Lessons Learned from CERN's High-Gradient RF Test Stands

Lee Millar[1,2]

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

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

International Workshop on Future Linear Colliders (LCWS 2019), Sendai, Miyagi, Japan

30 Oct 2019

Contents

High Power Test Stands at CERN

To test the novel structures and high power RF components for CLIC, CERN has developed a high gradient test programme.

Today, said programme is comprised of three test stands:

- **Xbox 1**: 50 MW klystron, 50 Hz, connection with CLEAR (e- LINAC)
- **Xbox 2**: 50 MW klystron, 50 Hz
- **Xbox 3**: 4x6 MW klystrons, 400 Hz (4 structure test slots)
- ***Sbox**: 45 MW klystron, 50Hz, S-band (3 GHz)*

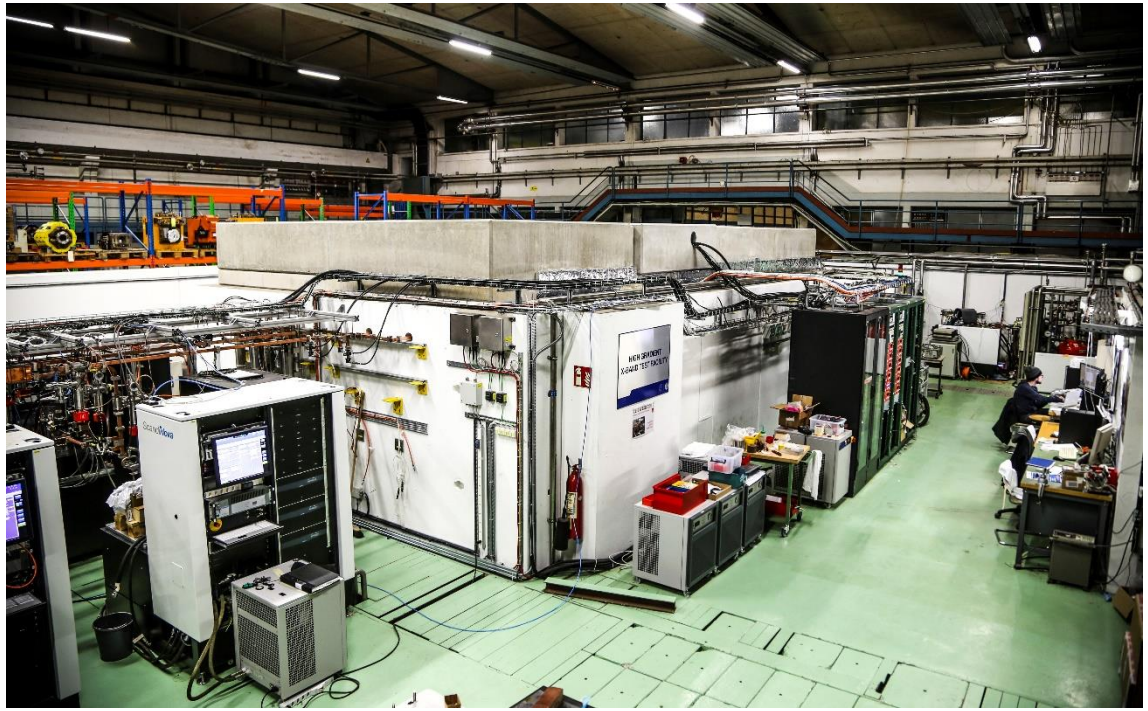


Figure: X-band high gradient test facility at CERN.

High Power Test Stands at CERN

We have experienced going from a single manually operated test stand to six which are operating 24/7.

- We now run at high gradient for long periods of time uninterrupted.

Lets examine some observations which have emerged from this experience…

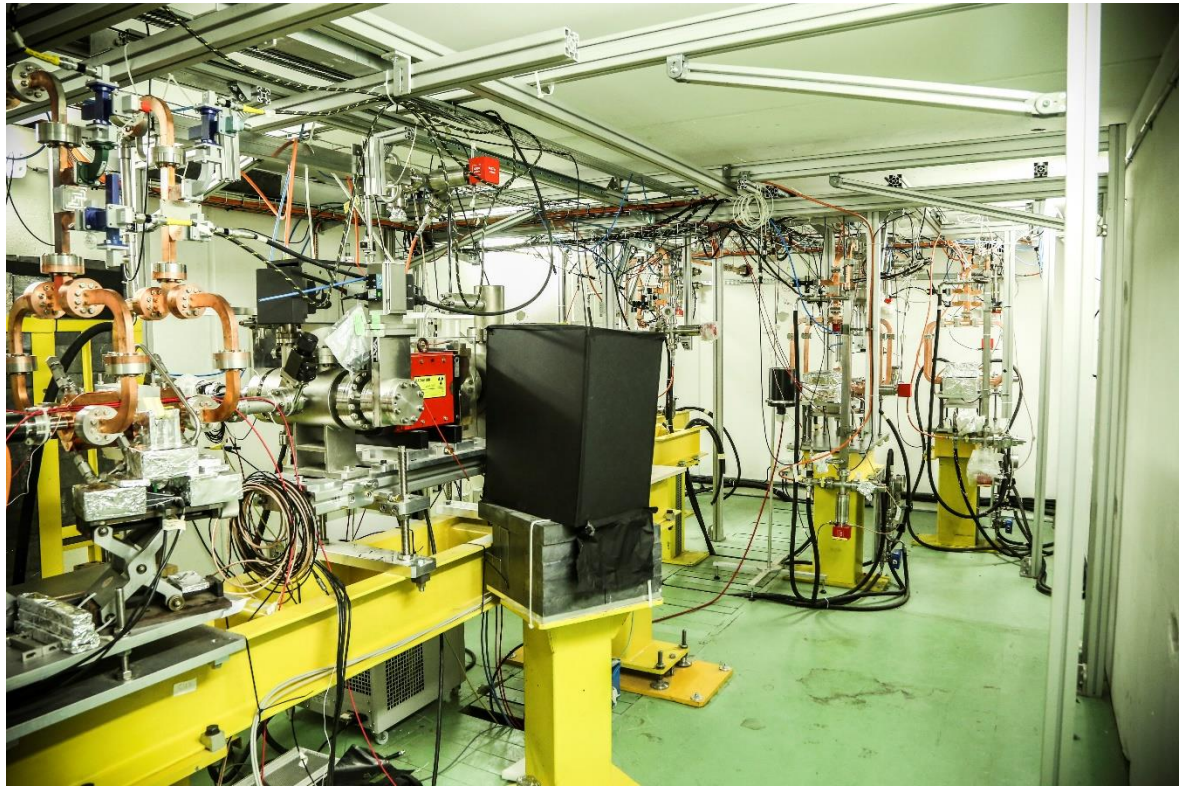


Figure: X-band test slots inside the Xbox bunker.

Contents

The Conditioning Process

Breakdowns limit high power operation immediately after manufacture, structures must instead be conditioned.

This generally follows three phases:

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

II. **Drop the power, increase the pulse length (50, 100, 150, 200ns) and ramp back up.**

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

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

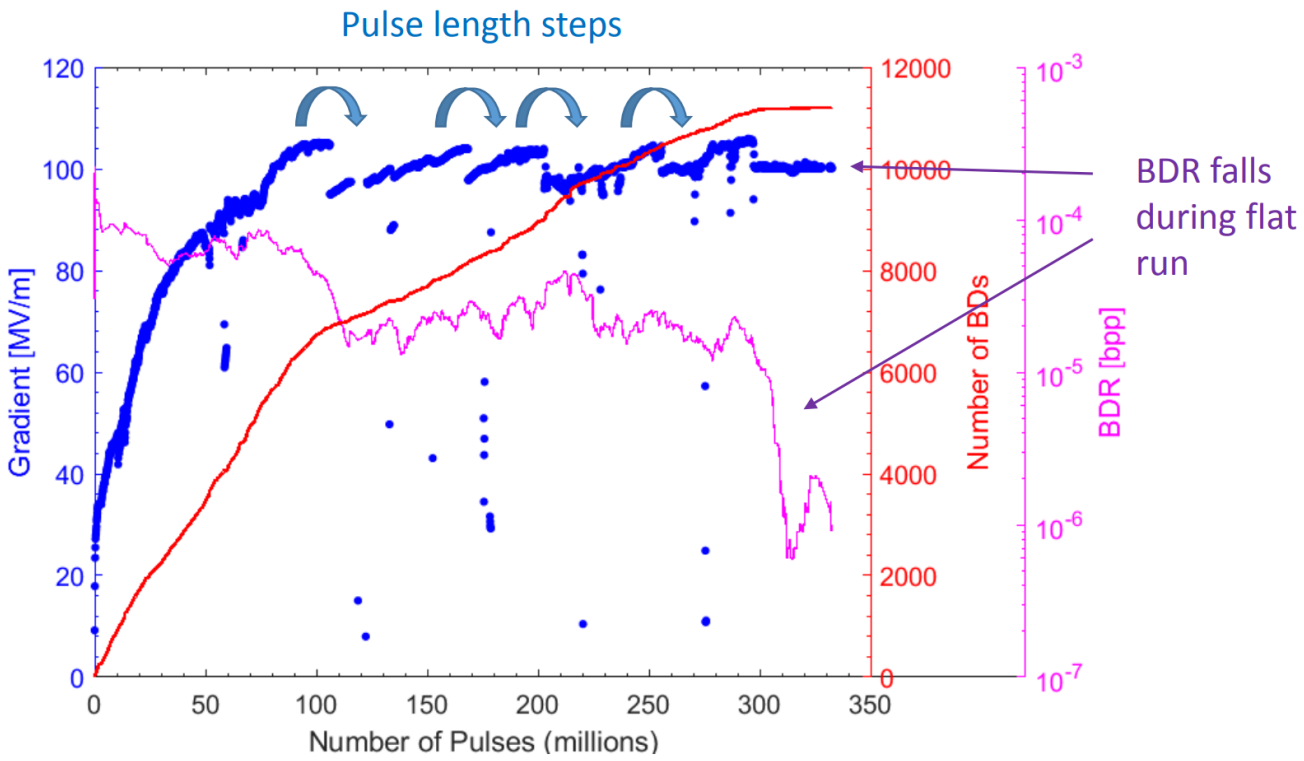


Figure: A typical conditioning curve.

