

# HIGH-GRADIENT RF BREAKDOWN STUDIES WITH NARROW WAVEGUIDE\*

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## Abstract

A narrow wave guide made of copper was studied for investigating the characteristics of high-gradient RF breakdown in various materials. The obtained data was compared with previously obtained data of a narrow waveguide of stainless-steel and copper. A significant difference was found between the characteristics of the two materials: stainless-steel and copper. Stainless-steel showed higher durability of RF breakdown than copper. The testing procedure, data handling, and data comparison are described in this report.

## INTRODUCTION

High-gradient RF breakdown study is one of the fundamental researches for normal-conducting high-energy accelerators since breakdowns could not only deteriorate the beam quality needed for the experiment but also cause the significant damage on the material surface of the structures. The study on the breakdown characteristics of materials can contribute to the estimation of the attainable acceleration field. We have studied the electrical discharge characteristics of various materials by using narrow waveguides having a field of around 200 MV/m at a power of 100 MW. In this study, we investigate the breakdown characteristics of copper and stainless-steel, such as the breakdown rate (BDR), and also the change of the surface profile due to breakdowns. Similar researches have been conducted at CERN with high-gradient DC field and at SLAC using simpler waveguides and single-cell cavity tests [1, 2, 3].

Since the last three years, we have been conducting high-gradient experiments using waveguides with small cross sections and made of stainless-steel (AISI-316L) and copper (OFC); the results have been reported in [4, 5, 6]. It is found that the stainless-steel waveguide has a better performance than the copper waveguide, and the former exhibits a smaller number of RF breakdowns at high electric fields. After testing the narrow copper waveguide (#CU002) at XTF, the old X-band Test Facility [4], it is tested at the new test facility, Nextef [7]. The test facility and data accumulation system during the RF processing and the post-processing run to take data of BDR were renewed [5]. Then, a systematic study on RF breakdown is carried out using a narrow stainless-steel waveguide (#SUS003). In this study, the same RF breakdown test is performed on another narrow copper waveguide (#CU005) and the breakdown characteristics of the two materials are compared. Since both narrow copper waveguides exhibit more frequent and serious RF breakdowns than the stainless-steel waveguide, the

ramping pattern of the processing and the evaluation of the BDR was changed from the #SUS003 test as described in next section to avoid a serious damage on the structure. Here, we report data handling and discuss the differences between the BDRs of stainless-steel and copper.

## HIGH-GRADIENT EXPERIMENTS

### RF Processing Scheme

As described in ref. 5, during the RF processing, the output power is varied by using a computer depending on the past processing history, the applied power, and the degree of vacuum. When the pressure in the waveguide increases, the power is maintained constant until the pressure reaches the normal level. When the pressure increases dramatically, the processing power is decreased and the processing is repeated from a lower power level. Occasionally, following a breakdown, many breakdowns tend to continuously occur in a very short time irrespective of the power level. We regard this phenomenon as a clean-up process: something like the recovery process of the surface in its profile, its physical or chemical properties damaged by serious breakdowns. The copper waveguide exhibits frequent breakdowns even at a low RF power. In order to prevent serious breakdown damages to the structure, the ramping pattern to recover from a break down was changed; both the pulse width and the RF power are reduced simultaneously once any interlock happened. A typical processing chart is shown in Fig. 1. In the top chart in Fig. 1, the blue line indicates the pulse width and the red line indicates the power level. The bottom chart shows the pressure around the narrow waveguide. The RF pulse width is varied from 40 ns to 400 ns with 20-ns steps, and the RF power is increased from a sufficiently low level to the target level.



Figure 1: Typical example of variations in pulse width and RF power during processing.

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## BDR Measurements

After the processing (Fig. 2), the BDR of #SUS003 and #CU005 were measured as functions of the RF power and pulse width to investigate their dependence on the material characteristics. Figure 3 shows the history of the RF power (red) and pulse width (blue) during the measurement of BDR of #CU005. For obtaining each data value, the target power was maintained constant for approximately 24 h and the breakdown events were counted. The RF pulse width was varied from 40 ns to 400 ns with 5 steps (40, 100, 200, 300, and 400 ns), the RF power was ramped from a low level to the target level, and the BDR was measured at each step. The measurements were performed at a fixed repetition rate of 50 pps.

