HIGH-GRADIENT EXPERIMENTS WITH NARROW WAVEGUIDES

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Abstract

High-gradient RF breakdown studies have been in progress at Nextef (New X-band Test Facility at KEK) since 2006 [1]. To study the characteristics of different materials on high-field RF breakdown, we have performed high-gradient experiments by using a narrow waveguide that has a field of around 140 MV/m [2]. The first high-gradient test was conducted by using a waveguide made of copper at XTF, the old X-band Test Facility at KEK. The second high-gradient test has been conducted by using a stainless-steel waveguide at Nextef. The result of second test showed that the stainless-steel waveguide had a better performance for a high electric field and fewer RF breakdowns than the copper waveguide. The high-gradient tests of the copper and stainless-steel waveguides are described in this paper.

INTRODUCTION

XTF was relocated to Nextef in 2007 in order to conduct high-power tests of X-band accelerator structures and fundamental researches on RF breakdowns [3]. For conducting a breakdown study, reliable RF sources and measurement systems were required and great efforts were made to establish a reliable system. The interlock controls for RF processing and breakdown measurement systems were replaced with a new scheme that was improved as well. It took almost half a year to accomplish the RF processing of RF components such as guard windows, directional couplers and dummy loads. The copper and stainless-steel waveguides were tested in order to launch high-gradient experiments at Nextef.

NARROW WAVEGUIDE

A narrow waveguide is a size-reduced X-band rectangular waveguide (WR90); the width of the regular rectangular waveguide was decreased from 22.86 mm (λ_g ~ 32.15 mm) to 14 mm (λ_g ~ 76.59 mm) in order to obtain a group velocity of 0.3 c and the height, from 10.16 mm to 1 mm in order to yield a field gradient of 200 MV/m at an RF power of 100 MW at the center [2]. In order to investigate the difference in the high-field capability, a stainless-steel (AISI-316L) waveguide was manufactured and tested to facilitate a comparison with the copper waveguide tested earlier. Table 1 shows the parameters of the copper and stainless-steel narrow waveguides obtained through measurements and calculations (HFSS). Figure 1 shows a photograph of a narrow stainless-steel waveguide (#SUS003).

Table 1: RF parameters of waveguides.

product name	#CU002	#SUS003
material	Copper (OFC)	stainless-steel (AISI-316L)
vswr	1.44	1.12
loss [dB]	-0.42	-1.56
vswr (HFSS)	1.0405	1.0765
loss [dB] (HFSS)	-0.258	-1.830
E-filed at 100 MW (HFSS) [MV/m]	212.34	189.25

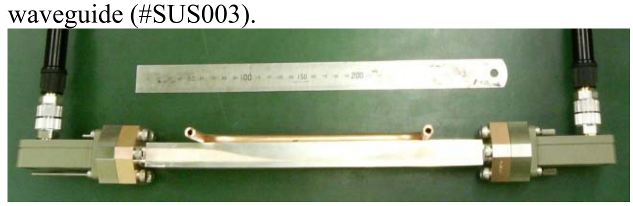

Figure 1: Narrow waveguide of stainless-steel (#SUS003).

HIGH-GRADIENT EXPERIMENTS

Setup for Breakdown Observation

RF power is supplied to a narrow waveguide from a PPM-focused klystron, which is operated at 11.424 GHz with a pulse width of 400 ns, a pulse repetition rate of 50 Hz, and a peak output power of approximately 50 MW. Acoustic sensors and photomultipliers (PMT) are located along the waveguide in order to observe breakdown events, as shown in Fig.2. Figure 3 shows a measurement system of a RF pulse that is detected by using a crystal diode and an oscilloscope that calculates the power, VSWR, and power loss. Every RF pulse is calculated, and the digital data of 10 successive pulses are saved for analyzing the waveform when some interlock controls such as HV, Trig, and RF trip are selected. In order to distinguish the breakdown in the narrow waveguide from the breakdown that occurred at another location, a waveform analysis system is under development. Forward

