Recent rf high-gradient testing results

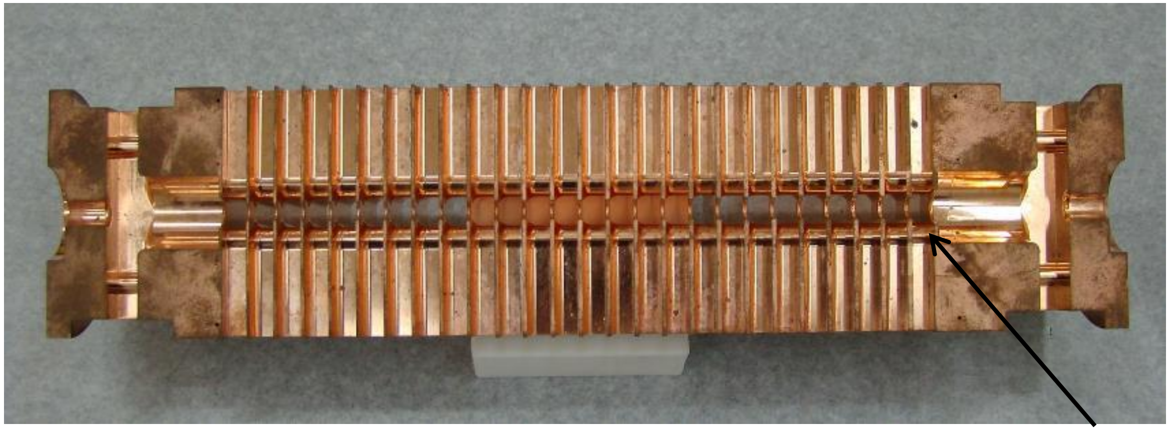
Jorge Giner Navarro
on behalf of the XBOX team
Mini-MeVArc meeting
22/03/2016 CERN, Geneva

Outline

- Introduction
- High gradient conditioning
- The Xboxes
- Xbox-1: Test of TD26CC (Dogleg experiment)
- Xbox-2: Test of T24OPEN
- Xbox-2: Test of CRAB cavity
- Summary

Introduction

CLIC Main Linac accelerating structures



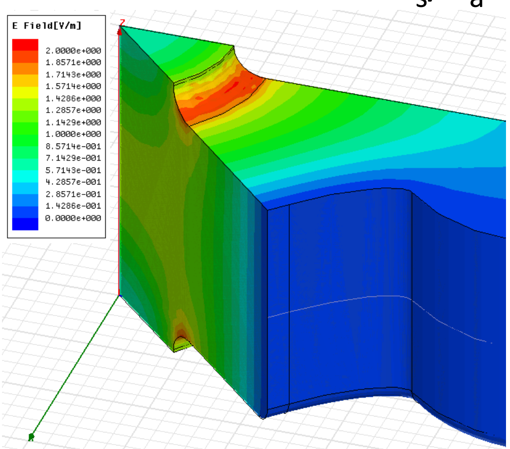
25 cm

6 mm diameter beam aperture

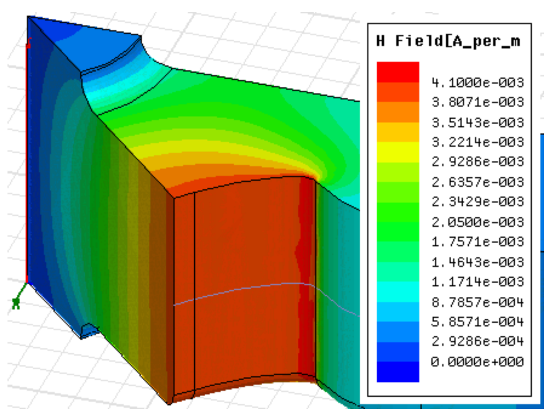
Micron–precision disk

HOM damping waveguide

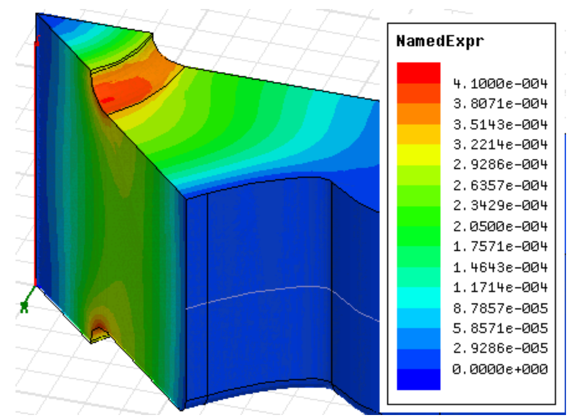
Surface electric field E_s/E_a



Surface magnetic field H_s/E_a



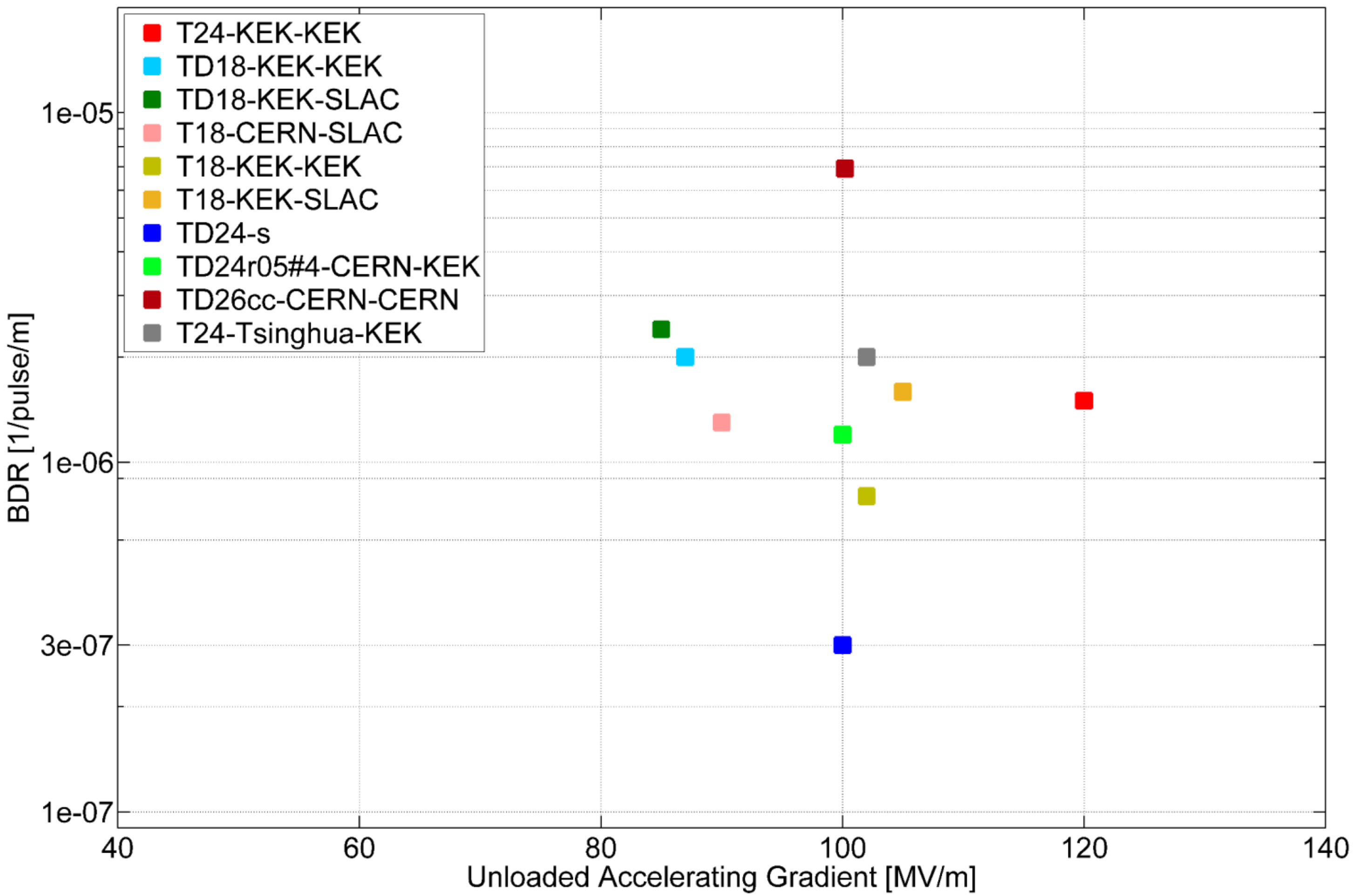
Modified Poyting vector S_c/E_a^2



Introduction

Summary of tested CLIC X-band structures

$$\mathrm{BDR} \propto E_0^{30}\,\tau^5$$



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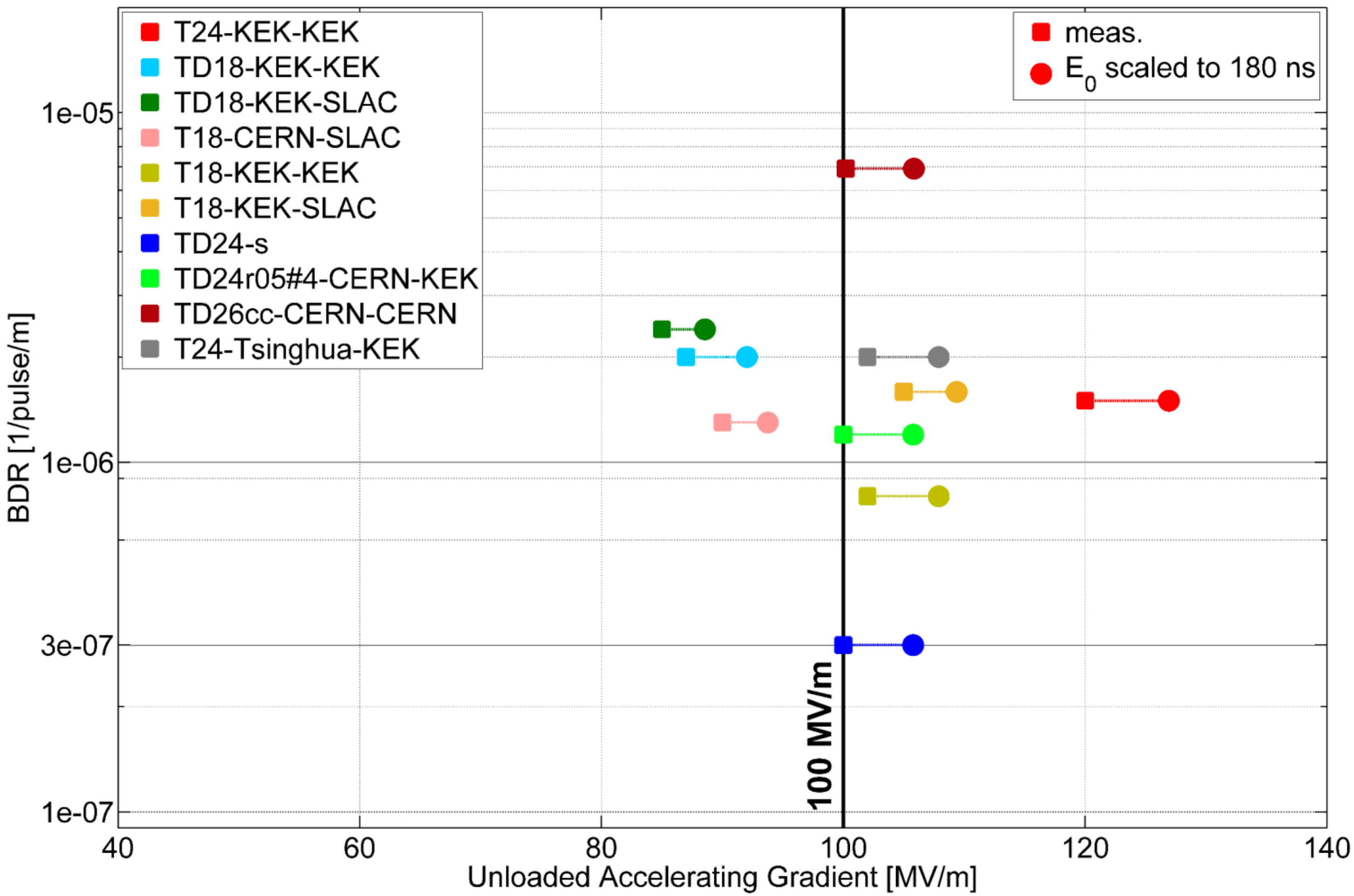

