SPECTROGRAPHIC APPROACH TO STUDY OF RF CONDITIONING PROCESS IN ACCELERATING RF STRUCTURES

H. Tomizawa[1], T. Taniuchi[1], H. Hanaki[1], Y. Igarashi[2], S. Yamaguchi[2], A. Enomoto[2]
Accelerator Division, Japan Synchrotron Radiation Research Institute (SPring-8)
1-1-1 Kouto, Mikazuki-cho, Sayo-gun, Hyogo 679-5198, Japan[1]
High-Energy Accelerator Research Organization (KEK)
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan[2]

Abstract

The acceleration gradient of a linac (linear accelerator) is limited by rf breakdown in its accelerating structure. We applied an imaging spectrograph system to study the mechanism of rf breakdown phenomena in accelerating rf structures. Excited outgases emit light during rf breakdown, and the type of outgases depend on surface treatments and rinsing methods for their materials. To study rf breakdown, we used 2-m-long accelerating structures and investigated the effects when high-pressure ultrapure water rinsing (HPR) treatment was applied.

We performed experiments to study the outgases under rf conditioning with quadruple mass spectroscopy and imaging spectrography. As a result, we were able to observe instantly increasing signals at mass numbers of 2 (H_2), 28 (CO), and 44 (CO_2) but not 18 (H_2O) just after the rf breakdown. We also conducted spectral imaging for the light emissions from atoms in a vacuum that are excited by rf breakdown. Without HPR, we observed atomic lines at 515 nm (Cu I), 622 nm (Cu II), and 711 nm (C I). With HPR, 395 nm (O I), 459 nm (O II), 511 nm (Cu I), 538 nm (C I), 570 nm (Cu I), 578 nm (Cu I), 656 nm (H I), and 740 nm (Cu II) were observed.

INTRODUCTION

Recently, rf structures have become necessary for higher-gradient acceleration. A range of contaminants and micron-sized particles may remain on the surface following different treatments. Those contaminants are field emitters, and outgassed due to the rf breakdown in rf structures. The lower the outgassing rates and the fewer the contaminating particles, the lower the breakdown rate.

It has been reported that the high-pressure ultrapure water rinsing (HPR) technique is very effective in improving the field gradients for normal conducting and superconducting rf structures [1]. This is because HPR treatment eliminates particle contamination on the surface, which is thought to be one of the causes of field emission.

To study rf breakdown, we applied this technique to the S-band 2-m-long disk-loaded accelerating structure. Microsecond-pulsed rf power (average accelerating field of 45 MV/m at maximum) was fed into these rf structures.

We performed experiments using quadrupole mass spectroscopy and imaging spectrography of atomic lines to study outgassing from the surface of rf structures. This imaging spectrograph system is useful for observing irreproducible phenomena such as rf breakdown, even for non-ultra-high vacuum conditions. Condensed gas and electrons play important roles in triggering the formation of aggressive plasma that acts against the copper surface. In our work, excited neutral and ionized gases in this plasma were observed as atomic lines in the real accelerating structures. Additionally, to reduce outgas rate, we applied chemical etching for rf pill-box-type single cavity (rf gun). With this treatment, we could achieve 206 MV/m of the maximal surface field.

EXPERIMENTAL SETUP

Tested accelerating structure

We performed experiments using the high-power test stand at KEK. We chose two S-band 2-m-accelerating structures which were prepared with the following fabrication processes:

A. A high-precision turning lathe with a diamond byte machined the disks and cylinders.
B. The electroplating fabrication method was applied to fix the disks and cylinders together.
C. HPR was applied to the assembled accelerating structure.

Note that these accelerating structures have a crescent-shaped cut opposite the waveguide iris (see Figure 1) to correct the asymmetry of the electromagnetic field.

For comparison, we prepared two different treated accelerating structures with and without HPR treatment (process C). One of the accelerating structures, while moving vertically (60 mm/min) and rotating (6.5 rpm), was rinsed by a nozzle-equipped pipe that jets high-pressure ultrapure water under optimal conditions.

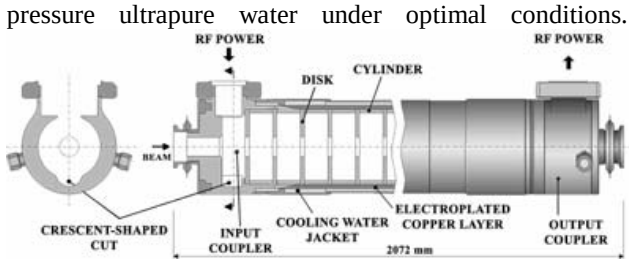

Figure 1: Schematic drawing of the accelerating structure

Following the HPR process, a scroll pump immediately dried the rf structure, and valves were attached in a clean room. After that, the structure was evacuated and then inserted into a high-power test stand without exposure to the atmosphere after assembly in the clean room.

Imaging spectrograph system

The imaging spectrograph monitor consists of three parts: a spectrometer (SPECIM; ImSpector), an image intensifier (SWAROVSKI; MK500) and a CCD-camera.