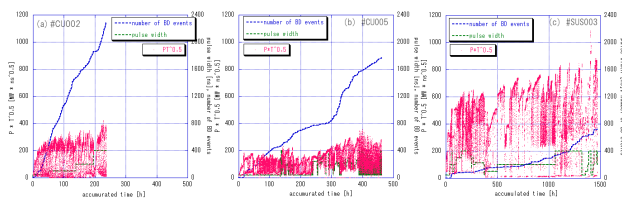


Figure 2: History of #CU002, #CU005, and #SUS003 during processing.

## RESULTS AND DISCUSSION

### RF Processing

Figures 2 (a), (b), and (c) show the processing history of #CU002, #CU005, and #SUS003, respectively [4, 5, 6]. Since the available power in our system was such as 200 ns-50 MW or 400 ns-40 MW, Figure 2 (c) shows that the maximum power for stainless-steel was limited by the system available power, while copper waveguides exhibit frequent breakdowns even at the lower power level, preventing them from further increasing the power. Both the copper waveguides showed a similar tendency even though the measurements were conducted in different

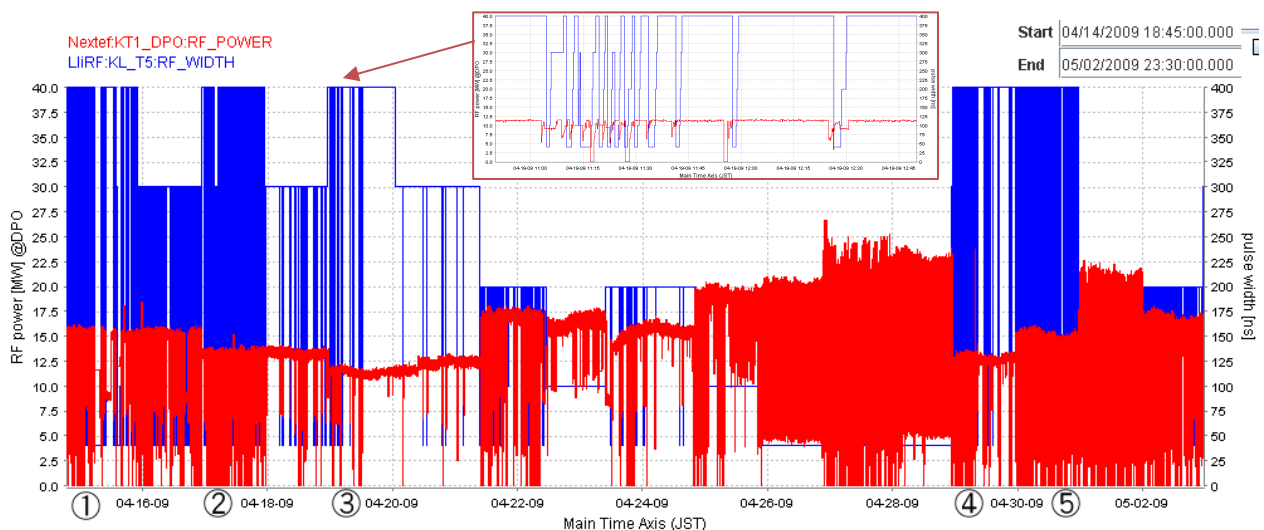


Figure 3: History of power and pulse width during the measurement of BDR of #CU005. Small figure shows the successive breakdown pattern after a serious breakdown.

systems where different processing methods were used. It should be noted that #SUS003 exhibited fewer breakdowns and attained higher power than #CU002 and #CU005. Figure 4 shows the breakdown limit during the processing for different pulse widths. From this figure, it is found that #SUS003 attained a higher  $P \cdot T^{1/2}$  value (the product of RF power and the square root of pulse width, which characterizes the surface temperature rise during the RF pulse) [3] than #CU002 and #CU005. These results show that stainless-steel has higher durability than copper.

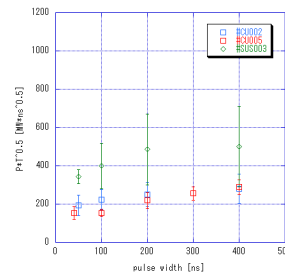


Figure 4:  $P \cdot T^{1/2}$  vs. pulse width of #CU002, #CU005, and #SUS003 waveguides.

### Evaluation of BDR

The BDR was calculated from the ratio of the number of breakdowns to the total number of pulses for periods during which both the power and the width remained constant at the target values. Figure 5 shows the measured BDR as a function of the maximum surface E-field. Here, we have taken different loss factors into account for the two materials. For example, the electric fields in copper and stainless steel waveguides at a power of 100 MW are 212 and 189 MV/m depending on the RF losses of -0.258 and -1.830 dB, respectively, as calculated by HFSS.