Introduction

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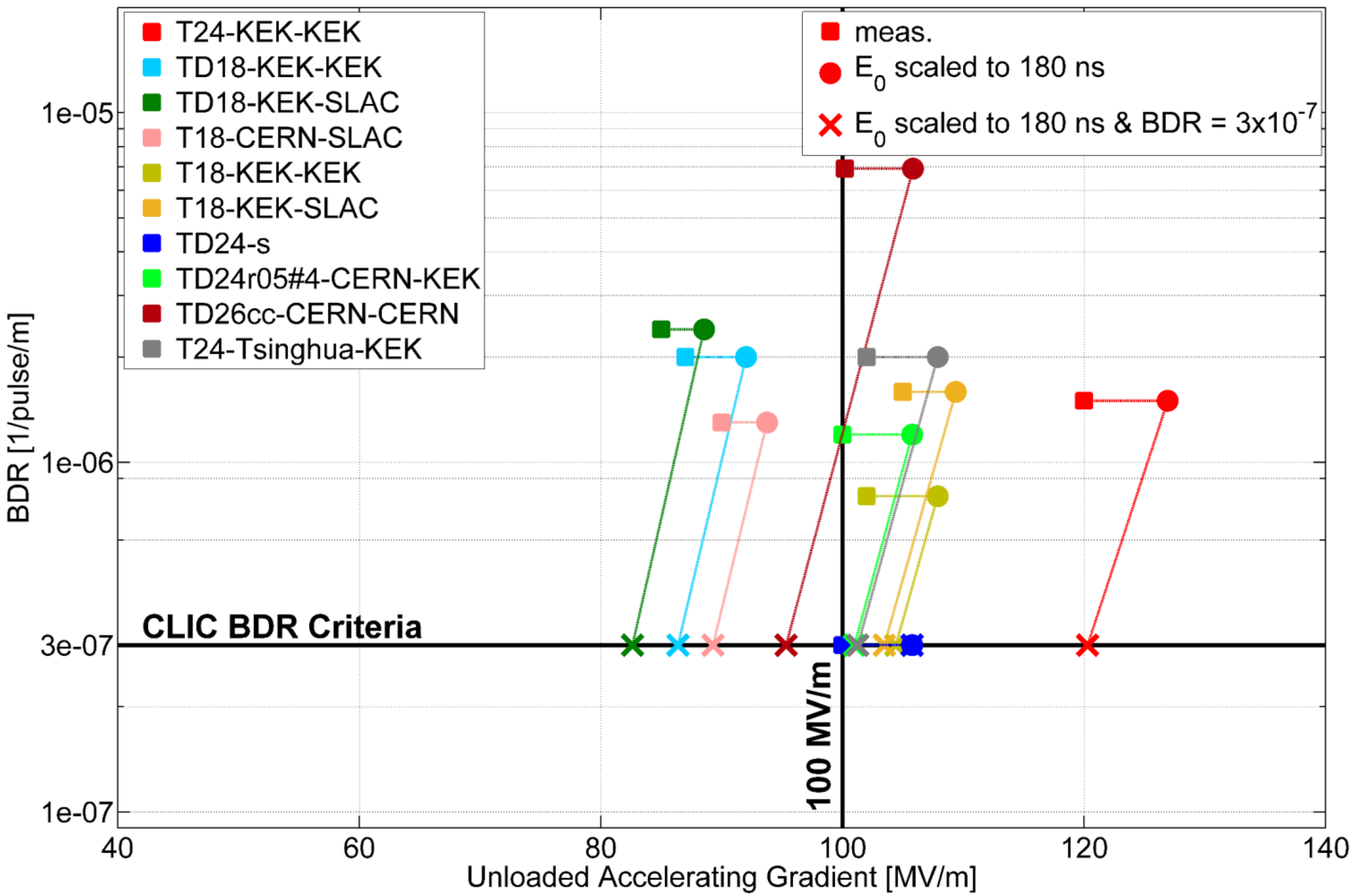
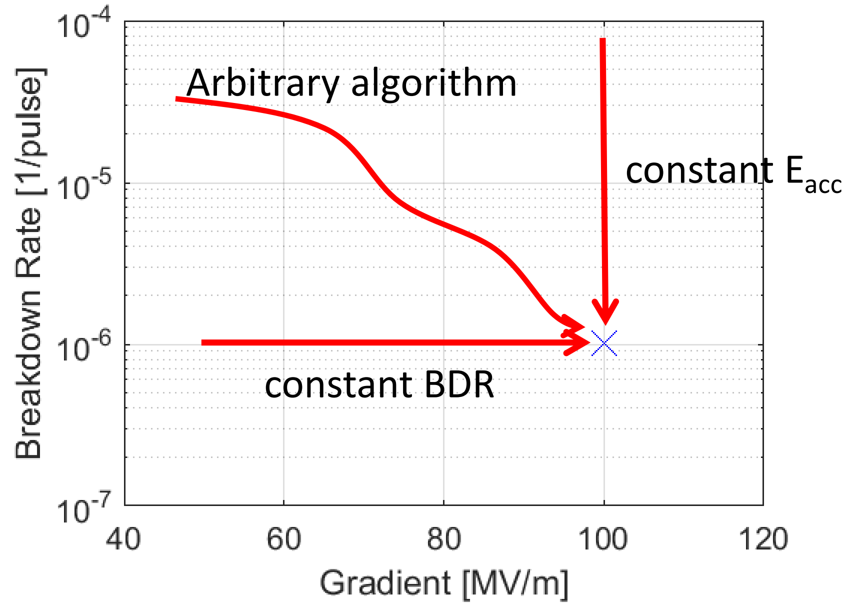


Introduction

What is **conditioning**?

After accumulating several pulses and breakdowns, the surface better resistance to vacuum arcs at higher electric fields.



Why do we study conditioning?

Conditioning is a long process (4-6 months) and therefore the high-power infrastructure implies extra cost. Time consumption needs also to be optimized with the perspective of industrialization of 50km series of accelerating structures.

High gradient conditioning

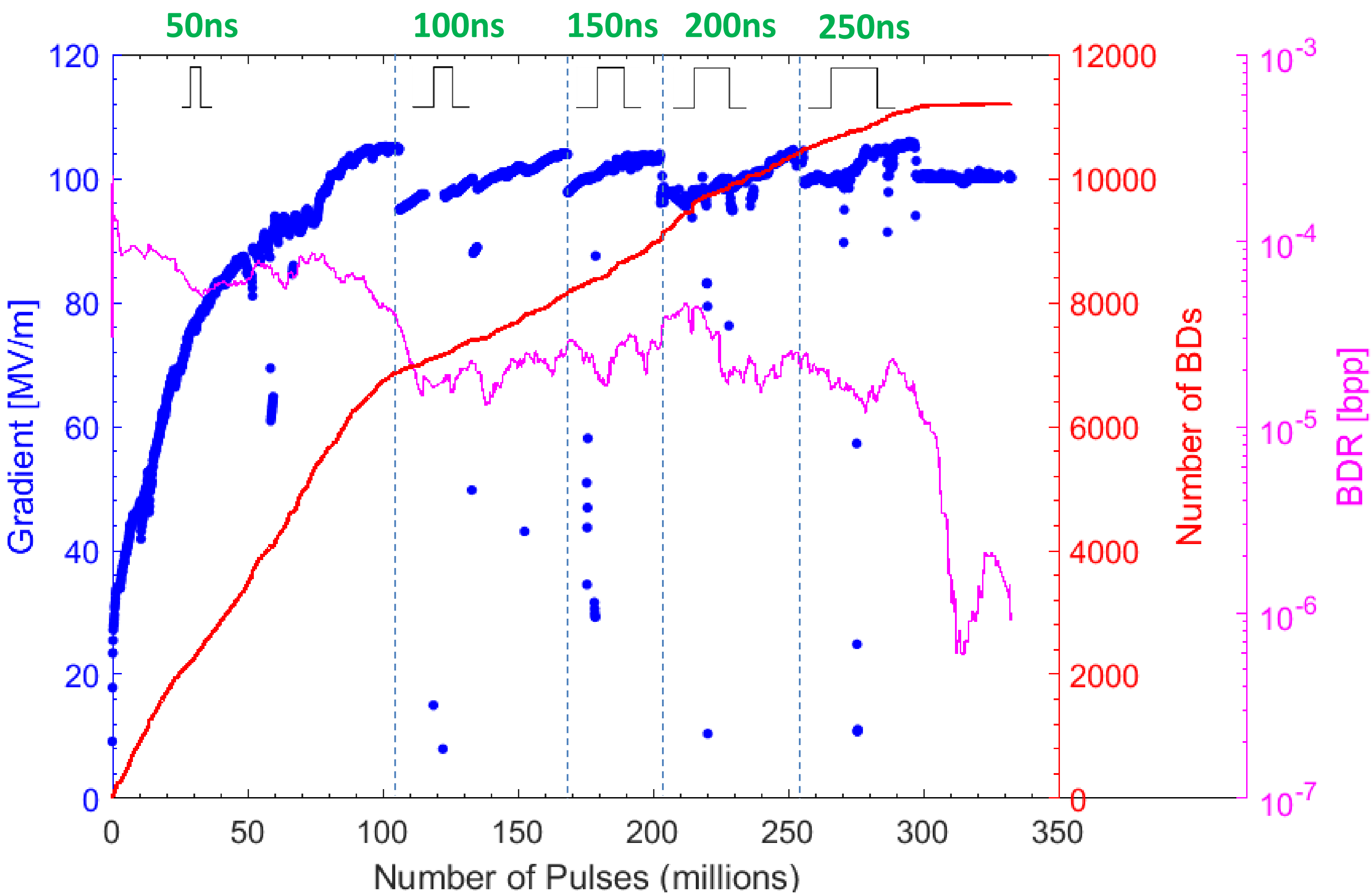
- Tests of different CLIC accelerating prototypes at CERN and KEK.
- The first idea was to compare conditioning evolution of similar structures tested with different operation settings
- Use of experimental scaling laws of Breakdown Rate with Pulse Length and Gradient

$$\mathbf{BDR} \propto \boldsymbol{E_0^{30}\,\tau^5}$$

- Normalized Gradient $$\boldsymbol{E_0^*} = \frac{\boldsymbol{E_0\tau^{1/6}}}{\mathbf{BDR}^{\mathbf{1/30}}}$$
- Normalized BDR $$\mathbf{BDR}^* = \frac{\mathbf{BDR}}{\boldsymbol{E_0^{30}\,\tau^5}}$$

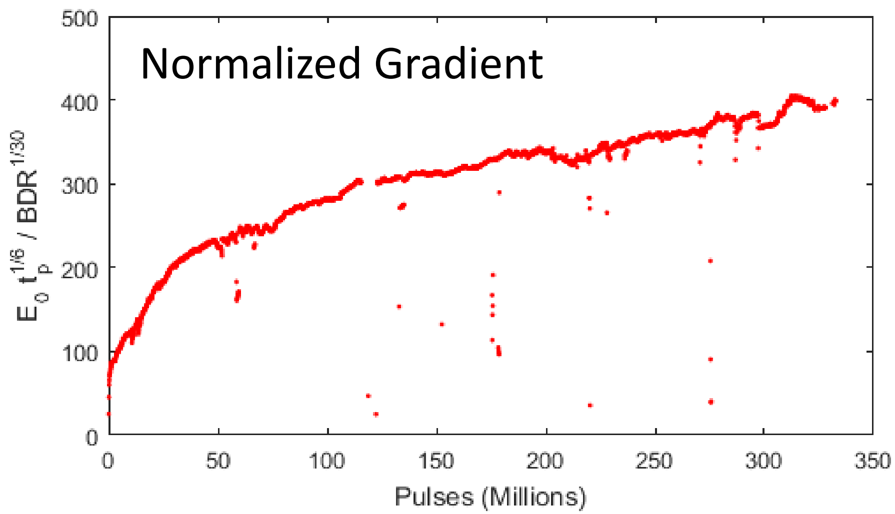
High gradient conditioning

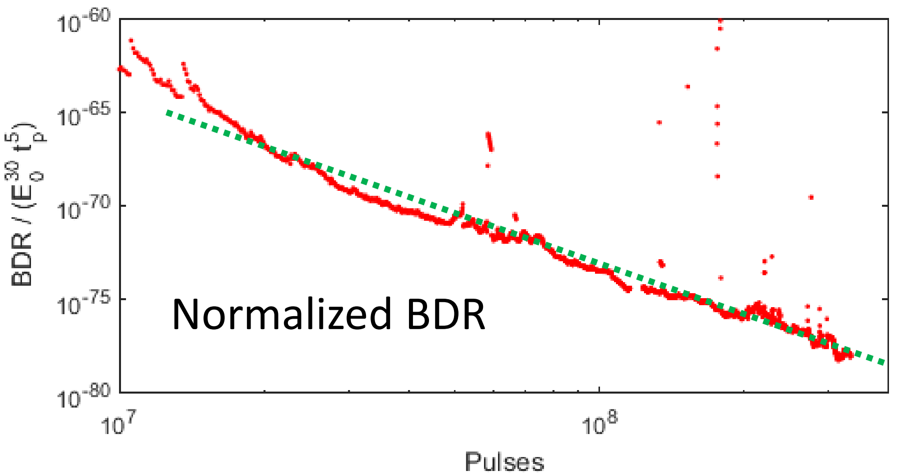
Example of a conditioning history. TD26CC#1 tested in Xbox-1: user-defined pulse length, automated control of gradient at fixed BDR



High gradient conditioning

Example of a conditioning history. TD26CC#1 tested in Xbox-1: user-defined pulse length, automated control of gradient at fixed BDR





- Smooth curve
- Steps in pulse length not visible

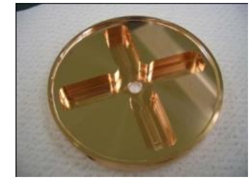
Normalized gradient and normalized BDR represents the conditioning state of the structure.

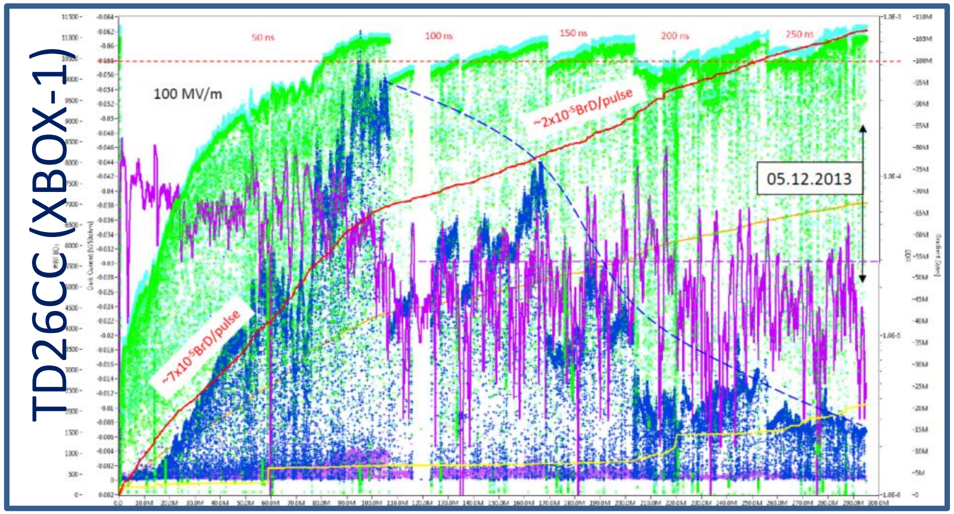
Conditioning curve follows a power law dependence with number of pulses

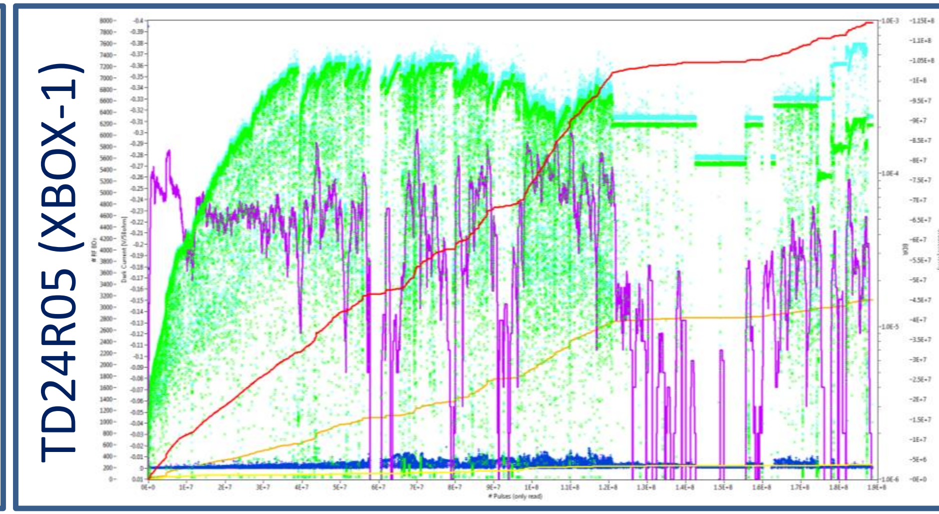
$$\mathrm{BDR}^* \propto n_{pulses}^{-9.2}$$

