High-Gradient Conditioning

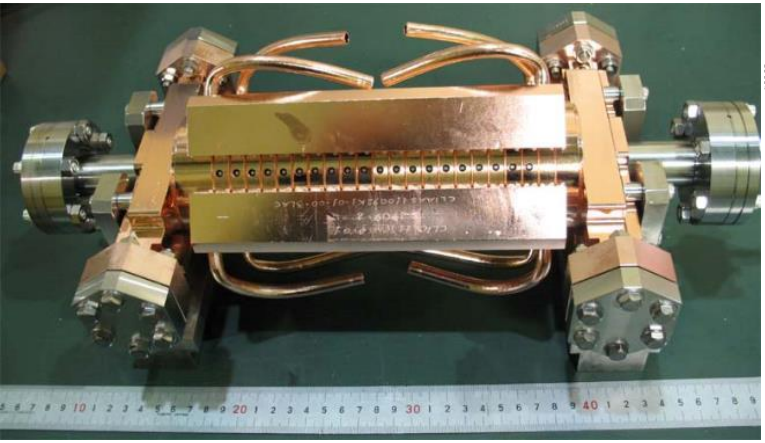
Walter Wuensch, CERN

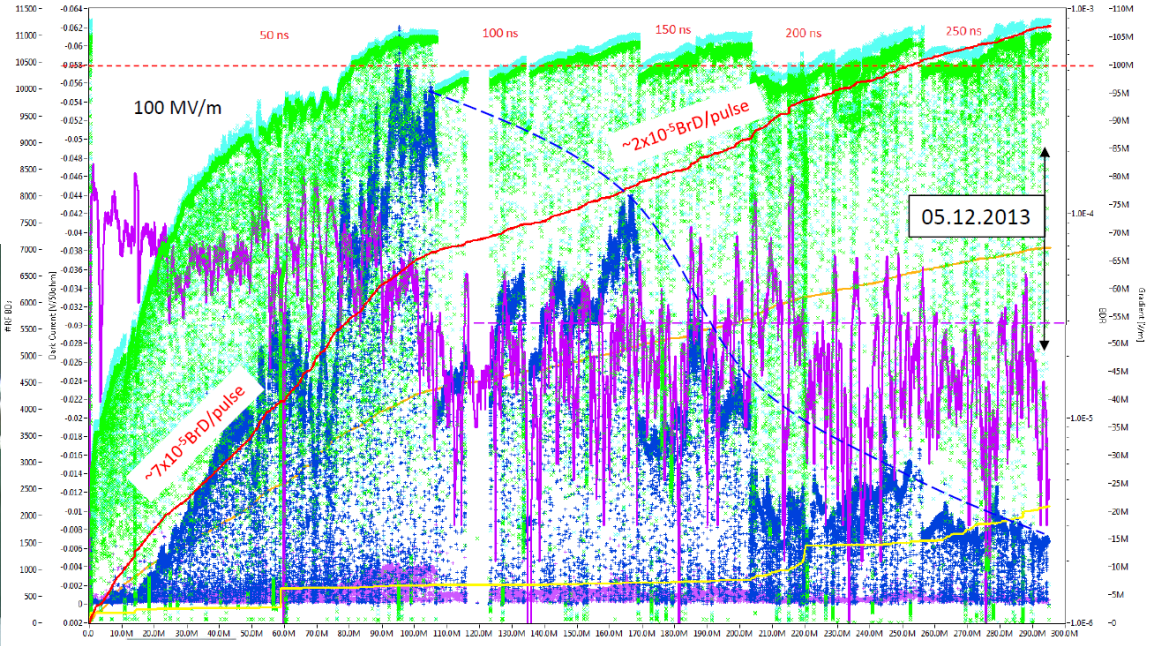
Introduction

A normal conducting rf cavity does not run at its full gradient just after turning it on for the first time after fabrication.

Instead the performance gets better and better as you run it.

We call the period of operation from initial turn-on to nominal performance **conditioning**.

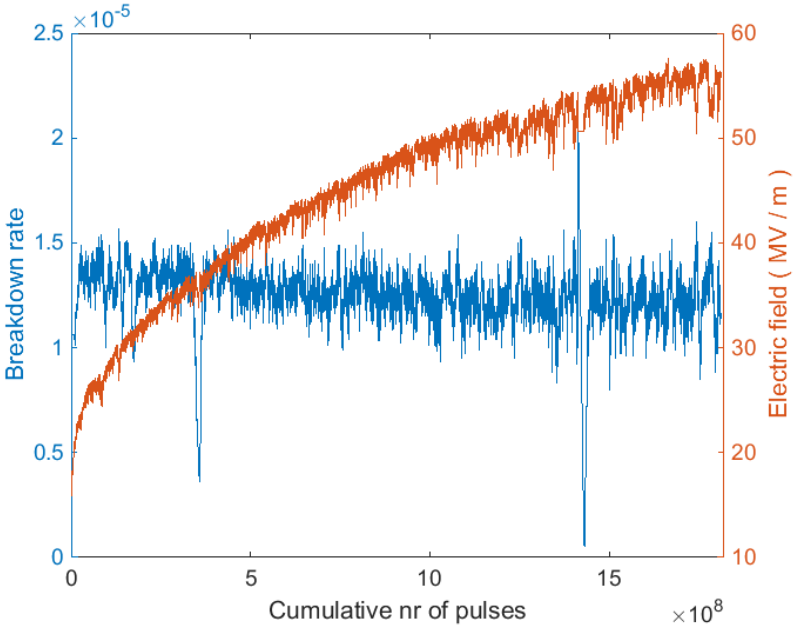




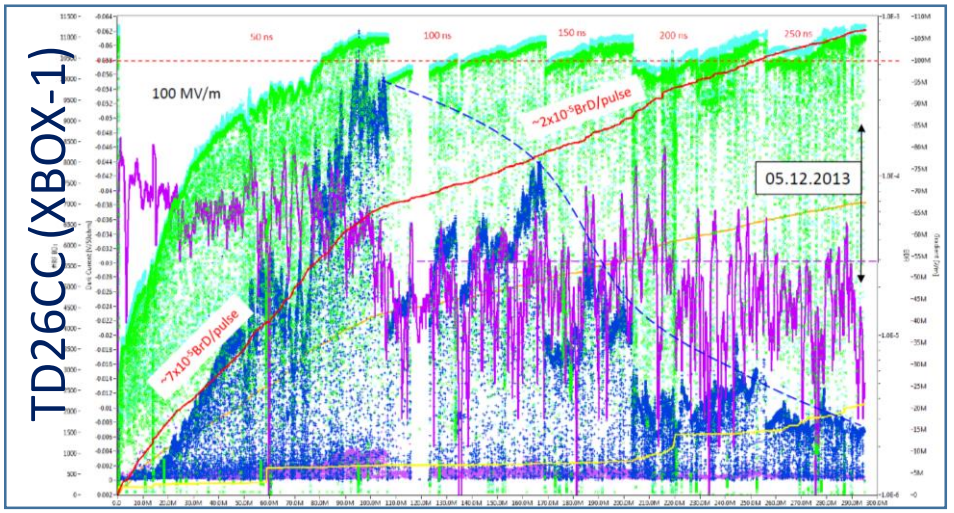
Something like 4-5 months

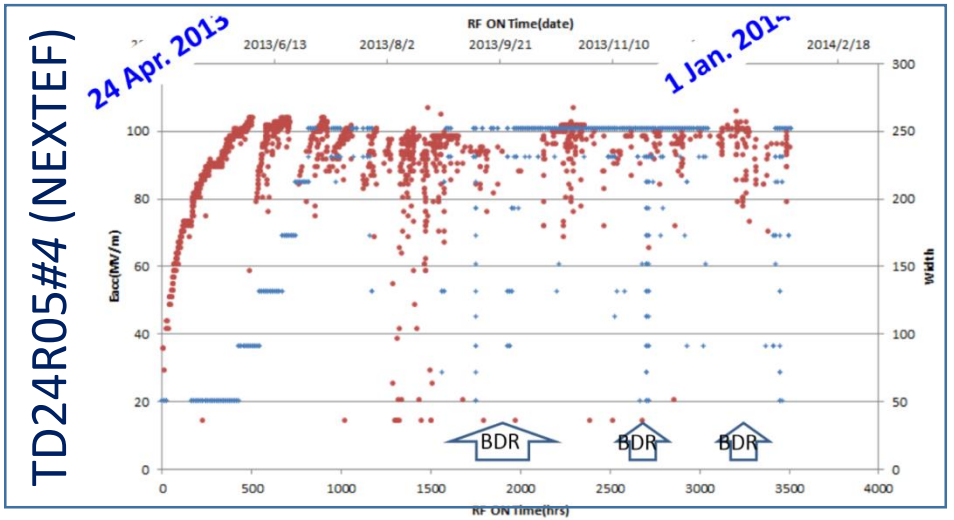
Digging deeper

Conditioning is common:



