4th International Workshop on Mechanisms of Vacuum Arcs

Studies of breakdowns at high-gradients in TBTS/CTF3

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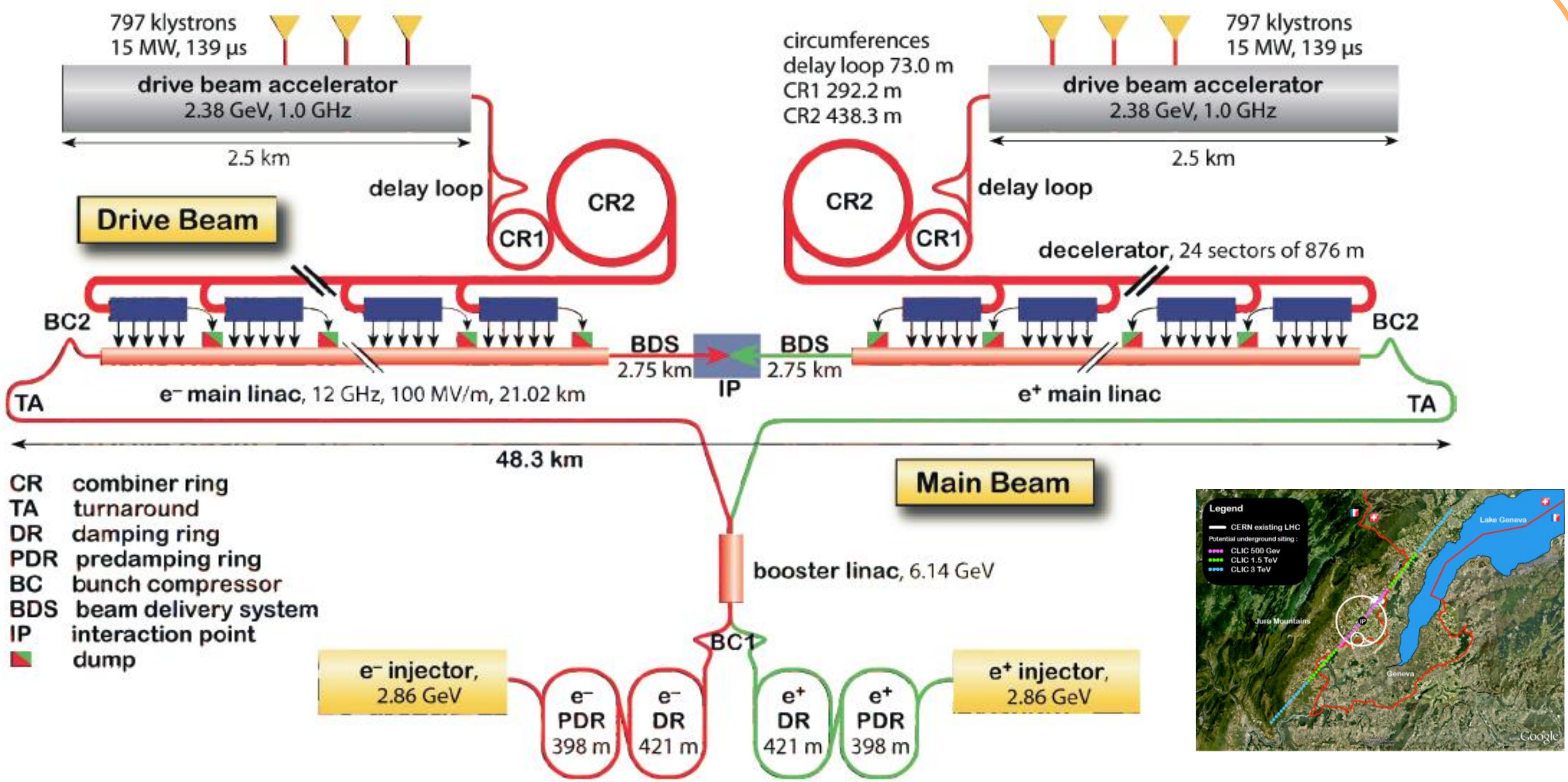
Breakdowns reduce luminosity

CLIC Compact Linear Collider

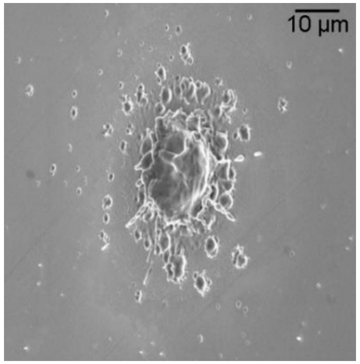


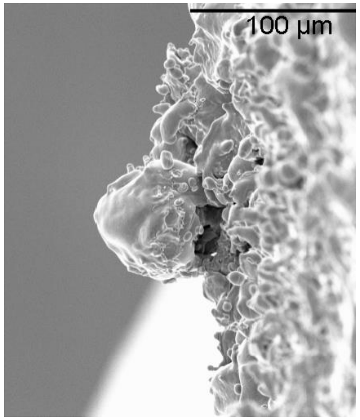
- Breakdowns (only 10 μm) will stop collisions in CLIC (48 km): scale $2{:}10^{10} \approx$ an ant stops the Earth;
- In CLIC there will be a breakdown every 2 sec, which is equivalent to the breakdown rate of 3×10^{-7} bd/pulse/m;
- CLIC should keep the maximum luminosity of 6×10^{34} $cm^{-2}s^{-1}$ for 20 years (the total number of BD is $\sim2\times10^{8}$).

Objectives

- Breakdown rate at the nominal gradient of 100 MV/m;
- Evolution of the breakdown rate: conditioning and degradations;
- Beam-arc interactions;
- Evidences of any pre-cursor;
- Recovery after breakdowns;
- Breakdown locations and dependences;
- Breakdown dynamics.