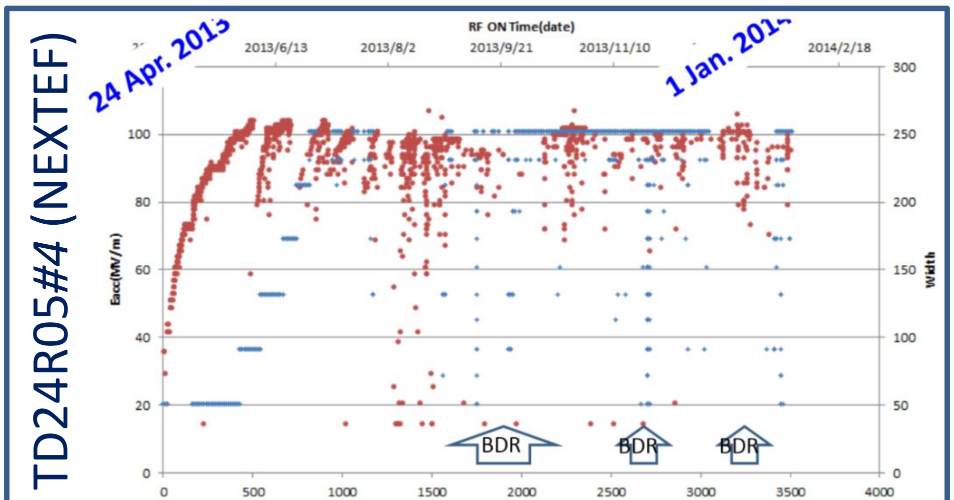
High gradient conditioning

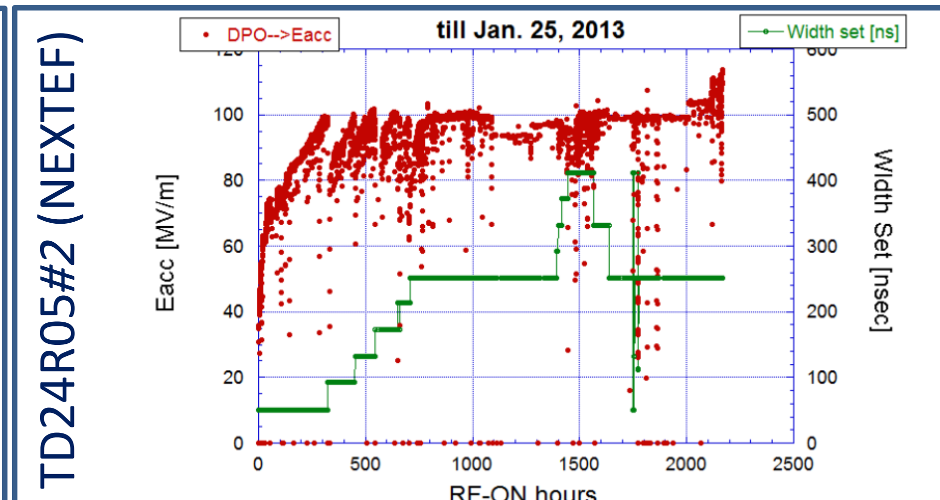
Collection of conditioning histories of CLIC-G prototypes



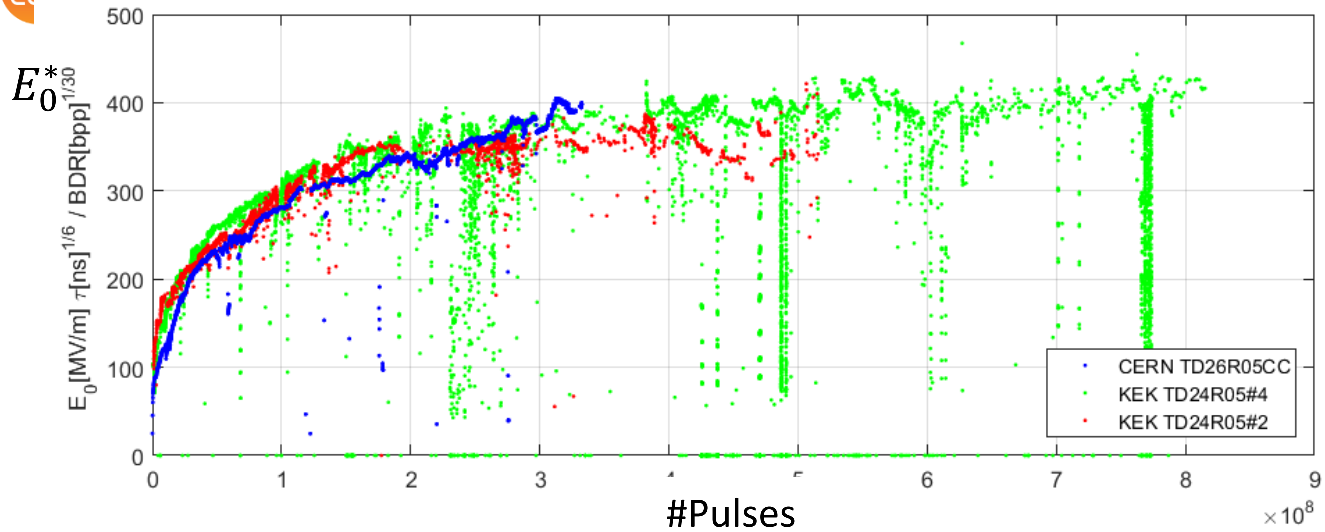


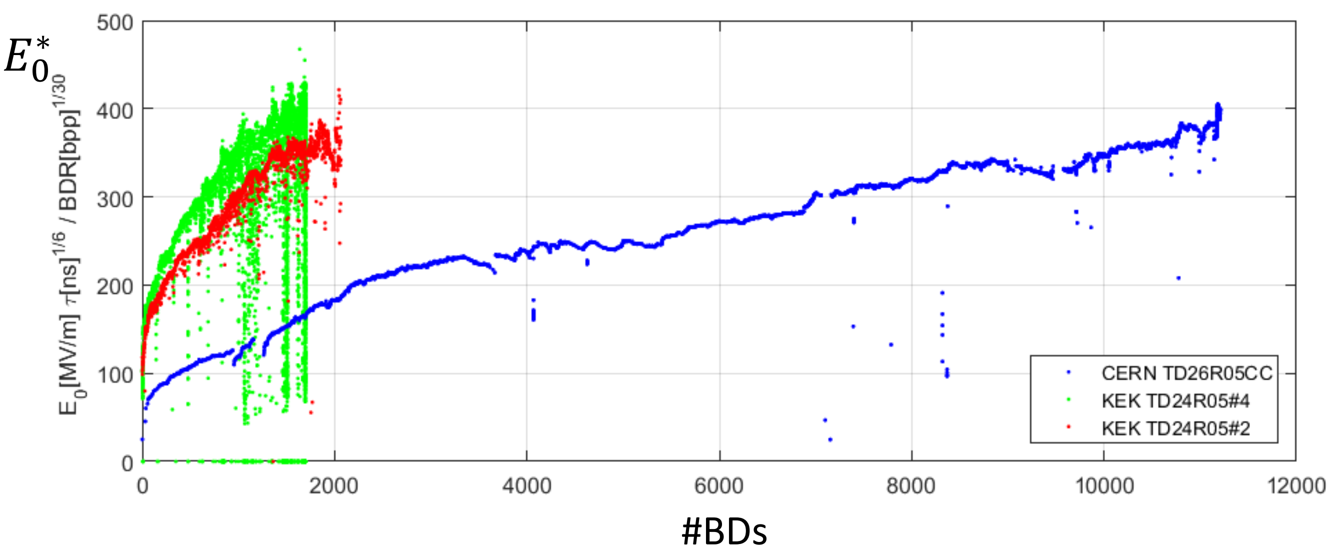






High gradient conditioning





Conditioning to high-gradient is given by the <u>pulses</u> 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

Pub: W. Wuensch et al. *Comparison of the conditioning of high gradient accelerating structures*. PRAB 19, 032001 (2016)

The Xboxes

CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz
Beam test capabilities

Previous tests:
2013 TD24R05 (CTF2)
2013 TD26CC-#1 (CTF2)
2014-15 T24 (Dogleg)

Ongoing test:
Aug2015- TD26CC-#1 (Dogleg)

CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz

Previous tests:
2014-15 CLIC Crab Cavity

Ongoing test:
Sep2015- T24OPEN

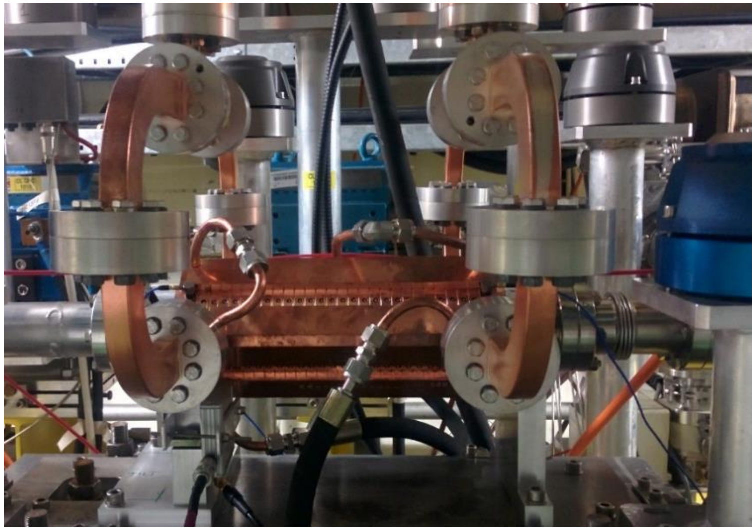
4x Toshiba 6MW 5us klystron
4x Scandinova Modulators
Rep Rate 400Hz

Medium power tests (Xbox-3A):
2015 3D-printed Ti waveguide
2015 X-band RF valve

1. Test of TD26CC-#1 structure (Dogleg experiment)

Test of the TD26CC-#1 structure

The structure


TD26CC-N1 installed at the beamline of the CTF3 Linac

The TD26CC-N1 was processed in 2013 by Xbox-1 at CTF2 after a long test of 6 months.

The test at **100 MV/m** gradient and **250 ns** pulse length showed a **breakdown rate of 7e-6 bpp/m**.

For CLIC requirements we expected a performance at a maximum gradient of **95 MV/m**

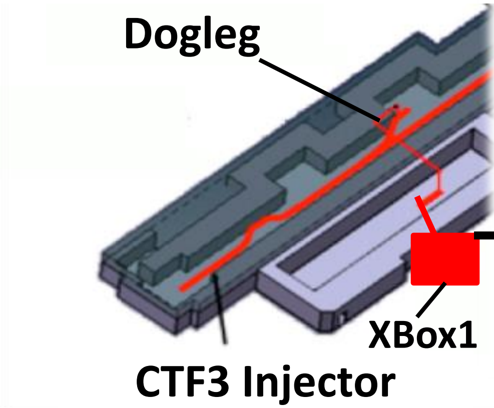
This structure was accidentally **vented** for few weeks at the testing place.

It was re-baken out at 650 deg C and installed again for a new test at the CTF3 Linac for the **Dogleg beam-loading experiment**.

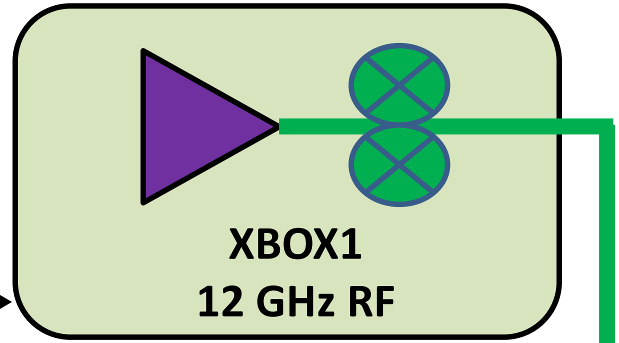
We found that the structure **needed to be reconditioned**.

