Introduction to rf acceleration

Accelerating structures

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MeVArc 4
Chamonix, France
4 November 2013

Now – acceleration with high gradient!

We are now going to look at what happens when you operate an rf structure at high-gradient and high-power.

Accelerating gradient is one of the main performance limitations for linear colliders and why we have been so interested in participating in and contributing to a breakdown physics community.

To remind you of the CLIC parameters: the accelerating gradient is 100 MV/m, an input power of around 64 MW and a pulse length of around 180 ns giving a pulse energy of 12 J.

High-power behavior is not described by a nice, clear theory, with proofs and theorems.

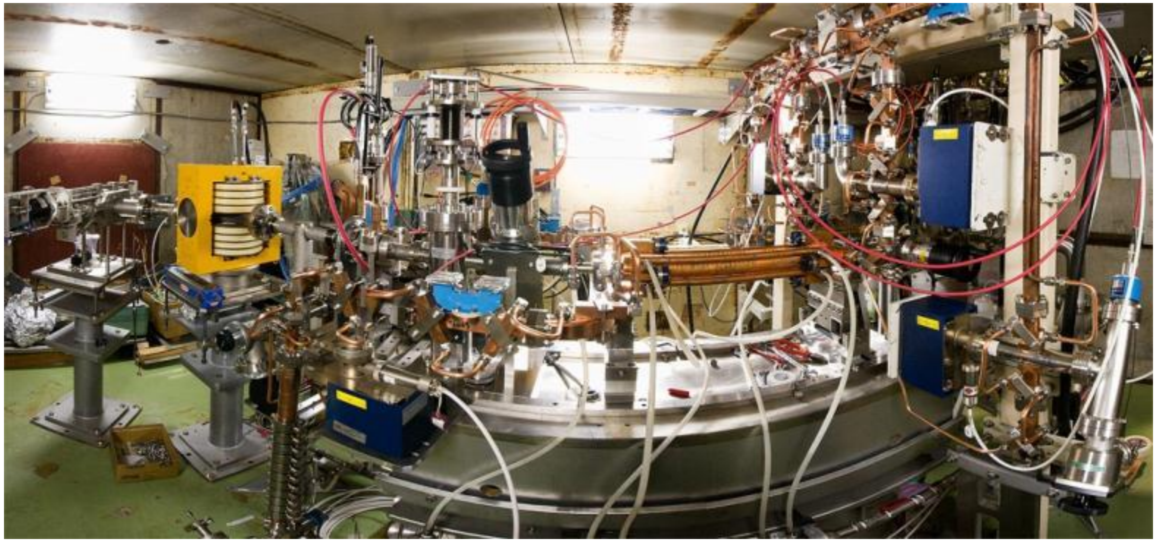
Instead what we have is picture emerging from the fog. I will describe the current understanding of how rf structures behave at high-power:
- How achievable gradient and power level depend on rf geometry.
- The physics of high-power phenomenon.
- Technology and why we think it works.

To do this I will cover:
1. Experiments and results.
2. Scaling laws

- What does a high-power rf test look like? You will see more when you visit CERN on Friday.
- What happens when an rf structure breaks down?

High-power rf testing requires significant infrastructure.

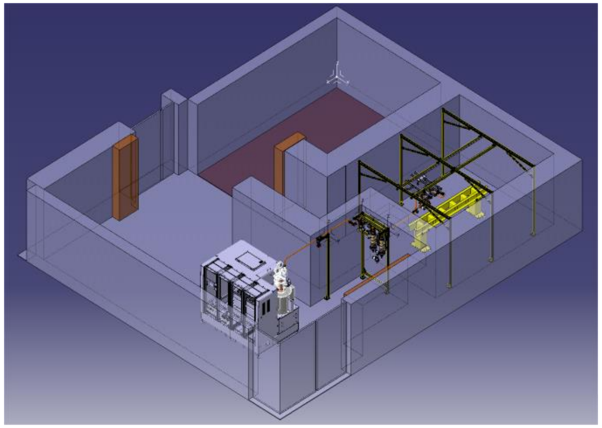
Klystron-based test stands for CLIC



NEXTEF at KEK

ASTA at SLAC

XBox1 at CERN

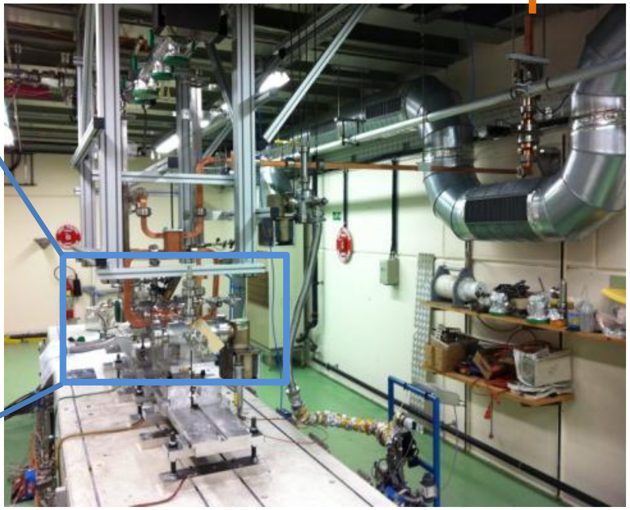


Xbox-2 at CERN based on XL-5
Xbox-3 at CERN based on 6 MW tube

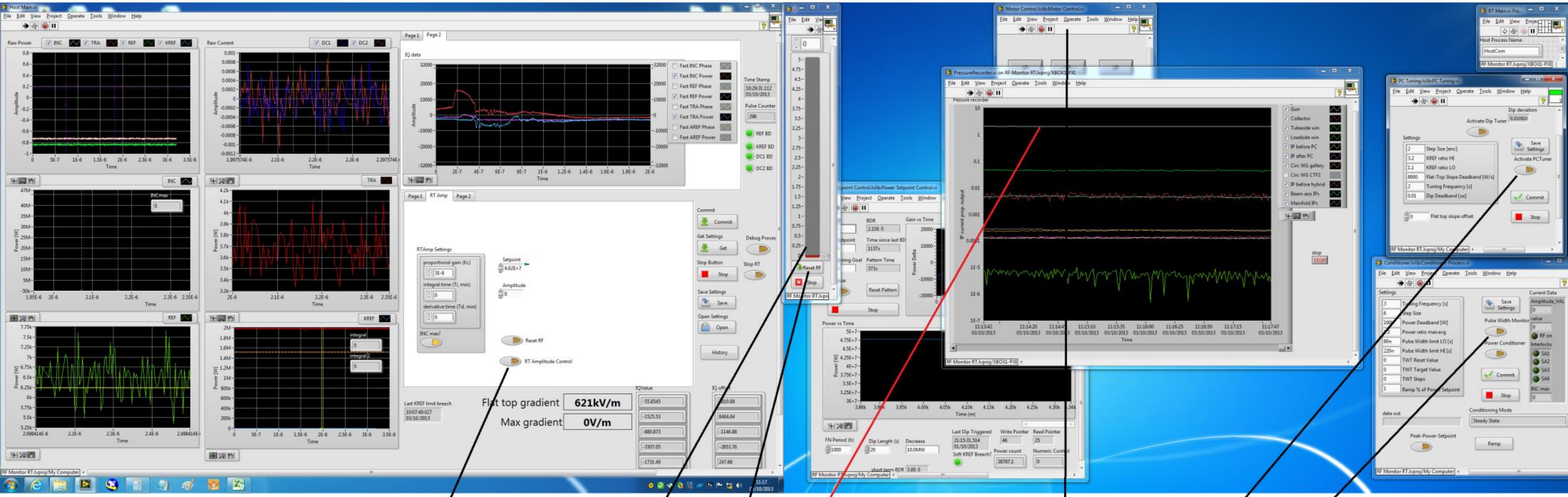
Layout of the CERN x-band test stand (X-box 1)

Clockwise from top-left:

- Modulator
- Pulse compressor
- DUT + connections
- Accelerating structure



Operator display



Flat top gradient 621kV/m
Max gradient 0V/m

2. Toggle and then turn OFF RT amplitude control

3. press Reset RF

1. Turn OFF Pulse Width Monitor

5. Deactivate PC tuner

8. Increase voltage of attenuation in Amplitude Control.vi

9. If tuning is good activate PC tuner (press Set Zero position when dip is good)

4. Reset and Trig the modulator at 250 V

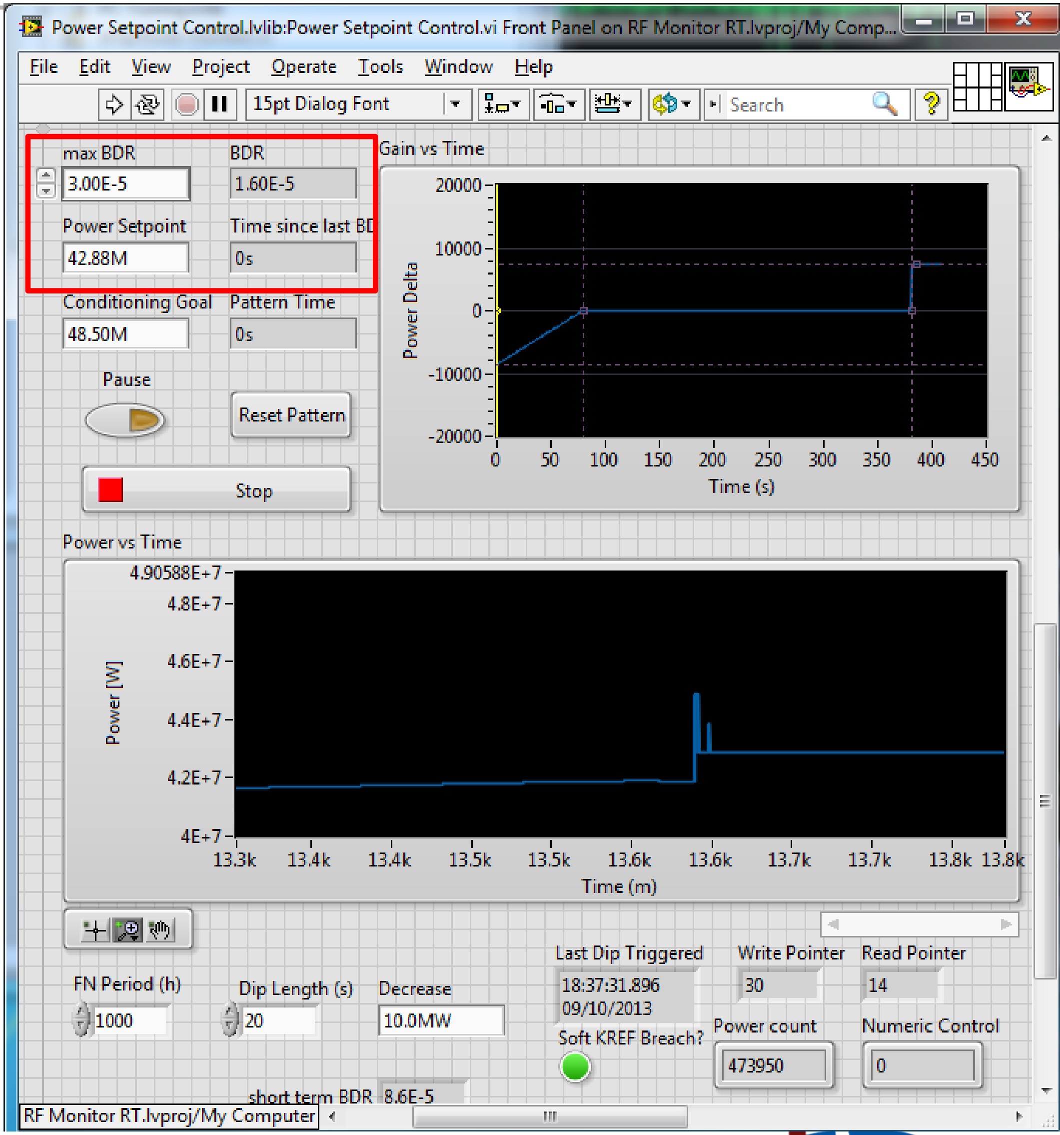
6. Tune pulse compressor to cold state (step 1000 then back to 20)

7. Ramp modulator voltage while checking gun vacuum level

10. Switch ON pulse width monitor(1) and RT amplitude control(2)

Cavity Conditioning Algorithm

- Automatically controls incident power to structure.
- Short term: +10kW steps every 6 min and -10kW per BD event.
- **Long Term**: Measures BDR (1MPulse moving avg.) and will stop power increase if BDR too high.



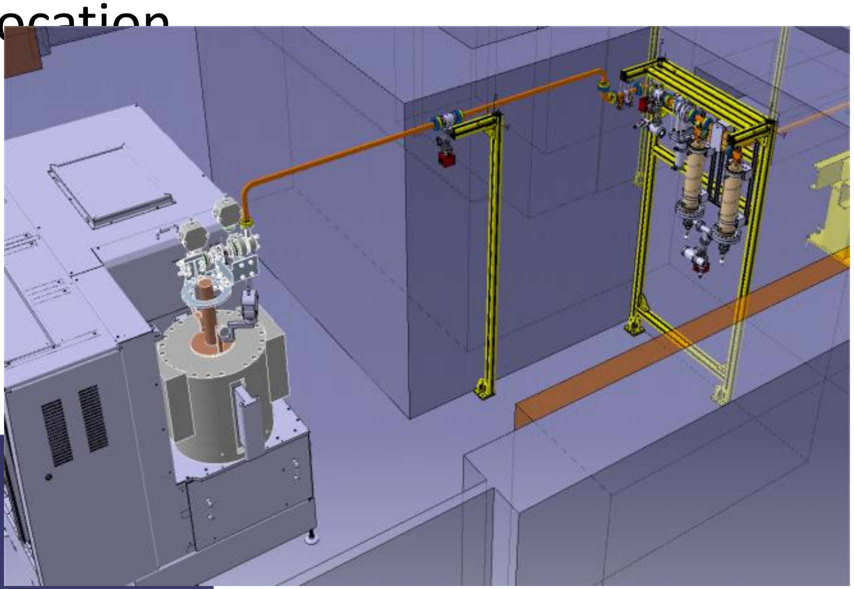
Power Setpoint Control.lvlib:Power Setpoint Control.vi Front Panel on RF Monitor RT.lvproj/My Comp...

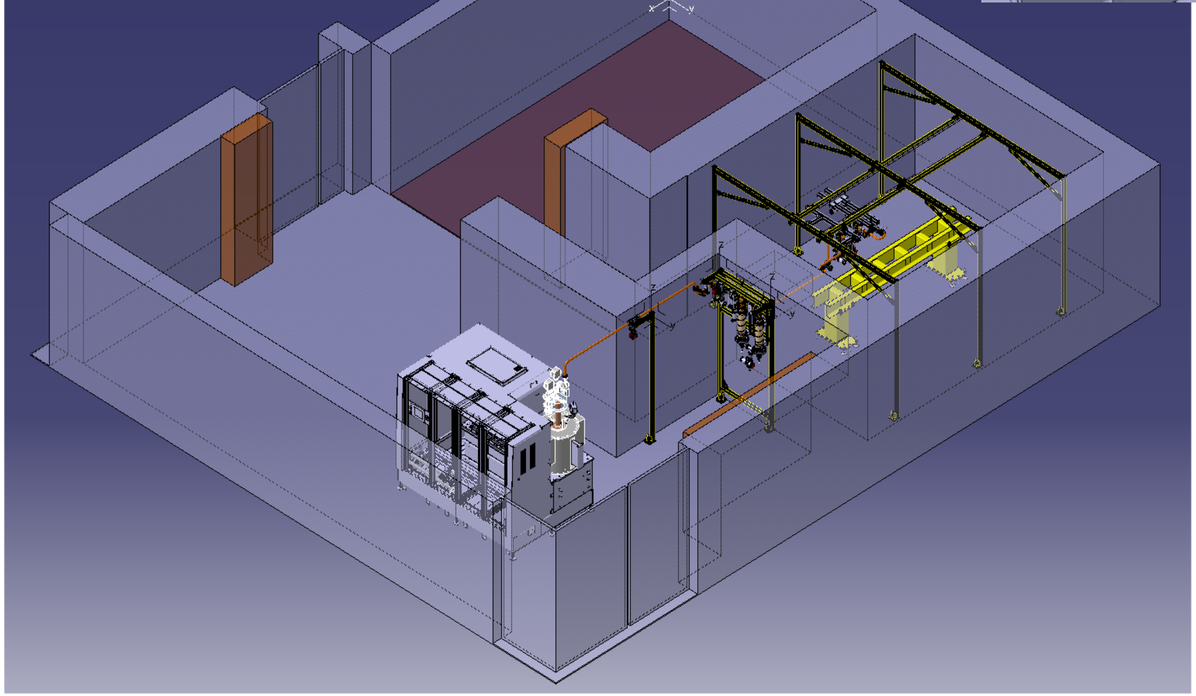
max BDR: 3.00E-5
BDR: 1.60E-5
Power Setpoint: 42.88M
Time since last BD: 0s
Conditioning Goal: 48.50M
Pattern Time: 0s