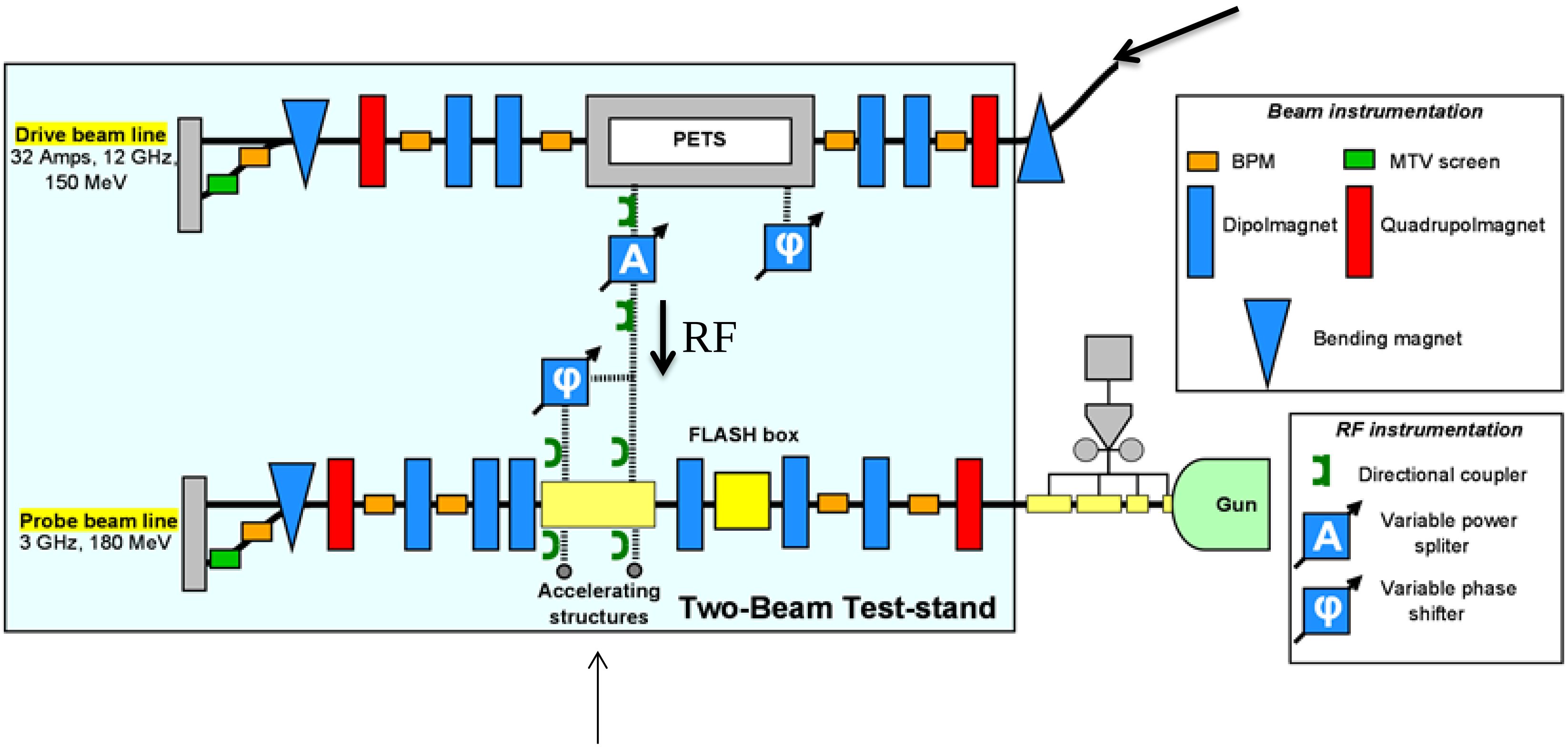
SEM pictures of the surface after electrical discharges





TBTS setup in CTF3

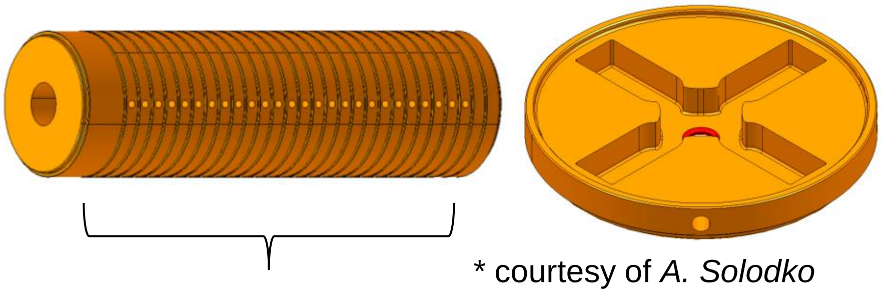
Electron beam from CTF3



X-band accelerating structures

Accelerating structure (TD24)

Structure | Regular cell



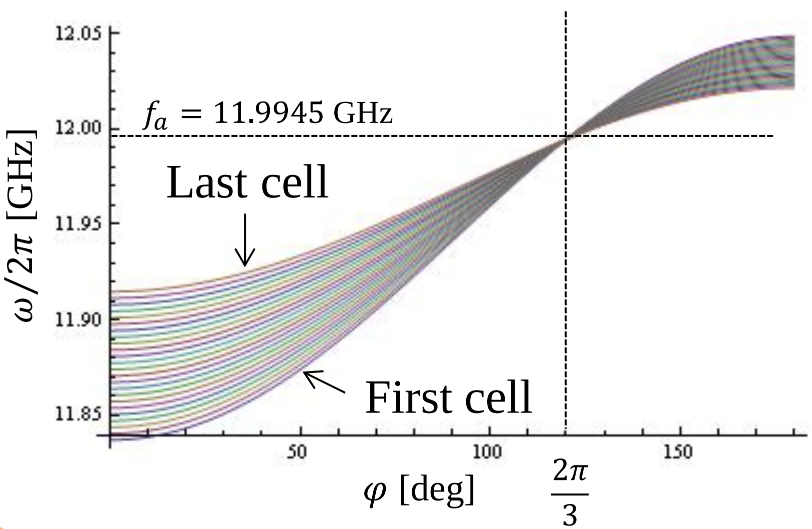
* courtesy of *A. Solodko*

cells: 24 regular + 2 matching

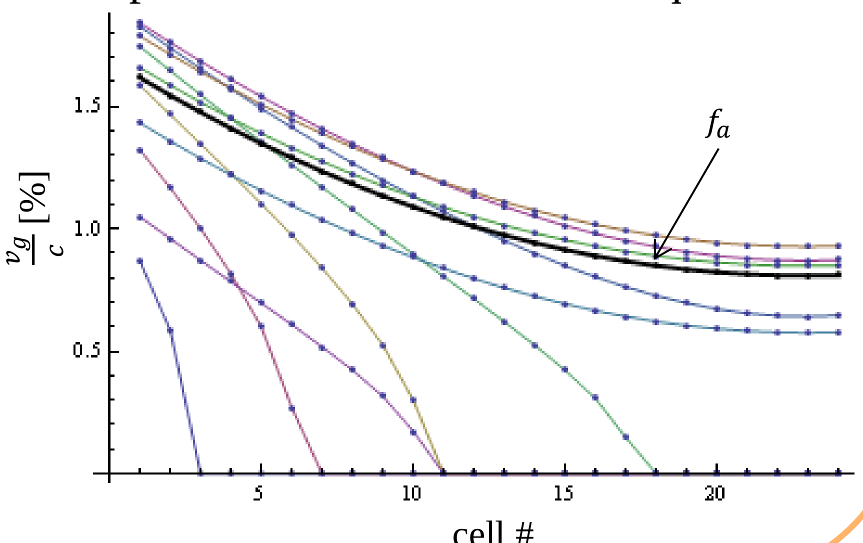
In the first order approximation the cells are linear time-invariant systems with a frequency response as the following:

$$s_{21}(\Delta f) = \begin{cases} \exp\left(\frac{2\pi c}{3 v_g}\left(\left(i - \frac{1}{2Q}\right)\frac{\Delta f}{f_a} - \frac{1}{2Q}\right)\right), & f_0 < f < f_\pi \\ 0, & otherwise \end{cases}$$

