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EXPERIMENTAL STUDY OF SURFACE RF MAGNETIC FIELD ENHANCEMENT CAUSED BY CLOSELY SPACED PROTRUSIONS*

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Abstract

The RF magnetic field enhancement between two closely spaced protrusions on a metallic surface has been studied theoretically. It is found that a large enhancement occurs when the field is perpendicular to the gap between the protrusions. This mechanism could help explain the melting that has been observed on cavity surfaces subjected to pulsed heating that would nominally be well below the melting temperature of the surface material. To test this possibility, an experiment was carried out in which a pair of copper "pins" was attached to the base plate of an X-band cavity normally used to study pulsed heating. Melting was observed between the pins when the predicted peak temperature was near or exceeded the copper melting temperature.

INTRODUCTION

We have theoretically investigated the effect of a pair of identical, very small diameter, parallel, cylindrical, metallic, surface protrusions on an applied RF magnetic field in which the flux lines thread between them. The pins concentrate the flux lines, enhancing the magnetic field on the inner surfaces [1]. This is to be distinguished from the magnetic enhancement from general surface features, for example, those associated with sharp edges in normal conducting structures [2] and surface bumps and pits in superconducting cavities [3-6], where the radius of curvature of the surface is the main factor in determining the enhancement, as opposed to the gap opening between above-surface structures.

To verify our theoretical findings and explore the surface damage due to high pulsed heating temperatures (close to the melting point), we fabricated 4 pairs of short, cylindrical, copper pins and brazed them to a sample plate of a TE01 cavity used for pulsed-heating studies [7]. The electric field on the surface of the plate is nominally zero so only magnetic field effects are observed. The pins have a height of 2.5 mm and radius of 0.5 mm. They were all located at the radius of maximum pulsed heating on the sample plate. Different gap distances were used for the pairs, two that should produce a magnetic field enhancement of about 3.3 and two with about 2.3. This is illustrated in Fig. 1, where the solid line is the result of a simulation for the pin size, and the squares indicate the enhancement deduced from the measured pin spacing. The surface field around the pin pair is shown in the color maps of Fig. 2. The magnetic field is enhanced almost uniformly from the bottom of the pin to the start of its rounded tip. The electric field, which nominally increases linearly above the surface, is enhanced in small areas at the rounded tips. The ratio of maximum electric field to the maximum magnetic field is about 190 Ω with a magnetic field enhancement of 3.2.

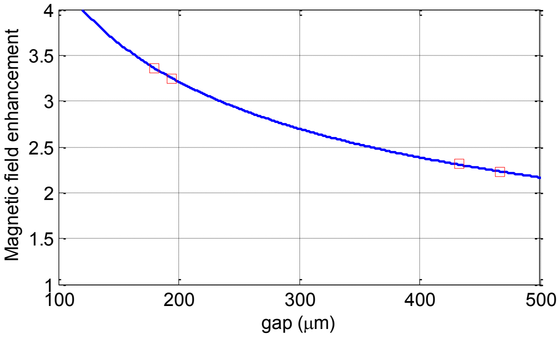

Figure 1: Peak surface magnetic field enhancement between the pin pairs with different gap distances.

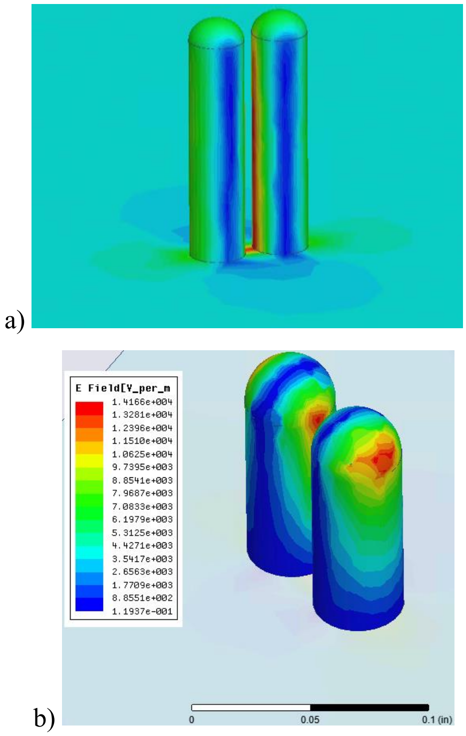

Figure 2: Simulated maps of the surface a) magnetic and b) electric field on and around a pin pair for the narrow gap case.

