High Gradient Test Results at CERN

Lee Millar[1,2] on behalf of the Xbox team

[1]Lancaster University Engineering Department: *Graeme Burt*

[2]CERN, BE-RF Section: *Walter Wuensch*

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Overview of the Xboxes

- The Xboxes are X-band (12GHz) test stands located at CERN in Geneva, Switzerland.
- Constructed to develop and test the main accelerating structures and novel (12GHz) RF components for CLIC at high power.
- Aim to shed light into the conditioning and breakdown processes.
- Also used for developing external applications such as FELs (Free Electron Lasers), Compton/Thomson sources or medical and security LINACS.
- For full specs see “X-band test facilities at CERN” by Nuria Catalan Lasheras

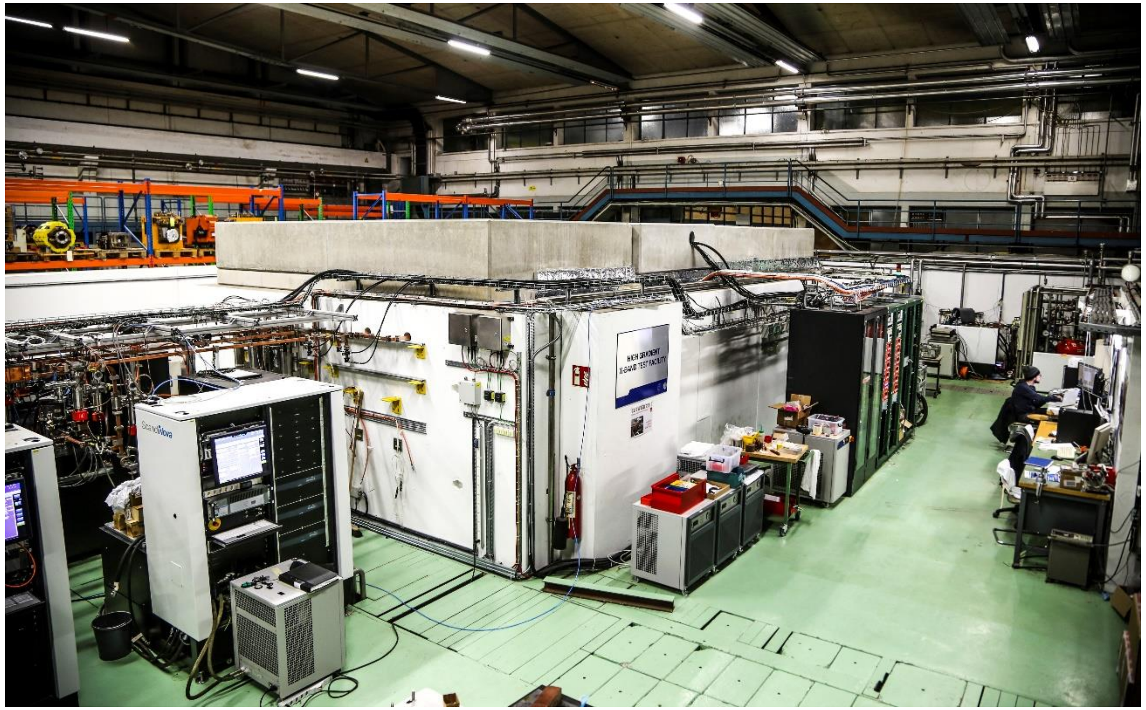


Figure: X-band high gradient test facility at CERN
(Picture courtesy of Matteo Volpi).

Breakdown

- Small defects/foreign bodies/dislocations on the surface can enhance the electric field by factors of 30-100.
- This results in field emission.
- The emitted current scales as [1]:

$$\bar{I}_F = \frac{5.7 \times 10^{-12} \times 10^{4.52\varphi^{-0.5}} A_e(\beta E_0)^{2.5}}{\varphi^{1.75}} \, exp\left(-\frac{6.53 \times 10^9 \times \varphi^{1.5}}{\beta E_0}\right)$$

- This results in intense local heating effects i.e. Nottingham, Ohmic
- At high fields this heating can vaporise the emitter, forming a plasma in the accelerating cavity which is accompanied by several effects.

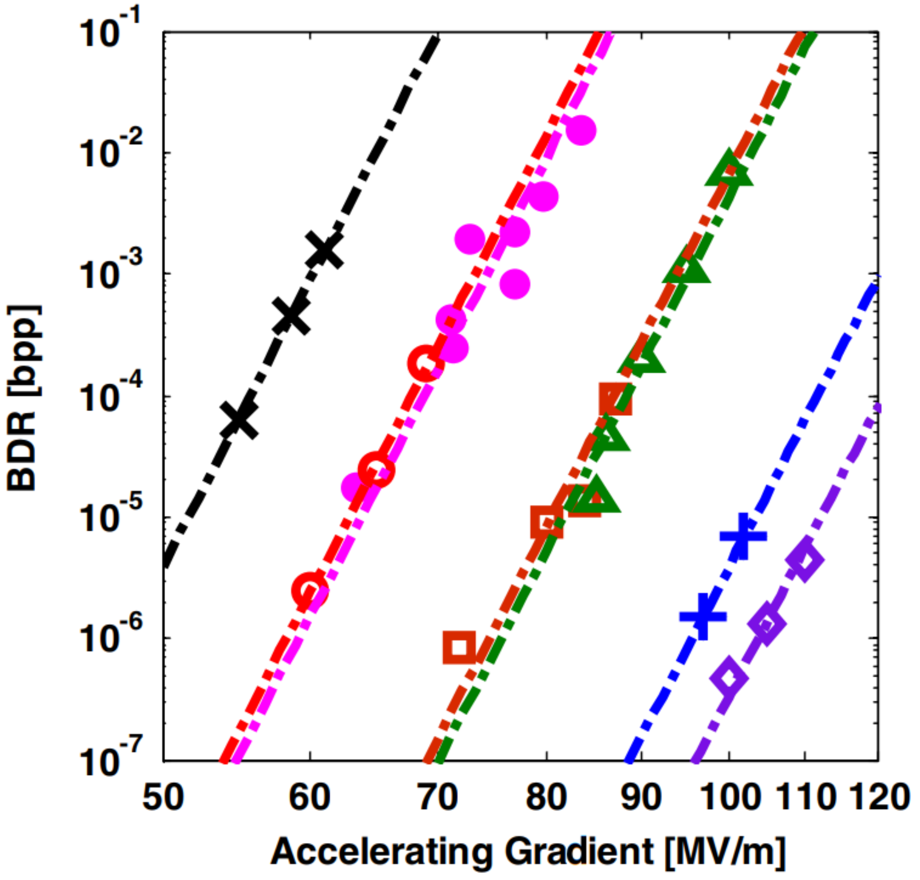


Figure: Breakdown rates (per pulse) vs accelerating gradient for various structures.[2]

Effects of Breakdown

Breakdowns are accompanied and often detected by:

- A drop in transmitted power
- Spike in the reflected power
- Increased dark current signals
- Increased X-ray emission

In general this means beam loss/degradation.

In a collider context this means luminosity loss on that pulse.

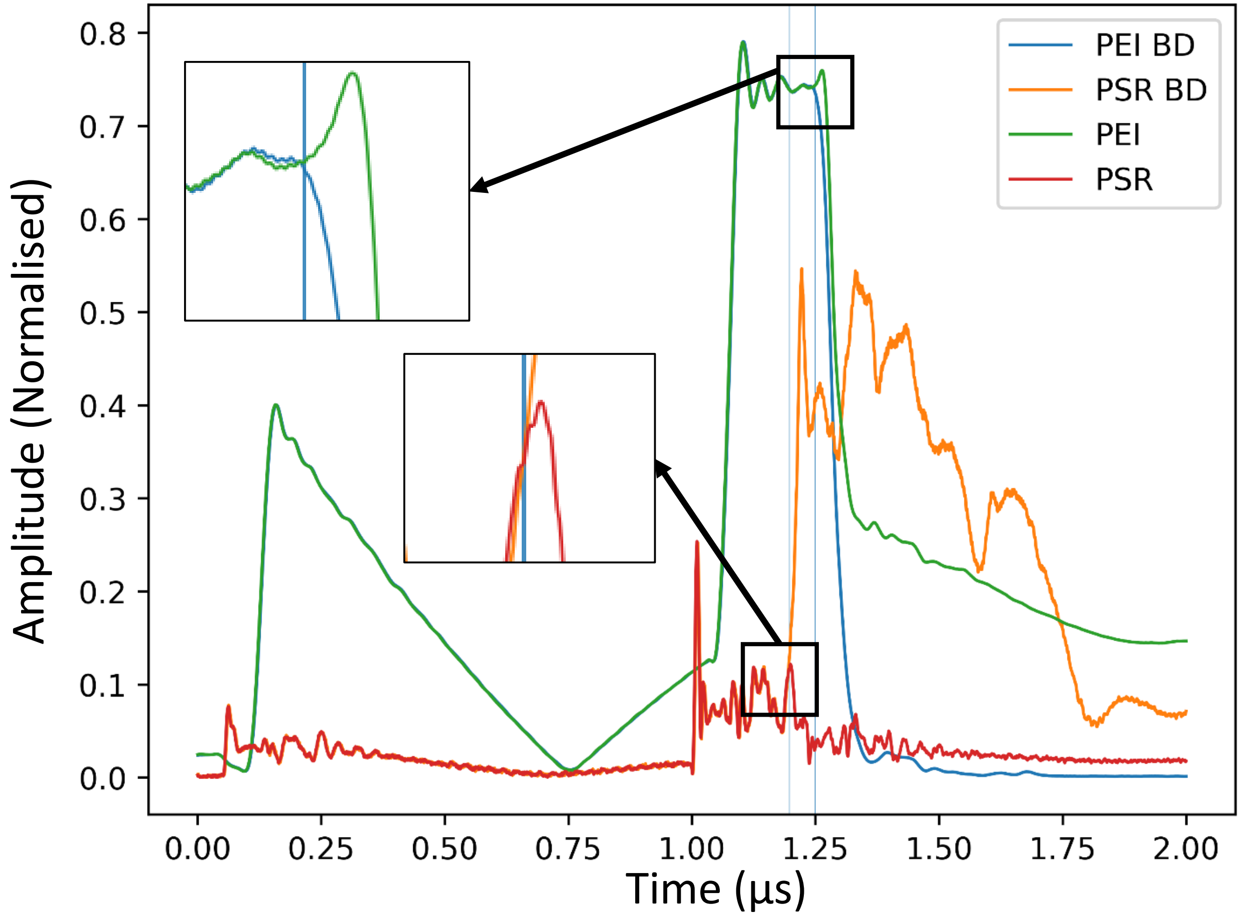


Figure: Normal transmitted and reflected RF signal (green and red) and transmitted/reflected signals during a breakdown (blue and orange).

Overview of the Conditioning Process

To date the Xbox test stands have successfully conditioned many structures (and high power RF components).

Generally follows three phases:

I. **Increasing gradient/power while keeping constant BDR.**

II. **Drop the power, increase the pulse length and ramp back up.**

III. **Finally, the BDR drops.**

A key point is that **conditioning takes many (≈hundreds of millions) pulses and is reproducible.**

Various other effects e.g. dark current, radiation emission, vacuum phenomena also observed (See talk from Jan Paszkiewicz tomorrow for more detailed discussion).

