Behavior of High Gradient RF Structures During Long-Term Operation

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Overview of the X-boxes

- The X-boxes 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.

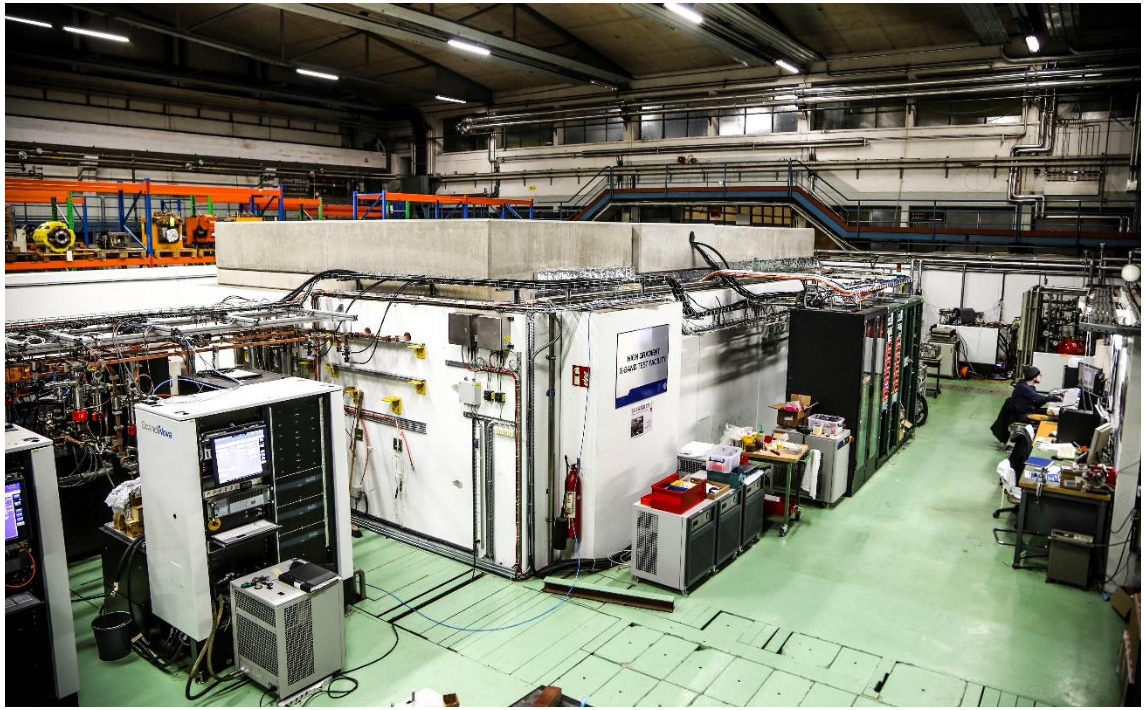


Figure: X-band high gradient test facility at CERN.

X-box 2

- 50MW CPI Klystron.
- ScandiNova Modulator.
- 1.5μs pulse length.
- 50Hz rep rate.
- SLED-I type pulse compressor.
- PSI T24 N2 last structure (pictured right).

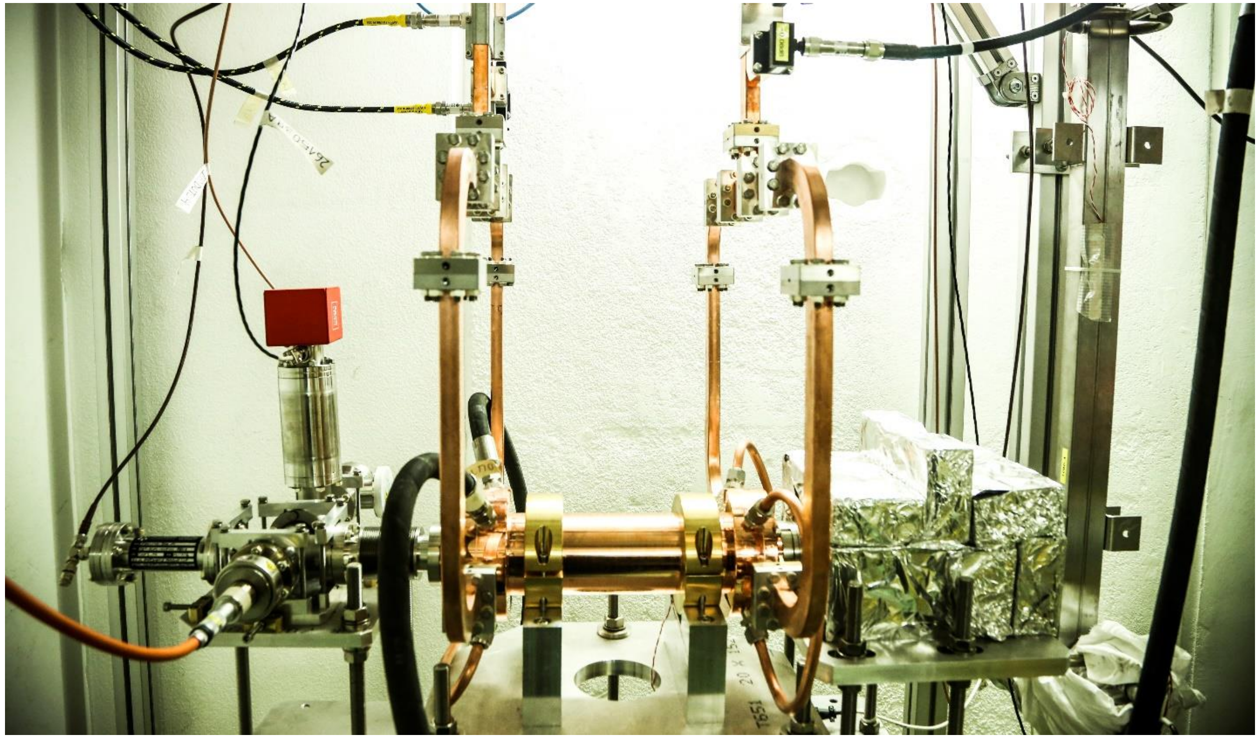


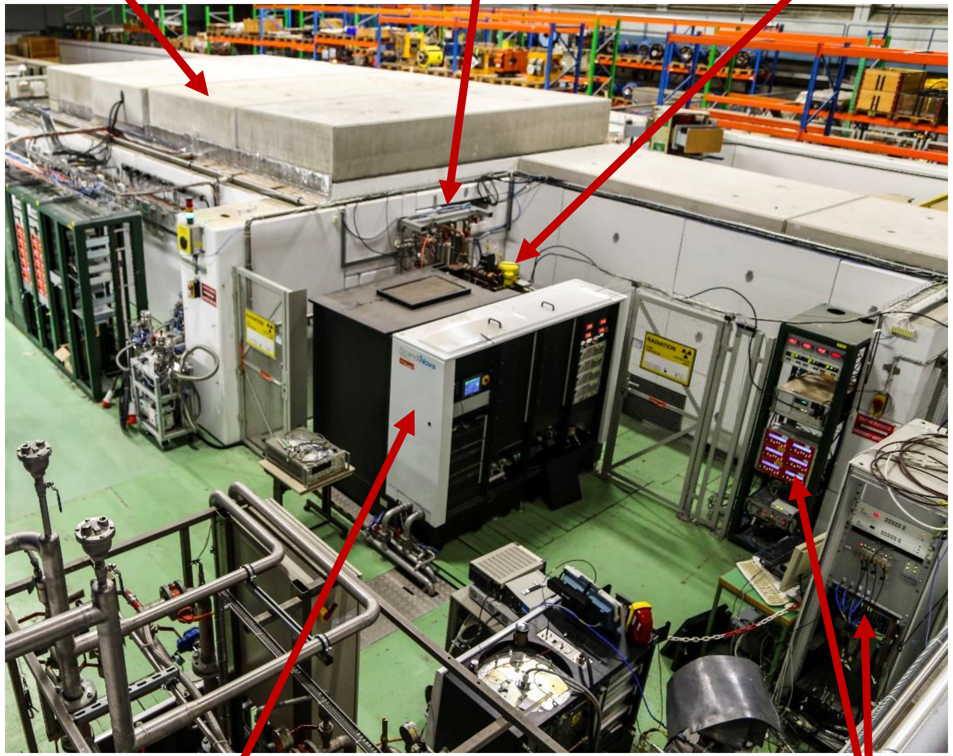
Figure: T24 Structure installed in the Xbox-2 test slot. (Photo courtesy of Matteo Volpi)