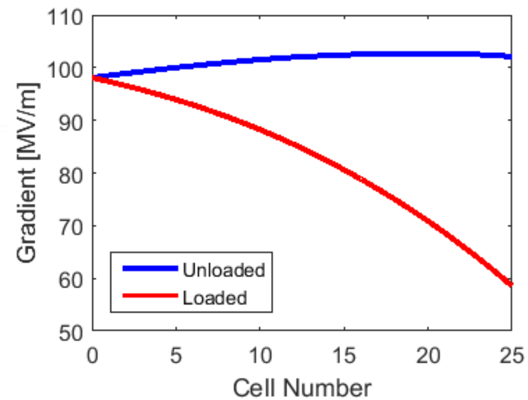
Test of the TD26CC-#1 structure

The Dogleg experiment

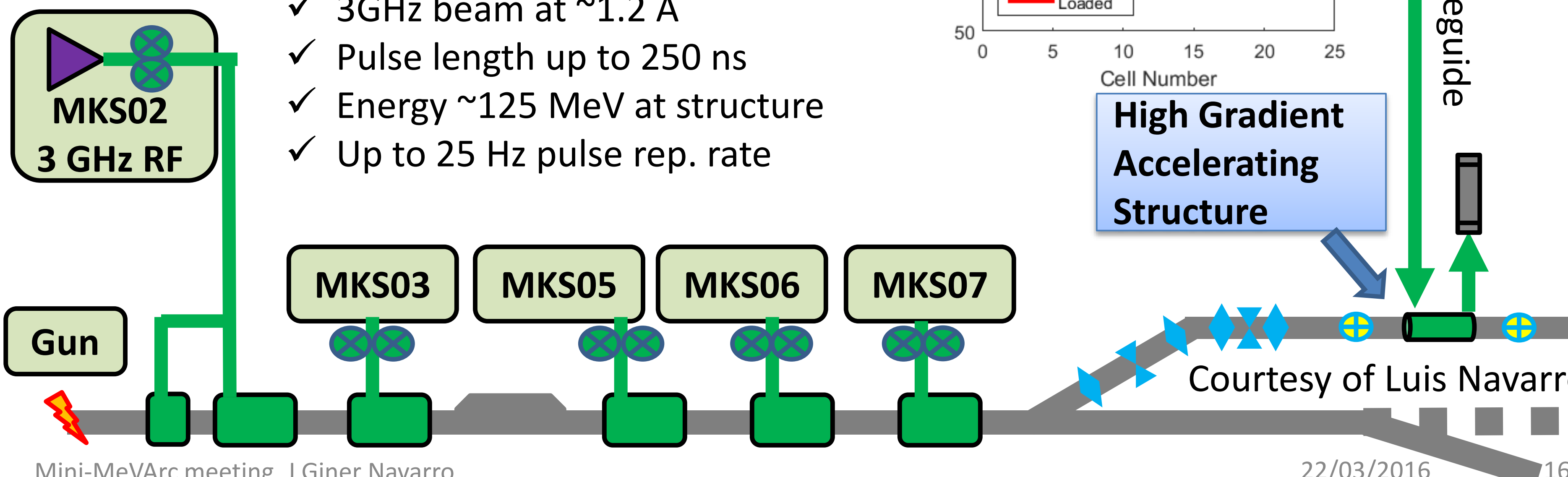


12 GHz RF:
- ✓ 90 MW RF power
- ✓ Up to 50 Hz rep. rate





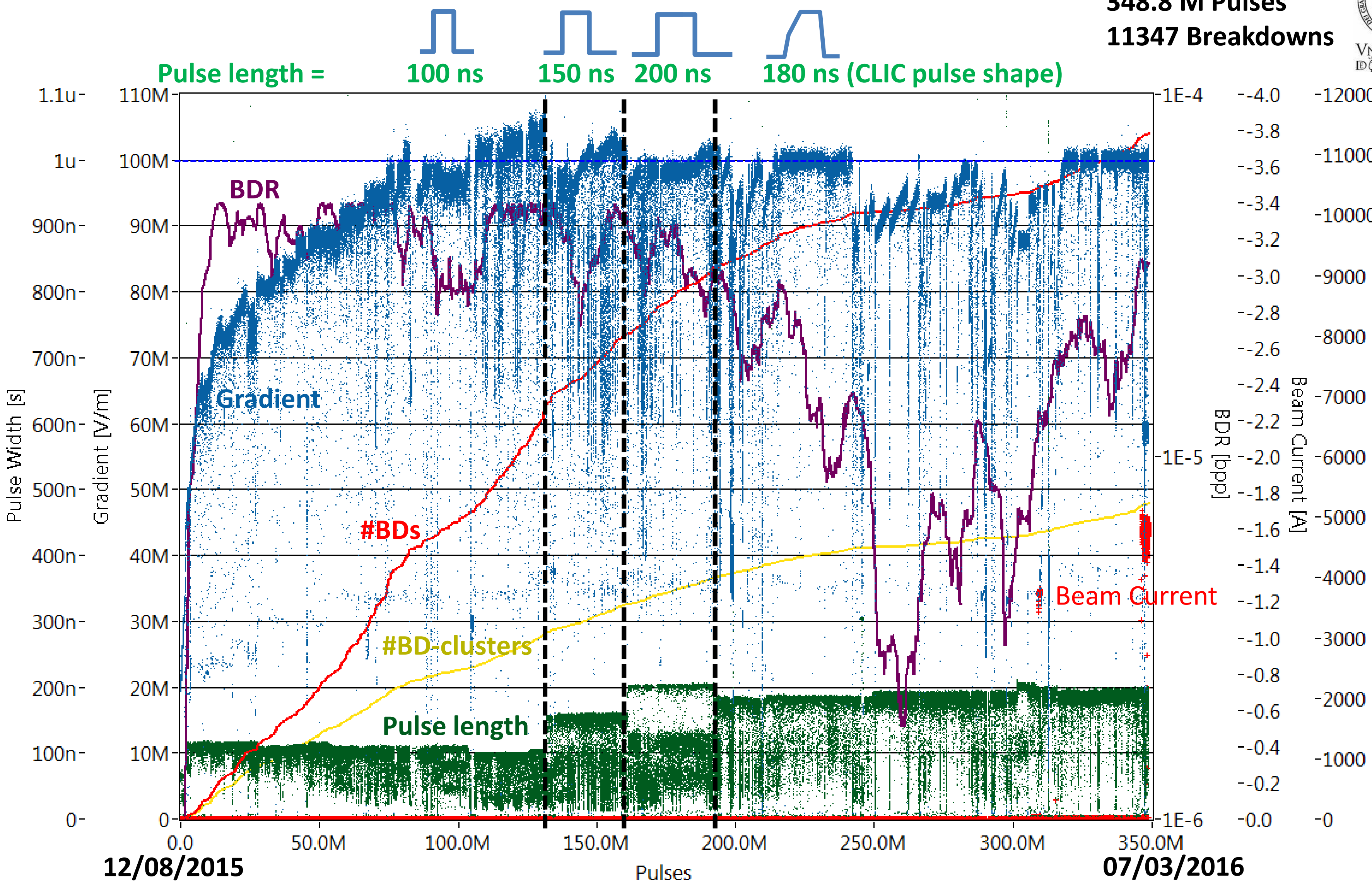
Beam:
- ✓ CTF3 Drive Beam modified
- ✓ 3GHz beam at ~1.2 A
- ✓ Pulse length up to 250 ns
- ✓ Energy ~125 MeV at structure
- ✓ Up to 25 Hz pulse rep. rate



Courtesy of Luis Navarro

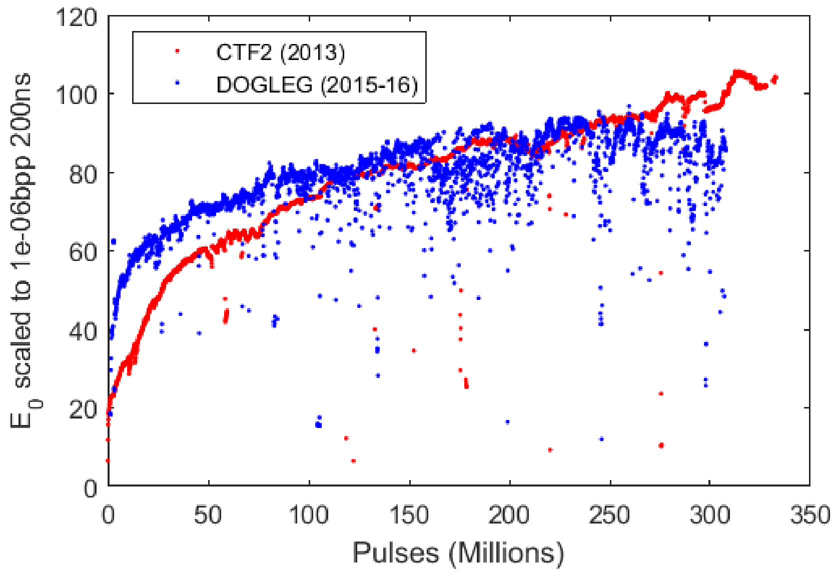
Test of the TD26CC-#1 structure

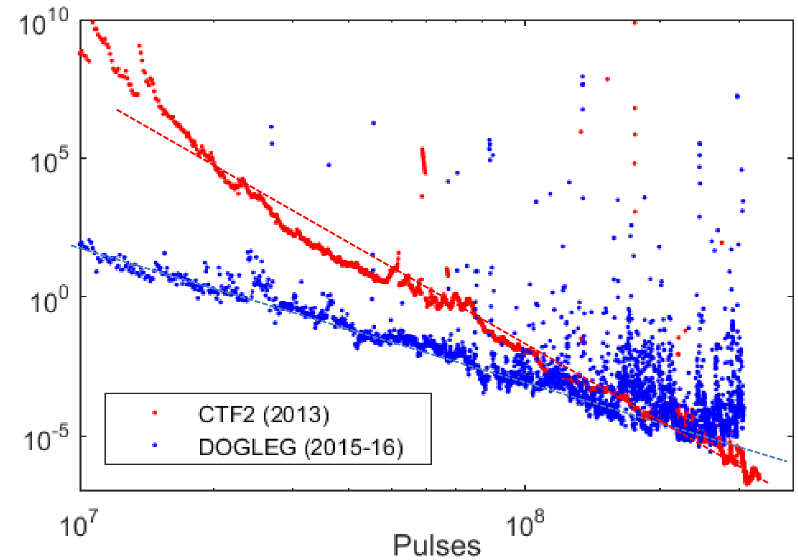
Full history



Test of the TD26CC-#1 structure

Current status





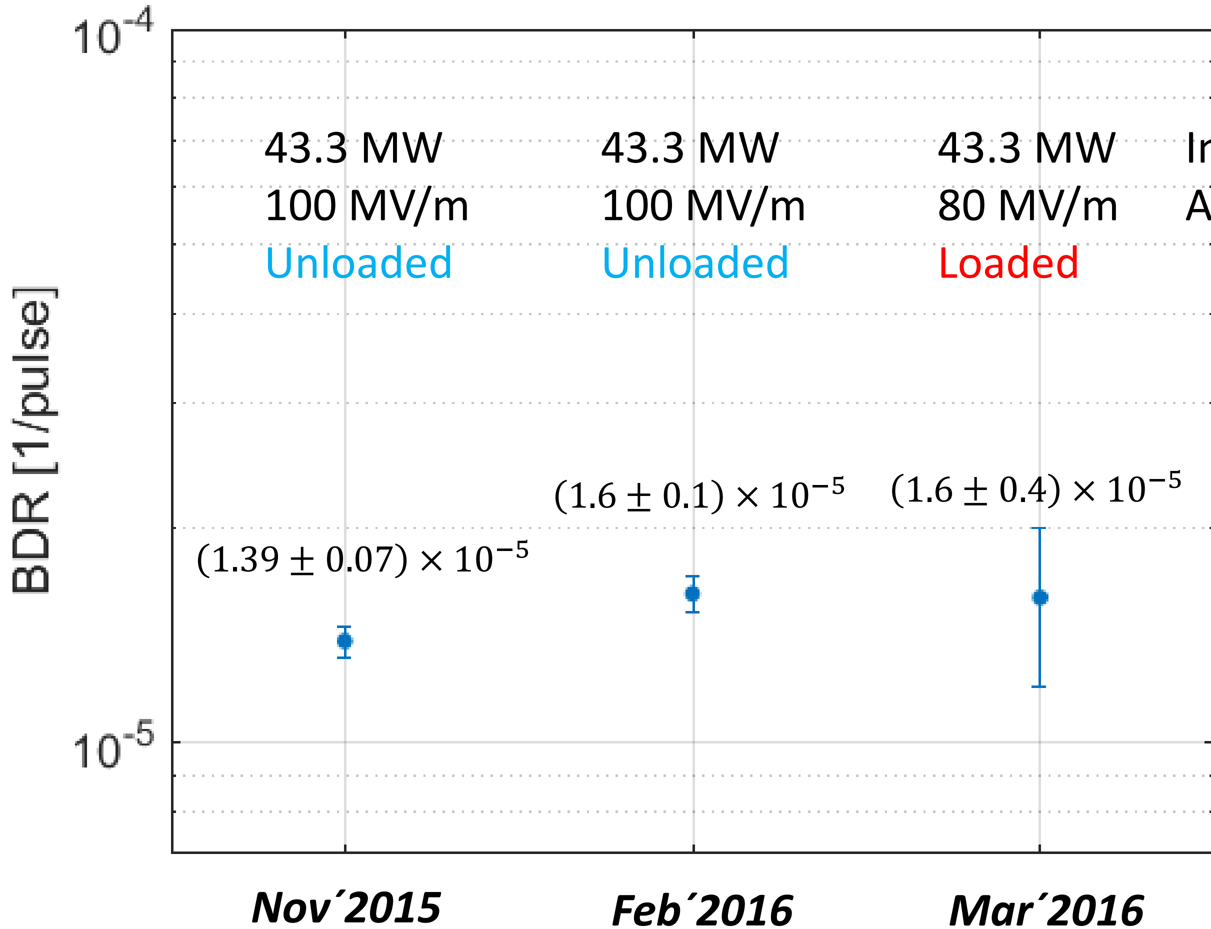
Current conditioning (blue) saturating or getting worse, but we do not blame the structure: we have stability problems with the Xbox-1 TWT amplifier which triggers high peak spikes quite often and induces breakdowns in the structure with a high probability.

Comparing to the test at CTF2 in 2013 (red):

- After venting and re-bake out the structure started in good conditioning level
- The conditioning speed seems much lower and it hasn't arrived to the best performance despite having triggered the same number of pulses

Test of the TD26CC-#1 structure

Beam-loading preliminary results



First Breakdown Rate measurements unloaded and loaded

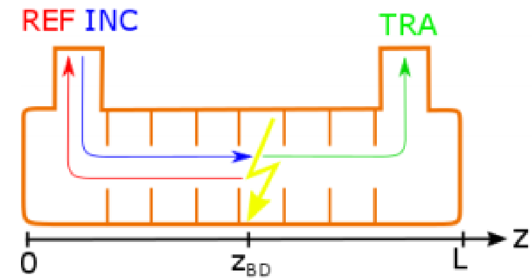
Still Preliminary! Need of more statistics with beam

Test of the TD26CC-#1 structure

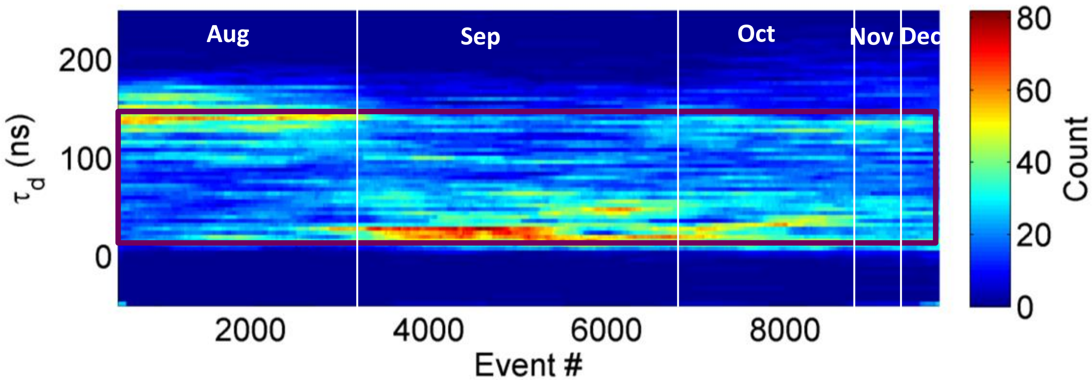
Breakdown analysis

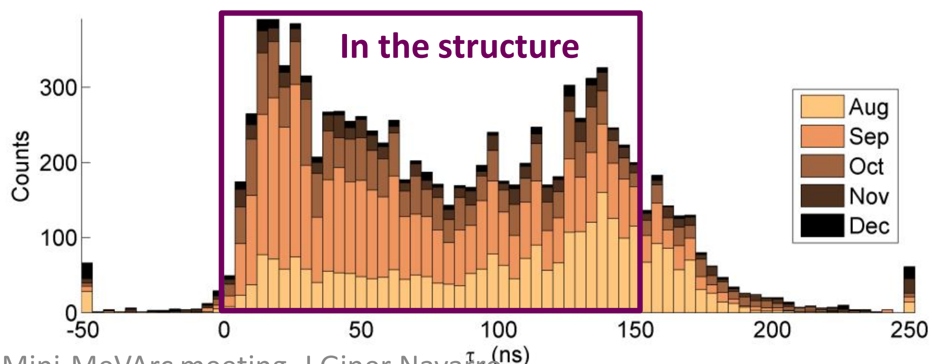
First we started to see more breakdowns at the end of the structure. Later, they concentrated at the beginning of the structure.
Now they seem to distribute uniformly along the structure.