The spectrometer was used as an imaging spectrograph that captures a line image and disperses it into a spectrum in a direction orthogonal to the line image. These optics are based on the Prism-Grating-Prism (PGP) technique, yielding a direct-sight imaging spectrogram in which light passes through a straight optical axis. After an image is converted to a spectral line image, the image intensifier (I.I.) amplifies the light by a factor of more than 10^4, making it possible to take a spectrogram of a light emitter with low brightness. The CCD camera then changes the intensified spectral line images into video frames.

All image data were recorded on digital videotapes since rf breakdown is unpredictable. Each frame contains the line pixels in one dimension (spatial axis) and the spectral pixels in the other dimension (spectral axis), providing full spectral information for each line pixel. It was possible to obtain spectral information over the entire visible region (380 - 780 nm). For this spectrograph system, we calibrated the absolute wavelength with an He-Ne laser (633 nm) and a mercury lamp (shortest spectral line: 404 nm). We obtained a resolution and geometrical resolution of 8.9 nm and 2.4 nm/dot, respectively. Note that, if two spectral lines are separated by more than 8.9 nm, the spectral peaks' wavelength accuracy is 2.4 nm.

The data analysis system was specially developed for this imaging spectrograph. It automatically searched video frames for rf breakdown phenomena. The selected frames had an integrated pixel brightness along the spectral axis that was greater than the threshold level. In this experiment, most of the frames were full of radiation noise during rf breakdown. This method is very effective for avoiding background noise on the video images.

Experimental setup in high-power test stand

We constructed a test stand for high-power tests on the accelerating structures. A klystron with a maximum peak rf power of 45 MW and a SLED-type pulse compressor, used to generate a high-power rf pulse, were installed on the stand. The pulse width and repetition rate of the rf pulse were 4.0 μsec and 50 Hz, respectively, and the klystron output power level was gradually increased. The reflection of the rf power from the accelerating structure, or waveguides, and the vacuum pressure of the ion pumps were used as an interlock to stop the rf power. The vacuum pressure of the accelerating structure was maintained at around $1{\cdot}10^{-6}$ Pa during rf conditioning.

We installed a quadrupole mass spectrometer and an imaging spectrograph system to study the gases released from the surface of accelerating structures during rf conditioning. In order to improve sensitivity, an ABB Extrel quadrupole mass spectrometer with 19-mm diameter rods was employed. We installed the imaging spectrograph camera to directly view the crescent-shaped cuts in the coupler cavities. These were some of the most likely locations for rf breakdown, because the surface current densities at these locations are 10 times higher than those at other sections [2]. Indeed, we often observed blackened areas damaged by rf breakdown in these cuts.

EXPERIMENTAL RESULTS

Spectrography of rf breakdown in the accelerating structure without HPR

The initial test was carried out in the accelerating structure but without HPR treatment. After the rf conditioning, an average accelerating field of 40 MV/m was obtained after $1.0{\cdot}10^8$ shots (542 hours). Also, the high-power test was terminated due to a time limit. The system experienced 4559 trips due to interlocks with VSWR, which measures rf reflection due to rf breakdown in the accelerating structures. An imaging spectrogram and the light spectrum of light emission as a result of rf breakdown after rf conditioning (elapsed time: 631 hours) are shown in the upper and lower parts of the right side of Figure 2, respectively. The light spectrum clearly shows the atomic lines of outgases at 515 nm (Cu I) 622 nm (Cu II), and, as the most dominant line, at 711 nm (C I).

Spectrometer and I.I.-camera for the imaging spectrograph

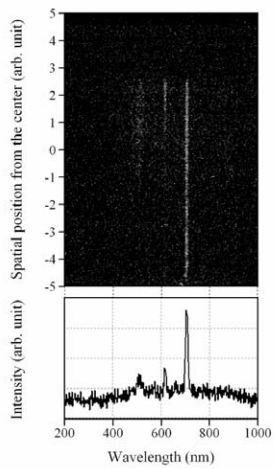

Figure 2: Spectrogram (upper) and light spectrum (lower) of light emission as a result of rf breakdown in the rf-conditioned accelerating structure without HPR treatment (elapsed time: 631 hours; average accelerating field: 30 MV/m)

Spectrography of rf breakdown in the accelerating structure with HPR

The next test was carried out using the accelerating structure with HPR treatment (average water pressure: 5.0 MPa). After the rf conditioning, an average accelerating field of 45 MV/m was obtained after $6.4{\cdot}10^7$ shots (356

hours); however, this gradient was limited by the klystron output power. The system experienced 1894 trips due to interlocks with VSWR. The left and right sides of Figure 3 show two imaging spectrograms with the light spectra at elapsed times of 307 (during rf conditioning) and 677 (after rf conditioning) hours, respectively. The left spectrogram and light spectrum in Figure 3 shows the atomic lines at 395 nm (O I), 515 nm (Cu I), 570 nm (Cu I), 578 nm (Cu I), and, as the most dominant lines, 459 nm (O II) and 656 nm (H: Balmer alpha). In the right spectrogram and light spectrum of Figure 3 only 538 nm (C I), 656 nm (H: Balmer alpha), and 740 nm (Cu II) were observed. After rf conditioning (elapsed time: 677 hours), we observed only these three lines.