X-box 2

Radiation Bunker

Pulse Compressor

Klystron

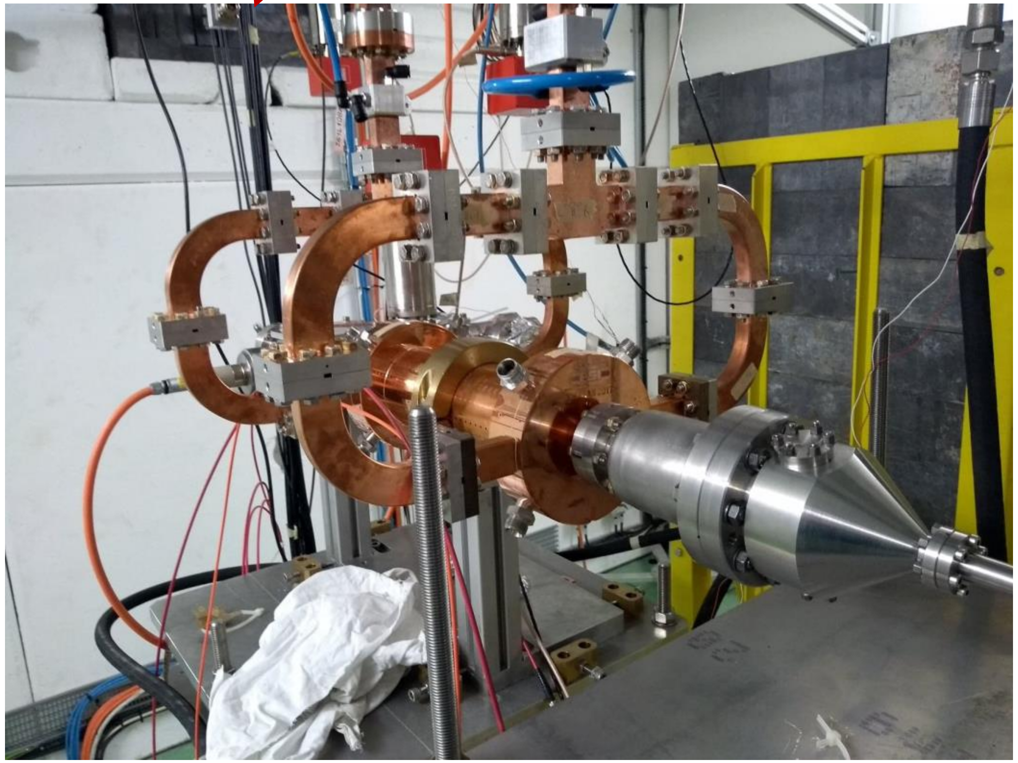


ScandiNova Modulator

SSA and LLRF/PXI Racks

Feeds this structure

Waveguide entry here



Breakdown

- Small defects/foreign bodies/dislocations on the surface can enhance the electric field by a factor 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.

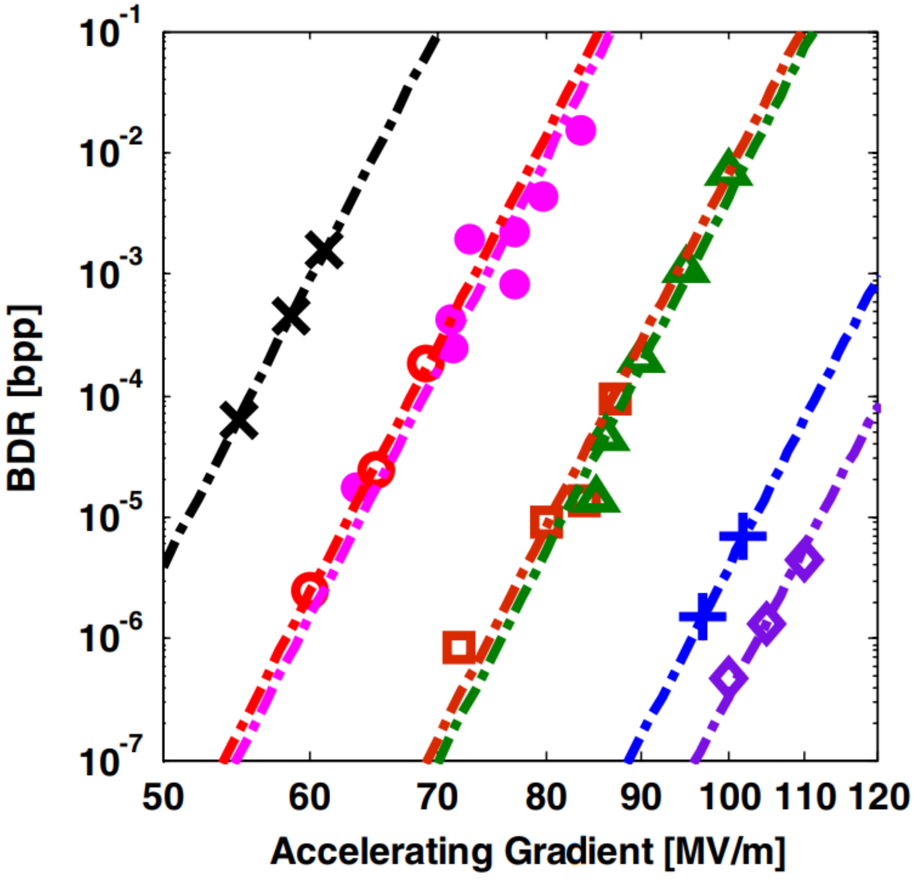


Figure: Breakdown rates (per pulse) vs accelerating gradient for various structures.[2]

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.

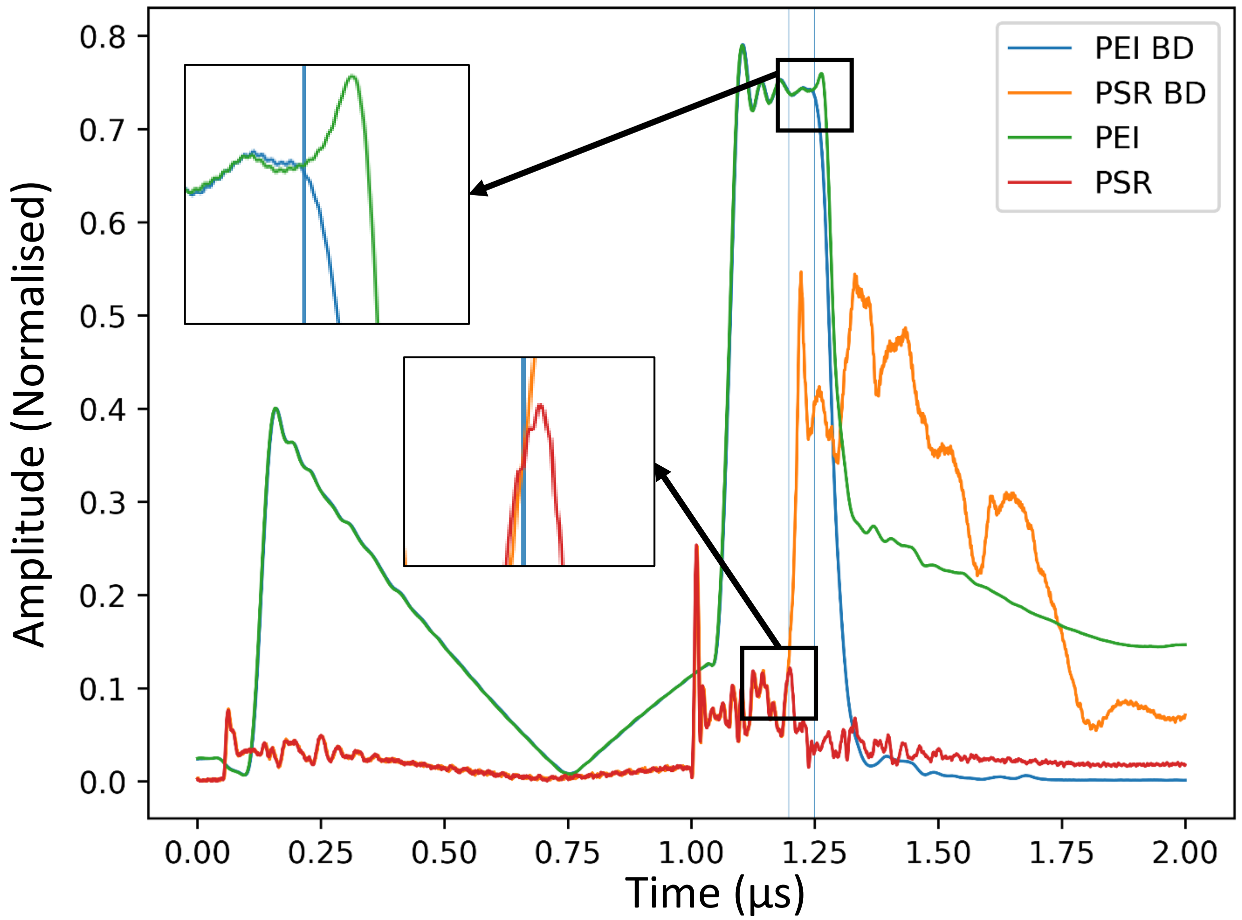


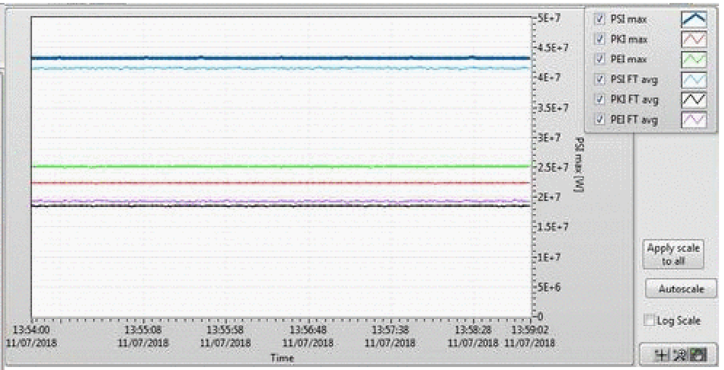
Figure: Normal transmitted and reflected RF signal (green and red) and transmitted/reflected signals during a breakdown (blue and orange).

Operation in Realtime

Waveform Display

Peak Power Levels

Interlock Statuses



Conditioning

- Breakdowns are the limit on high power operation immediately after manufacture.
- Structures must be conditioned i.e. The power is gradually increased over time while monitoring for breakdowns.
- After this the accelerator/component is capable of operating at high power.
- Breaking down too frequently can permanently damage components.
- Structures condition on the **number of pulses not the number of breakdowns [2]**.