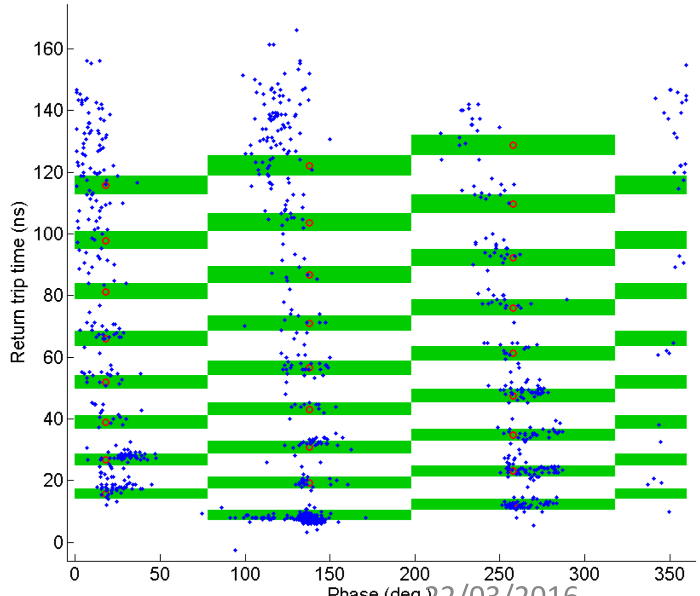
R. Rajamaki



The combination of timing and phase information provides better accuracy in breakdown localization.







2. Test of T24OPEN structure

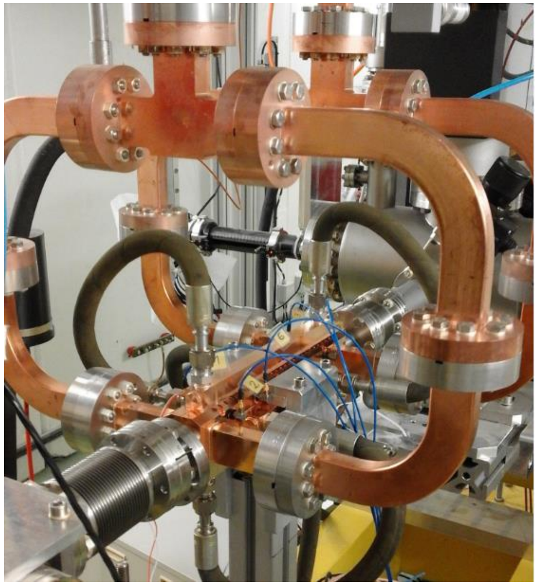
Test of the T24OPEN structure

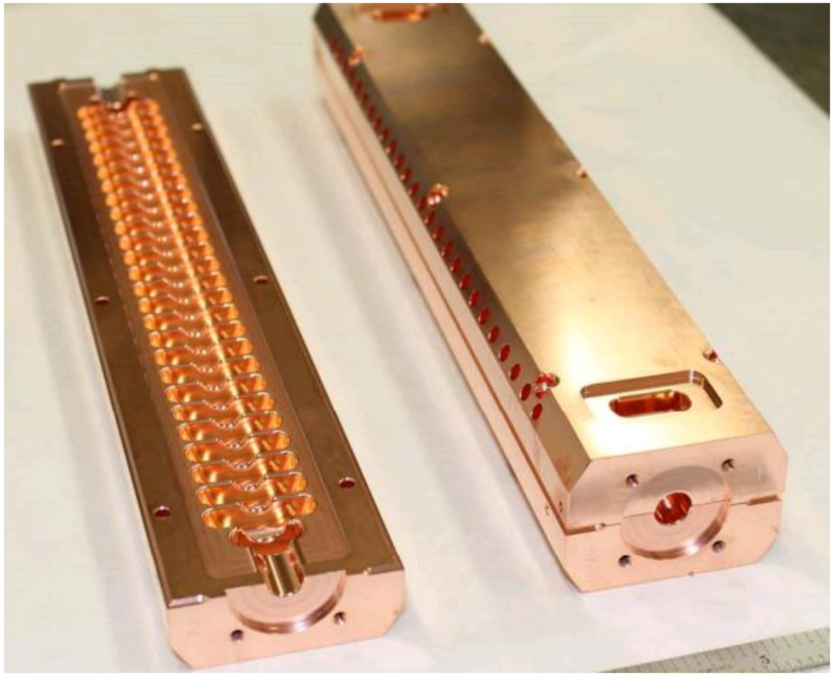
CLIC-G "open"prototype built in halves and brazed in SLAC:

24 regular cells (20cm-long) and no HOM damping

Milled structures present high interest because of its multiple advantages: costs, materials, treatment…

T24OPEN installed in Xbox-2



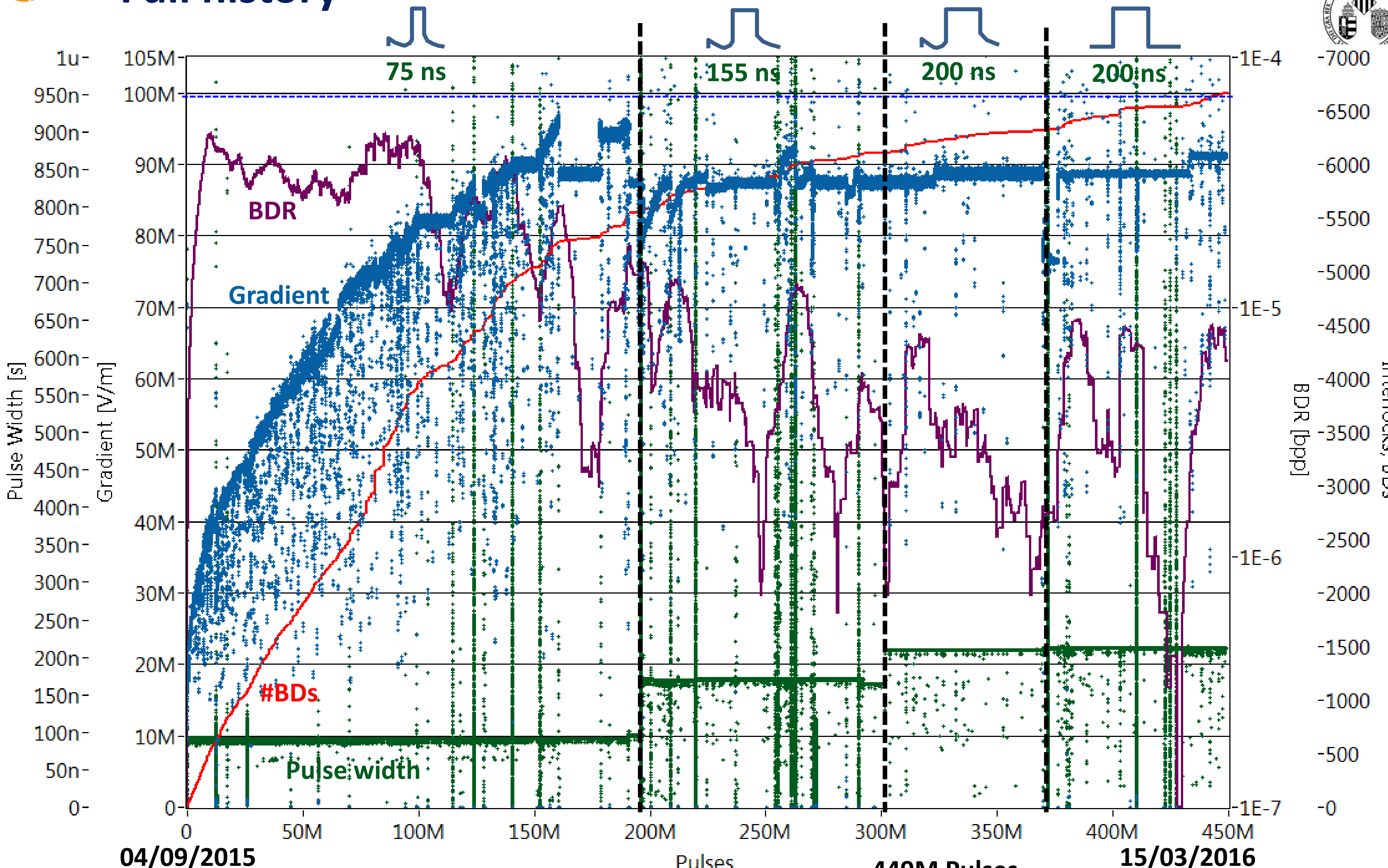


A. Grudiev, H. Zha, V. Dolgashev

The T24OPEN structure was installed in Xbox-2 and started running on 04/09/2015

Test of the T24OPEN structure

Full history

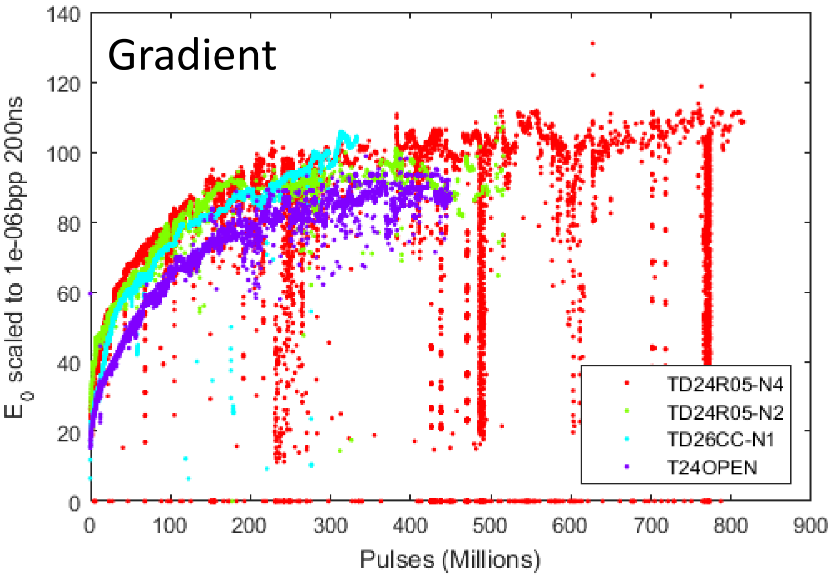


04/09/2015 **15/03/2016**

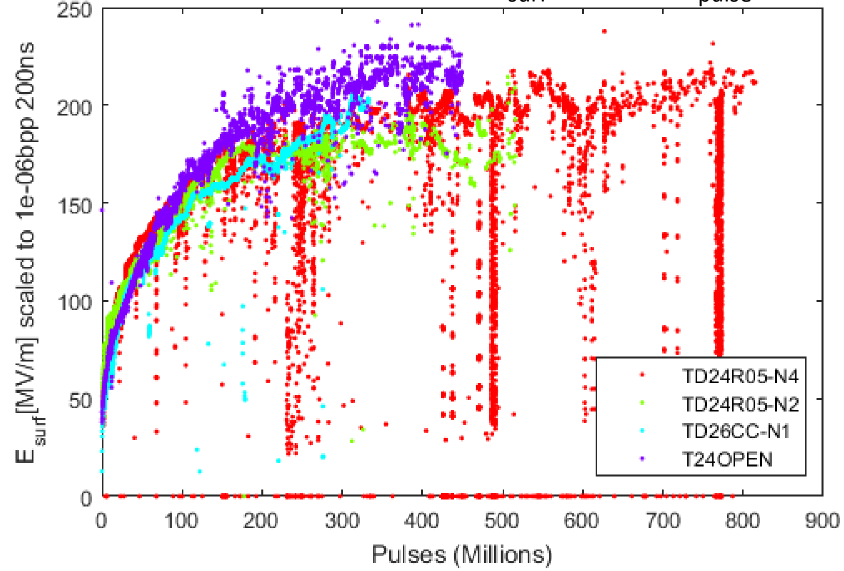
449M Pulses
6662 Breakdowns

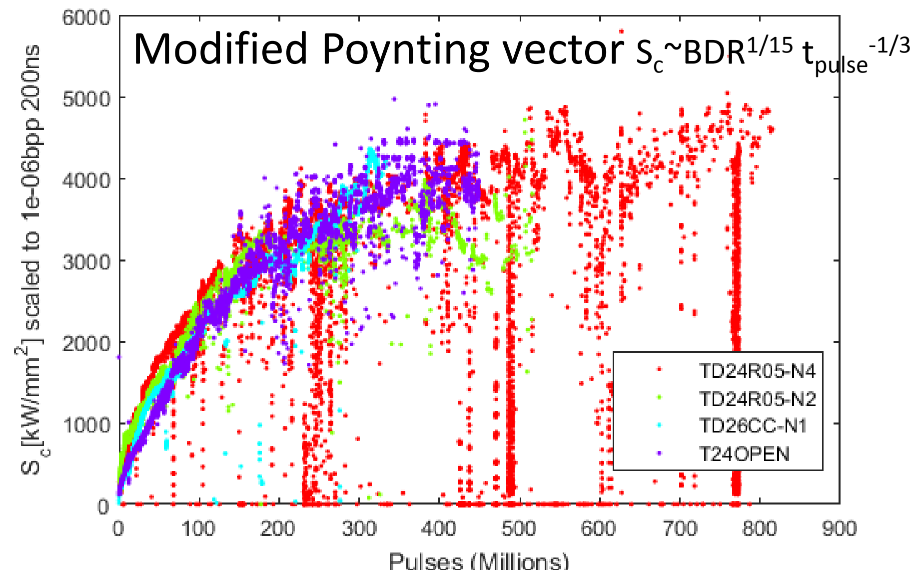
Test of the T24OPEN structure

Conditioning history



Surface electric field E_{surf}~$BDR^{1/30}\ t_{pulse}^{-1/6}$





Unlike other CLIC designs, the T24OPEN presents 20% higher surface E fields and S_c for the same gradient, but lower surface H fields, and this is observed in the conditioning curves.