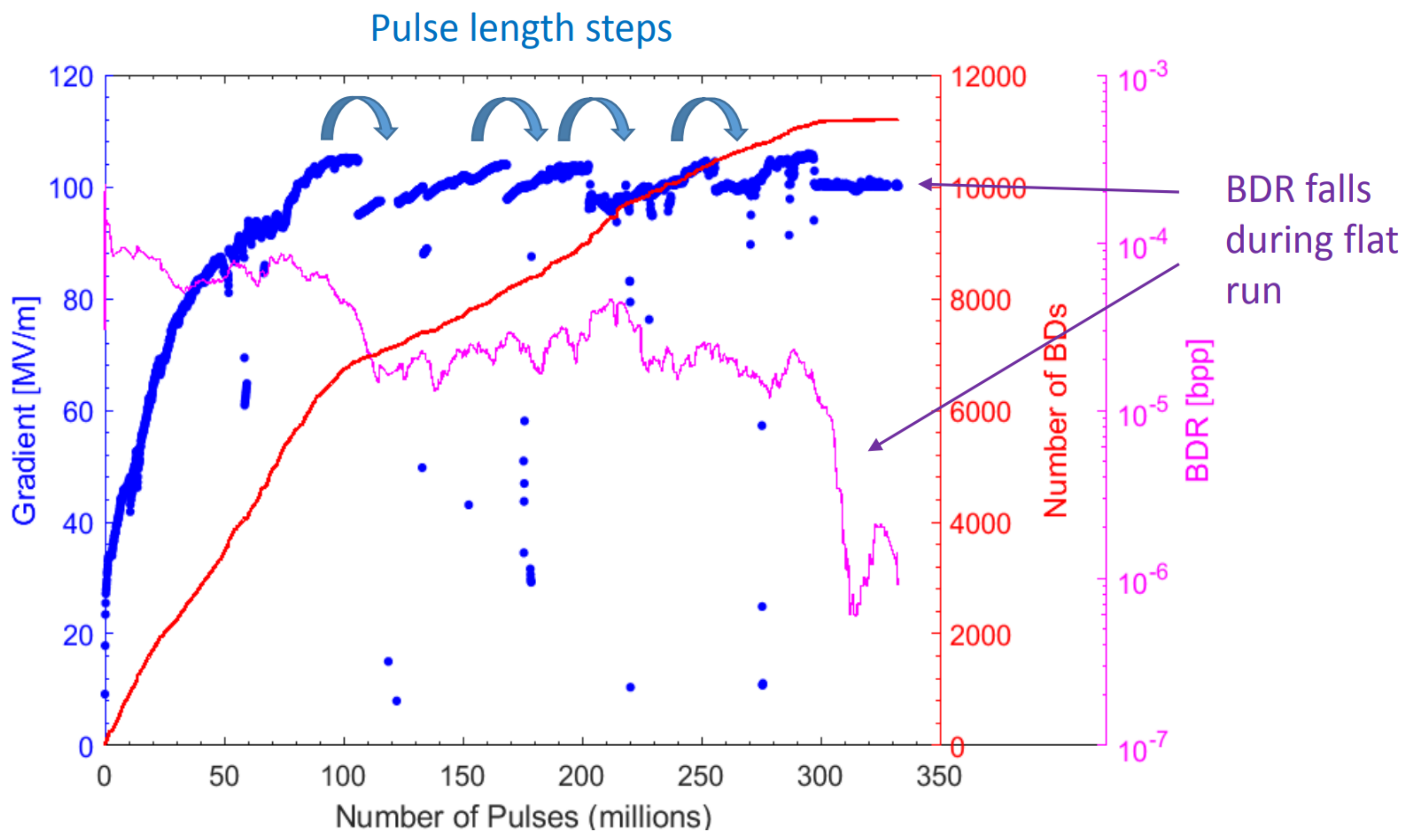


Figure: Typical example of a conditioning curve.

Devices Tested in 2018

Test Slot	Devices Tested
Xbox-1	TD26CCR05N2
Xbox-2	T24PSI1, T24PSI2
Xbox-3A	Spiral Load, Variable Phase Shifter, RF Terminator N1, T24 N4
Xbox-3B	Compact Load, RF Terminator N2/4, Variable Power Splitter, T24 N5
Xbox-3C	TD24 Baked Out, New SLED-I Pulse Compressor
Xbox-3D	TD24SiC2, TD24 Not Baked Out
Sbox (S-band)	BTW1

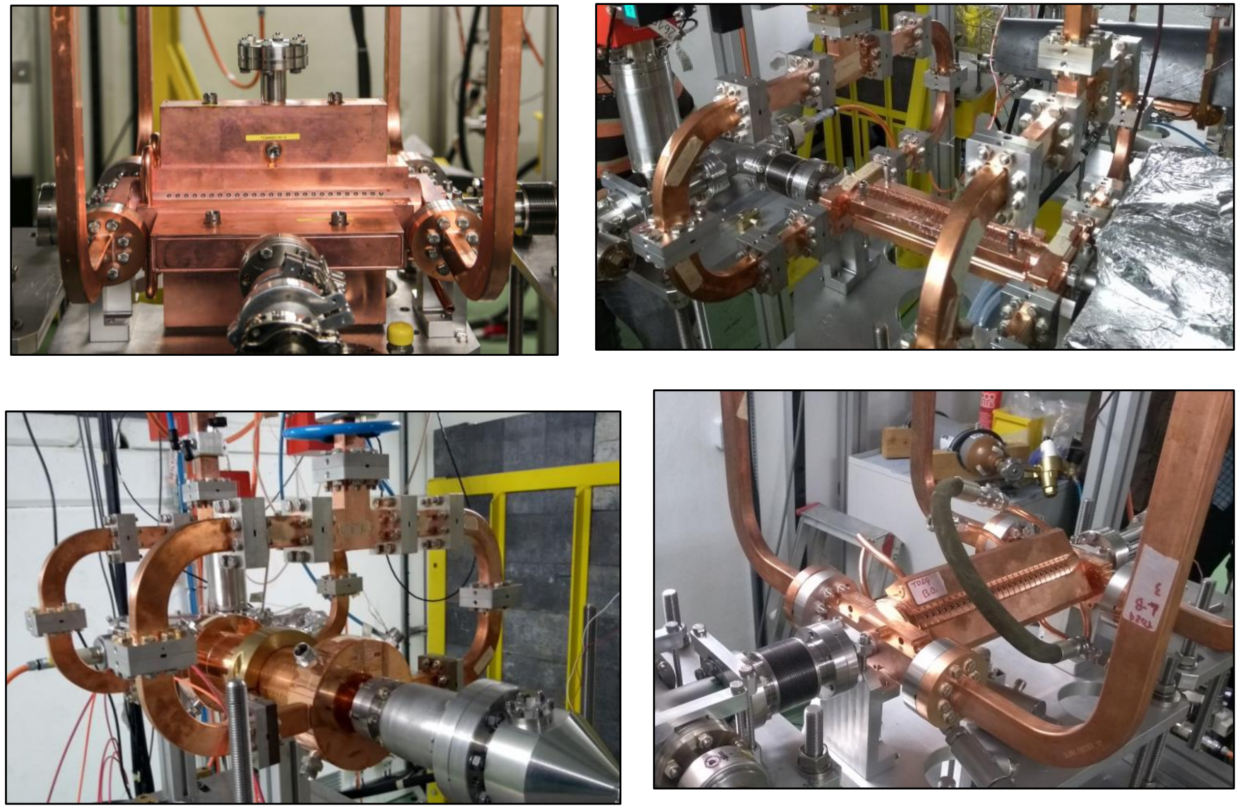
Note: Structures in red changed test slots during conditioning.

Structures Tested in 2018

In total we tested fifteen components in 2018, eight of which were X-band structures:

- TD26CCR05N2*
- T24 BO*, UBO*
- T24 N4,* N5*
- T24PSI1, T24PSI2
- TD24 SIC N2

Note: * = still undergoing testing



Figures: TD24 SiC (top left), T24 N4 (top right), PSI2 (bottom left) and TD24 BO (bottom right) structures installed in test slots.

Xbox-1: TD26CCR05N2

One structure has remained in Xbox-1 for the duration of 2018.

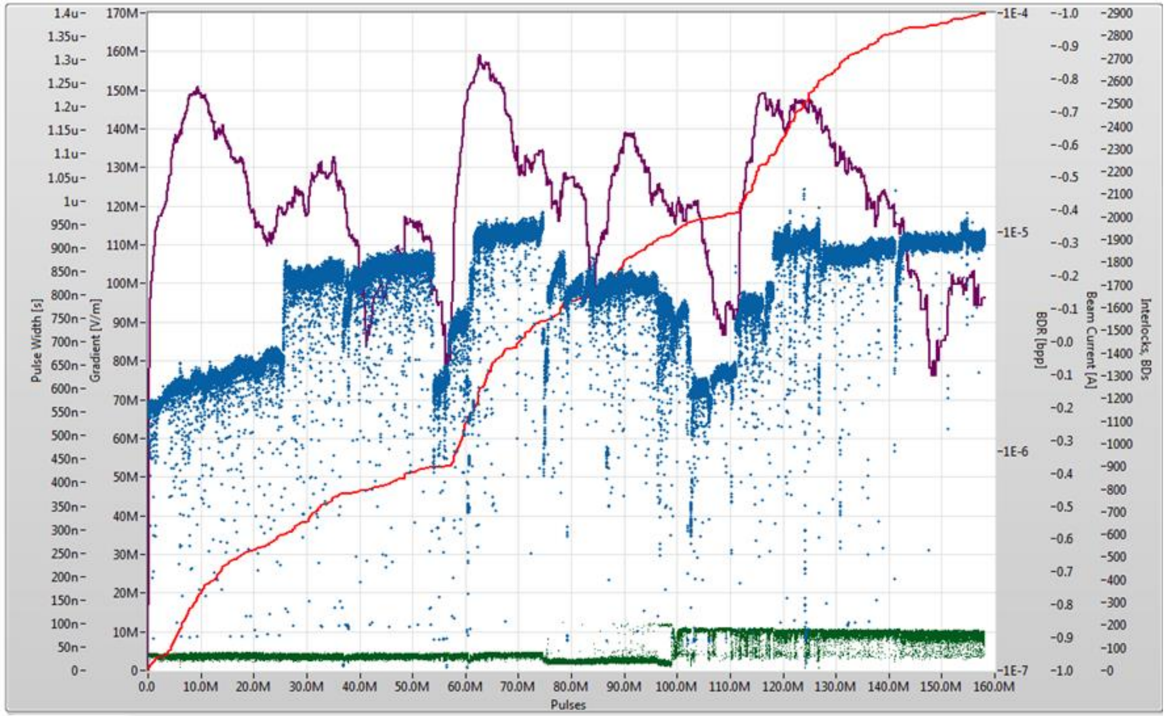
- CLIC Baseline Design, HOM Dampers, Compact Couplers.
- Reached 110 MV/m at ≈100ns pulse length.

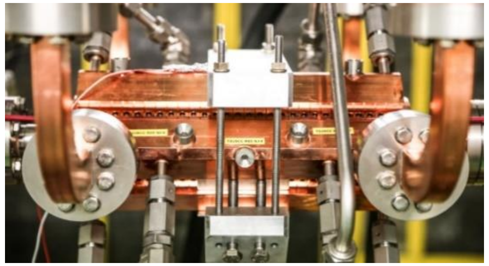
Little runtime in recent months has been achieved due to frequent interruptions. Completed and ongoing activities include:

- Klystron replacement
- Design and installation of a new LLRF scheme.
- Software update.
- Connection to the CLEAR facility for future experiments.

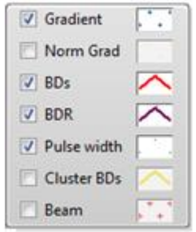
Currently the water for CTF-3 is off however testing is planned to resume shortly, quickly reached 36MW input power at 50ns again before the winter shutdown.