The Conditioning Process

It has also become apparent that:

- Structures condition on the **number of pulses not the number of breakdowns [1]**.
- Cleanliness of preparation shown to affect number of breakdowns during conditioning, **not ultimate performance. [2]**

Conditioning is now **automated and accomplished algorithmically**[3,4], however occasionally we must deviate from the aforementioned "ideal" case…

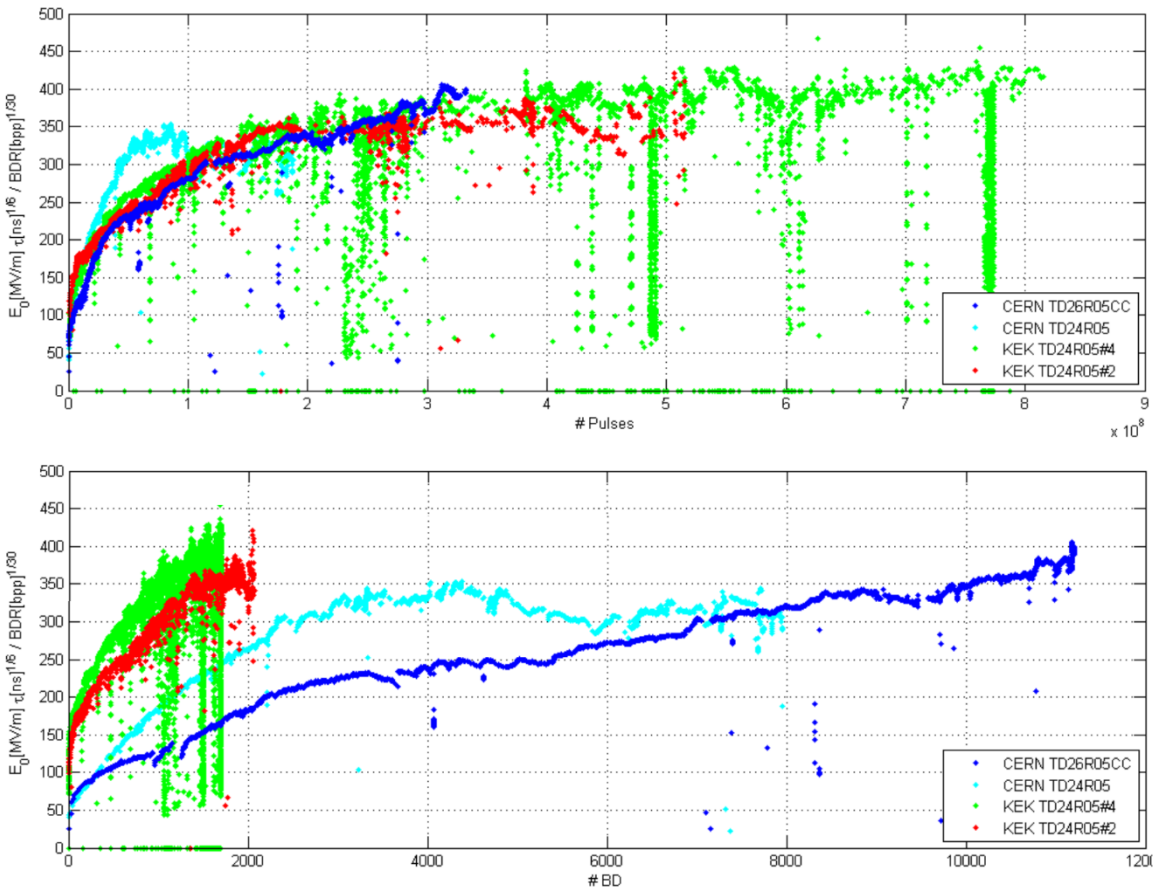


Figure: Scaled gradient vs. cumulative no. pulses (top) and scaled gradient vs. cumulative no. breakdowns (bottom) for four different structures.

Effect of Switching Off the RF on Conditioning

Interlocks or access may require a period of inactivity (vacuum maintained but no high power RF).

Anecdotal evidence suggests this can **result in a temporarily increased BDR when restarting.**

- Suggested that this may be migration of water back to high field regions.
- 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".

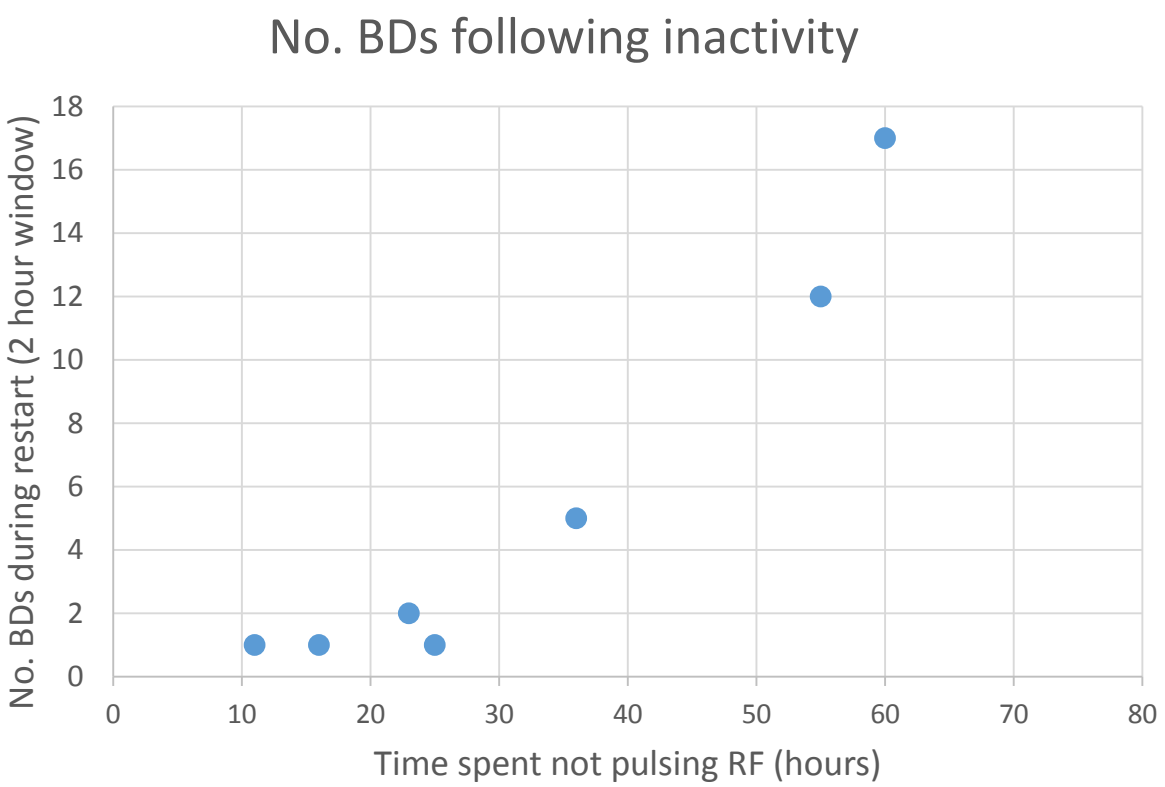


Figure: BDs upon restart after a long switch off for the PSI N2 structure in XB2 (Vacuum integrity was maintained (<1E-10 mbar) and power was held constant).

Restarting a High Gradient LINAC

As shown on the previous slide, when operating close the limit it takes time to re-establish prior conditions following a period of inactivity.

To reduce the number of BDs which occur, a slow recovery ramp has now been implemented in our software following a period of inactivity.