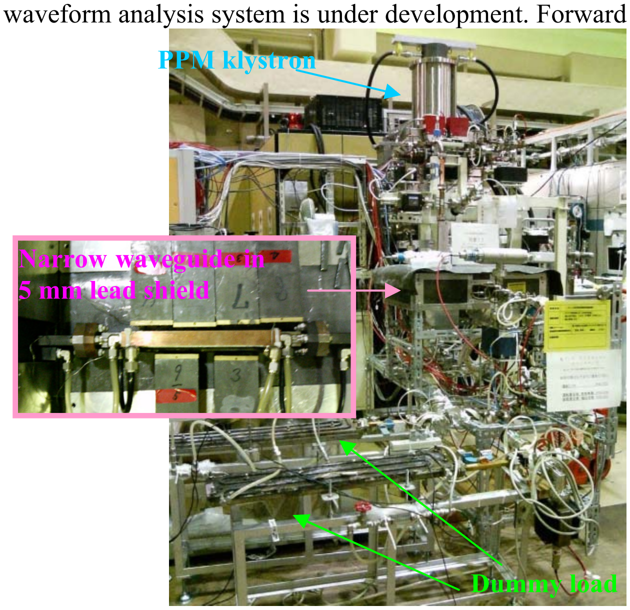

Figure 2: Experimental setup at Nextef.

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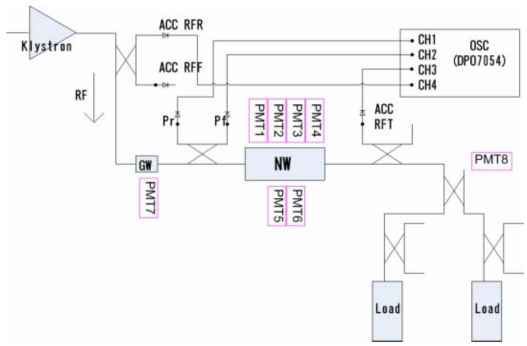

Figure 3: Measurement system of RF pulses.

and reflected RF waves observed in a directional coupler located upstream and downstream of the narrow waveguide are saved in a digital oscilloscope. By comparing these data with the pulse shortening or reflected power due to the breakdown, we can distinguish the breakdown occurred at the guard window, for example. It is possible to add other information such as the photomultiplier signal or X-ray detector to the analysis. This enables us to measure the true breakdown at the narrow waveguide more precisely.

Scheme of RF Processing

During the processing, the RF pulse width is varied from 50 ns to 400 ns and the output power is varied by changing the input drive power of the klystron under the fixed applied voltage to the klystron at a fixed repetition rate of 50 pps. The time interval and the output power increments are controlled by a computer in accordance with the past processing history depending on the experienced power and the condition of the vacuum. When the pressure in the waveguide increases, the power is kept constant until the pressure reaches a normal level. When the pressure increases dramatically, the processing power is decreased and the processing is repeated from a lower power level. We have not yet established an efficient and optimal processing scheme, but we are investigating appropriate pattern of RF processing in order to avoid serious breakdown damages to the structure.

Since the narrow #CU002 and the narrow #SUS003 waveguides were tested at different locations and under different system conditions, it is difficult to compare the processing difference directly. The processing time for #CU002 was a month and depended on the XTF operation scheduling. #SUS003 has been operated for approximately one year due to the launch of the high-gradient experiments at Nextef.

Figures 4 (a) and (b) show the processing history of #CU002 and #SUS003, respectively. The number of breakdown events depends on the RF power used during the processing of #CU002 and #SUS003 and is shown in Figs.5 (a) and (b), respectively. The breakdown events of the two sample waveguides have different distributions. #SUS003 experienced fewer breakdown events and attained a higher power than #CU002. We presume that this difference was partly due to the system difference, i.e., different protection scheme, although there was different material dependence. Figures 5 and 6 shows the electric field and the temperature-related parameter $PT^{1/2}$ (the product of the RF power and the square root of the pulse width) as the function of the pulse width. #SUS003 attained a higher electric field and $PT^{1/2}$ than #CU002. However, from this result, we concluded that 50 MW of RF power is not sufficient to obtain the gradient limit of stainless-steel at a short pulse width.