Dispersion curves for 24 cells

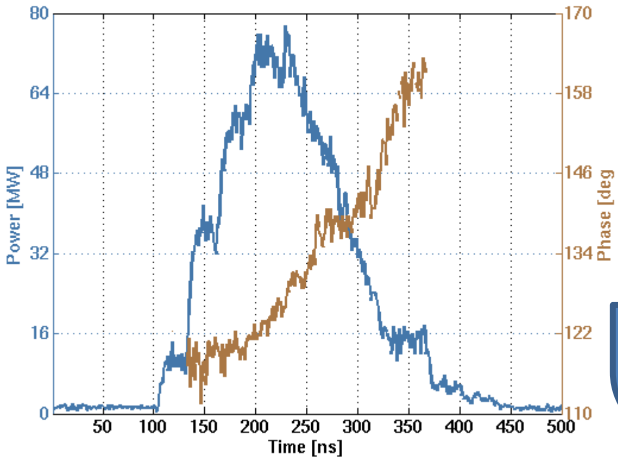


Group velocities for different frequencies

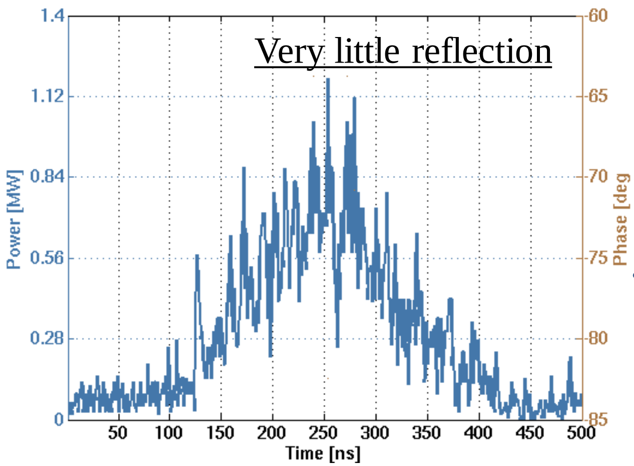


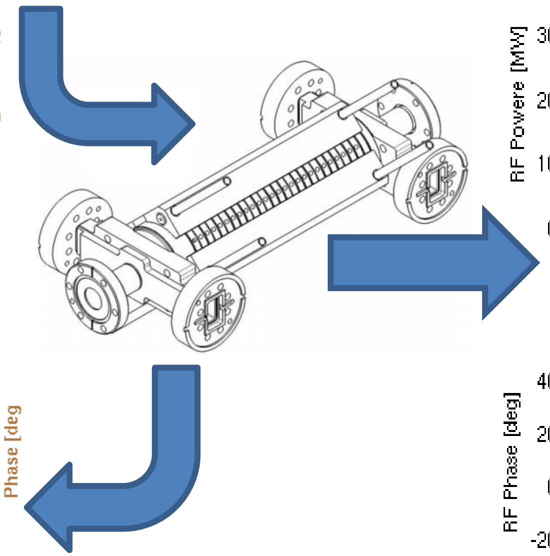
RF Transmission

Incident RF



Reflected RF



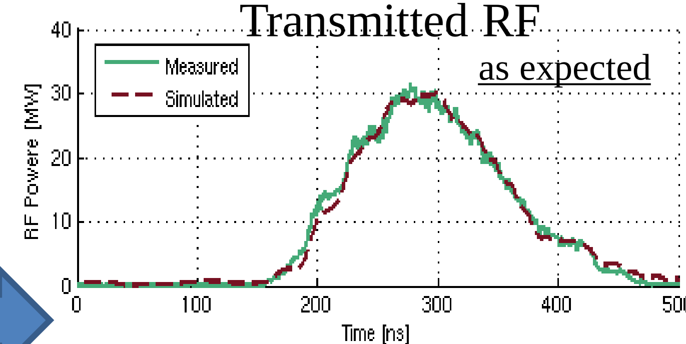


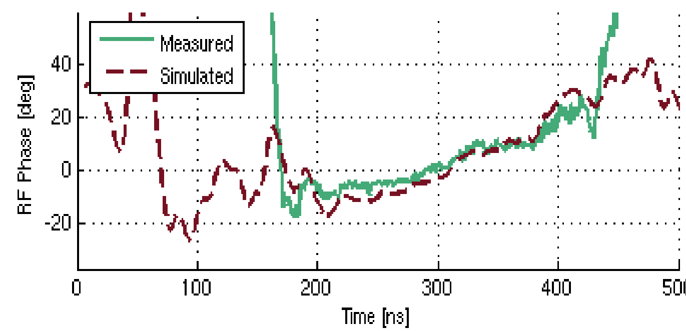
The frequency response of the structure:

$$S_{21}(\Delta f) = \exp\left(\frac{2\pi}{3}\sum_{1}^{24}\frac{c}{v_g}\left(\left(i-\frac{1}{2Q}\right)\frac{\Delta f}{f_0}-\frac{1}{2Q}\right)\right),$$