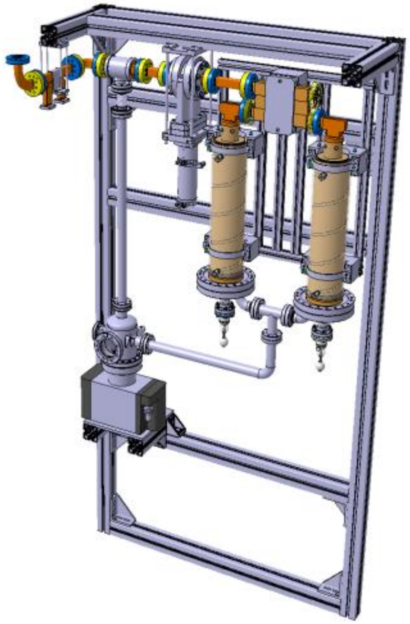
FN Period (h): 1000
Dip Length (s): 20
Decrease: 10.0MW
Last Dip Triggered: 18:37:31.896 09/10/2013
Write Pointer: 30
Read Pointer: 14
Soft KREF Breach?
Power count: 473950
Numeric Control: 0
short term BDR: 8.6E-5

RF Monitor RT.lvproj/My Computer

X-Box#2 at one of its possible location







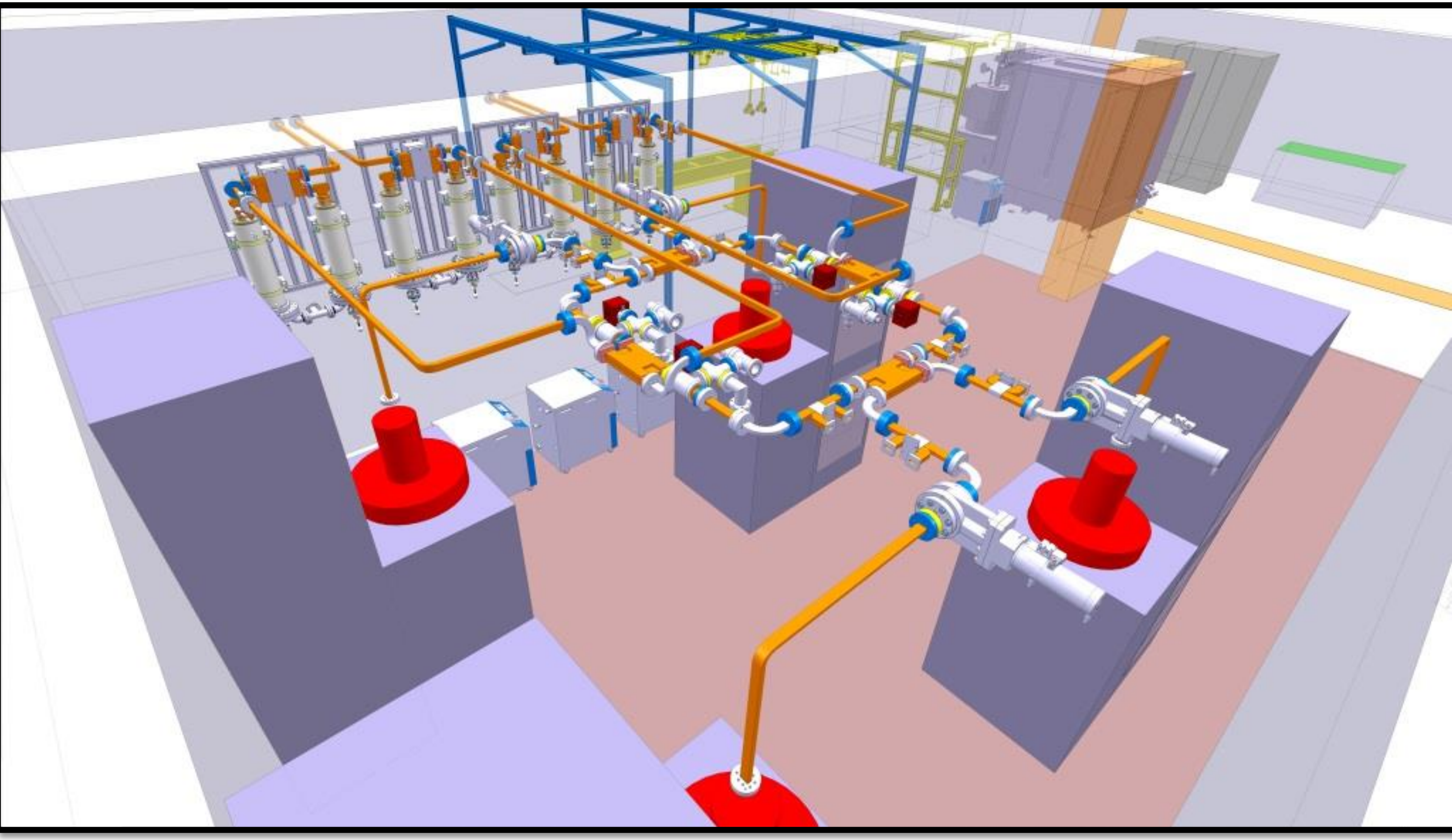
Preparation of future test stands

N. Catalan Lasheras, I. Syratchev, G. Mcmonagle
CLIC project meeting 11.10.2013

Status of Xbox2

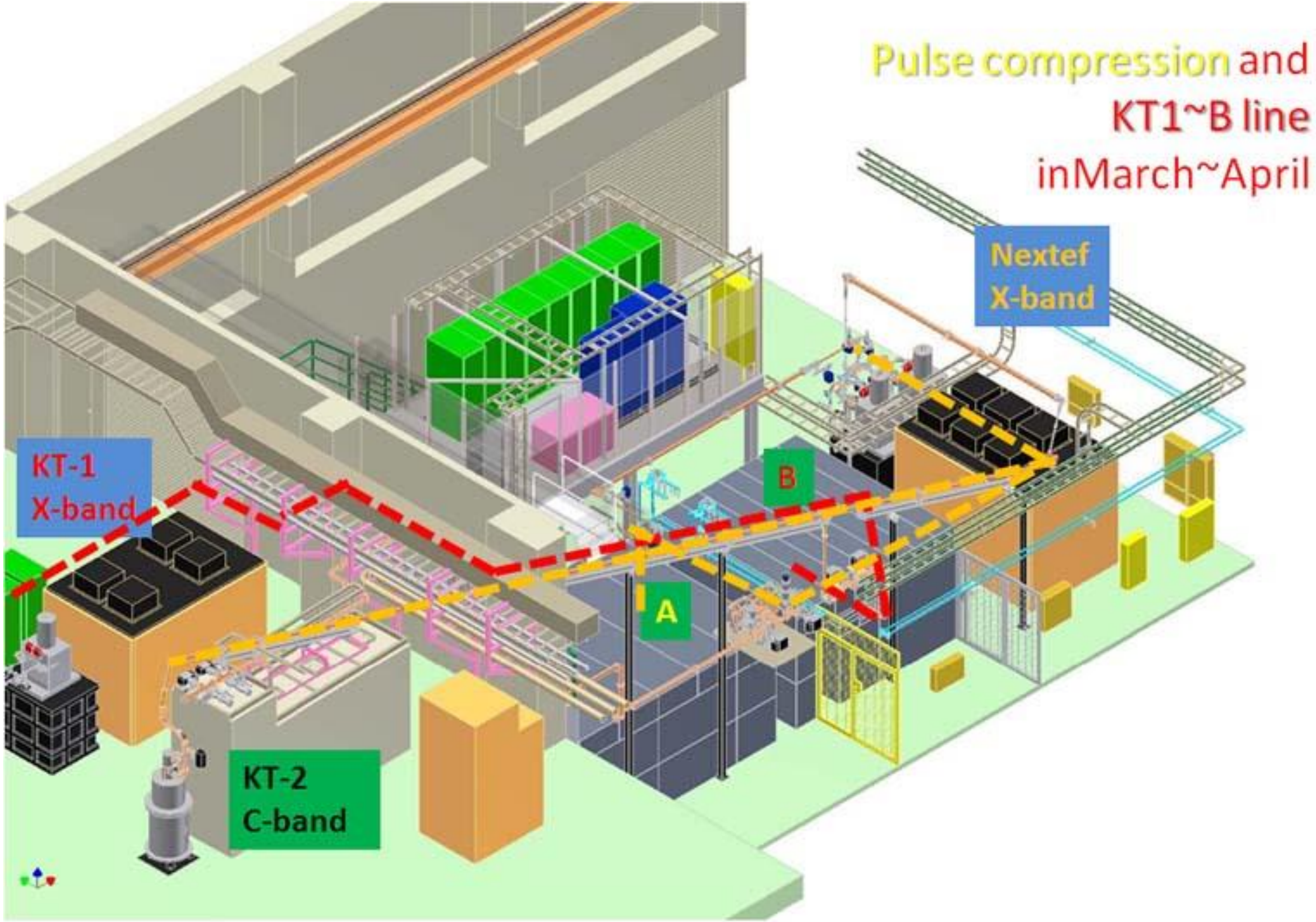
- Modulator arrived, installed and tested succesfuly to the require voltag, pluse length and stability
- Klystron being currently tested in SLAC
  - Some problems with testing network solved.
  - Testing now at 25MW at 1.5 us
  - Expected delivery in November

Preparation now underway at CERN for Xbox-3

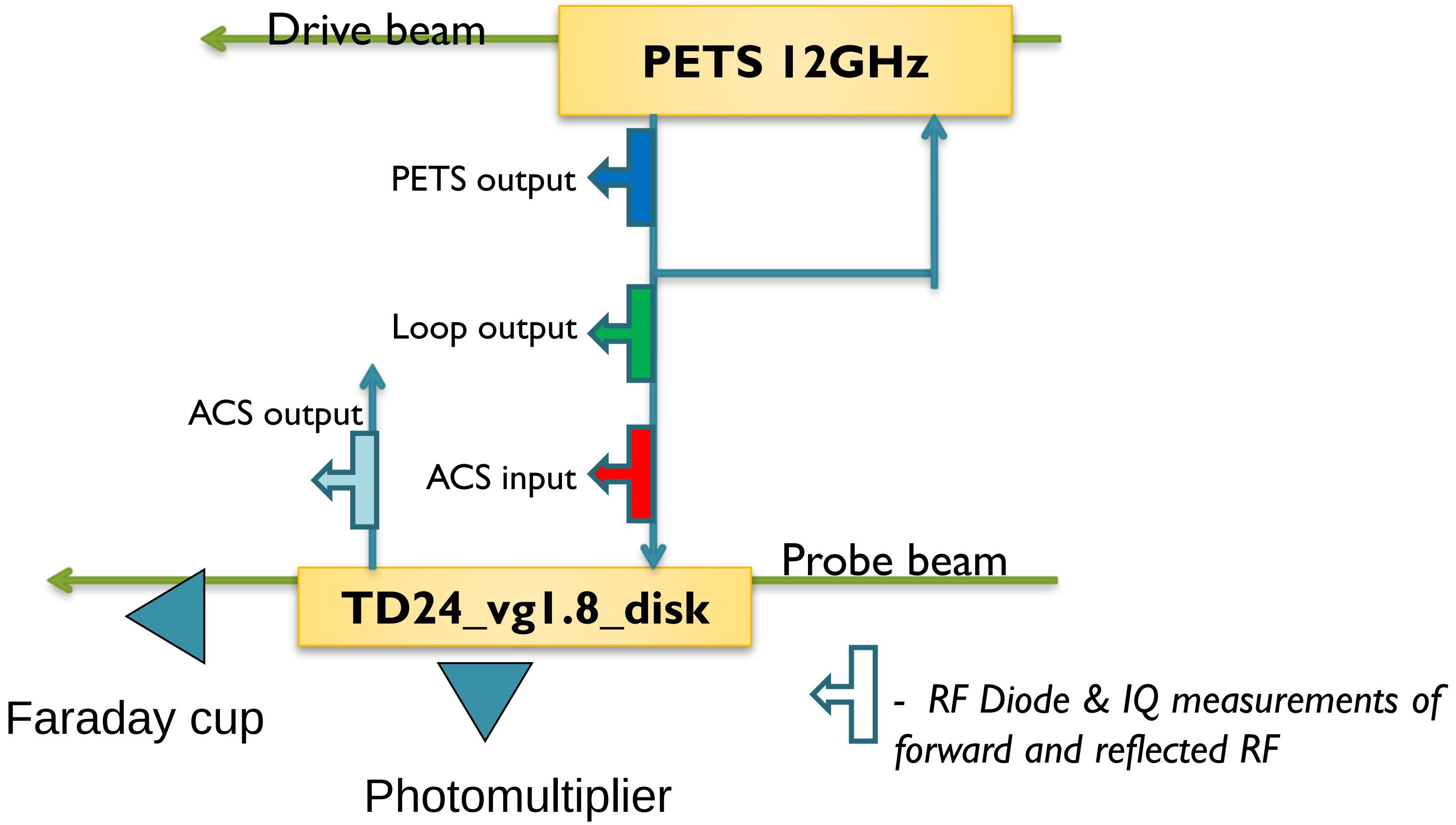


Based on combining four 6 MW Toshiba klystrons

Nextef expansion is being proceeded



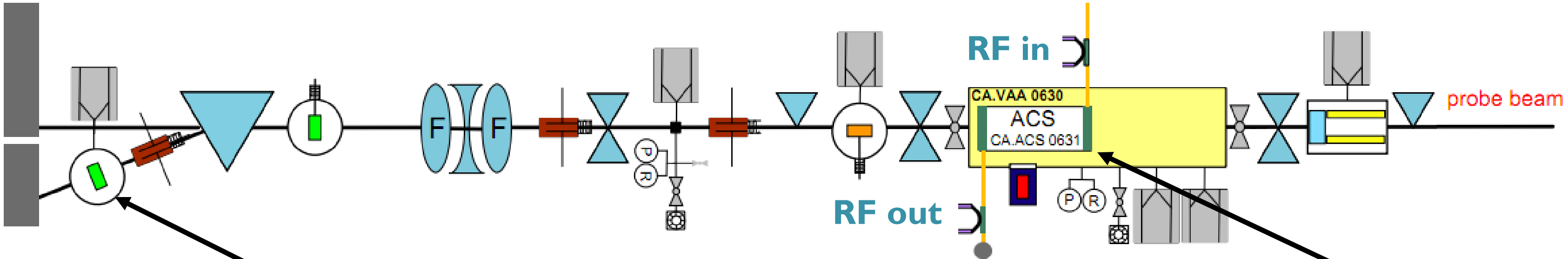
BD detection



- *RF Diode & IQ measurements of forward and reflected RF*

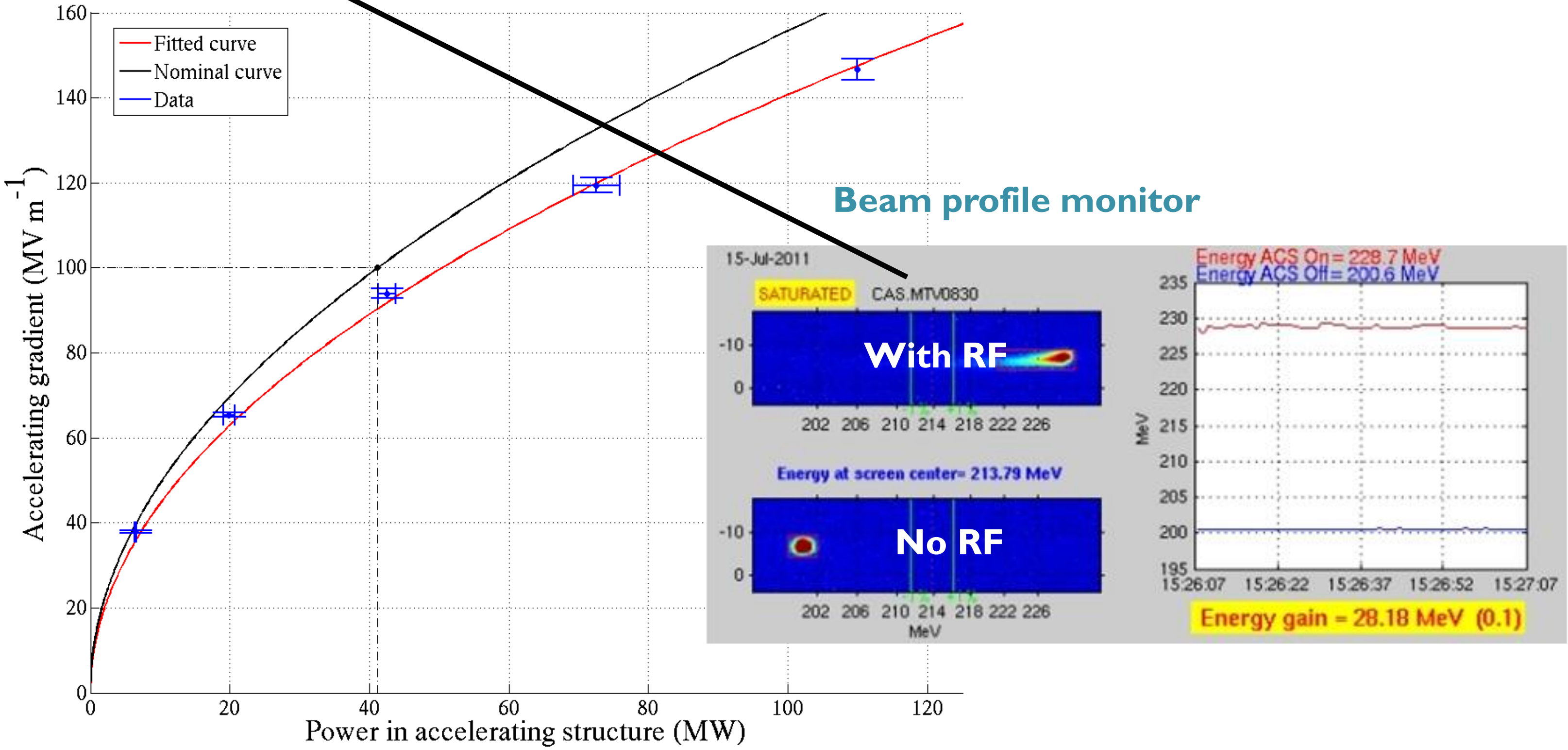
- Breakdowns in the recirculation loop are detected only from the reflected power (*Pref / Pfwd > ~15%*).
- Breakdowns in attenuator and the waveguide are detected from the missing energy (*Utran / (Ufwd * transmission factor) > 15%*)
- Breakdowns in the ACS are detected from the reflected power, the missing energy, the Faraday cup and the photomultiplier.

