OBSERVATION OF LIGHT EMITTED FROM AN RF WINDOW OF A HIGH-POWER INPUT COUPLER DURING RF CONDITIONING

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Abstract

We have performed a high-power test of an input coupler for the ARES cavity system at the SuperKEKB accelerator, focused on light emitted from the RF window, with continuously observing the light. In this paper, we report the results, that might lead to better understandings of high-power RF windows.

INTRODUCTION

A high-power input coupler is a device used to feed the radio-frequency (RF) power from a high-power source, such as a klystron, into a cavity, which is one of the most important components for high-power rf systems. We have developed high-power input couplers for the normal-conducting accelerating cavity system ARES [1, 2] (hereinafter, "ARES couplers") at the SuperKEKB accelerator [3], which are capable of handling 800 kW input RF power of the continuous wave (CW) [4, 5].

Inside the ARES coupler, there is an RF window, made of alumina ceramics, to separate vacuum and air regions. Since the secondary electron yield of alumina ceramics is much higher than that of copper, thin coating of titanium nitride (TiN[1]) is applied to the surface to suppress multipactoring[2]. Such TiN coating enables us to condition input couplers up to or over several hundred kW (CW). However, some ARES couplers have a RF window which emits significant light, during high-power conditioning or accelerator operation, with no clear conditioning effect. Even though most of the mass-produced ARES couplers have been conditioned close to or over 800 kW, understanding of the light emission and conditioning effect on RF windows should be essentially important to develop, mass-produce with high fabrication yield, and stably operate for a long time, high-power input couplers. In this study, as a first step for the purpose, we performed a high-power test for one of the the mass-produced ARES couplers (hereinafter, "ICUT": Input Coupler Under Test), focused on light emitted from the RF window.

INPUT COUPLER UNDER TEST (ICUT)

The schematic diagram is shown in Fig. 1. The ARES coupler has a coaxial line (WX77D) with a loop for coupling to the magnetic field of the TE_{013} mode in the energy-storage cavity of the ARES three-cavity system. The coaxial parts,

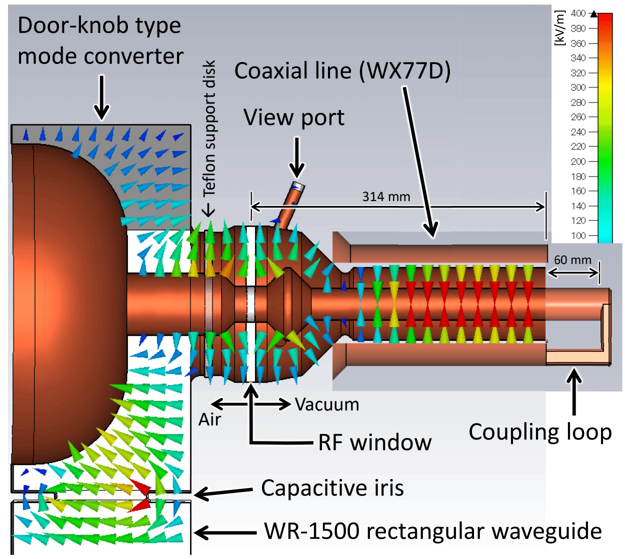

Figure 1: Schematic diagram of the ARES coupler. The cones indicate an instantaneous electric field for an input RF power of 800 kW with a minimum reflection (< −30 dB).

except for the RF window and Teflon support disk, which are exposed to vacuum are made of oxygen free copper. The outer conductor of the coaxial line of WX77D has a finely-grooved structure in its surface to completely suppress multipactoring [6]. The RF window of the ARES coupler is a disk of alumina ceramics (HA-95) with inner and outer diameters of 38 mm and 166 mm, respectively, and a thickness of 10 mm. The surface in the vacuum side is coated with 10 nm-thickness TiN to suppress multipactoring. Before this high-power test, we performed ozonized-water rinsing of the coaxial part including the RF window, followed by six-day vacuum baking with a temperature just below 100 °C [7], which was demonstrated to be effective in suppressing light emission on RF windows, and significantly reducing conditioning times [5]; therefore, this process has been a standard preprocessing for high-power testing of ARES couplers. For an RF power input to the ICUT (P_{inp}) of 800 kW, the surface of the RF window is exposed to an electric field with approximately 60 kV/m in amplitude near the outer conductor and 340 kV/m in amplitude near the inner conductor. This field strength is an order of magnitude lower than those in high-power RF systems of large-scale linacs in pulsed operation.

