New EM field quantity limiting achievable accelerating gradient

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Motivation

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

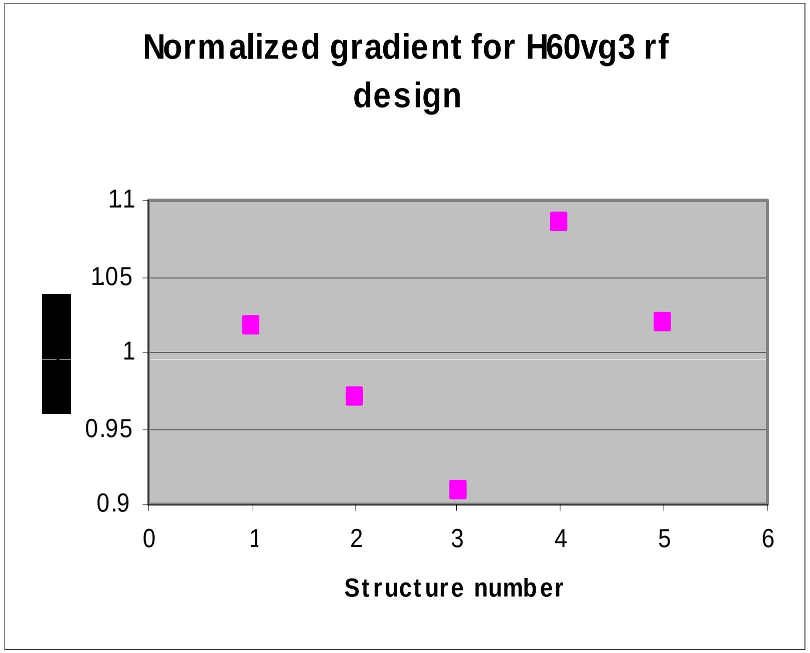
Introduction

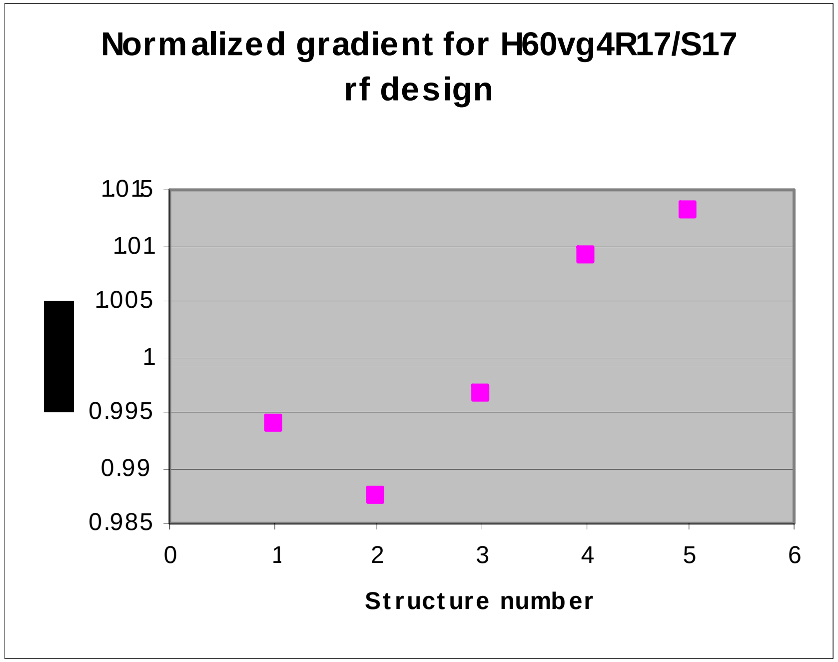
The high-gradient performance depends on:

1. Geometry of the cavity: rf design
2. Surface of the cavity : anything else than rf design
   - Material
   - Heat treatment
   - Machining
   - Chemical treatment
   - Etc…

