of two exponentials suggests that the data has been sampled from two distributions, both individually Poissonian but with different event rates

•We posit the following hypothesis: The two terms of the distribution each correspond to a different kind of breakdown event:

- •Primary breakdowns, that happen independently all the time
- •Follow-up breakdowns, that have been caused by previous breakdowns, through the creation of features particularly susceptible to breakdown



SEM image of breakdown crater, Timko et al 2010

Two-Rate Statistics

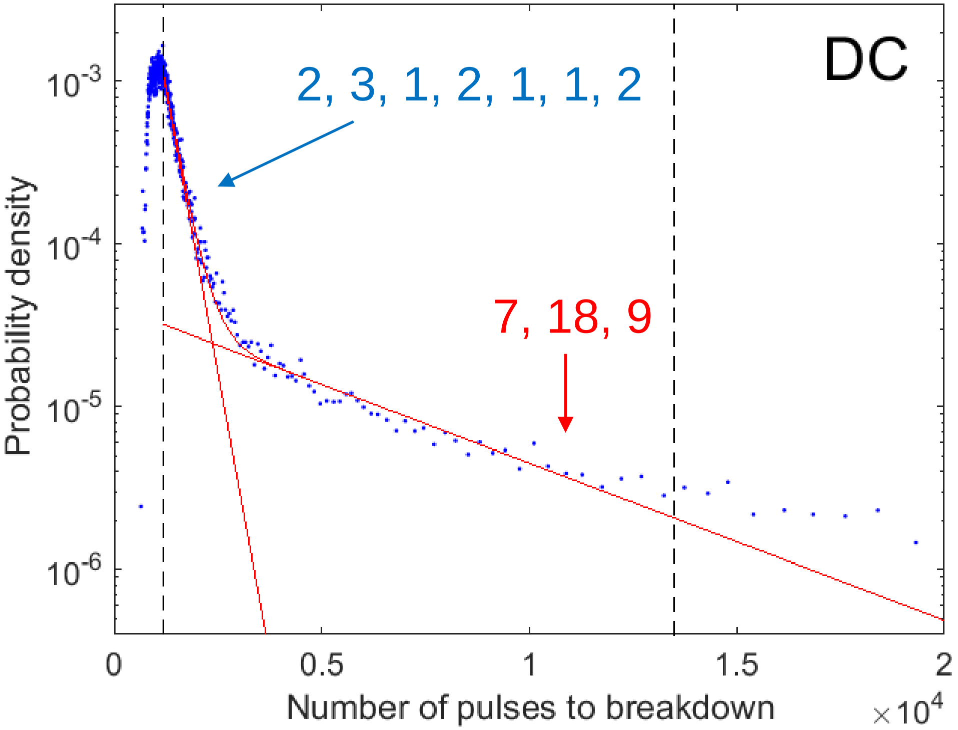
•Or, to visualize what was just explained, let's return to the operational history vector and to number of pulses to breakdown:

□: non-breakdown pulse, ■: primary BD, ■: follow-up BD

□□□□□□■□■□□■□□□□□□□□□□□□□□□□□□■■□■■□□□□□□□□□■■□■□□□□

7 2 3 18 1 2 1 9 1 2

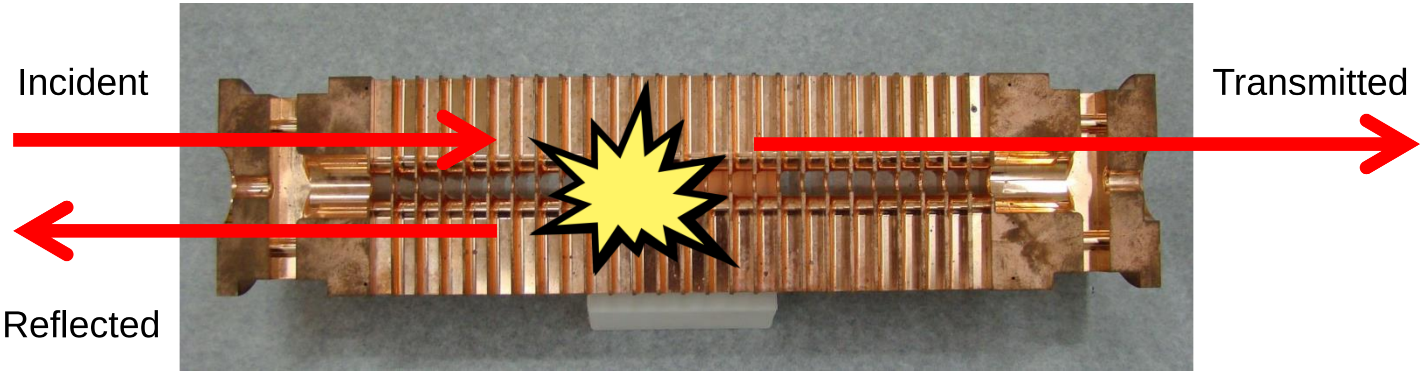
•Red numbers are values for nr of pulses to BD for primary BDs, blue for follow/up BDs. Red and blue are individually Poissonian, giving a two-exponential probability density when put together