Status: Testing ongoing.





Figures: TD26CCR05N2 (left), conditioning curve (top) with legend (right).



Xbox-2: T24PSI N1/2

Overview:

- “Tuning free” technology.
- Manufactured by The Paul Scherrer Institute (PSI) using the same production line as SwissFEL.
- Allowed opportunity for a comparative study between the vacuum brazed technology applied by PSI to the diffusion bonding, which is presently used by CERN for CLIC structures.

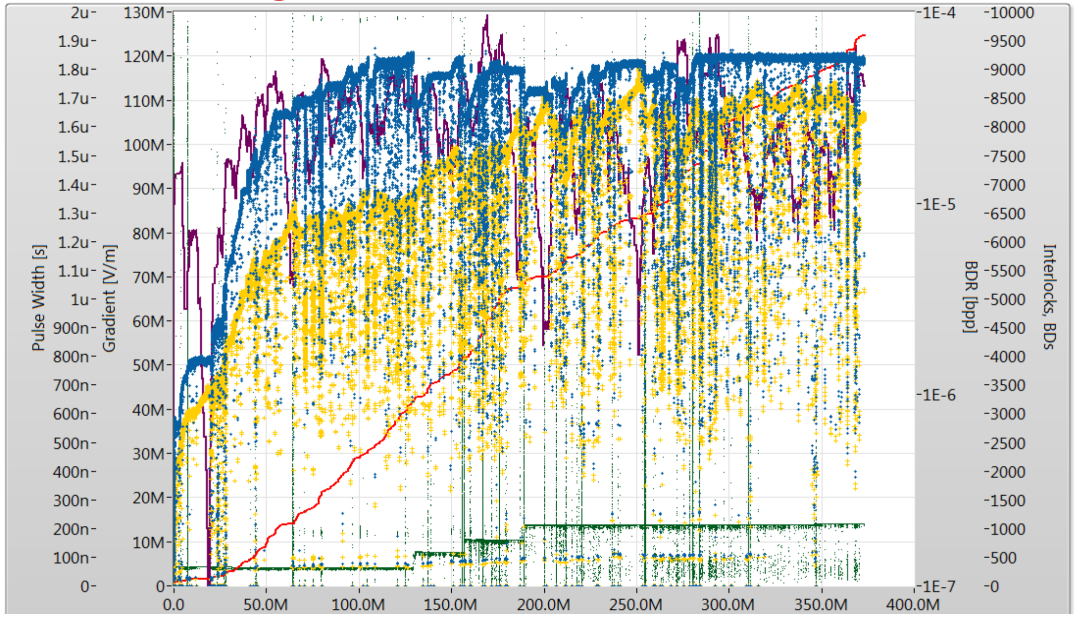
T24 PSI N1 (left):

- Reached 120MV/m at 200ns pulse length during testing.

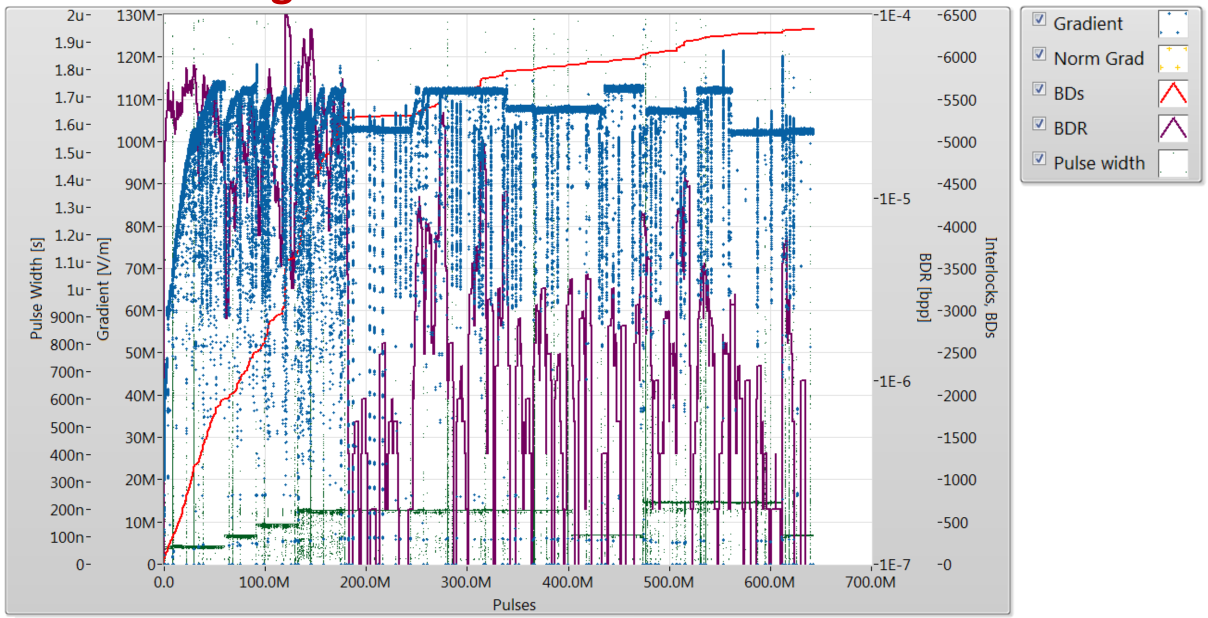
T24 PSI N2 (right):

- Ran long term at different pulse length and gradients to investigate BDR dependencies (more on this later).
- Ran at 103MV/m for over 3 days uninterrupted without a BD

Status: Testing Concluded

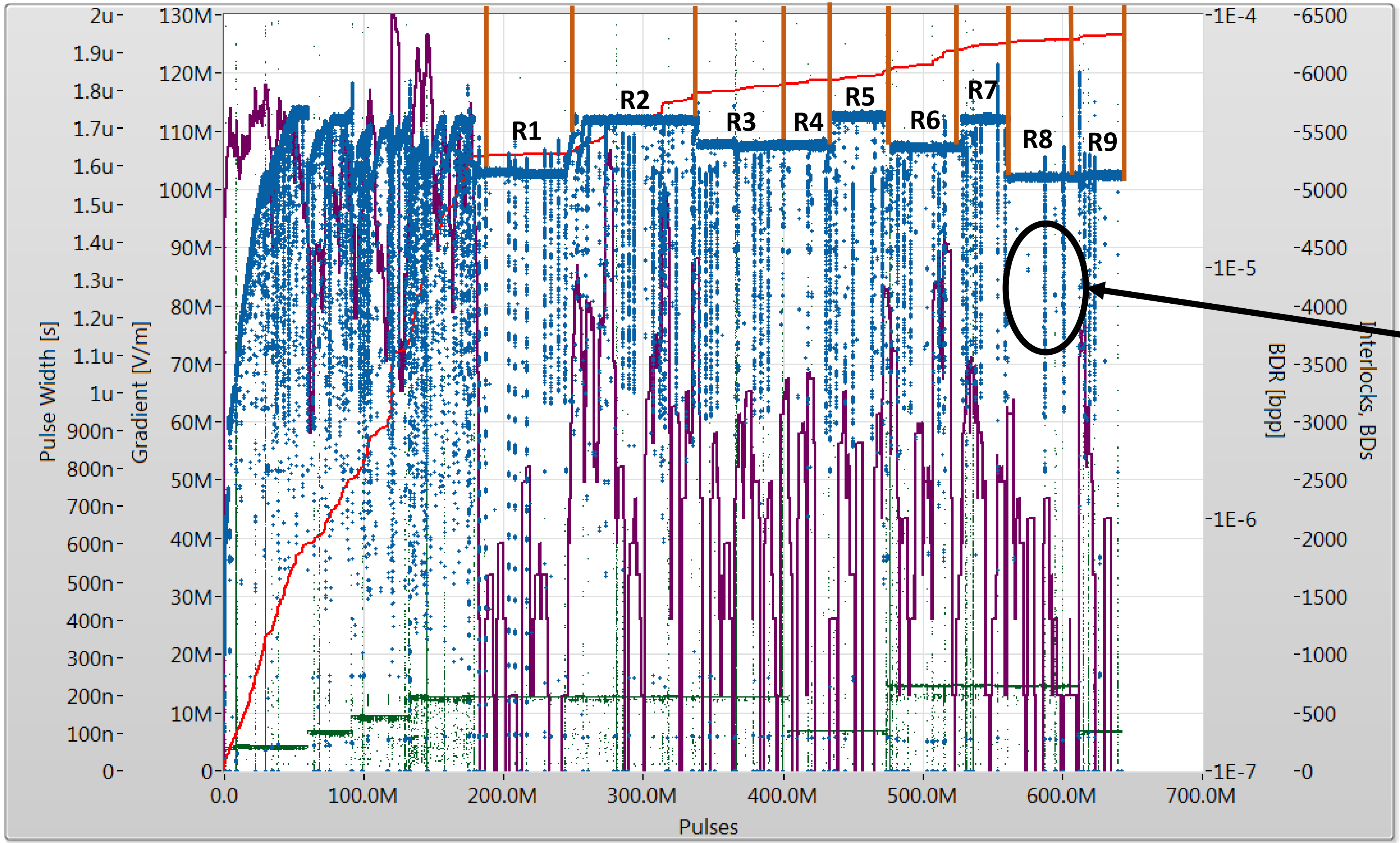


Status: Testing Concluded



Figures: Conditioning curves for the PSI1 (left) and PSI2 (right) structures.

T24PSI N2 Conditioning Summary



NB: Regular power drops due to dark current measurements

Run	Gradient (MV/m)	Pulse Length (ns)	Pulses (millions)
1	103	200	68
2	108	200	64
3	112	200	91
4	108	100	32
5	112	100	41
6	108	CLIC	54
7	112	CLIC	34
8	103	CLIC	37
9	103	100	31