Introduction

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





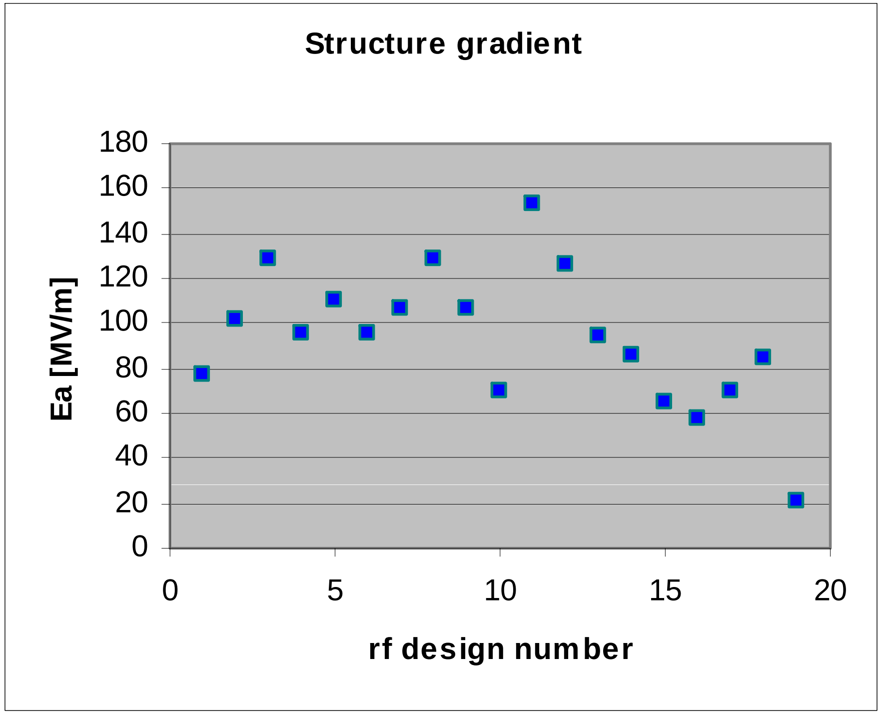
N.B. Variation of up to tens of percents can be expected from the difference in the surface state, statistics and measurement setup.