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[1] The exact composition is TiN_xO_y.
[2] Multipactoring is a phenomenon arising from secondary electron emissions after impact of primary electrons and repetition of this process driven by the RF field, also known as multipacting.

EXPERIMENTAL SETUP

As shown in Fig. 2, we used a 1 MW CW klystron with a four-port circulator to protect it. The high RF power was fed into an energy-storage cavity through the ICUT, taken out through an output coupler, and finally terminated in a 1 MW dummy load. The output coupler is the same type of the ICUT, and already conditioned over 800 kW. We set the coupling-loop angle of the ICUT to be 45°, that is intermediate between the maximum and minimum couplings, and the same angle as in the SuperKEKB operation, and then adjusted the coupling-loop angle of the output coupler so that the RF power reflected from the energy-storage cavity should be about 1 % or lower of the input RF power during high-power operation.

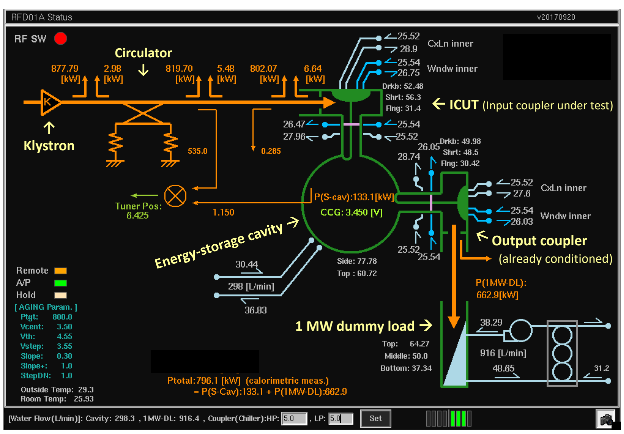

Figure 2: Schematic diagram of the high-power test stand (drawn by Mikio Tanaka, MITSUBISHI Electric System & Service Co.,Ltd.).

The ICUT has three view ports with a window made of Kovar glass, located at equal distances in the azimuthal direction (i.e. 120° interval), to see the RF window as shown in Fig. 3. To the view ports, we attached three different "light detectors": (1) an arc sensor with a photodiode (S1722-02, Hamamatsu Photonics K.K.), (2) a high-sensitivity television (TV) camera (WATEC WAT-231S2, color), and (3) a hyperspectral camera (NH-KE3, EBA JAPAN Co., Ltd. [8]). The same type of arc sensors have been used in the (Super)KEKB operation for interlock to protect the RF windows at the operational stations controlled with the conventional analog LLRF system. The high-sensitivity camera can detect images with an illumination of 0.02Lux/F1.2. Figure 4 shows an example of images of light emitted from the RF window, where the color looks light magenta. As for the hyperspectral camera, the gain of each pixel was calibrated using a uniform light provided by an integrating sphere, and the absolute wavelength was calibrated using a red HeNe laser (632.8 nm), as described in [9].

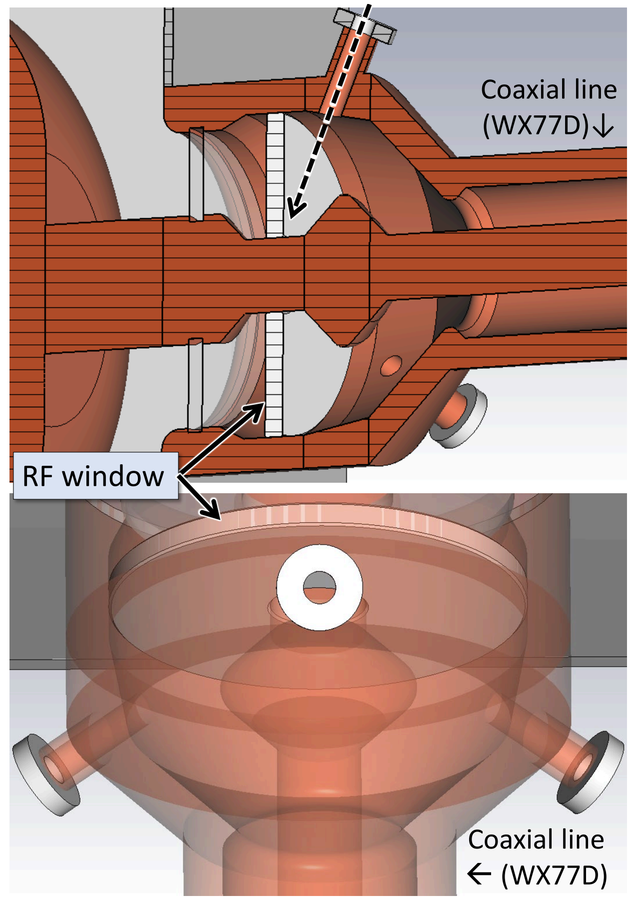

Figure 3: Schematic diagram of the ICUT focused on the view ports.

