STATUS OF HIGH POWER TESTS OF NORMAL CONDUCTING SINGLE-CELL STANDING WAVE STRUCTURES *

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INTRODUCTION

Our experiments are directed toward the understanding of the physics of rf breakdown in systems that can be used to accelerate electron beams at ~ 11.4 GHz [1]. The structure geometries have apertures, stored energy per cell, and rf pulse duration close to that of the NLC [2, 3] or CLIC [4]. The breakdown rate is the main parameter that we use to compare rf breakdown behavior for different structures [5] at a given set of rf pulse parameters (pulse shape and peak power) at 60 Hz repetition rate. In our experiments, the typical range of the breakdown rate is from one per few hours to ~ 100 per hour. To date we have tested 29 structures. We consistently found that after the initial conditioning, the behavior of the breakdown rate is reproducible for structures of the same geometry and material, and the breakdown rate dependence on peak magnetic fields is stronger than on peak surface electric fields for structures of different geometries [6]. Below we report the main results from tests of seven structures made from hard copper, soft-copper alloys and hard-copper alloys. Additional details on these and other structures will be discussed in future publications.

GEOMETRIES AND MATERIALS

The single-cell standing wave structure consists of three parts: the input coupler cell, the high-gradient middle cell, and the end cell [1]. The geometry of the high-gradient middle cell is based on the geometry of a periodic accelerator structure cell. In this paper we discuss structures of two baseline geometries. Table 1 lists the parameters for these two cells. In this table Z_0 is 120π Ohm, *a* is the iris aperture, $\lambda = 26.242$ mm is the wavelength at 11.424 GHz, and t is the iris thickness. All the field-dependent parameters are normalized to 100 MV/m accelerating gradient for the speed of light particle.

The names of the single-cell structures are derived from the names of the corresponding periodic structures plus the manufacturer's name and a serial number. Some structures have additional features, which we also add to its name. An example of a name is: 1C-SW-A5.65-T4.6-Clamped-Cu-SLAC-#1. Here 1C is the number of high-gradient cells (1 cell in this case), A5.65 is the iris aperture in mm, T4.6 is the iris thickness in mm, "Clamped" is a distinguishing feature, SLAC is the manufacturer, and #1 is the serial number. Here we present results for the following structures:

- three low-shunt-impedance structures made of soft-copper alloys: 1C-SW-A5.65-T4.6-CuAg-SLAC-#1, CuCr-SLAC-#1, CuZr-SLAC-#1
- one high-shunt-impedance, soft-copper-alloy structure: 1C-SW-A3.75-T2.6-CuAg-SLAC-#1
- one low-shunt-impedance, hard-copper, clamped: 1C-SW-A5.65-T4.6-Clamped-Cu-SLAC-#1
- one low-shunt-impedance, hard-copper structure joined by electroforming: 1C-SW-A5.65-T4.6-Electroformed-Cu-Frascati-#1
- one high-shunt-impedance, hard-CuZr, clamped: 1C-SW-A3.75-T2.6-Clamped-CuZr-SLAC-#1

The motivation for the study of hard copper and the hard and soft-copper alloys came from results of our pulse heating experiments [7]. In these experiments discs of different materials were exposed to pulse rf magnetic fields, with estimated pulse temperature rise of up to 110°C. Discs made of high-temperature annealed soft copper showed signs of surface damage at about 50°C estimated pulse heating temperature. The discs made of hard copper and hard-copper alloys (CuCr, CuZr) had significantly less damage at 110°C. In our tests of single-cell standing-wave structures made of soft copper, the breakdown rates showed strong direct correlation with peak surface magnetic field and peak pulse heating temperature [6]. Typically, the breakdown rates were below one per hour at pulse surface heating of about 40°C. To check if the before-test resistance to pulse heating damage is relevant to rf breakdown performance, we tested cavities made of hard copper, soft-copper alloys, and hard-copper alloys.

