Geometric dependence of radio-frequency breakdown in normal conducting accelerating structures

Valery Dolgashev,[1,a)] Sami Tantawi,[1] Yasuo Higashi,[2] and Bruno Spataro[3]
[1]*SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*
[2]*High Energy Accelerator Research Organization, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[3]*INFN-LNF, 00044 Frascati, Italy*

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We present the experimental results of a systematic study of rf breakdown phenomenon in high vacuum accelerator structures. In this study, the surface processing, geometry, and materials of the structures have been varied, one parameter at a time. The breakdown rate or alternatively, the probability of breakdown/pulse/meter has been recorded for different operating parameters. These statistical data reveal a strong dependence of breakdown probability on surface magnetic field, or alternatively on surface pulsed heating. This is in contrast to the classical view of electric field dependence. We will present our experimental methodology and results showing this remarkable correlation. © *2010 American Institute of Physics*. [doi:10.1063/1.3505339]

Over the years, our basic understanding of gradient limits of room temperature linear accelerators, built from pure copper, have changed dramatically. The original studies by Loew and Wang[1] painted an optimistic picture for the attainable gradients, predicting a gradient close to 300 MV/m if one operated at high enough frequency, Ku-band, for example. This is in contrast to the long-lived S-band SLAC linac, which has operated for decades at 17 MV/m. At that time, no special attention had been paid to the statistical nature of the problem or to the possibility of structure detuning due to repetitive breakdown, which leads to structure erosion. Later, experiments with beam driven cavities predicted no frequency scaling that favors higher frequencies in the range between 21 to 39 GHz.[2] These experiments again neglected the statistical nature of the phenomenon, and the possibility of geometrical dependence. This led to the original choice of the CERN's compact linear collider (CLIC) frequency of 30 GHz.[3] Later, initial testing of the next linear collider (NLC)[4] accelerator structures resulted in structures detuning at much lower gradients. Eventually, the NLC design was limited to a loaded gradient of 52 MV/m. Experiments with 30 GHz structures also faced similar limitations. Nonetheless, the ultimate limit was set by the statistical nature of the phenomenon. For collider applications, in particular, with several kilometers of linear accelerators, the breakdown probability needs to be very low $<10^{-6}$/pulse/meter. These statistical constraints, which are application dependant, limit the practical attainable gradient for a given structure.

Dependence of the breakdown phenomenon on the magnetic field rather than the electric field was conjectured in (Ref. 5). Later, combining all the available data around the world for the phenomenon, Grudiev *et al.*[6] came up with an empirical quantity that involves the magnetic field to describe the phenomenon. However, in these papers, the experimental data were collected under different testing conditions with different cleaning and manufacturing techniques at different frequencies and with different structure circuit parameters and rf coupler geometries. The structure circuit parameters play a dual role. First, they control the local variation to the Poynting vector, and hence the ratio between electric and magnetic fields on the surface, for a given group velocity, for example. Second, they determine the mutual coupling between cells and how energy flows from one part of the structure to another in the event of a breakdown.

Here, we present the true systematic study of the phenomenon, in which parameters are varied one at a time. One of the most difficult aspects of studying breakdown phenomenon is the cost of these studies. Building and processing the structures and the associated microwave couplers is expensive enough to limit the number of structure built/year at any laboratory to only a few. Furthermore, collecting breakdown statistics requires a long time and depends on the availability of high repetition rate hundred-megawatt class microwave sources.

Interpreting the data collected from testing full length accelerator structures does not lend itself directly to the basic physics underlaying the phenomenon. The mutual interactions between large set of cavities that comprise the structure result in a complex system; one is often studying the system interactions rather than the origin of the breakdown phenomenon.

To overcome these limitations, we have designed a special microwave mode converter which launches the TM_{01} mode into a circular cylindrical waveguide. This was used in conjunction with a special flange to guarantee the continuity of axial currents. This mode converter coupler is then used to feed a simple standing-wave accelerator structure. This allowed us to eliminate the cost of building an rf coupler for each structure. As for the accelerating structure, only the central cell of the structure mimics the high electric and magnetic fields in a full-scale standing-wave structure. This cell is surrounded by two matching cells that mimic, from a circuit point of view, the rest of the standing-wave structure. These matching cells and the mode couplers that transform the TE_{10} mode of rectangular waveguide into the "accelerating" circular TM_{01} mode, operate at much lower fields than the central test cell. The rf for all of these experiments was 11.424 GHz.