CERN dc system





Importance

Conditioning has very important consequences for our rf structures:

Practical – Conditioning takes a long time, a few months in the case of high-gradient CLIC structures, so adds an important cost. If we understood what exactly is changing during conditioning we could for example:

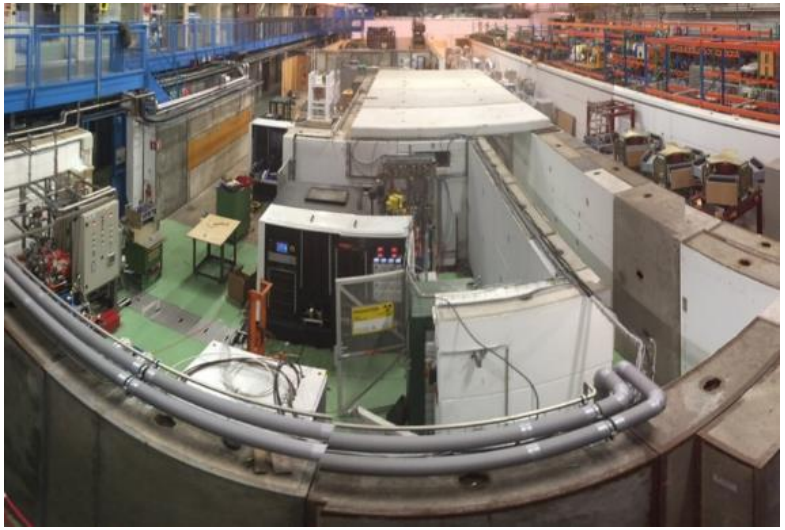
- Target development of better preparation techniques for the structures
- Optimize the operational strategy we use during conditioning

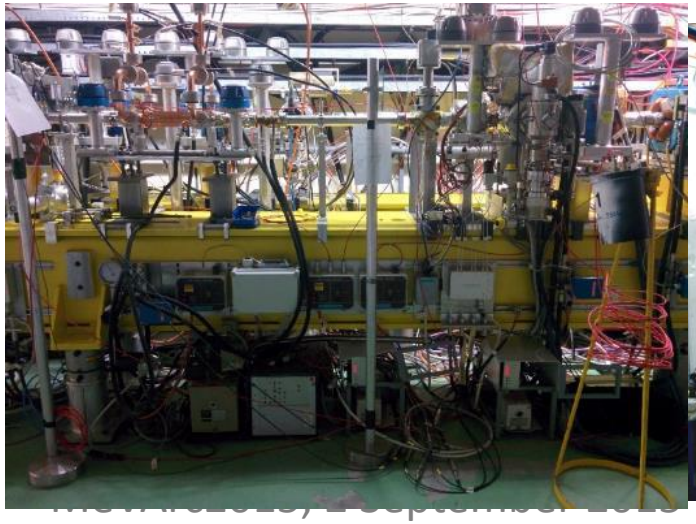
Structures which are easier to condition may also run better in the long-term, less chance of damage etc. Cheaper, better, faster!

Scientific – Conditioning improves the combination of higher gradient and lower breakdown rate in structures. If we could determine what exactly is happening at and near the structure surface we would necessarily understand something important about what causes breakdown. This also gets around the fundamental problem of studying a breakdown in a place where it has already occurred.

X-band test stands

One of our top priorities is to complete Xbox-3 this year and operate all our three X-band klystron-based tests stands through at least 2018.

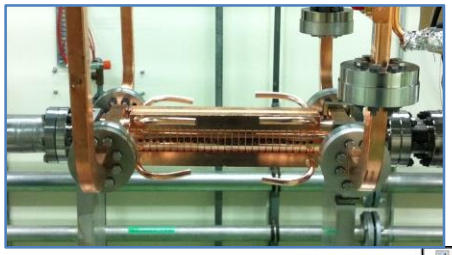


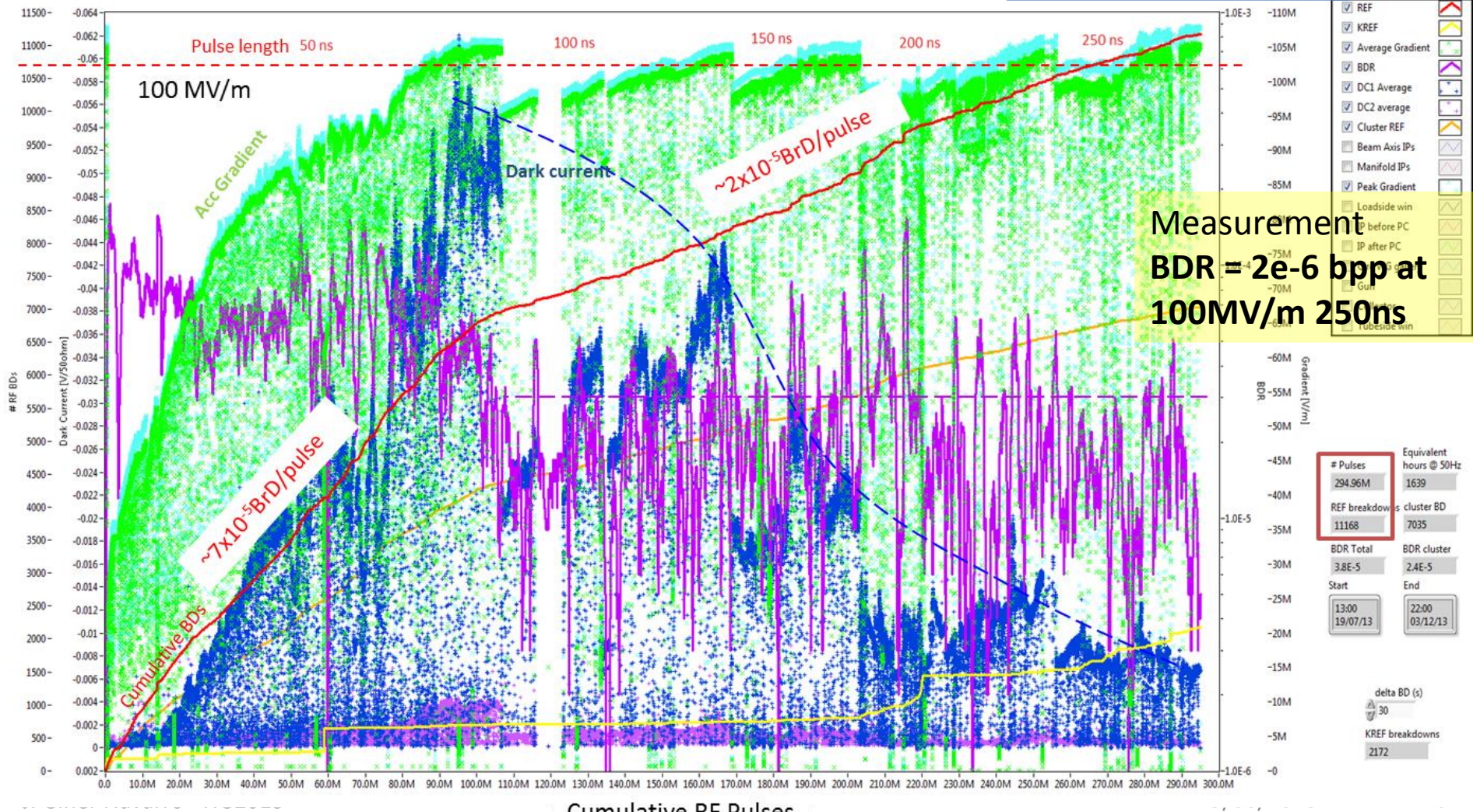


Conditioning data

Xbox-1: TD26CC#1 full conditioning history

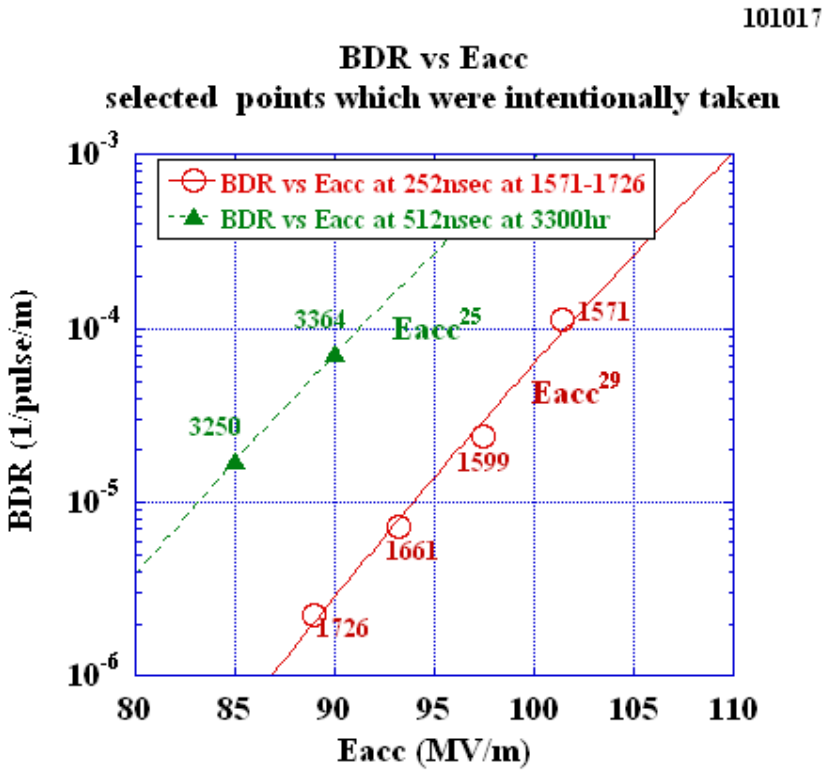
An **automatic conditioning algorithm** was enable to keep a constant BDR while increasing the power.