Figure 4: Example of images of light emitted from the RF window recorded with the high-sensitivity camera (P_{inp} = 218 kW).

RESULTS

RF conditioning

Figure 5 shows the whole history of this RF conditioning. We performed this high-power test during only daytimes of total nine days (Day 1 to Day 9). The horizontal axis indicates elapsed time starting from switching the RF switch

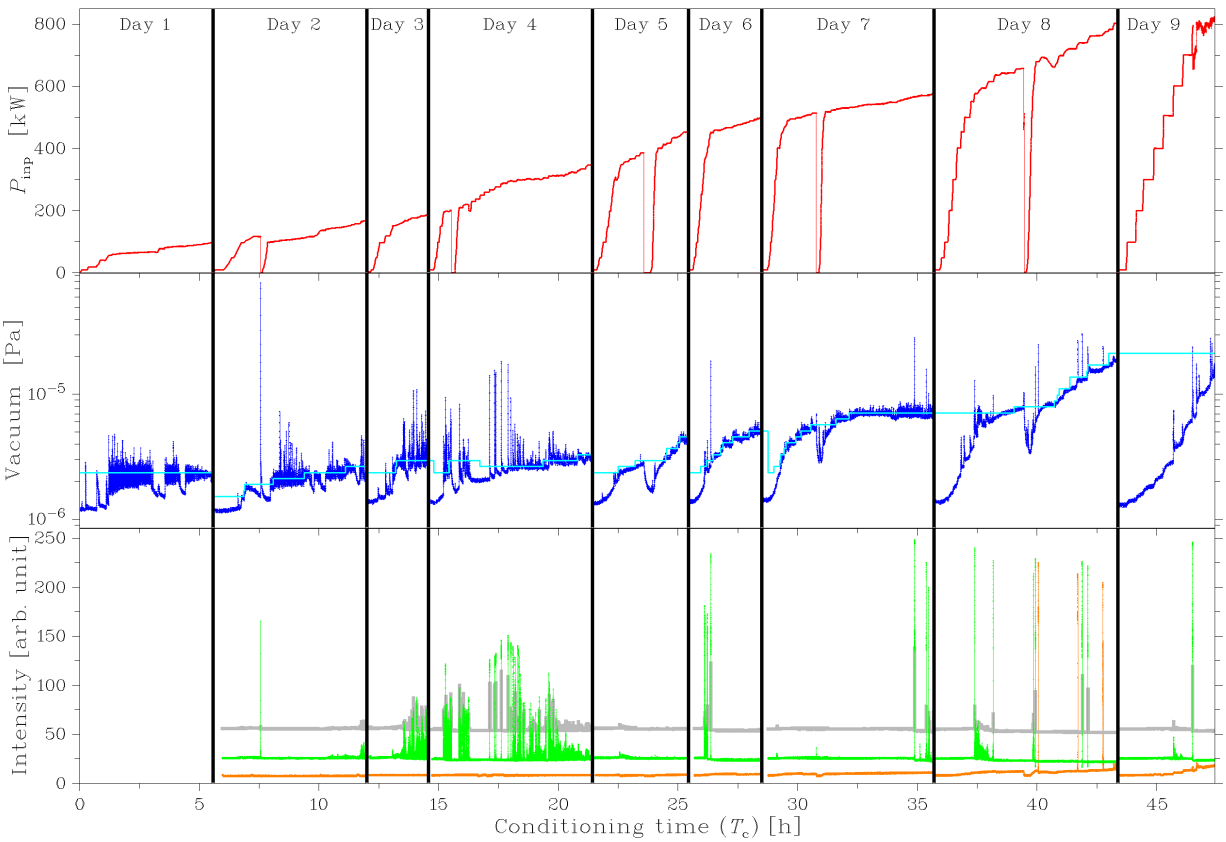

Figure 5: Whole history of RF conditioning in this high-power test. The upper history is on the RF power input to the ICUT. The blue plots in the middle history is on the vacuum pressure in the energy-storage cavity, recorded every second, where the vacuum interlock level was 4×10^{-5} Pa. The light blue lines indicate the reference vacuum pressure specified in the automatic conditioning by computer control. If the vacuum pressure is higher than the reference pressure, the RF power is stepped down until the vacuum pressure becomes lower than the reference pressure, and then the RF power is gradually stepped up as long as the vacuum pressure remains lower than the reference pressure. The step-up slope is proportional to the difference between the reference and vacuum pressures. The lower history is on the intensities of light emitted from the RF windows recorded with the high-sensitivity cameras every 1/30 seconds, where the green plots are on the ICUT, the orange ones on the output coupler shown with −20 offset, and the gray ones indicate ten-second moving averages of the light intensity on the ICUT shown with +30 offset.