[a)]Electronic mail: dolgash@slac.stanford.edu.

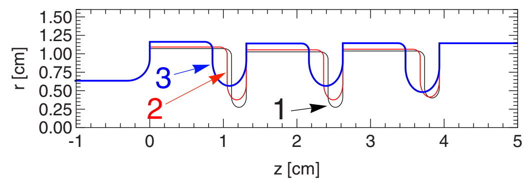

FIG. 1. (Color online) Geometries of three standing wave structures: (1) $a/\lambda=0.105$; (2) $a/\lambda=0.143$; and (3) $a/\lambda=0.215$. rf power is fed into the structure from the right. A cutoff waveguide is on the left.

With this arrangement breakdowns occur predominantly in the high gradient cell while the two other cells have surface conditions unperturbed by the breakdowns. This was confirmed repeatedly through the autopsy of many structures.

Using reusable couplers, we have been able to compile results from close to 30 different experiments over a three year time period. All the experiments were done at SLAC using a 50 MW klystron operating at 60 Hz repetition rate. The structures have been built at different laboratories around the world, SLAC, KEK, and INFN-Frascati.

The first set of experiments was aimed at verifying the reproducibility of the data as follows:

- We verified that the measured breakdown rates for a given geometry and a given type of copper is consistent irrespective of the laboratory that built it. This, indeed was the case.
- We studied the dependence of the breakdown rates on the type of copper used. We tested following three purities:

(1) Oxygen free high conductivity copper with purity of 99.99%.
(2) Hot isostatic pressurized copper with purity of 99.9999%.
(3) Ultrapure copper with purity of 99.999 99%.

These three different grades of copper gave very similar results. Within the measurement tolerances, they cannot be distinguished.

We also studied surface preparation and cleaning techniques. Ultimately a structure was built at KEK and processed with techniques similar to superconducting rf structures, which included rinsing with pressurized ultrapure water.

When we compare the breakdown rate of the clean structure to a normally processed copper structure built at SLAC, the two structures are virtually undistinguishable. The only difference observed was in the processing time. Typically accelerator structures take some time to reach their steady-state gradients; during that time the power is changed gradually and the breakdown rate at a given power level drops or increases with time. The origin of this processing phenomenon for copper structures is still an open problem. However, the ultraclean structure was processed faster. The next set of experiments concerned the geometrical effects on the breakdown rates at a given gradient. Three different types of structures were constructed. Each of them have different iris diameters. The iris shape of these structures is elliptical to reduce electrical field on the iris tips by decreasing the local curvature at the high electric field region. The structure shapes are shown in Fig. 1 and the properties of the high field cell of these structures at a gradient of a 100 MV/m are summarized in Table I. The breakdown rate was measured for these structures and the results are shown in Figs. 2(a)–2(c). One can see from the first two figures that the data does not correlate at all with either the accelerating gradient or the surface electric field. For the same breakdown probability one finds that the spread in the effective surface elec-

TABLE I. Parameters of periodic structures normalized to 100 MV/m accelerating gradient.

Structure number	1	2	3
Stored energy (J)	0.153	0.189	0.298
Q-value (10^3)	8.59	8.56	8.38
Shunt impedance (MΩ/m)	102.891	82.598	51.359
H_{max} (MA/m)	0.290	0.325	0.418
E_{max} (MV/m)	203.1	202.9	211.4
Losses in a cell (MW)	1.275	1.588	2.554
a (mm)	2.75	3.75	5.65
a/λ	0.105	0.143	0.215
$H_{max}Z_0/E_{acc}$	1.093	1.224	1.575
t (mm)	2	2.6	4.6
Iris ellipticity	1.385	1.692	1.478