A comparison is pictured right. →

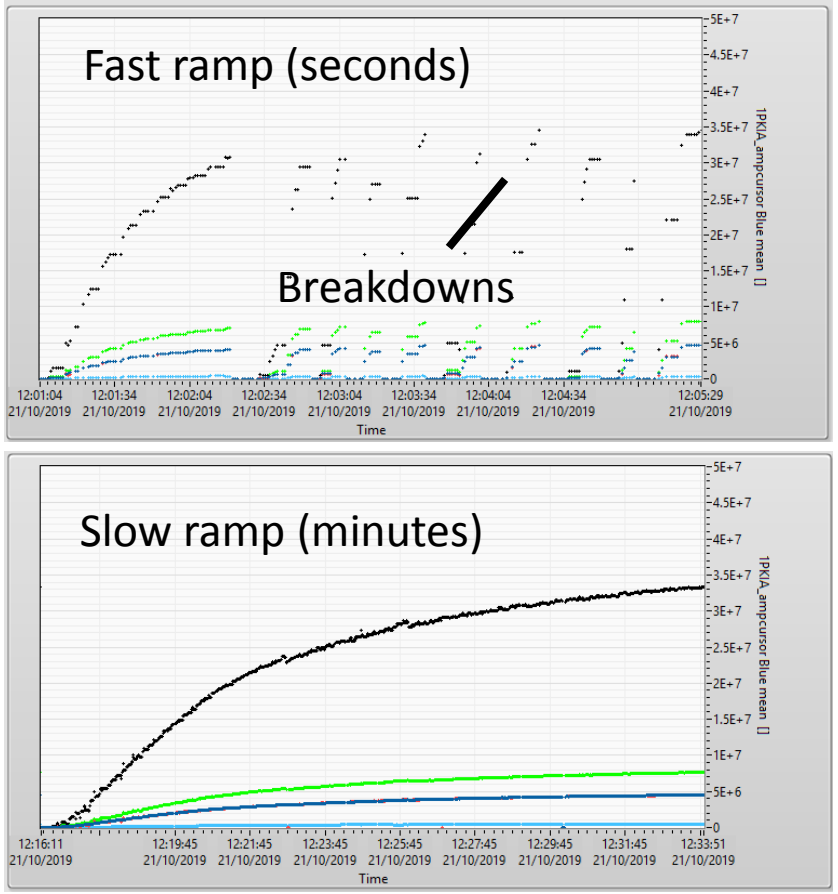


Figure: Peak power during restart following several days without RF and a setpoint of 35MW. Top plot shows a quick ramp (≈ seconds) followed by several breakdowns before restabilising while the bottom shows a slow power ramp (≈ minutes) with no breakdowns during ramping.

Effect of Atmospheric Exposure on Conditioning State

Occasionally, a line may have to be opened for maintenance.

After exposure to air, a structure must be reconditioned however we reach the **previously achieved gradient faster than was initially possible** and with fewer breakdowns.

- Implies a well defined underlying physical mechanism which results in a sustained change to the surface properties of the material.
- For further examples see [5]

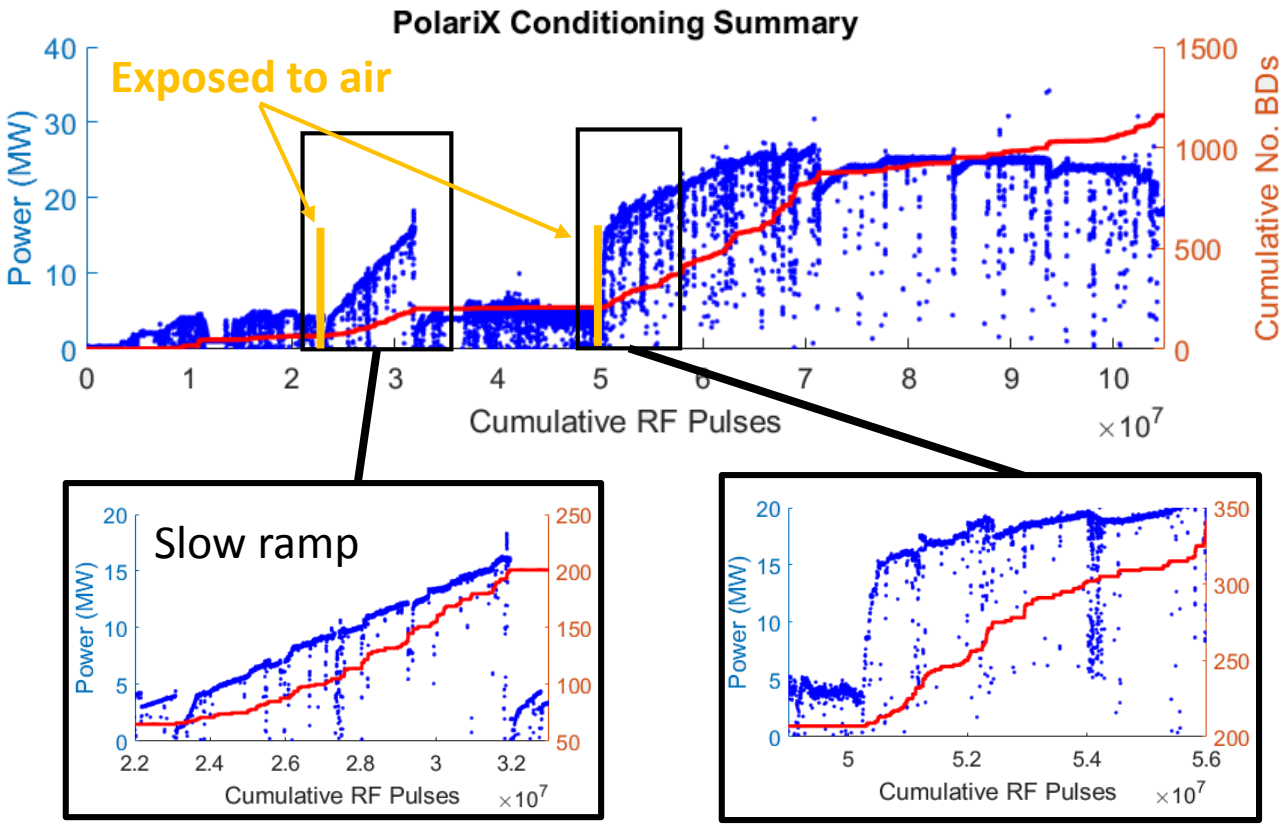


Figure: PolariX Conditioning history. For a more detailed overview of this test see bonus slides.

Contents

Xbox-3 Test Stand Arrangement

Unlike the other test stands, Xbox-3 has **four 6MW klystrons** and four test slots, each equipped with a pulse compressor.

To increase the peak power capability, each pair of klystrons is combined via a novel 3dB hybrid combination scheme.

- Facilitates the use of lower power (cheaper) klystrons.
- Higher rep rate capability (up to 400Hz).
- Lower voltage requirement.

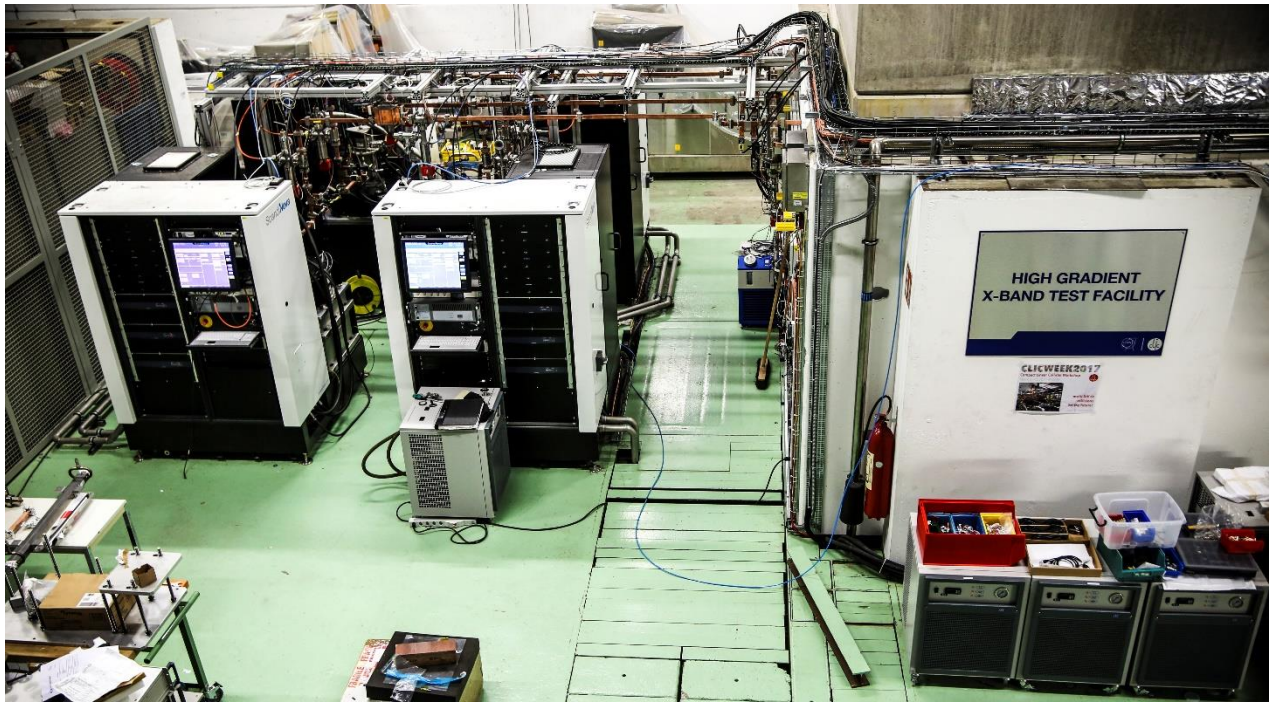
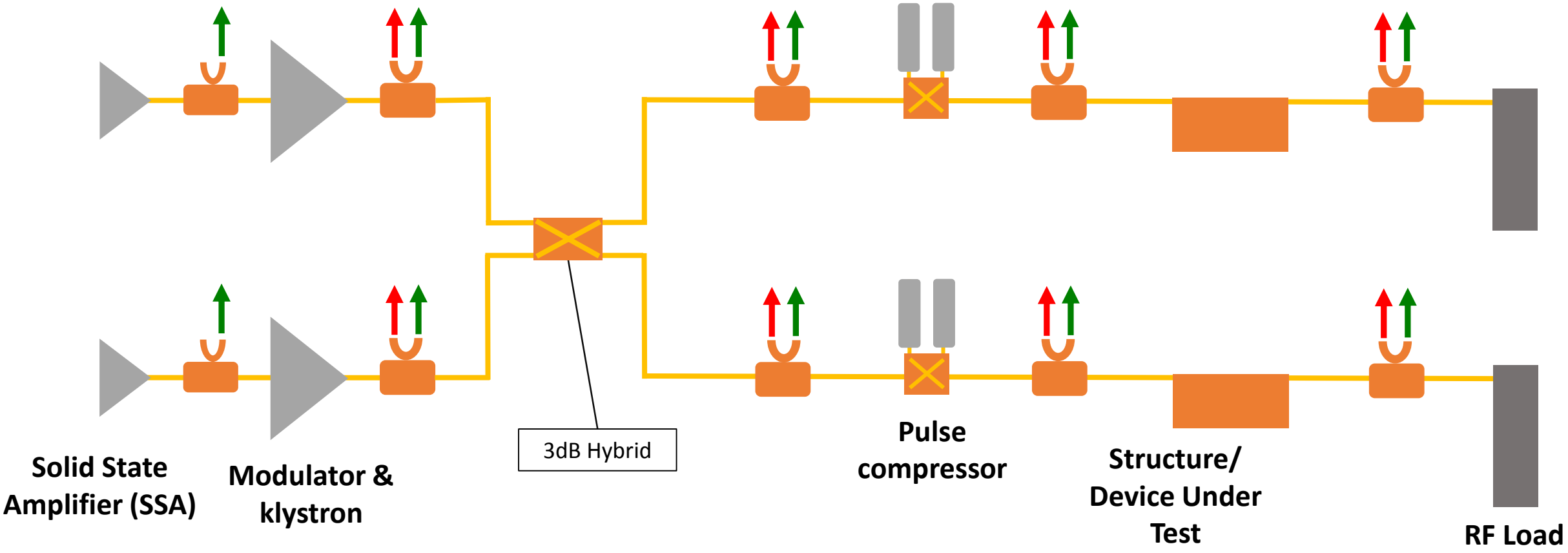