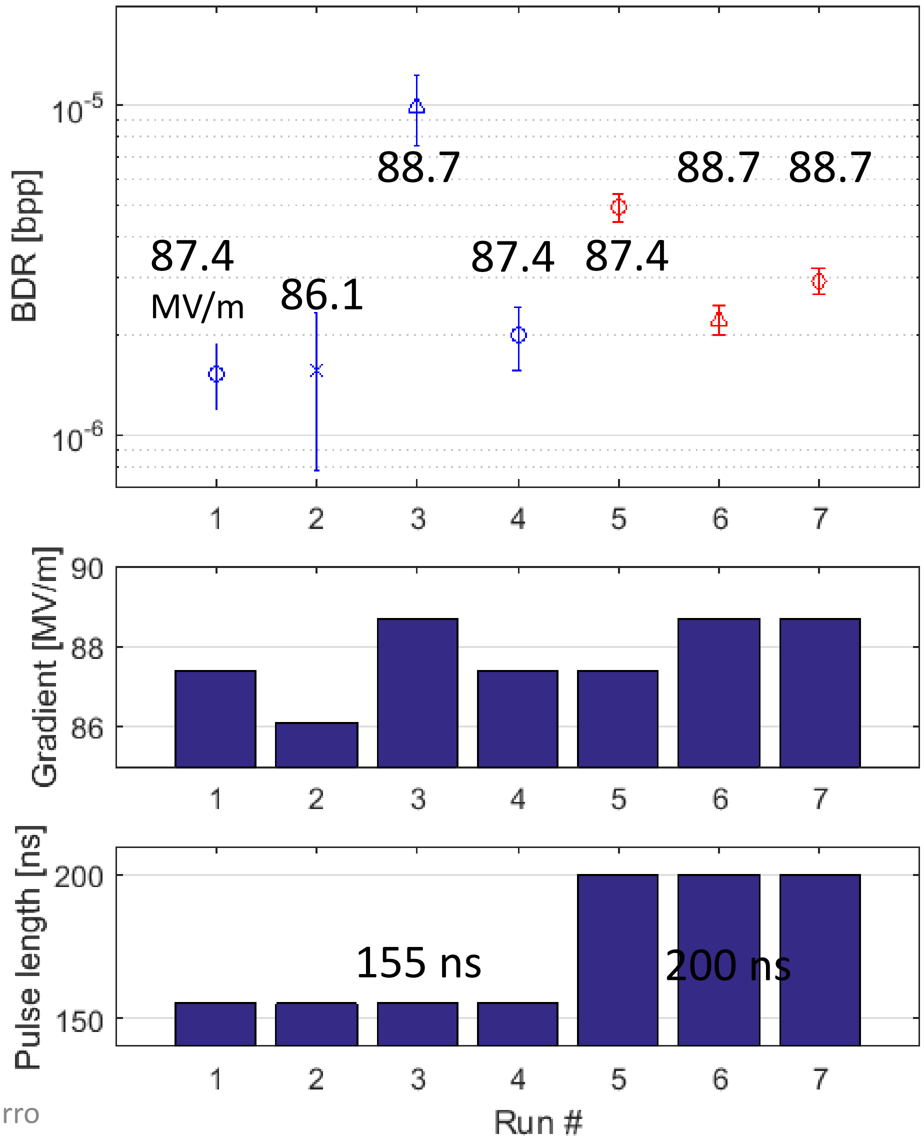
E_{surf} rises faster in time and S_c fits better with conditioning curves of previous tests.

Test of the T24OPEN structure

Current status

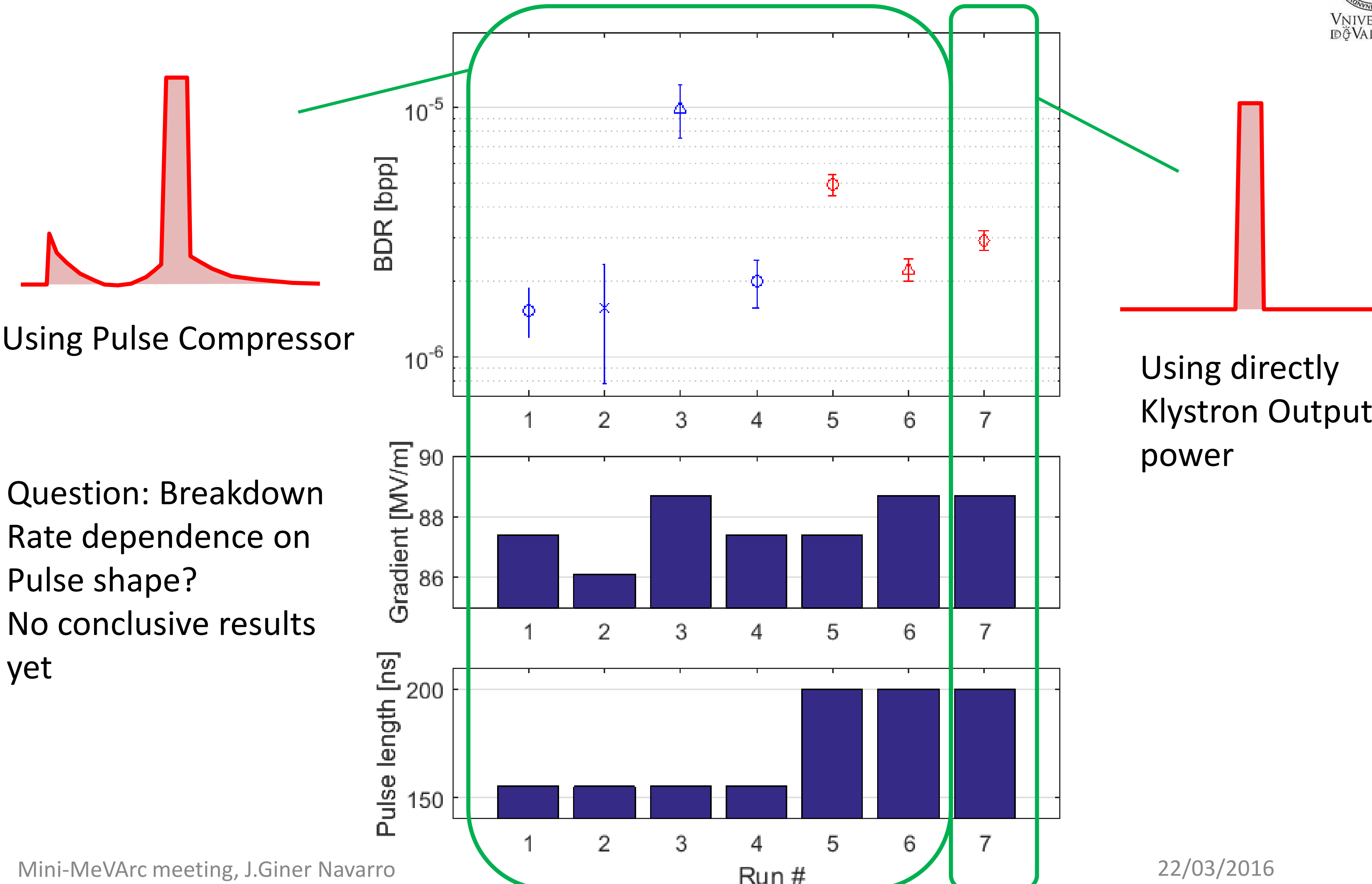
We performed BDR measurement at different gradient levels and pulse lengths.

No power laws dependences were found because structure was still conditioning!



Test of the T24OPEN structure

Current status



Question: Breakdown Rate dependence on Pulse shape?

No conclusive results yet

Test of the T24OPEN structure

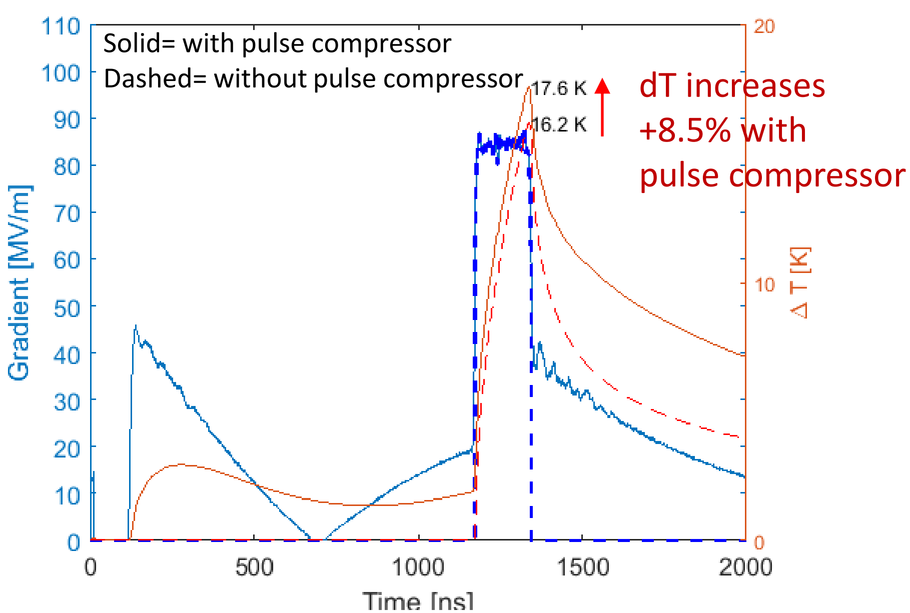
Breakdown Rate dependence on pulse shape

Pulsed surface heating

$$\Delta T(t) = \frac{R_s}{2\rho c_\epsilon\sqrt{\pi\alpha_D}}\int_0^t \frac{H_s^2(t')}{\sqrt{t-t'}}dt'$$

For flat pulse of length t_p

$$\Delta T(t_p) \propto P_0\sqrt{t_p}$$

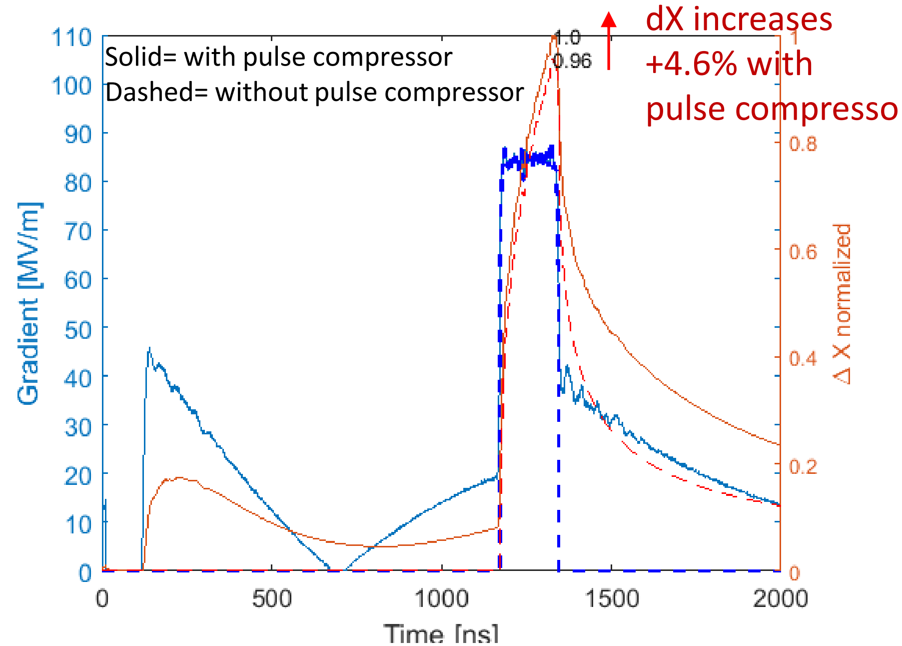


87.5 MV/m → **91 MV/m** (+4.2%)

From experimental results: $Pt_p^{1/3} = const$

We define:

$$\Delta X = \int_0^t \frac{P(t')}{(t-t')^{2/3}}dt'$$



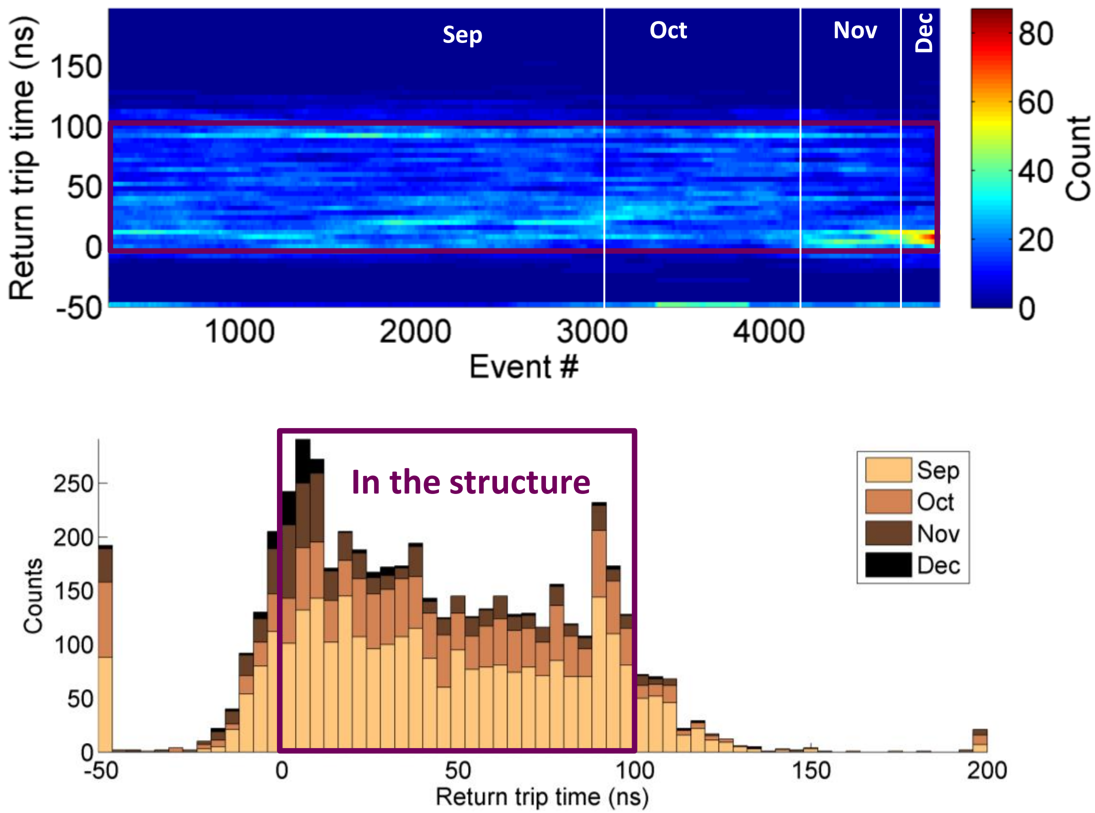
87.5 MV/m → **89.5 MV/m** (+2.2%)