Measurement of Breakdown Rate

After processing, the breakdown rates (BDRs) of #SUS003 were measured as a function of the RF power and the pulse width. Figure 8 shows the power history during the measurement of BDR. Constant power was fed for approximately 24 h and the breakdown events were counted. Many RF breakdowns in a short time were observed after a serious breakdown that associated the pressure jump under the long pulse width condition. The unstable condition observed on June 11, 2008, after the stable period shown in Fig. 8 is such a case. We regard this phenomenon as a kind of processing. In order to consider the BDR data as a function of RF power, we need to complete these processing processes. Figure 9 shows the BDR of #SUS003 as a function of RF power. Although the breakdown events fluctuate, there is a trend that BDR increases if the power increases, and the relation between the BDR and the input power has an exponential nature, as shown in Fig. 9.

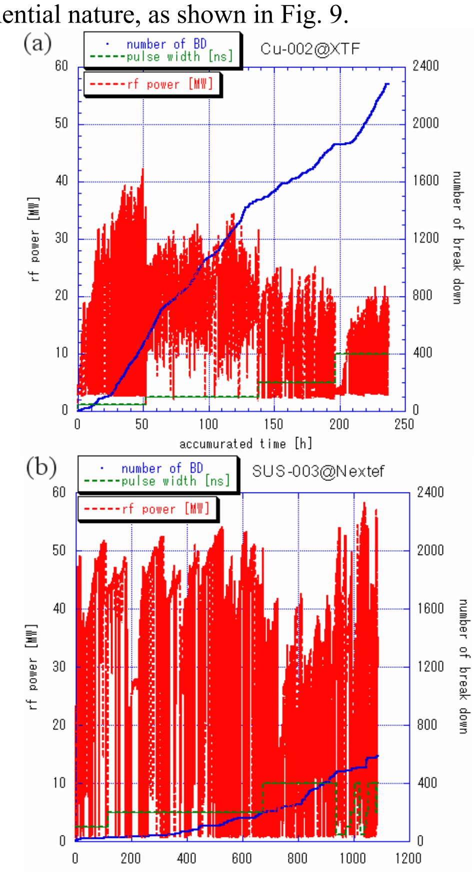

Figure 4: Power history of (a) #CU002 and (b) #SUS003 during processing.

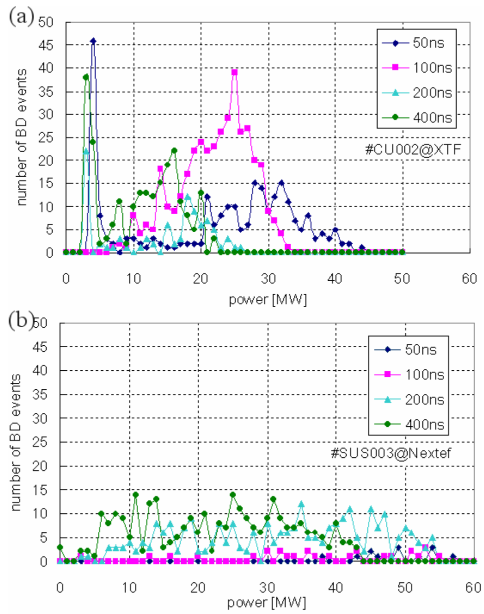

Figure 5: Power distribution of breakdown events of (a) #CU002 and (b) #SUS003 during processing.

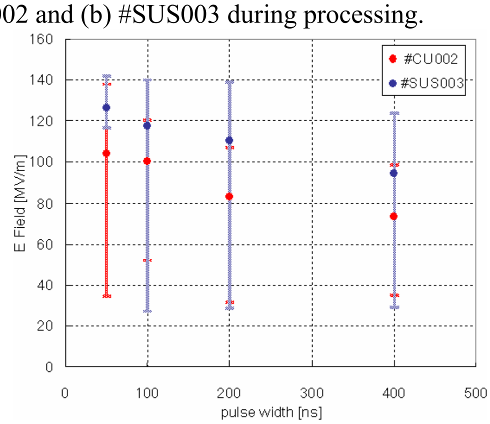

Figure 6: E-field of #CU002 and #SUS003.