on until off each day, defined as "conditioning time" (T_c) in this paper. We reached P_{inp} = 800 kW at the end of the 8th day (Day 8), T_c = 43.2 hours. On the last day (Day 9), we took data of various quantities including RF powers, pickup fields, calorimetric powers, temperatures, and the vacuum pressure at equilibrium state.

On the second day (Day 2), there was only one interlock activation. This event was caused by human error leading to an unintended increase of the input RF power in a short time, and then the vacuum pressure largely spiked accompanied by a strong light emitted from the RF window of the ICUT. The interlock activations on the fourth, fifth, and eighth days (Day 4, Day 5, Day 8, respectively), are not related to the high-power performance but due to radiation regulation or operational safety. On the seventh day (Day 7), there was a reflection-power interlock activation due to cavity breakdown arising from vacuum arc near the coupling loop of the ICUT inside the energy-storage cavity. Therefore, there was no interlock activation due to any failure related to the performance of the ICUT, showing good and typical performance among the mass-produced ARES couplers.

Light intensity

The intensities of light emitted from the RF windows recorded with the high-sensitivity cameras are shown in the lower histories in Fig. 5, where we did not record the footages on the first day (Day 1) because the preparation was not in time; however, there was no light emission at all on Day 1 as far as visual observation. It is clear that each vacuum spike for RF powers higher than a certain threshold corresponds to a light-intensity spike on the ICUT or output coupler with the exception of a few vacuum spikes. Examples of the significant exception are the several vacuum spikes at P_{inp} = 800 kW after the last light-intensity spike at T_c = 46.5 h.

Such RF power threshold increased day by day: 142, 151, 193, 327, 360, 368, 572, 590 kW, on Days 2 – 9, respectively, showing an excellent conditioning effect.

The light emission together with the vacuum spike should be a result of multipactoring on the RF window. Power dependence of the vacuum and light-intensity spikes can be seen in Fig. 5 around P_{inp} = 250 ~ 300, 570, and 750 kW.

It is also clear that the height of the light-intensity spikes became higher with higher RF powers. However, as can be seen in the gray plots in the lower history in Fig. 5, the integrals for RF powers higher than 600 kW are contrarily lower than those for < 600 kW. This means that multipactoring driven by higher RF powers grows and collapses more rapidly.

Throughout this high-power test, there was no arc-sensor interlock activation.

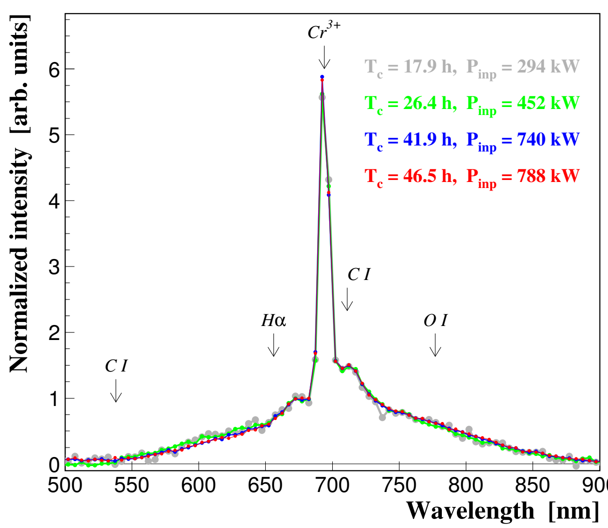

Figure 6: Measured spectra of the light emitted from the RF window of the ICUT at four moments of vacuum and light-intensity spikes. All the spectra are normalized for the area of wavelength between 600 and 800 nm.