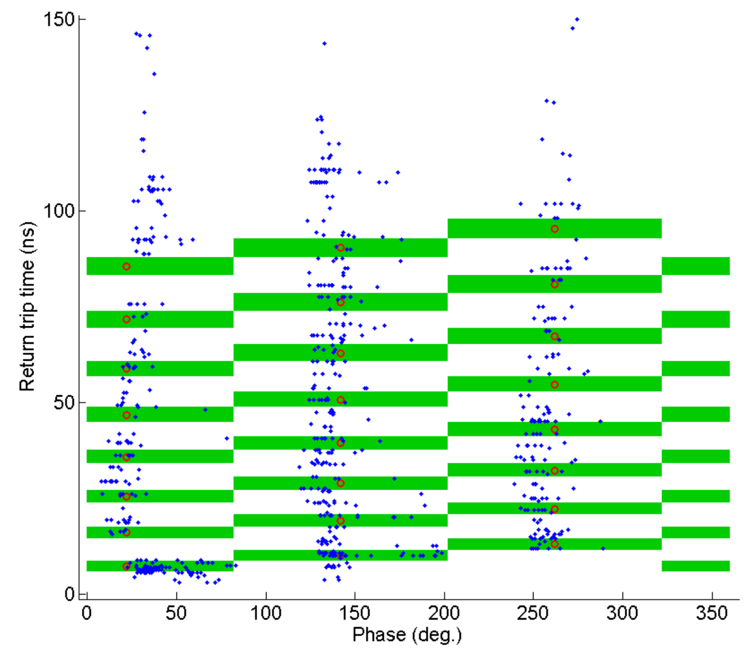
Test of the T24OPEN structure

Breakdown analysis

R. Rajamaki

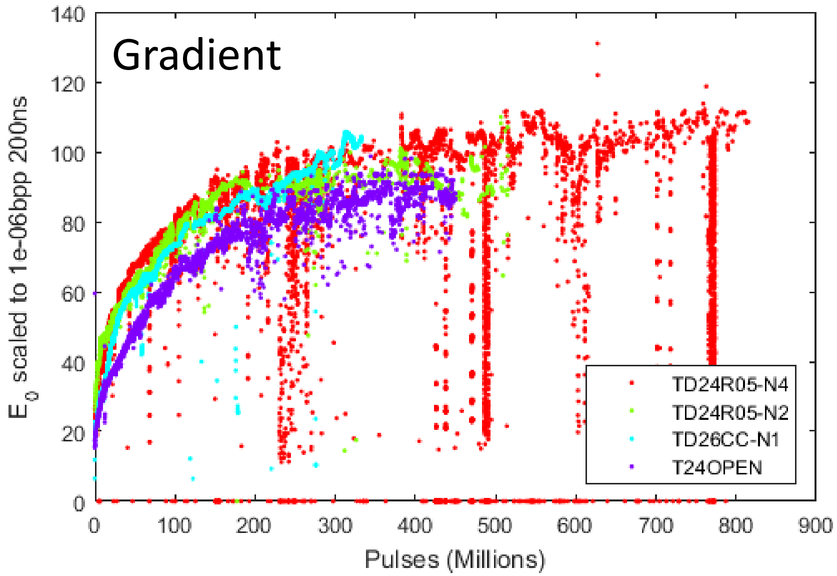
Good performance of the structure regarding the uniform distribution of breakdowns, until the last month of operation when it started to become hotter in the front.



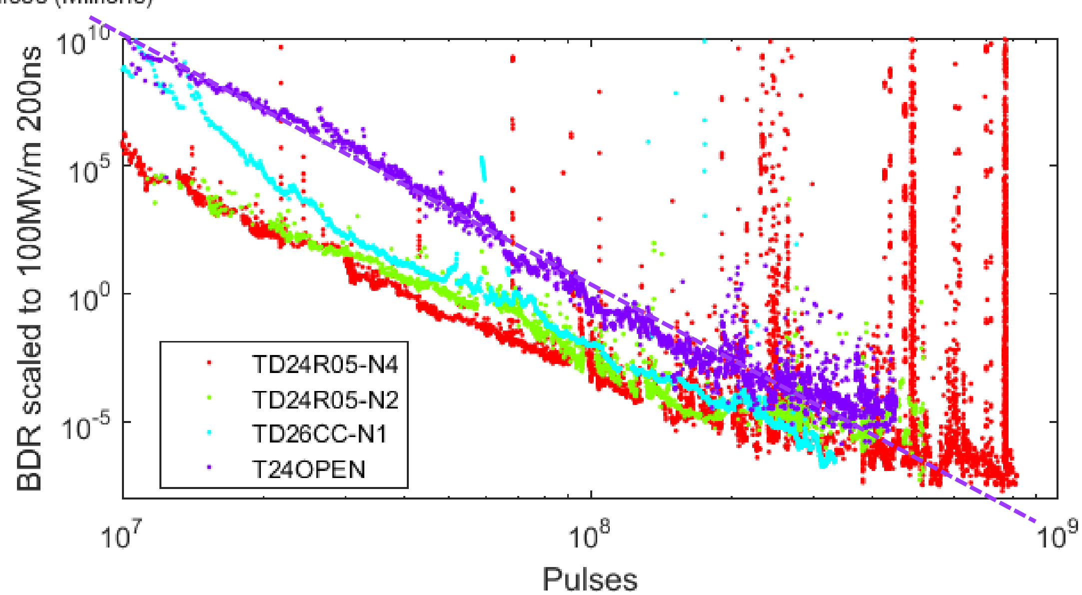


Test of the T24OPEN structure

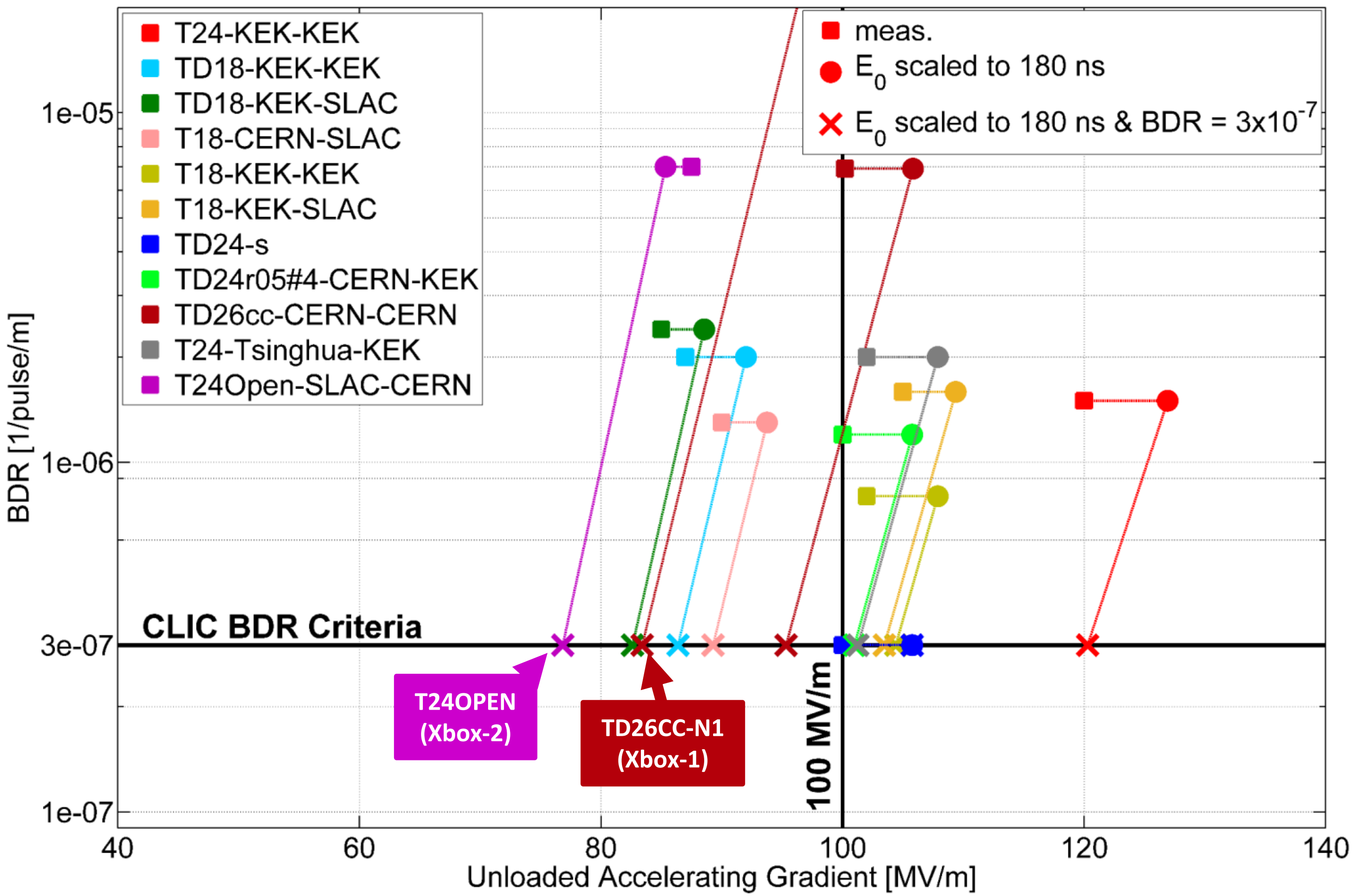
Conditioning history



Normalized BDR also decreases following a power law at a similar conditioning speed, meaning that follows the same mechanism as seen in disk-based structures



Summary

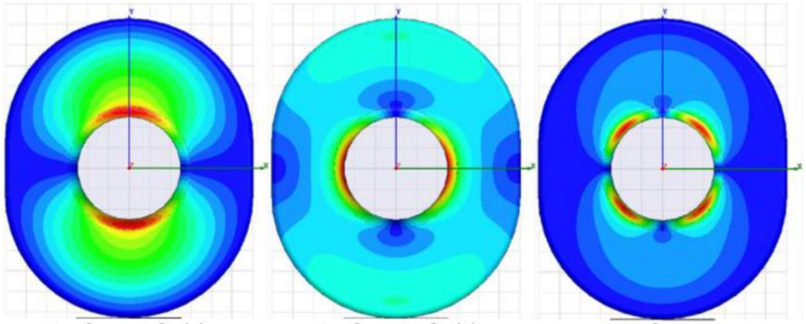


T24-KEK-KEK
TD18-KEK-KEK
TD18-KEK-SLAC
T18-CERN-SLAC
T18-KEK-KEK
T18-KEK-SLAC
TD24-s
TD24r05#4-CERN-KEK
TD26cc-CERN-CERN
T24-Tsinghua-KEK
T24Open-SLAC-CERN
meas.
E0 scaled to 180 ns
E0 scaled to 180 ns & BDR = 3x10-7
1e-05
1e-06
3e-07
1e-07
BDR [1/pulse/m]
CLIC BDR Criteria
T24OPEN
(Xbox-2)
TD26CC-N1
(Xbox-1)
100 MV/m
40
60
80
100
120
140
Unloaded Accelerating Gradient [MV/m]

3. Test of CRAB cavity

Test of the CRAB cavity

The structure



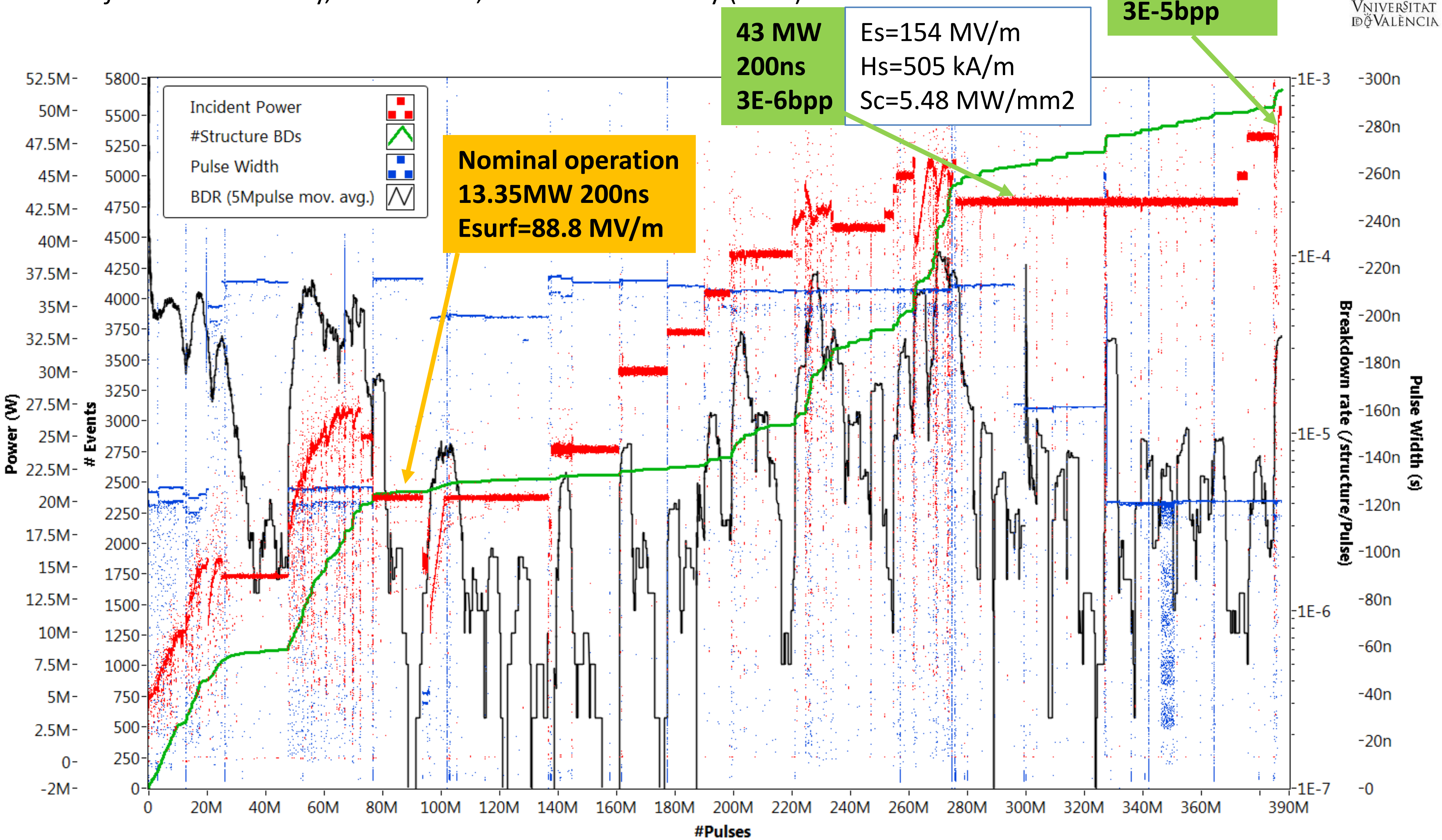
Property	CLIC T24 (unloaded)	LCLS deflector	CLIC Crab (un-damped)
Input Power	37.2 MW	20 MW	13.35 MW
Transverse Kick	-	24 MV	2.55 MV
Peak surf. E-field	219 MV/m	115 MV/m	88.8 MV/m
Peak surf. H-field	410 kA/m	405 kA/m	292 kA/m
Peak Sc	3.4 MW/mm^2	-	1.83 MW/mm^2
Group Velocity	1.8-0.9%c	-3.2%c	-2.9%c
# Cells	24	117	12

Designed to tilt the bunch before the interaction point at in order to improve CLIC luminosity.
Particular interest due to the surface field distribution and possible correlation with breakdowns.
Tested in Xbox-2 from October 2014 to May 2015.