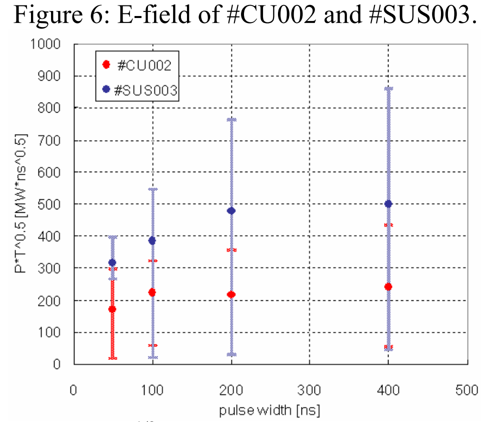

Figure 7: $PT^{1/2}$ plot of #CU002 and #SUS003.

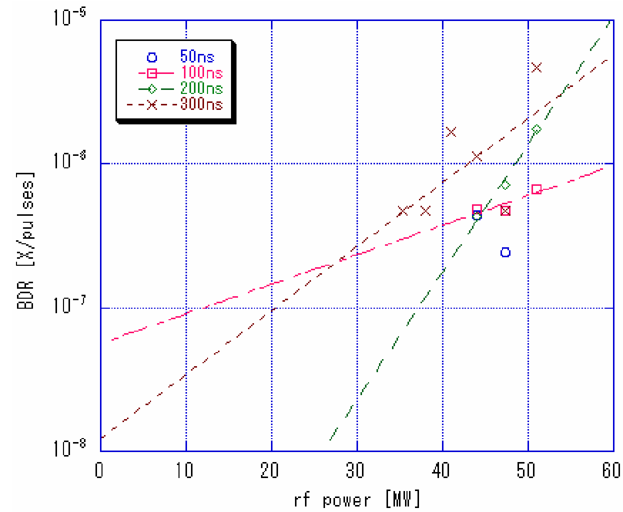

Figure 9: Breakdown rate as a function of a pulse width of #SUS003.

SUMMARY

The experimental setup for RF breakdown studies is almost established at the recently developed Nextef station. Breakdown diagnoses including waveform analysis are being developed and will be useful for a more reliable measurement. Breakdown tests on different materials are being performed. The prototypes #CU002 and #SUS003 have been tested under different systems, and the results have been compared. After obtaining the tentative test results, we have concluded that stainless-steel probably has a higher capability for the breakdown threshold than copper. We plan to test the narrow waveguide made of #CU004, another stainless-steel material, and other materials by using different surface treatments and fabrication method. A detailed analysis will be possible using this Nextef station.

REFERENCES

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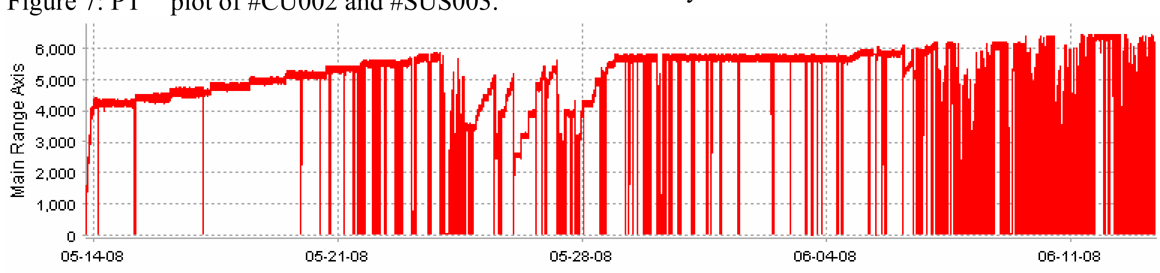

Figure 8: Power history during the measurement of BDR at 300 ns. The vertical axis corresponds to RF power.