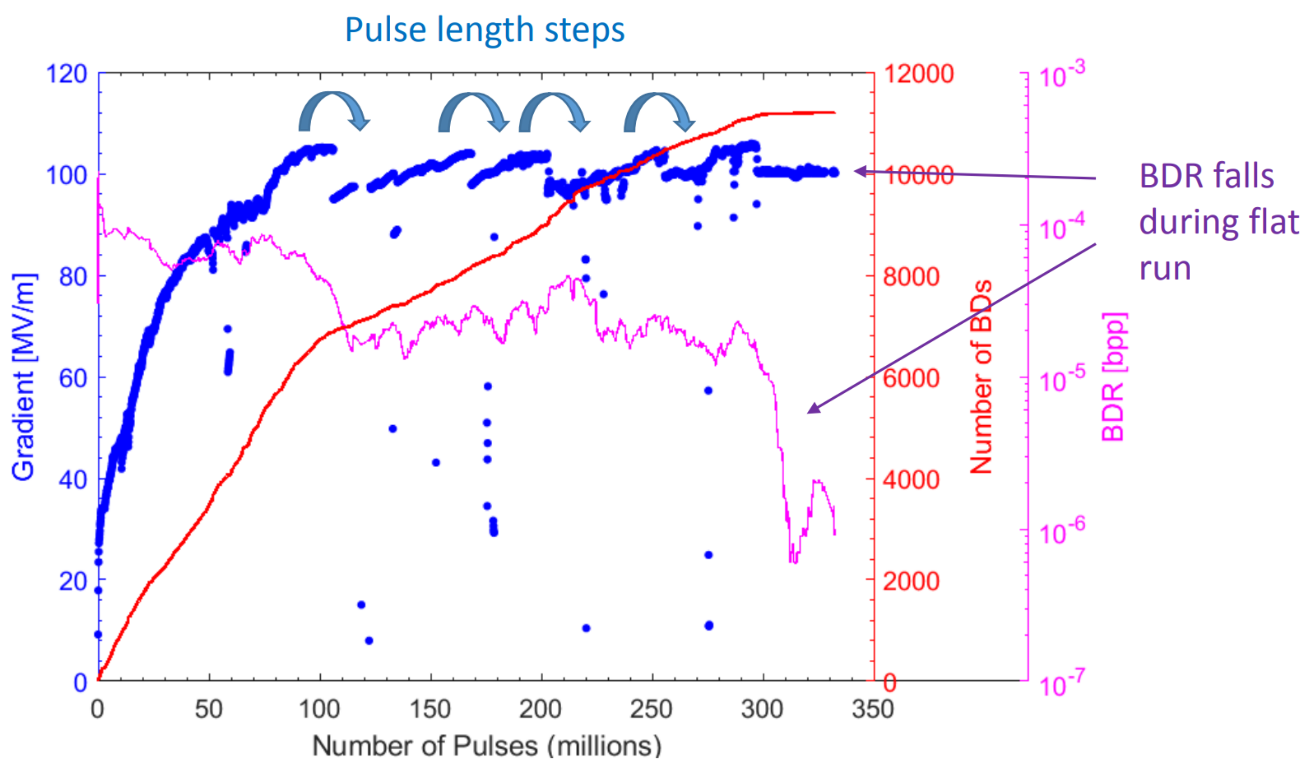


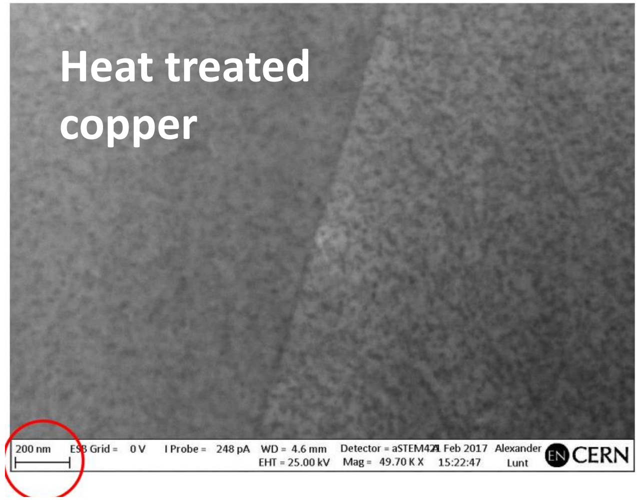
Figure: A typical conditioning curve.

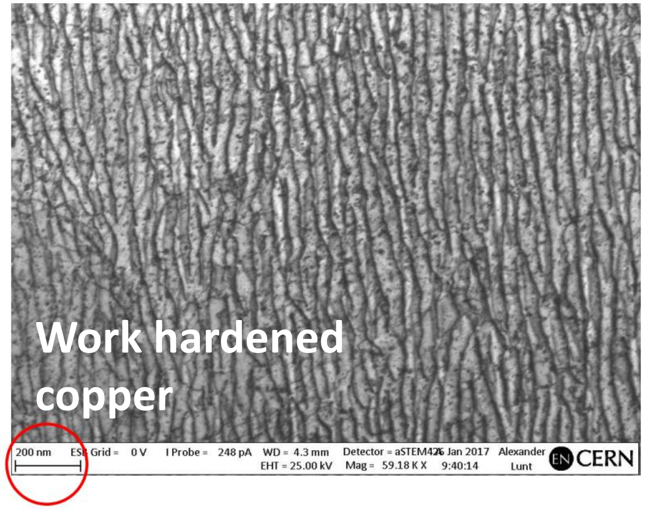
Conditioning as a Hardening Process

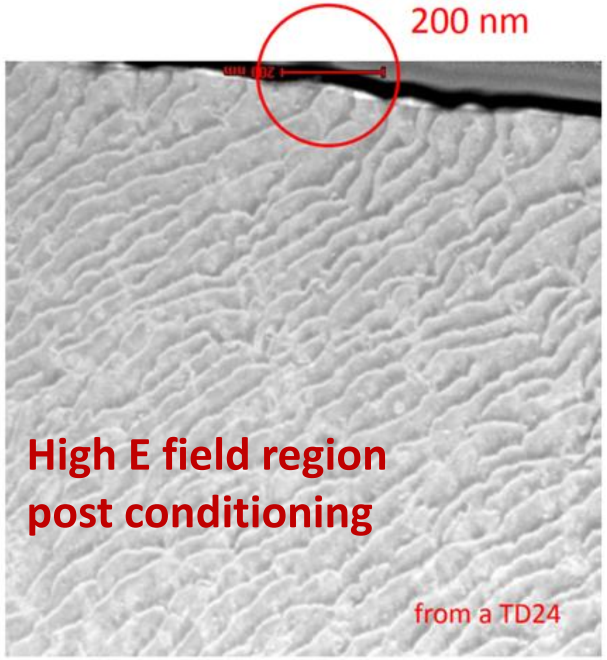
- Various theories proposed, one being that copper in its annealed state has dislocations which can migrate under the stress of an applied electric field.
- This can lead to ejection of atoms from the surface which may then be ionised by field emission currents and cause a subsequent breakdown.
- The electric field stress, σ can be given by [3]:

$$\sigma = \frac{\varepsilon_0 E^2}{2}$$

- This produces an effect similar to work hardening at the surface.
- Interlocked pattern prevents future migrations and hence BDs.







(Images taken from [3], courtesy of Enrique, Yinon and Ina)

Conditioning Phases

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 phenomenon also observed (Too much to cover here, see talks from Jan and David for more details).

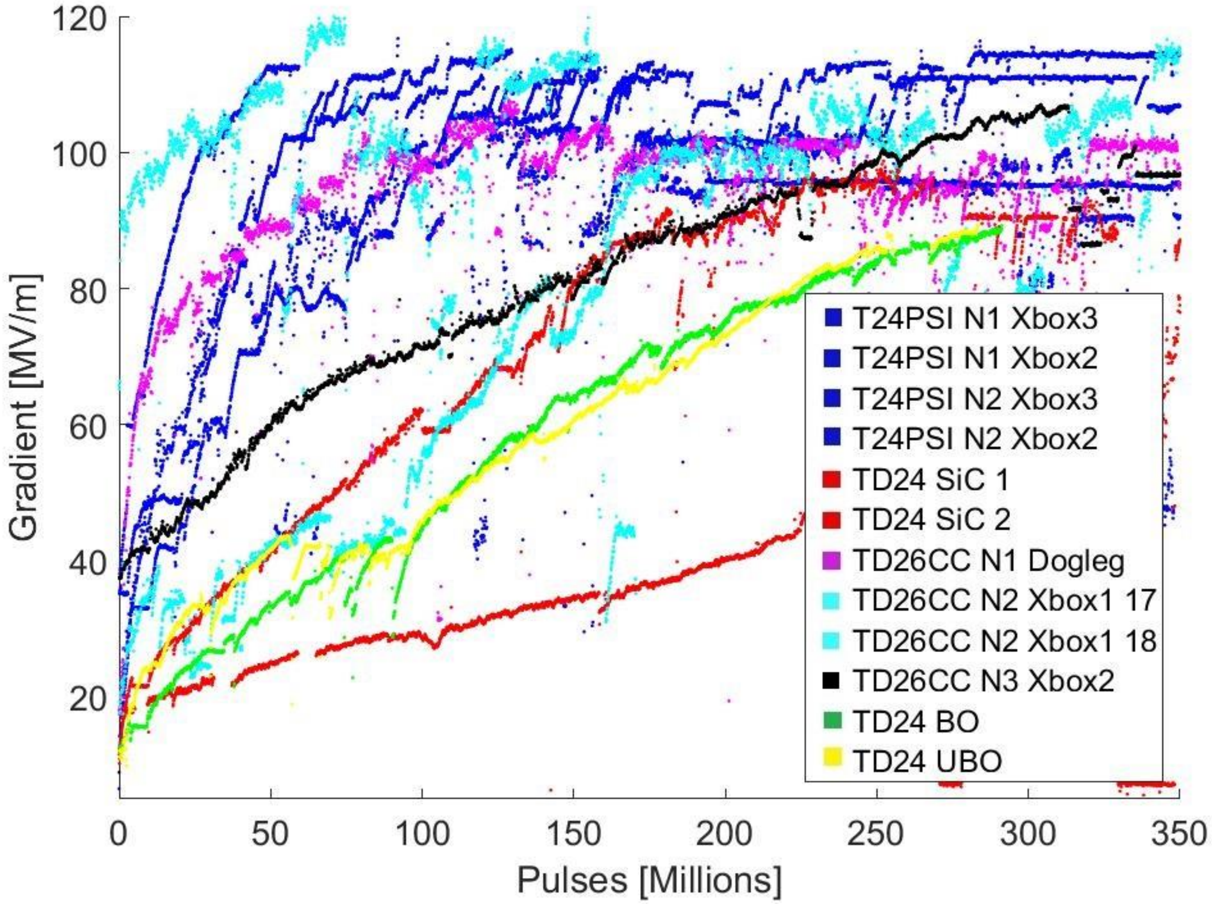


Figure: Summary of structures conditioned to date. (Plot courtesy of Anna Vnuchenko)

Long Term Running

- In summary, we have learned much about breakdown and conditioning (we have logged billions of pulses and are running as we speak).
- However what becomes important when running for **long periods** at full spec?
- Several key issues emerge -lets cover our most recent structure and some observations.