Test of the CRAB cavity

Full history

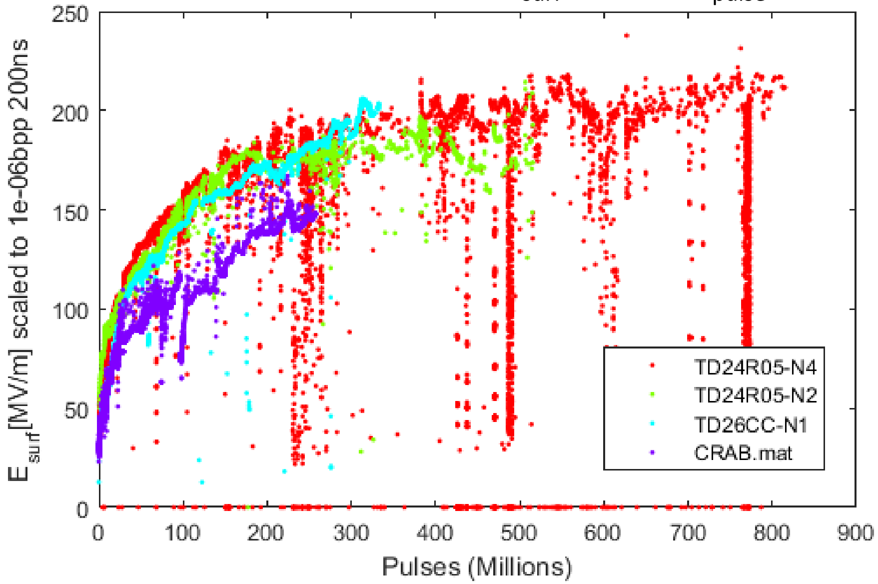
Reference. B. Woolley, Ph.D. Thesis, Lancaster University (2015)



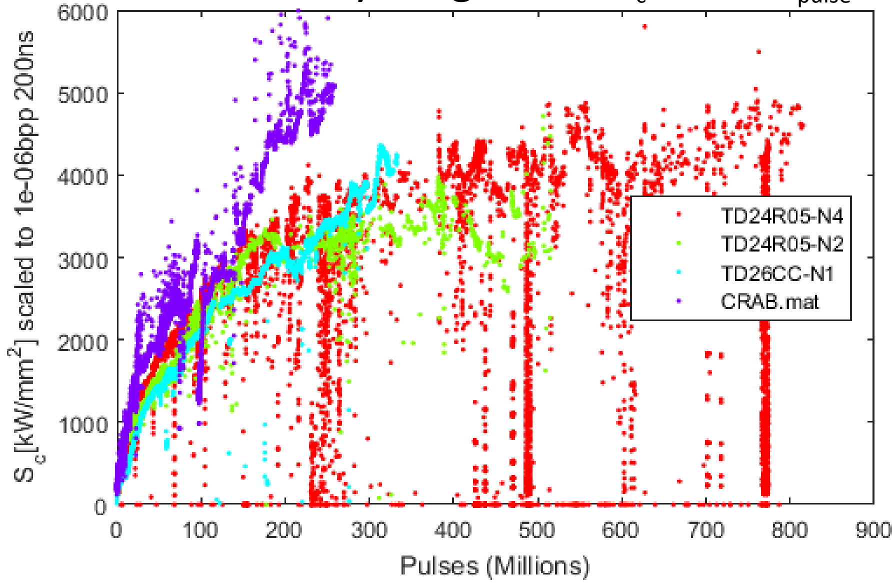
Test of the CRAB cavity

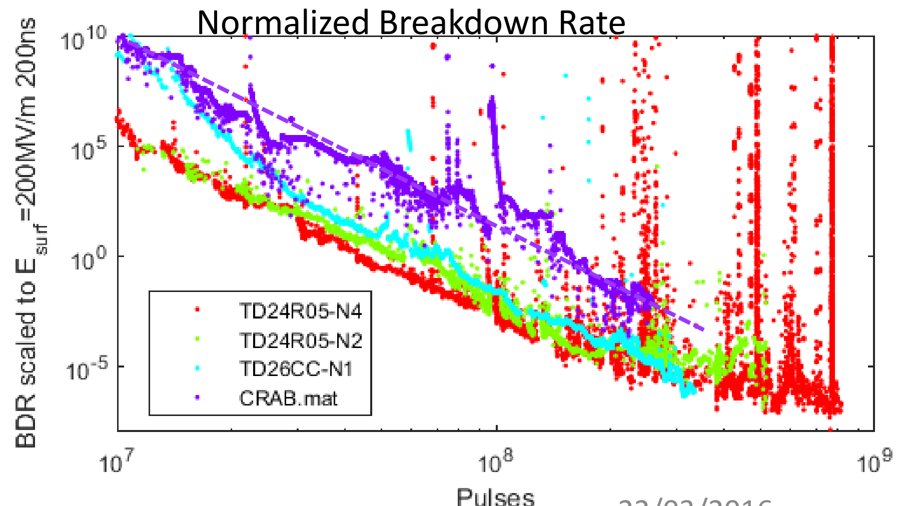
Conditioning histories

Surface electric field $E_{surf} \sim BDR^{1/30} t_{pulse}^{-1/6}$



Modified Poynting vector $S_c \sim BDR^{1/15} t_{pulse}^{-1/3}$





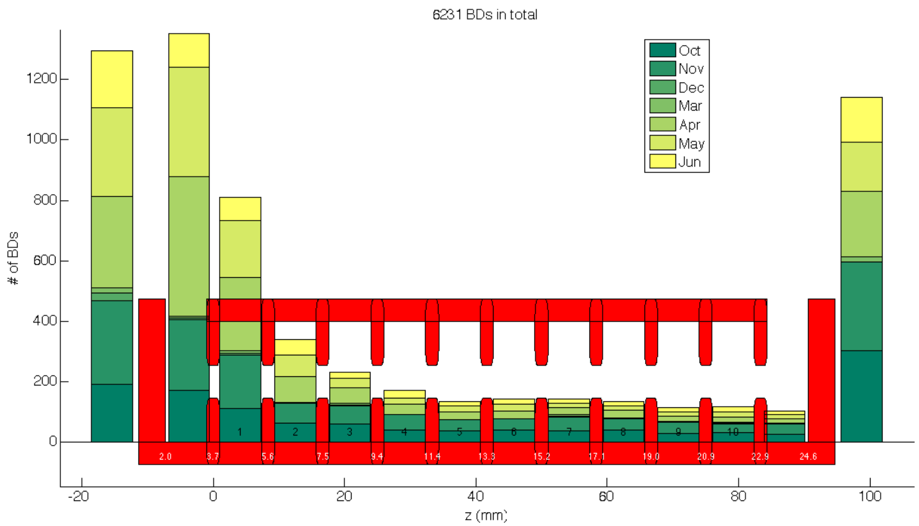
The structure has reached higher levels of Sc, but surface E field were lower.

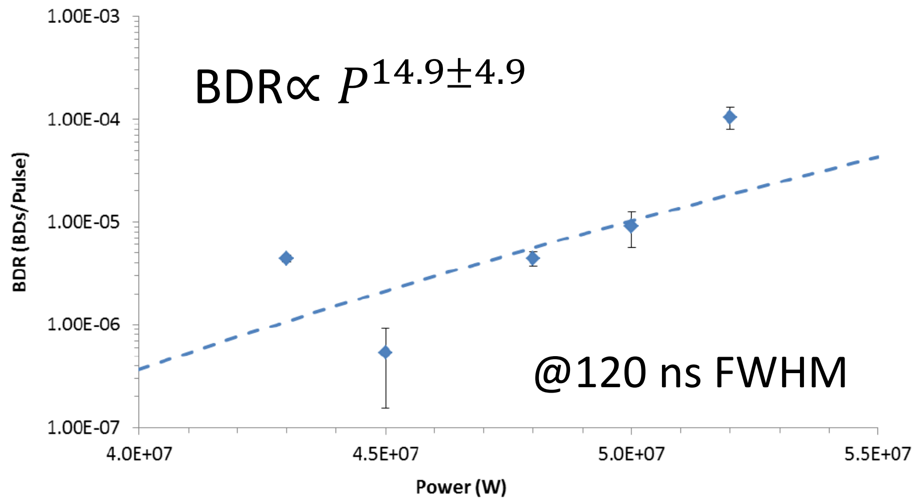
Breakdown rate seem to decrease with similar rate than other CLIC accelerating structures.

Test of the CRAB cavity

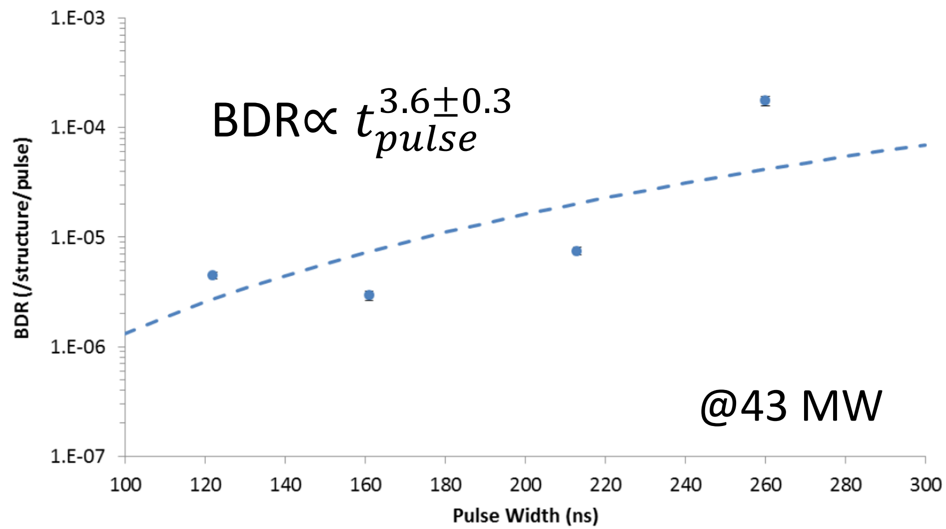
Breakdown analysis and BDR Scaling laws

B.Woolley, Ph.D. Thesis, Lancaster U. (2015)



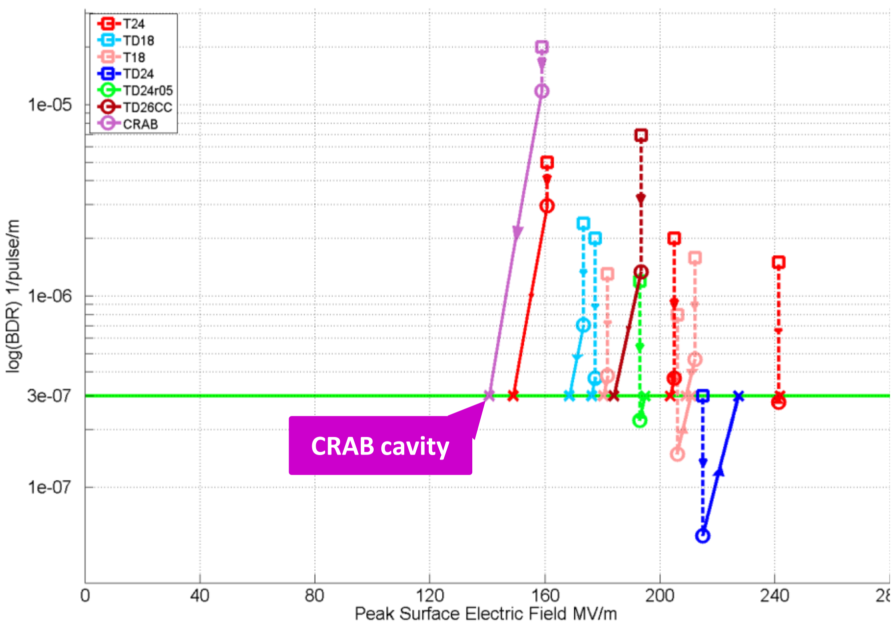


Surface fields decays exponentially from input to output (constant impedance structure).
Good performance over nominal operation.
BDR measurements consistent with other tests

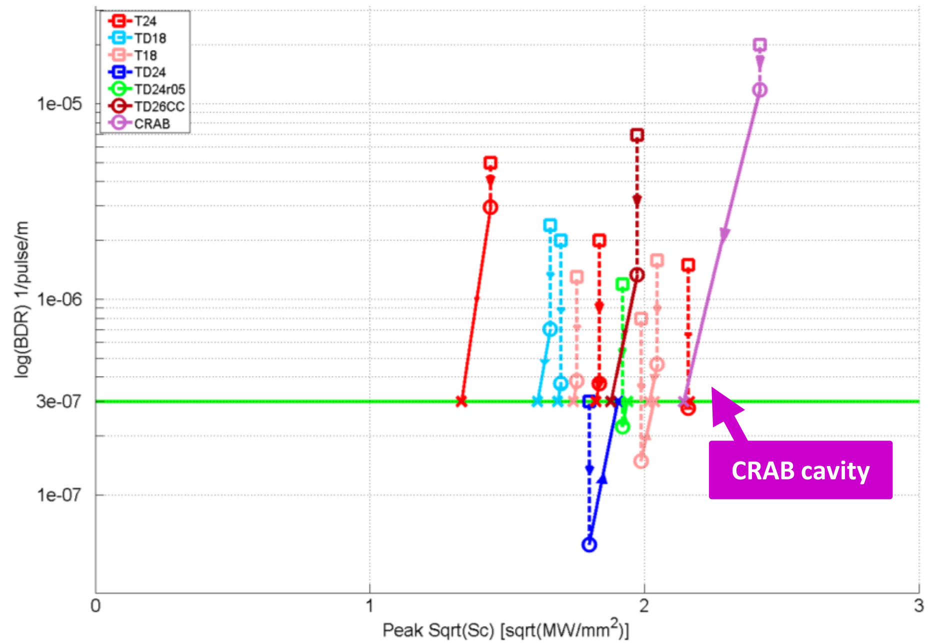


Post-mortem SEM analysis presented on Wednesday by E.Rodriguez-Castro and B.Woolley

Summary



In terms of peak surface E field



and peak Modified Poynting vector

Summary

- The CERN contribution of the CLIC High-Gradient testing programme is now at the level of **two high-power test stands** operating at the same time. The third is on commissioning
- Re-condition of TD26CC-N1 is ongoing: good performance but still below the status in 2013.
- First measurements of BDR with beam-loading. Preliminary results shows similar performance at the same input power.
- New prototype T24OPEN is being tested in Xbox-2: good performance so far and still being processed.
- Trying to measure BDR dependence on pulse shape (with and without pulse compressor).
- Comparison of conditioning histories supports the modified Poynting vector as a limiting quantity.

Thank you for your attention