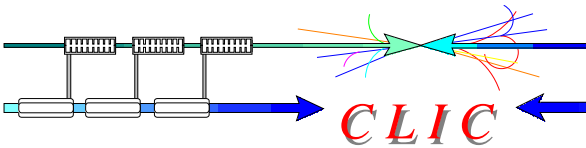


Comprehensive Analysis of RF Test Results and the New RF Constraints

18.01.2008

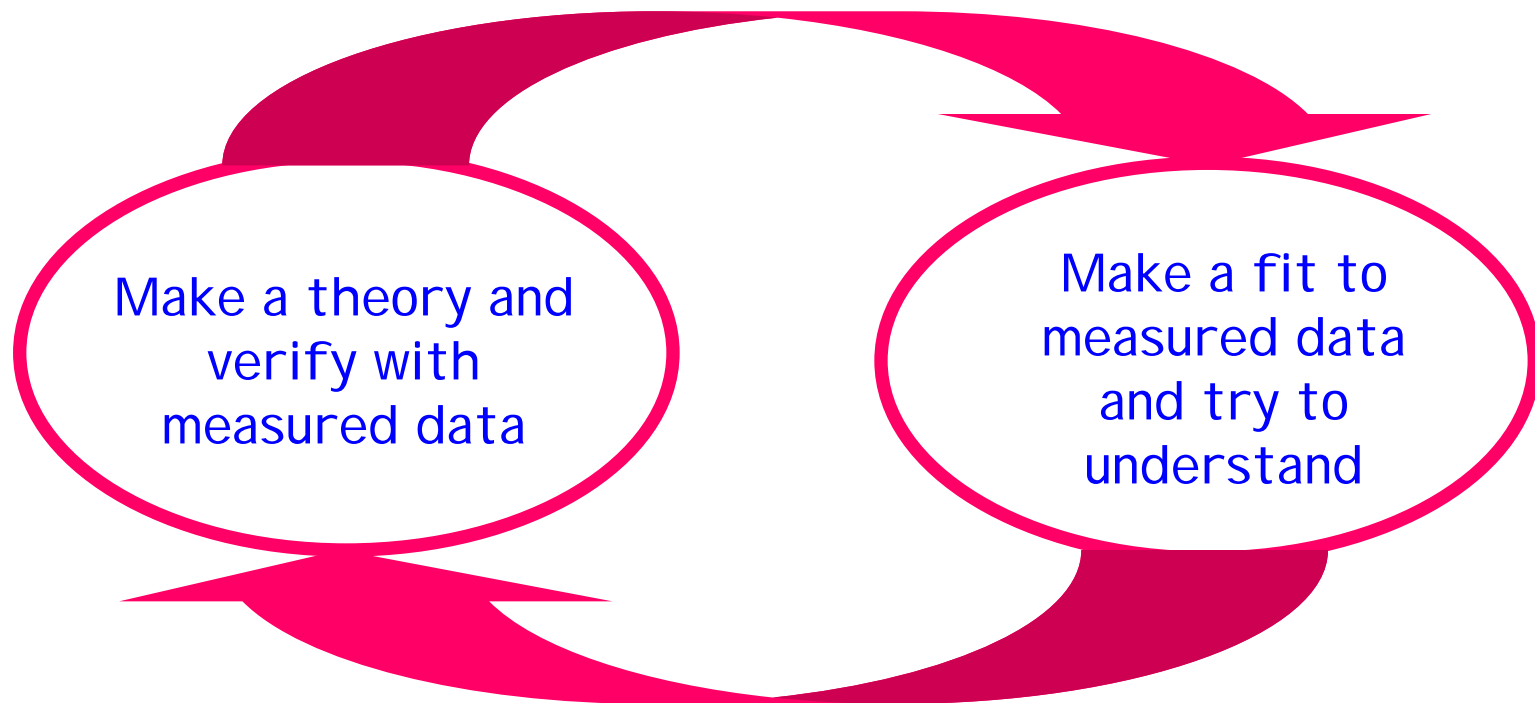
Alexej Grudiev and Walter Wuensch

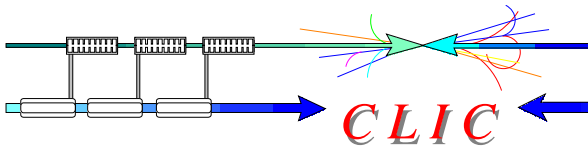


Motivation



To provide rf designers with a local field quantity which limits high-power/high-gradient performance in the presence of rf breakdowns.



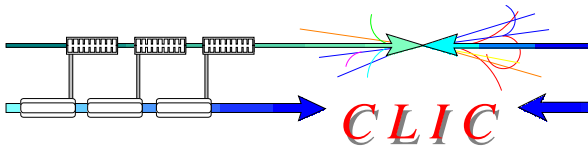


Introduction



The high-gradient performance depends on:

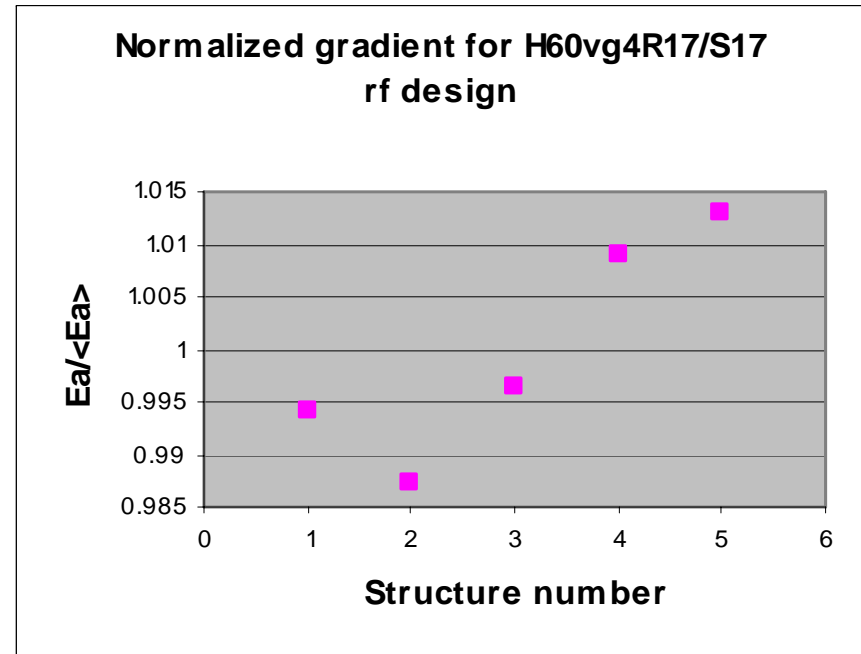
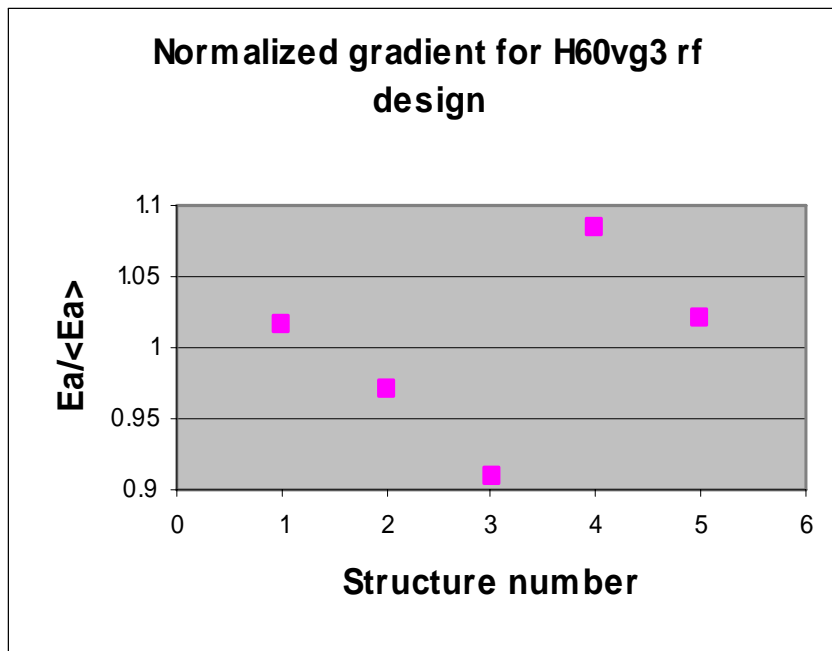
1. Geometry of the cavity: rf design
2. Surface of the cavity : anything else than rf design
 - Material
 - Heat treatment
 - Machining
 - Chemical treatment
3. Measurement technique and experimental setup



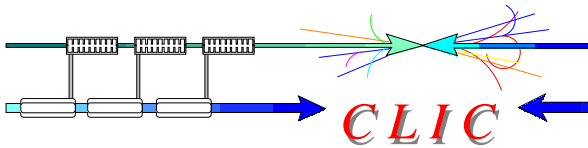
Introduction



Variation of high-gradient performance of the same rf design.