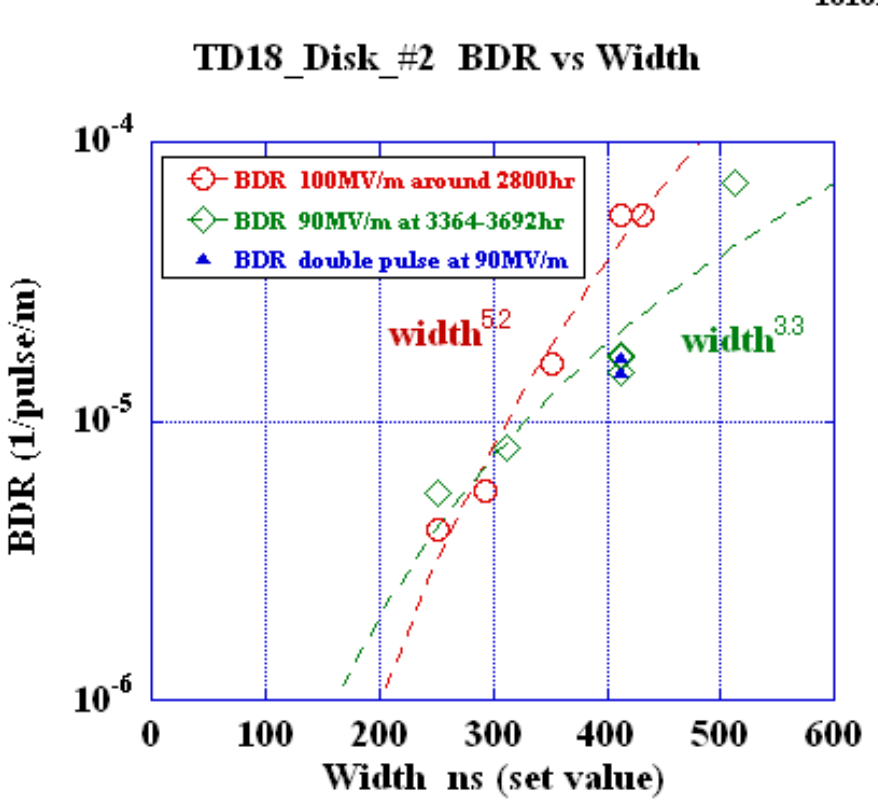




Measurement
BDR = 2e-6 bpp at 100MV/m 250ns

Important dependencies





For a fixed pulse length

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

For a fixed BDR

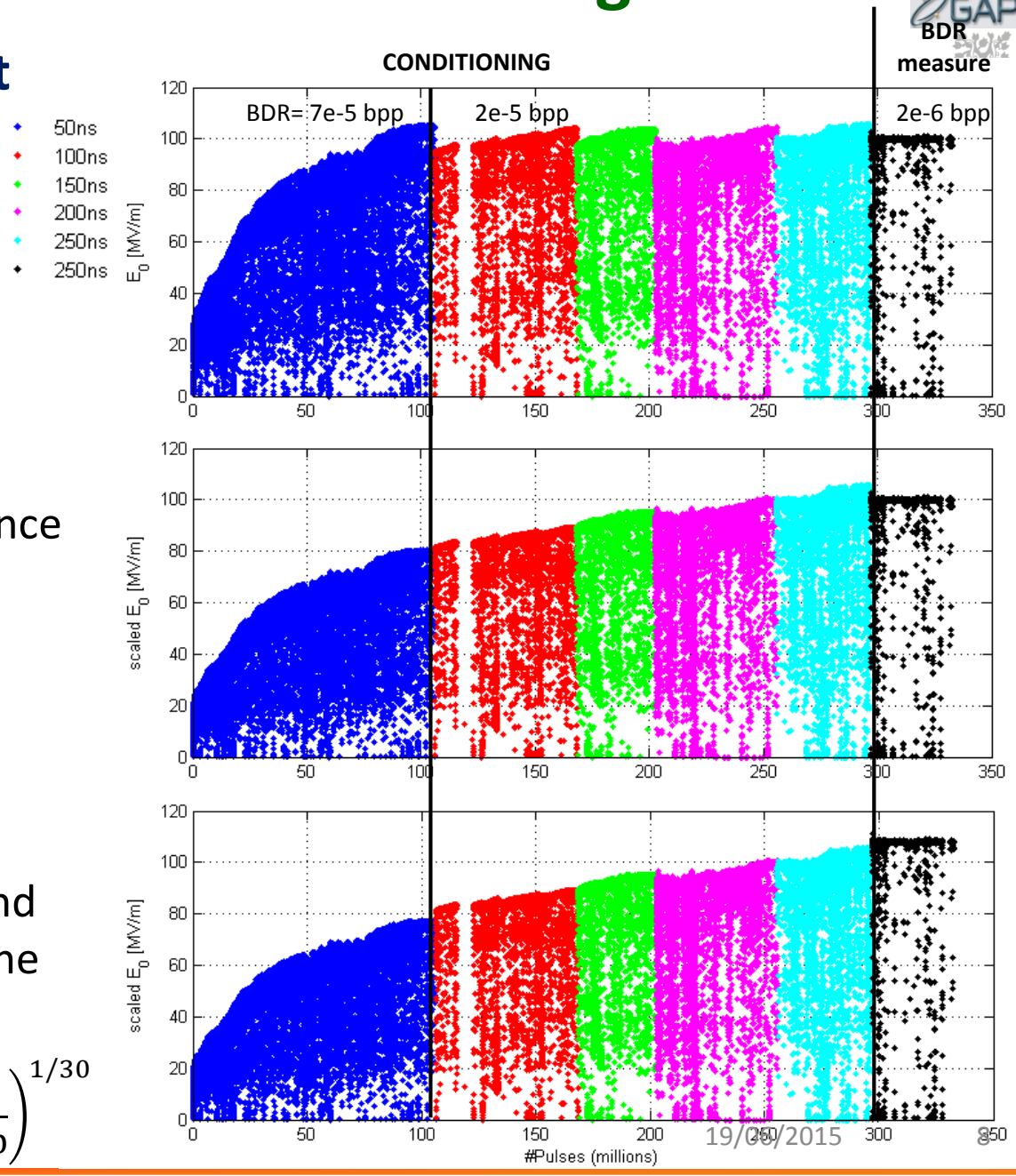
$$E_a \cdot t_p^{1/6} = const$$

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

Scaling: description of conditioning state

TD26CC#1 scaled gradient

Raw data full history



Equivalent gradient curve with constant pulse length of **250ns** since the beginning

$$E_0^{scaled} = E_0 \left(\frac{t_p}{250\text{ns}} \right)^{-1/6}$$

Equivalent gradient curve with constant pulse length of **250ns** and constant BDR of **2e-5 bpp** since the beginning

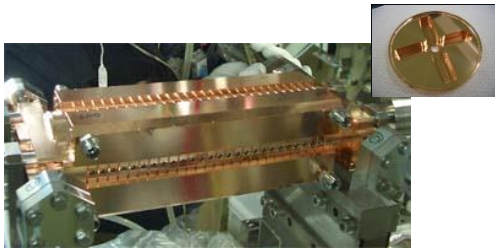
$$E_0^{scaled} = E_0 \left(\frac{t_p}{250\text{ns}} \right)^{-1/6} \left(\frac{\text{BDR}}{2 \cdot 10^{-5}\text{bpp}} \right)^{1/30}$$