when $\max f_0 < \frac{\omega}{2\pi} < \min f_\pi$

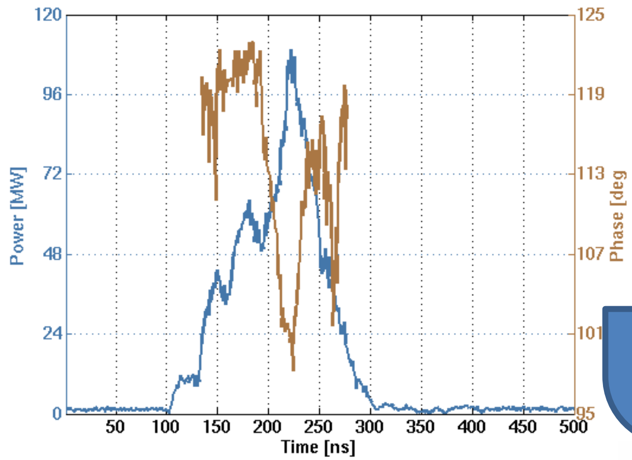
Transmitted RF



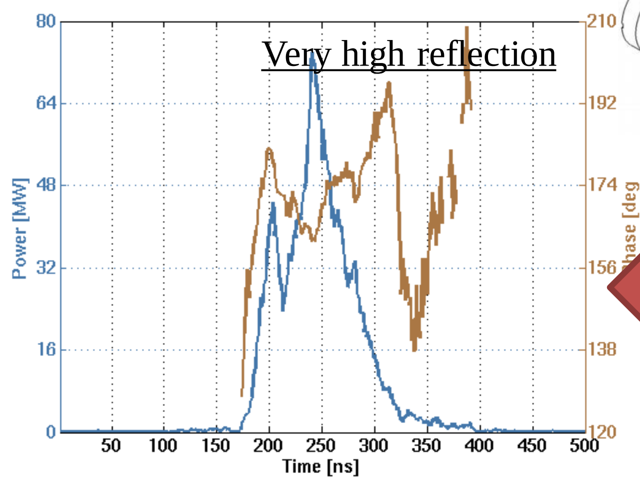


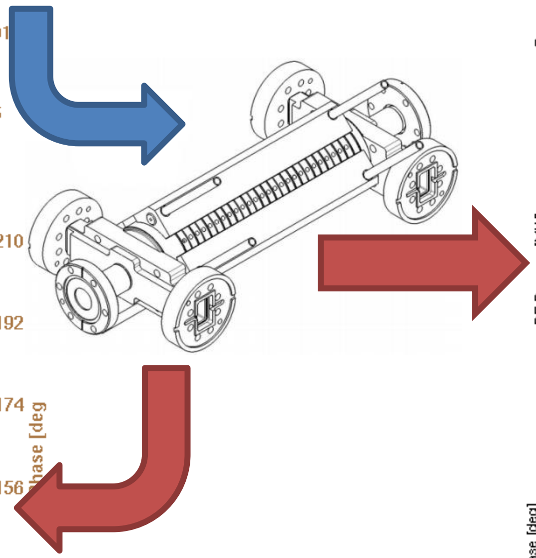
RF Breakdown

Incident RF

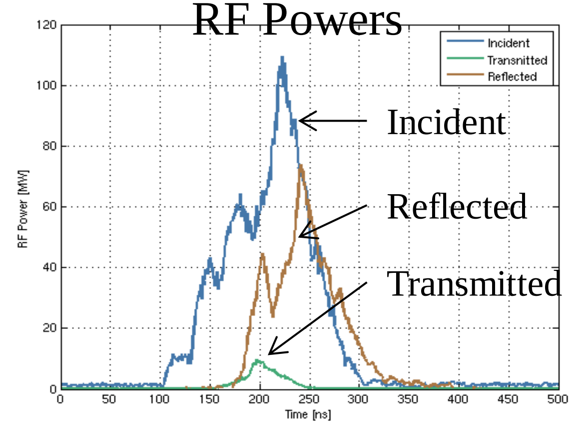


Reflected RF

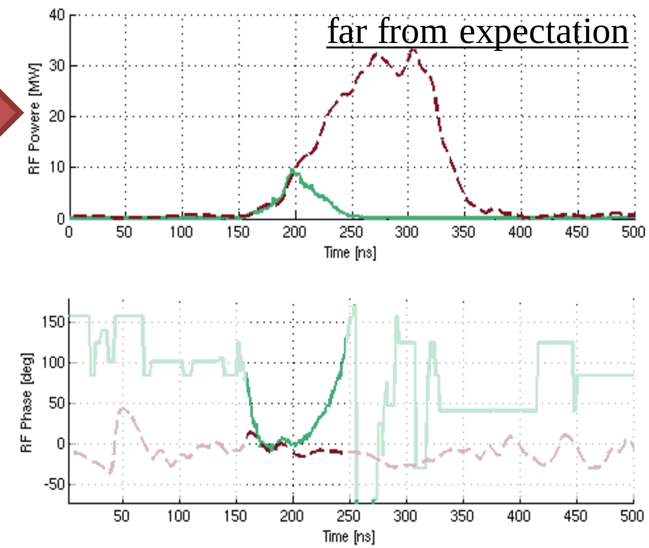




RF Powers

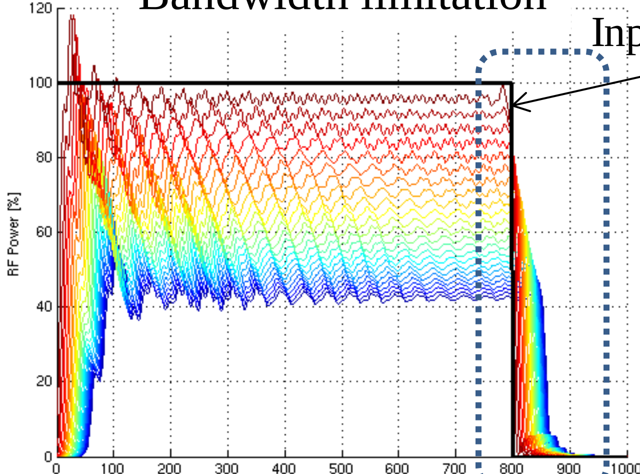


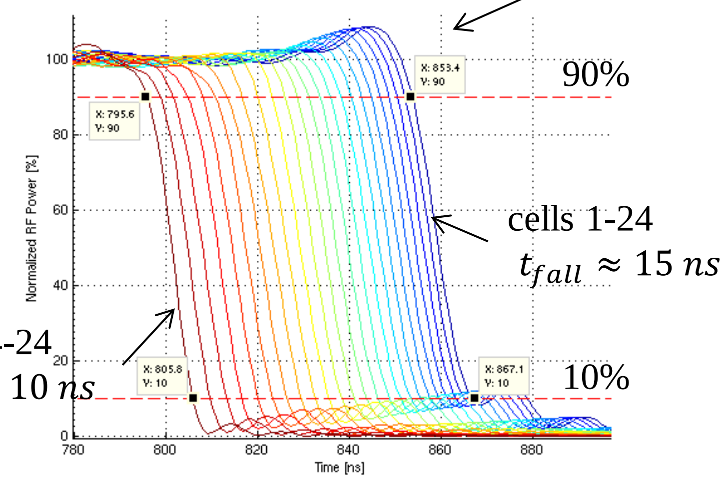
Transmitted RF



Cease of RF transmission

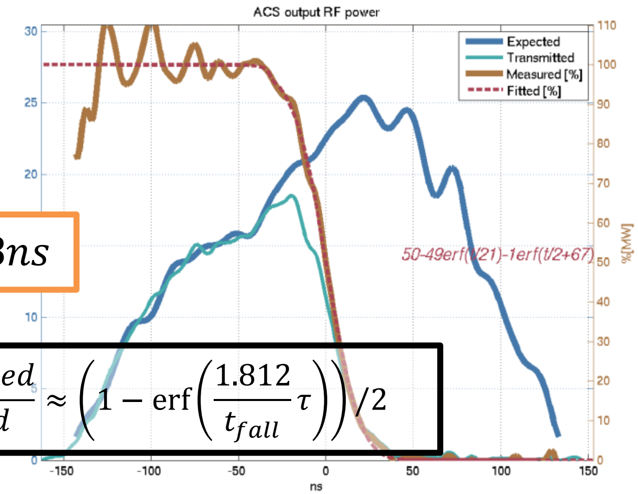
Bandwidth limitation





Output response: injecting into different cells