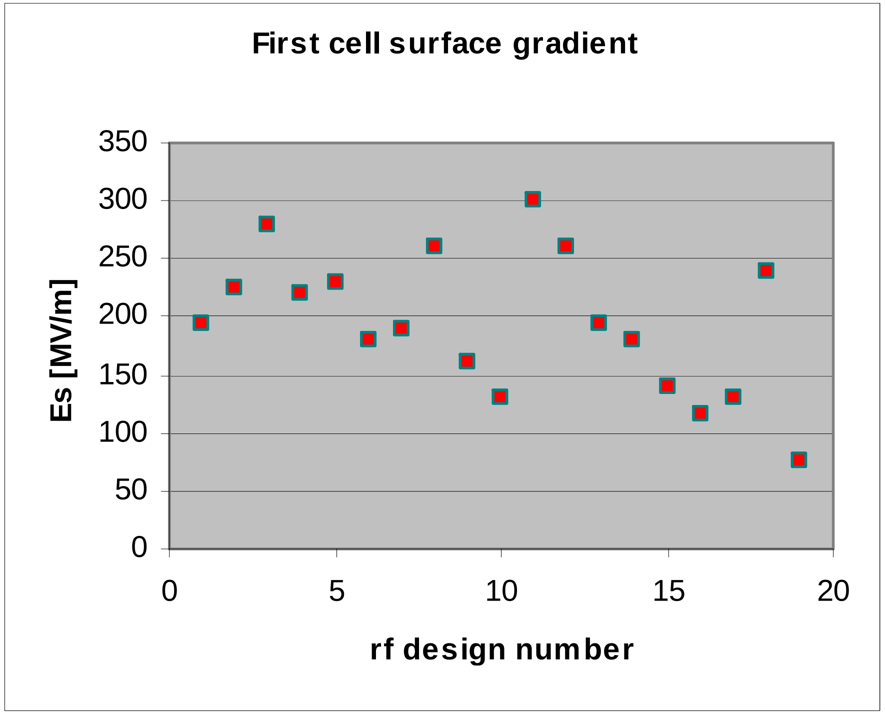
Experimental data @ BDR=10^{-3}, 100ns

	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	77.7
2	T53VG5R	11.424	120	4.45	1.66	1	5	101
3	T53VG3MC	11.424	120	3.9	1.66	1	3.3	128.7
4	H90VG3	11.424	150	5.3	4.2	1	3	95
5	H60VG3-FXB6	11.424	150	5.3	4.4	1	2.8	110
6	H60VG3S18	11.424	150	5.5	4.6	1.15	3.3	95
7	H60VG3S17-FXC5	11.424	150	5.3	3.7	1.34	3.6	107
8	H75VG4S18	11.424	150	5.3	3.04	1.36	4	128.5
9	H60VG4R17-2	11.424	150	5.68	3.65	1.37	4.5	106.4
10	HDX11-Cu	11.424	60	4.21	1.45	2.4	5.1	69.3
11	CLIC-X-band	11.424	120	3	2	1	1.1	153.3
12	SW20a565_1Cell	11.424	180	5.65	4.6	3.4	0	125.7
13	SW20a375	11.424	180	3.75	2.6	1.7	0	94.3
14	2pi/3	29.985	120	1.75	0.85	1	4.7	86.3
15	pi/2	29.985	90	2	0.85	1	7.4	65.5
16	HDS60L	29.985	60	1.9	0.55	2.5	8	57.3
17	HDS60S	29.985	60	1.6	0.55	2.4	5.1	70.2
18	HDS4Th	29.985	150	1.75	0.55	1	2.6	84.9
19	PETS9mm	29.985	120	4.5	0.85	1	39.8	20.6

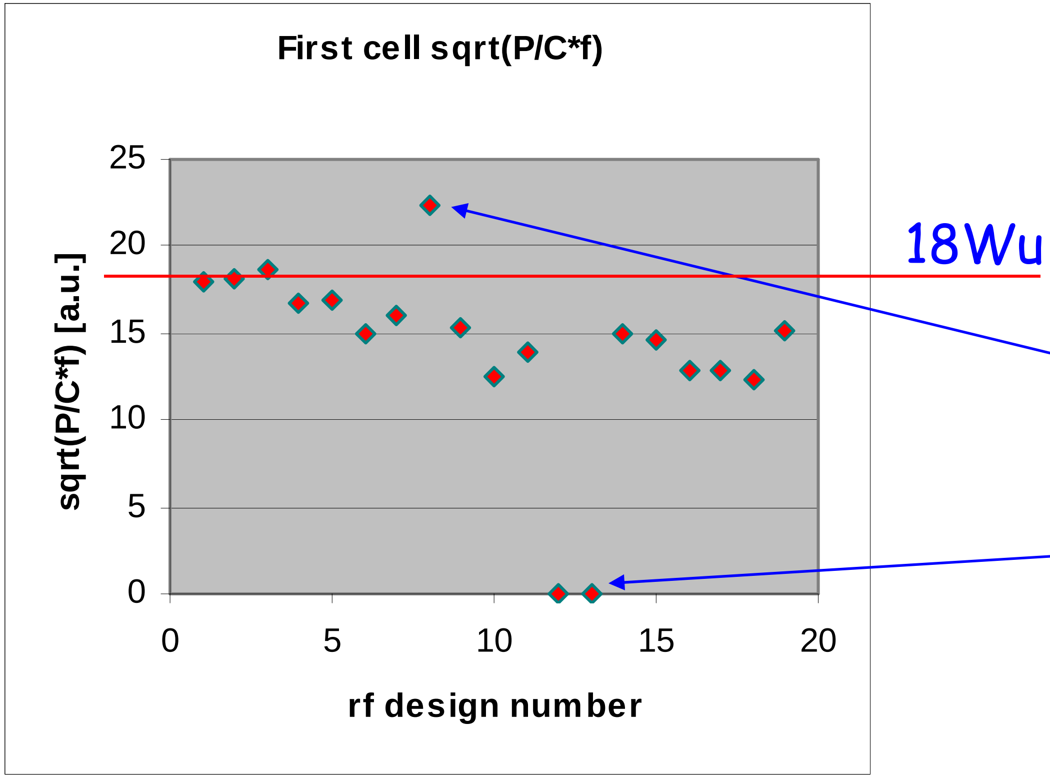
Measurement data were scaled to 100 ns pulse length using $P \cdot t_p^{1/3}$ = const and to BDR=1e-3 using typical slope.