Collection of conditioning histories

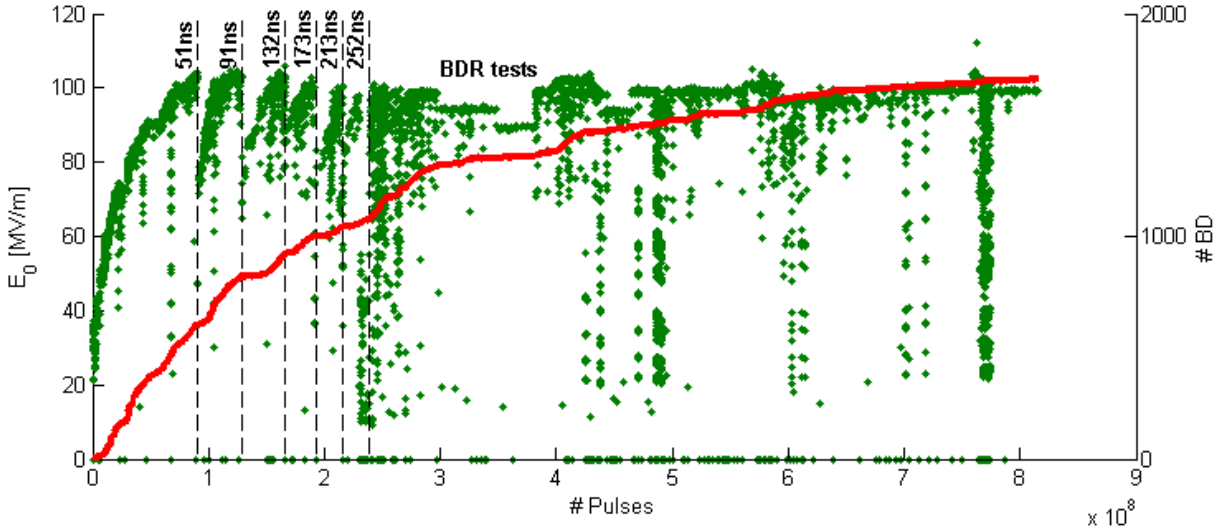
NEXTEF: TD24R05#4 full history and scaling

Conditioning and fixed-gradient tests carried out in NEXTEF test stand (KEK) for the TD24R05 structure provides a source of comparison with our data.

Data courtesy of T. Higo

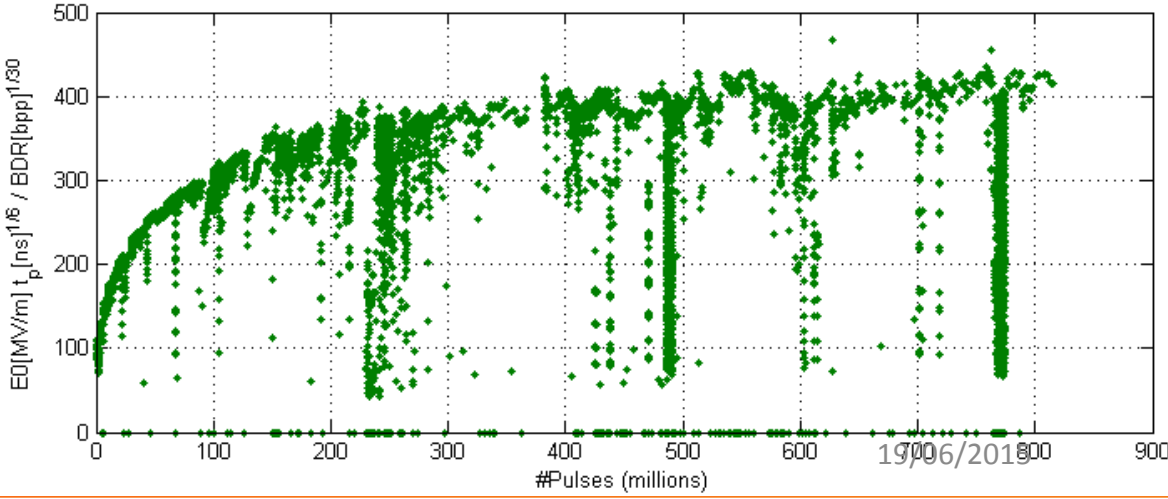


TD24R05_#4



Scaled gradient

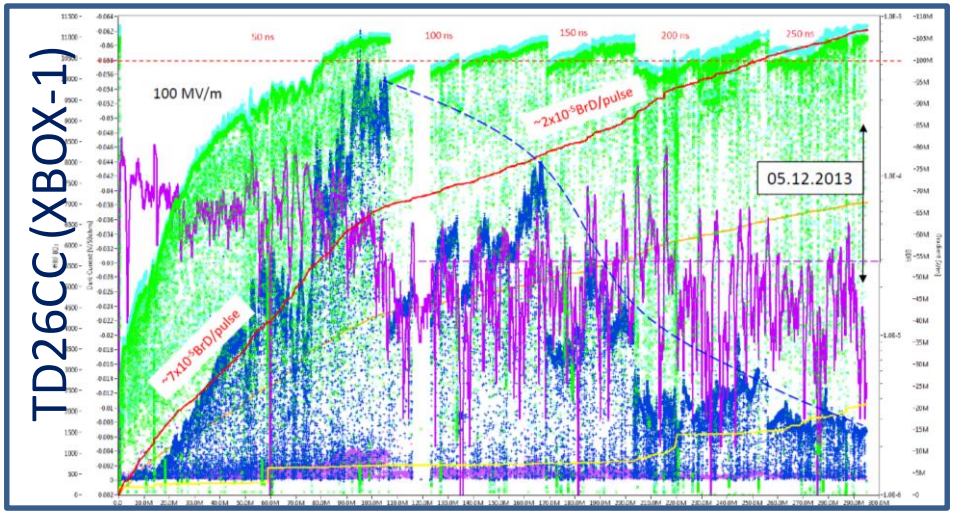
$$E_0^* = \frac{E_0\, t_{pulse}^{1/6}}{\mathrm{BDR}^{1/30}}$$



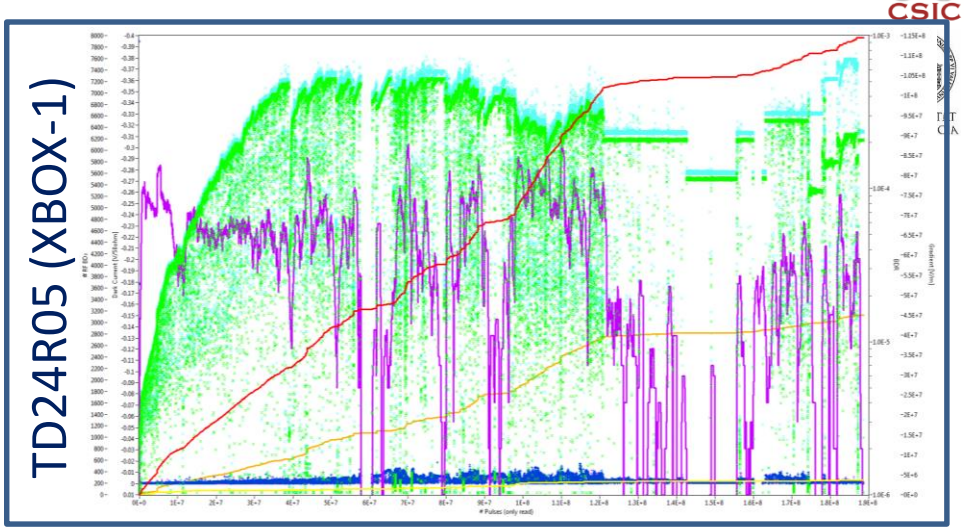
Collection of conditioning histories

CLIC damped (TD) structures

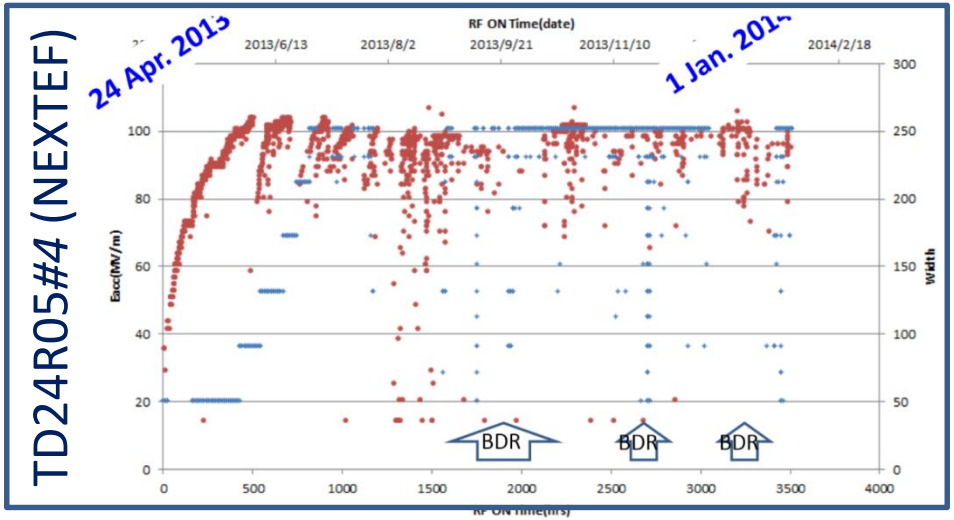
TD26CC (XBOX-1)