Acceleration



Accelerating structure

Beam profile monitor



15-Jul-2011

SATURATED CAS.MTV0830

With RF

Energy at screen center= 213.79 MeV

No RF

Energy ACS On = 228.7 MeV

Energy ACS Off = 200.6 MeV

Energy gain = 28.18 MeV (0.1)

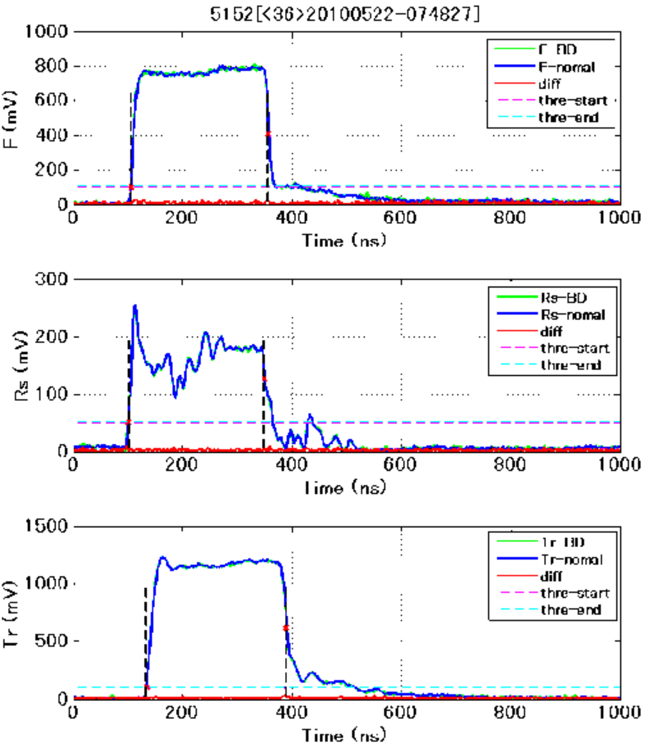
The acceleration of 145 MeV/m has been achieved.
(CLIC acc.g. is 100 MV/m)

51+52 Normal pulse #36

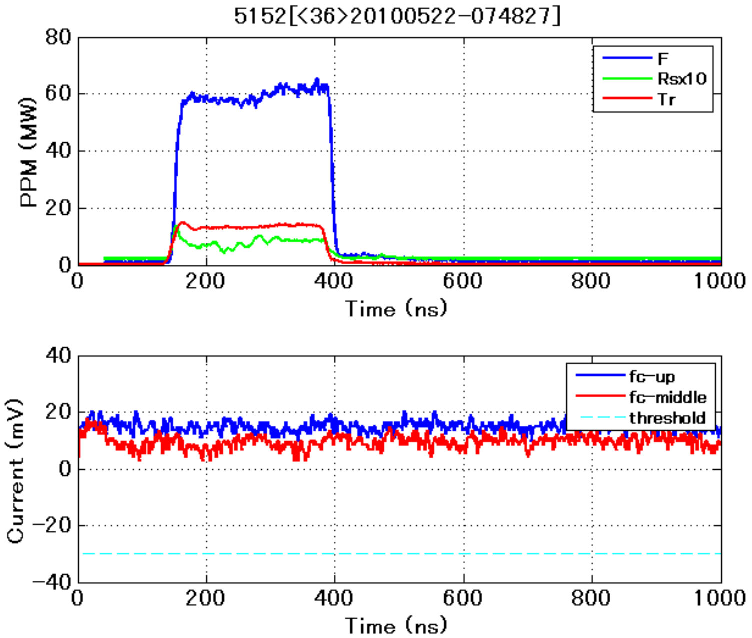
Incident (F)

Reflected (Rs)

Transmitted (Tr)



F **RsX10** **Tr**



FC-UP **FC-Mid** **Threshold**

Last pulse

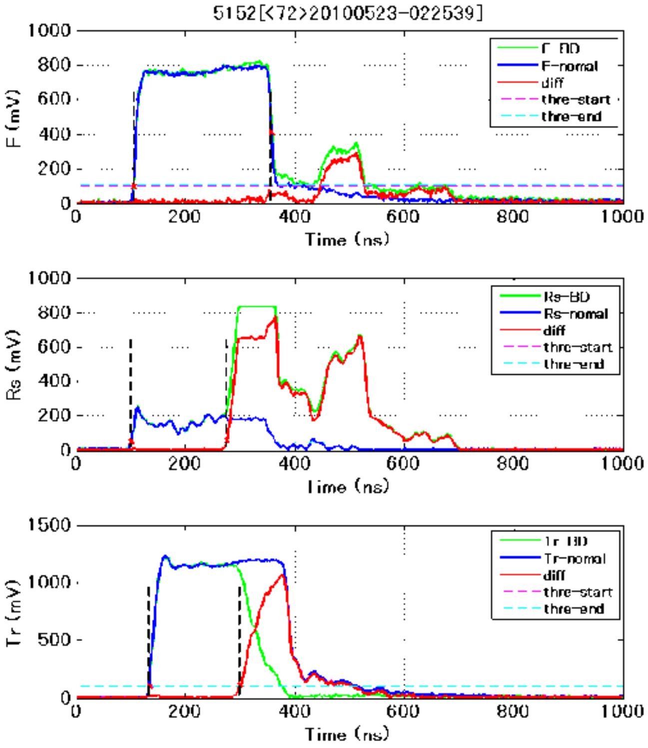
Last pulse but one

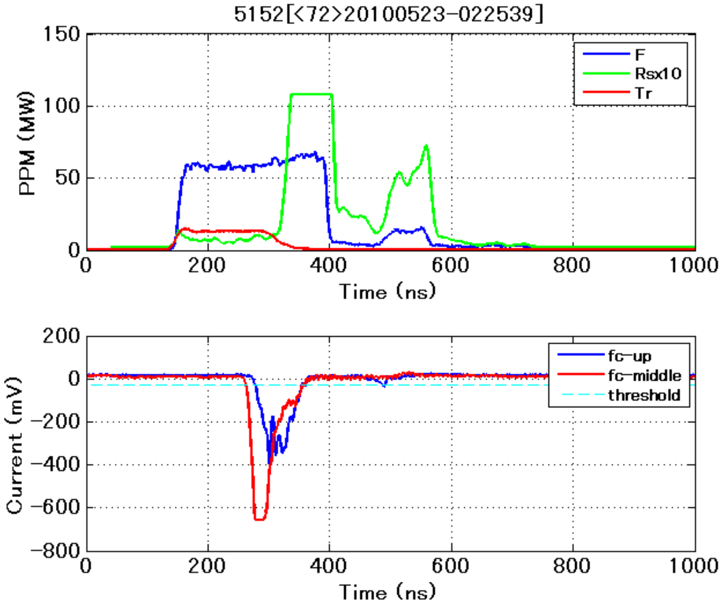
Difference between the two

Dashed lines = Analysis threshold

T. Higo, KEK
Test of TD18 structure

51+52 typical BD pulses
#72 Reflected RF back from klystron again

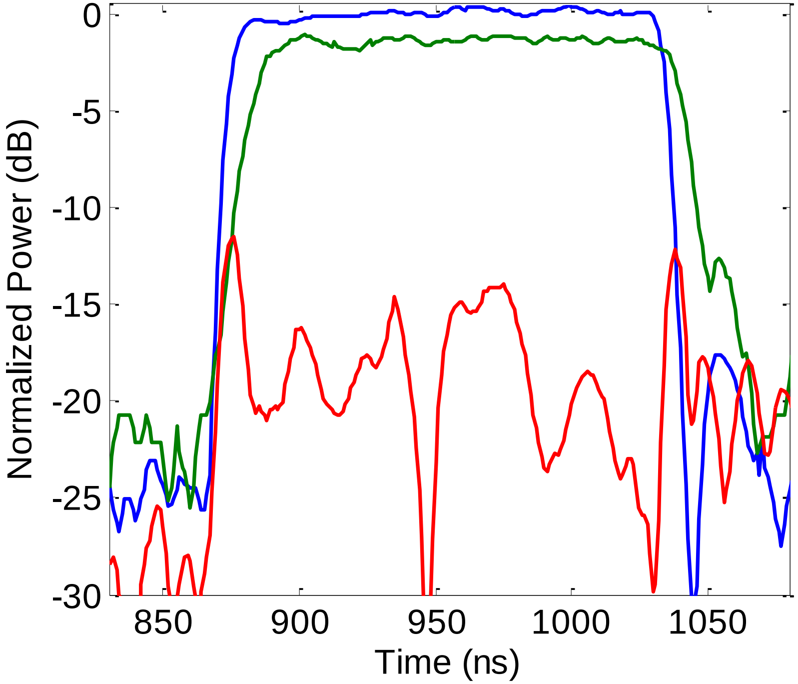


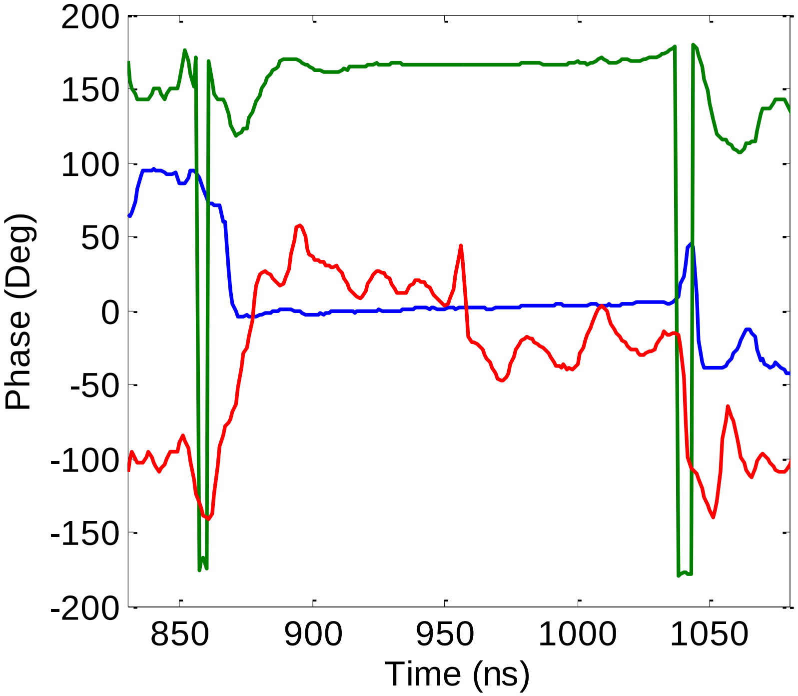


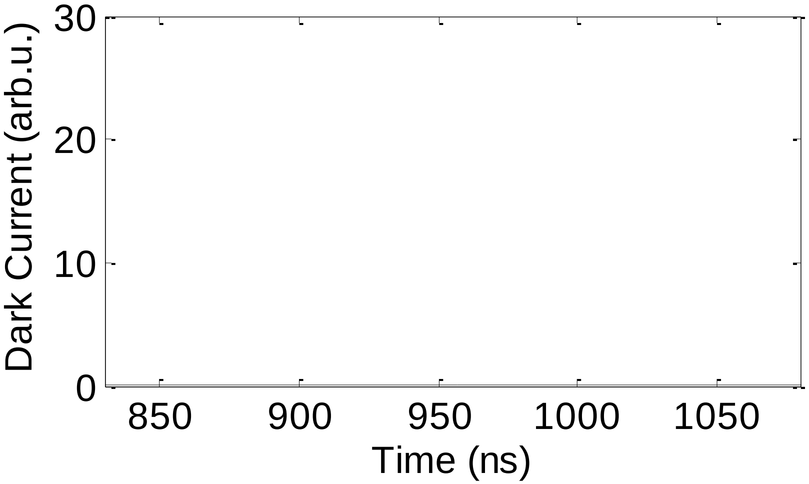
T. Higo, KEK
Test of TD18 structure

1: TW

Normal Waveforms of TD18 (s11 = -26.55 dB, s21 = -1.37 dB)





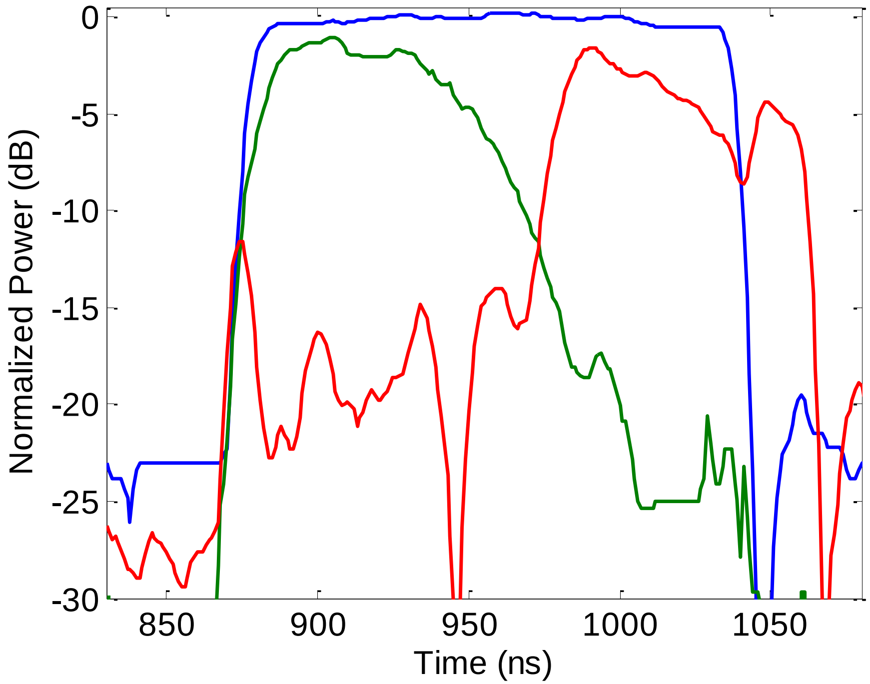


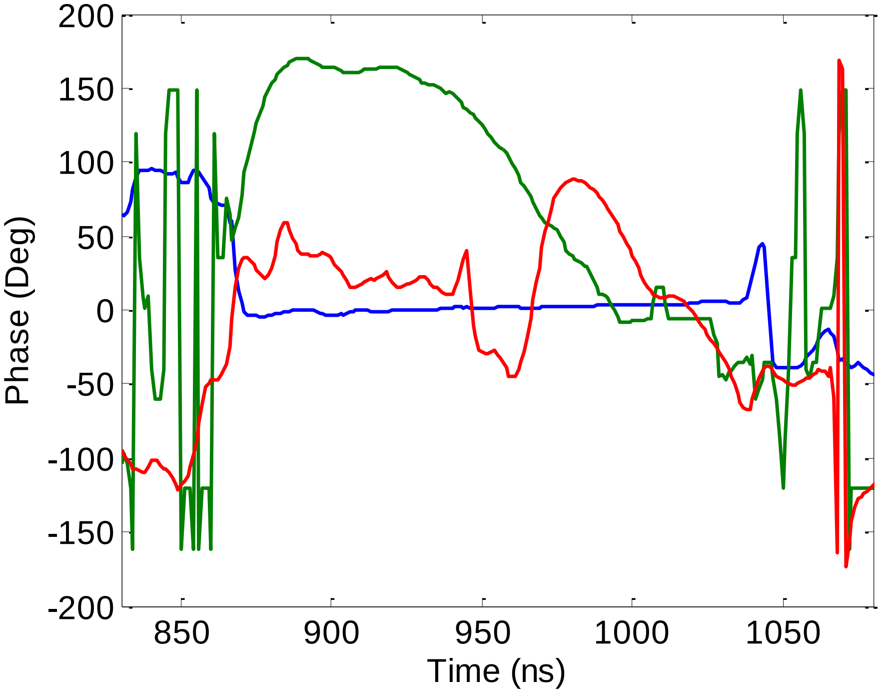
Blue – Input Forward, Green – Output Forward, Red – Input Reflected, Black – dark current.