Accelerating and surface gradients





Power over circumference



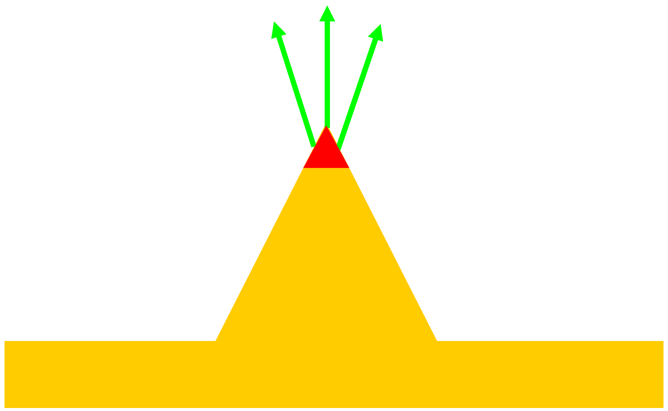
Much better agreement

but

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

Breakdown initiation scenario

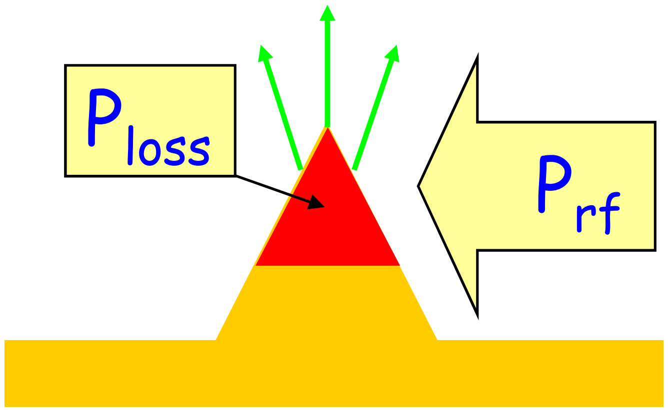
1. Field emission currents J_{FN} heat a (possible) breakdown site up to a temperature rise ΔT on each pulse.
2. After a number of pulses the site got modified so that J_{FN} increases so that ΔT increases above a certain threshold.
3. Breakdown take place.