Empirical Breakdown Scalings

It has been proposed empirically that surface electric field, pulse length and BDR are related [2]:

$$BDR \propto {E_a}^{30}$$

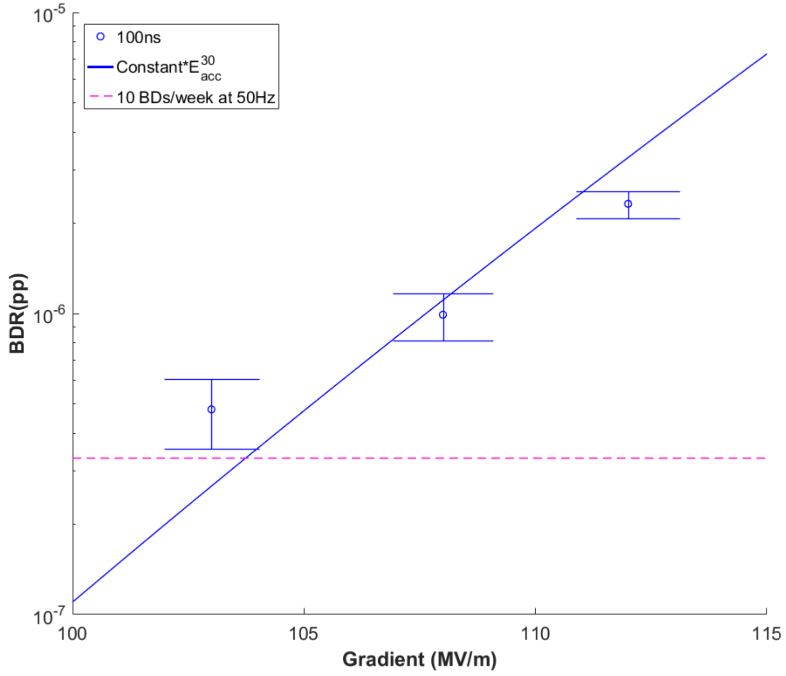
$$BDR \propto {t_p}^{5}$$

$$Constant = \frac{{E_a}^{30}{t_p}^{5}}{BDR}$$

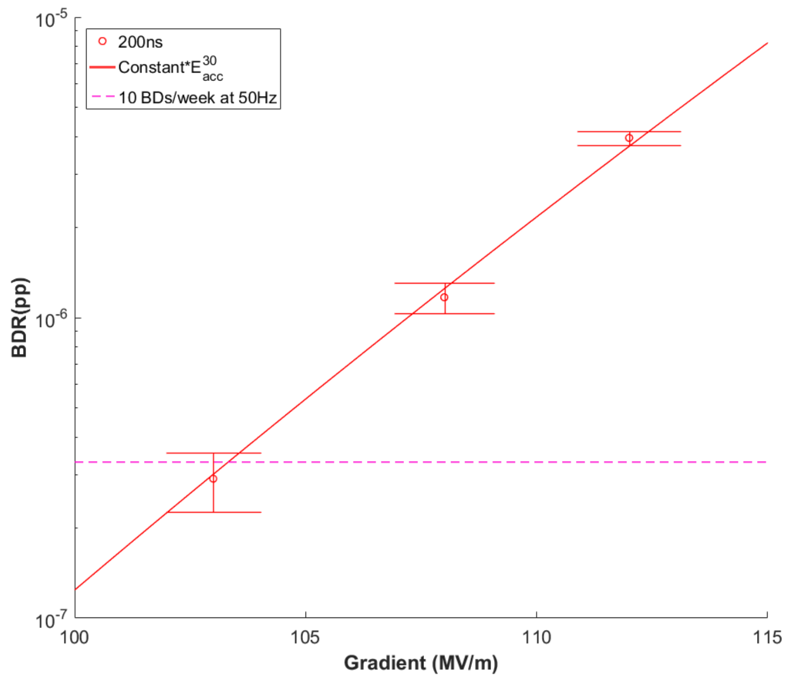
However the exact power scaling has been found to vary from structure to structure.
A physical model based on defect formation has also been proposed [3].

BDR Results of Flat Runs

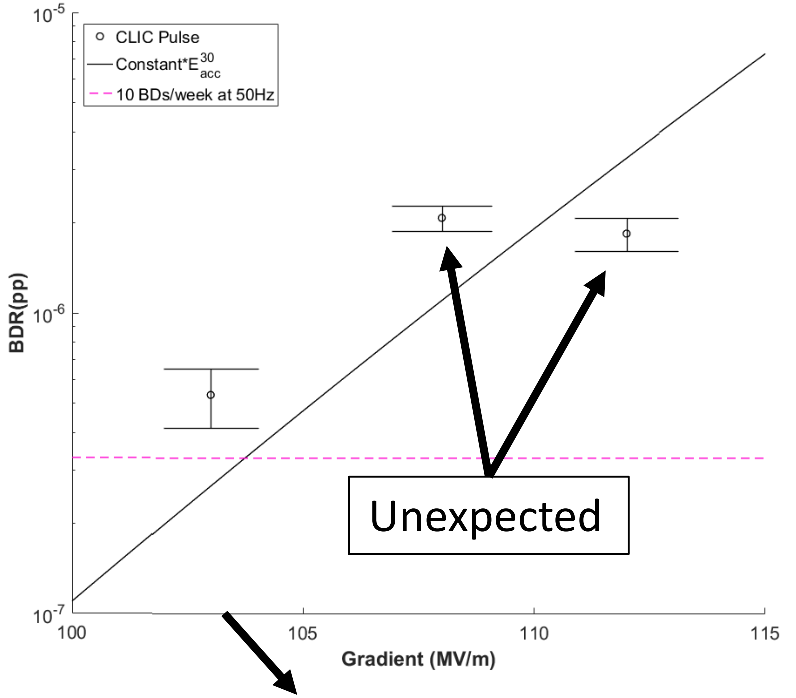
100ns Pulse



200ns Pulse



CLIC Pulse



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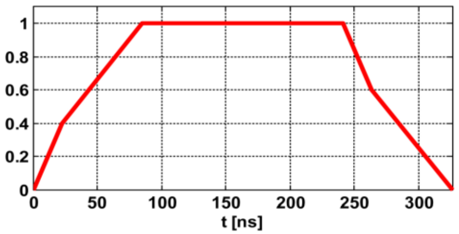
5	112	100	41				



Breakdown Localisation

- When conditioning, the power is increased while holding the BDR constant.
- However the breakdowns are generally not uniformly distributed.
- On several structures breakdowns have gradually migrated to the front (RF input) of the structure.
- Does not necessarily degrade performance over time. (We finished by running over 3 days without a BD)

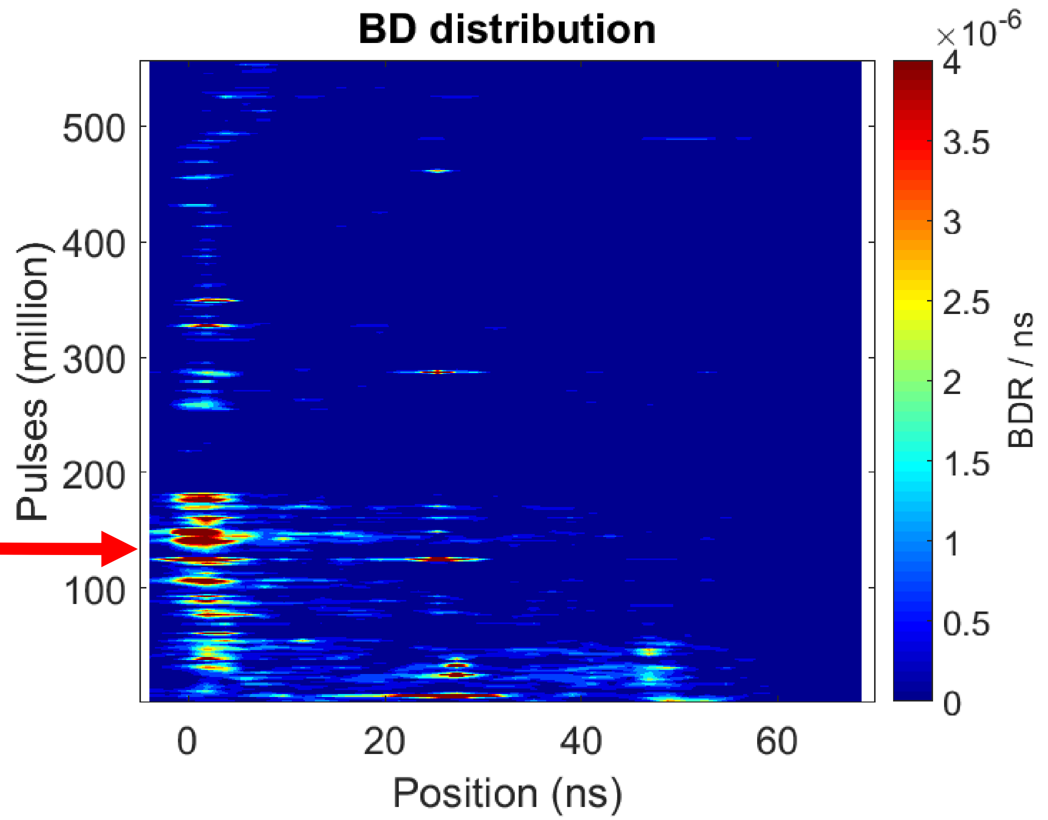


Figure: BD timing during the PSI N2 conditioning showing most breakdowns occurred at the start of the structure.
(Thanks to Jan Paszkiewicz for the BD heatmap plotter)

Xbox-3 Line 4: TD24 SiC N2

A TD24 structure with **Si**licon **C**arbide for HOM damping.

- Reached approximately 48 MW input power (110 MV/m @ 60 ns).
- Algorithm malfunctioned during breakdown clusters and prevented further increases in gradient.
- Post test analysis is ongoing, software has since been modified to take appropriate action.

Status: Testing concluded, analysis ongoing.

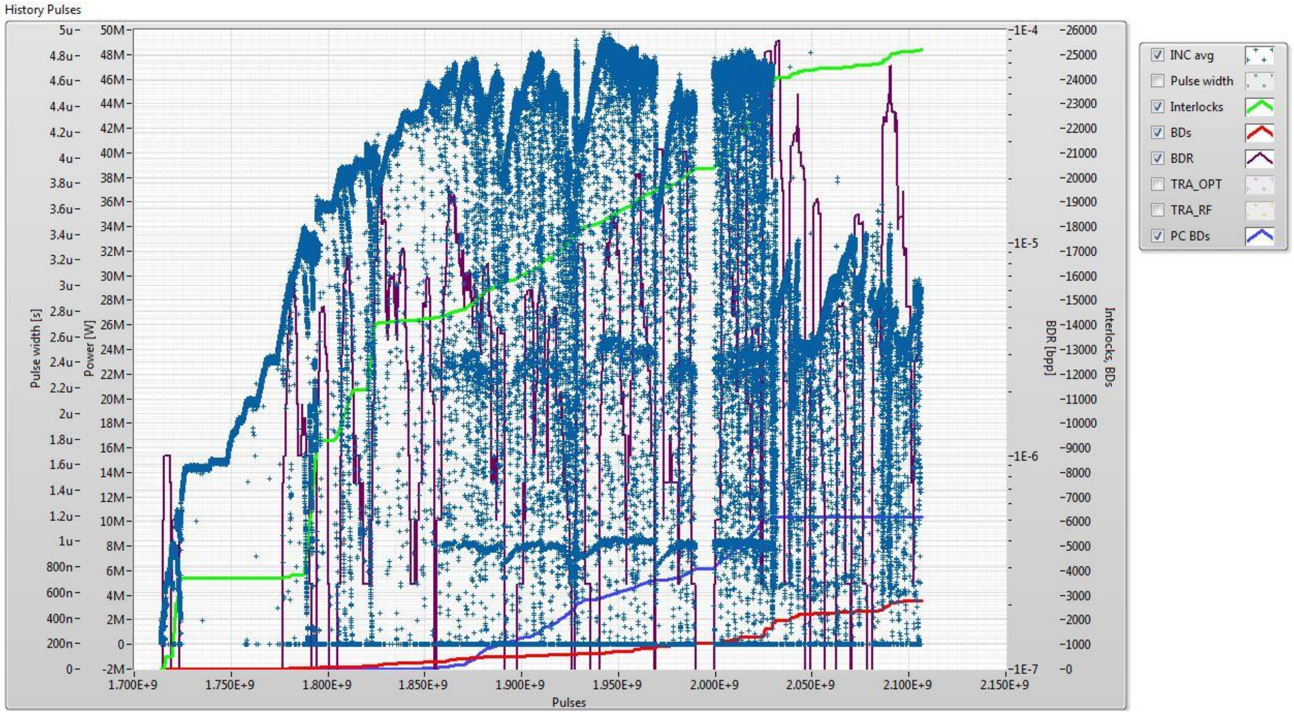
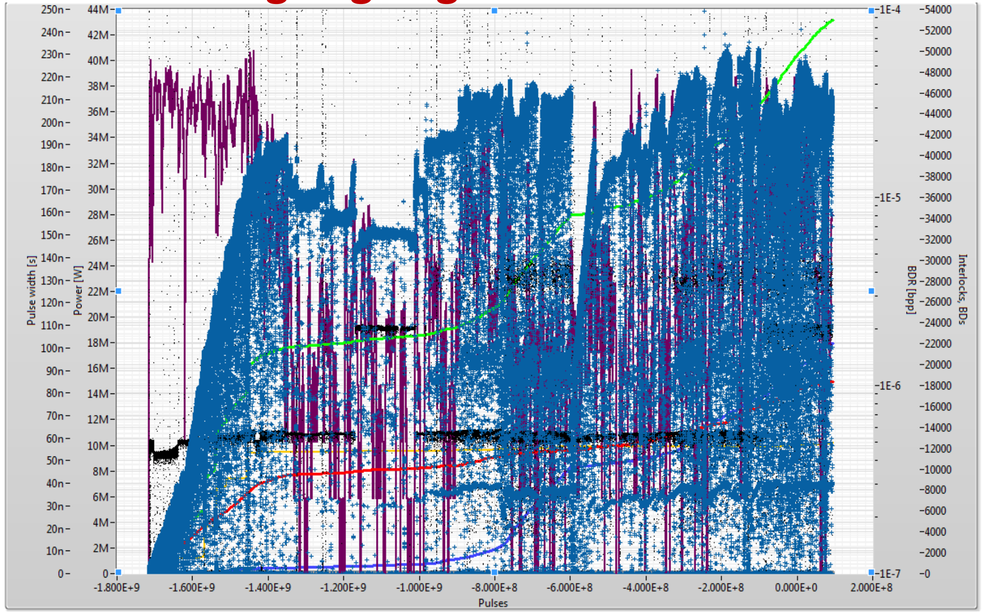


Figure: Conditioning History for the TD24 SiC N2 Structure.