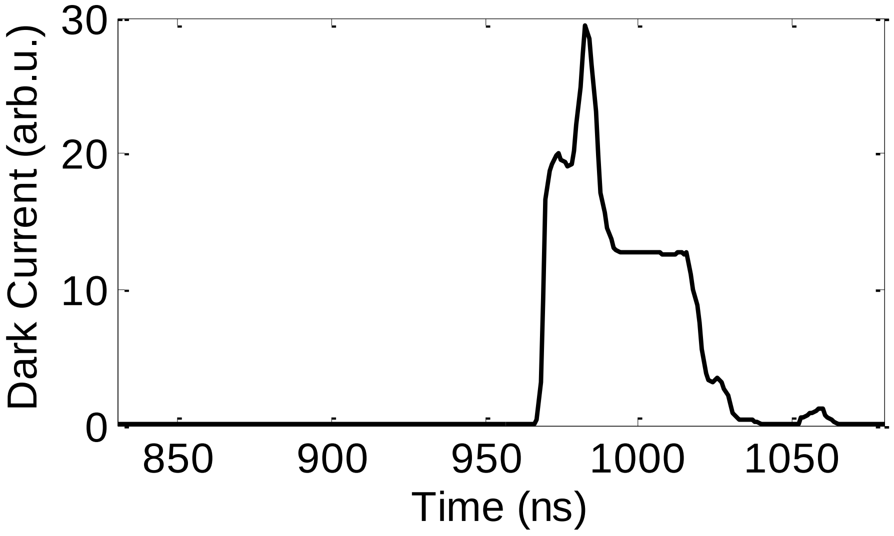
F. Wang, SLAC
Test of TD18 structure

1: TW

Breakdown Waveforms of TD18



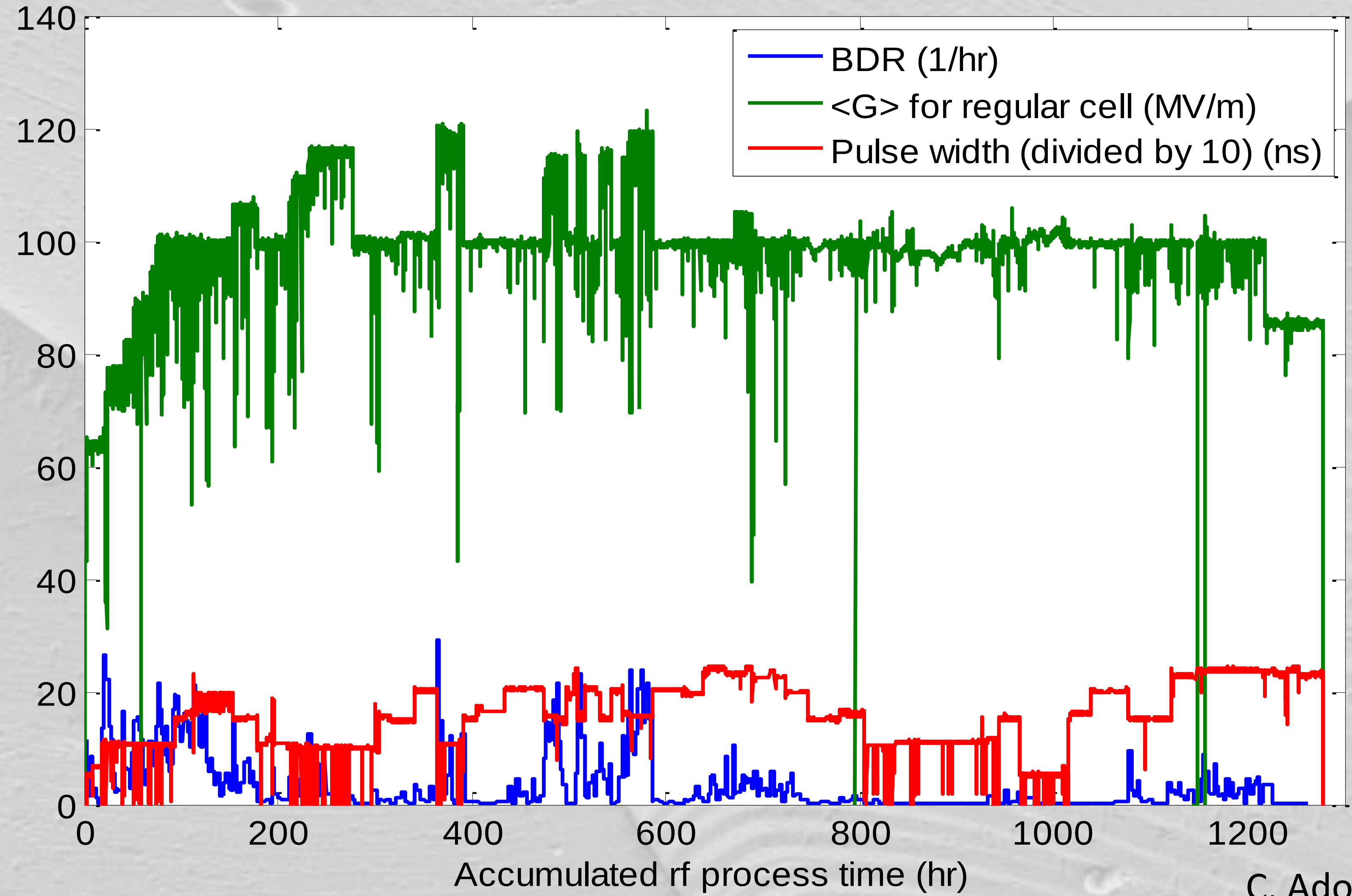




Blue – Input Forward, Green – Output Forward, Red – Input Reflected, Black – dark current.

F. Wang, SLAC
Test of TD18 structure

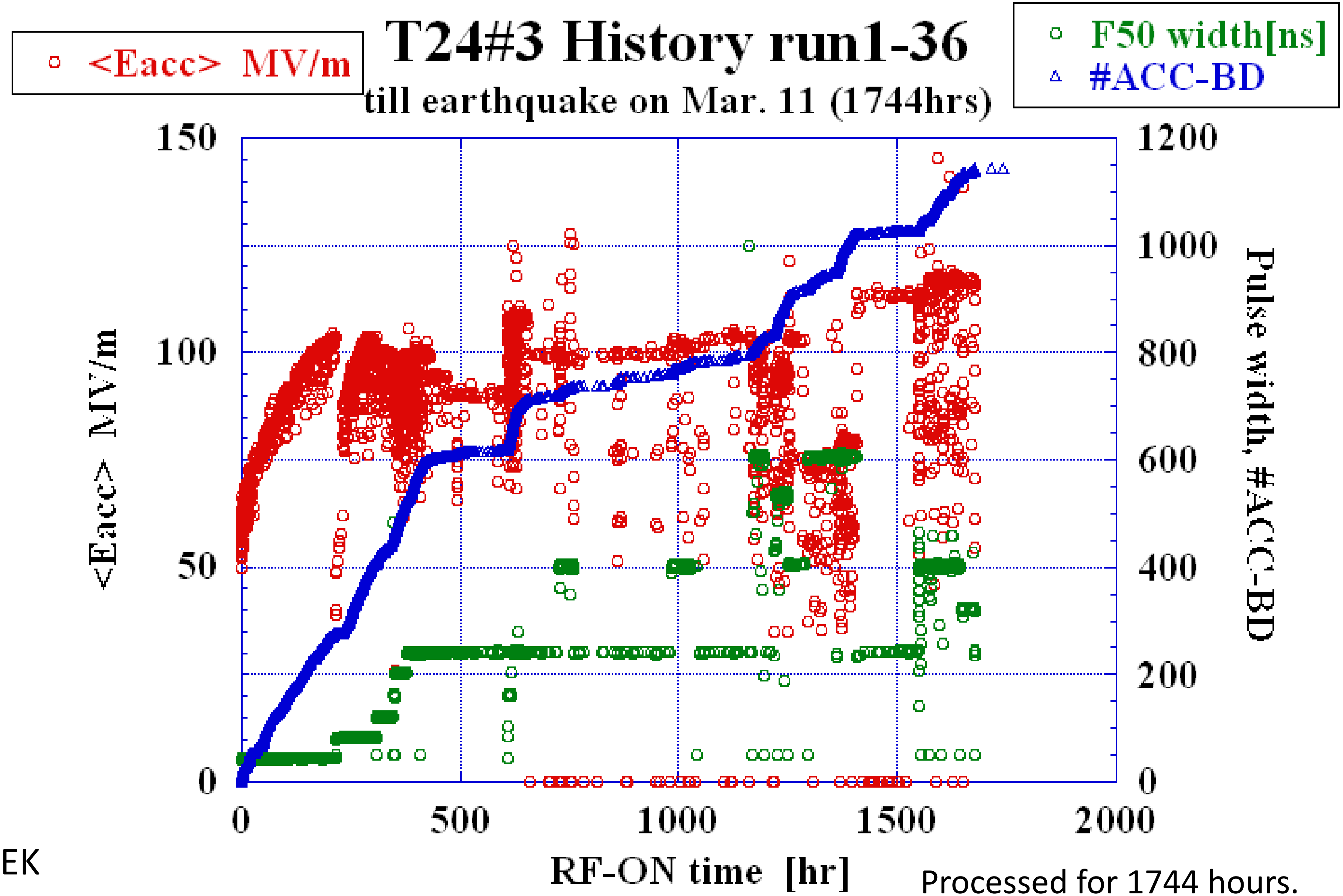
High Power Operation History



Final Run at 230 ns: 94 hrs at 100 MV/m w BDR = 7.6e-5
60 hrs at 85 MV/m w BDR = 2.4e-6

TD18

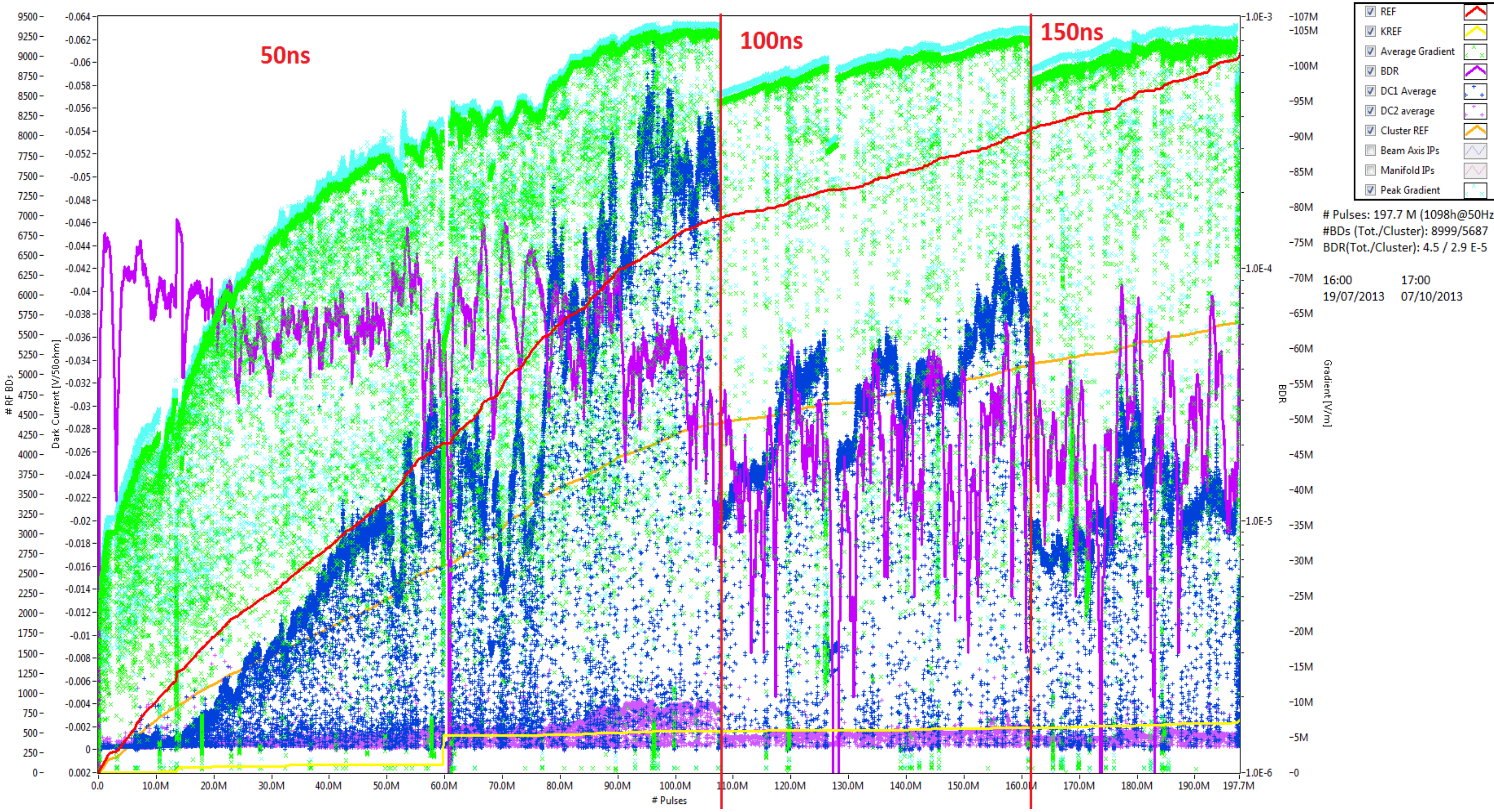
C. Adolphsen
F. Wang
SLAC



KEK

Processed for 1744 hours.

Results: TD26CC



Pulses: 197.7 M (1098h@50Hz

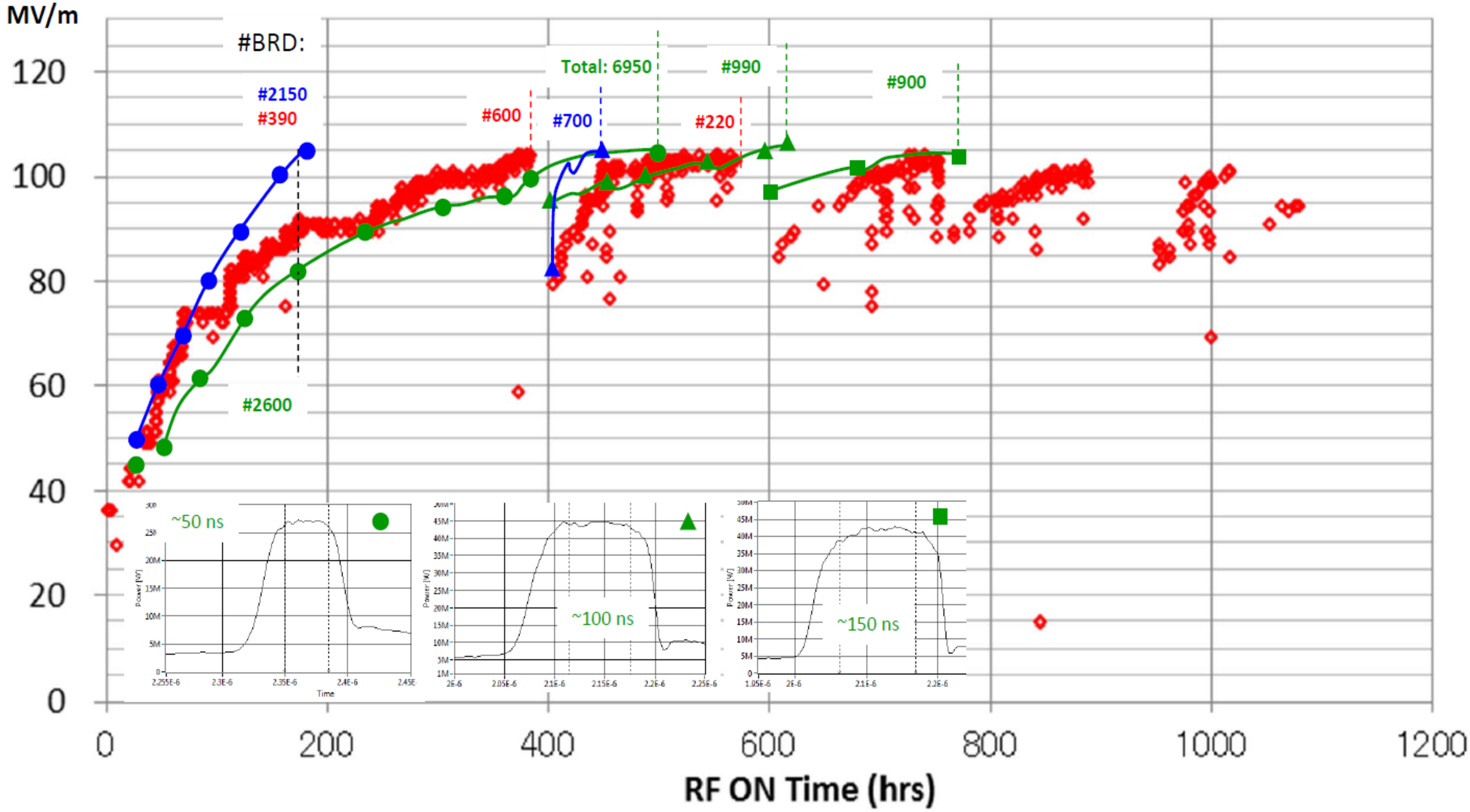
#BDs (Tot./Cluster): 8999/5687

BDR(Tot./Cluster): 4.5 / 2.9 E-5

16:00 19/07/2013

17:00 07/10/2013

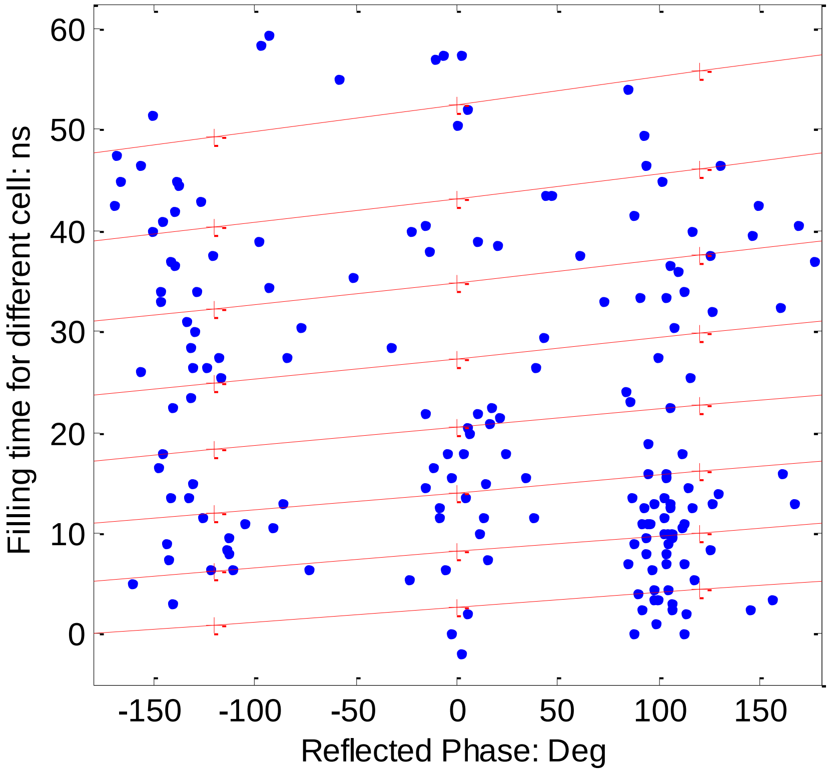
Comparison of the TD24R05(KEK); TD24R05(CERN) and TD26R05CC (CERN) processing histories.

