

Compact waveguide-type ceramic window for radio frequency cavity in synchrotron storage ring

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In this study, a waveguide-type radio frequency (rf) ceramic window with a simple structure was developed for vacuum-sealing rf cavities up to 250 kW in the synchrotron storage ring of a fourth-generation light source. The rf window was designed for easy and quick replacement in the event of ceramic failure. It was assembled with low dielectric loss tangent ($\tan \delta$) alumina ceramic in a copper frame for mounting between waveguide flanges. The ceramic surface was coated with titanium nitride (TiN) to suppress multipactor discharge. However, two problems occurred during the high-power rf operation test: overheating of the ceramic due to an unexpectedly high $\tan \delta$ and multipactor discharge on the ceramic surface. To eliminate high- $\tan \delta$ alumina before welding the window, screening methods were developed to remove such alumina. To suppress the discharge, a magnetic field was applied to the ceramic plate, which was coated with diamondlike carbon (DLC), a material with a lower secondary electron yield (SEY) than TiN. After these countermeasures were implemented, an operation at 250 kW rf was maintained for more than a week without interruption.

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I. INTRODUCTION

In the 2020s, several fourth-generation light sources were designed and constructed. The lattices of their storage rings have been designed with multibend magnets and equipped with numerous accelerator components. Therefore, beam-accelerating radio frequency (rf) cavities are required to fit the small spaces within the rings. A TM020-mode cavity was developed that can be installed in such a small space [1]. Because the compact coupling tuner is directly equipped with a port of the TM020-mode cavity, an rf window specifically designed for the cavity was developed [2–5]. A schematic of the TM020-mode cavity and the rf window is shown in Fig. 1. The rf window has a simple structure consisting of a ceramic plate coated with titanium nitride (TiN). TiN coatings are often used to mitigate multipactor discharges and surface arcing because

of their secondary electron yield (SEY), which is defined as the ratio of the number of primary electrons to the number of secondary electrons. The rf window is mounted between the waveguide flanges and can be easily replaced

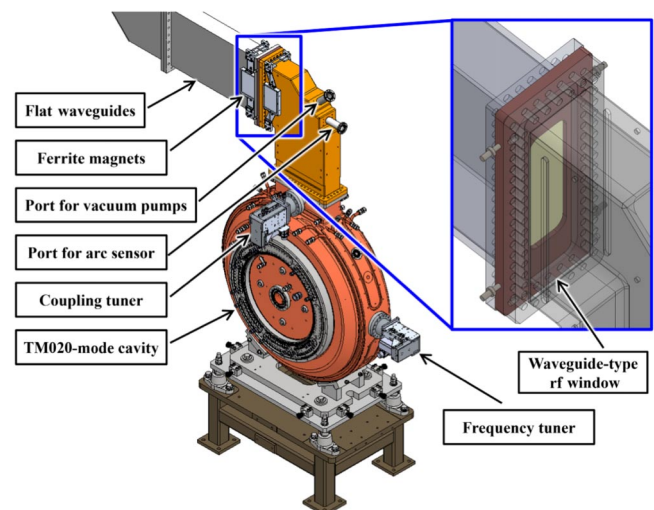


FIG. 1. Schematic of the TM020-mode radio frequency (rf) cavity and rf window.

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with a spare if it malfunctions. The rf window is connected to the TM020-mode cavity through an H-bend waveguide with ports for mounting the vacuum pumps and an arc sensor so that the rf window is not directly irradiated by the radiation coming from the beam. The rf electric and magnetic fields become high in the small cross-sectional waveguide. Therefore, only the heights of the rf window and waveguide along the beam direction must be compact, whereas the widths of these components are flexible.

Several rf windows were manufactured, and their performance was tested using high-power rf. However, the tests revealed two problems: cracks in the ceramic plates and frequent multipactor discharges on the vacuum-side ceramic surfaces. The first problem was caused by the low manufacturing quality of ceramic plates with $\tan \delta$ higher than required. Non-destructive methods were then developed to screen for ceramic plates with higher $\tan \delta$ before manufacturing the rf windows. The second problem was suppressed by applying suitable magnetic fields to the ceramic surface. Countermeasures were implemented, and rf windows were installed in the rf system of NanoTerasu [6]. After installation, we continued to develop a more effective method to suppress the multipactor discharge using diamond-like carbon (DLC) as a coating material on the ceramic surface. In this paper, we present the details of the rf window and the implemented countermeasures.