As described before, a serious breakdown leads to numerous successive breakdowns with a complex recovery process. One example is shown in a small graph in Fig. 3, where many breakdowns occur at lower powers

or shorter pulse lengths than target values after a large breakdown until recovering back to the situation where the stable operation sustains in a long period. In the case of a high power and a long pulse, which implies a high pulse energy  $P \cdot T^{1/2}$ , the BDR fluctuates significantly due to the frequent large breakdowns. The significant fluctuations in BDR are shown in Fig. 6, where the fluctuations are shown at intervals of 8 h for the total data acquisition time of 24 h and 400-ns pulse width data. The BDR is analyzed carefully with respect to the data acquisition scheme and the reliability of the obtained BDR discussed above. Figure 5 shows the BDR for 24 h along with the statistical error. Larger errors may be introduced because of the fluctuations in the abovementioned unknown breakdown phenomena.

It was found that stainless-steel has higher durability than copper. It was also observed that the exponential slopes of the BDR of copper plotted as a function of surface E-field were higher than those of stainless-steel. The BDR of #SUS003 for a pulse width of less than 100 ns was very low because our available power was too low to produce any breakdowns in this narrow pulse width.

This study is the first evaluation of the BDR in high-gradient RF breakdowns in waveguides. These narrow-waveguide dimensions of the present study were chosen not only to have a small group velocity like a realistic accelerator guide, but also to have both the higher magnetic field and the high electric field. Therefore, we hope that the results of this study will be very useful for the development of high-gradient accelerators.

In ref. 2, the breakdown limit was measured using narrow waveguides made of different materials. However, the cross section of the waveguide was reduced in the E- or H-plane independently; this is different from this study in which the cross section of the waveguides is reduced in both planes simultaneously and E- and H-fields are both high. The data published in ref. 2 showed that the breakdown field level of stainless-steel is higher than that of copper, which is consistent with our data. In the breakdown test using DC voltage reported in ref. 1, stainless-steel also showed significantly a higher breakdown field than copper, which is also consistent with our data.

From the DC breakdown experiments on various materials reported in ref. 1, it is found that Ti, Ta, and Mo are suitable candidates for our future studies.

## SUMMARY

The breakdown characteristics of copper and stainless-steel were studied by using narrow waveguides. It was found from the BRD measurement that the gradient reached with stainless-steel waveguide was much higher than the copper one. The exponential slopes of the BDR of stainless-steel plotted as a function of the surface E-field were lower than those of copper. Comparing the two materials at a BDR of  $10^{-6}$  level, the gradient of stainless-steel is much higher (more than 100 MV/m) than that of copper (only 60~80 MV/m).

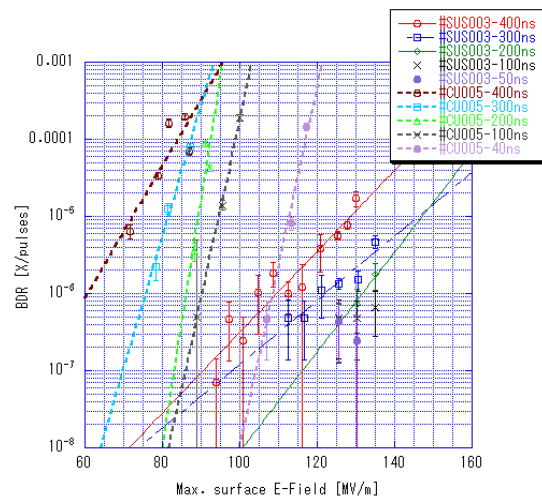


Figure 5: BDR vs. maximum surface E-field for different pulse widths of #SUS003 and #CU005 waveguides.

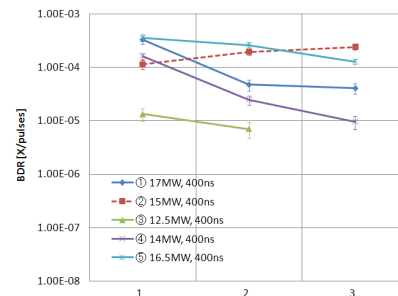


Figure 6: Fluctuations in BDR during each one third of the 24 h measurement carried out for 400 ns.

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