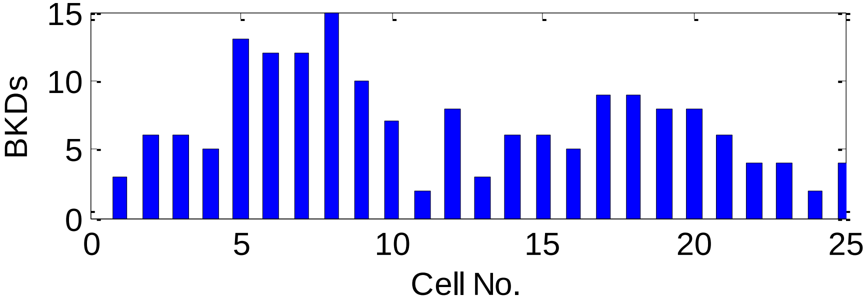


10.10.2013

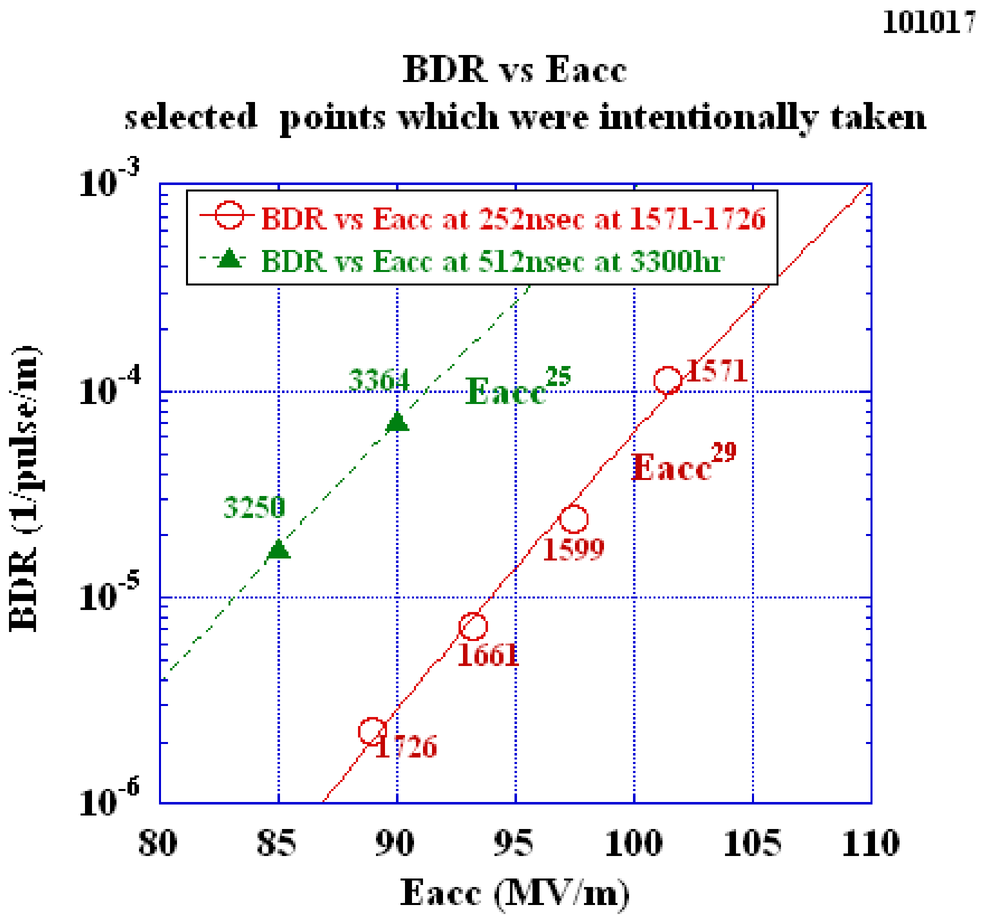
*50Hz vs. 60 Hz included

Breakdown Distribution for T24_SLAC_Disk1 of Last 50 Hours





Relevant data points of BDR vs Eacc

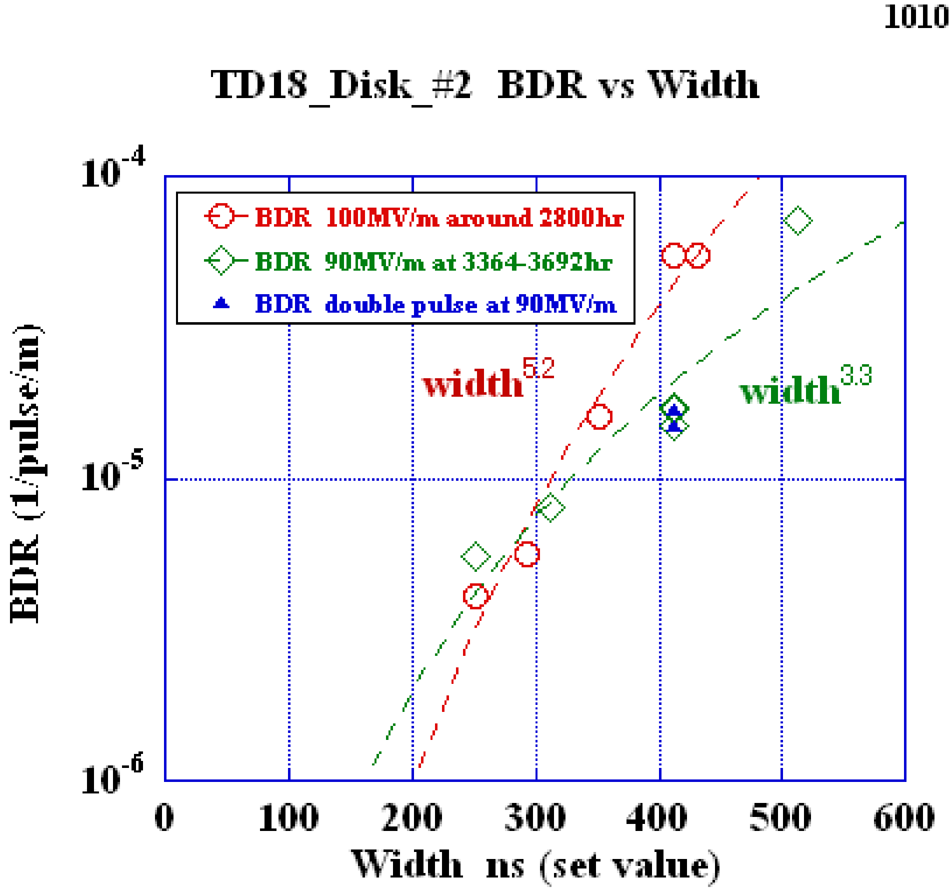


TD18

Steep rise as Eacc, 10 times per 10 MV/m, less steep than T18

TD18_#2 BDR versus width

at 100MV/m around 2800hr and at 90MV/m around 3500hr



TD18

Similar dependence at 90 and 100 if take usual single pulse?

Summary on gradient scaling

For a fixed pulse length

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

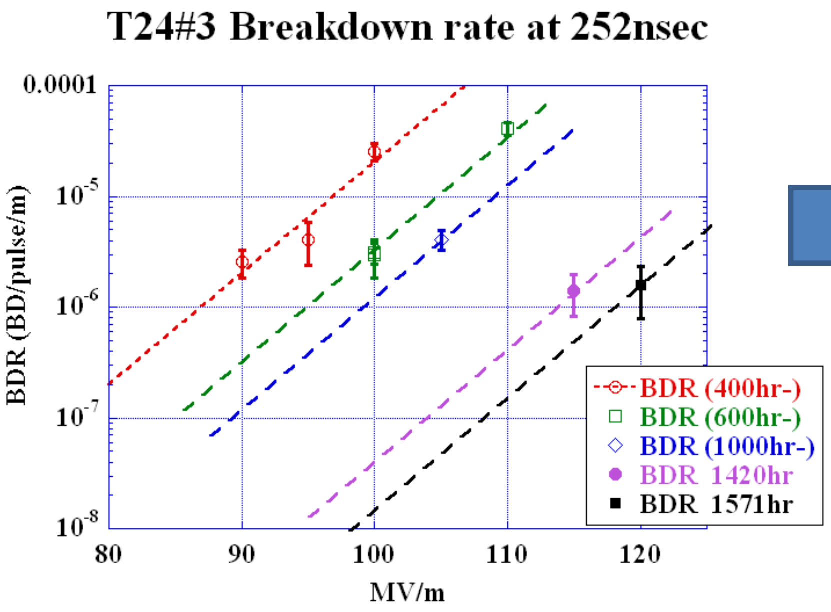
For a fixed BDR

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

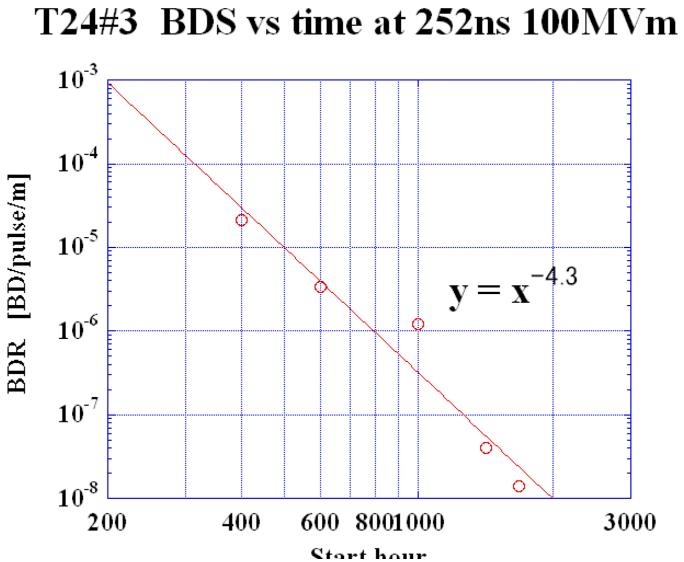
$$\frac{E_a^{30} \cdot t_p^5}{BDR} = const$$

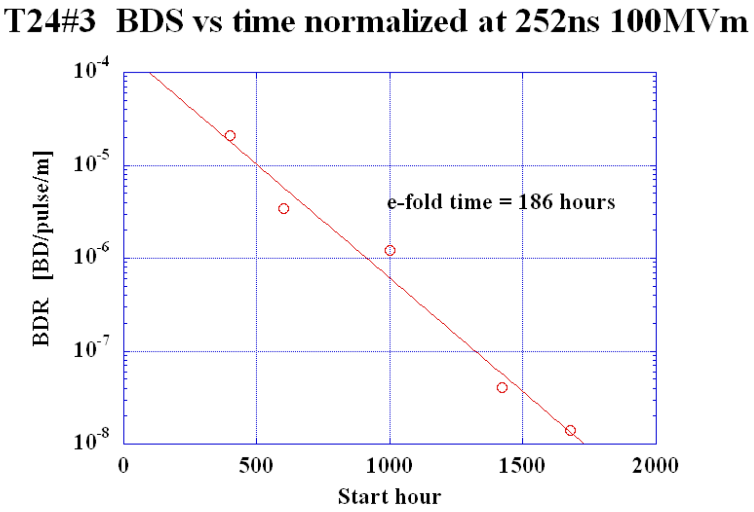
- In **a** Cu structure, ultimate gradient E_a can be scaled to certain BDR and pulse length using above power law. It has been used in the following analysis of the data.
- The aim of this analysis is to find a field quantity X which is geometry independent and can be scaled among **all** Cu structures.

T24#3
BDR evolution at 252ns normalized 100MV/m


T24#3 Breakdown rate at 252nsec

Assuming the same exponential slope as that at 400hr


T24#3 BDS vs time at 252ns 100MVm

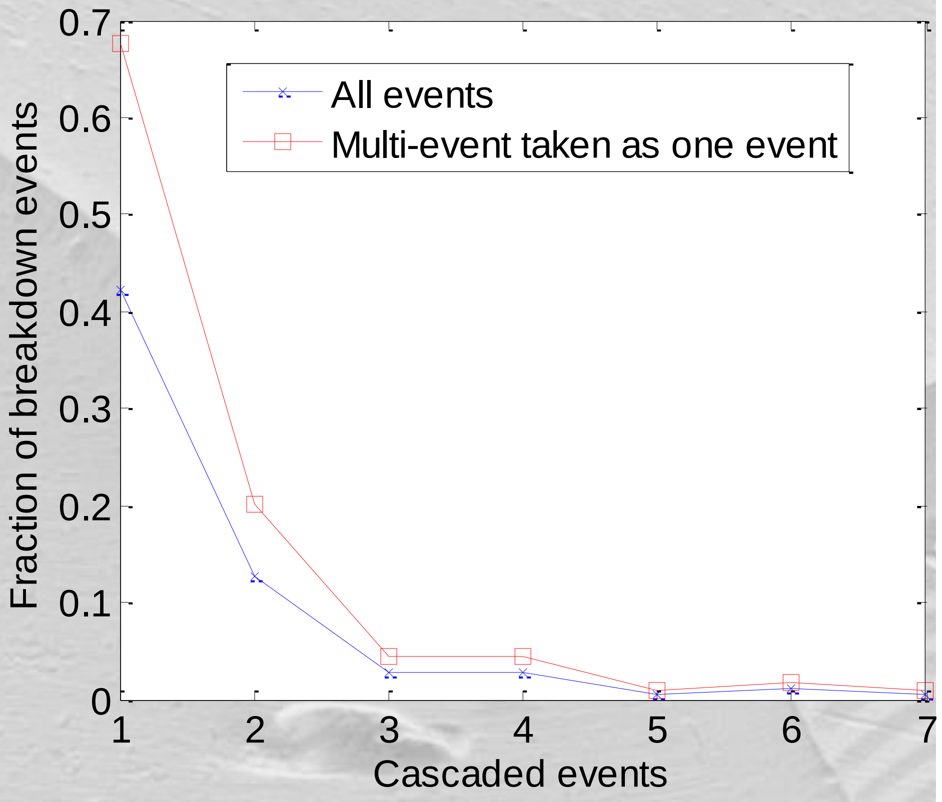

T24#3 BDS vs time normalized at 252ns 100MVm

We understand the BDR has been kept decreasing.