N.B. Variation of up to tens of percents can be expected from the difference in the surface state, statistics and measurement setup.

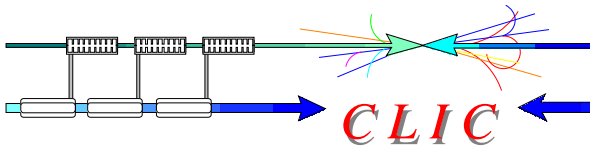


Experimental data @ $BDR=10^{-6}$, 100ns



	RF design name	f [GHz]	dphi [deg]	a1 [mm]	d1 [mm]	e1	vg1 [%]	Ea [MV/m]
1	DDS1	11.424	120	5.7	1	1	11.7	59.4
2	T53VG5R	11.424	120	4.45	1.66	1	5	80.9
3	T53VG3MC	11.424	120	3.9	1.66	1	3.3	102.2
4	H90VG3	11.424	150	5.3	4.2	1	3	77.7
5	H60VG3-FXB6	11.424	150	5.3	4.4	1	2.8	80.8
6	H60VG3S18	11.424	150	5.5	4.6	1.15	3.3	76.0
7	H60VG3S17-FXC5	11.424	150	5.3	3.7	1.34	3.6	83.3
8	H75VG4S18	11.424	150	5.3	3.04	1.36	4	101.0
9	H60VG4R17-2	11.424	150	5.68	3.65	1.37	4.5	82.6
10	HDX11-Cu	11.424	60	4.21	1.45	2.4	5.1	55.3
11	CLIC-X-band	11.424	120	3	2	1	1.1	120.4
12	SW20a565_1Cell	11.424	180	5.65	4.6	3.4	0	100.1
13	SW20a375	11.424	180	3.75	2.6	1.7	0	75.2
14	2pi/3	29.985	120	1.75	0.85	1	4.7	68.6
15	pi/2	29.985	90	2	0.85	1	7.4	48.7
16	HDS60L	29.985	60	1.9	0.55	2.5	8	45.5
17	HDS60S	29.985	60	1.6	0.55	2.4	5.1	55.8
18	HDS4Th	29.985	150	1.75	0.55	1	2.6	67.4
19	PETS9mm	29.985	120	4.5	0.85	1	39.8	16.4

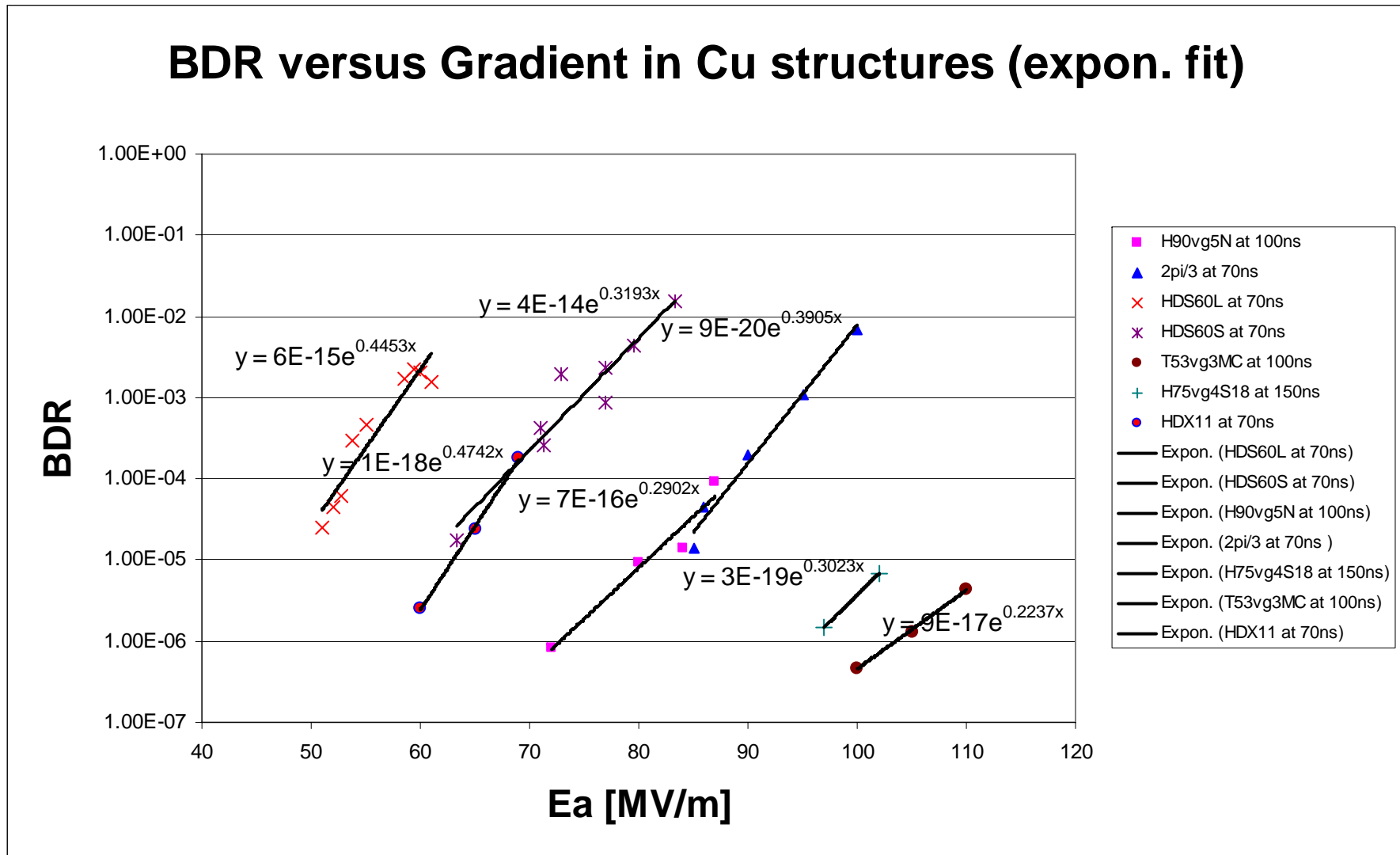
Measurement data were scaled to 100 ns pulse length and to $BDR = 10^{-6}$.



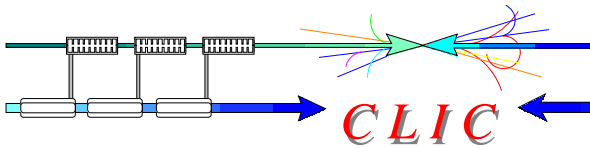
BDR versus Gradient scaling



BDR versus Gradient in Cu structures (expon. fit)



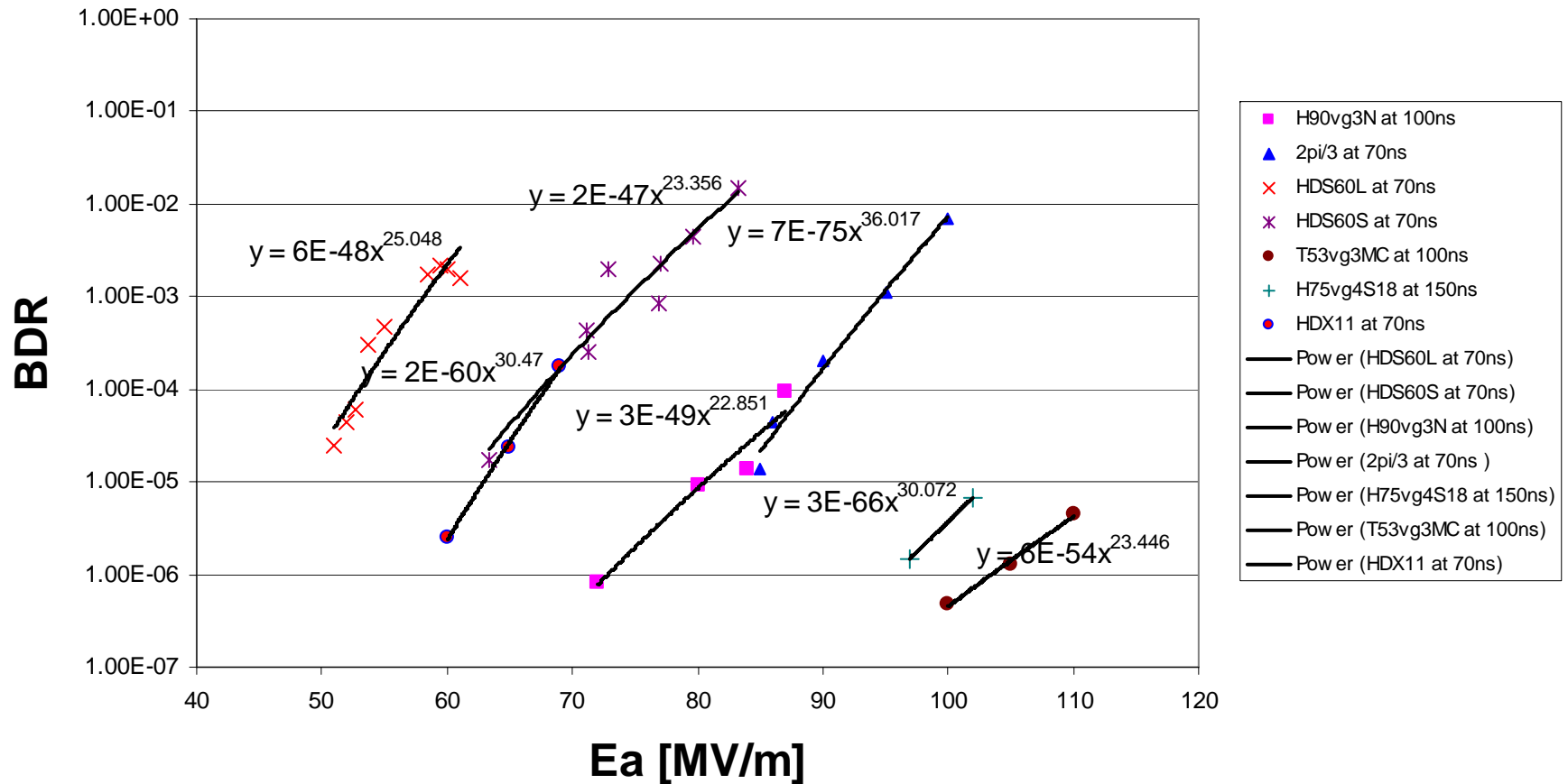
Exponential fit requires different slope depending on the gradient