Most of our high gradient structures have both vacuum and rf joints made by high temperature brazing or bonding. This high temperature processing softens the metal, thus reducing its resistance to pulse heating damage. To evaluate the effect of the initial hardness on the rf breakdown performance, we first obtained reference data from structures made of soft materials. We already have data on soft-copper structures. For this series of tests, we made high temperature brazed structures from these copper alloys: CuZr, CuCr, and CuAg. To test the hardened metals we used two techniques: 1) the cells were clamped then put into a vacuum tank; 2) the cells were clamped then electroplated [8] with a layer of copper to insure vacuum integrity.

RESULTS

The testing procedure is described in [5, 6]. Here we show data for hard copper and for soft and hard-copper alloys comparing them to the soft-copper data. The data is obtained by powering the structures with a shaped pulse that simulates multibunch beam loading. The rf pulse has a charging time of ~170 ns followed by a flat part ranging from 100 to 600 ns. Typically we run a structure with with 100 ns, 150 ns, 200 ns, 400 ns, and 600 ns flat part to study the pulse-length dependance of the breakdown rate. All the data shown was taken after initial processing.

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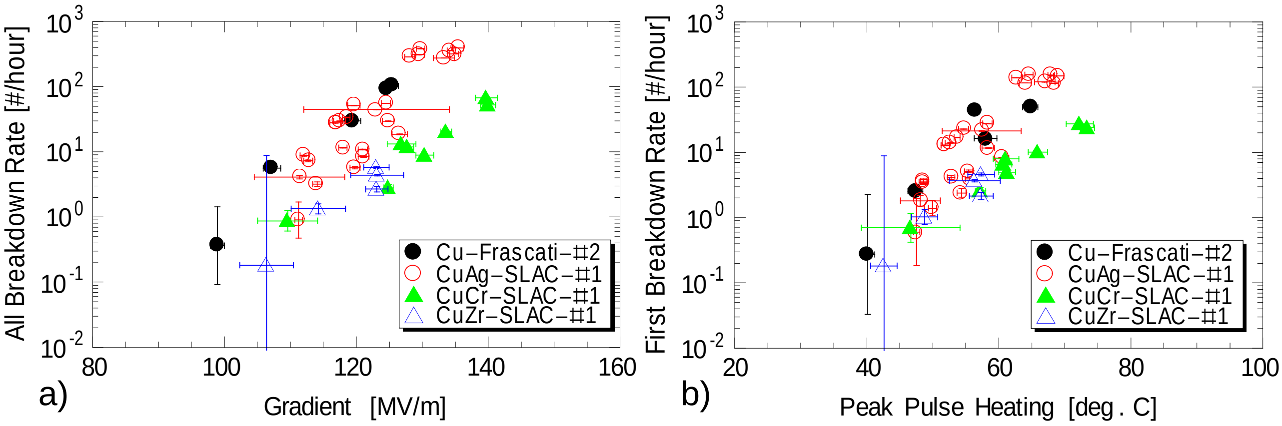

Figure 1: Breakdown rates for low-shunt-impedance soft-metal structures: 1C-SW-A5.65-T4.6-Cu, CuAg, CuCr, CuZr. The data is for a shaped rf pulse with a 150 ns flat part.

Table 1: Parameters of periodic structures normalized to 100 MV/m accelerating gradient.

Structure name	A3.75-T2.6-Cu	A5.65-T4.6-Cu
Stored energy [J]	0.189	0.298
Q-value [10^3]	8.56	8.38
Shunt impedance [MOhm/m]	82.598	51.359
H_{max} [MA/m]	0.325	0.418
E_{max} [MV/m]	202.9	211.4
Losses in a cell [MW]	1.588	2.554
a [mm]	3.75	5.65
a/λ	0.143	0.215
$H_{max}Z_0/E_{acc}$	1.224	1.575
t [mm]	2.6	4.6
Iris ellipticity	1.692	1.478