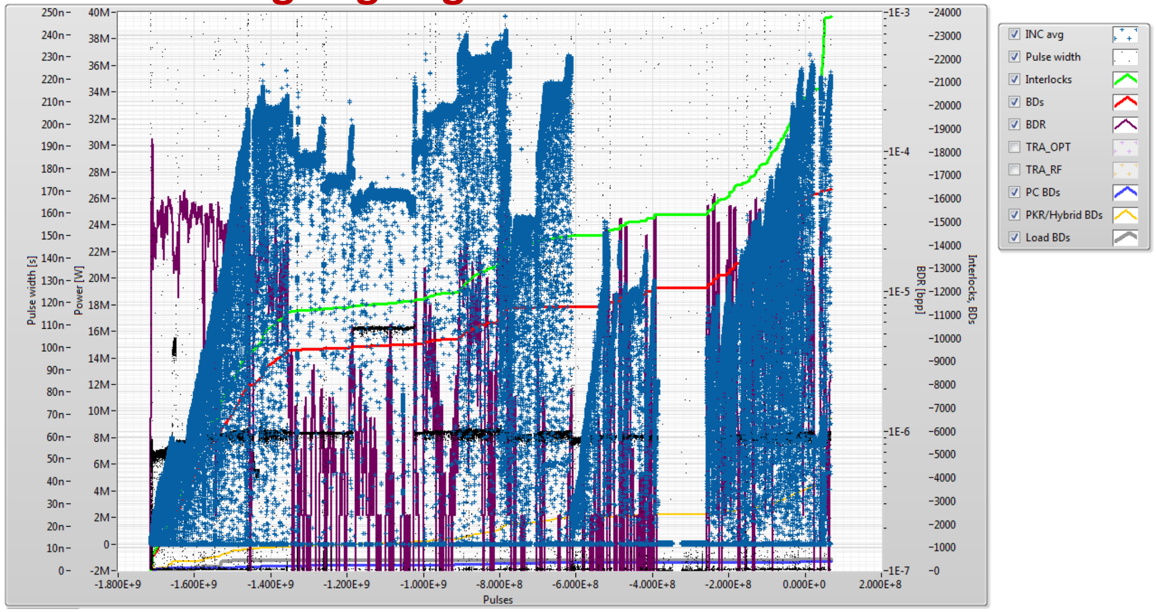
Xbox-3 Line 3/4: TD24 BO/UBO

- Two T24 undamped structures, one of which has undergone a bake out prior to installation in the test stand.
- Performing similarly having reached 40 MW (97 MV/m) and 38MW (95MV/m) respectively at 60ns.
- Significantly higher radiation and breakdown current observed compared with previous structures.
- Drops over time however due to the exponential dependence on field the conditioning is currently limited by radiation thresholds.

Status: Testing ongoing.



Status: Testing ongoing.



Figures: Conditioning curves for the TD24 BO (left) and TD24 UBO (right) structures.

T24 BO/UBO Dark Current Comparison With Other Structures

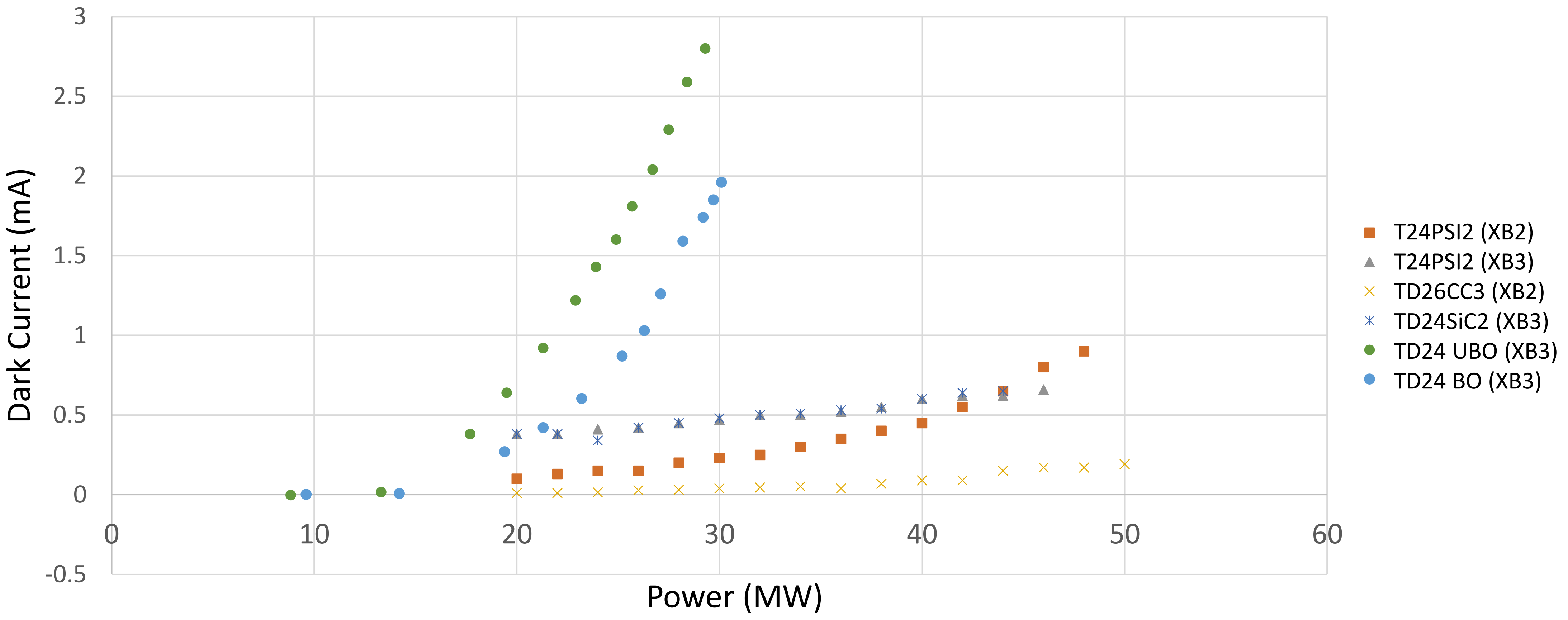


Figure: Dark current power scan for various structures.

Temperature Dependence

- Radiation also found to vary depending on the ambient temperature.
- This is thought to be due to temperature change altering the phase velocity of the structure equivalent to if the RF input frequency was changed. Consequently the lower phase velocity captures lower energy dark currents better.
- For more details of this phenomenon see “Simulations of Dark Current Dependencies on Frequency using CST Particle Studio” given at CLIC Workshop 2018 by T.G. Lucas.

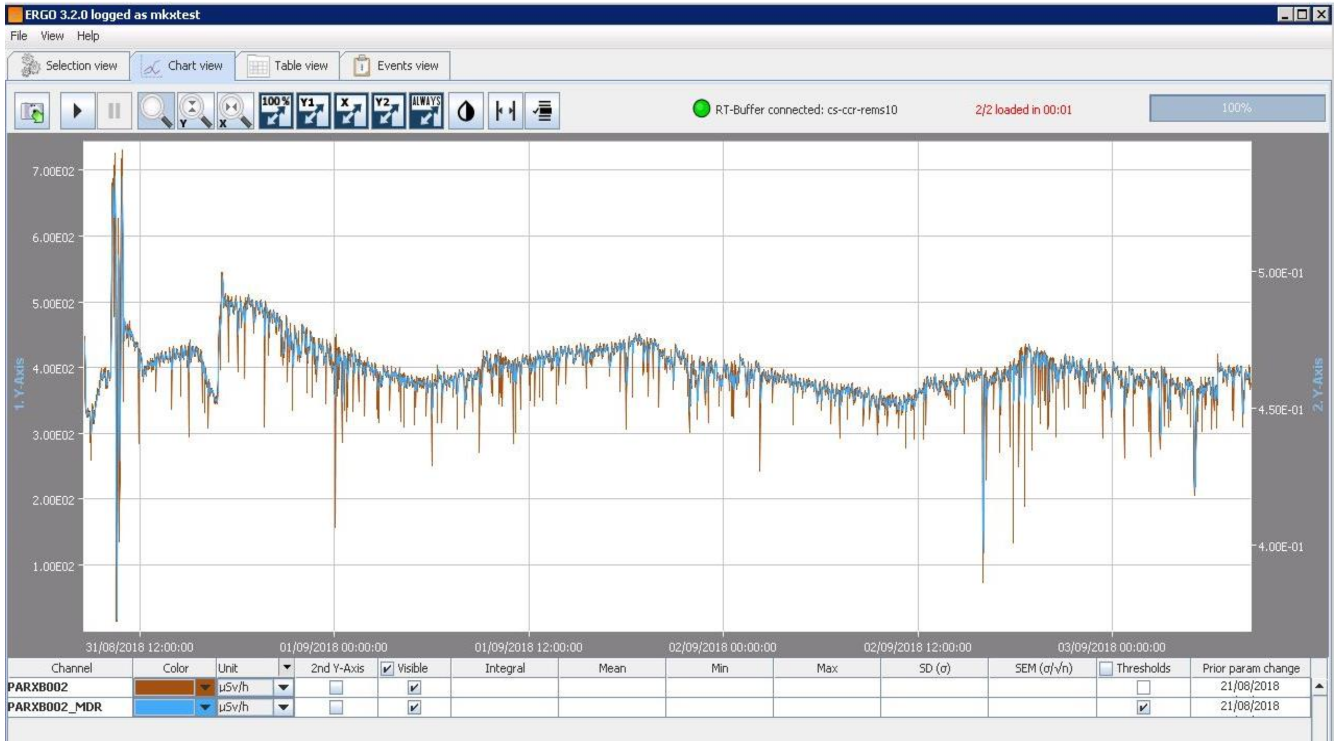
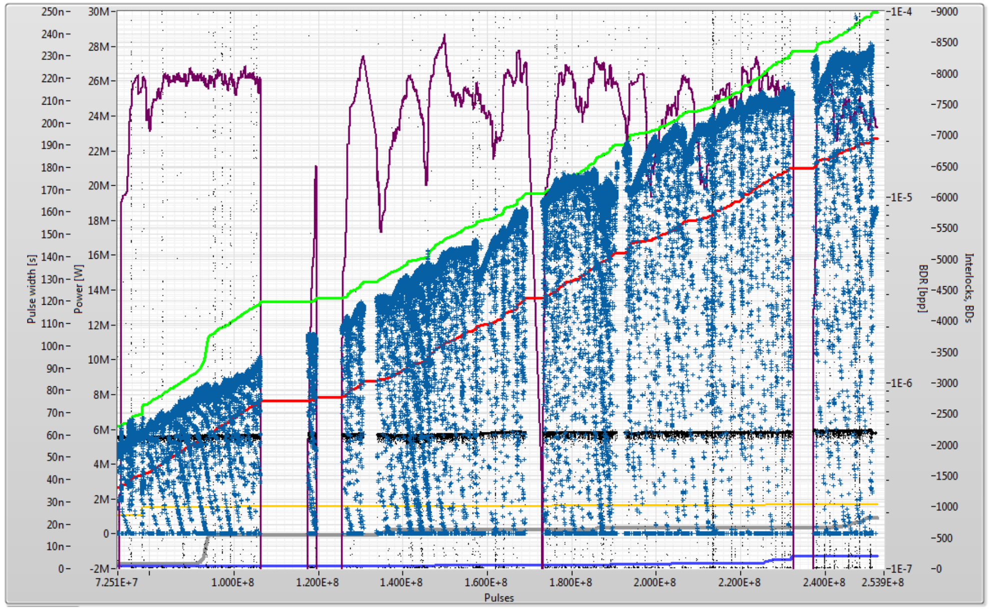