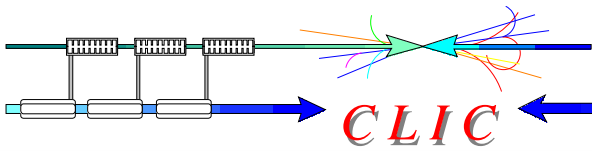
BDR versus Gradient scaling



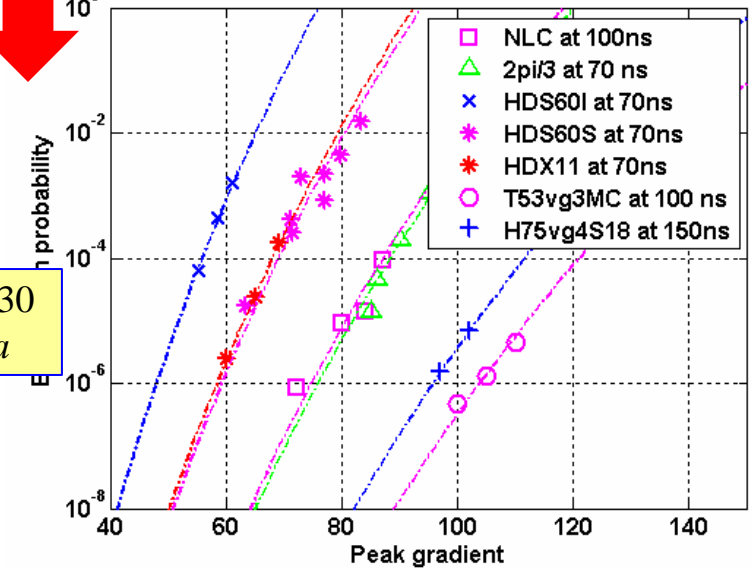
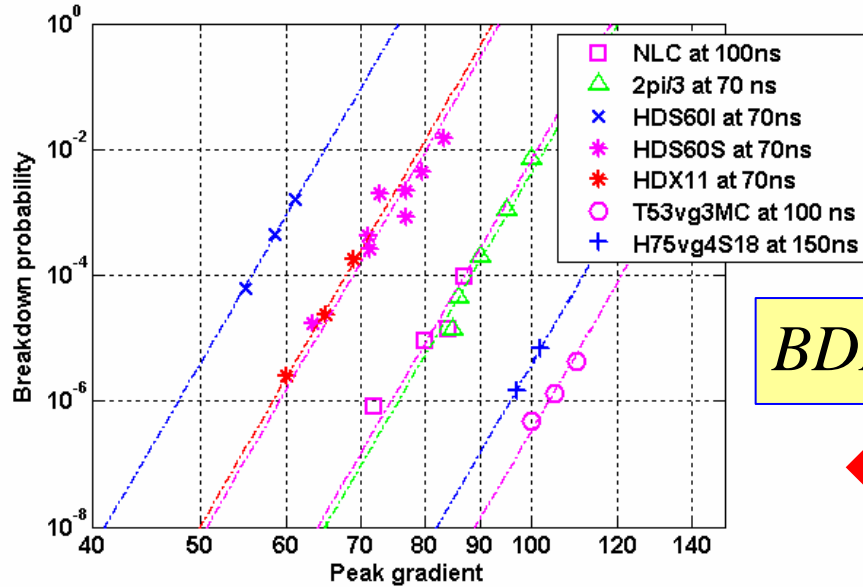
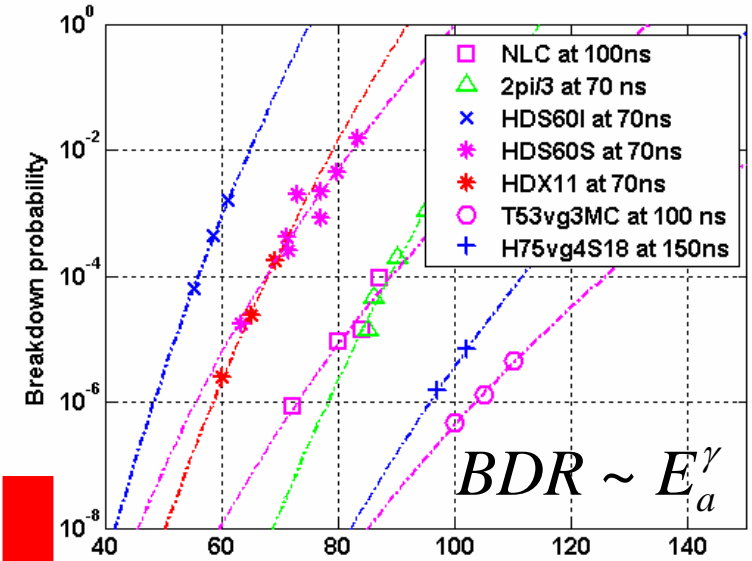
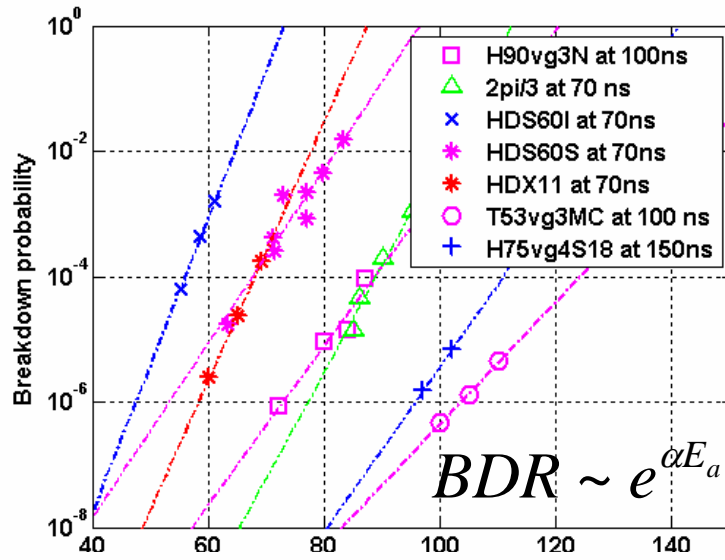
BDR versus Gradient in Cu structures (power fit)

