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A NEW LOCAL FIELD QUANTITY DESCRIBING THE HIGH GRADIENT LIMIT OF ACCELERATING STRUCTURES

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Abstract

A new local field quantity is presented which gives the high-gradient performance limit of accelerating structures in the presence of vacuum rf breakdown. The new field quantity, a modified Poynting vector S_c, is derived from a model of the breakdown trigger in which field emission currents from potential breakdown sites cause local pulsed heating. The field quantity S_c takes into account both active and reactive power flow on the structure surface. This new quantity has been evaluated for many X-band and 30 GHz rf tests, both travelling wave and standing wave, and the value of S_c achieved in the experiments agrees well with analytical estimates.

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INTRODUCTION

Limitations coming from the rf breakdown in vacuum strongly influence the design of a high gradient accelerating structures. Rf breakdown is a very complicated phenomenon involving effects which are described in different fields of applied physics such as surface physics, material science, plasma physics and electromagnetism. No quantitative theory to date satisfactorily explains and predicts rf breakdown levels in vacuum. In the framework of CLIC study [1] a significant effort has been made to derive the high-gradient limit due to rf breakdown and to collect all available experimental data both at X-band and at 30 GHz to use to check the validity of the limiting quantity. The quantity has been used to guide high gradient accelerating structure design and to make quantitative performance predictions for structures in the CLIC high power testing program [2].

EXPERIMENTAL DATA

The quest to accumulate high-gradient data in a coherent and quantitatively comparable way focused on two frequencies: 30 GHz, the old CLIC frequency, and 11.4 GHz which is the former NLC/JLC frequency and is very close to the new CLIC frequency of 12 GHz. To our knowledge only at these two frequencies has a systematic study been done where the structure accelerating gradient was pushed up to the limit imposed by the rf breakdown and where relevant parameters were measured. In particular all available data where the breakdown rate (BDR), the probability of a breakdown during a pulse, was measured at certain gradient and pulse length was collected. Data from structures where the performance was limited by an identified defect or by some other area of the structure such as the power couplers which are not directly related to the regular cell performance were not included. The main parameters of the structures are summarized in the Table 1 which shows the rather large variation in group velocity (from 0 up to ~40 % of the speed of light), rf phase advance (from 60 to 180 degree per cell) and iris geometry which is available for analysis. The experimentally achieved value of the gradient scaled to pulse length of 200 ns and breakdown rate of 10^{-6} per pulse as described below is presented together with the corresponding references.

In a typical high-gradient experiment, the BDR is measured at fixed value of accelerating gradient and pulse length. On the other hand, it is most convenient to compare performance with the achieved gradient at a fixed value of the pulse length and BDR. To do this the measured data has had to be scaled. This involves two steps - first scaling the gradient versus pulse length and then scaling the gradient versus BDR. Both of these scaling behaviours have been measured in a number of structures but not systematically in all cases. In order to scale the data for the structures where these scaling laws have not been measured a general scaling law which us consistent with all measured data has been applied.

The dependence of gradient on pulse length at a fixed BDR has well established scaling law observed in many experiments (see for example [3]):

$$E_{acc} t_p^{1/6} = const \qquad (1)$$

where E_{acc} denotes the gradient and t_p the pulse length. It was also confirmed by fitting the data for the structure numbers 3, 4, 8, 9, 10, 12, 13, 18, 20 in Table 1.

For the gradient versus BDR dependence at a fixed pulse length the different scaling laws which have been used are exponential (see for example [3]) and a power law. In this paper, we have used a power law:

$$E_{acc}^{30} / BDR = const \qquad (2)$$

It was also confirmed by fitting the data for the structure numbers 3, 8, 10, 12, 13, 18, 20, 21 in Table 1.

Finally, (1) and (2) can be combined into,

$$E_{acc}^{30} t_p^{5} / BDR = const \qquad (3)$$

This general scaling law has been used to scale the collected experimental data to the pulse length of 200 ns and BDR of 10^{-6} per pulse. The results are presented in the last column of Table 1.