Figure: XB3 Klystrons/modulator and radiation shielded bunker.

Xbox-3 Test Stand Arrangement



Experience with the Xbox-3 Combination Scheme

With this scheme we can achieve **~42 MW for 200ns pulsed at 200Hz** in each test slot and have successfully tested many components/structures.

However, this brings with it several new aspects which must be considered:

- Lines coupled in terms of RF, klystrons must produce identical pulses.
- Lines coupled in terms of vacuum. ∴ Without valve/window this means a component change interrupts both lines.
- Increased control system complexity.
- Increased data consumption/channels required per test slot.
- Effectively doubles the downtime due to klystron/modulator problems.

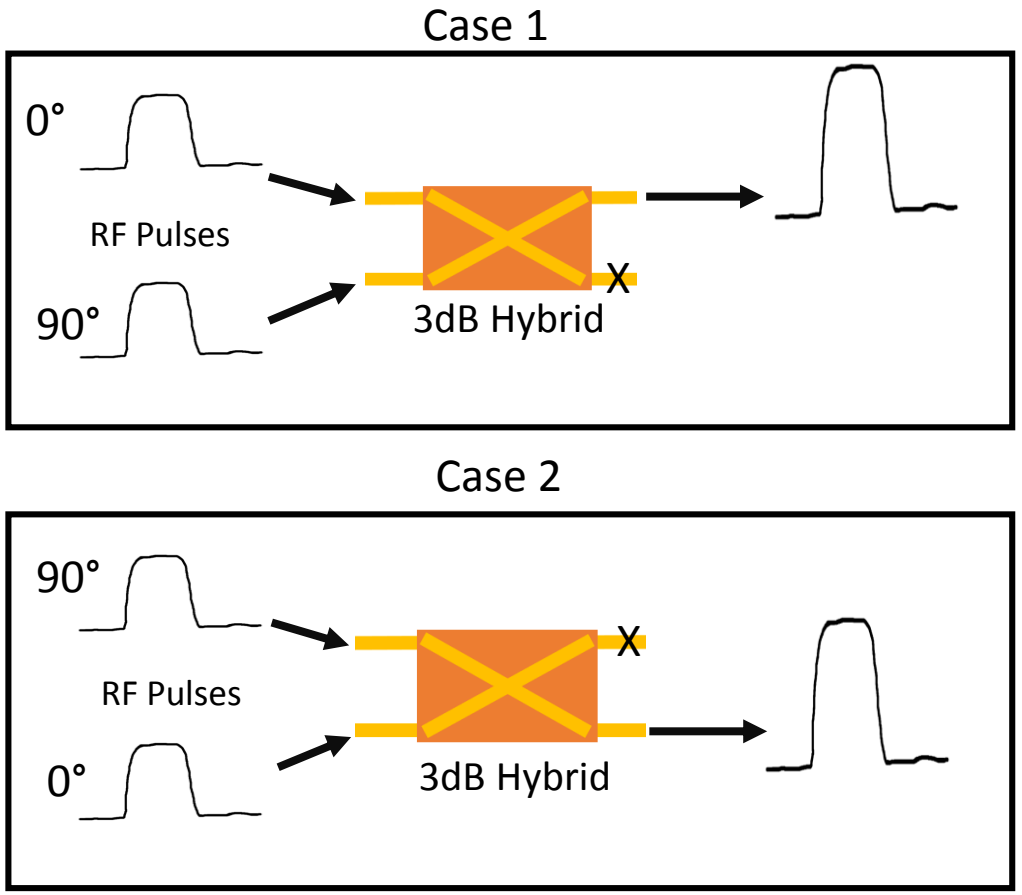


Figure: Principle of the power combination scheme in XB3.

Experience with the Xbox-3 Pulse Compressors

Each test slot uses a pulse compressor to increase the peak power capability, however the average power is higher on XB3.

- After a BD the system interlocks the RF for several seconds, **at high rep rates this is sufficient to detune the high-Q cavities**.
- An inconsistent pulse is now being sent to the DUT, may cause issues if feeding back on peak/average power.
- XB3 now adjusts the RF frequency based on the pulse shape to match the cavities ω_0 until thermal equilibrium is restored.
- Adds other effects (changing group velocity/ field distribution).

We are now investigating the effects in addition to thermal stability options but the problem will always exist at some level.

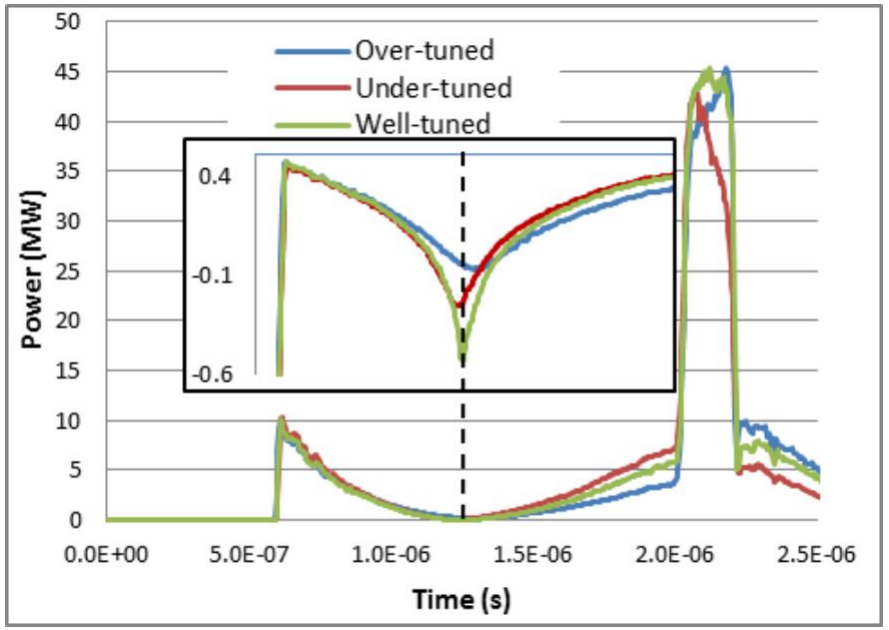


Figure: Pulse compressor output from an over, under and well tuned pulse compressor respectively. [3]

Experience with the Xbox-3 Combination Scheme

To date the system has been commissioned and is running as we speak, however whether or not this combination approach is appropriate will naturally depend on the application i.e. finding a compromise between system complexity, cost, reliability etc.

This has been a superficial overview, however we are now testing four structures simultaneously for the first time and accumulating data.