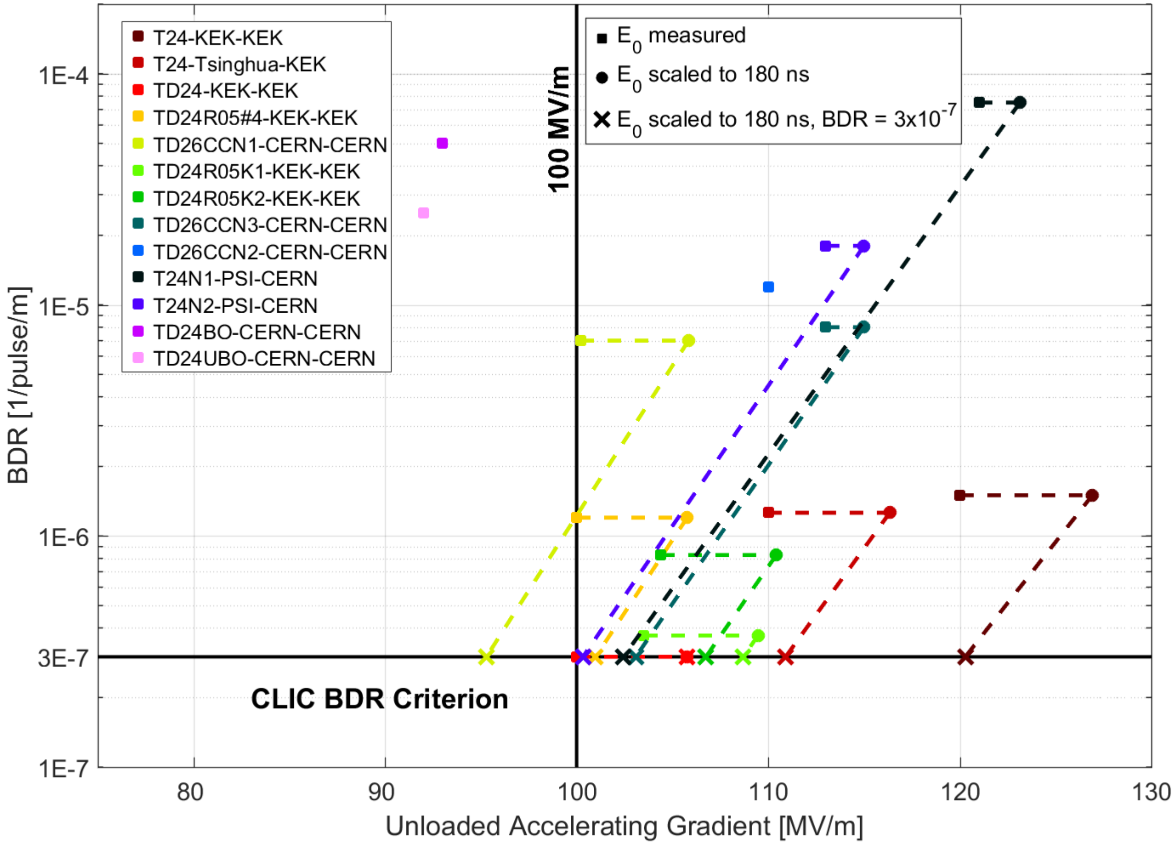


Figure: Prototype structure performances scaled to CLIC specs. Note peak surface electric field is approximately 2.2 times these values.

Most recent structure – PSI T24 N2

Specifications:

- 11.994 GHz
- **T**apered with **24**(2) accelerating cells.
- 120° Phase advance/cell.
- Iris aperture diameter 6.3mm (input) - 4.7mm (output)
- Iris thickness 1.67mm (in) – 1mm (out)
- Group velocity V_{gin}=1.8, V_{out}=0.9 (%c)
- Fill time 59ns.

Manufactured by The Paul Scherrer Institute (PSI) using the same production line as SwissFEL.

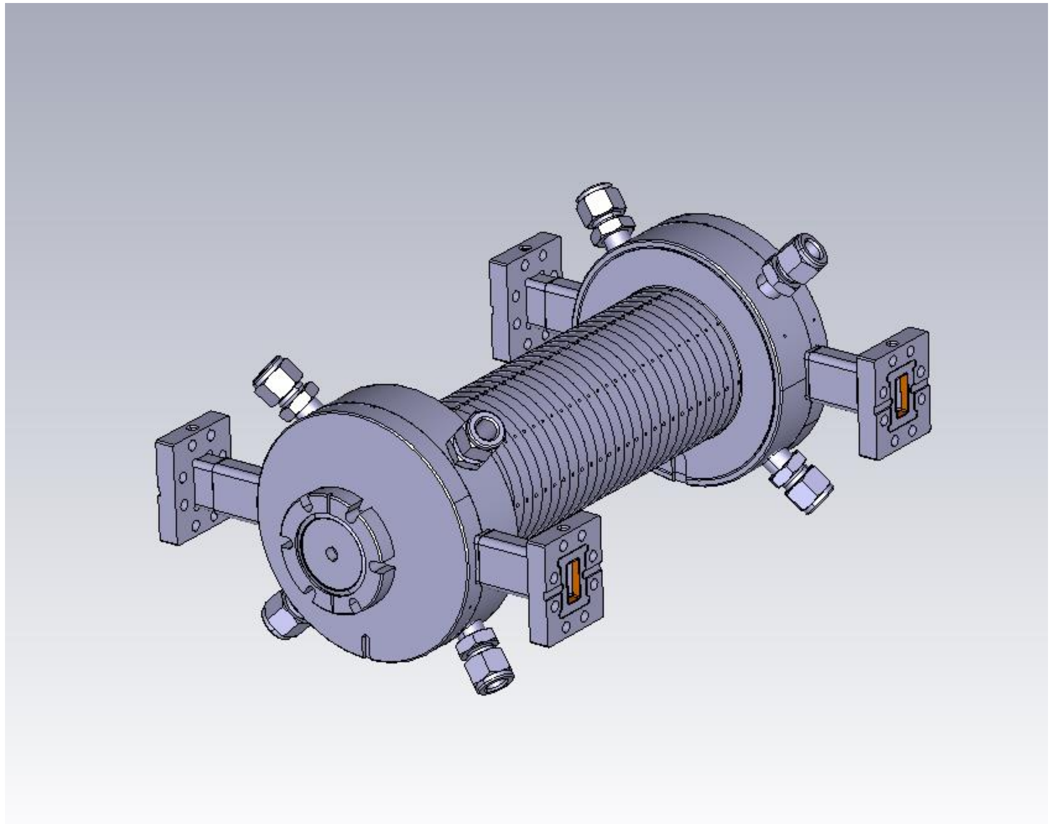
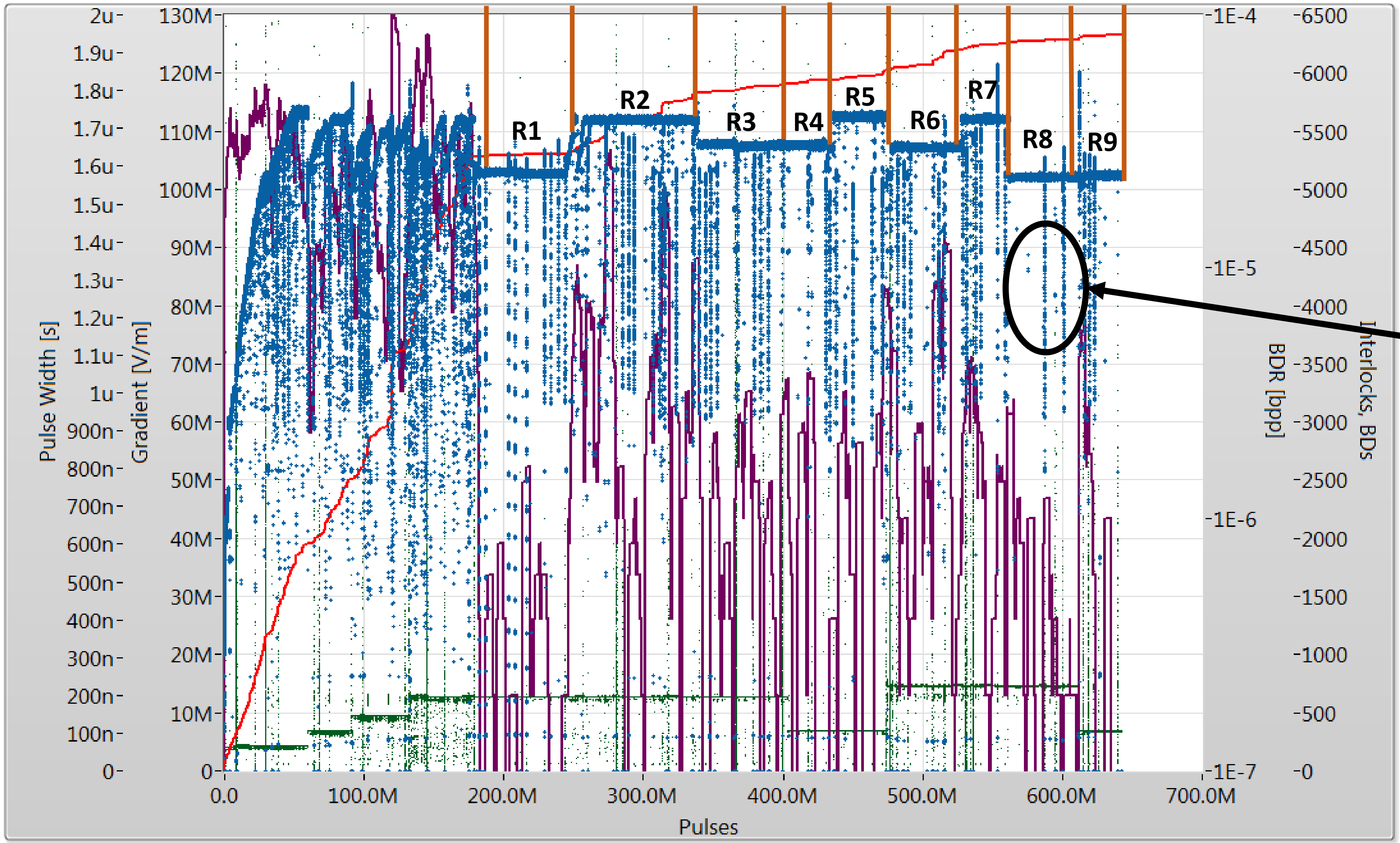