RF BREAKDOWN CONSTRAINTS

For a long time, the surface electric field was considered to be the main quantity which limits accelerating gradient because of its direct role in field

Table 1: Structure parameters used in the analysis. From left to right: number for references in the following figures, name, frequency, rf phase per cell, group velocity and first iris radius, thickness and tip ellipse ratio (except for T18vg2.6-Out, where v_g/c, a, d and e are given for the last regular cell), and the accelerating gradient (average or single cell depending on the structure type) scaled to the pulse length of 200 ns and BDR of 10^{-6} per pulse.

N	Name	*f* [GHz]	Δφ [°]	v_g/c [%]	*a* [mm]	*d* [mm]	*e*	E_{acc} [MV/m] @ 200 ns, 10^{-6} 1/pulse
1	DDS1	11.424	120	11.7	5.7	1.0	1	52.9 (average) [4]
2	T53vg5R	11.424	120	5.0	4.45	1.66	1	72.0 (average) [4]
3	T53vg3MC	11.424	120	3.3	3.9	1.66	1	91.1 (average) [4]
4	H90vg3	11.424	150	3.0	5.3	4.2	1	69.2 (average) [4]
5	H60vg3	11.424	150	2.8	5.3	4.4	1	72.0 (average) [4]
6	H60vg3S18	11.424	150	3.3	5.5	4.6	1.15	67.7 (average) [3, 4]
7	H60vg3S17	11.424	150	3.6	5.3	3.7	1.34	74.2 (average) [3, 4]
8	H75vg4S18	11.424	150	4.0	5.3	3.04	1.36	90.0 (average) [4]
9	H60vg4S17	11.424	150	4.5	5.68	3.65	1.37	73.6 (average) [3, 4]
10	HDX11	11.424	60	5.1	4.21	1.45	2.4	49.3 (first cell) [5]
11	CLIC-X-band	11.424	120	1.1	3.0	2.0	1	107.3 (first cell) [6]
12	T18vg2.6-In	11.424	120	2.6	4.06	2.79	1.21	114.5 (average) [7]
13	T18vg2.6-Out	11.424	120	1.0	2.66	1.31	1.15	114.5 (average) [7] v_g/c, *a*, *d*, *e* for last cell
14	SW1a5.65t4.6	11.424	180	0	5.65	4.6	3.4	92.2 (single cell) [8]
15	SW20a3.75	11.424	180	0	3.75	2.6	1.7	67.0 (average) [4]
16	SW1a3.75t2.6	11.424	180	0	3.75	2.6	1.7	135.6 (single cell) [8]
17	SW1a3.75t1.66	11.424	180	0	3.75	1.66	1	135.2 (single cell) [8]
18	2π/3	29.985	120	4.7	1.75	0.85	1	61.1 (first cell) [9]
19	π/2	29.985	90	7.4	2	0.85	1	43.3 (first cell) [10]
20	HDS60L	29.985	60	8.0	1.9	0.55	2.5	40.5 (first cell) [11]
21	HDS60S	29.985	60	5.1	1.6	0.55	2.4	49.7 (first cell) [11]
22	PETS9mm	29.985	120	39.8	4.5	0.85	1	14.6 (last cell) [12]

emission. The magnetic field was considered to be unimportant. However, as more data has become available, it is clear that the maximum surface electric field could not serve as an ultimate constraint in the rf design of high gradient accelerating structures because the large variation of achieved surface electric field as shown in Fig. 1(top).

Recently, new ideas have appeared about the importance of power flow in the accelerating structures. The proposal that the ratio of the input power to the iris circumference, *P/C*, is the parameter which limits gradient in travelling-wave structures (TWS) is presented in [13]. The square root of *P/C* (to be linear in field quantity) is plotted in Fig. 1(middle). It is evident that P/C shows much smaller spread than surface electric field and therefore is a better constraint to be used in rf design. Nevertheless, there are shortcomings which limit its applicability:

- Structure number 8 exceeds significantly all the others.
- Standing-wave structures (SWS) are not described by definition as there is essentially no power flow through the iris aperture.
- Data achieved at different frequencies must be scaled inversely with frequency.

The last point is also confirmed by an observation that scaled structures achieve the same gradient at the same pulse length and BDR [5, 11]. This observation also favours an idea that it is a combination of local electric and magnetic fields which sets a limit to achievable gradient rather than an integral parameter which must then be scaled with frequency.