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



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

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

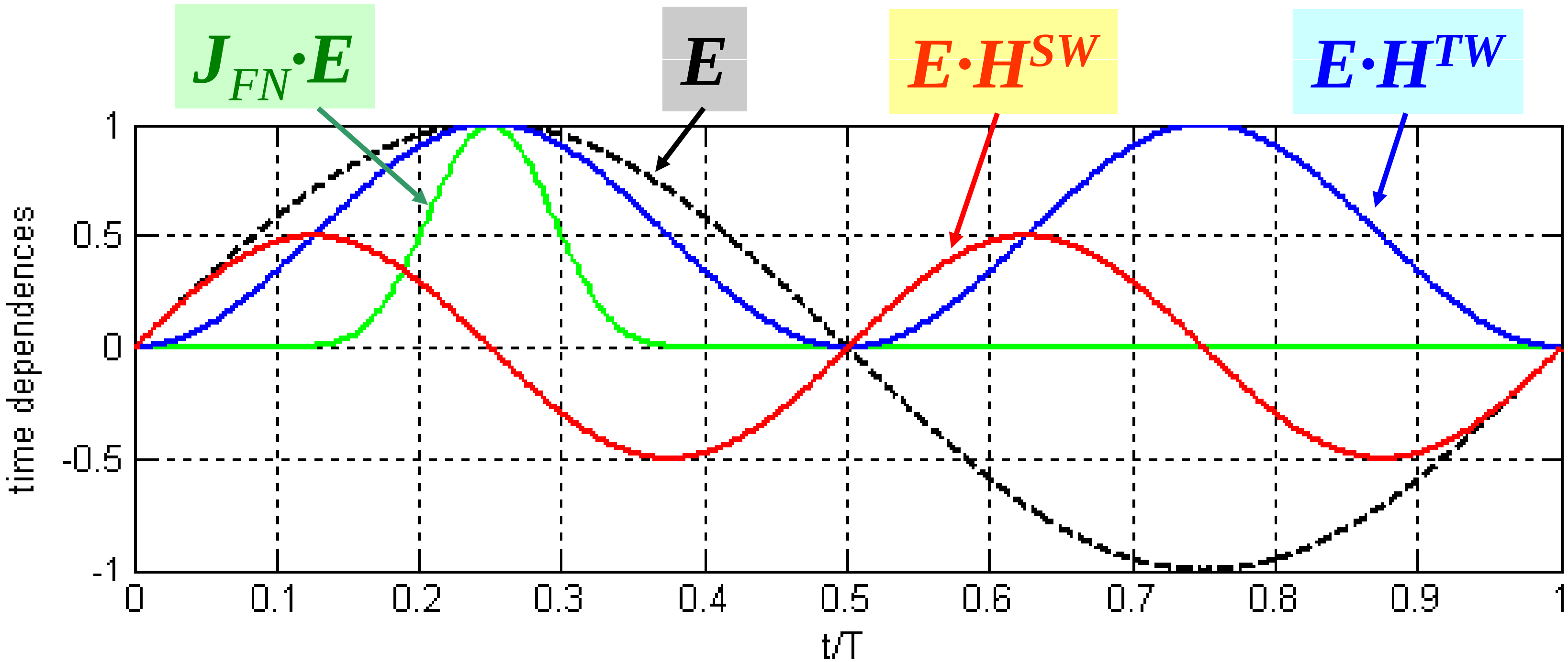
$$P_{rf} = \oint_S E \times H \, ds$$

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

Field emission and power flow

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

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



Field emission and rf power coupling

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

$$P_{coup} = \int_0^{T/4} P_{rf} \cdot P_{loss}\, dt \Big/ \int_0^{T/4} P_{loss}\, dt$$
$$= C^{TW} E_0 H_0^{TW} + C^{SW} E_0 H_0^{SW}$$

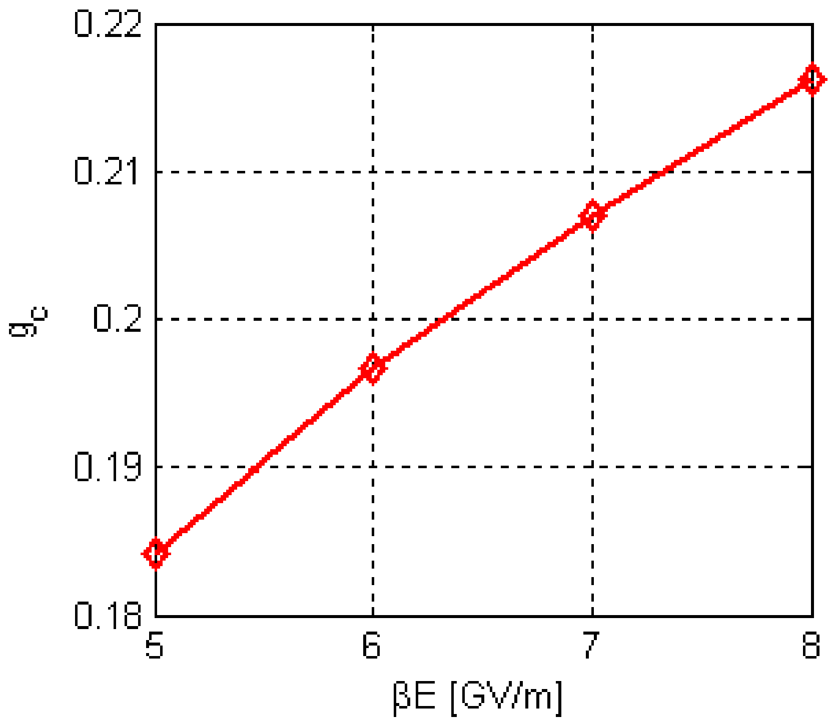
Assuming that all breakdown sites have the same geometrical parameters the breakdown limit can be expressed in terms of modified Poynting vector S_c.