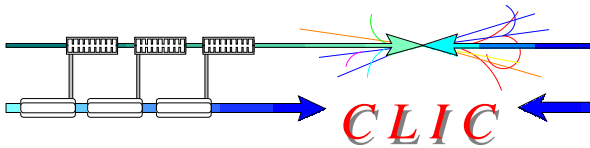


Power fit can be done with the same power for all gradients

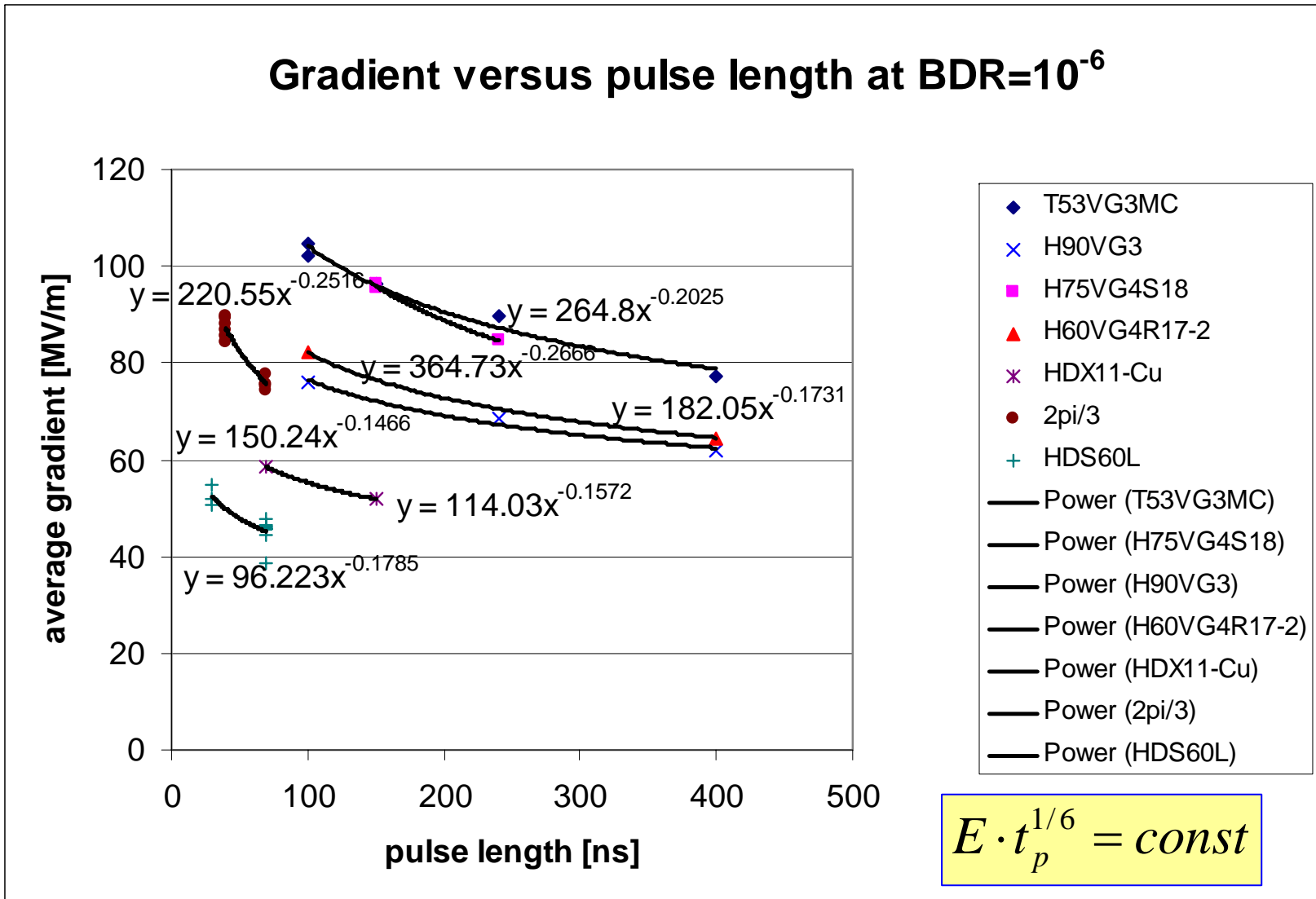


BDR versus Gradient scaling

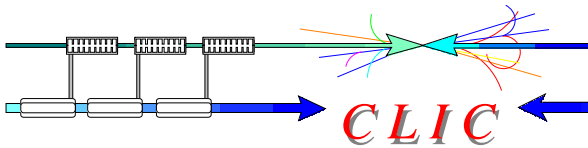




Gradient versus pulse length scaling



N.B. This is very well known scaling law being confirmed again and again



Summary on gradient scaling



For a fixed pulse length

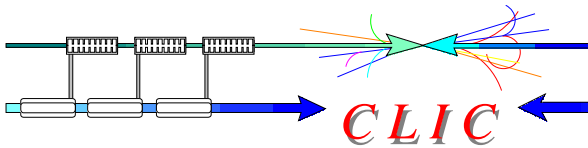
$$BDR \sim E_a^{30}$$

For a fixed BDR

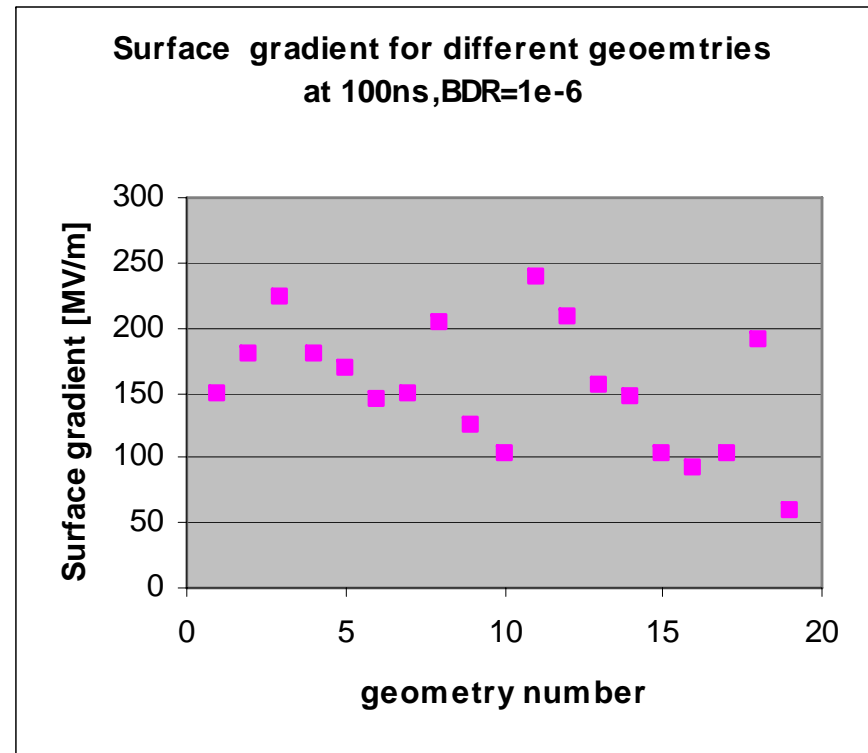
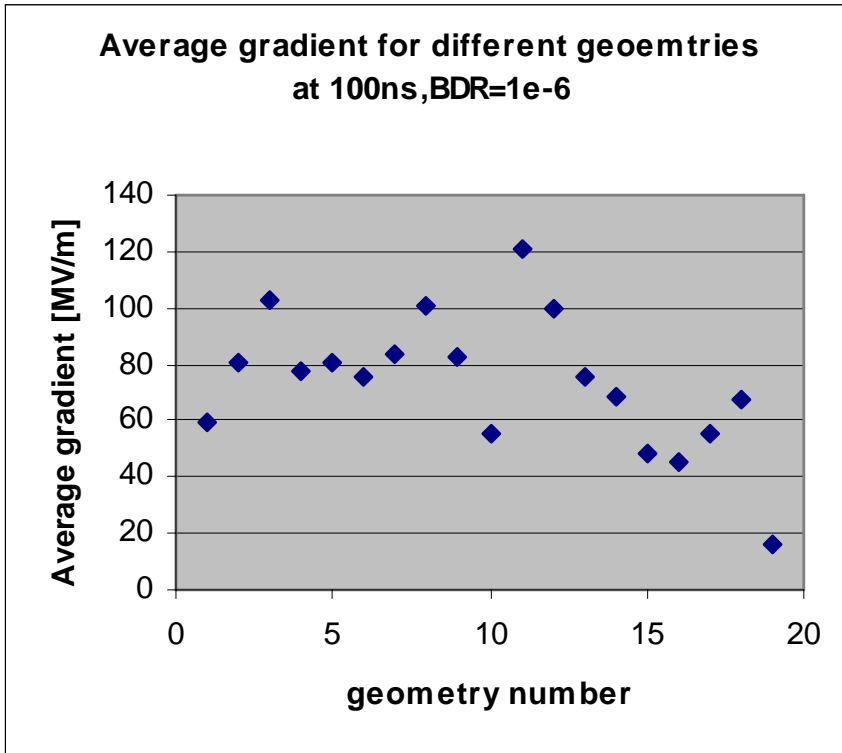
$$E_a \cdot t_p^{1/6} = const$$

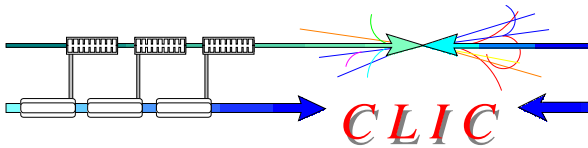
$$\frac{E_a^{30} \cdot t_p^5}{BDR} = const$$

- 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.