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TEST SETUP

The test cavity has a loaded quality factor Q_L = 3.3×10^4, with a coupling β of 0.38. The output from an X-band klystron was attenuated by about 6 dB to power the cavity. The RF pulse duration was 1.5 μs during the test. Without enhancement, the expected peak magnetic field and corresponding peak pulsed heating on the surface of the flat sample plate are shown in Fig. 3 for a square input pulse of 1 MW.

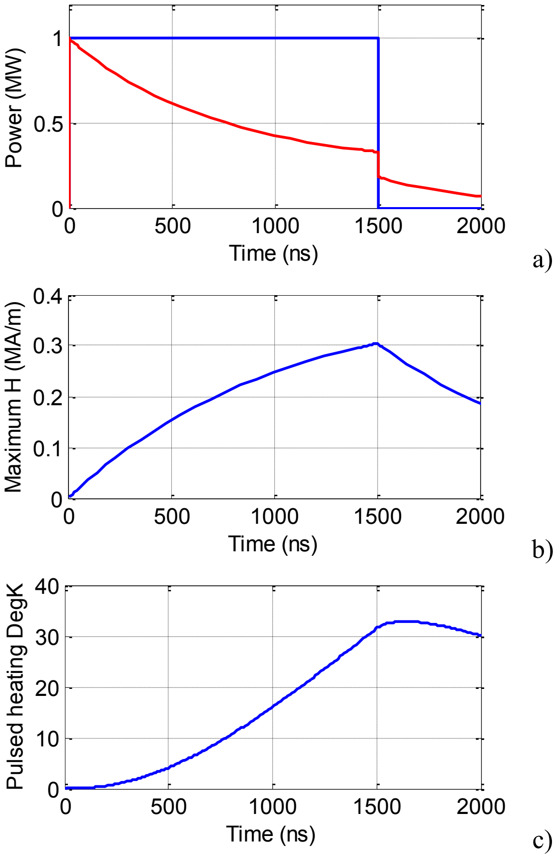

Figure 3: a) Input RF power (blue) and reflected power (red) from the cavity, b) maximum unperturbed surface magnetic field on the sample plate and c) the corresponding pulsed heating.

The test only lasted a few hours. Most of this time, the cavity was operated with 2.8 MW of input power, for which the predicted peak temperature on the pin surfaces is 1,031 °C, just below the copper melting point (1,085 °C). Few vacuum or reflected rf trips occurred during this time, but they increased rapidly if the input power was increased. The cavity was also operated at 3.56 MW for a few minutes during which frequent vacuum and reflected rf trips occurred. At this power level, the expected peak surface temperature on the pins is about 1,300 °C, significantly above the copper melting point.

RESULTS

After the test, we removed the sample plate and had SEM images taken of the pin surfaces. For the large gap pairs (small magnetic field enhancement), there is no visible damage on the pin inner surfaces, as can be seen in Fig. 4. In this case, the maximum pulsed heating was 460 °C for about 0.2 million pulses, about 5% of the pulses that visibly damage a copper surface from fatigue related effects with 70 °C pulsed heating [8].

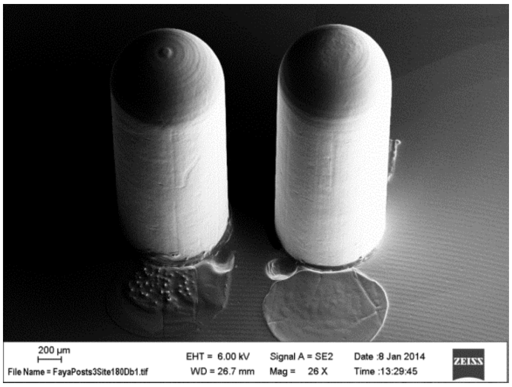

Figure 4: SEM image of one of the large gap pin pairs after the high power test. Note that the 'puddle' of material at the base of the pins, including the protrusions, is from the braze material flowing during the braze process. This material is not pure copper and has a somewhat lower melting temperature of 955 ^{0}C.