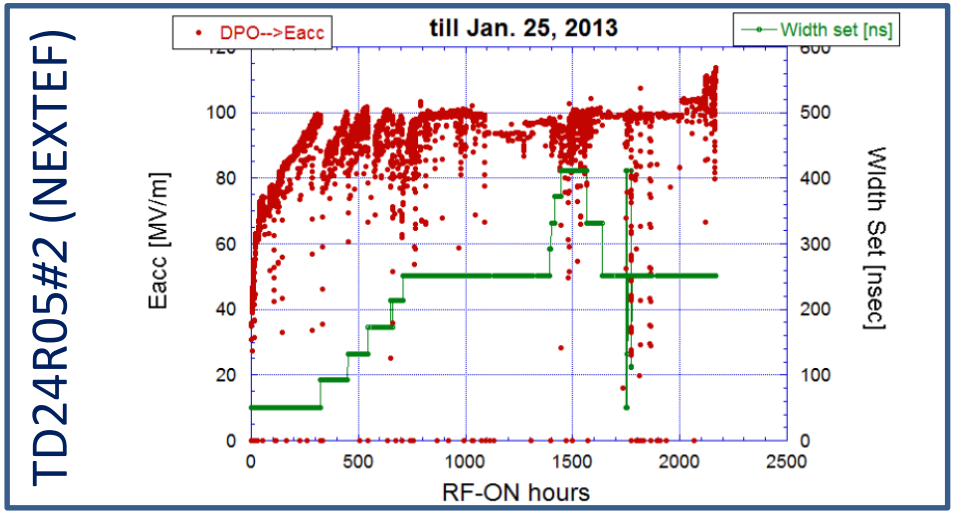
TD24R05 (XBOX-1)



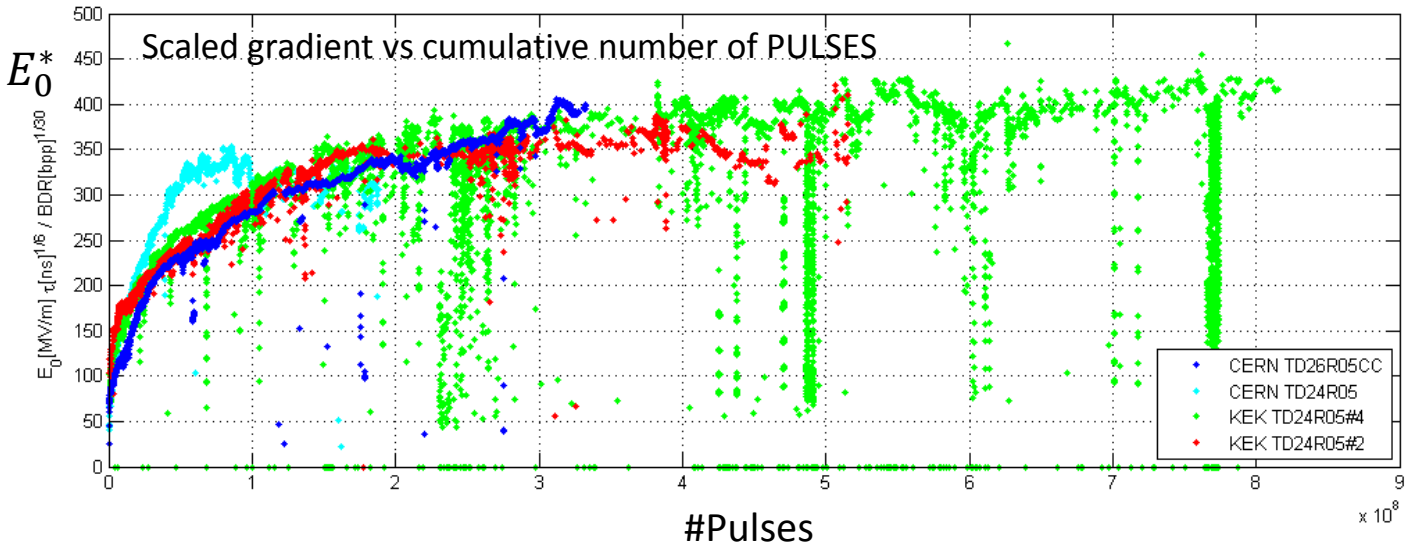
TD24R05#4 (NEXTEF)

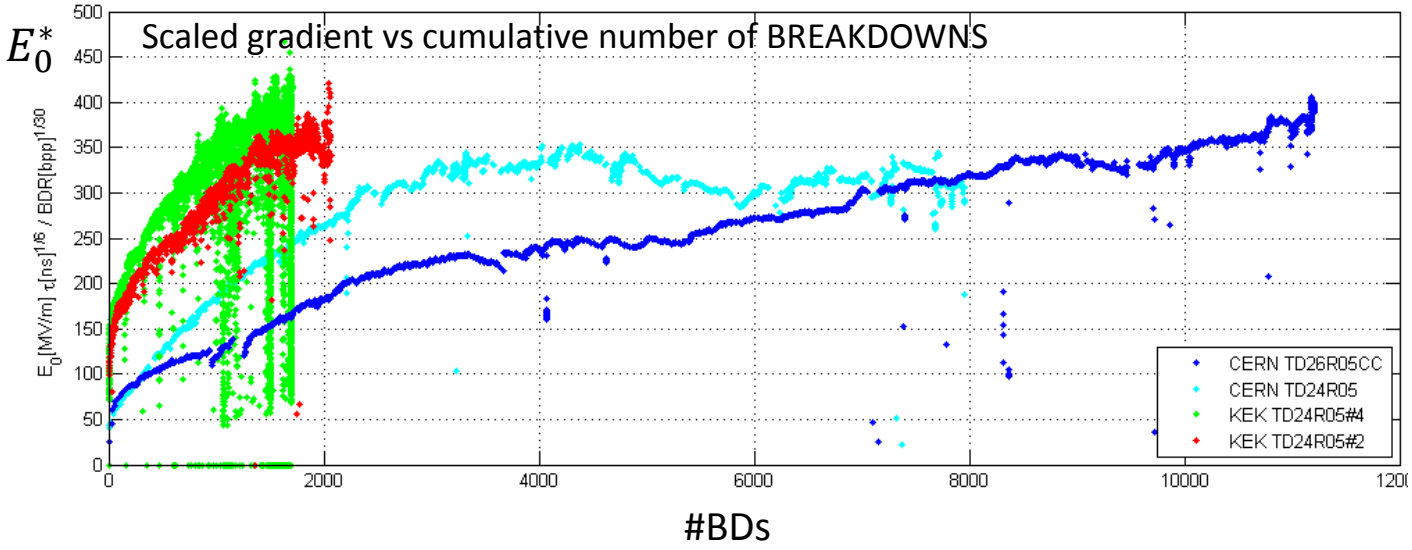


TD24R05#2 (NEXTEF)