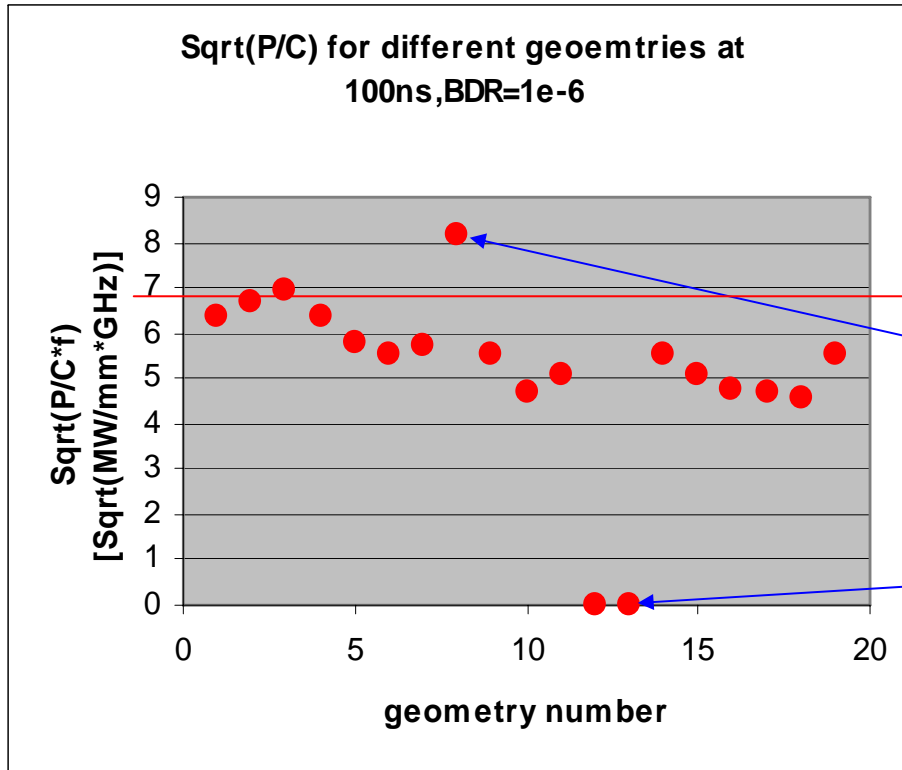


Accelerating and surface gradients





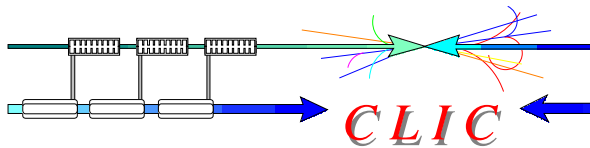
Power over circumference



Much better agreement
but

18Wu

1. This is not a local field quantity.
2. H75vg4S18 does not really fit.
3. Does not describe standing wave structures.

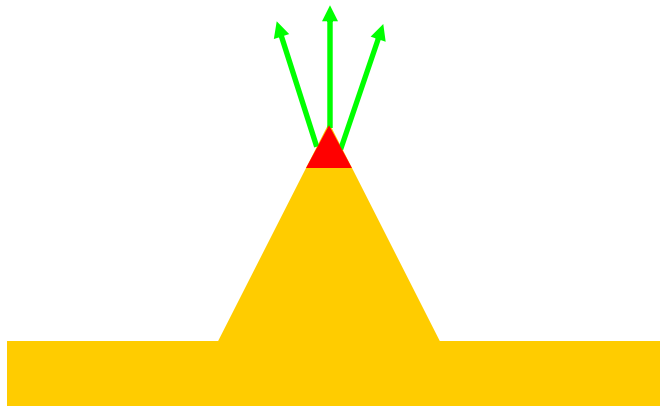


Breakdown initiation scenario



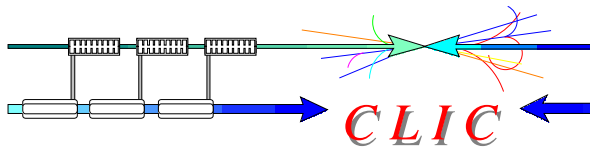
Qualitative picture

- Field emission currents J_{FN} heat a (potential) breakdown site up to a temperature rise ΔT on each pulse.
- After a number of pulses the site got modified so that J_{FN} increases so that ΔT increases above a certain threshold.
- Breakdown takes place.

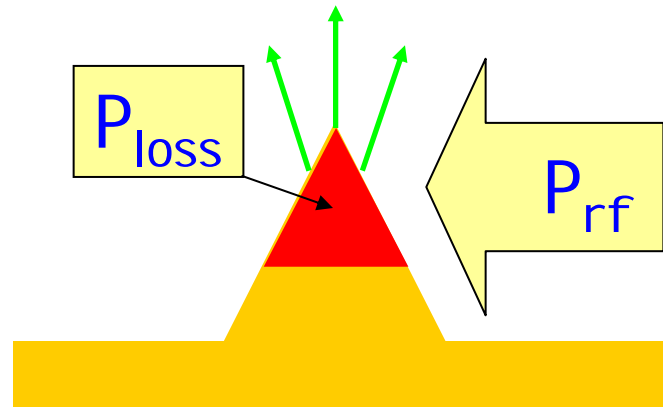


This scenario can explain:

- Dependence of the breakdown rate on the gradient (Fatigue)
- Pulse length dependence of the gradient (1D÷3D heat flow from a point-like source)



Field emission and rf power flow

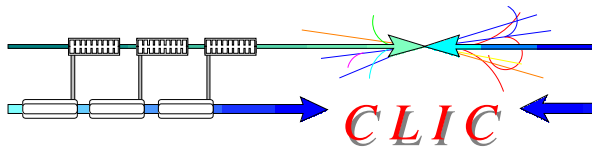


$$\Delta T \approx P_{loss} < P_{rf}$$

$$P_{loss} = \int_V J_{FN} \cdot E \, dv$$

$$P_{rf} = \oint_S E \times H \, ds$$

There is no other source of energy in the cavity then rf energy.

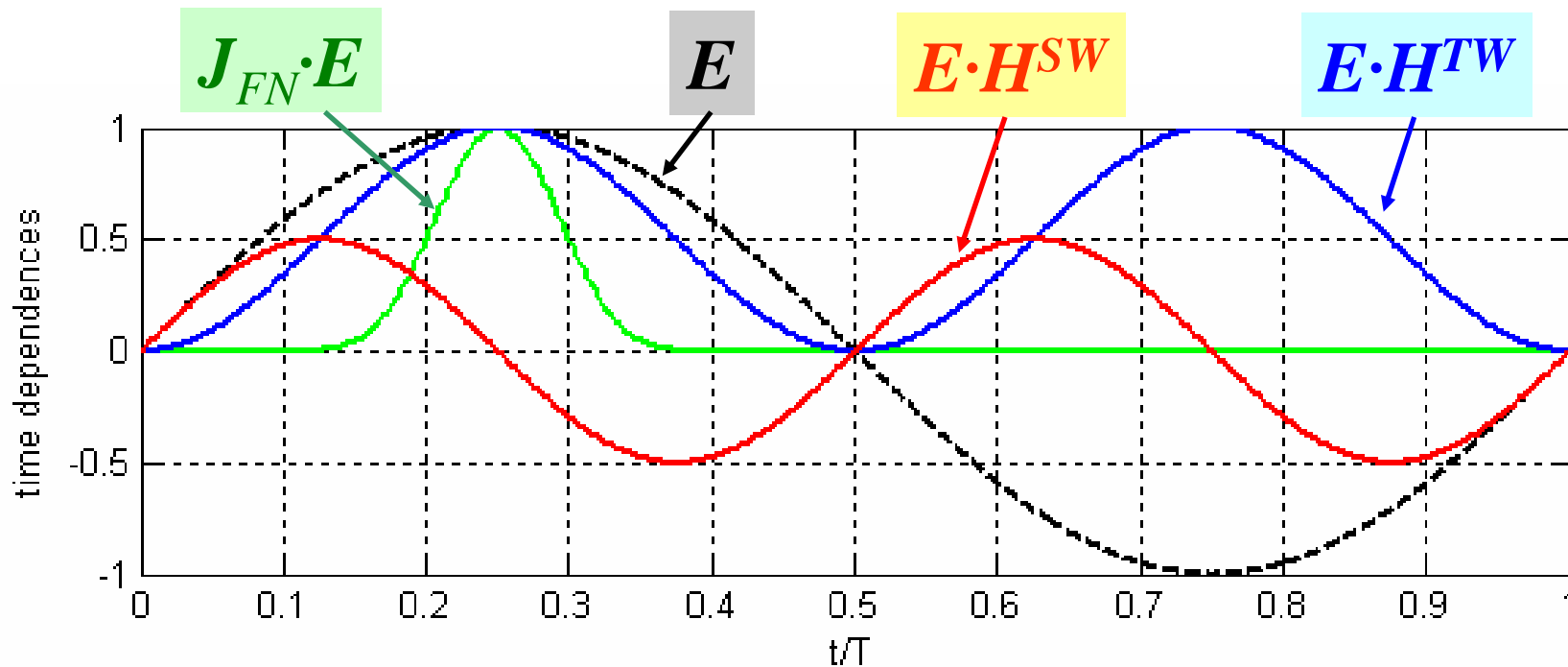


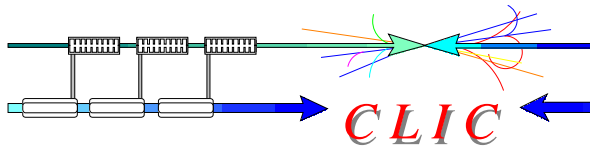
Field emission and power flow



$$\mathbf{E} \times \mathbf{H} = E_0 \cdot H_0^{TW} \sin^2 \omega t + E_0 \cdot H_0^{SW} \sin \omega t \cos \omega t$$

$$J_{FN} \cdot \mathbf{E} = A E_0^3 \sin^3 \omega t \cdot \exp\left(\frac{-62 \text{ GV/m}}{\beta E_0 \sin \omega t}\right)$$