Figure: Radiation level variance over the course of several days.

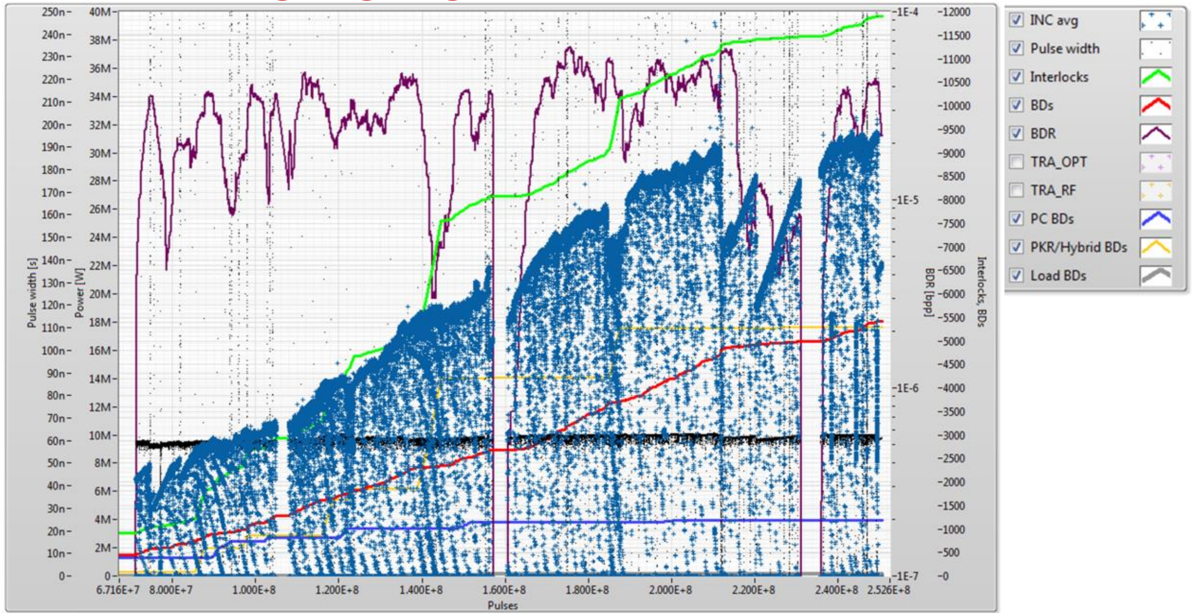
Xbox-3 Line 1 / 2: T24 N5/4

- Both structures installed in late 2018 and still currently undergoing testing. 38.5MW
- Conditioning process is proceeding well with structures at 28MW (85MV/m) and 30MW (88MV/m)
- Demonstrates algorithms new approach to cluster management, conditioning algorithm working well to date.

Status: Testing ongoing.



Status: Testing ongoing.



Figures: Conditioning curves for the T24 N5 (left) and T24 N4 (right) structures.

Structure Summary Plot

The conditioning process is a many body problem which can vary depending on a number of variables including:

- The structure/component
- Available power
- Vacuum
- Radiation
- Choice of algorithm
- Pulse shape

We can renormalize via the empirically obtained dependencies of E, BDR and τ:

$$E_0 \propto BDR^{\,1/30} * \tau^{\,-1/6}$$

This provides a comparison in term of the CLIC baseline specifications.

A higher normalised gradient suggests a low BDR at high field and long pulse length and vice versa.

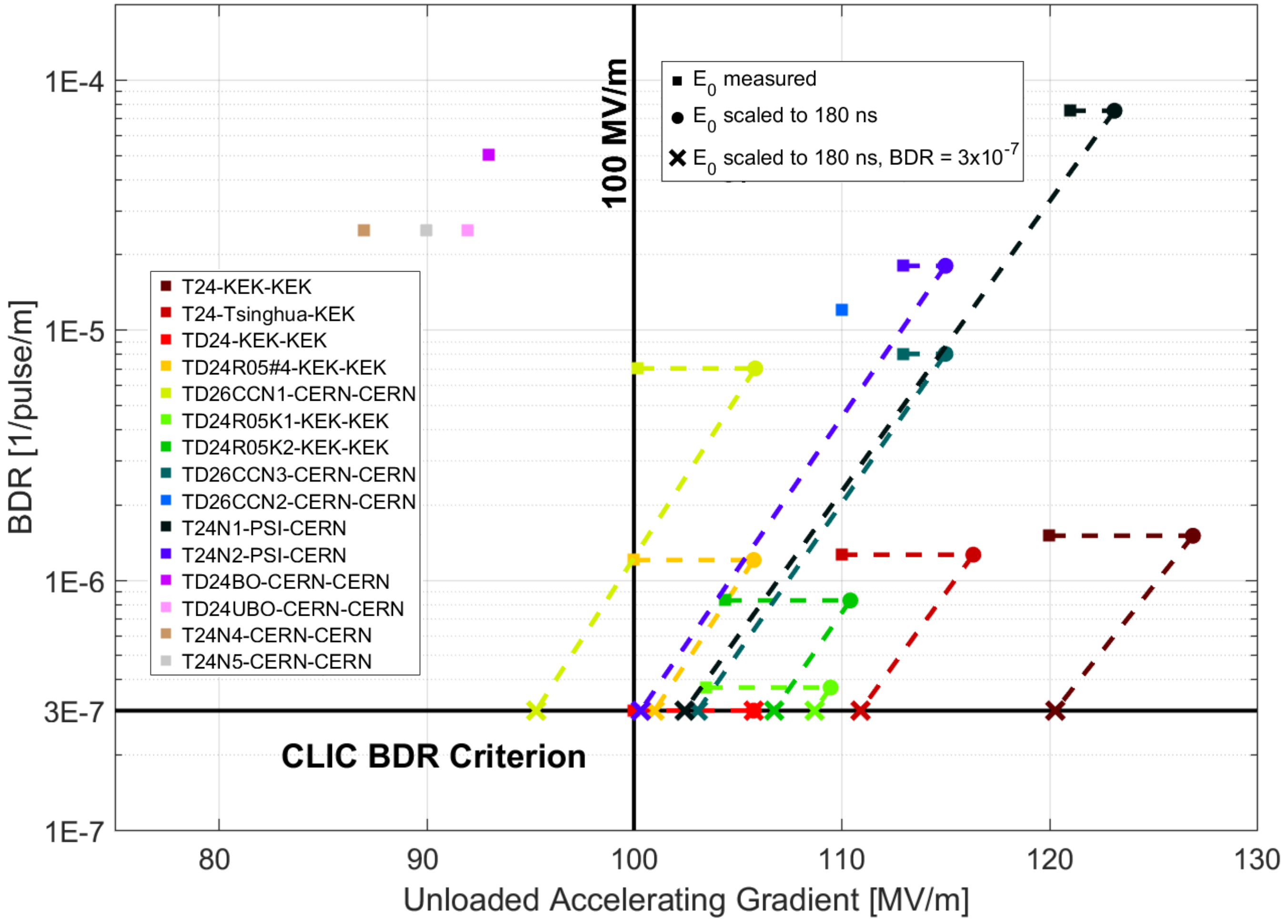
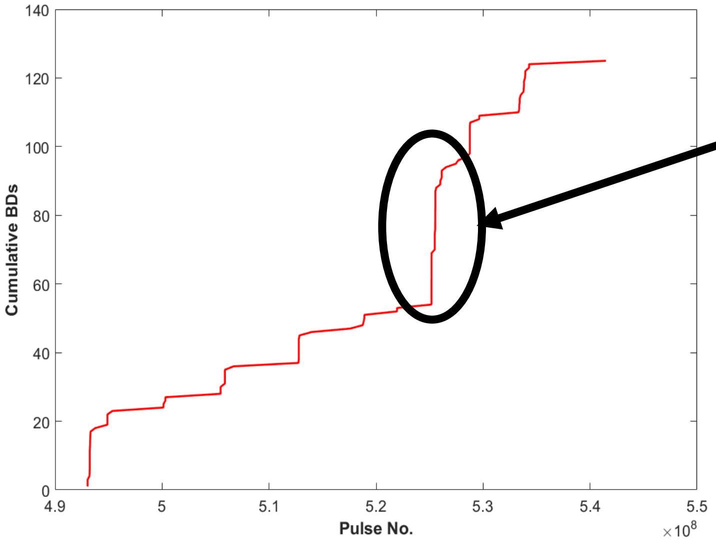


Figure: Scaled Gradients for various accelerating structures tested to date.

Lessons Learned - Clustering

- When taking BDR measurements, clusters (as pictured below) can dominate BDR measurements.
- No definite cause has been found, so far appears to be probabilistic at high gradients.
- However they can be managed and updated software now provides protection during testing.