Figure: PSI T24 Rendering.

Conditioning Summary



NB: Regular power drops due to dark current measurements.
(See Jan Paszkiewicz talk)

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 Scaling Laws

A number of theories have been proposed. One empirical suggestion is that surface electric field, pulse length and BDR are related[2]:

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

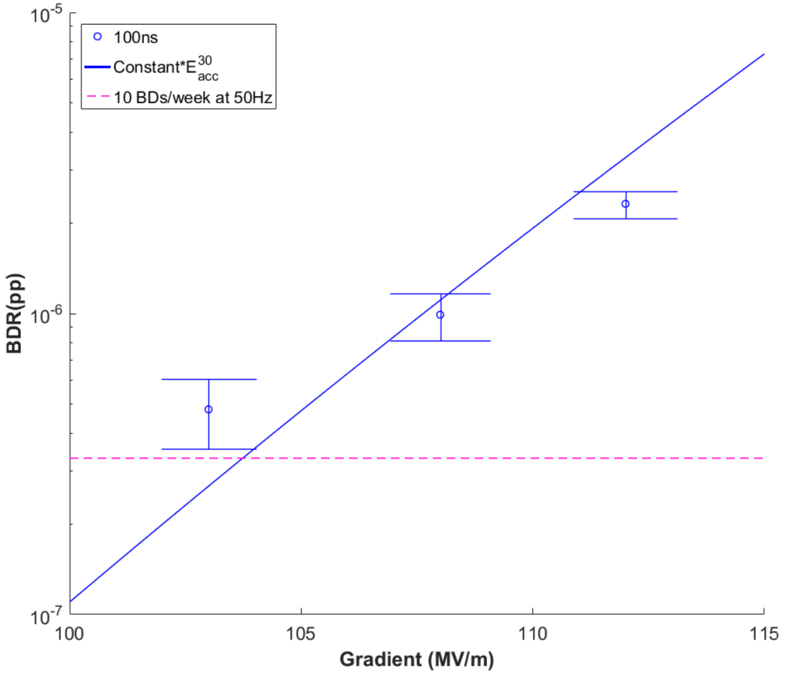
$$BDR \propto {t_p}^{5}$$

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

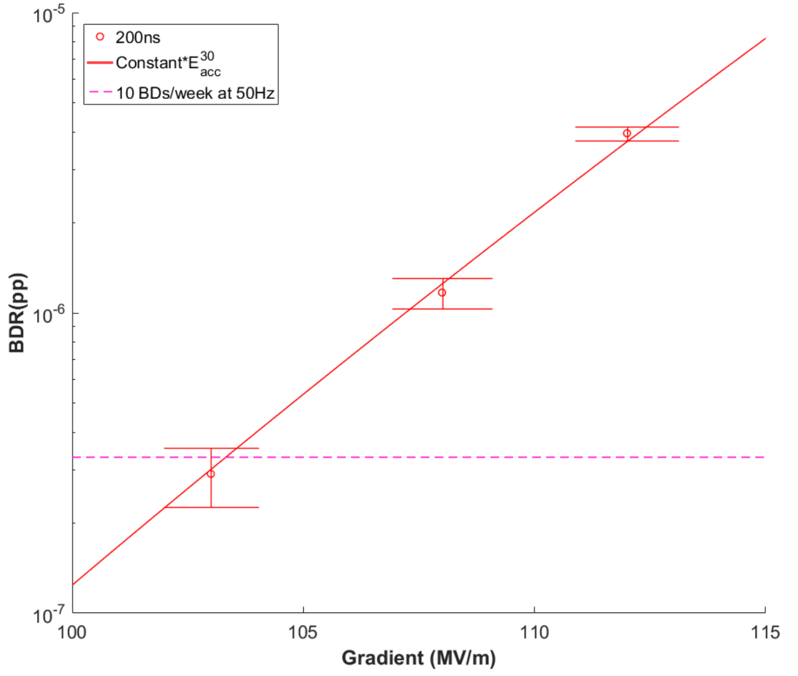
However the exact power scaling has been found to vary from structure to structure. Other suggestions include a physical model based on defect formation and on the plastic response of dislocations [4,5].

BDR Results of Flat Runs

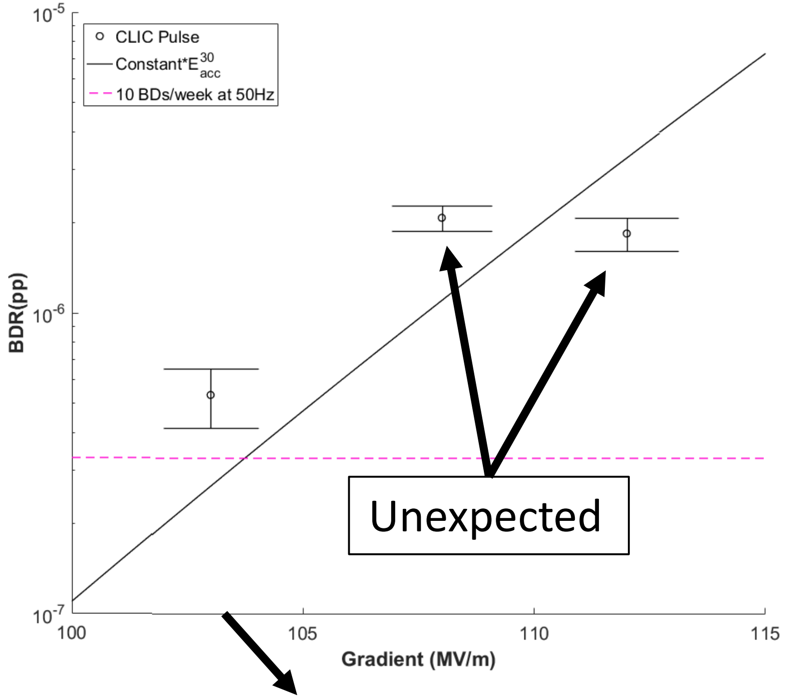
100ns Pulse



200ns Pulse



CLIC Pulse



Run	Grad (MV/m)	Pulse Length (ns)	Pulses (Millions)	Run	Grad (MV/m)	Pulse Length (ns)	Pulses (Millions)
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4	108	100	32	9	103	100	31
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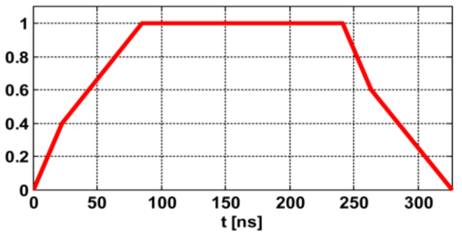
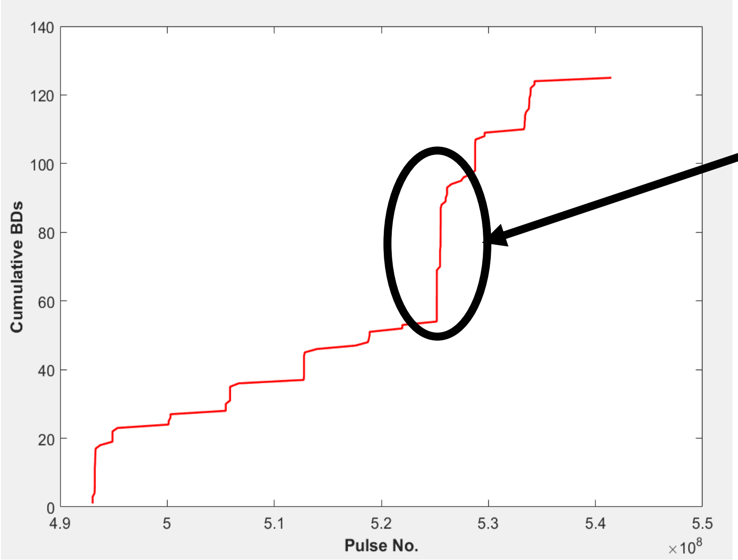


Clustering

- 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.