Soft-copper-alloy structures

We tested three low shunt impedance structures made of soft-copper alloys. A subset of the results for the 150 ns flat part of the rf pulse is shown on Fig. 1. The gross behavior of the alloy structures were similar to that of the soft-Cu structure, with CuCr and CuZr having slightly lower breakdown rate than the Cu structure. The difference is more pronounced at breakdown rates of 10 to 100 per hour. The CuAg structure was one of the structures with lower breakdown rate (by a factor of ∼100) during initial processing compared to after this processing. The after-processing breakdown rate for the CuAg is very similar to that of the soft-Cu structure (see Fig. 1). The autopsy of the structures, including scanning electron microscope evaluation, showed breakdown-damage patches on high electric field areas and pulse heating damage in high magnetic field areas, both characteristic for soft-Cu structures.

Hard-copper structures

We tested two strictures made of hard Cu: one clamped (1C-SW-A5.65-T4.6-Clamped-SLAC-#1) and the other clamped and plated with copper (1C-SW-A5.65-T4.6-Electroformed-Frascati-#1). The results for the shaped rf pulse with the 150 ns flat part are shown on Fig. 2. After the initial processing, the electroformed structure performed similarly as the soft-Cu structures. The performance of the clamped structure was better than both electroformed and soft-copper structures: the breakdown rate of ∼3/hour occurred at ∼60 °C peak pulse heating for the clamped structure and at ∼50 °C for the soft-copper KEK-#2 structure (Fig. 2 b)). Autopsy of both hard-copper structures showed two features distinguishing them from soft-copper and soft-copper-alloy structures: 1) there was no visible pulse heating damage (we calculated highest pulse heating ∼80 °C for the electroformed structure and ∼100 °C for the clamped) and 2) both structures exhibited erosion of the clamped joint in the high gradient cell. We speculate that the joint erosion could increase the breakdown rate and thus adversely affects the characterization of the new materials.

Hard-copper-zirconium structure

To mitigate the joint erosion in the hard-CuZr structure (1C-SW-A3.75-T2.6-Clamped-CuZr-SLAC-#1) we increased the pressure on the joint to improve contact. The autopsy revealed plastic deformation of the joint and no erosion. The performance of this structure is shown on Fig. 3. In Fig. 3a) we compare the soft-CuAg and hard-CuZr structures of the same shape. The breakdown rate of the hard-CuZr structure was higher than that of the soft-CuAg structure at gradients above ∼140 MV/m. In Fig. 3(b) we compare breakdown rate *vs.* peak pulse heating temperature for soft-Cu and the hard-CuZr structures. Typically the breakdown rate is highly correlated with the pulse heating temperature. The breakdown rate for the hard-CuZr structure is higher than for the soft-Cu structures, and the correlation between the breakdown rate and the peak pulse heating temperature is weaker. We speculate that the zirconium particles on the surface of the metal changed the physics of the breakdown trigger, thus it become less dependant on the pulse length. As with the hard-Cu structures, we did not see pulse heating damage of the hard-CuZr cells (highest pulse heating was ∼90 °C).