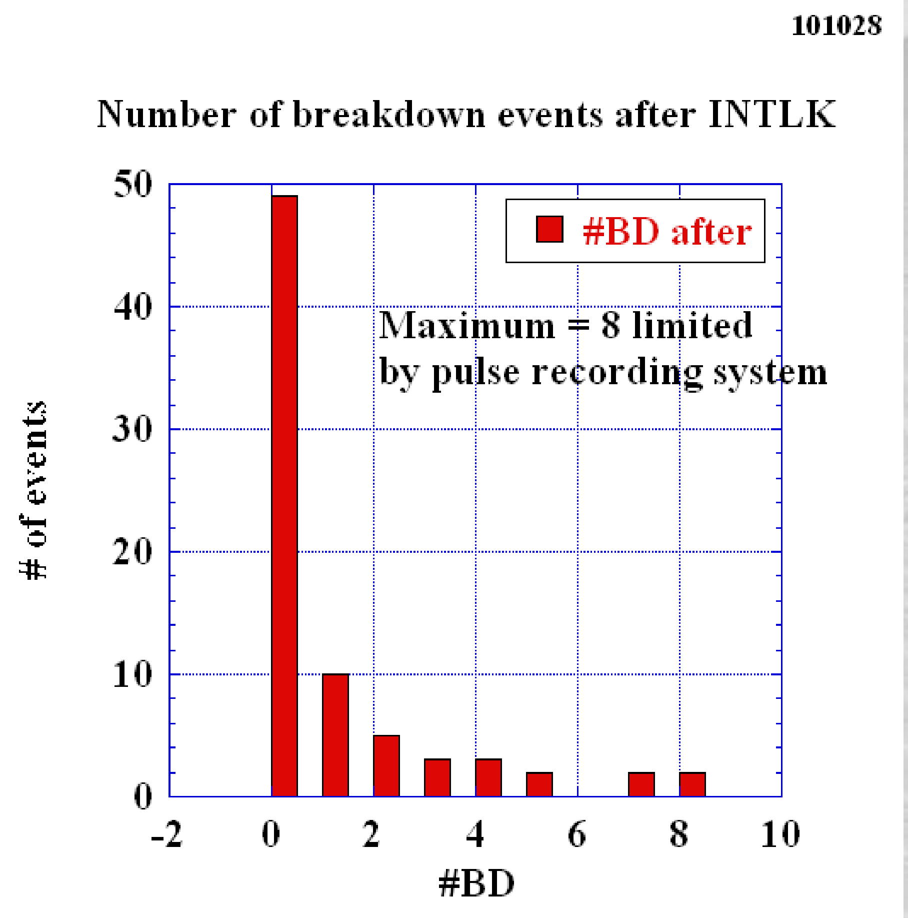
From T. Higo

Breakdown sequence statistics

Both sets of measurements were made on TD18s



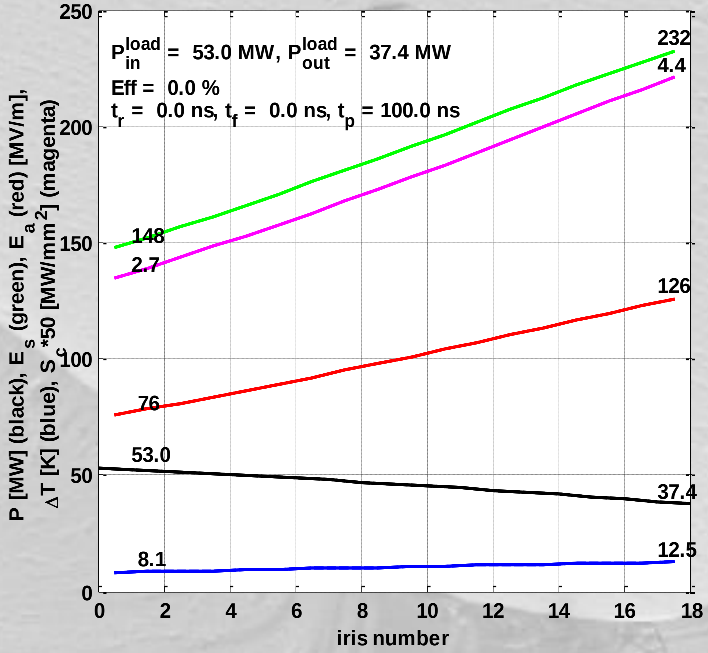
SLAC



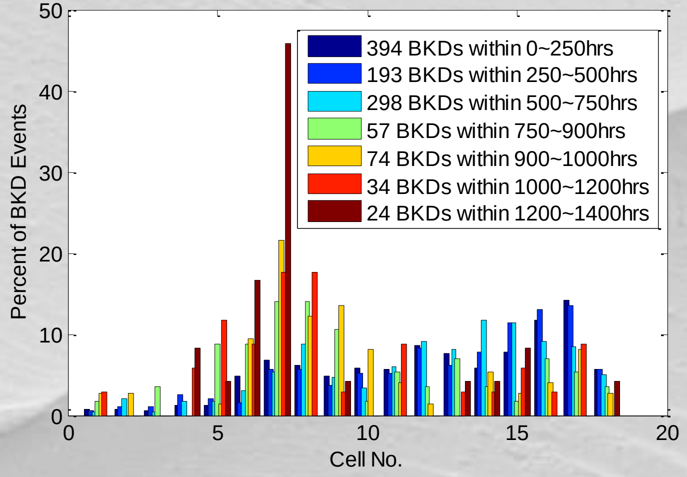
KEK

This kind of data is essential for determining rf hardware – on/off/ramp? – and establishing credible operational scenarios.