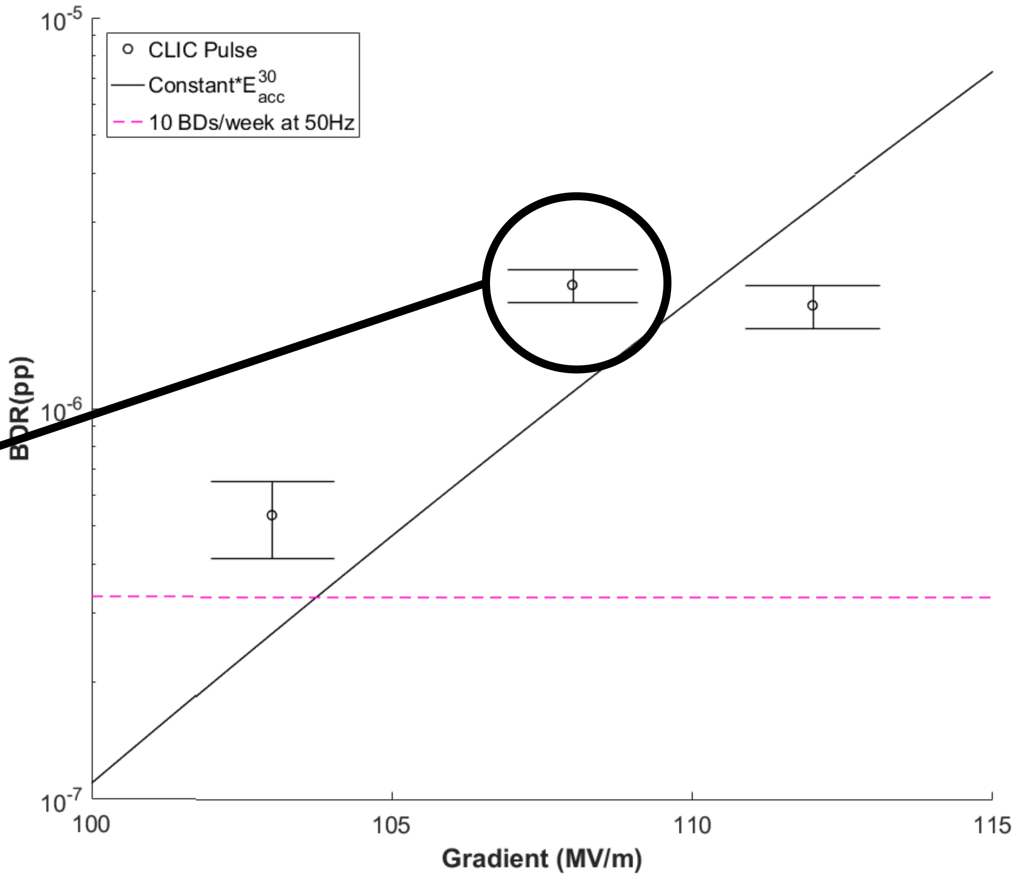
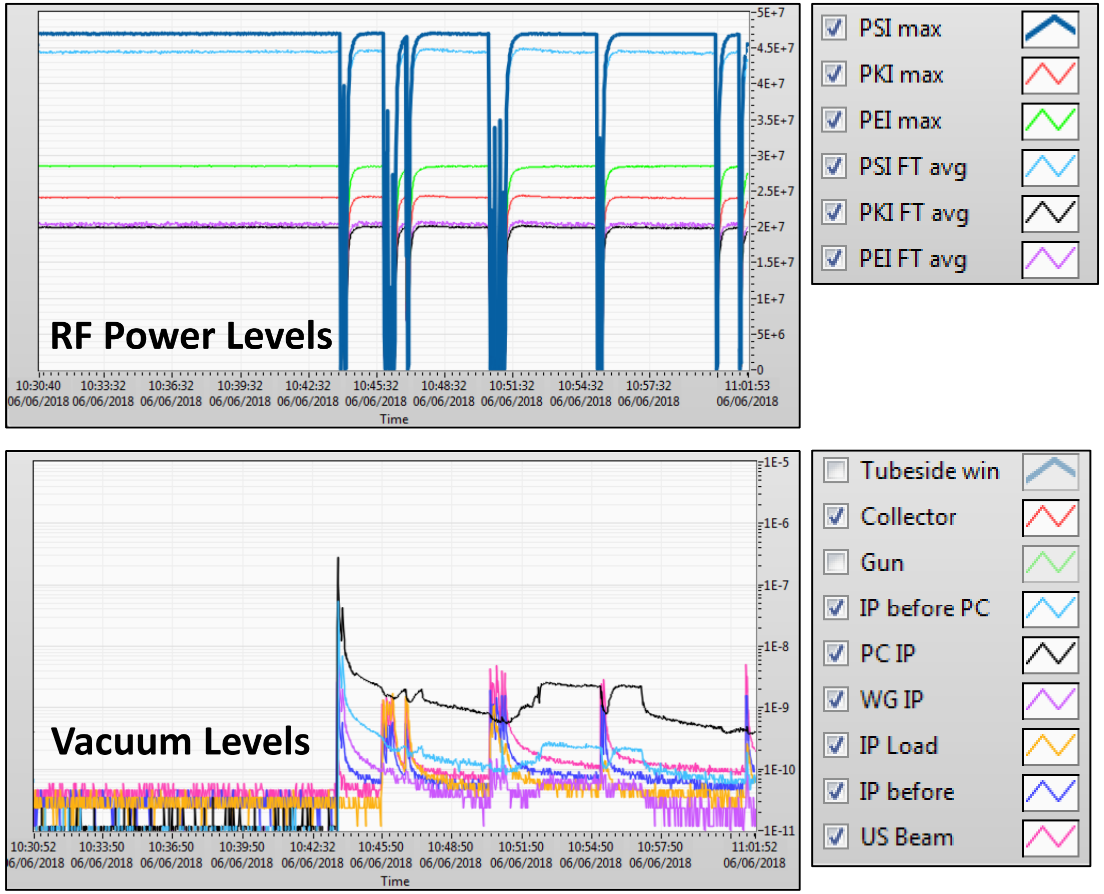


Figure: CLIC Pulse data points for the PSI2 structure, a fitted empirical scaling (top) and Pulse No vs Cumulative BDs (left).

Clustering

- Looking closer, data shows ~75% BDs in PSI2 structure did not occur as isolated events (Isolated defined as occurring more than 1000 pulses apart i.e. 20s at 50Hz).
- Suggests that at high fields BDs are more likely to occur in groups during operation.
- Also results in higher residual vacuum levels.
- **In a high gradient facility this can be prevented/stopped by temporarily decreasing the gradient.**
- The gradient may then be gradually ramped back up to the previously achieved level.



Figures: Peak RF power (top) and vacuum levels (bottom) during clustering as displayed in real-time on the GUI.

Persistence of Conditioning

- When breaking vacuum, the structure and line must be reconditioned.
- However, some prior conditioning persists.
- This has been observed in three structures in 2018: PSI N1/2 (pictured right) and TD24 SiC.
- Structures were removed from test slots and exposed to air before being reinstalled in an alternative slot.
- Each structure reached the previously achieved gradient in fewer pulses than were initially required.

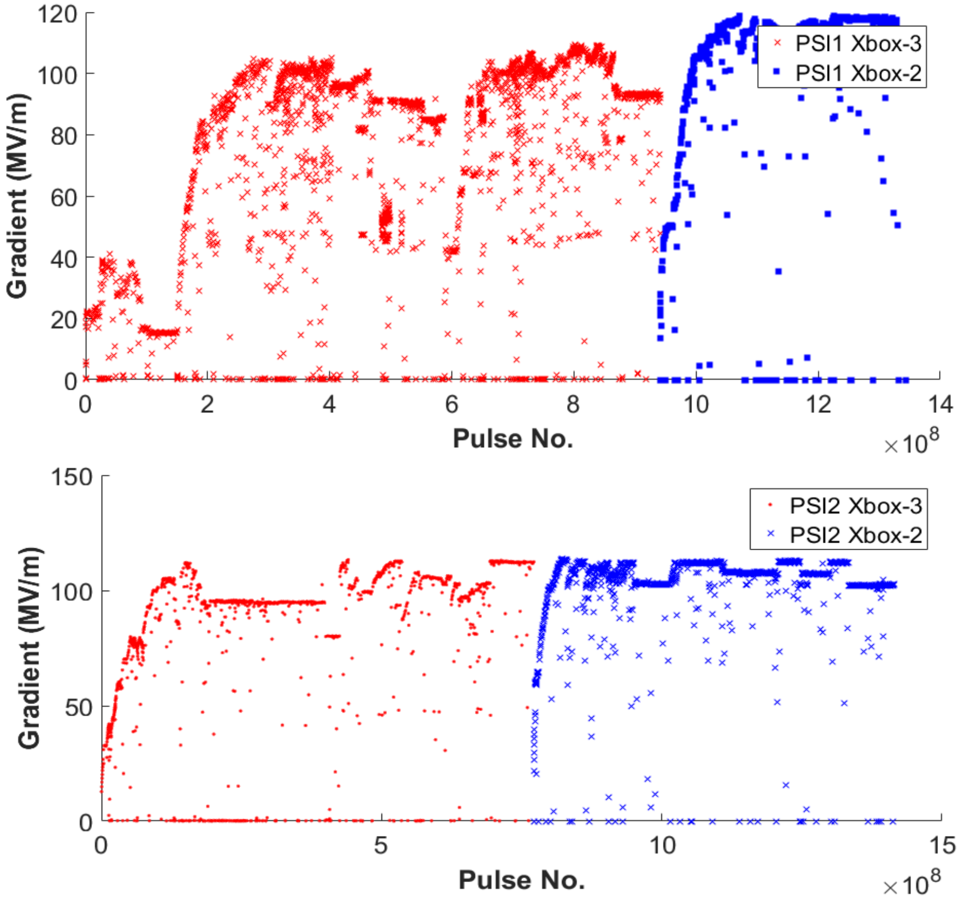


Figure: T24PSI2 Conditioning to 100MV/m in XB3 and reconditioning in XB2 after exposure to air respectively.

Transient Behaviour

- Still early, however anecdotal evidence suggests switching off results in a temporarily increased BDR even when vacuum is maintained (less than 1E-10 mbar in X-box 2).
- Little quantifiable data due to a lack of long fixed gradient runs, without this the BDR is algorithmically held constant.
- Suggestions that this may be migration of water back to high field regions during the lack of RF.
- Additional studies coming soon (hopefully).
- If true, there is an optimisation to be made in any high gradient facility:
  - Increased power consumption?
  - OR switch the system off and endure a higher BDR/spend time “reconditioning”.

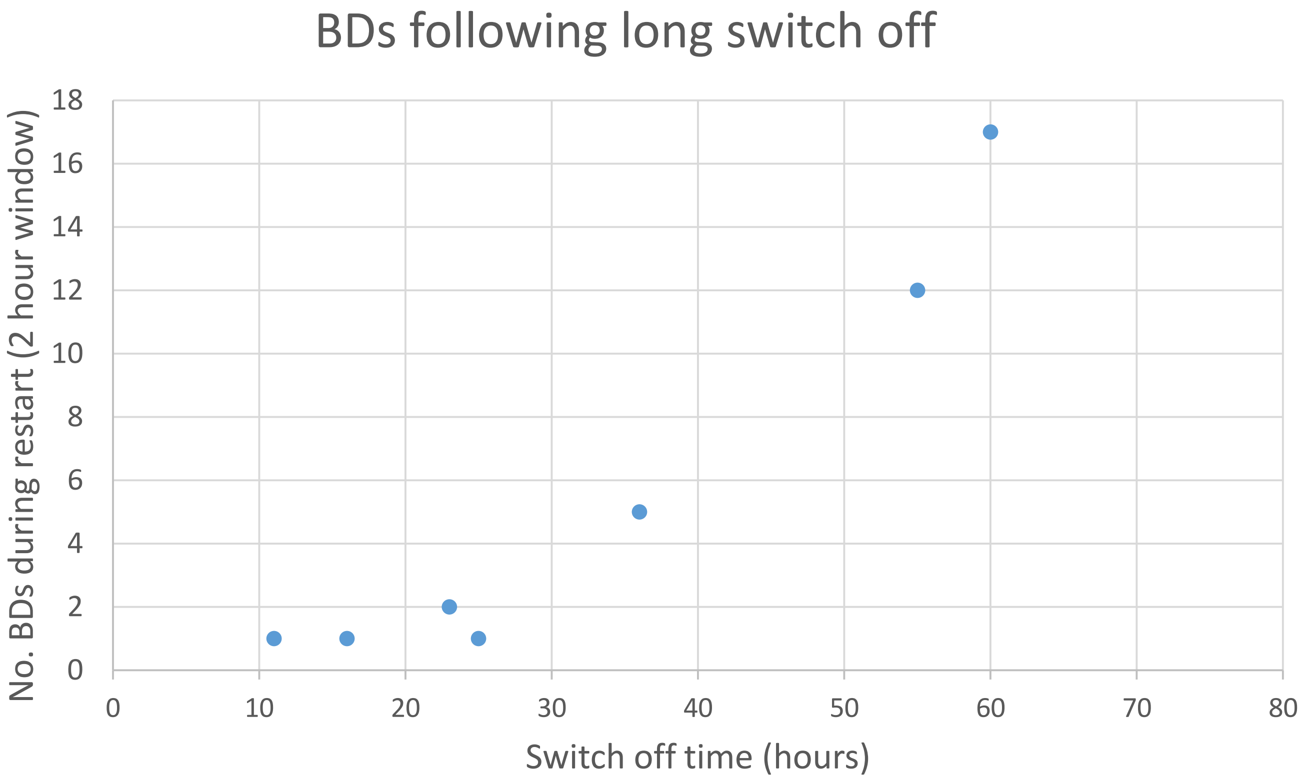


Figure: BDs upon restart after a long switch off for the PSI N2 structure after having been conditioned to high gradient at long pulse length. (Vacuum integrity was maintained)