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

Field emission and rf power coupling

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

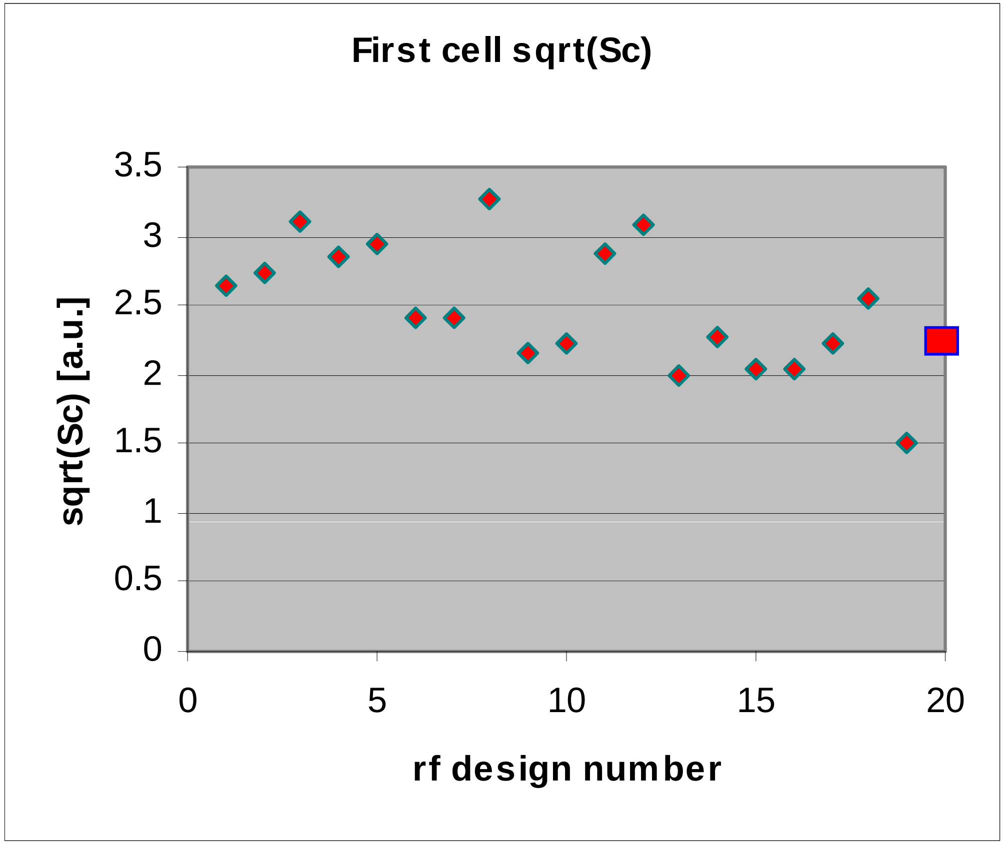
$$g_c = \frac{\int_0^{\pi/2} \sin^4 x \cos x \cdot \exp\left(\frac{-62\,GV/m}{\beta E_0 \sin x}\right) dx}{\int_0^{\pi/2} \sin^5 x \cdot \exp\left(\frac{-62\,GV/m}{\beta E_0 \sin x}\right) dx}$$



$g_c = 0.2$

is assumed in the following analysis of the measurement data

New rf breakdown constraint



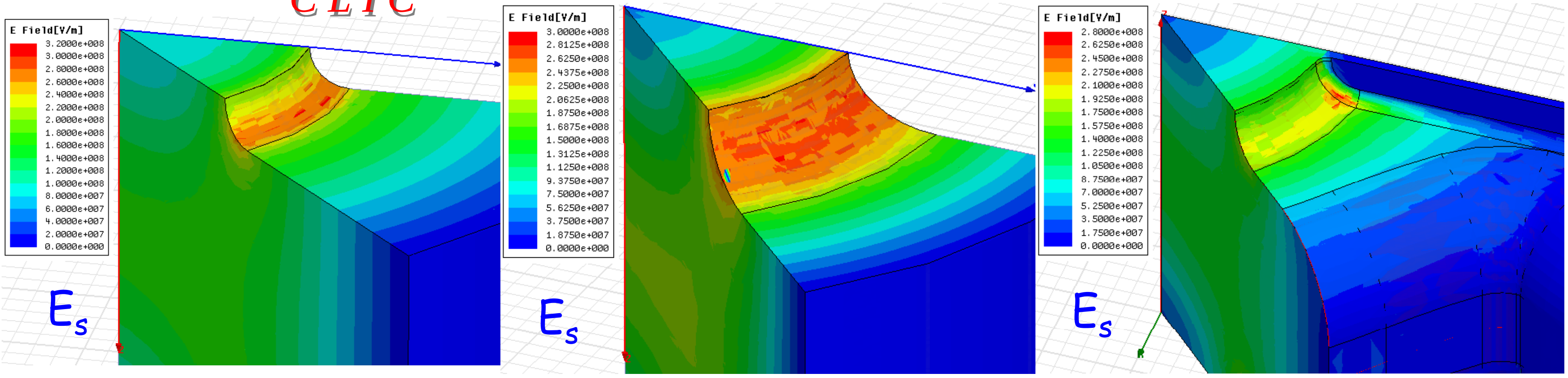
$$S_c = \mathrm{Re}\{\mathbf{S}\} + 0.2 \cdot \mathrm{Im}\{\mathbf{S}\}$$