Breakdown localization

•If our hypothesis is true, we'd expect follow-up breakdowns to happen close to where the primary breakdown did

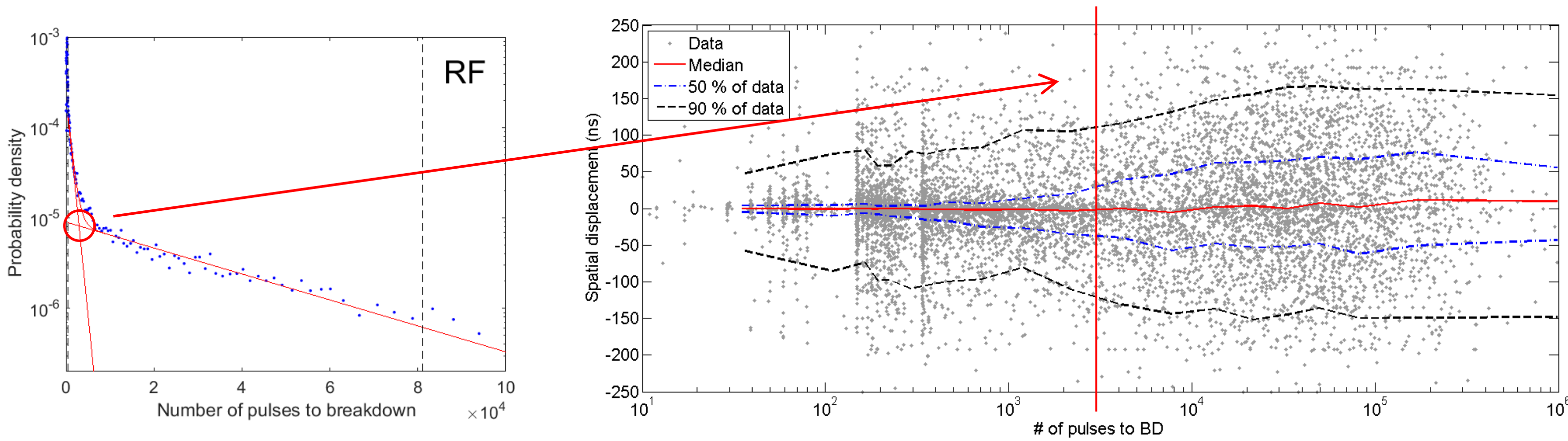
•Xbox-1 has a limited capability to localize a breakdown when it happens, by measuring and comparing the time delays between transmitting RF power, and picking up power transmitted through, and power reflected back by the breakdown:



•These time delays are not one-to-one functions of breakdown position, but give a rough 1D position coordinate

Breakdown localization

•For the RF measurement data previously presented, the distance between every pair of two subsequent breakdowns is plotted against the number of pulses between them:



•We see that breakdowns that happen soon after the previous one also tend to happen close in space, with the spatial correlation converging towards no correlation as nr of pulses between the breakdowns increases.

Conclusions

- We have found that observed breakdown statistics can be explained by there being two kinds of breakdown events, both individually Poissonian:

  - Primary breakdowns happening independently, all the time, at a low probability on any given pulse

  - Follow-up breakdowns that can only happen when induced by a previous breakdown, but with a high probability on any given pulse when so induced

Conclusions

•This has implications breakdown studies: Instead of asking how this or that variable affects *the* breakdown rate, we should ask questions like: Does it affect the primary rate? The follow-up rate? Does it make breakdowns more or less likely to cause follow-up breakdowns? etc. Examples:

•The oft-used relation BDR ~ $E^{30}\tau^{5}$

- •When E or τ is increased, is the increase in (overall) BDR due to getting more primary breakdowns, or due to a higher number of follow-ups per primary?

•Is it possible to prevent follow-up breakdowns from happening, e.g. by slowly ramping up the power after a breakdown? How should an accelerator be operated in this regard to maximize the time we are running at full power without breakdown?