In contrast, for the small gap pin pairs, there is unmistakable damage, as can be seen in Fig. 5. On the inner surfaces, there appears to be copper melting and copper splattering, likely from rf breakdown. Near the base of the pairs, deep crevasses are present that resemble the melting seen on a sharp waveguide edge in an XL4 klystron (see Fig. 6).

This damage is very different from the fatigue related changes to a flat surface that occurs after millions of pulses with temperatures increases as low as 70 degC [9]. In particular, in this case one sees rows of copper ‘ridges’ that have been pushed-up from the surface instead of clusters of melted copper. In our case, with the melting temperature exceeded, the electric field between the pins likely caused the melted copper to be ‘exploded’ off of the surface (such copper splatter has been seen before in low phase advance per cell accelerator structures [9]) However, on the outside pin surface where the electric field is largest (up to 190 MV/m during the test) but where the magnetic enhancement is low, no damage is seen. Thus we believe that the damage on the inner surface is not simply from rf breakdown, which would have been mostly near the top of the pins anyway where the electric field is largest.

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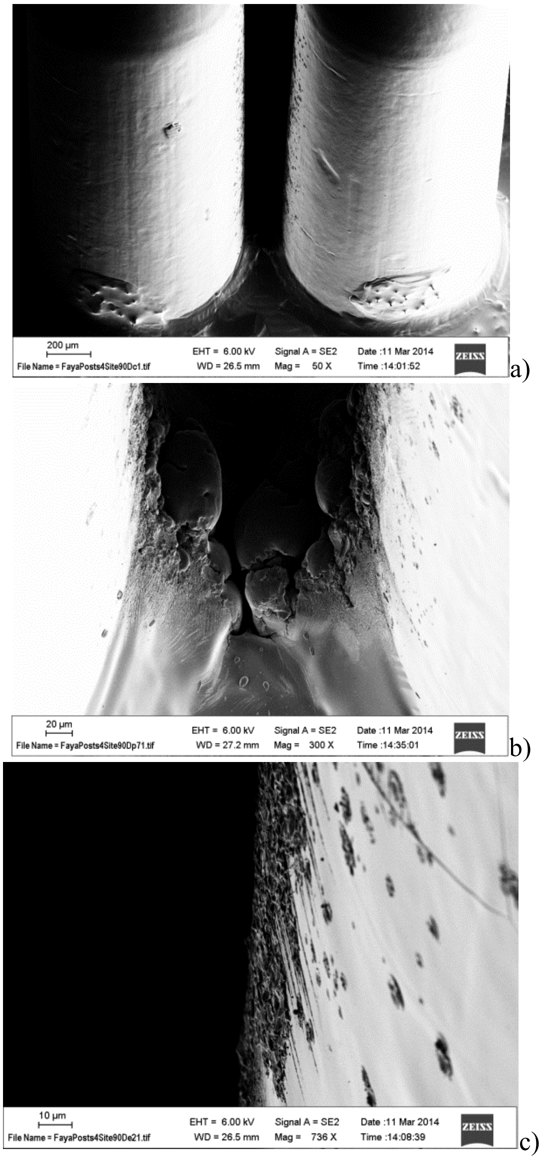

Figure 5: SEM images of one of the small gap pin pairs: a) over view of the damage, b) major melting at the base and c) melting and probably copper splatter from rf breakdown.

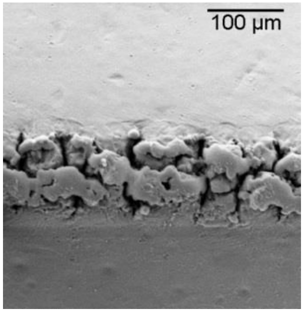

Figure 6: SEM image of the damage at the output cell opening to the waveguide in an XL4 klystron. An enhanced rf current runs parallel to this sharp edge.

SUMMARY

In summary, we have shown that a pair of copper pins can enhance the magnetic field to a level to induce melting and breakdown on their inner surfaces. Such damage could also occur in rf devices with closely spaced protrusions of various geometries, and may be the cause of the damage observed in some cases.

ACKNOWLEDGMENT

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