II. DESIGN OF RF WINDOW

A. Structure

Photograph and assembly drawing of the rf window are shown in Figs. 2 and 3. The specifications are presented in Table I. The window consists of a racetrack-shaped ceramic plate, a copper sleeve, and a chromium-copper flange. A Kyocera 479B alumina ceramic was used [7], which has a $\tan \delta$ of less than 1×10^{-4} at 509 MHz. An rf wave passing through the ceramic plate deposits energy proportional to $\tan \delta$, heating the ceramic plate. If the

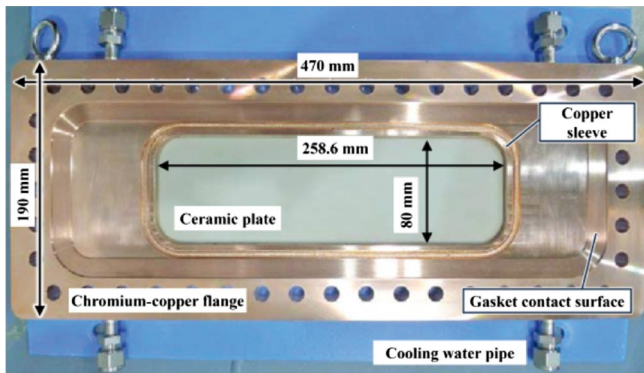


FIG. 2. Photograph of the rf window. The thicknesses of the ceramic plate and the chromium-copper flange are 5 and 18.4 mm, respectively.

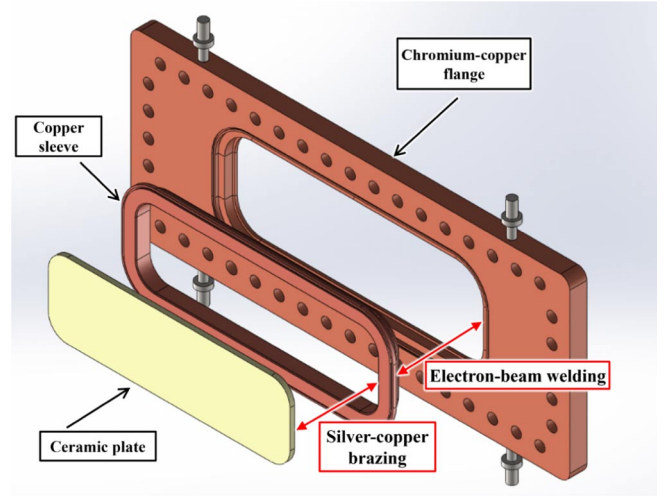


FIG. 3. Assembly drawing model of the rf window between the ceramic plate, copper sleeve, and chromium-copper flange.

temperature increases significantly, the ceramic plate fails because the stress exceeds its tolerance. Therefore, $\tan \delta$ must be less than 1×10^{-4} . This is a self-matching rf window, so the transmission frequency depends on the dimensions of the ceramic plate. The required dimensions to achieve a transmission frequency of 509 MHz were determined through the rf window, resulting in $258.6 \times 80 \times 5$ mm. The vacuum-side surface of the plate was coated with a 5- to 10 nm-thick TiN layer. The window was fabricated using a two-stage joining process because it was difficult to join the ceramic plate and flange directly. First, a plate with a metallized edge was silver-copper brazed onto a copper sleeve. Second, the assembly was inserted into and joined to a chromium copper flange via electron-beam welding. The dimensions of the chromium-copper flange were $470 \times 190 \times 18.4$ mm. The flange had two 8-mm-diameter channels for cooling water. This rf

TABLE I. Specification of the radio frequency (rf) window.

Frequency	509 MHz
Bandwidth (VSWR < 1.1)	34.4 MHz
Transmission rf power	<250 kW
Ceramic plate dimensions	$258.6 \times 80 \times 5$ mm
Outer size of the flange	$470 \times 190 \times 18.4$ mm
Inner bore size of the waveguide	381×100 mm
Ceramic material	Alumina, Kyocera 479B
Coating material	Titanium nitride (TiN) 5–10 nm-thick
Dielectric loss tangent ($\tan \delta$)	$<1 \times 10^{-4}$ (around 5×10^{-5})

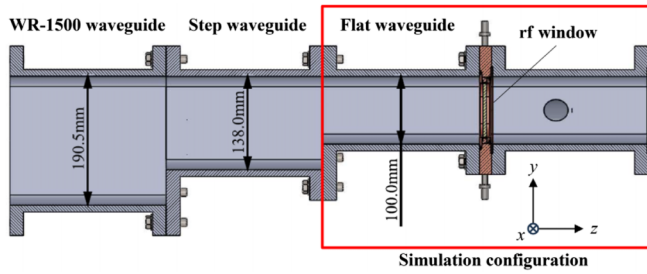


FIG. 4. Cross-sectional schematic view of the WR-1500 waveguide, step waveguides, and rf window. The heights of the bores of the waveguides decrease gradually, 190.5, 138.0, and 100.0 mm, to connect with the rf window.

window was installed in a WR-1500 waveguide system via flat and step waveguides, as shown in Fig. 4.