A NEW QUANTITY

The new proposed field quantity is based on the following considerations. First, at very low values the BDR is determined mainly by processes which accumulate over many pulses rather than during a single pulse. Local pulsed heating of future breakdown sites by the field emission currents is consistent with this

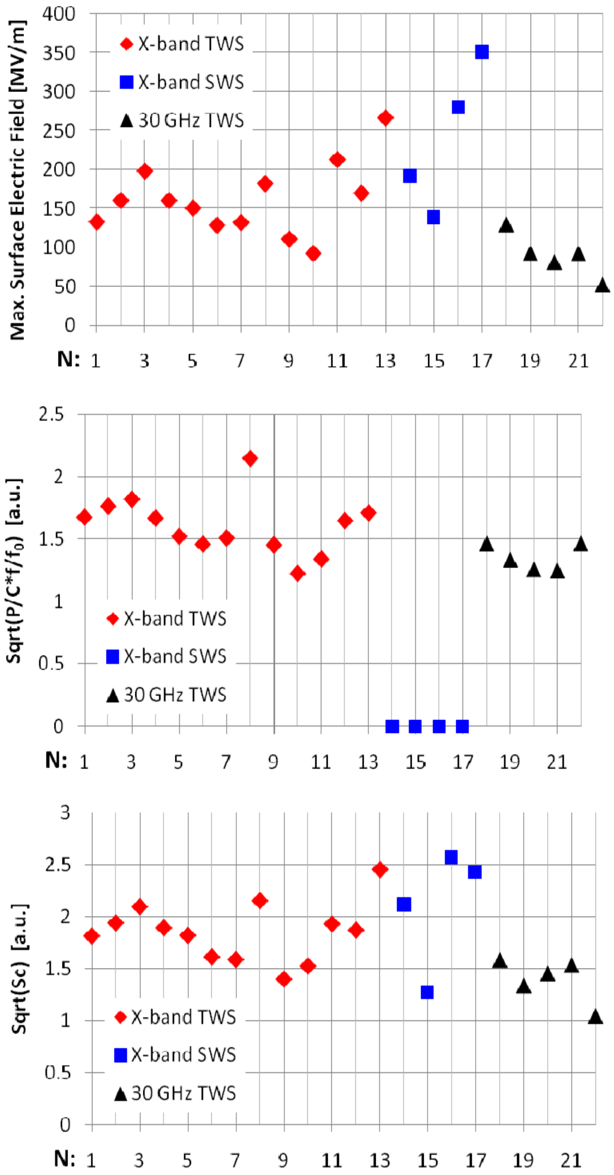

Figure 1: Maximum surface electric field (top), square root of P/C (middle) and square root of S_c (bottom) are scaled to pulse length of 200 ns and BDR of 10^{-6} per pulse and plotted for the structures presented in Table 1. For P/C, 30 GHz data scaled by factor 30/11.4.

postulate. The actual trigger of a breakdown can be via many mechanisms and its combinations - mechanical fatigue and fracture, melting, gas desorption – the details of which are not relevant for further considerations. Second, any heating requires power and there is no other source of power other than rf power flow on the surface. This is naturally described by the complex Poynting vector *S*. The real part, $\mathrm{Re}\{S\}$, describes active power flow along TWSs. It is however zero in SWSs. $\mathrm{Im}\{S\}$ describes reactive power flow inside the cells and is non-zero in all rf structures. Electric and magnetic fields are in phase in $\mathrm{Re}\{S\}$ 90 degree out of phase in $\mathrm{Im}\{S\}$. Thus the reactive power flow couples much more weakly to the field emission current than active power flow. Taking this into account along with the exponential dependence of emission current on electric field the new quantity, the modified Poynting vector:

$$S_c = \mathrm{Re}\{S\} + \mathrm{Im}\{S\}/6 \qquad (4)$$

is proposed. The square root of S_c is plotted in Fig. 1(bottom) and demonstrates rather good agreement between the structures from Table 1. It effectively combines the surface electric field and P/C limits and can be used as a single rf breakdown constraint in rf design. Its numerical value should not exceed 5.5 W/μm^2 in order to have BDR below 10^{-6} 1/pulse at pulse length of 200 ns.

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