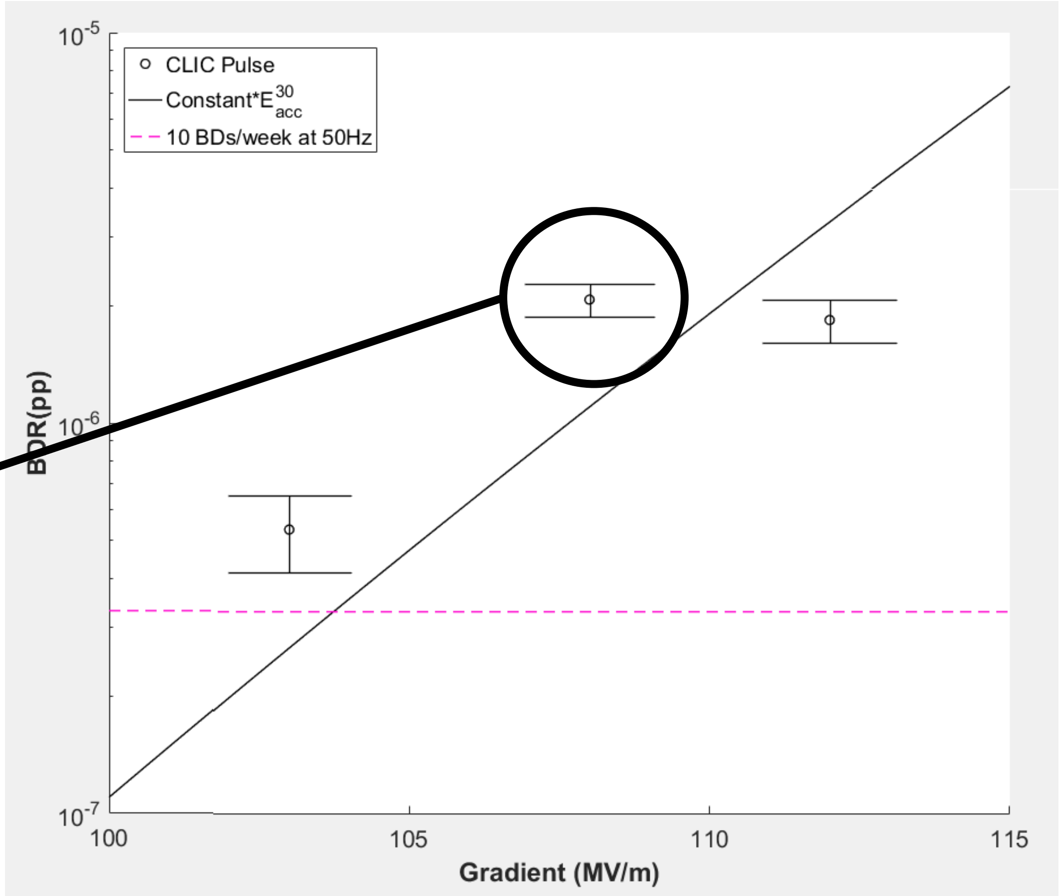
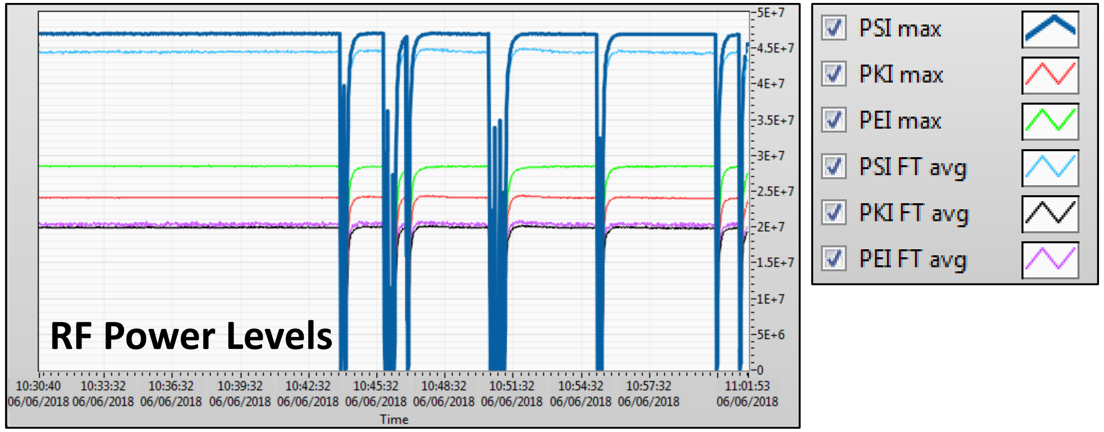
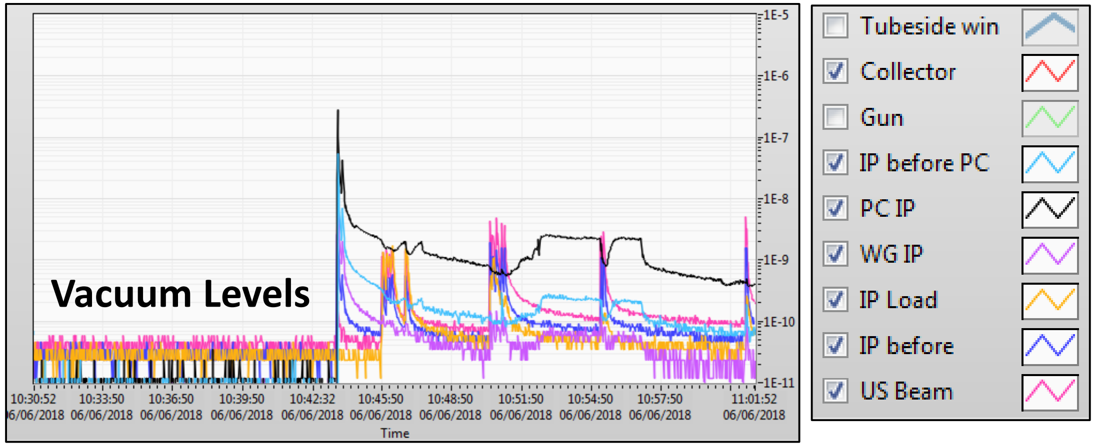


Figure: CLIC Pulse data points and a fitted empirical scaling (top) and Pulse No vs Cumulative BDs (left).

Clustering

- ~75% BDs in this 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.
- **Can be prevented/stopped by temporarily decreasing the gradient.**
- The gradient may then be ramped back up to the nominal level over the course of minutes.