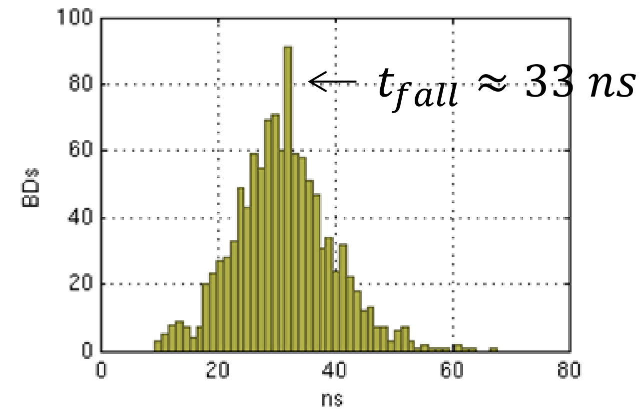
Measurements



$t_{fall} \approx 38ns$

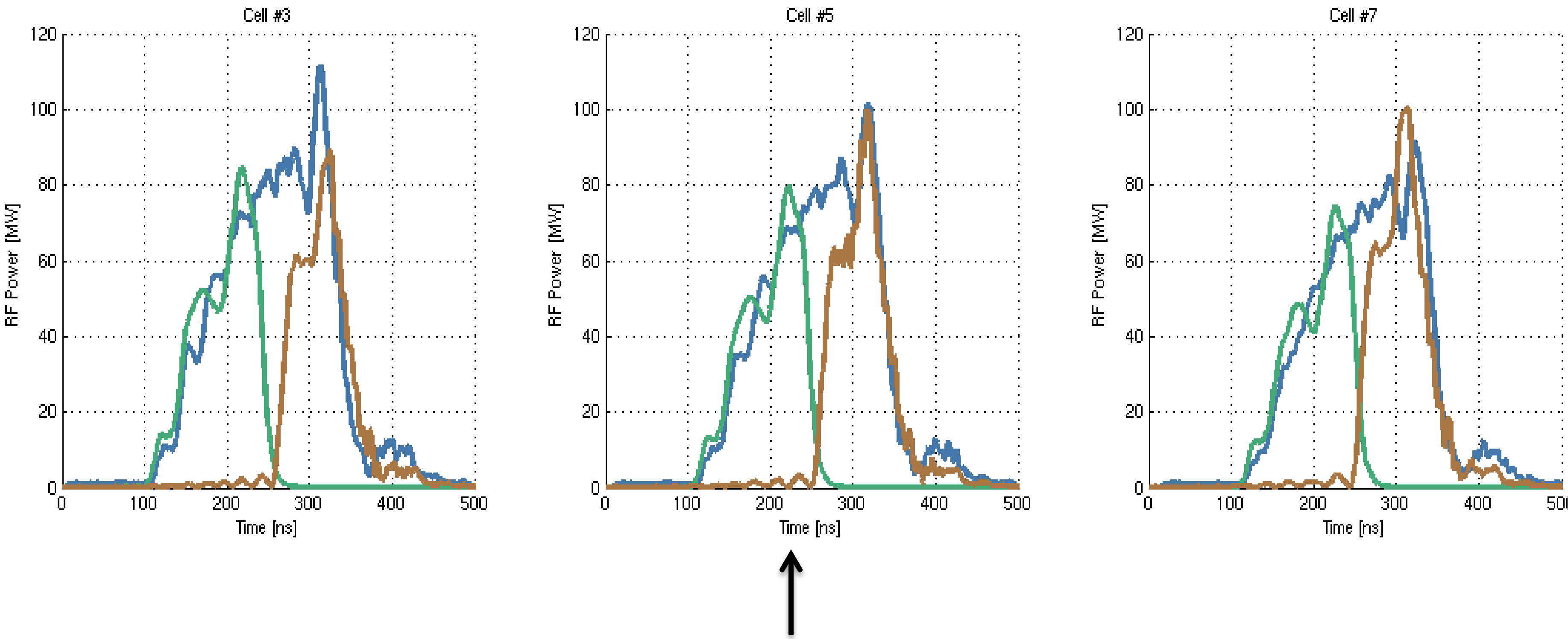
$$\frac{Transmitted}{Expected} \approx \left(1 - \mathrm{erf}\left(\frac{1.812}{t_{fall}}\tau\right)\right)/2$$

Distribution of t_{fall}



=> There is a transient after breakdowns

Breakdown location

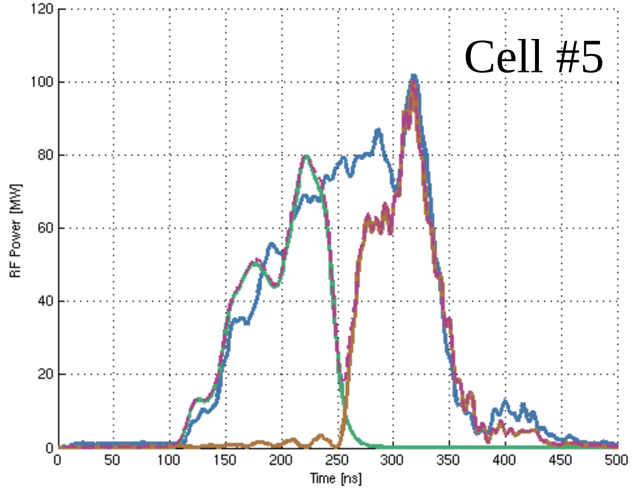


The best match:

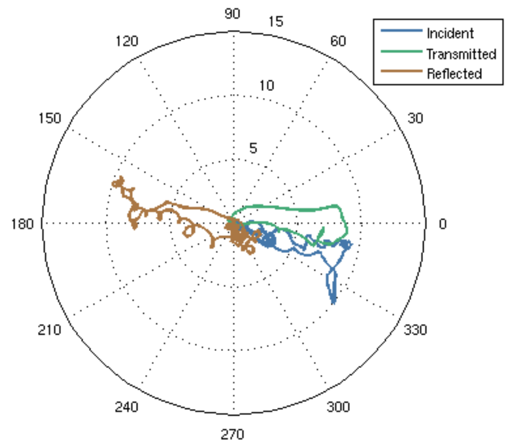
- The beginning of cease of transmission is at the same time as the beginning of reflection;
- Reflection follows the incident RF at the end of the pulse.