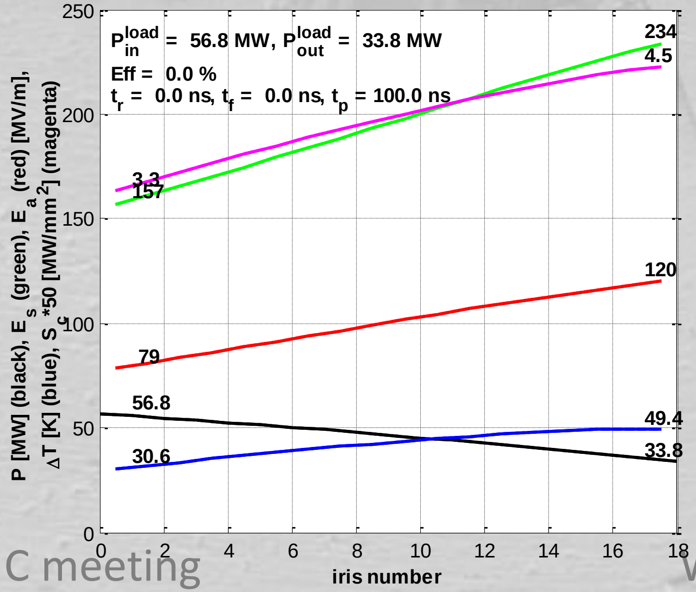
18 series breakdown rate distributions



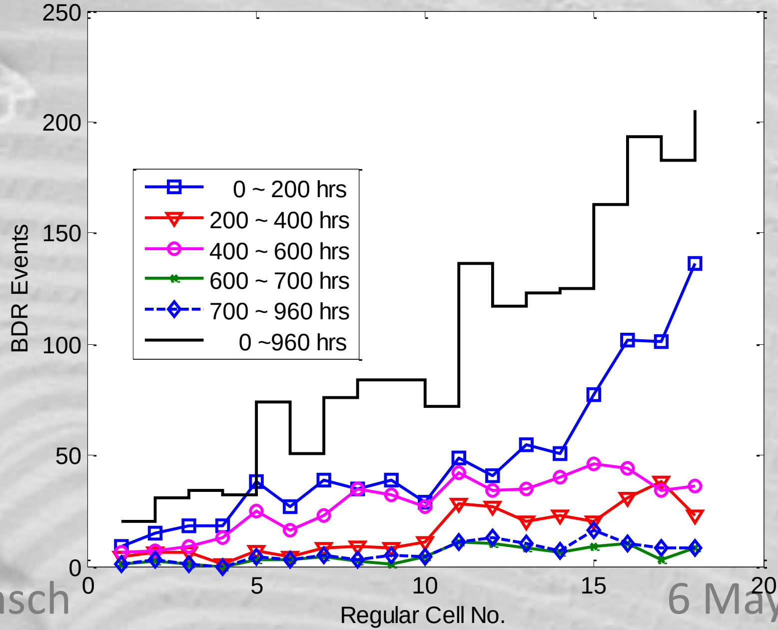
T18



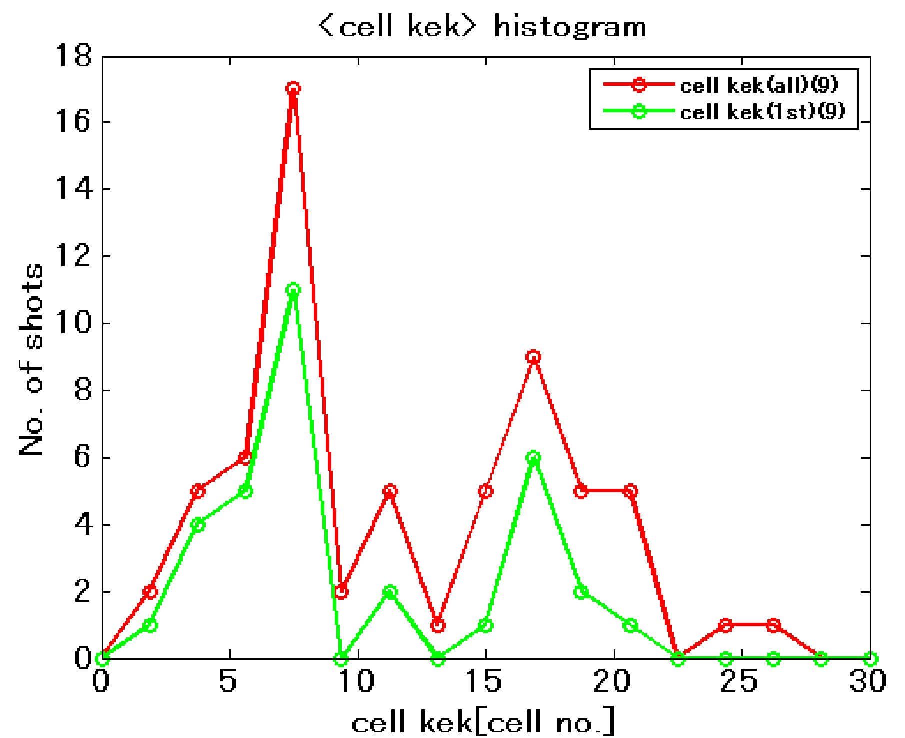
SLAC

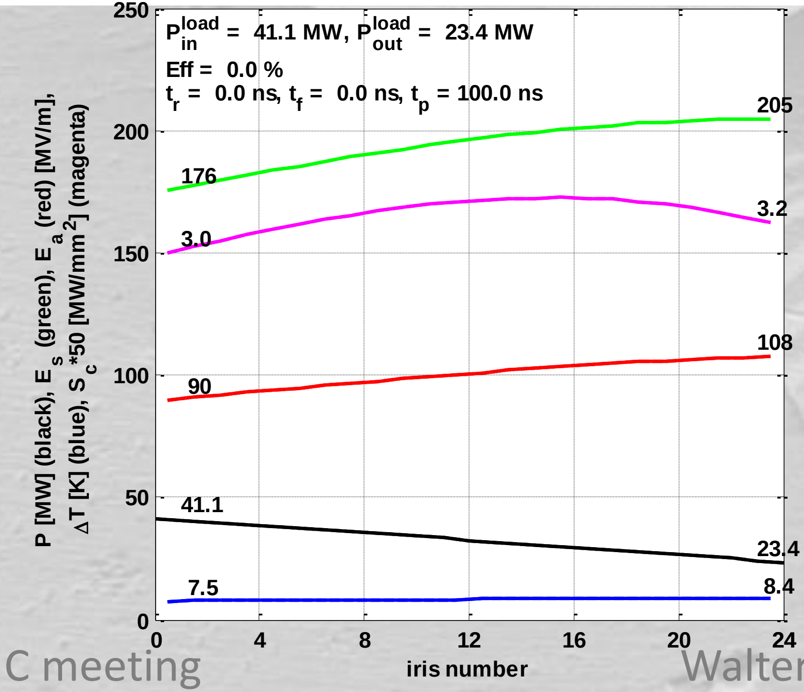


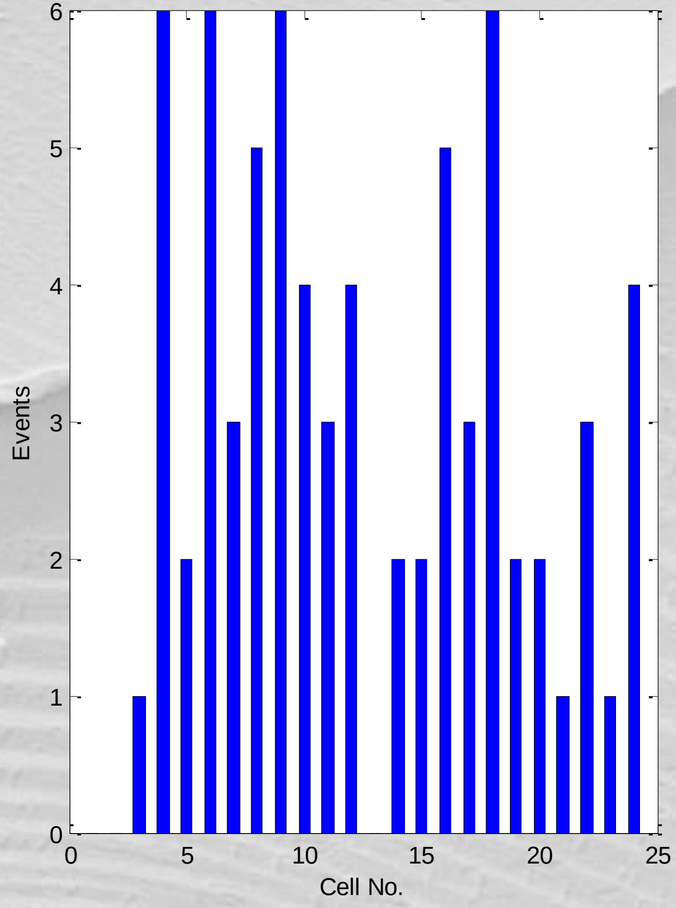
TD18



T24 breakdown location distributions

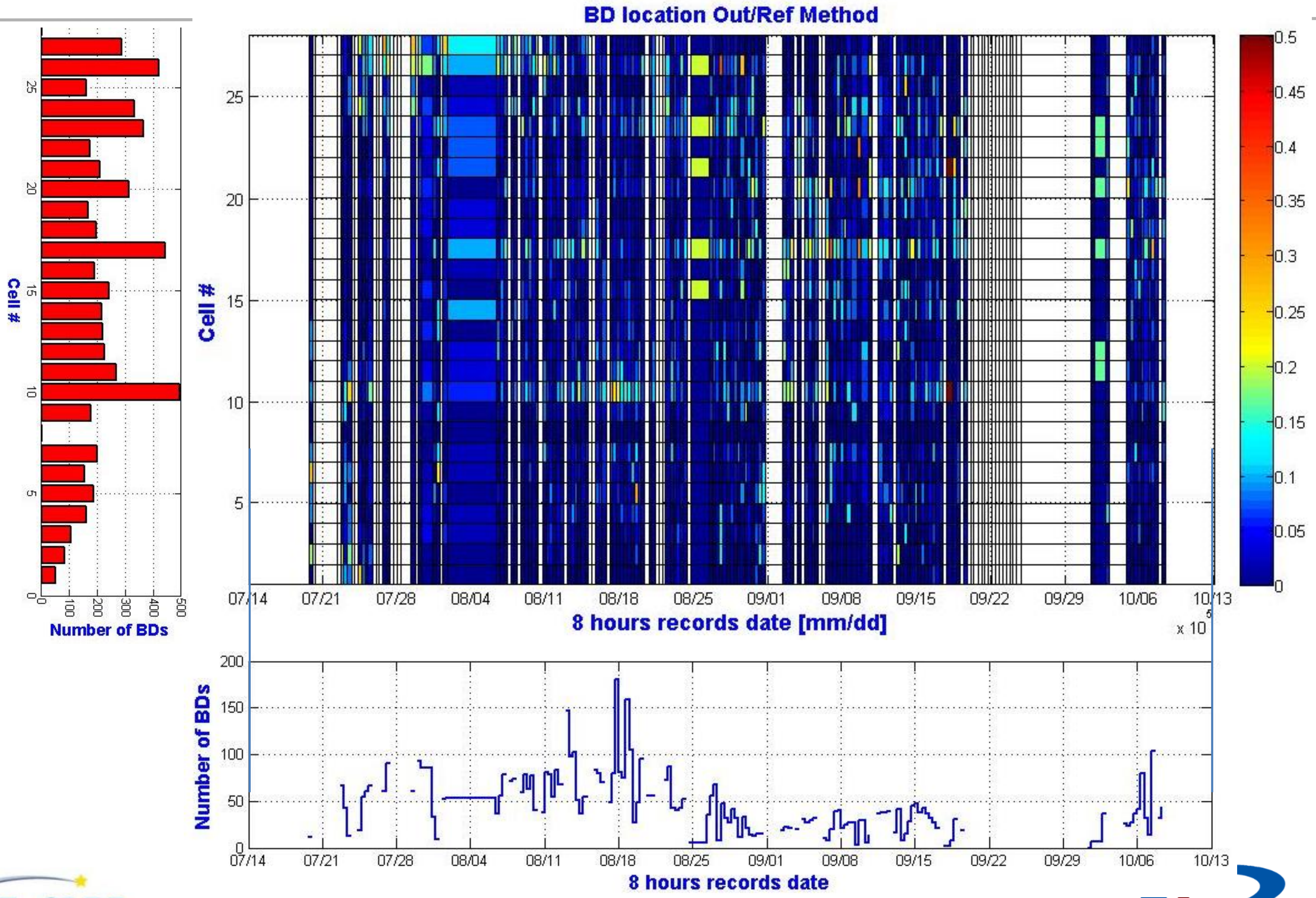




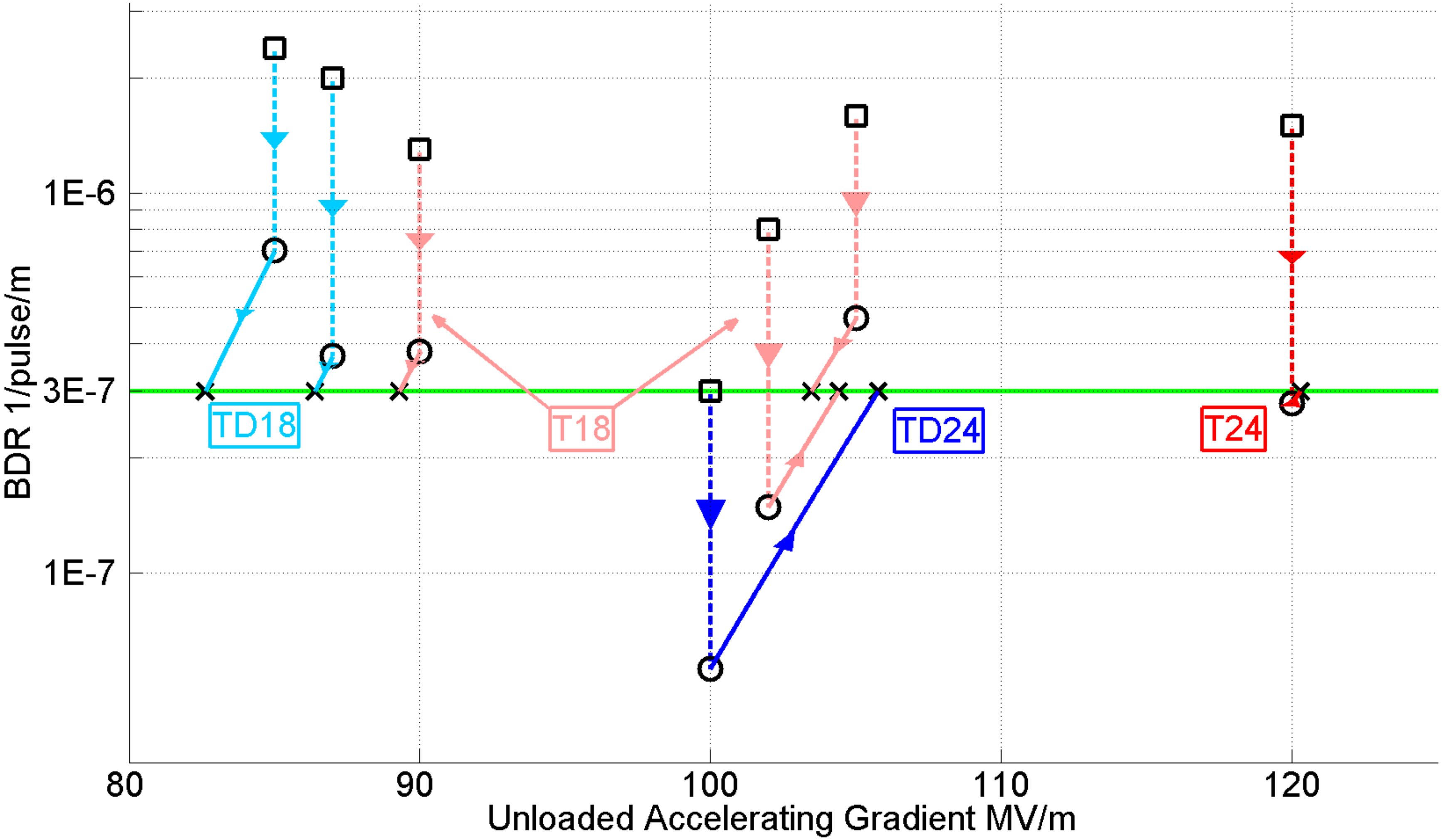


SLAC

Results: TD26CC BD Location



Accelerating gradient test status: 4-9-2012



Quantifying geometrical dependence of high-power performance

Importance of geometric dependence - motivation

As you have seen in other presentations, there is a strong interplay between the rf design of accelerating structures and the overall performance of the collider.

One of the strongest dependencies is emittance growth as function of the average iris aperture which acts through transverse wakefields.

The iris aperture also influences required peak power and efficiency through its effect on group velocity.

But crucially, the iris aperture has an extremely strong influence on achievable accelerating gradient.

Very generally, we expect that the gradient of an rf structure should be calculable from its geometry if material and preparation are specified.

The big questions

Where does such a geometrical dependency come from?

Can we quantify the dependence of achievable accelerating gradient on the geometry?

Trying to understand, derive and quantify geometrical dependence has been a significant effort because an essential element of the overall design and optimization of the collider.

The basic approach

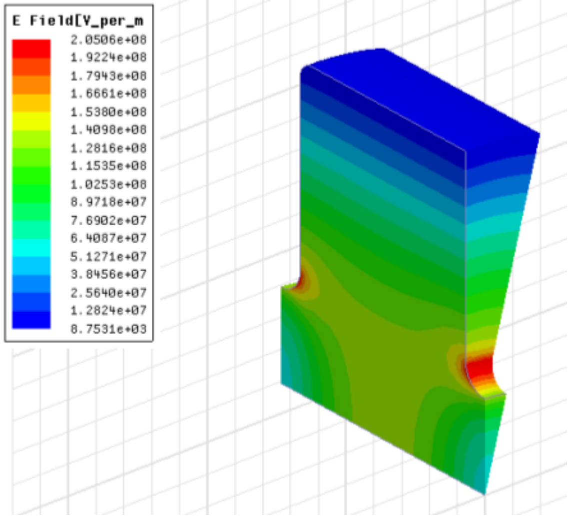
The basic element is to express our high-power limits as a function of the unperturbed fields inside our structures – like the electric field limit in dc spark.

So first we are going to make sure that we have a feel for how those fields vary as a function of geometry.

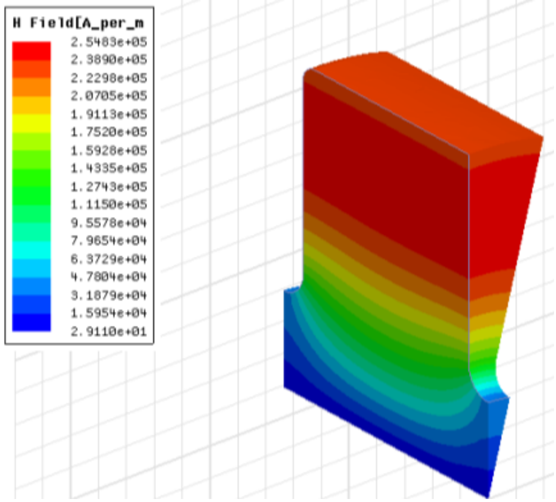
We use a specific example of iris variation for a fixed phase advance in a travelling wave structure.

Field distribution

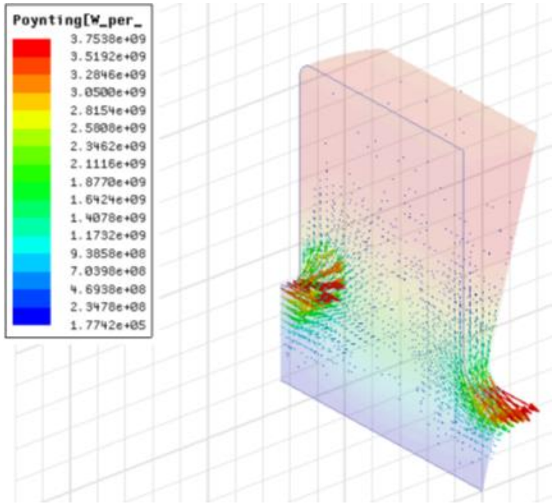
Electric field (V/m)



Magnetic field (A/m)



Poynting vector (W/m^2)



- Simulation in HFSS12
- Field values are normalized to accelerating gradient, E_{acc}=100MV/m
- Frequency: 11.424GHz
- Phase advance per cell: 120 degree
- *Iris radius*: 3mm
- v_g /c= 1.35%

Overview of how different types of structures actually behave – results of high-power tests of accelerating structures to PETS

Achieving high gradients has been a high profile concern for CLIC and NLC/JLC since roughly 2000. Here are the target specifications we have had:

	frequency [GHz]	Average loaded gradient [MV/m]	Input (output for PETS) power [MW]	Full pulse length [ns]
NLC/JLC	11.424	50	55	400
CLIC pre-2007				
Accelerating	29.928	150	150	70
PETS	29.985	-5.7	642	70
CLIC post 2007				
Accelerating	11.994	100	64	240
PETS	11.994	-6.3	136	240

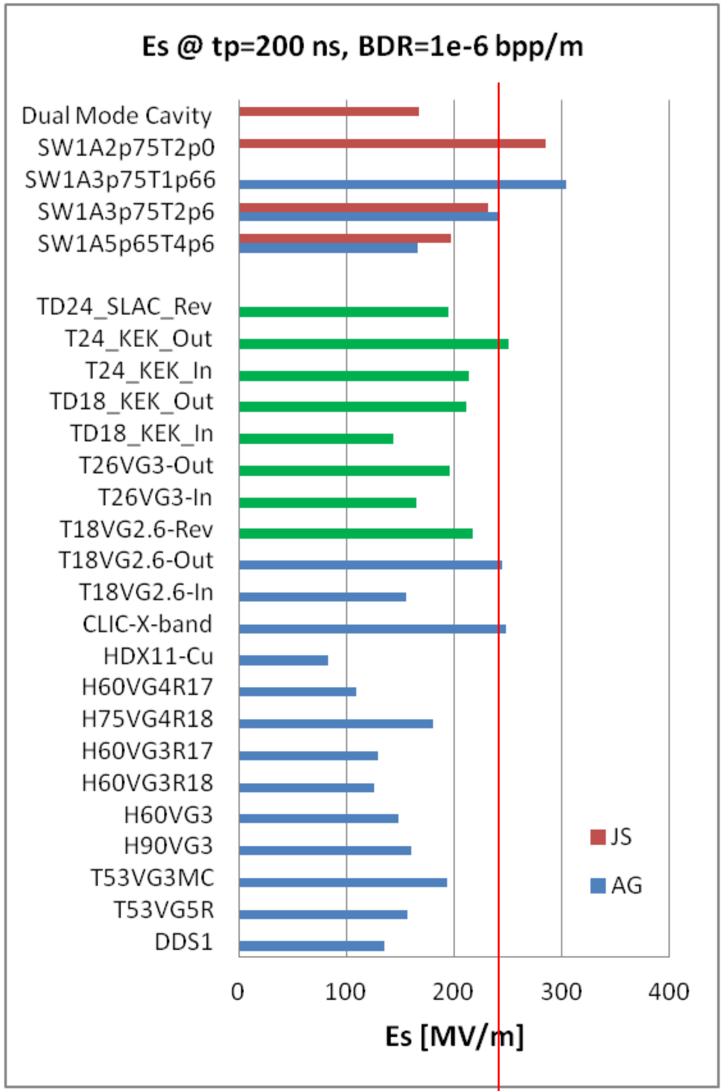
Trying to achieve these specifications has resulted over the years in the test of many structures of diverse rf design.

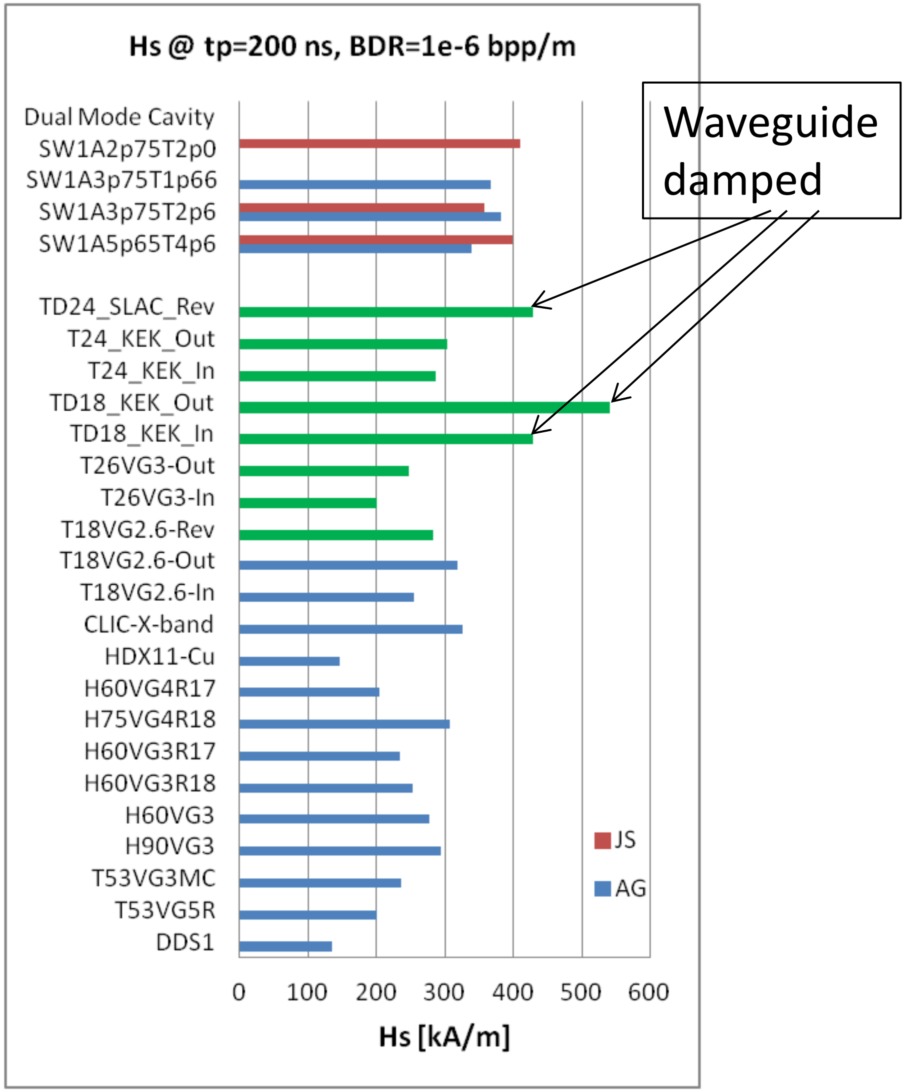
The preparation and testing conditions of the test structures which were built were not always the same – these processes also evolved over the period the structures were being developed.

But the wide variety of structure geometries were tested under reasonably similar conditions.

So we have used this unique set of data to try to understand and then quantify the geometrical dependency of gradient.

Maximum surface electric and magnetic fields





Waveguide damped

Es = 250 MV/m or higher has been achieved in several cases: very low or zero group velocity

What do can make out of this mess?

My personal conclusion from looking at data like this, was that a something else is important, beyond *E* and *B* surface fields.

This something felt like it had to be related to the power flowing through the structure. In particular some kind of power density, since larger apertures generally support larger powers.

This is reasonable when you think about what we know about breakdown.

Field emission is pico or nano amps. Breakdowns in rf and dc produce 10’s, 100’s even kA of current.

A lot of power is needed to accelerate so much current. The breakdown must need to be “fed” with the necessary power so power density is crucial.