As such, **many of these effects are to be quantified soon.**

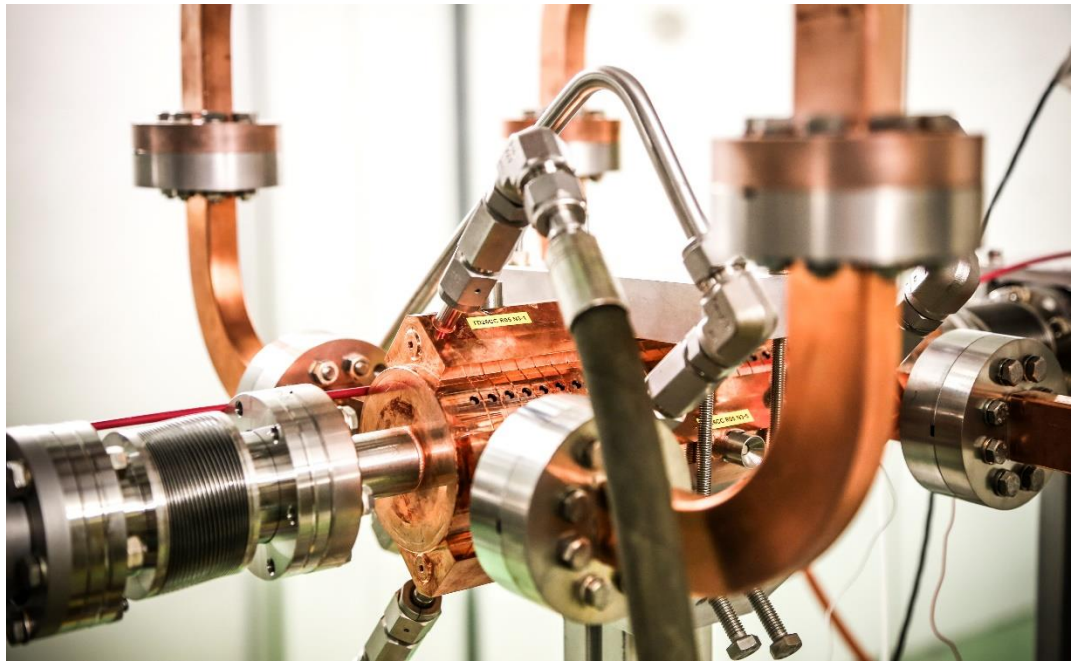


Figure: A TD26 previously installed in XB3.

Contents

1. Introduction to the High Gradient Test Stands at CERN
2. Operational Issues and Lessons Learned
   - Observations on Conditioning
   - Experience with the Xbox-3 Combination Scheme
   - **Statistics of Breakdown at High Gradient**
3. Summary and Conclusion

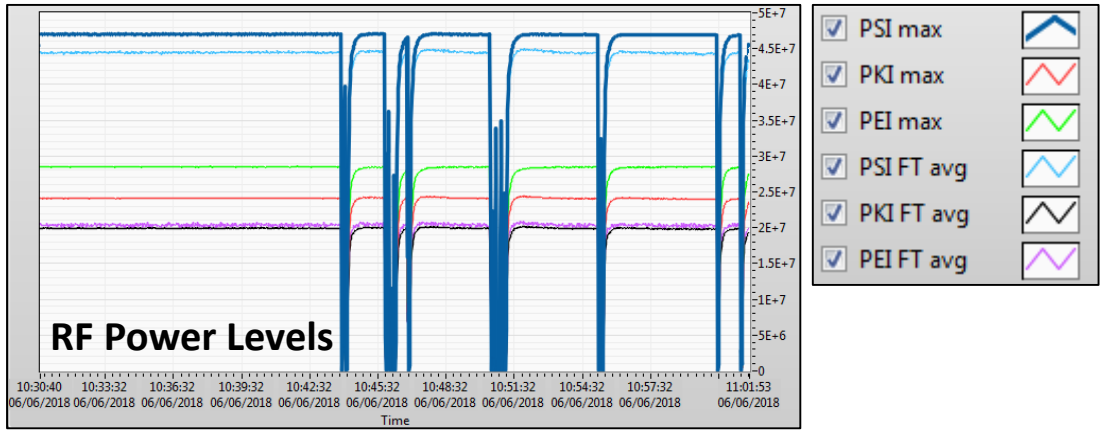
Statistics of Breakdown at High Gradient

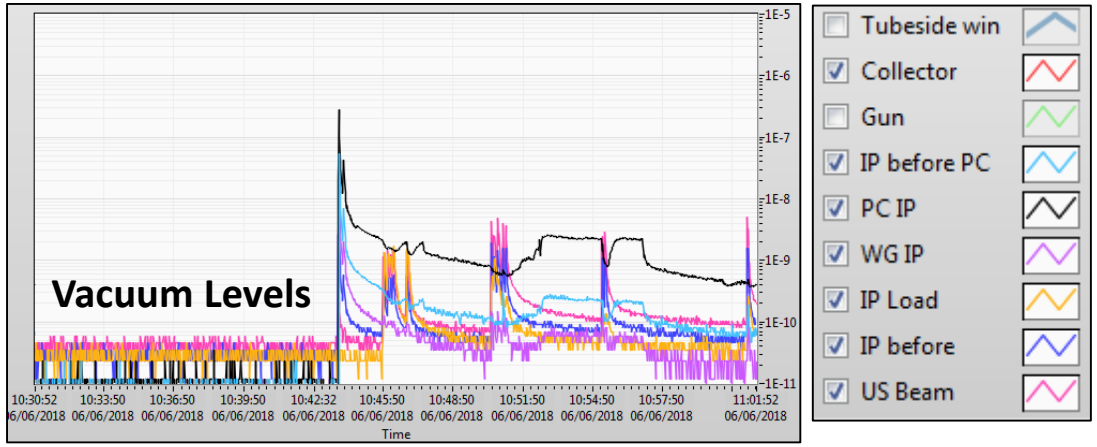
In accelerator facilities, machines typically run stably within the design specifications.

As we test structures to the operational limit we necessarily push our systems towards instability.

Close to the limit the probabilistic behaviour of breakdowns appears to change:

- The BDR tends to manifest not as a constant and stable BDR but rather as **successions of BDs in a short timeframe** i.e. a cluster (example pictured right).....



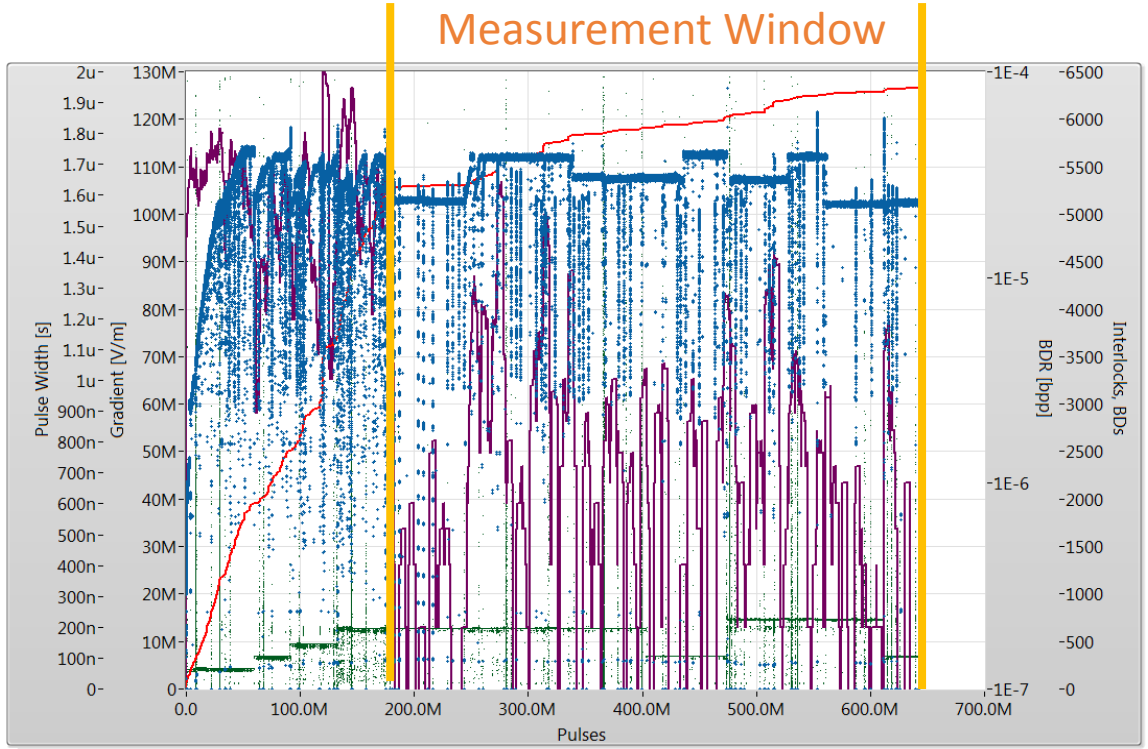


Figures: Peak RF power (top) and vacuum levels (bottom) during clustering as displayed in real-time on the GUI.

Statistics of Breakdown at High Gradient

In 2018, we ran a PSI2 T24 structure for several months at fixed gradients.

- **~75% BDs** during this time 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** (higher probability of follow-ups).
- Additionally they tend to occur spatially close to one another, although breakdowns do tend to occur in the first cell in the later stages of testing so it is difficult to draw conclusions.
- For more details see[2,6]



Figures: Conditioning history of the PSI2 structure showing the flat gradient runs from 200M pulses on.

Contents

Summary of Recently Tested Components

We have recently tested many X-Band components including:

1. High Power Variable Phase Shifter
2. High Power Variable Power Splitter
3. PolariX TDS (World first!)
4. Barrel Open Cavity (BOC) Pulse Compressor
5. Correction Cavity Chain (CCC)

And of course many more in addition to those currently under test. For a more comprehensive overview of these tests see the bonus slides.