Single breakdown

RF Powers



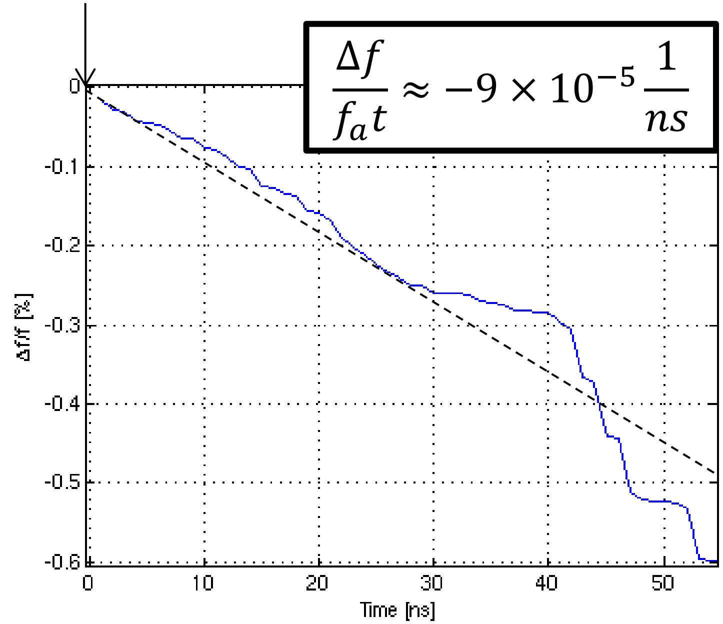
RF Fields



Detuning of cell #5 during breakdown

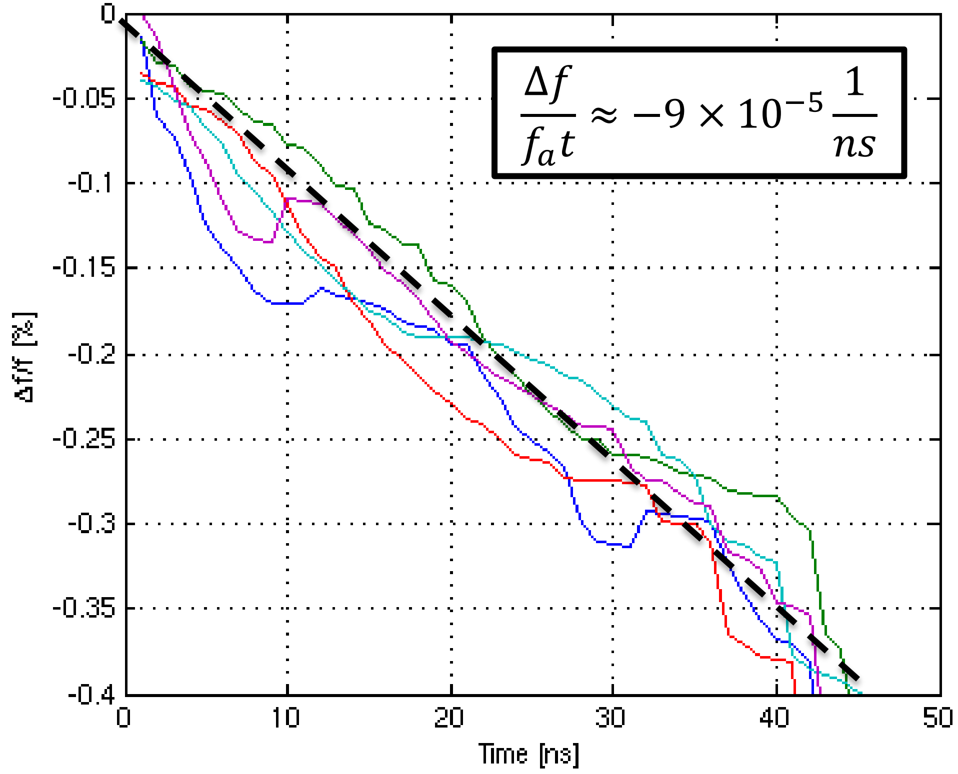
$$\min_{\Delta f(t)}\left(\widehat{RF_{inc}}\cdot\prod_{\substack{n=1,\\ n\neq 5}}^{24} s_{21}^{n}(f)\,s_{21}^{5}\big(f+\Delta f(t)\big)-\widehat{RF_{tran}}\right)$$

Beginning of breakdown



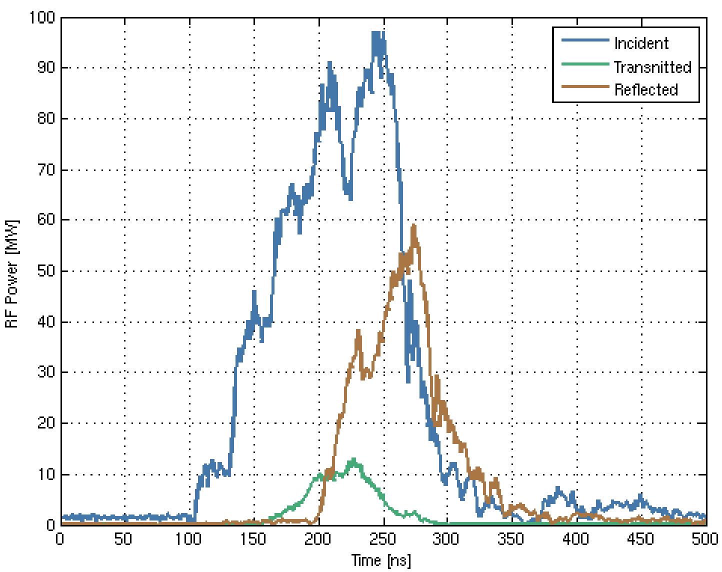
$$\frac{\Delta f}{f_a t}\approx -9\times 10^{-5}\,\frac{1}{ns}$$

Detuning of cell#5 during breakdowns



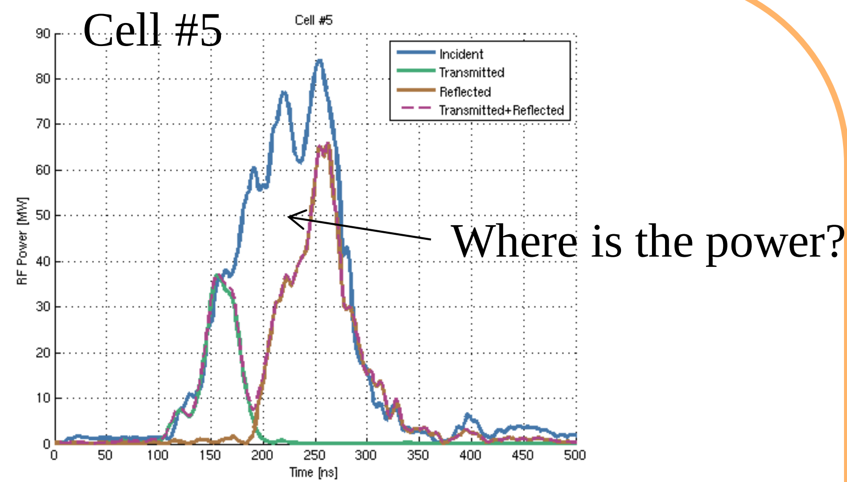
Where is the location of BD?