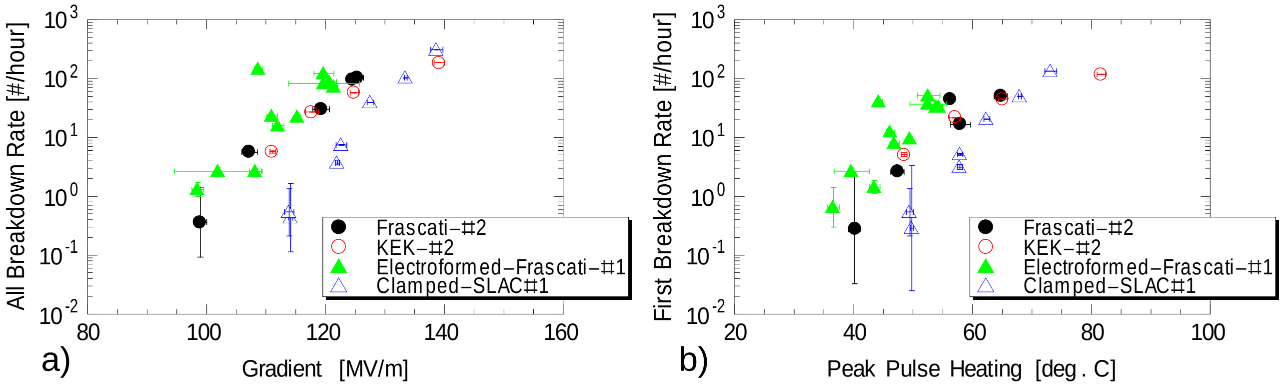

Figure 2: Breakdown rate for four low-shunt-impedance copper 1C-SW-A5.65-T4.6 structures: the two soft-copper structures are the Frascati-#2 and KEK-#2, and the two hard-copper structures are the Electroformed-Frascati-#1 and Clamped-SLAC-#1. The data is for a shaped rf pulse with a 150 ns flat part.

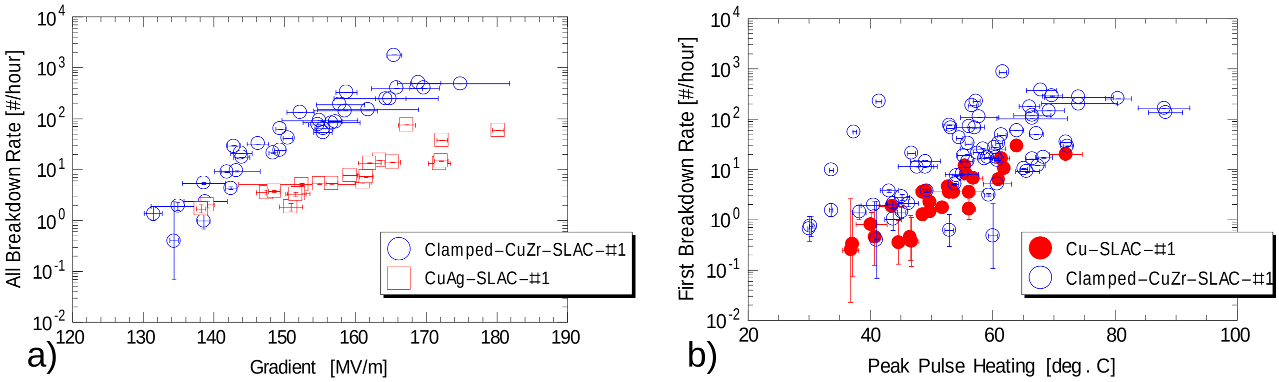

Figure 3: a) Breakdown rate for two high-shunt-impedance copper-alloy structures (1C-SW-A3.75-T2.6, soft CuAg and hard CuZr), for a shaped rf pulse with a 150 ns flat part. b) Breakdown rate for two high-shunt-impedance structures (1C-SW-A3.75-T2.6, soft Cu and hard CuZr), data for shaped rf pulses with pulse lengths 85 to 300 ns (soft Cu) and 100 to 600 ns (hard CuZr).

SUMMARY

The structures made of soft-copper and soft-copper alloys show similar and reproducible behavior: the breakdown rate is highly correlated with peak pulse surface heating temperature. High power RF tests of the hard-copper structures showed some improvement over soft copper but not as dramatically as we expected based on the tests of the pulse heating samples. Unlike for the soft-Cu structures, we did not observe pulse heating damage in the hard-Cu structures, although their breakdown rate correlated similarly with the peak pulse heating temperature. The breakdown performance of the high-shunt-impedance hard-CuZr structure was worse than for the soft Cu and soft-Cu alloys. Its breakdown rate did not have strong correlation with peak pulse heating temperature.

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