Comparison of conditioning evolution



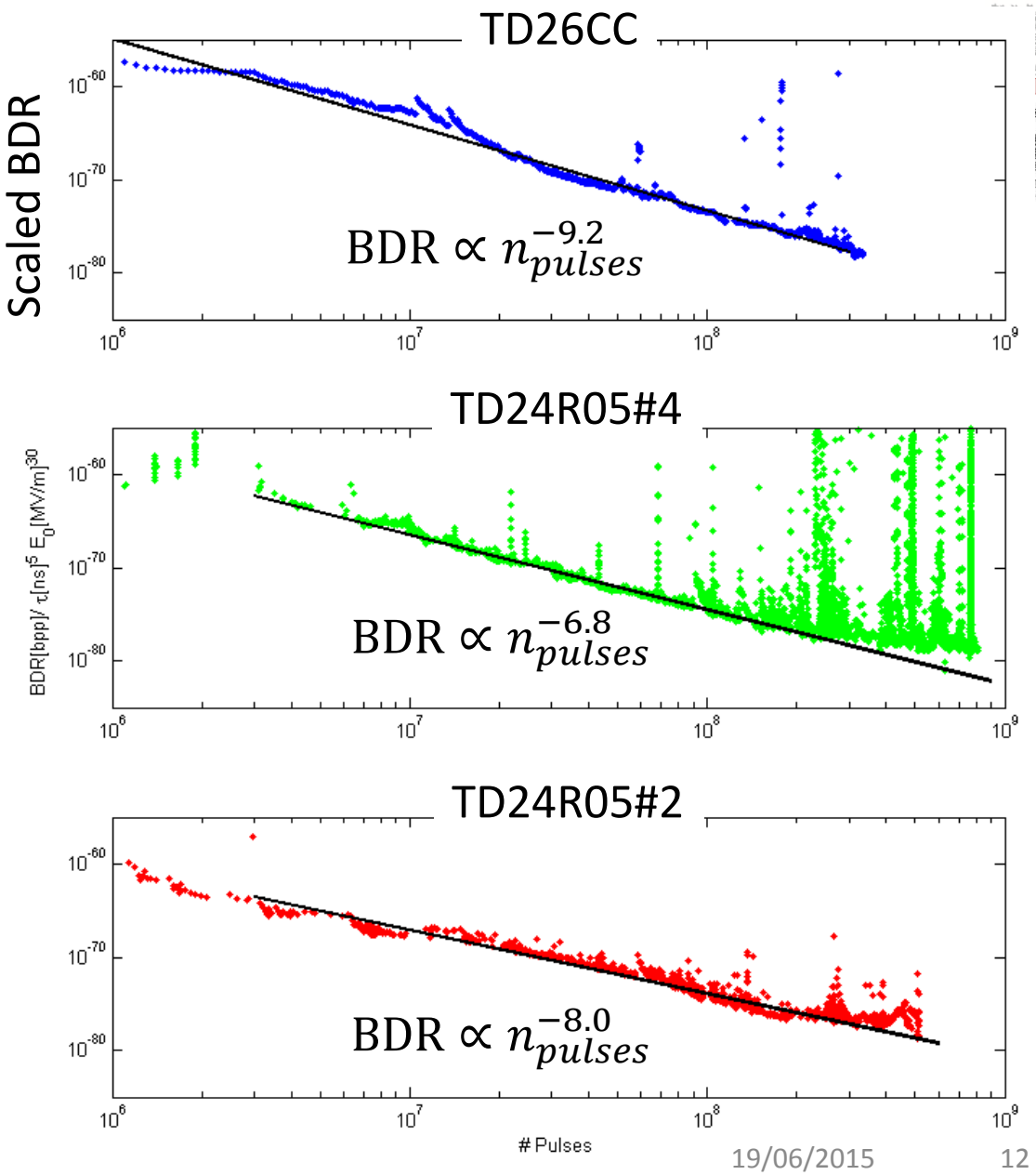


Conditioning to high-gradient is given by the pulses not the breakdowns

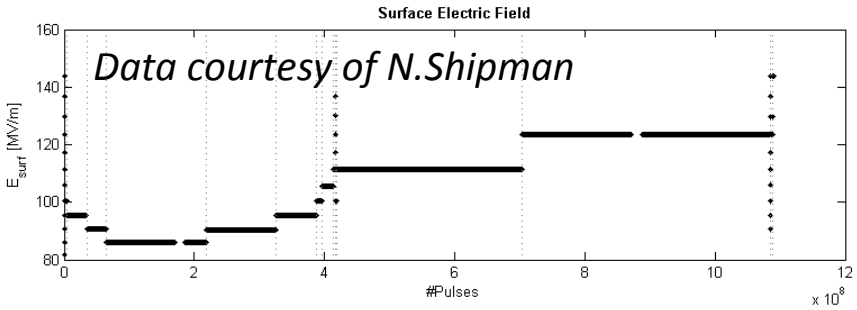
- RF pulses contribute to surface quality enhancement more than breakdown events (reduction of potential breakdown sites)
- Same conditioning speed at different breakdown rates

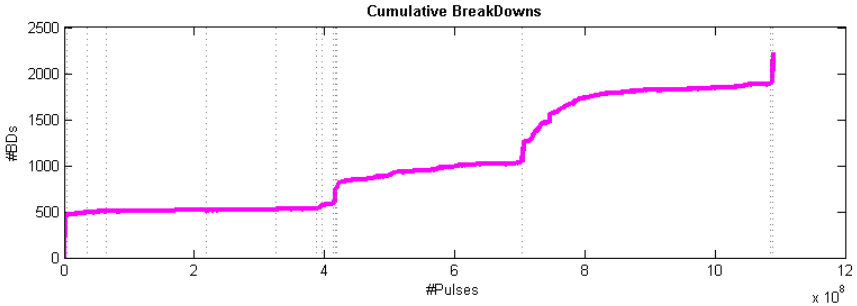
High-Gradient and Breakdown rate limits

- Limiting quantities must be studied: gradient, Sc, peak E and H field, pulsed surface heating…
- The trend at higher number of pulses might reach a limit in BDR
- New CLIC TD structure upcoming tests will confirm these results
- High repetition DC systems provide considerable new data to study conditioning phenomenology and operation dependencies.



Conditioning data Large Electrode System

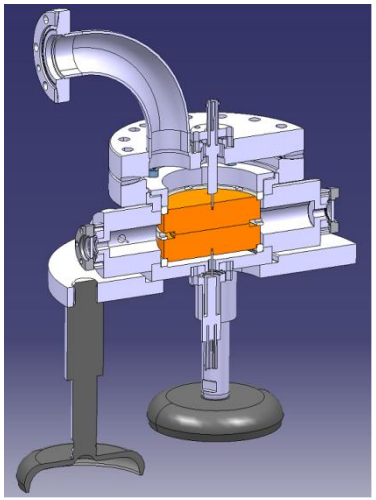


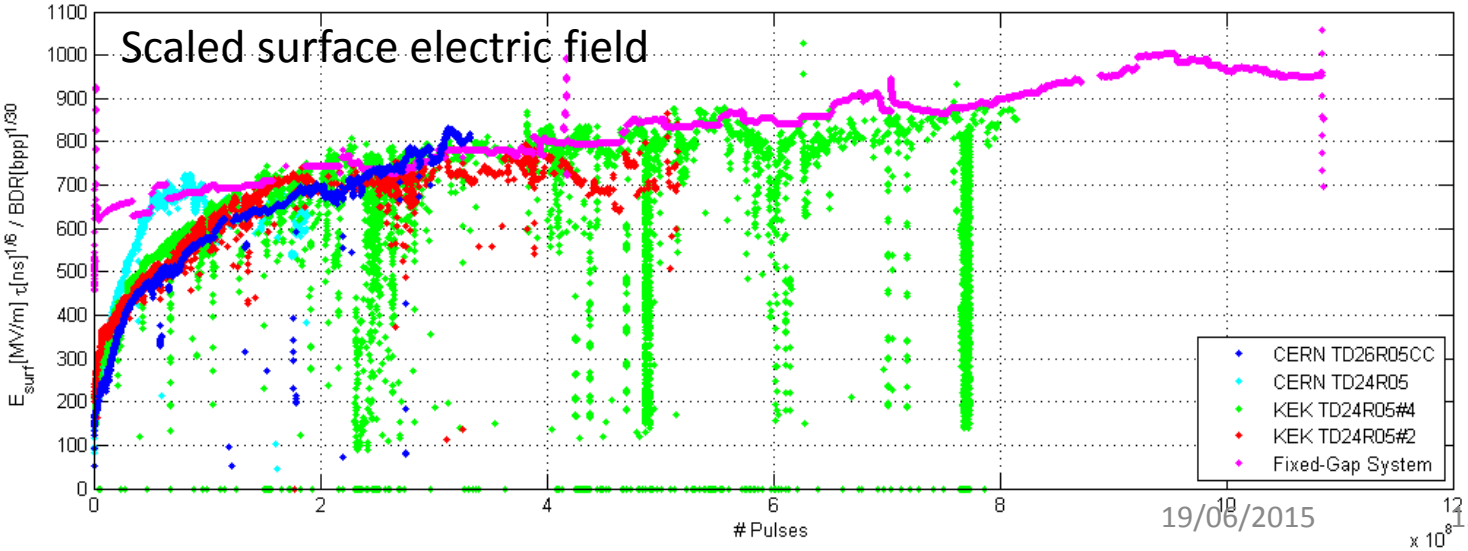


In the Large Electrode System at DC Spark lab (CERN), high electric fields are reproduced between two Cu electrodes, pulsing at a **repetition rate up to 1 kHz**.