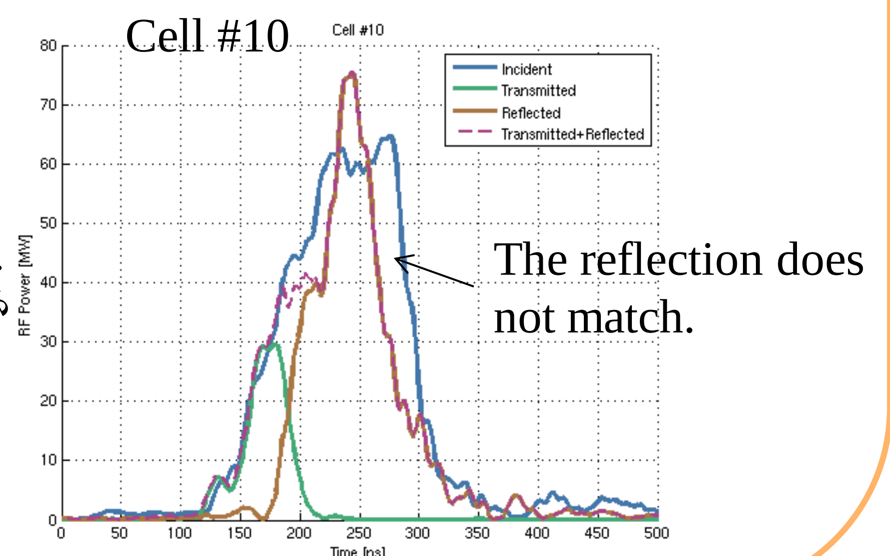
RF measurements



Matching reflection

Matching the raise and fall times

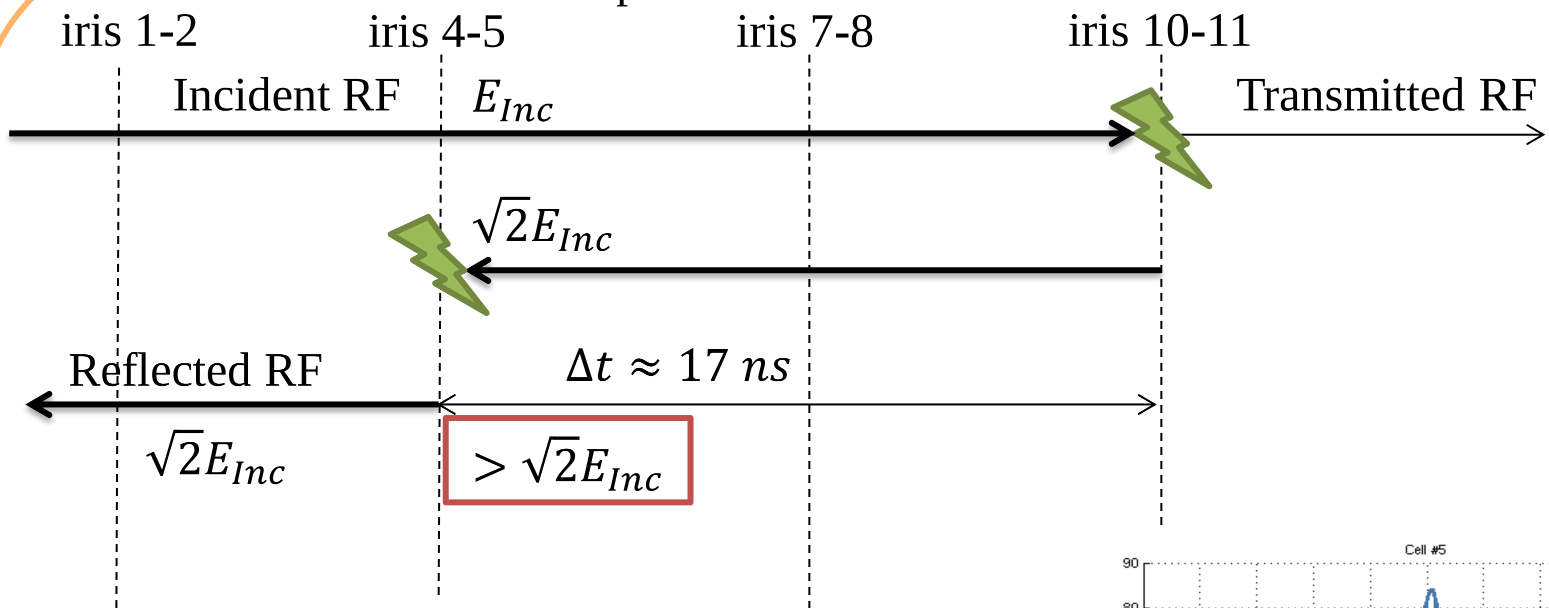




There is no cell such that the sum of the transmitted and reflected RF matches the incident RF.

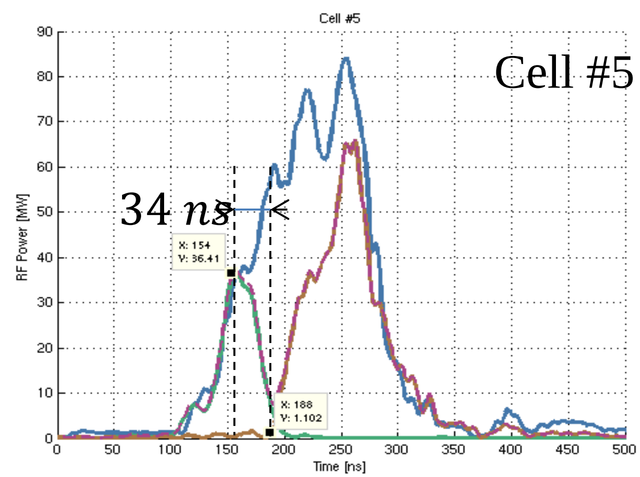
Double breakdowns

One of possible scenarios



Hypothese of a double breakdown explains the origin of missing power and it suggests that ~40% of RF power dissipated in 6 cells.

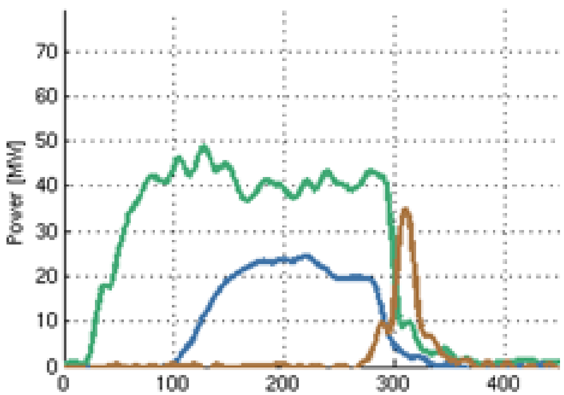
Double breakdowns can develop hot cells (4-11).