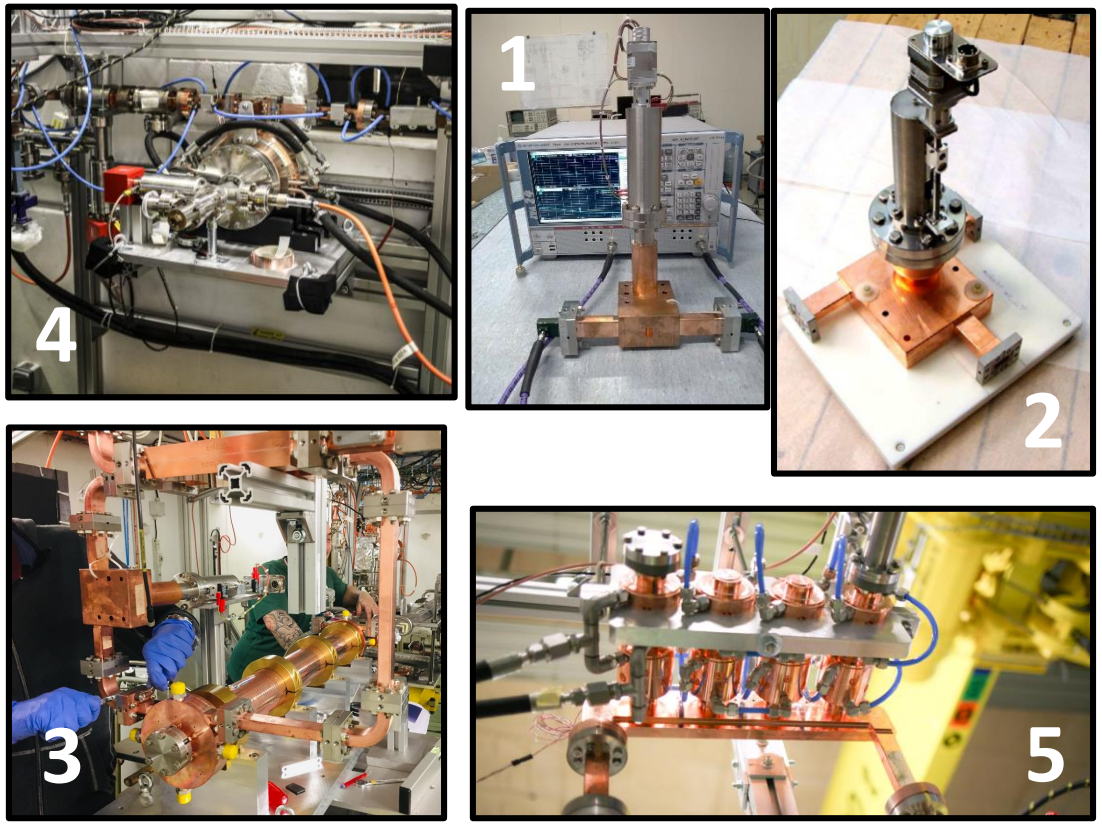


Figure: Scaled gradient vs. cumulative no. pulses (top) and scaled gradient vs. cumulative no. breakdowns (bottom) for four different structures.

Conclusion

We have three test stands which run at high gradient (>100MV/m) for long periods of time:

- By approaching the limit we necessarily push systems towards instability and as a product of this we learn of the limiting factors/weak points as they emerge.
- We are now in the process of quantifying such issues and their implications for a large machine.

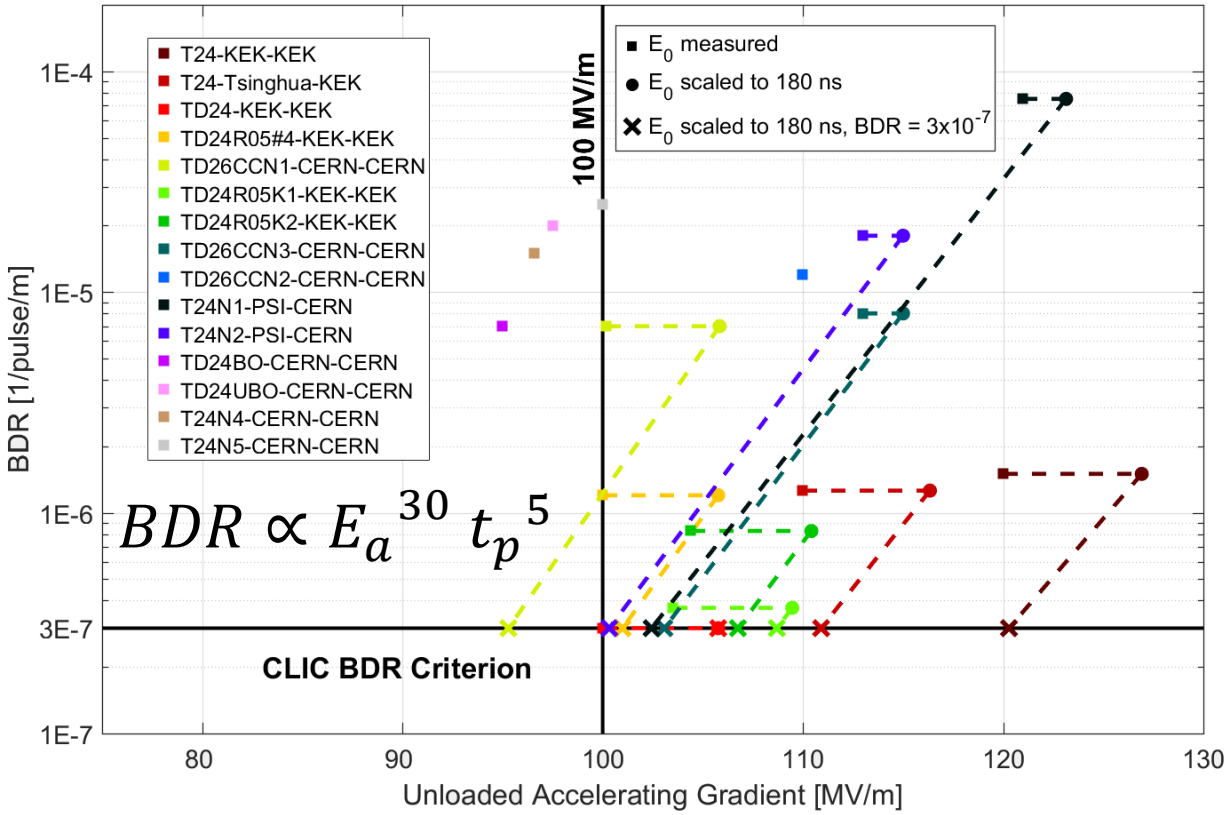


Figure: Summary of CLIC structures normalised to a pulse length 180ns and a BDR of 3×10^{-7} BDs per pulse per metre.

Thank you. Questions?