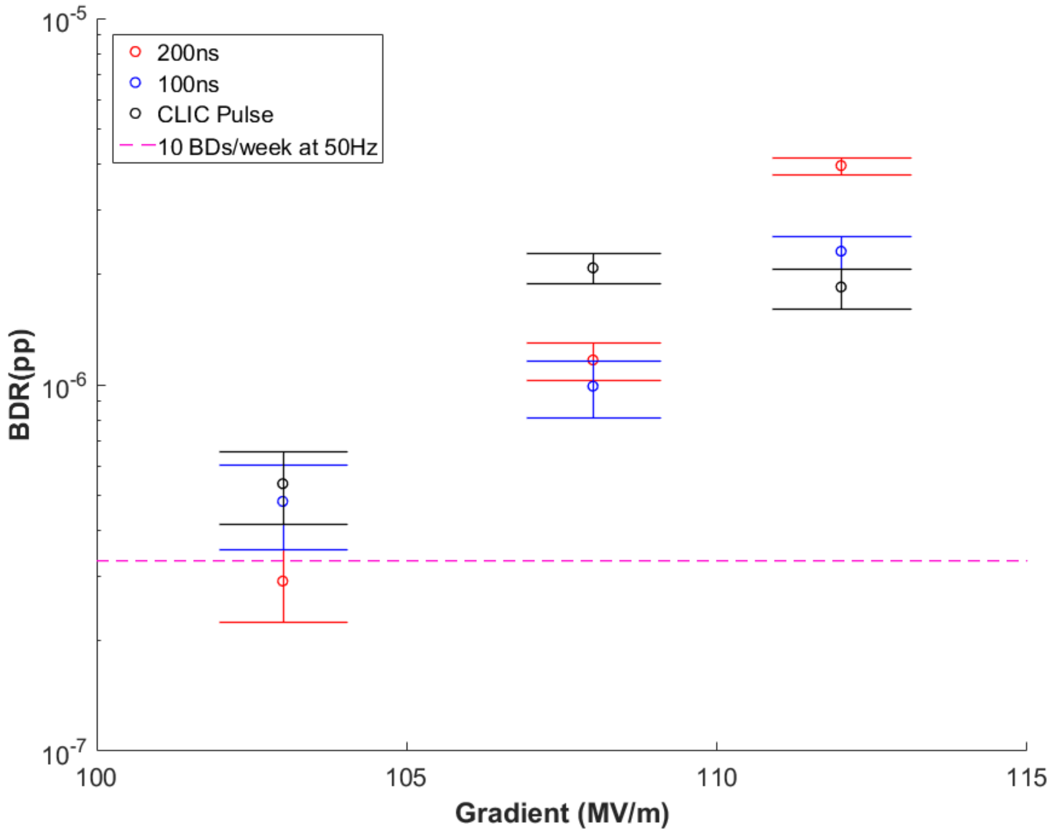




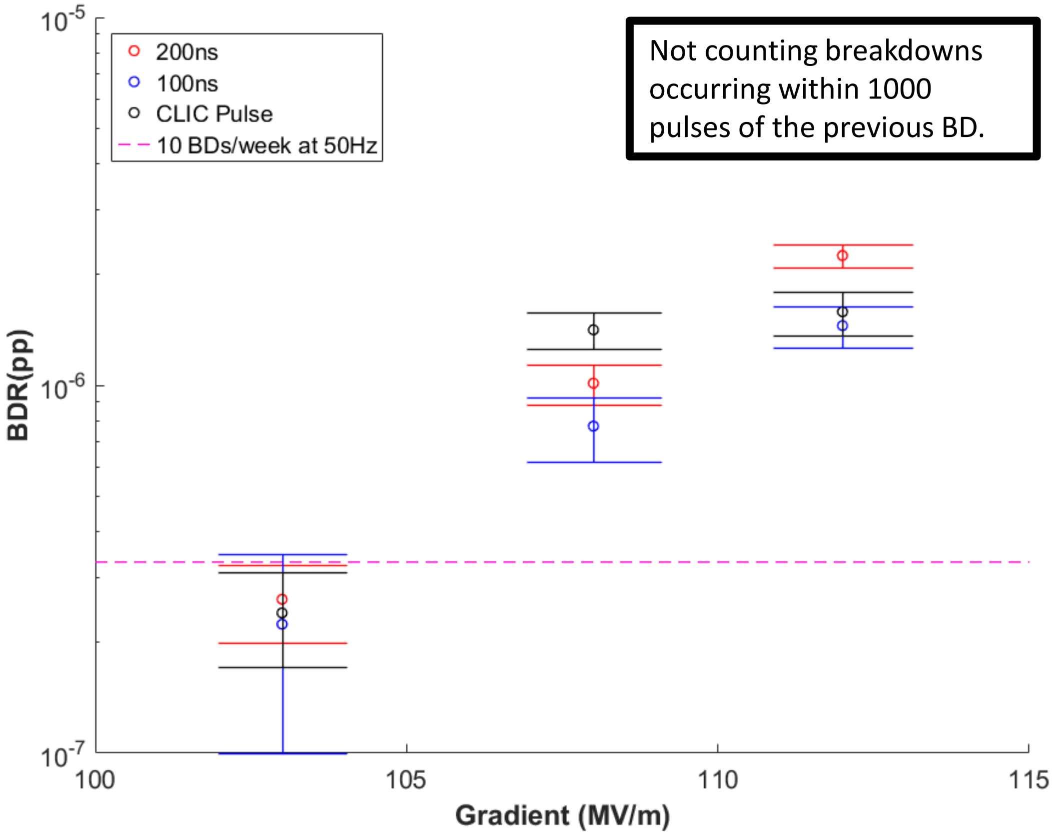
Figures: Peak RF power (top) and vacuum levels (bottom) during clustering as displayed in real-time on the GUI.

Comparison with ‘Event’ BDR

Conventional BDR



Event BDR



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

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)

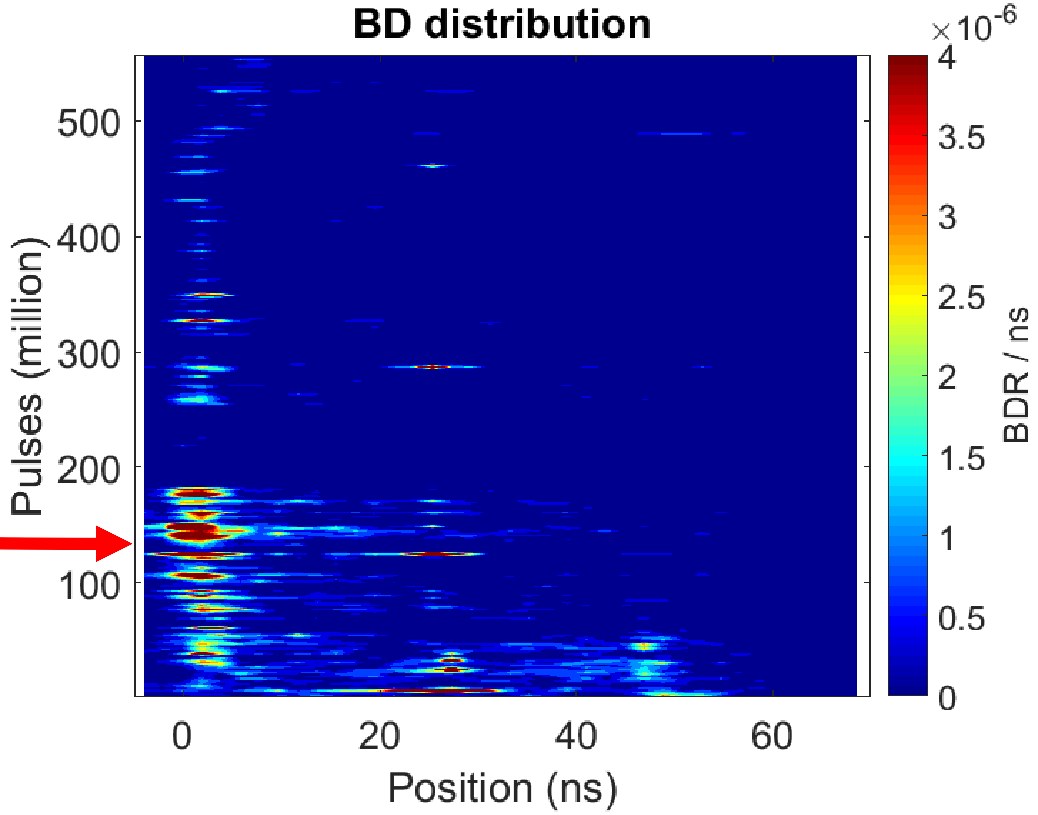


Figure: BD timing during the PSI N2 conditioning showing most breakdowns occurred at the start of the structure.
(Thanks to Jan Paszkiewicz for the BD heatmap plotter)

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 flat gradient runs.
- 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”.

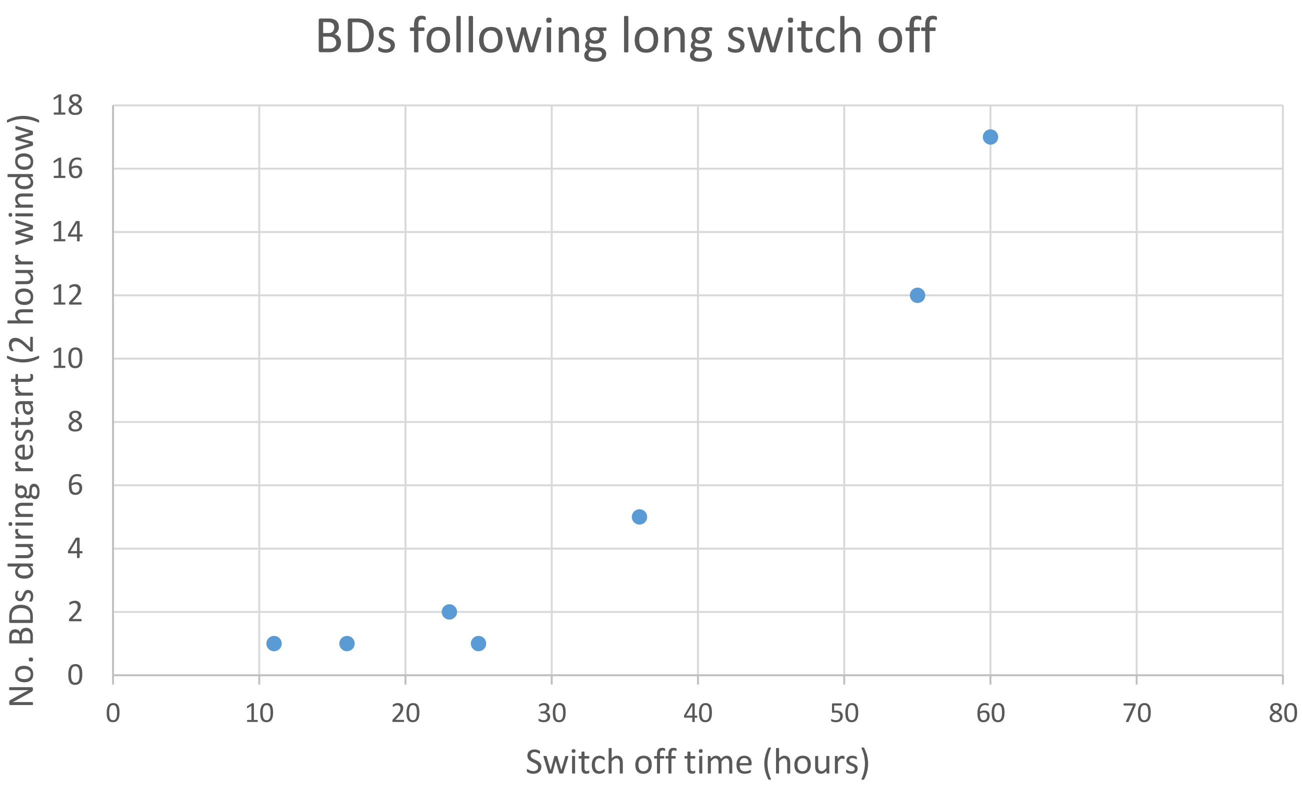


Figure: BDs upon restart after a long switch off for the PSI N2 structure. (Vacuum integrity was maintained)

Persistence of Conditioning

- When breaking vacuum, the structure and line must be reconditioned.
- However, any prior conditioning persists.
- PSI N2 was conditioned up to ≈100MV/m in one line before being exposed to air and switched.
- Reached the same gradient in a quarter of the initially required pulses.

