Conditioning of Large-Area Vacuum Breakdown Systems

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What is conditioning?

- The development of resistance to breakdown over the operational lifetime of a device
- Can be described as decrease in breakdown rate when device is run at constant voltage pulse amplitude and length
- Alternatively, conditioning can be described as increase in maximum pulse amplitude and/or length that can be used without exceeding a maximum permitted breakdown rate

Why does it matter?

- For most devices, breakdown is the main failure mode
  - Conditioning increases device reliability over its lifetime

- For some devices, breakdown is part of the intended mode of operation
  - Conditioning makes the device degrade over time

- For some devices, such as the CLIC accelerating structure, performance is proportional to voltage put in
  - Conditioning permits higher voltages and thus higher device performance at a given breakdown rate

- For the last kind of device, conditioning can be used as part of the device manufacturing process. To do this in an efficient way, the conditioning process must be understood.

Quantifying conditioning

- Experiments in various accelerator facilities have shown breakdown rate to depend on electric field strength E and voltage pulse length τ as follows:

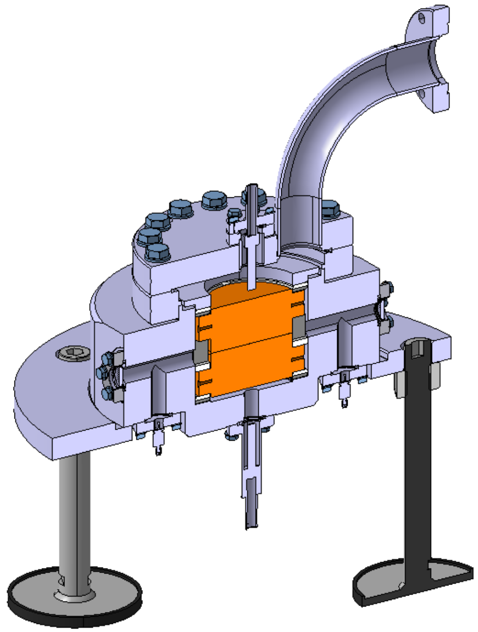
$$BDR \propto E^{30}\tau^{6}$$

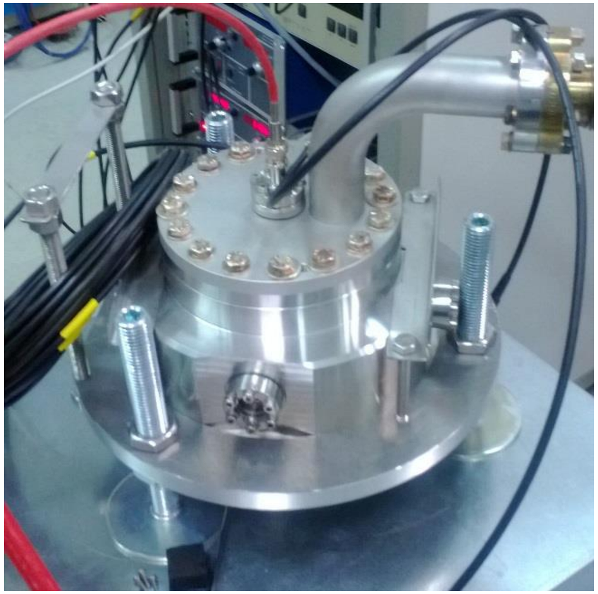
- To quantify the conditioning state of a structure in a way that is comparable across different values of E and τ, a quantity called *normalized breakdown rate* can be used:

$$BDR_N = \frac{BDR}{E^{30}\tau^{6}}$$

- One can also, by instead solving for E, use a normalized field strength $E_N = E\ BDR^{(1/30)}\ \tau^{(1/5)}$, but we will only use normalized BDR in this presentation

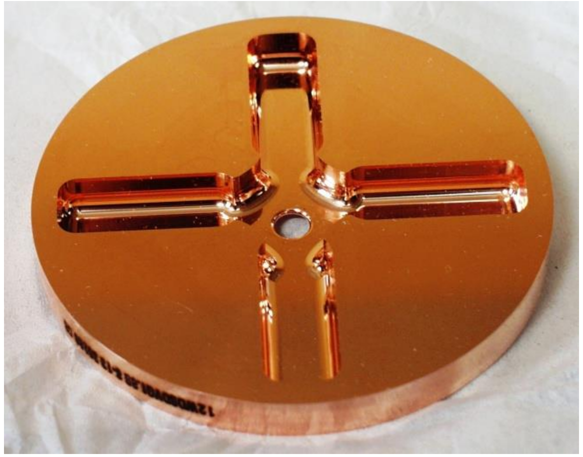
Our System





- System consists of a vacuum chamber with a pair of parallel copper disc electrodes of diameter 6.2 cm, separated by a 60 µm gap. Voltage pulses are applied across the electrodes at a repetition rate of up to 1 kHz, compared to 50 Hz for XBox, the CLIC test facility for prototype accelerating structures. High repetition rate and low hardware cost are the motivation for using these kinds of systems to complement the experiments in XBox.