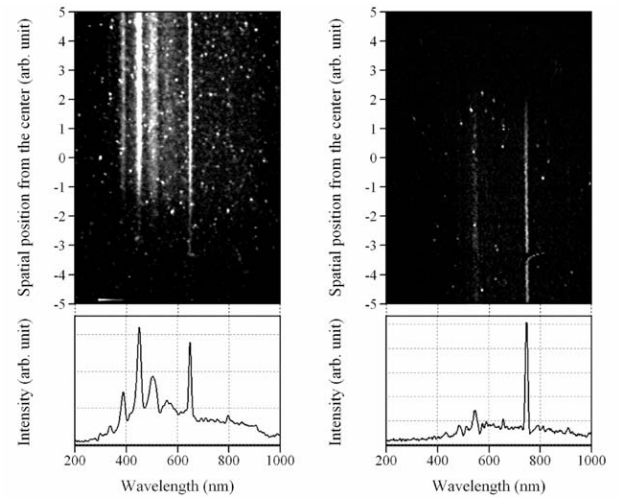

Figure 3: Spectrograms (upper) and light spectra (lower) of light emission as a result of rf breakdown in the accelerating structure with HPR treatment

The spectrograms (upper) and light spectra (lower) during rf conditioning (elapsed time: 307 hours; average accelerating field: 42 MV/m) and after rf conditioning (677 hours; 45 MV/m) are shown at left and right, respectively.

Results of gas and surface analysis

As a result of the gas analysis, we were able to observe instantly increasing signals at mass numbers 2 (H_2), 28 (CO), and 44 (CO_2) but not 18 (H_2O) just after rf breakdown in the accelerating structures. The mass spectrum without rf power is not significantly different from the spectrum before rf breakdown.

In addition, an XPS (X-ray photoelectron spectroscopy) surface analysis was performed on blackened areas of the crescent-shaped cuts in the coupler cavities (without HPR treatment). It was found that with the exception of copper, carbon (graphite) was the most dominant element on the blackened surface of rf-conditioned surfaces.

SUMMARY

We performed experiments to study the gas release from the surface of rf structures by employing quadrupole mass spectroscopy and imaging spectrography of atomic lines. This spectrographic method proved to be particularly useful for observing instantaneous irreproducible phenomena such as rf breakdown. Generally, in both of the accelerating structures, we were able to observe increasing quantities of H_2, CO, and CO_2 molecules immediately after the rf breakdown. These molecules may be either a result of being released from the surface or else generated in the recombination plasma induced by rf breakdown. According to the spectrograms of this recombination plasma, we mainly observed atomic lines of evaporated copper. Using an accelerating structure without HPR treatment, we observed that the atomic carbon line was the most intense, but no oxygen was detected. However, with HPR treatment, we observed only the atomic oxygen and hydrogen lines as the most dominant lines in the early stages of rf conditioning.

According to our experimental results, the HPR treatment can remove dust particles, although it causes different contaminant layers on the copper surface of the accelerating structure. One of these layers could be a thin oxidized layer, because an oxygen line glows in the early stages of rf conditioning but not after rf conditioning. This indicates that, by the end of rf conditioning, the copper surface of the accelerating structure became almost oxygen-free. This is noteworthy, as an oxidized layer is an insulator and allows rf breakdowns to become concentrated on the oxidized layer. Consequently, after rf conditioning, oxygen lines were not observed.

As a result, we found that the structure treated by the HPR process reached 45 MV/m with an rf-conditioning period 1.5-times shorter, a lower rf breakdown rate, and a lower dark current than the untreated one [2].

According to XPS, the most dominant element on the blackened surface, with the exception of copper, was carbon (graphite). We concluded that carbon ions in the plasma recombine with electrons on the copper surface due to the much higher electron density and low electron temperature in the material as compared with the vacuum.

In an additional high power test of rf gun with a chemical etching treatment, we could not measure any spectrum in visible region, because any significant rf breakdown has not occurred. For the next step, we are preparing a new system for imaging spectrography in the UV-region (200 – 400 nm). To study spectra at this shorter wavelength, rf breakdown phenomena will be easier to observe (even for not significant rf breakdown) due to the plasma chemical reactions described in this paper.

REFERENCES

[1] K. Saito, et.al. Proceedings of the 6th Workshop on Superconductivity, 4-8 October, 1993, CEBAF, Newport News, USA, pp. 1151-1159.

[2] Y. Igarashi, S. Yamaguchi, A. Enomoto, T. Oogoe, K. Kakihara, S. Ohsawa, H. Tomizawa, T. Taniuchi, and H. Hanaki, Proceedings of the 2003 Particle Accelerator Conference, 12-16 May, 2003, Portland, Oregon, in printing.