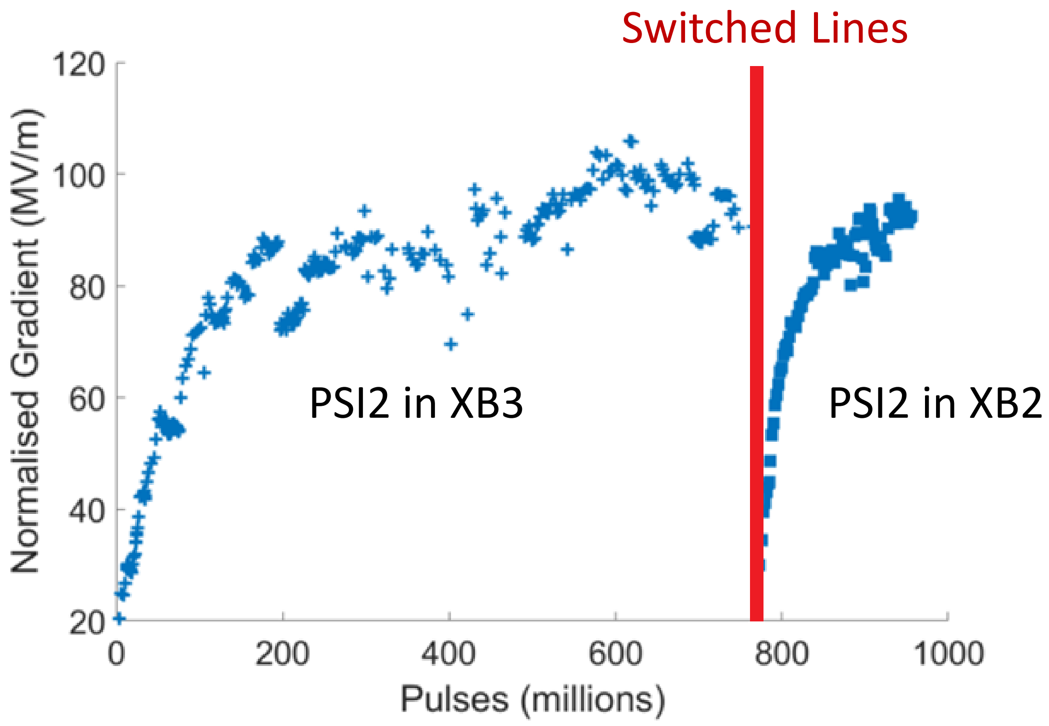


Figure: T24PSI2 Conditioning to 100MV/m in XB3 and reconditioning in XB2 after exposure to air respectively.

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 it can be managed by temporarily decreasing the gradient.

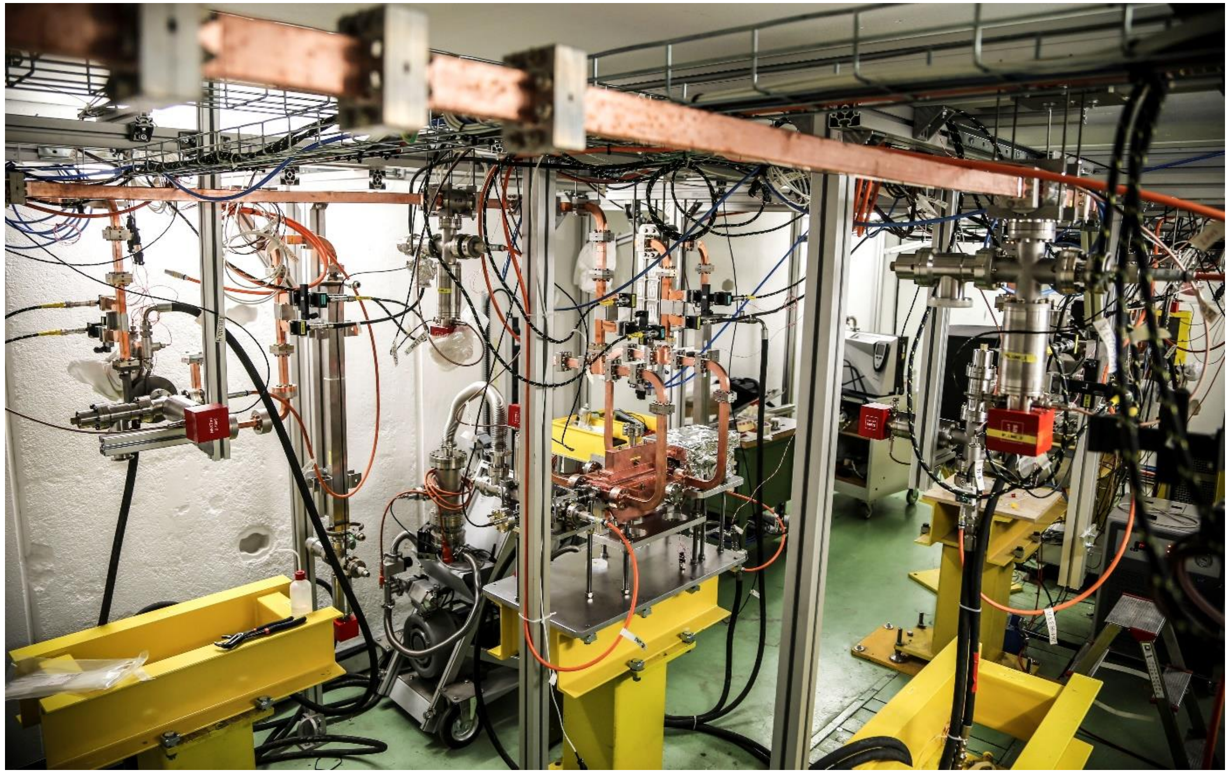


Figure: Xbox test slots inside the shielded bunker.

Future Plans

- We have 6 X-band test stands running and plan to continue data taking for the foreseeable future.
- Components coming soon to XB2:
  - CCC (Correction Cavity Chain)
  - BOC Pulse Compressor (Barrel Open Cavity)
  - TDS (Transverse Deflecting Structure)
  - CLIC SS (SuperStructure)
- We can run at high gradient for long periods, the next logical step is test a complete set-up and run at full spec.
- Experimental plan under works.
- First data coming 2019.

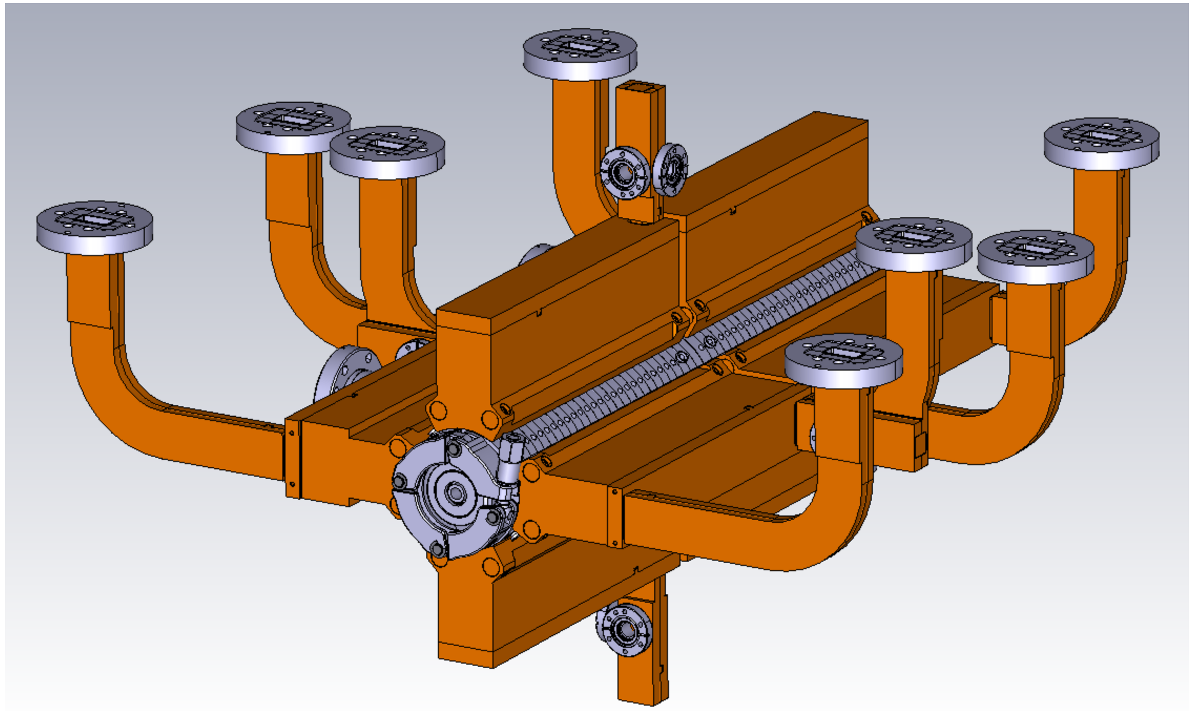


Figure: Rendering of the CLIC Superstructure due for installation in X-Box 2.

Thank you. Questions?

References

- [1] - *Electron Emission in Intense Electric Fields,* R.H Fowler and L. Nordheim
- [2] - *Comparison of the conditioning of high gradient accelerating structures*, D. Alberto et al.,, American Physical Society 2016 Phys. Rev. ST Accel. Beams, Vol. 19
- [3] - *Ultimate Field Gradient in Metal Structures*, W. Wuensch, Presentation at IPAC 2017, Available online: http://accelconf.web.cern.ch/AccelConf/ipac2017/talks/moyca1_talk.pdf
- [4] – *Defect model for the dependence of breakdown rate on external electric fields,* Nordlund and F. Djurabekova, Phys. Rev. ST Accel. Beams 15, 071002 (2012).
- [5] – *Stochastic Model of Breakdown Nucleation under Intense Electric Fields*, Zvi Engelberg et al. (2018). Physical Review Letters. 120. 10.1103/PhysRevLett.120.124801.