Our System



- Key feature is that area subjected to electric field is orders of magnitude larger than a breakdown spot. This is analogous to CLIC accelerating structures, which consist of series of cells (right image) separated by irises which each have a few cm^2 of contiguous surface subjected to breakdown field.

- Just to give an idea: assume a breakdown spot size of diameter 10 µm. To cover the entire electrode (left image) in breakdown spots would require 38 million non-overlapping breakdowns. This fact is what drives conditioning: The majority of the surface will never see a breakdown, but feel the effect of every voltage pulse applied over the electrodes

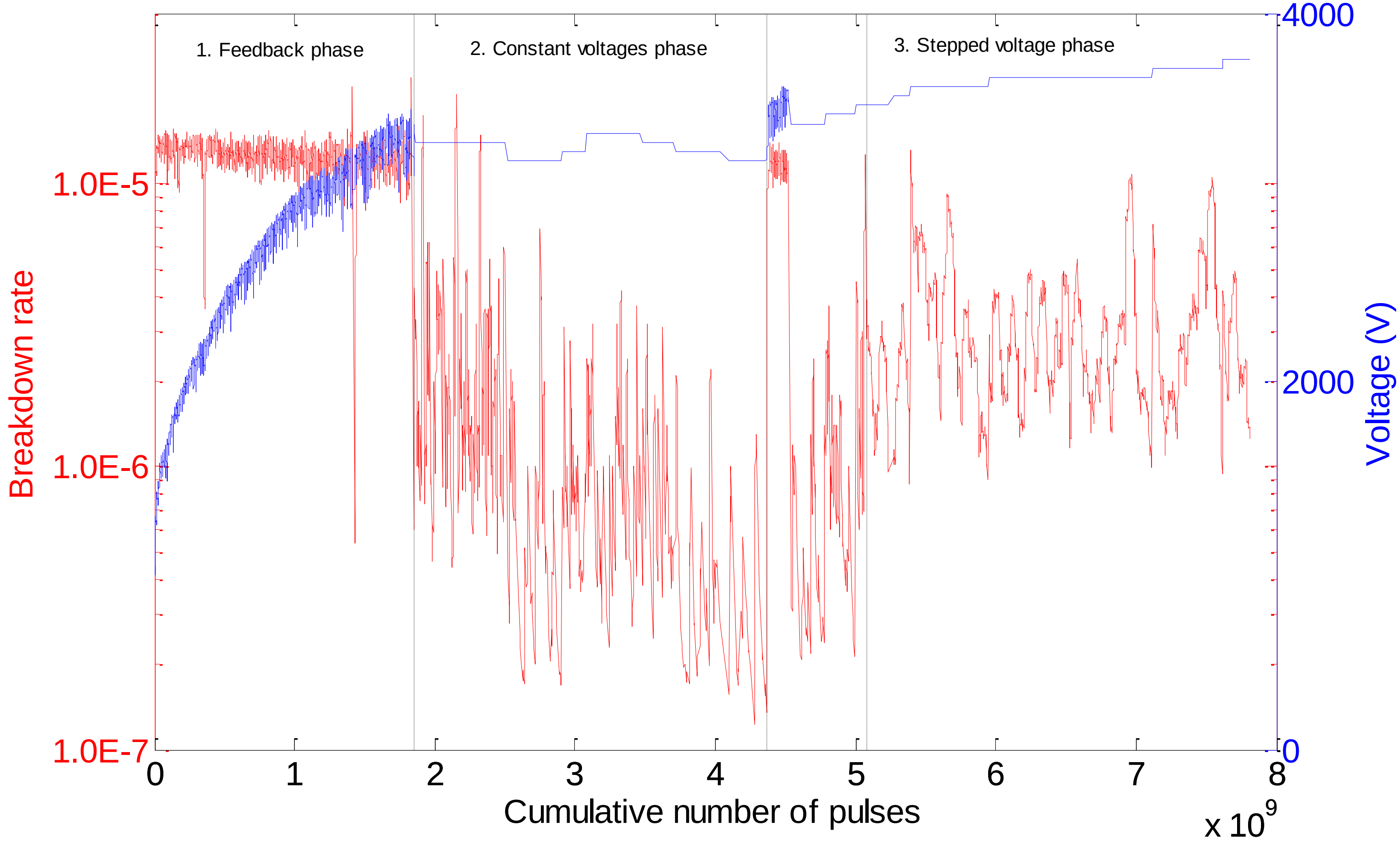
The Experiment

- The experiment was started 16.4.2015 and has been running largely uninterrupted since then, and had 36493 breakdowns over 7.8 billion pulses