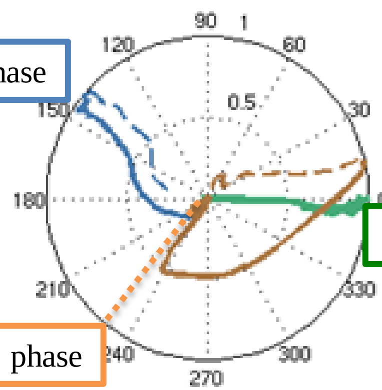


Location distribution of primary breakdowns

Secondary breakdowns are not included

Illusion of a hot cell

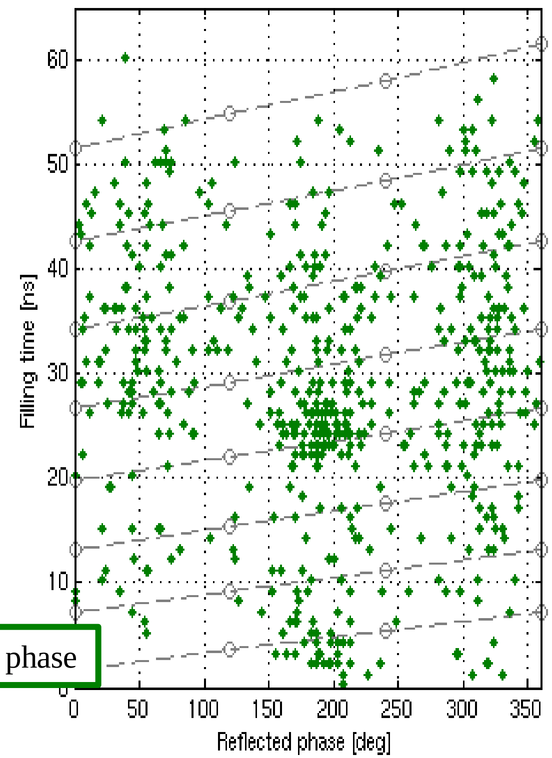


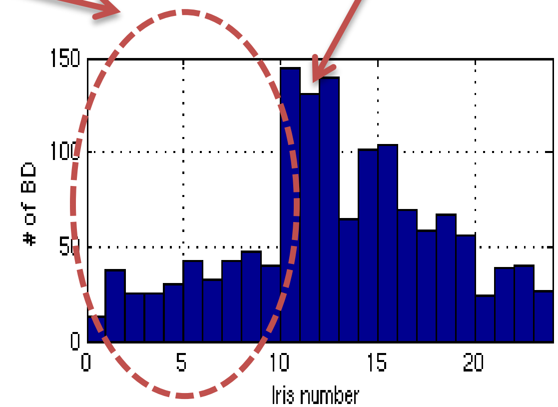


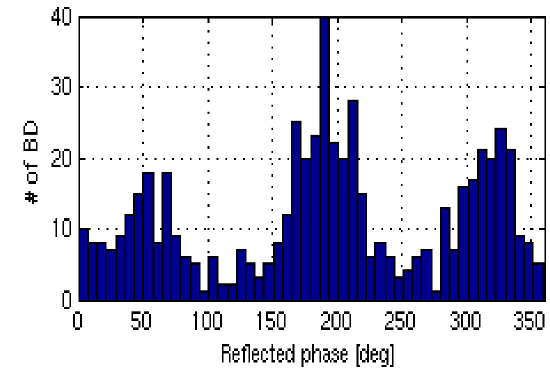
Transmitted phase

Incident phase

Reflected phase







Breakdown rate (BDR)

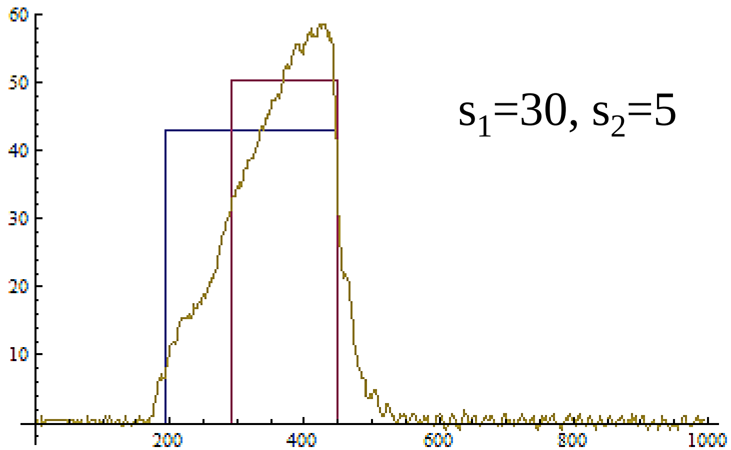
Scaling low

Breakdown rate scaling low for any pulse shape:

$$BDR \propto \left(\int |E(t)|^{s_1/s_2} dt\right)^{s_2}$$

where E – field level and *s1*,*s2* – const.

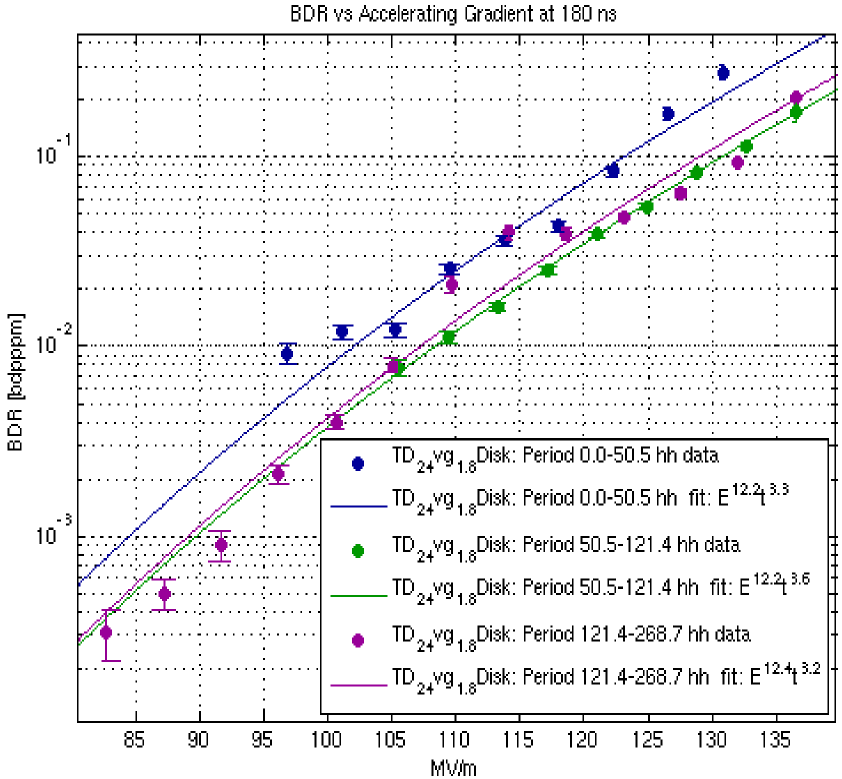
Scaling to a rectangular pulse



s_1=30, s_2=5

Yellow line – forward power;
Red line – (∫E(t)s1/s2 dt / 160)s2/s1;
Blue line – ∫E(t)s1/s2 dt / 100 s1/s2.

Breakdown rate



$\frac{s_1}{s_2} \approx 4$, it suggests that the breakdown rate strongly depends on the pulsed surface heating.

Summary

TBTS facility is used to validate X-band technology with a particular interest to understand the breakdown phenomena. The presented work revised data of the tested structure TD24 and the following results have been obtained:

- Developed a technique to estimate time resolved S21-parameters of a breaking down cell-iris;
- Changes of S21-parameters during the breakdown can be associated with close to a linear detuning of the cell-iris;
- Revealed double breakdowns lead to substantial power losses and high-fields, which can be a source of the surface damage leading to higher breakdown rates;
- The “hot-cell“ in TD24 is determined based on only primary breakdowns, the secondary breakdowns can flatten the distribution.

TD24 parameters

	120°/cell		comments
f [GHz]	11.995		
S12	0.6542		
t_f [ns]	64.55		
Q^{Cu}	5732		
Gradient averaged over all cells			
V_{26} [V]@P_{in} = 1 W	3340		2 matching +24 regular cells L_{acc} = 227.7 mm,
G_{26} [V/m]@P_{in} = 1 W	14661		
P_{in} [MW]@<G_{26}=100MV/m>	46.5		
Gradient averaged over regular cells only			
V_{24} [V]@P_{in} = 1 W	3078		24 regular cells only L_{acc} = 200.0 mm,
G_{24} [V/m]@P_{in} = 1 W	15390		
P_{in} [MW]@<G_{24}=100MV/m>	42.2		* *A. Grudiev, 25/03/10*

Single breakdown: measurements