Field emission and rf power coupling



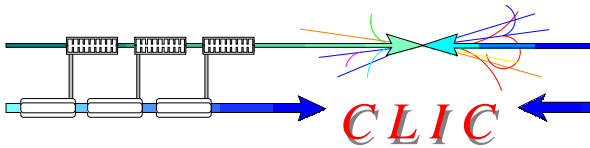
What matters for the breakdown is the amount of rf power **coupled** to the field emission heating.

$$P_{coup} = \frac{\int_0^{T/4} P_{rf} \cdot P_{loss} dt}{\int_0^{T/4} P_{loss} dt}$$

$$= C^{TW} E_0 H_0^{TW} + C^{SW} E_0 H_0^{SW}$$

Assuming that all breakdown sites have the same geometrical parameters the breakdown limit can be expressed in terms of modified Poynting vector S_c .

$$S_c = E_0 H_0^{TW} + \frac{C^{SW}}{C^{TW}} E_0 H_0^{SW} = \text{Re}\{\mathbf{S}\} + g_c \cdot \text{Im}\{\mathbf{S}\}$$

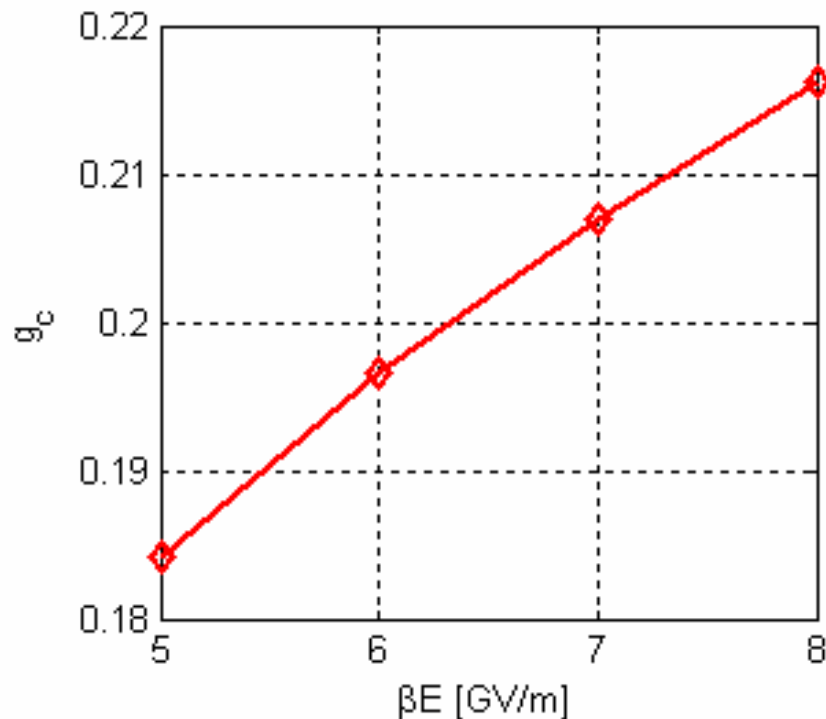


Field emission and rf power coupling



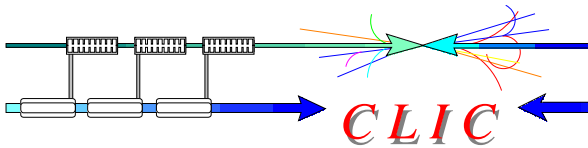
Constant g_c depends only on the value of the local surface electric field βE_0

$$g_c = \frac{\int_0^{\pi/2} \sin^4 x \cos x \cdot \exp\left(\frac{-62 \text{ GV/m}}{\beta E_0 \sin x}\right) dx}{\int_0^{\pi/2} \sin^5 x \cdot \exp\left(\frac{-62 \text{ GV/m}}{\beta E_0 \sin x}\right) dx}$$

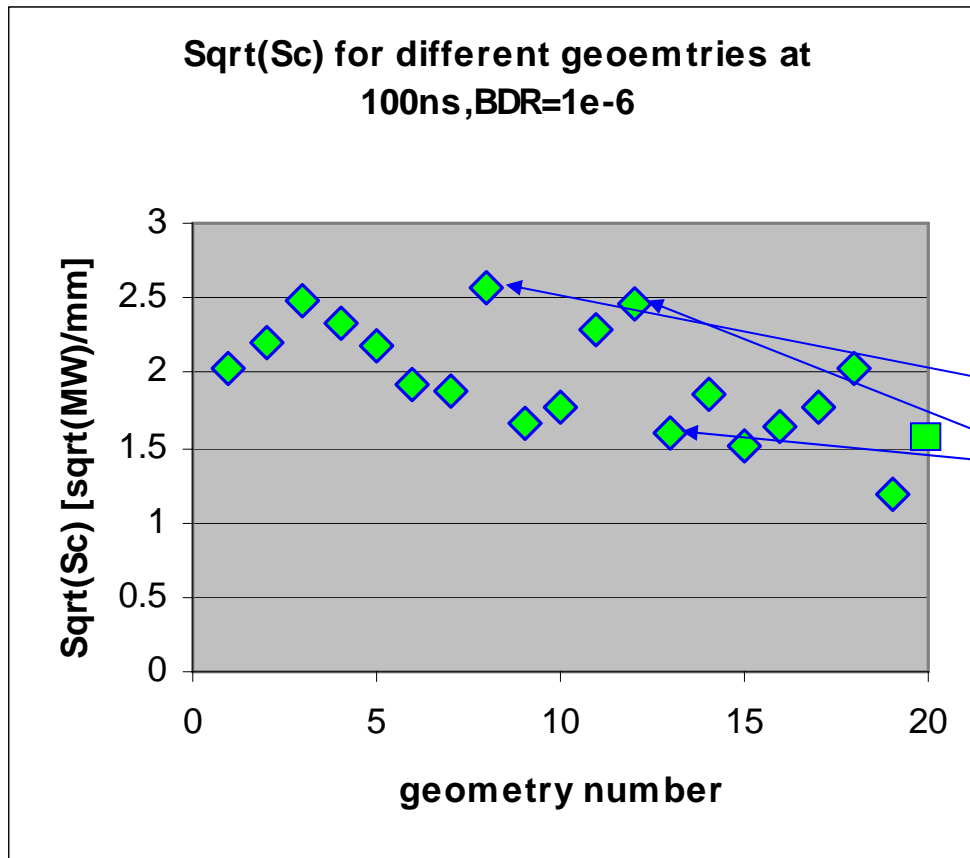


$$g_c = 0.2$$

is assumed in the following analysis of the measurement data



New rf breakdown constraint



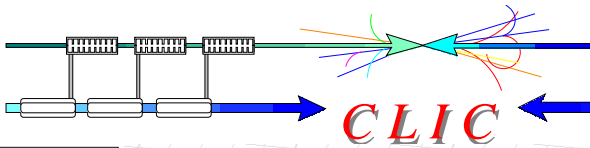
Spread is almost the same as P/C,
but in addition