- The experiment consisted mainly of 3 phases, in order:
  1. **Feedback phase**, decrease voltage if a BD happens soon after last BD, increase voltage if run long enough without BD. Same algorithm as used in most experiments at XBox.
  2. **Constant voltages phase**, manually set levels, moving up and down in voltage.
  3. **Stepped voltage phase**, run at a constant voltage and increase it by a constant-size step whenever a target BDR of 10^{-6} is reached. This algorithm has recently been adapted by XBox as well.

  Some other measurements were done between phases 2 and 3 but they are ignored here for lack of interesting results.

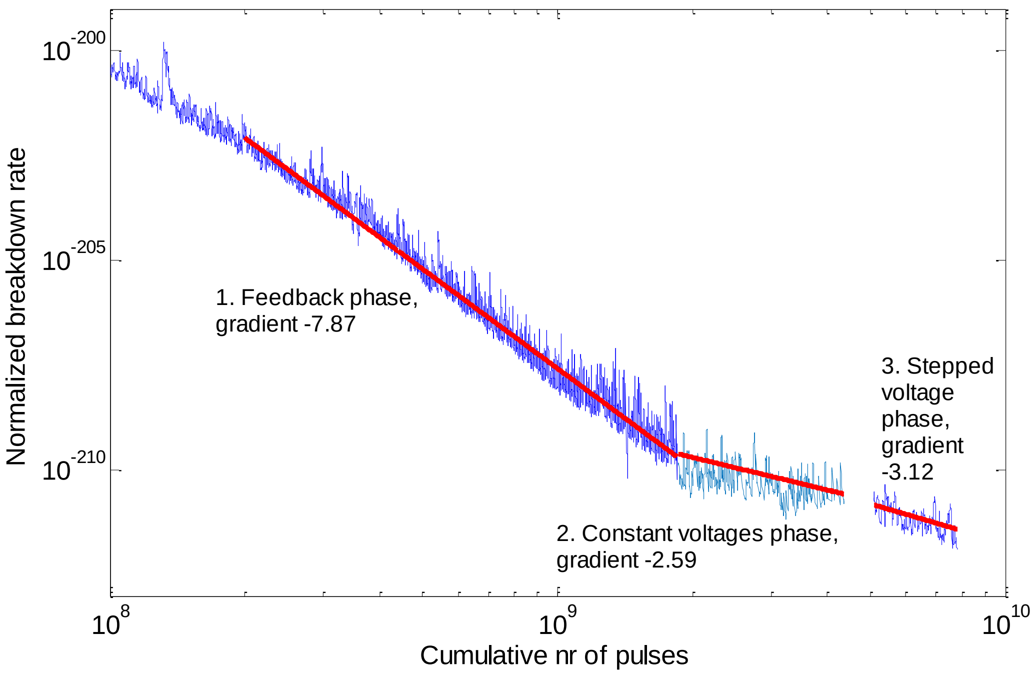
Experiment overview



- The 3 phases are shown, with the evolution of voltage and breakdown rate over the course of the experiment

Conditioning rate

- On a log-log plot of normalized BDR vs cumulative nr of pulses, each phase is individually very linear
- The feedback phase has the fastest conditioning, with a gradient of -7.87, which very closely matches results from XBox



- The significant difference in gradient suggests that choice of algorithm matters greatly for achieving a good conditioning rate
- The fact that each phase is individually very linear in log-log suggests that the difference in conditioning gradient is not due to saturation, which would show as the relationship leveling off within the phase during which it happens

Conclusions

- Using the same conditioning algorithm used for prototype accelerating structures at XBox, we have obtained remarkably similar conditioning behaviour, validating the use of our system for conditioning studies

- We have seen that choice of conditioning strategy matters greatly for the purpose of achieving the most amount of conditioning in a given time

    - Our system, with its high repetition rate, is ideally suited for the testing of conditioning strategies

- No signs of saturation were seen even after 7.8 billion voltage pulses, suggesting that large-area breakdown systems will keep conditioning over the entire course of their operational lives