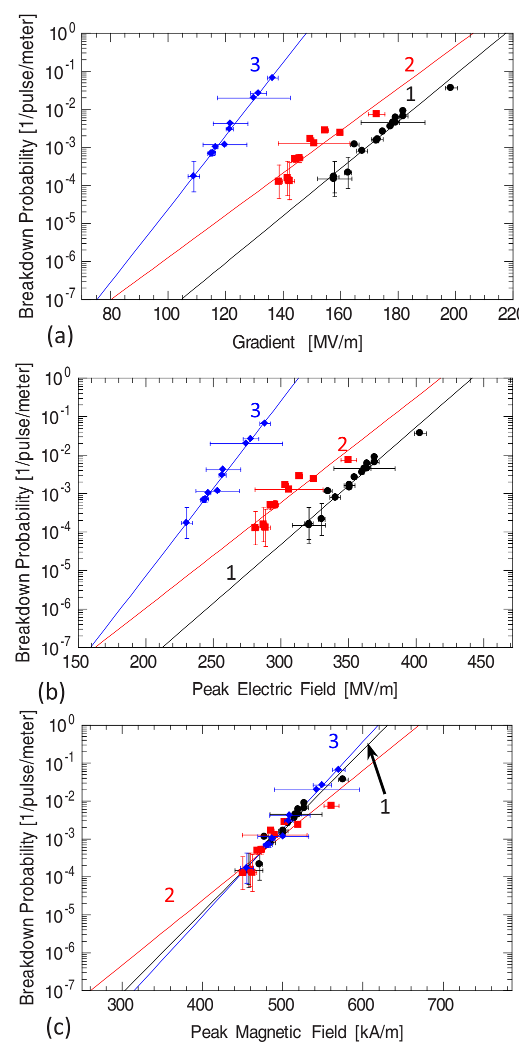

FIG. 2. (Color online) Comparison between three different structures with different apertures. The size of the vertical error bar on the plot is proportional to the $1/\sqrt{n}$, where n is the number of breakdowns during the experiment. The size of the horizontal error bar equals to the standard deviation of the measured value.

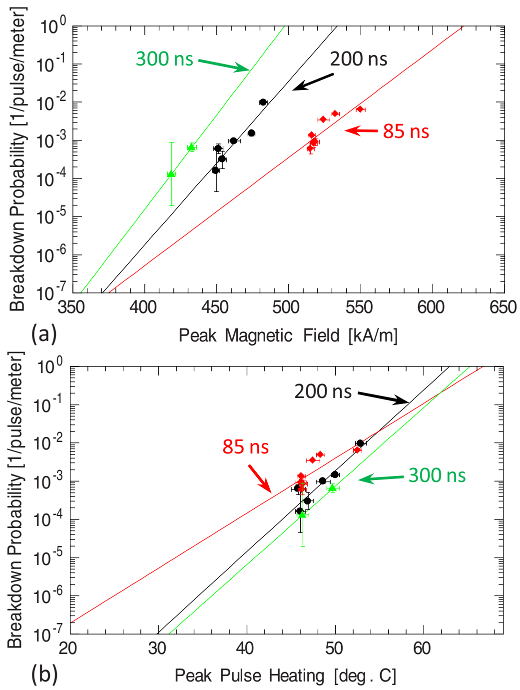

FIG. 3. (Color online) Breakdown rates as a function of peak magnetic field (a) and as a function of the peak pulsed heating during the pulse (b).

tric field is close to a factor of 1.4. Two accelerating structures; one operating at 250 MV/m surface field while the other at 350 MV/m yet they have the same breakdown rate. The picture is quite different if one looks at the third figure. Most of the data correlates very well with peak magnetic field.

Breakdown probability varies with pulse duration as well as peak fields. Breakdown probability as a function of the pulse length gives us a preferred view to the pulsed heating picture rather than the peak magnetic field picture. Figure 3 shows that the data would correlate better if one took the pulsed heating as the figure of merit. The peak pulsed heating is proportional to the square of the magnetic field; see Ref. 7. Indeed, the physics behind this is still an open problem. Furthermore, pulsed heating is just a figure of merit that combines the square of the magnetic field and roughly the square root of the pulse length. Certainly a theory that explains the origin of this experimental data is now needed.

To summarize we have made a systematic study of different geometries for standing-wave accelerator structures. The commonly believed ideas about peak electric field and the related dark currents as the root cause of rf breakdown does not correlate well with our data. However, the data correlates very well with the peak surface pulsed heating caused by the surface magnetic field. We performed a systematic study in which all other effects such as surface processing and manufacturing techniques could be eliminated from the process, and the results clearly show the importance of the magnetic fields in characterizing the breakdown process. The natural extension of this work is to carry these studies to materials that have higher tolerance to surface fatigue due to pulsed heating effects[8] such as CuZr and CuCr rather than pure copper. This extension is currently being investigated by the authors with encouraging preliminary results.

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