This has resulted in the development of two power-density based design criteria:

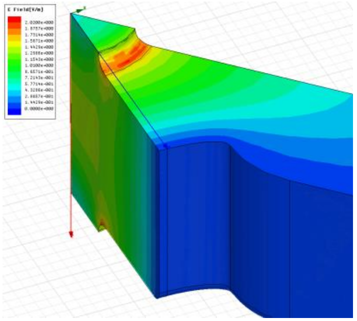
$$\frac{P}{\lambda C} = \text{const}$$

global power flow

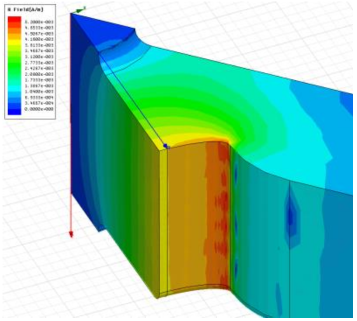
$$S_c = \mathrm{Re}(\mathbf{S}) + \frac{1}{6}\mathrm{Im}(\mathbf{S})$$

local complex power flow

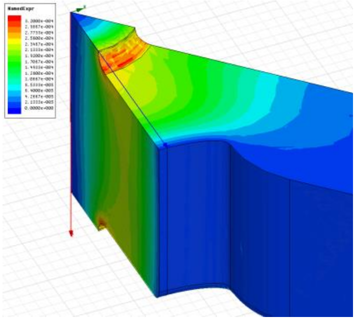
E_s/E_a



H_s/E_a



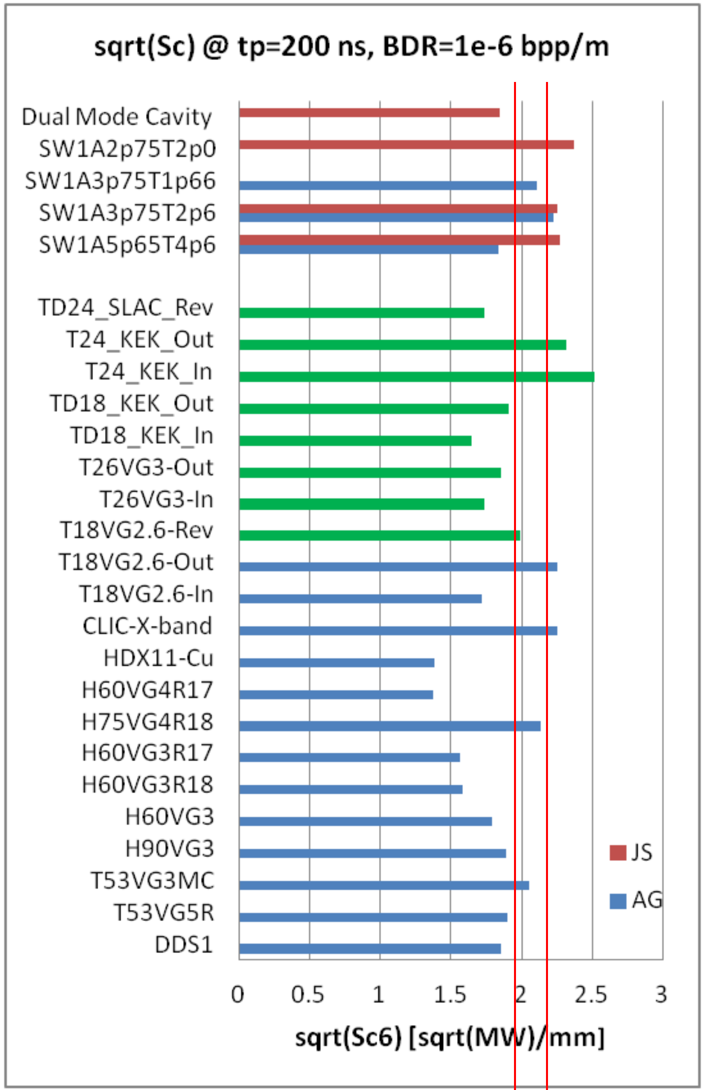
S_c/E_a^2

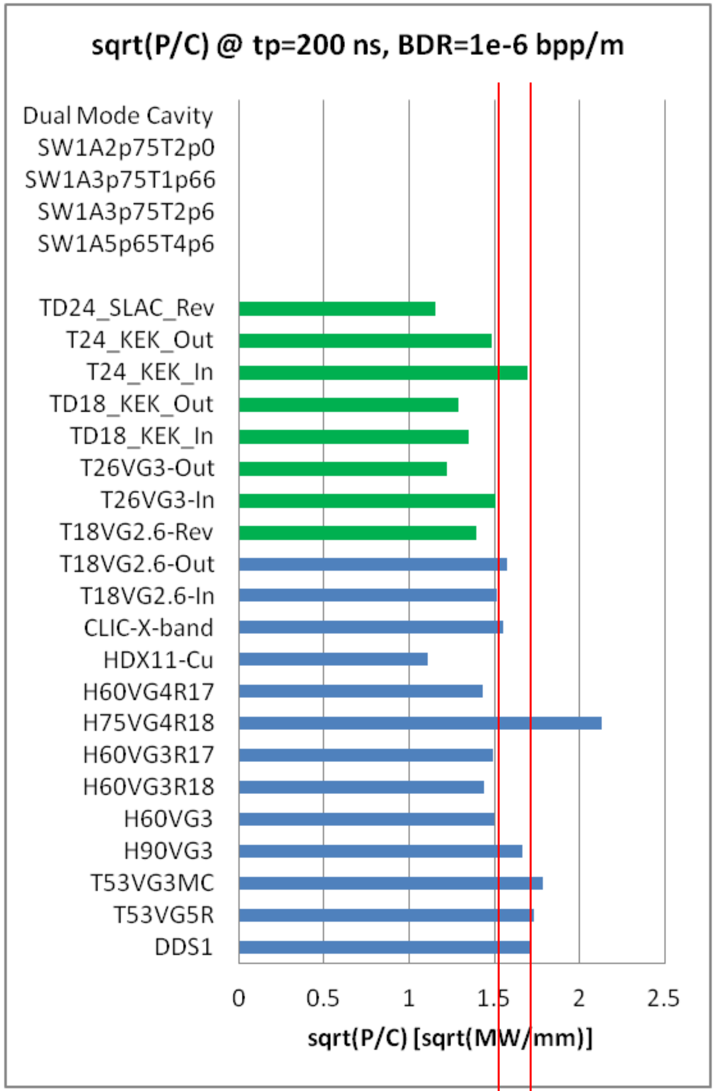


New local field quantity describing the high gradient limit of accelerating structures.
A. Grudiev, S. Calatroni, W. Wuensch (CERN).
2009. 9 pp.
Published in Phys.Rev.ST Accel.Beams 12 (2009) 102001

There is no proof (yet) but rather the general set of physical arguments plus reasonably good consistency with measurements.

Power flow related quantities: Sc and P/C



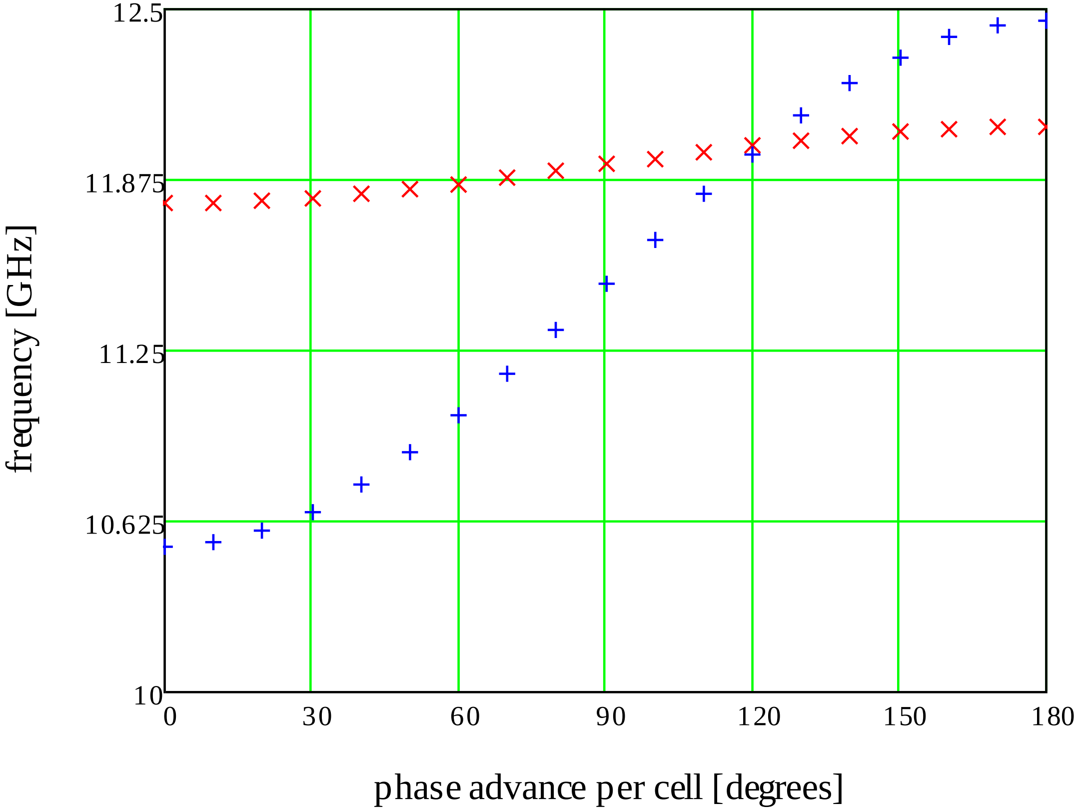


Sc = 4 - 5 MW/mm^2

P/C = 2.3 – 2.9 MW/mm

Another aspect of geometrical dependence – bandwidth.

Lower group velocity structures support larger surface fields. Lower group velocity is lower bandwidth – think of the dispersion curves – which could make it harder to feed the breakdown transient, when currents shoot from nano to kA.

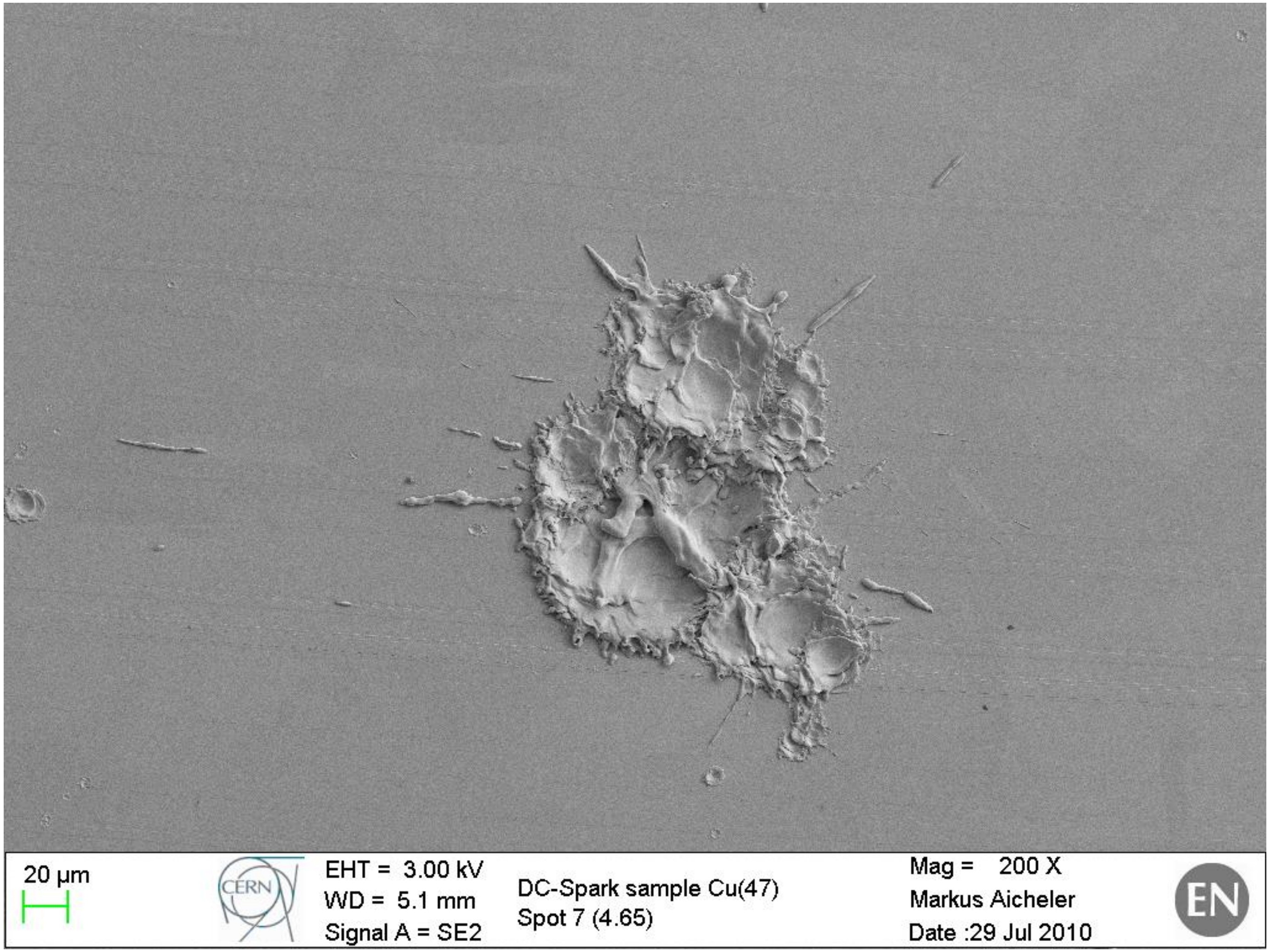


Summary of turn on times

Test	Frequency	Measurement	Result
Simulation dc spark			5-10 ns
New DC System	DC	Voltage Fall Time	12-13ns
Swiss FEL (C-Band)	5.7GHz	Transmitted Power Fall Time	110 - 140ns
KEK T24 (X-Band)	12GHz	Transmitted Power Fall Time	20-40ns
CTF/TBTS TD24 (X-Band)	12GHz	Transmitted Power Fall Time	20-40ns
CTF SICA (S-Band)	3GHz	Transmitted Power	60-140ns

The turn on time could be related to the bandwidth of the structures or possibly the intrinsic size.

Breakdown!



From pA to kA and from Angstroms to 100s of μm to mms.

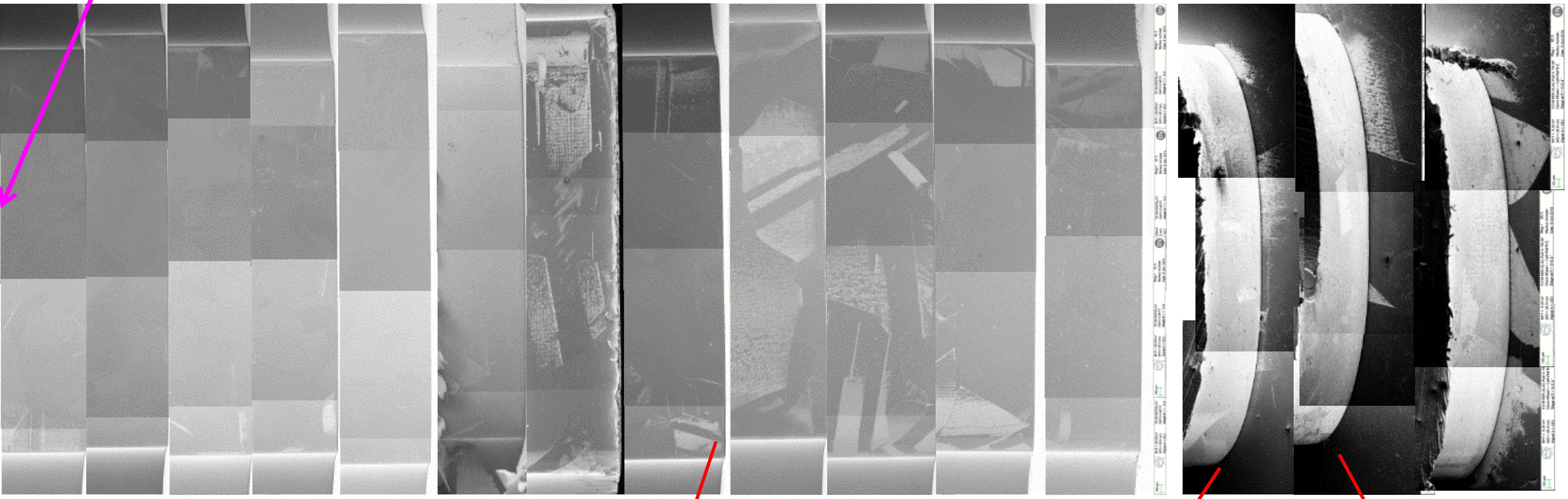
TD24 Pulsed surface heating limit

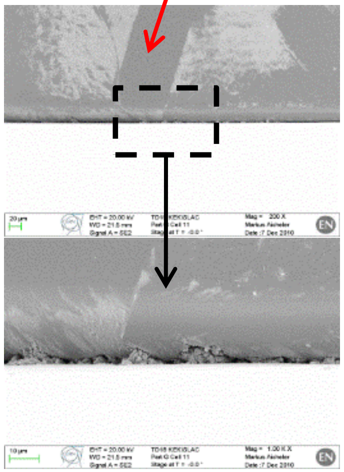
Cell # (cell #1 is a input matching cell):

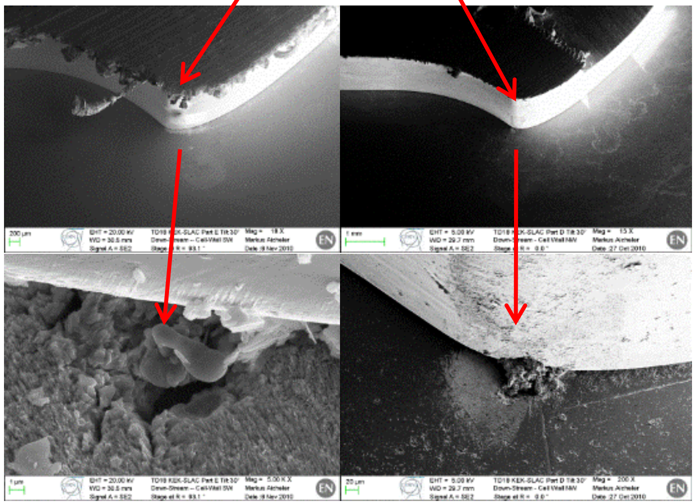
?16?

Last regular cell: 19

4 5 6 7 8 9 10 11 12 13 14 15 17 18







It seems that cell #10 (regular cell #9 ~ **middle cell**) exhibits the level of damage which could be considered as **a limit.**

A. Grudiev

Images courtesy of M. Aicheler: http://indico.cern.ch/getFile.py/access?contribId=0&resId=1&materialId=slides&confId=106251

Hardness Test Value

Pulsed Heating Test Samples

Copper (SLAC)

SPDT Copper (KEK)

HIP2 Copper (KEK)

HIP1 Copper (KEK)

CuZr Annealed (CERN)

CuCr Annealed (SLAC)

Single Crystal Cu (KEK)

E-Deposited Cu (KEK)

Silver Plated Cu (KEK)

CuZr Cold Worked (CERN)

Copper Silver (SLAC)

Copper Silver (KEK)

CuCr Non-Annealed (SLAC)

Glidcop (CERN)

Experimental study of rf pulsed heating

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(Received 9 September 2010; published 7 April 2011)