Analogous studies to RF accelerating structure tests can be driven in less time. New experiments are ongoing

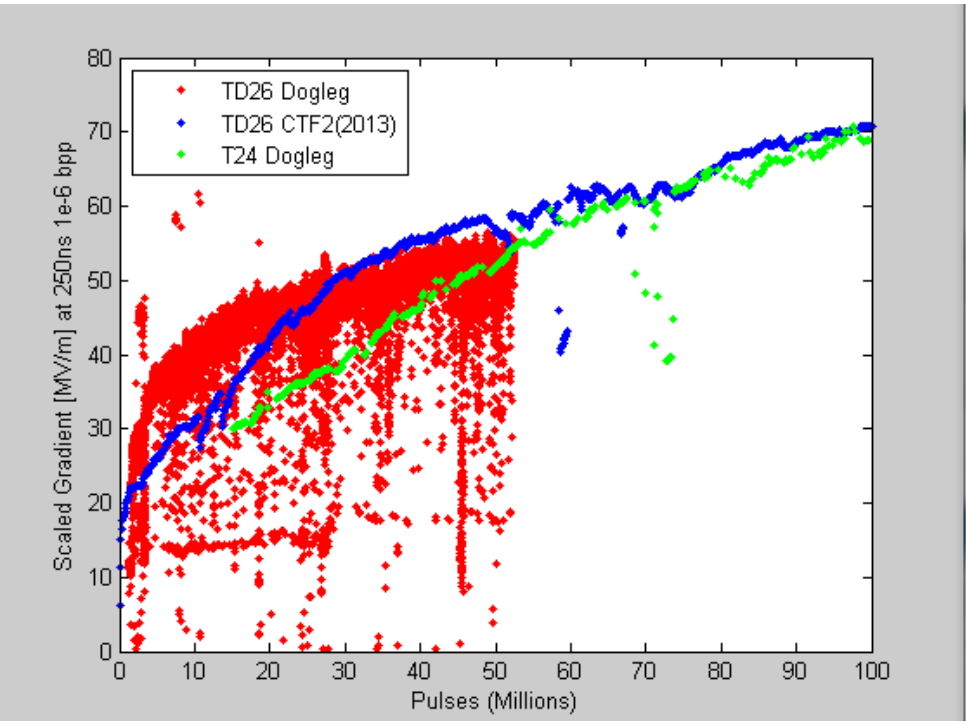
See **W. Wuensch, Recent resuts from the CERN dc spark system.** HG2015, Friday.19/06

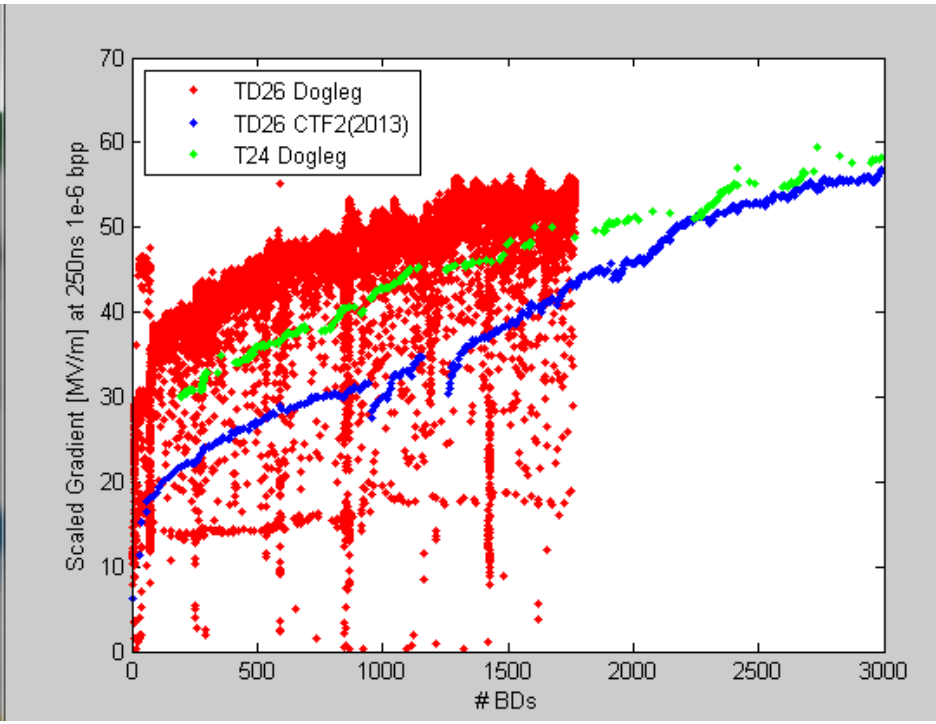




Reconditioning a structure

The TD26CC tested in XBox-1 in 2013 is being used again. It's had a complicated history, accidentally left exposed to air for a few weeks, 1.5 years have gone by, but then we baked it out at 650 °C in vacuum. Not a perfect experiment but gives insight into conditioning:

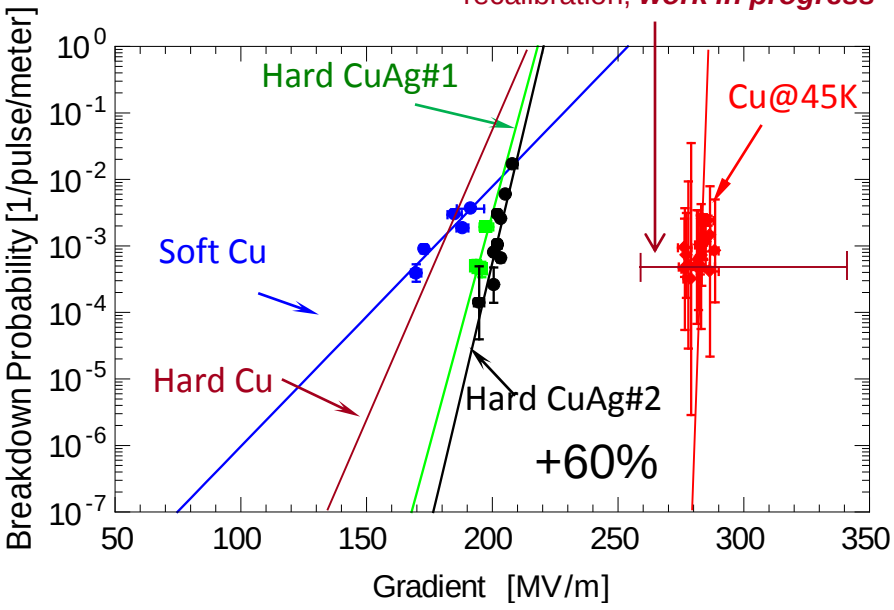


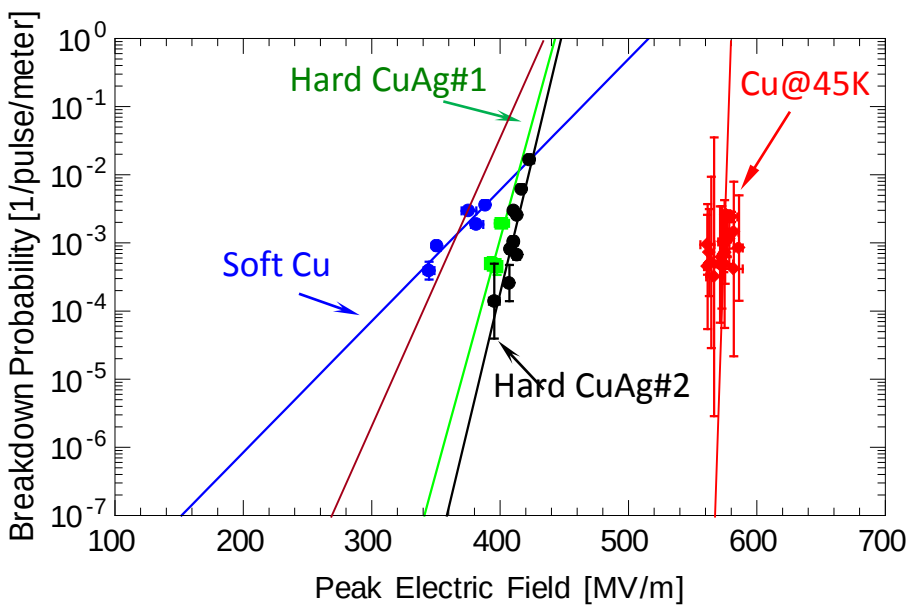


Now a brief analysis of recently reported high gradient results of a cooled cavity experiment carried out at SLAC.

Understanding the Physics of High Gradients has Established the Limits of Normal Conducting Copper Structures

Narrow error bar will be obtained after recalibration; ***work in progress***





- Basic physics experiments move to testing normal & SC engineered materials (2016-2017).
- Cost effective implementation of accelerator structures capable of operating *efficiently* at these gradients (basic development 2016-2017, and then growing effort to 2020)
- Build RF sources that can power these structures to high gradients (basic development 2016-2017, and then growing effort to 2020)
- New architectures for future facilities (colliders, light sources, etc.) will emerge when efficient RF systems to power linacs operating at these gradients become available
- Immediately, this technology will lead to RF guns with unprecedented brightness.