1. This is a local field quantity.
2. H75vg4S18 fits well.
3. It describes standing wave structures.

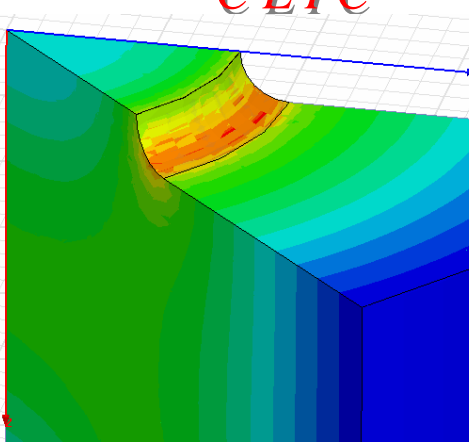
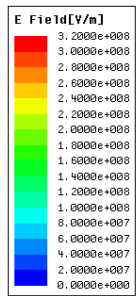
Depending on the degree of optimism we can choose $S_c = 3 \div 6$ [MW/mm²] at 100ns, BDR=1e-6 and scale it using:

$$S_c^{15} t_p^5 / \text{BDR} = \text{const}$$

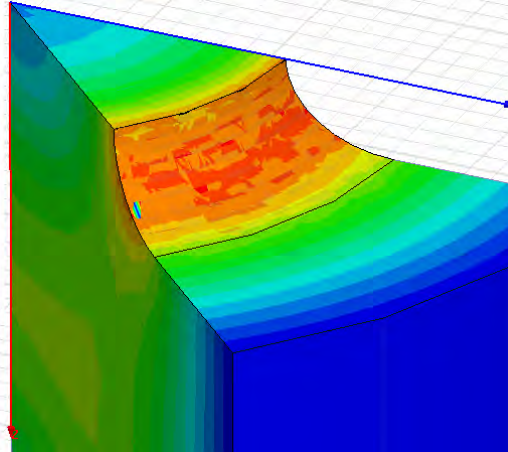
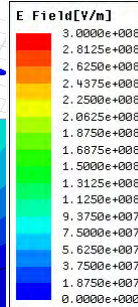
$$S_c = \text{Re}\{S\} + 0.2 \cdot \text{Im}\{S\}$$



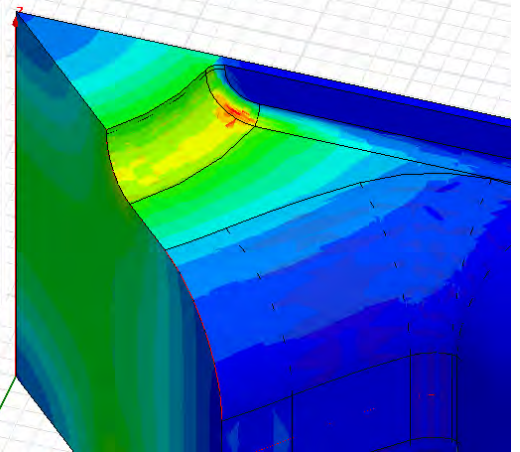
Surface distributions for low v_g



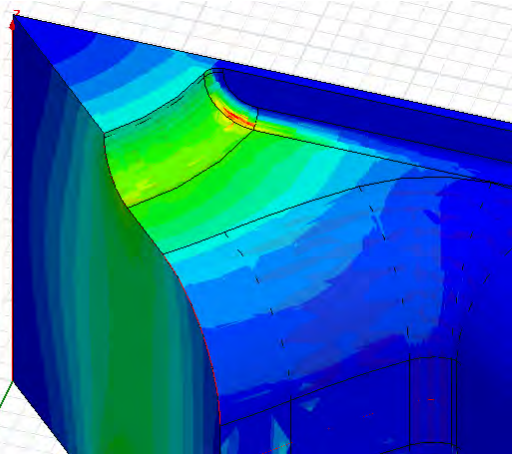
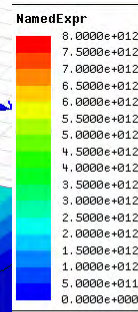
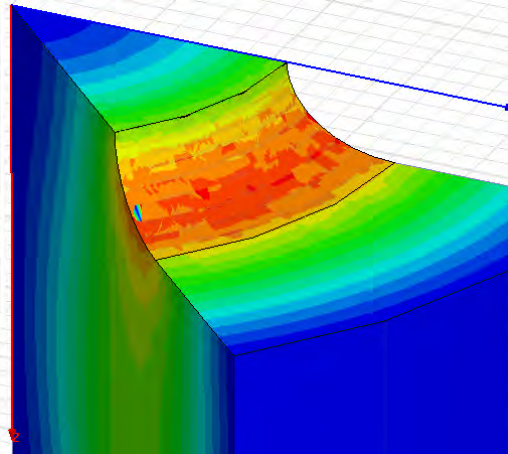
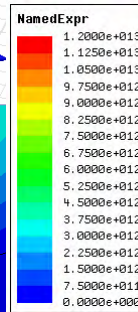
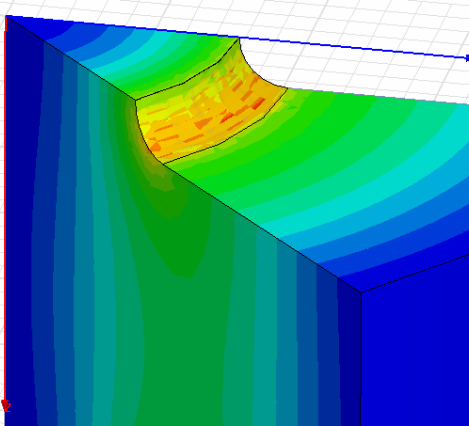
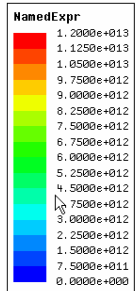
T53vg3



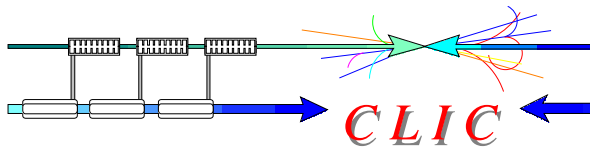
H75vg4S18



HDS4_tk



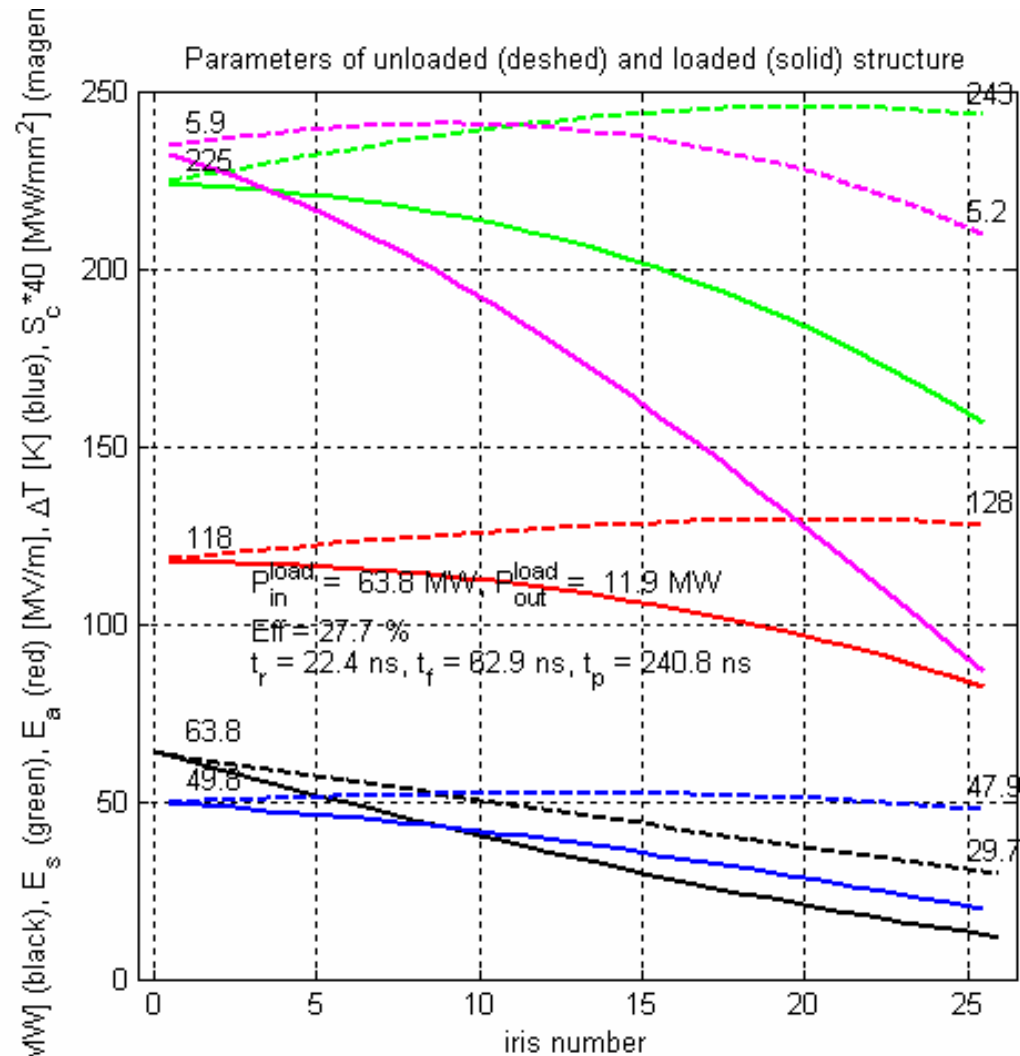
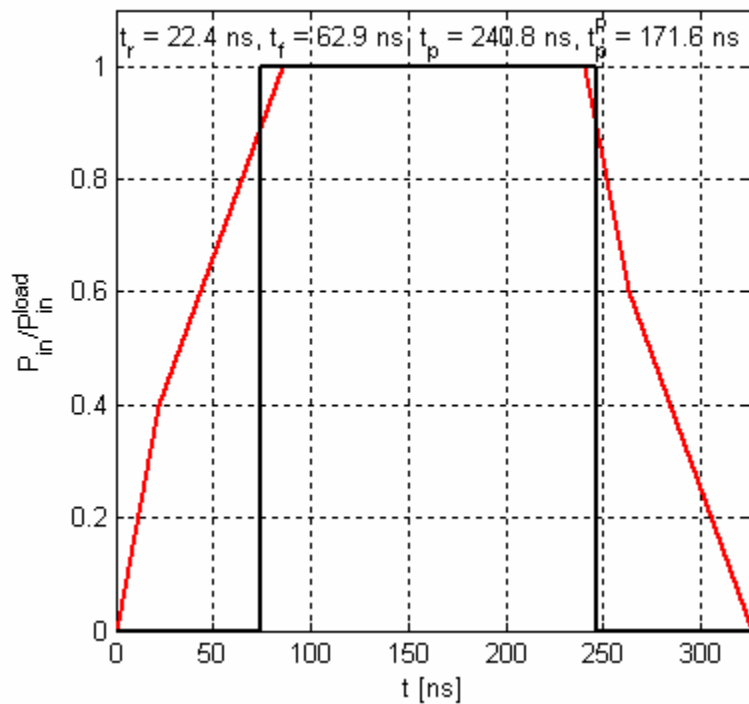
Surface distribution is similar to the electric field one