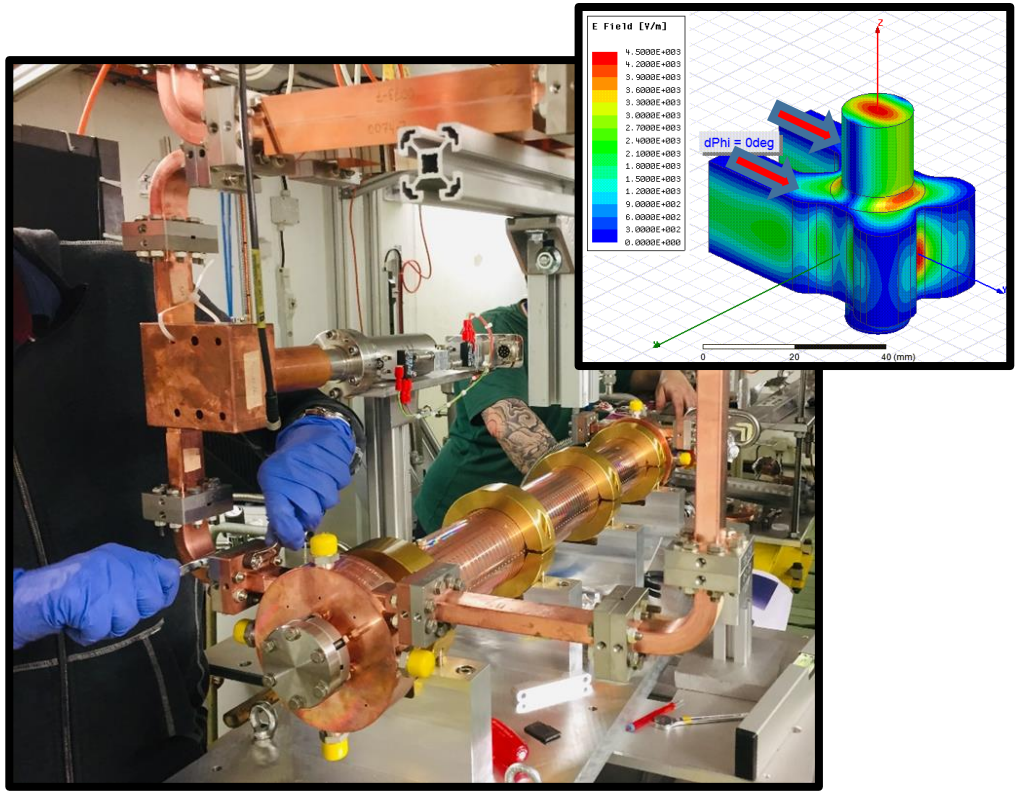
References

[1] - J. Giner Navarro, Breakdown Studies for High Gradient Rf Warm Technology in: CLIC and Hadron Therapy Linacs, University of Valencia, 2016.
[2] – Study of Basic Breakdown Phenomena in. Dolgashev, V.A. Tsukuba, Japan : s.n., 2010. XXV International Linear Accelerator Conference (Presentation).
[3] – B. Woolley, “High Power X-band RF Test Stand Development and High Power Testing of the CLIC Crab Cavity,” Lancaster University, United Kingdom, 2015.
[4] – L.Millar, “Conditioning and Operational Algorithms”, Presentation, Available online: https://indico.cern.ch/event/719535/
[5] – J.Paszkiewicz, “X-Band RF Test Stands at CERN” Presentation at SINAP, Shanghai, 4-8 June 2018, Available online: https://indico.cern.ch/event/675785/contributions/3022037/attachments/1661499/2662246/CERN_Xboxes_Jan_Paszkiewicz_HG18.pdf
[6] – L.Millar “Behaviour of High Gradient RF Structures During Long-Term Operation”, Presentation at Workshop on Mechanisms of Vacuum Arcs (Mini MeVArc), Uppsala University, Sweden
[7] – L.Millar, “Results of the PolariX TDS High Power Test at CERN, Presentation at International Workshop on Breakdown Science and High Gradient Technology (HG2019), Chamonix, France
[8] – V. del Pozo Romano, et al “High Power Conditioning of X-Band Phase Shifter and Power Splitter“, IPAC2019, Melbourne, Australia
[9] –Y. Jiang et al “Demonstration of a cavity-based pulse compression system for pulse shape correction”, PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 082001 (2019)
[10] – N. Catalan-Lasheras et al“HIGH POWER CONDITIONING OF X-BAND RF COMPONENTS “, 9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada
[11]- P.Wang et al,“rf design of a pulse compressor with correction cavity chain for klystron-based compact linear collider”, PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 112001 (2017)

Bonus Slide: PolariX-TDS

The **PolariX-TDS** (**Polari**zation **X**-band **T**ransverse **D**eflecting **S**tructures) is a collaboration between DESY, PSI and CERN established to develop an X-band transverse deflecting structure (TDS) capable of varying the polarization i.e. the kick direction. The prototype was high power tested at CERN's X-band test stand prior to installation at DESY.

- Conditioned up to 26.5MW at 100ns (peak power on the compressed pulse).
- **No clear structure limitation emerged.**
- Now installed and operational at DESY.
- For a detailed overview see [7]



Figures: The PolariX installed in the XB2 test slot and a gif showing the coupler's principle of operation (top right).

Bonus Slide: Variable Phase Shifter

A high power variable phase shifter tested in XB3 and XB2:

- Tested up to 44MW at 50ns flat top pulse length.
- Used to vary the polarization during testing of the PolariX TDS.
- Now installed in XB2 with a CLIC superstructure module.
- Identical model now in use at DESY in FLASHForward beamline for the PolariX.
- For a full overview see [8]

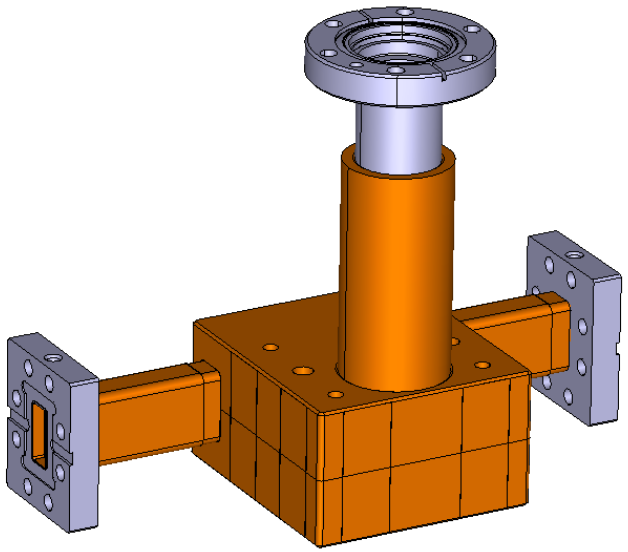
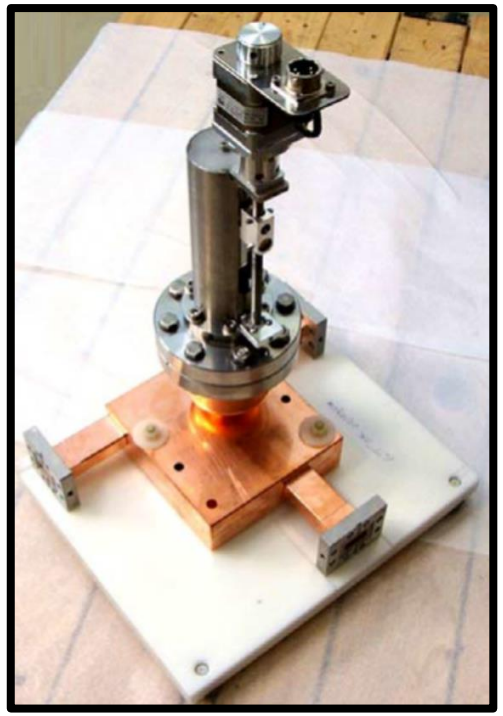


Figure: CAD model of the phase shifter.

Bonus Slide: Variable Power Splitter

- Tested up to 41MW at 100ns flat top pulse length.
- Now installed in a XB2 with CLIC Superstructure to vary the power between structures.
- For a detailed overview of the design and testing see[8] respectively.



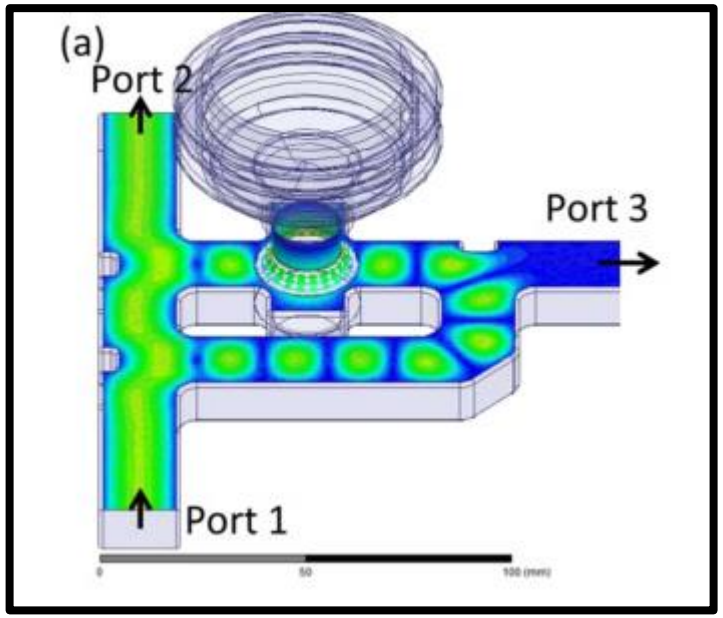


Figure: Phot of the power splitter (left) and HFSS Simulation of a configuration sending all incoming power to Port 2 (right).

Bonus Slide: BOC and CCC

A prototype X-band Barrel Open Cavity (BOC) has been manufactured at PSI and is now in use at CERN's Xbox-2 test stand.

- Maximum compressed pulse at ns
- No clear limit has emerged.

Additionally a Correction Cavity Chain manufactured by Tsinghua University is also under test. The principle of operation is that by adding resonant cavities at chosen area in the spectrum we may mimic a delay line in a compact manner to produce a flat top pulse.

For details on the testing/design see[9,11].