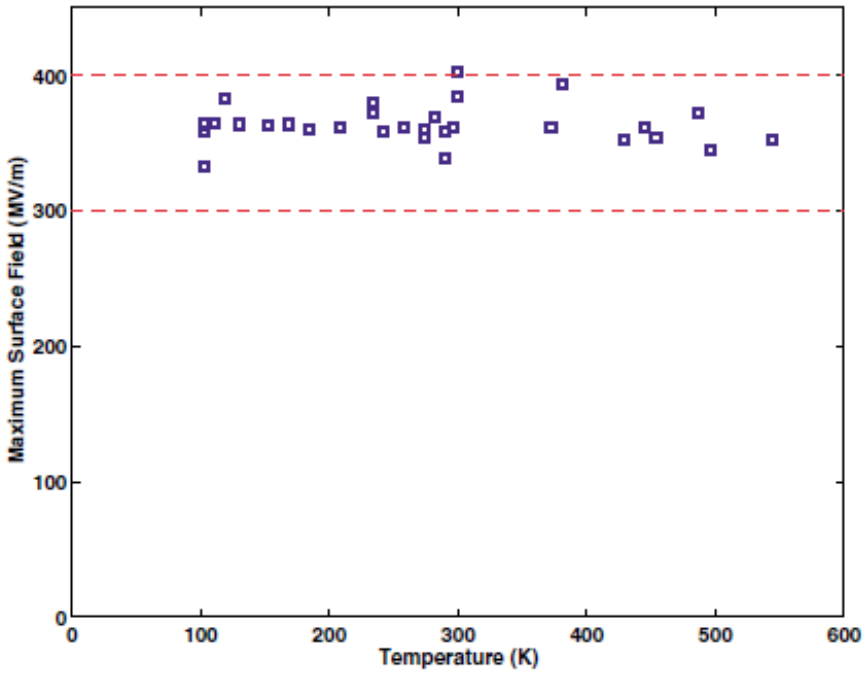


FIG. 6 (color online). Temperature dependence of maximum surface field.

Frequency and Temperature Dependence of Electrical Breakdown at 21, 30, and 39 GHz

H. H. Braun, S. Döbert, I. Wilson, and W. Wuensch*
European Organization for Nuclear Research (CERN), CH 1211 Geneva 23, Switzerland
(Received 1 July 2002; published 5 June 2003)

A TeV-range e^+e^- linear collider has emerged as one of the most promising candidates to extend the high energy frontier of experimental elementary particle physics. A high accelerating gradient for such a collider is desirable to limit its overall length. Accelerating gradient is mainly limited by electrical breakdown, and it has been generally assumed that this limit increases with increasing frequency for normal-conducting accelerating structures. Since the choice of frequency has a profound influence on the design of a linear collider, the frequency dependence of breakdown has been measured using six exactly scaled single-cell cavities at 21, 30, and 39 GHz. The influence of temperature on breakdown behavior was also investigated. The maximum obtainable surface fields were found to be in the range of 300 to 400 MV/m for copper, with no significant dependence on either frequency or temperature.

DOI: 10.1103/PhysRevLett.90.224801 PACS numbers: 29.17.+w, 41.75.Lx, 52.80.Pi, 52.80.Vp

We didn't measure breakdown rate and quote "maximum." From memory was probably around 10^{-2}

Walter Wuensch, CERN

$$BDR \propto e^{\frac{-E^f + \varepsilon_0 E^2 \Delta V}{k_b T}}$$

$$E^f = 0.8\ eV$$

$$\Delta V = 0.8 \times 10^{-24} m^3$$

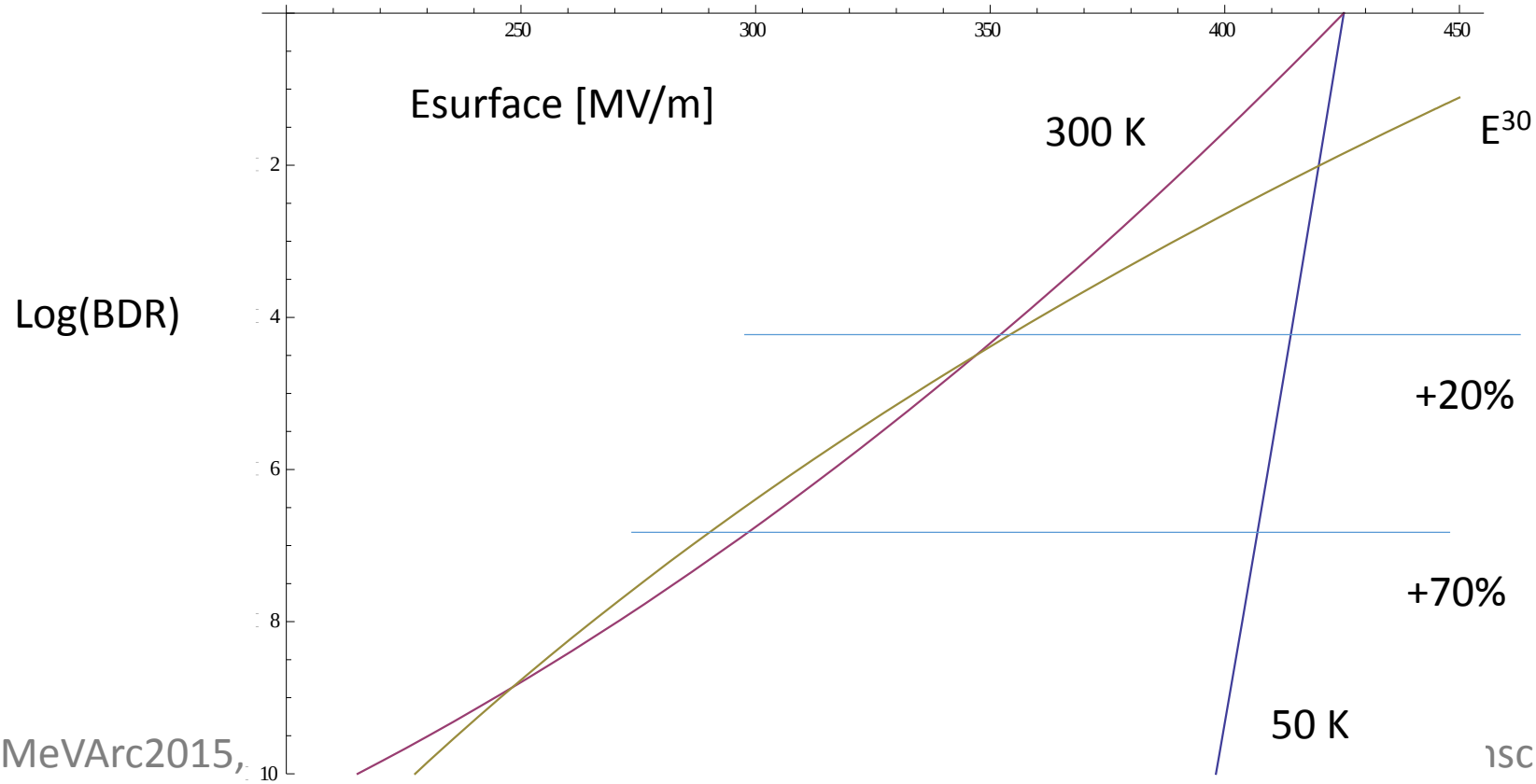
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 15, 071002 (2012)

Defect model for the dependence of breakdown rate on external electric fields

K. Nordlund and F. Djurabekova
Helsinki Institute of Physics and Department of Physics, University of Helsinki, P.O. Box 43, FIN-00014, Helsinki, Finland
(Received 1 August 2011; revised manuscript received 2 April 2012; published 11 July 2012)

We develop an analytical model for the vacuum electric breakdown rate dependence on an external electric field, observed in test components for the compact linear collider concept. The model is based on a thermodynamic consideration of the effect of an external electric field on the formation enthalpy of defects. Although strictly speaking only valid for electric fields, the model also reproduces very well the breakdown rate of a wide range of radio-frequency breakdown experimental data. We further show that the fitting parameter in the model can be interpreted to be the relaxation volume of dislocation loops in materials. The values obtained for the volume are consistent with dislocation loops with radii of a few tens of nanometers.

DOI: 10.1103/PhysRevSTAB.15.071002 PACS numbers: 52.80.Vp, 61.72.Lk, 29.20.Ej, 52.80.Mg



Conclusions

We understand now how to plot conditioning in such a way to show its fundamental features.
From this we have observed common and reproducible behaviour.
We are now in a position to begin to understand what is actually occurring during conditioning.
This will give the foundation to improve performance and to understand more about breakdown.

Thank you for your attention!