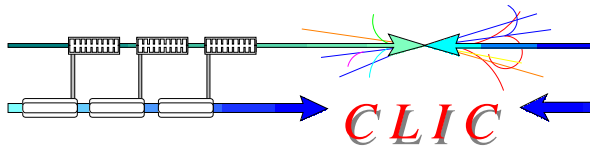


S_c in CLIC_G



S_c reaches 6.05 for nominal parameters.
 Scaling it to 100ns gives:
 $6.05 * (171.6/100)^{1/3} = 7.24$
 To be compared with the measured data.

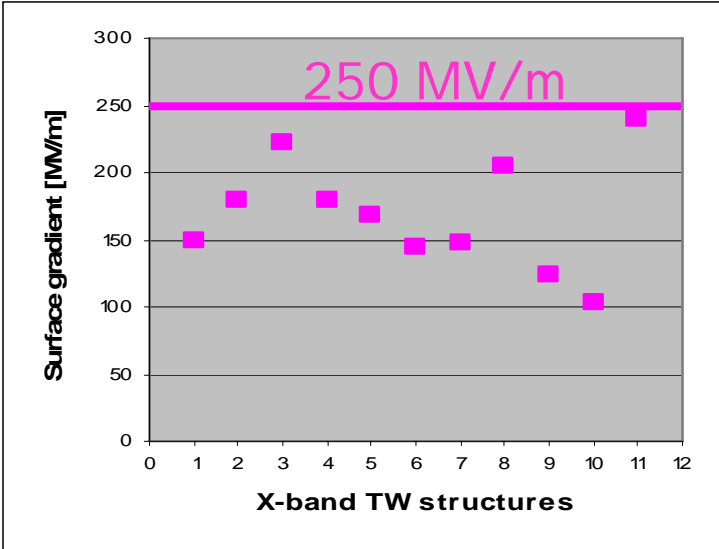
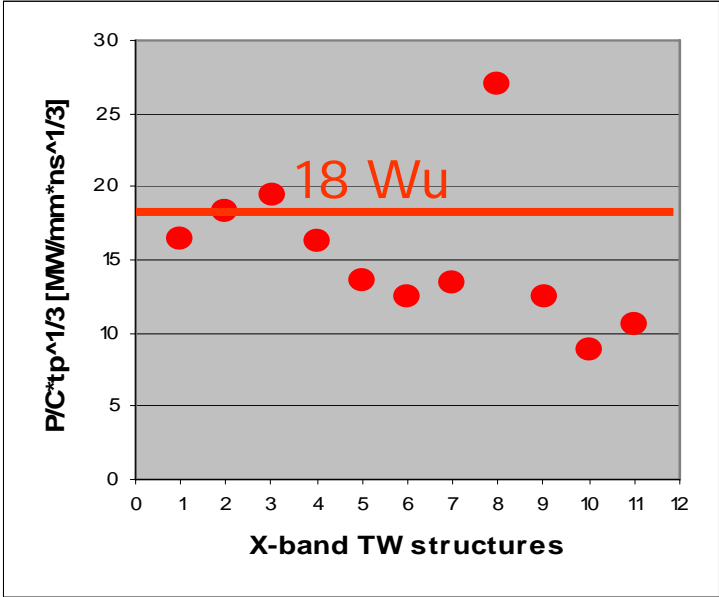
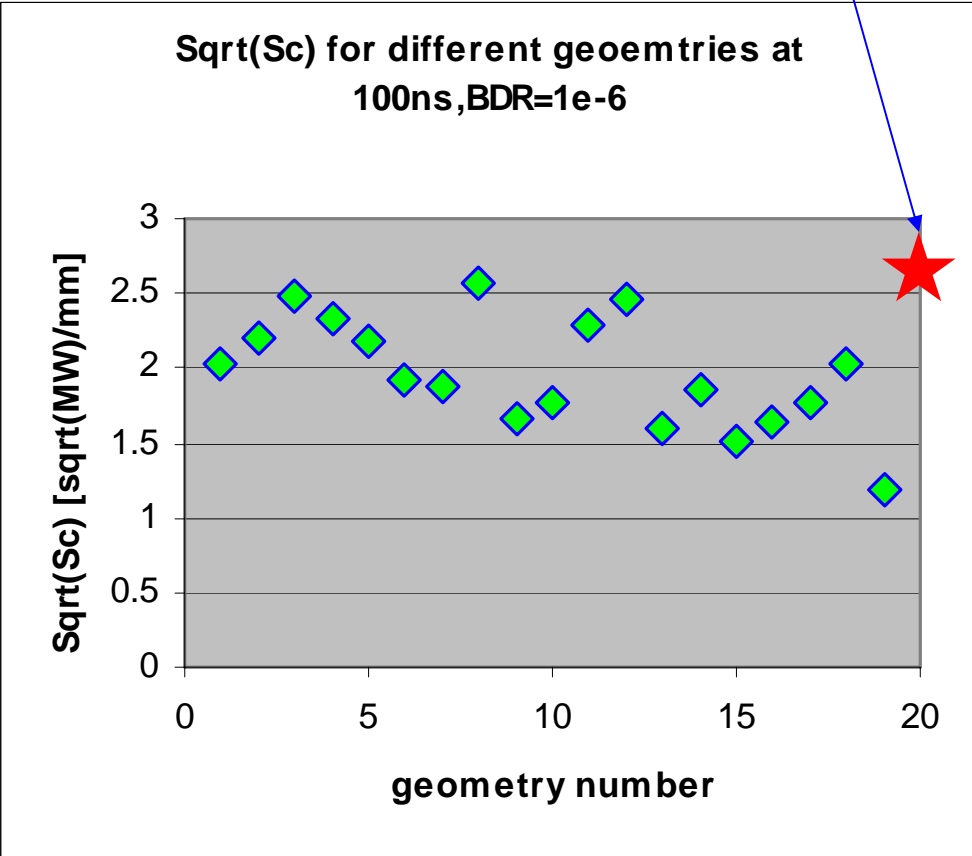


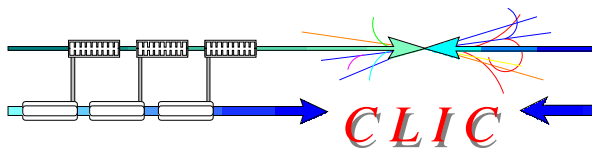


S_c in CLIC_G



Sc values in CLIC_G for the nominal parameters is very challenging





Predictions for test structures



Prediction of average unloaded gradient at rect. pulse length of 100ns and BDR=1e-6 based on the results achieved in T53vg3MC: 102.3MV/m at 100ns and BDR=1e-6:

19.5Wu or $S_c=6.2\text{MW/mm}^2@100\text{ns}$.

	TD18vg2.4	T18vg2.4	T28vg3	TD28vg3	CLIC_G
$P/C*(t_p^P)^{1/3}= 19.5\text{Wu}$					
Average unloaded gradient [MV/m]	132	136	110	104	134
$S_c=6.2\text{MW/mm}^2 @ t_p^P=100\text{ns}$					
Average unloaded gradient [MV/m]	109	106	105	103	120