Light spectra

Figure 6 shows light spectra measured with the hyperspectral camera in the visible region, selecting the light coming only from the RF window. We used a high-pass filter of 500 nm only for the spectrum at T_c = 26.4 h to confirm no ghost effect on the measured spectra in the visible region from the near-ultraviolet region. A clear well-known peak is seen at 694 nm which is attributed to luminescence of Cr^{3+} ions included in alumina ceramics of the RF window as impurities. No other clear peak is seen; e.g. atomic lines at 538 nm (C I), 656 nm (H: Balmer alpha), 711 nm (C I), 777 nm (O I), as observed in a surface flashover experiment of alumina [10] or an RF accelerating structure breakdown experiment [11]. The shape of the spectra did not change throughout this high-power test.

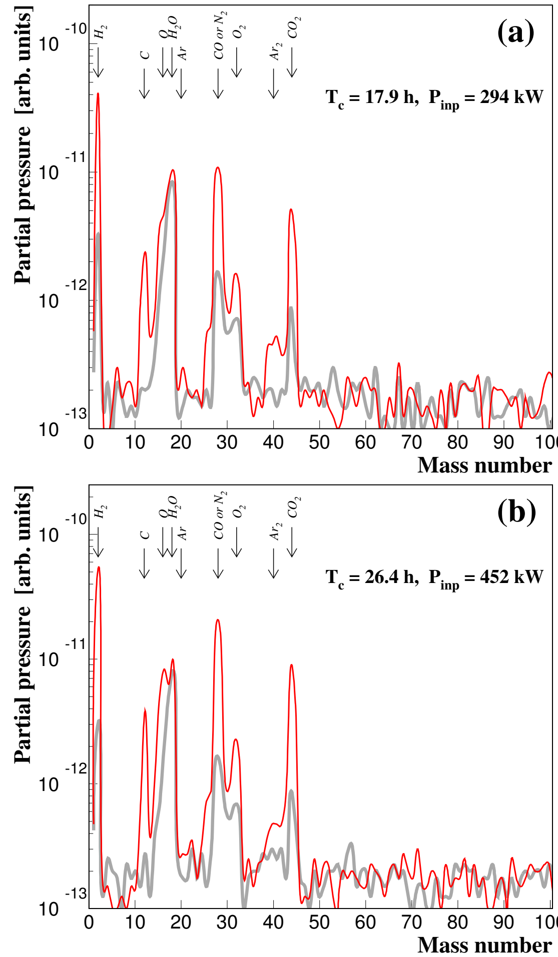

Figure 7: Mass spectra of the vacuum spikes at (a) T_c = 17.9 and (b) 26.4 hours. The gray lines are spectra immediately before the vacuum spikes, and the red ones during the vacuum spikes.

Mass spectra of vacuum spikes

We analyzed mass spectra of the vacuum spikes accompanied by the light emissions at T_c = 17.9 and 26.4 hours using a quadrupole mass spectrometer attached to the energy-storage cavity. The results are shown in Fig. 7. There is no increase in mass numbers around or higher than 50, while there are significant increases in mass numbers of 2 (H_2), 12 (C), 28 (CO), and 44 (CO_2), together with small increases in mass numbers of 16 (O) and 32 (O_2). Our observation is that the desorbed atoms of hydrogen, carbon, and oxygen did not contribute to light emission, which might be related to dynamics of multipactoring electrons and desorbed molecules / atoms.

SUMMARY AND FUTURE PROSPECTS

We performed a high-power test of one of the mass-produced ARES couplers for SuperKEKB up to 800 kW input RF power with continuously observing light emitted from the RF windows of the ICUT and output coupler.

The observed facts are:

- There exist RF-power thresholds for detection of light emitted form the RF window;
- Above the thresholds, each vacuum spike corresponds to a light-intensity spike on the ICUT or output coupler with the exception of a few vacuum spikes;
- Such RF-power threshold steadily increases as the RF conditioning proceeds;
- The height (integral) of the light-intensity spikes becomes higher (lower) with higher RF powers;
- In the spectra of the light emitted from the RF window, there is only one significant and well-known peak attributed to luminescence of Cr^{3+} ions included in alumina ceramics of the RF window as impurities, and no other significant peaks for atomic lines of hydrogen, carbon or oxygen;
- However, the vacuum spikes include hydrogen, carbon and oxygen analyzed with a quadrupole mass spectrometer.

Our future plans are to:

- Develop simulation and/or theory to explain the above observed facts,
- Understand the conditioning effect of RF windows,
- (Re)perform high-power tests of deteriorated or low-performance input couplers and compare the results with those of this study, and
- Measure light emitted from RF windows in the near-ultraviolet region to observe peaks of F^+- and/or F-center, which are known to be dominant sources of luminescence on alumina ceramics (e.g. see [10]).

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