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

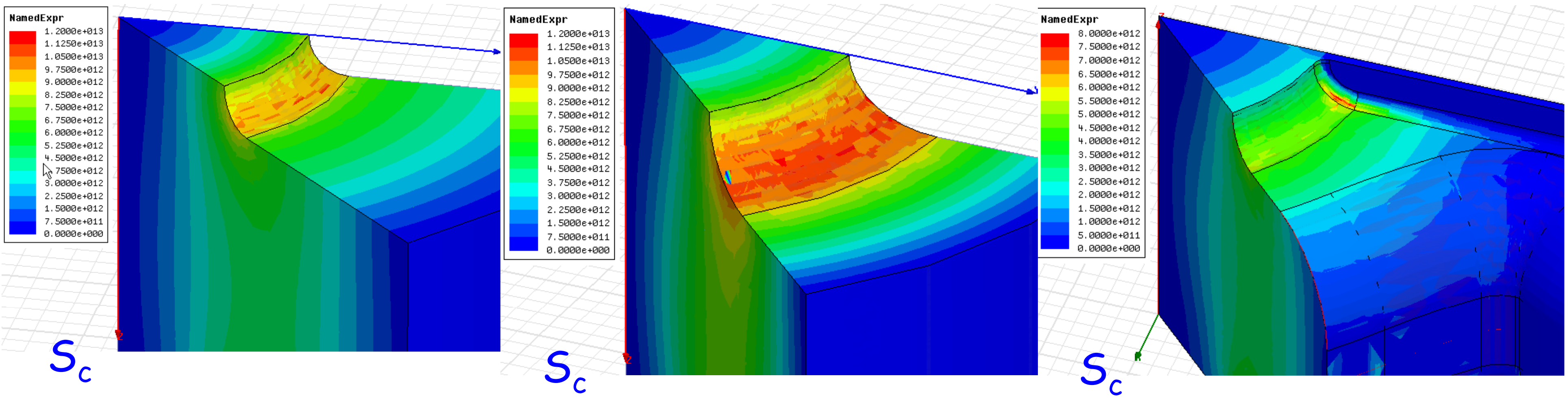
1. This is a local field quantity.
2. H75vg4S18 fits well.
3. It describes standing wave structures.

Depending on the degree of optimism we can choose S_c = 5 ÷ 9 [MW/mm^2] at 100ns, BDR=1e-3

Surface distributions for low v_g

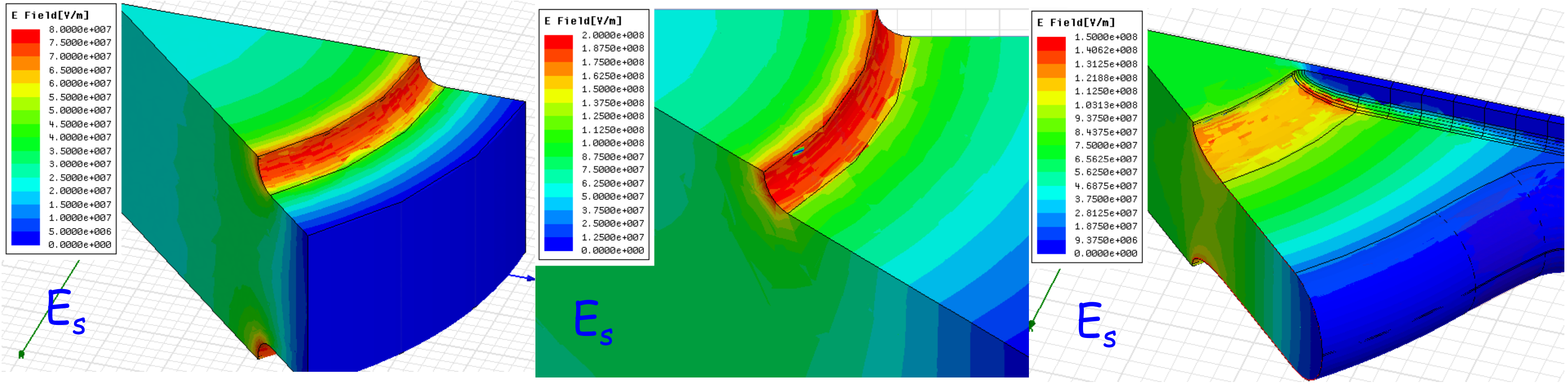


T53vg3 H75vg4S18 HDS4_tk



Surface distribution is similar to the electric field one

Surface distribution for high v_g



PETS9mm DDS1 HDS60S