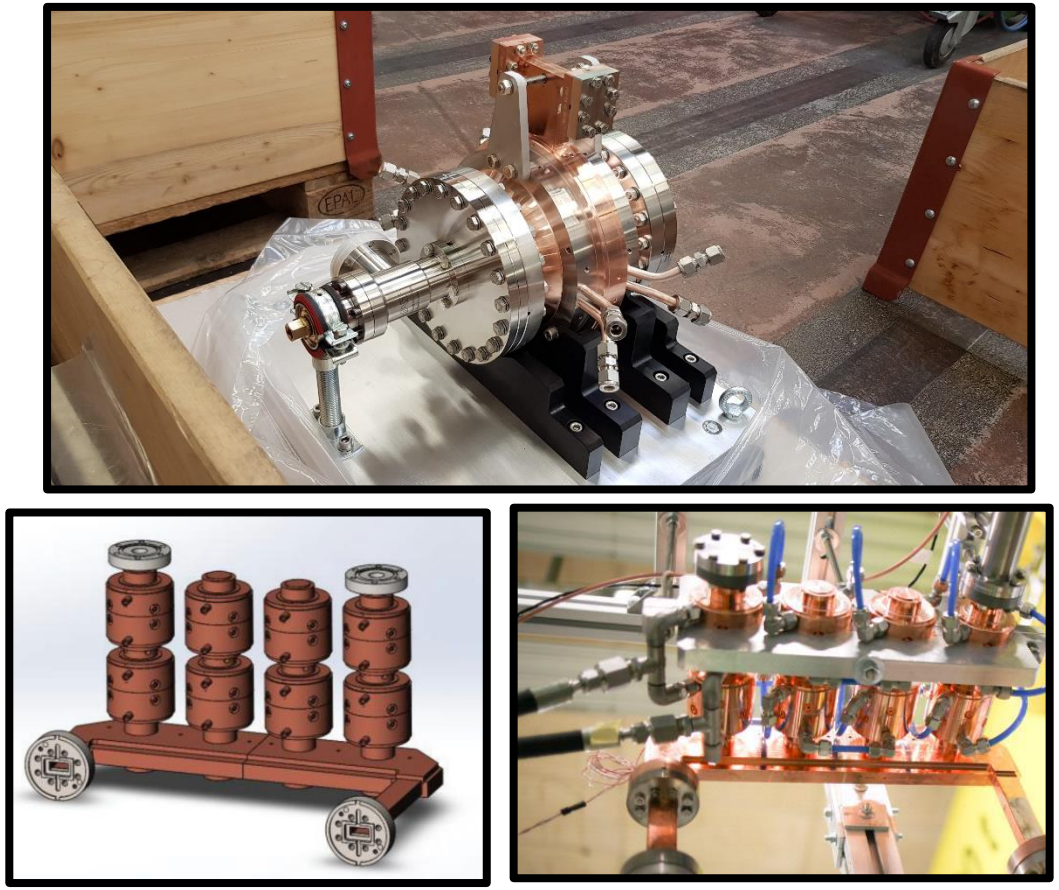
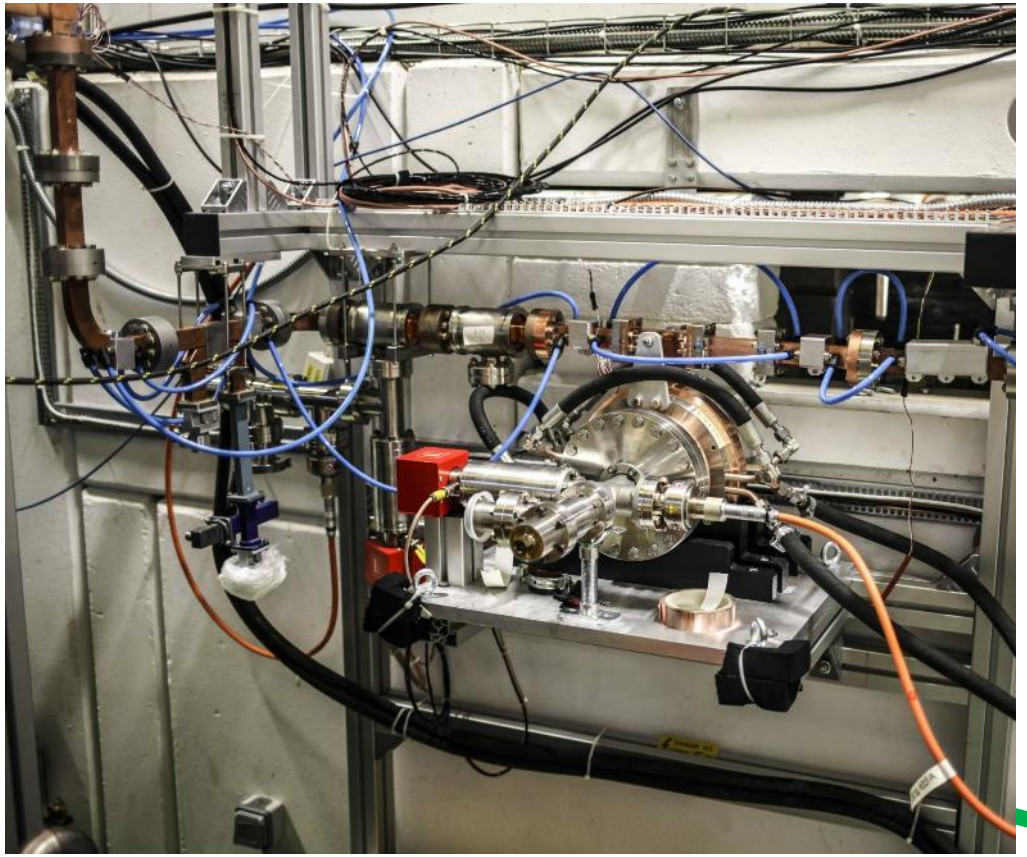
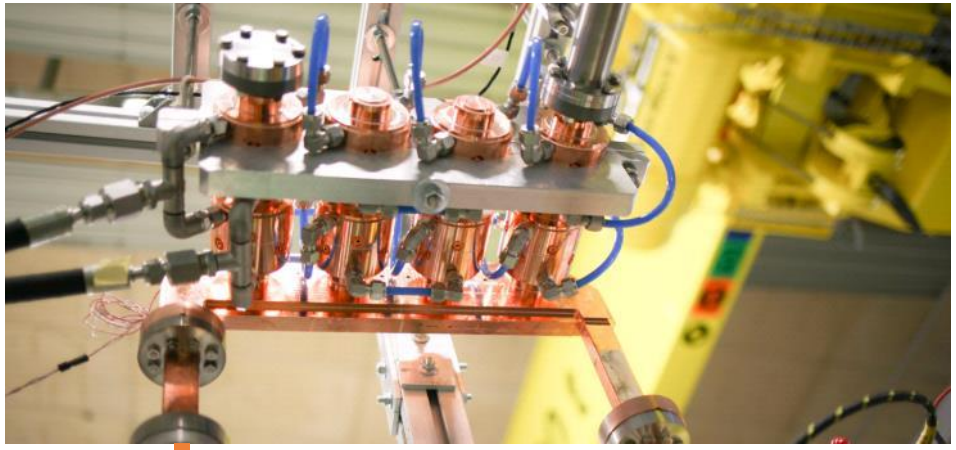
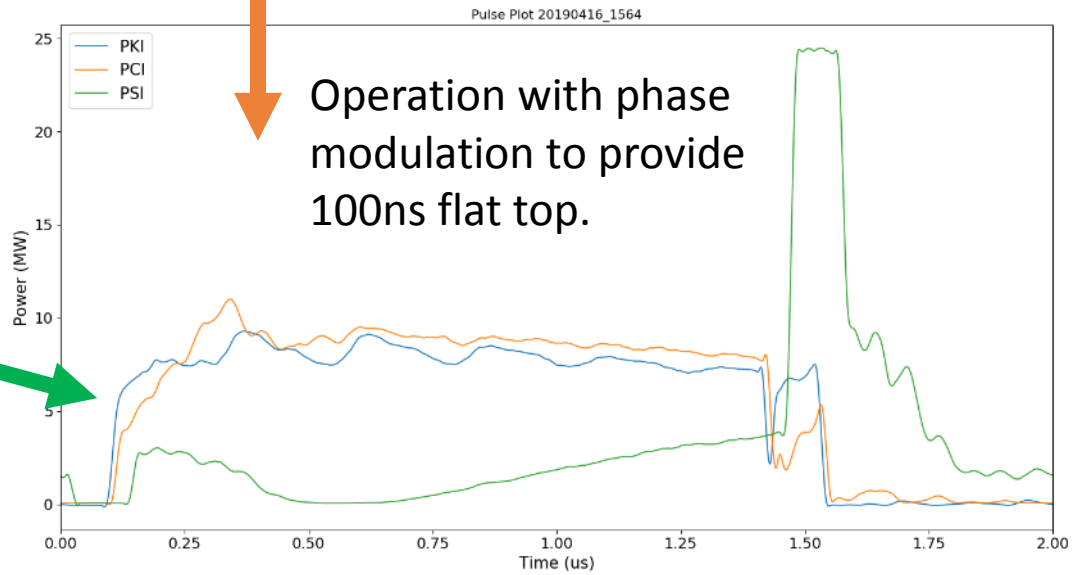


Figure: BOC before installation (top) correction cavity chain CAD model (bottom left) and the correction cavity chain installed in Xbox-2 (bottom right).

Bonus Slide: BOC/Correction Cavity Chain Operation







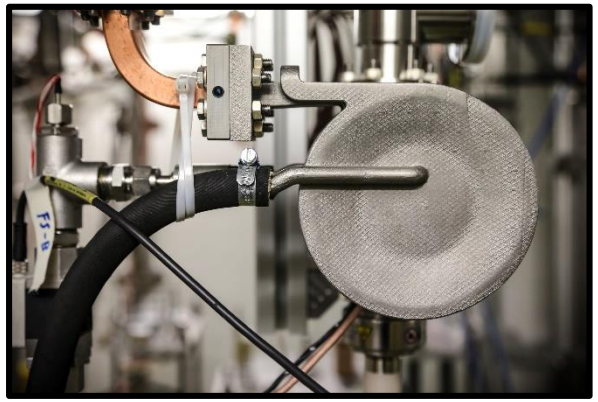
Operation with phase modulation to provide 100ns flat top.

Figures: BOC (left) and CCC (top right) and resultant waveforms of the klystron pulse, CCC output and compressed pulse respectively (bottom right).

Bonus Slide: Performance of RF Loads

Compact Spiral Load

- Additive manufactured (3D printed) from titanium.
- Operated from 50-200 ns up to 200Hz.
- Tested to 35.5 MW (Maximum available in the line) for 50ns and 25MW for 200ns.
- The maximum average power put into the load was 2.1 kW.



Stainless Steel Loads

- Operated from 50-200 ns up to 200Hz.
- Tested to 35.5 MW (Maximum available in the XB3 line at time of testing) for 50ns and at 25MW for 200ns.
- See[10] for more details on both.

Figures: Compact spiral load (top) and stainless steel load (bottom).