Conclusion

- We regularly run at >100MV/m and low BDR. (Over three days continuous operation without a BD at 103MV/m).
- Interesting effects emerge during long term running.
- Stopping RF pulses for extended periods of time can result in an increased BDR during restarts (Even if vacuum integrity is maintained).
- Clustering appears to be a limiting factor at high fields however we no have software in place to manage this.
- Breakdown rate dependencies are still under investigation as we accumulate additional data and statistics.
- We have many more structures and experimental plans underway, for a detailed plan see "X-band test facilities at CERN" by Nuria Catalan Lasheras

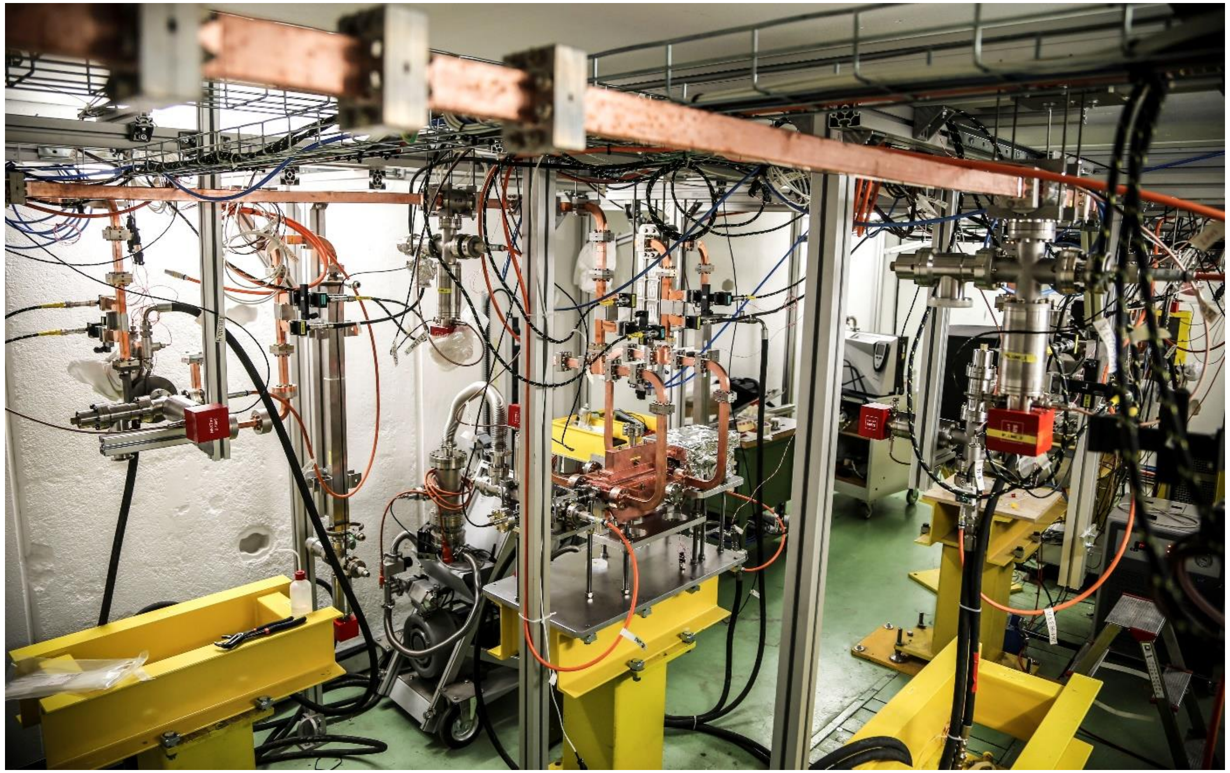


Figure: Xbox test slots inside the shielded bunker.

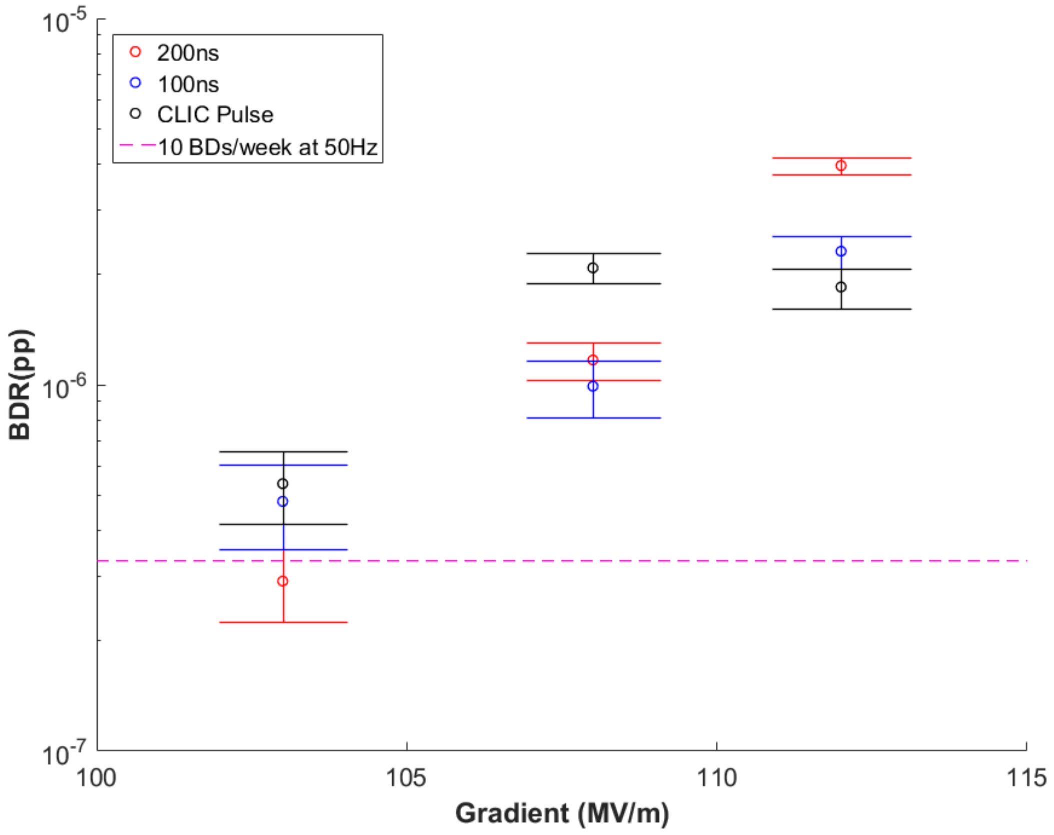
Thank you. Questions?

References

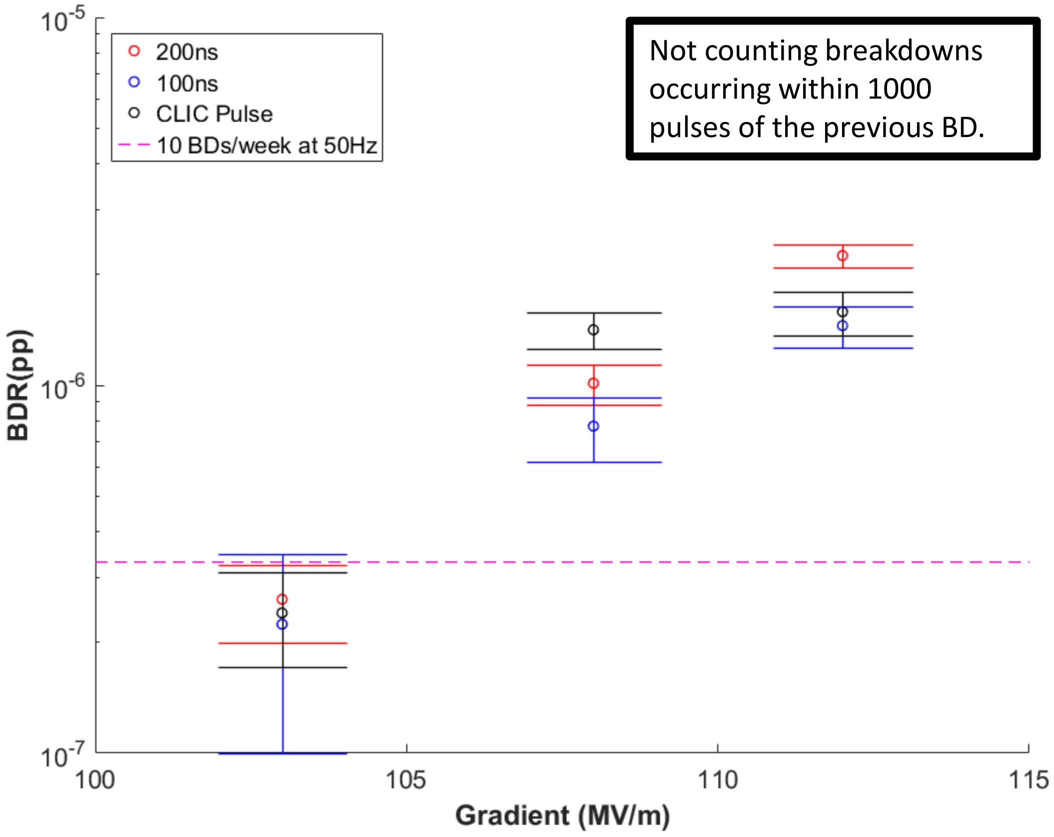
- [1] - *Electron Emission in Intense Electric Fields,* R.H Fowler and L. Nordheim
- [2] - *New local field quantity describing the high gradient limit of accelerating structure.* Wuensch, W. et al. American Physical Society, 2009, Phys. Rev. ST Accel. Beams, Vol. 12.
- [3] – *Defect model for the dependence of breakdown rate on external electric fields,* Nordlund and F. Djurabekova, Phys. Rev. ST Accel. Beams 15, 071002 (2012).
- [4] – *Stochastic Model of Breakdown Nucleation under Intense Electric Fields*, Zvi Engelberg et al. (2018). Physical Review Letters. 120. 10.1103/PhysRevLett.120.124801.

PSI2 Comparison with ‘Event’ BDR

Conventional BDR



Event BDR



Not counting breakdowns occurring within 1000 pulses of the previous BD.