B. rf and structural analyses

rf and structural simulations of the window were performed using ANSYS HFSS [8]. The bandwidth, electric and magnetic rf fields around the ceramic plate, temperature increase, and stress of the rf window were all estimated. The rf power (P), $\tan \delta$, and relative electric permittivity of the plate (ϵ) were set to 250 kW, 1×10^{-4} , and 10, respectively. The cooling water temperature was set at 30°C. Figure 4 shows the simulation configuration.

The dimensions of the iris in the rf window and ceramic plate were optimized to transmit at 509 MHz. According to the simulation results, the frequency bandwidth of rf transmission with a VSWR of less than 1.1 was 34.4 MHz (between 492.7 and 527.1 MHz), as shown in Fig. 5. The rf window was fabricated with a mechanical dimension error of ± 0.5 mm, and the deviation of the transmission frequency due to this error was estimated to be ± 5 MHz. The 34.4 MHz bandwidth covered the mechanical dimension error.

The electric and magnetic rf fields at 250 kW transmission through the rf window were simulated, and the results are shown in Figs. 6 and 7. The maximum

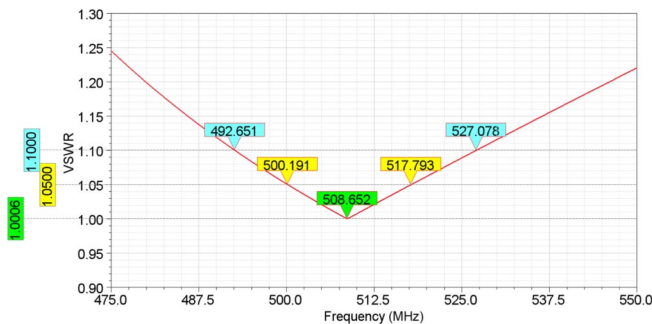


FIG. 5. Calculated voltage standing wave ratio (VSWR) distribution as a function of rf frequency for the rf window.

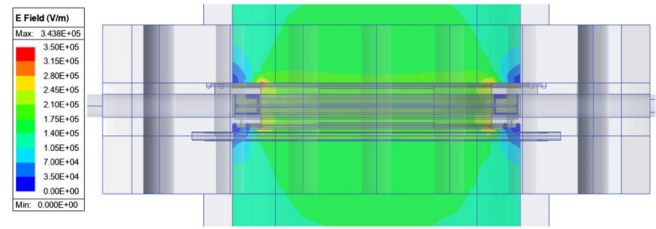


FIG. 6. Distributions of the rf electric field around the ceramic plate in the simulation at rf transmission of 250 kW and a ceramic loss factor $\tan \delta$ of 1×10^{-4} on the y - z plane.

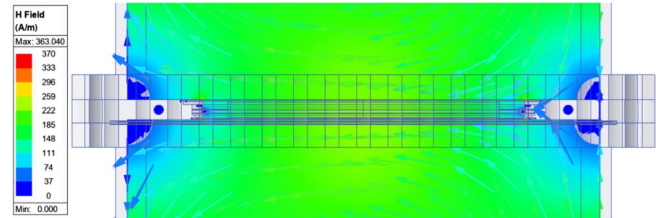


FIG. 7. Distributions of the rf magnetic field around the ceramic plate in the simulation at rf transmission of 250 kW and a ceramic loss factor $\tan \delta$ of 1×10^{-4} on the x - z plane. The color arrows indicate the magnetic field direction.

electric field in the ceramic plate was 3.4×10^5 V/m, which is significantly lower than the tolerance of alumina (1.6×10^7 V/m). In this case, the maximum temperature rise was estimated to be 28.8 K at the center of the ceramic plate due to dielectric power loss, and a maximum stress of 52.2 MPa was generated around the plate edges. The temperature and stress distributions are presented in Fig. 8, respectively. The stress tolerances of the ceramic and silver brazing were approximately 300 and 220 MPa, respectively. Therefore, the stresses on the ceramic plates were lower than their tolerances. These results confirmed that the rf window could transmit an rf power of 250 kW. The $\tan \delta$ of 1×10^{-4} corresponded to a safety factor of five, which was sufficient to ensure accelerator operation.

C. High power tests of the prototypes

Based on the simulation results, four rf windows were manufactured as prototypes, and their performance was verified using high-power rf tests. However, two critical problems were observed. The first was an unexpected temperature increase in the ceramic plates. Two ceramic plates in the four prototype rf windows cracked, making it impossible to seal the vacuum. The other problem was frequent multipactor discharges on the ceramic plate surfaces of all prototypes. These two problems were obstacles to stable power operation. Therefore, these problems were solved, and the countermeasures are described in the following sections.

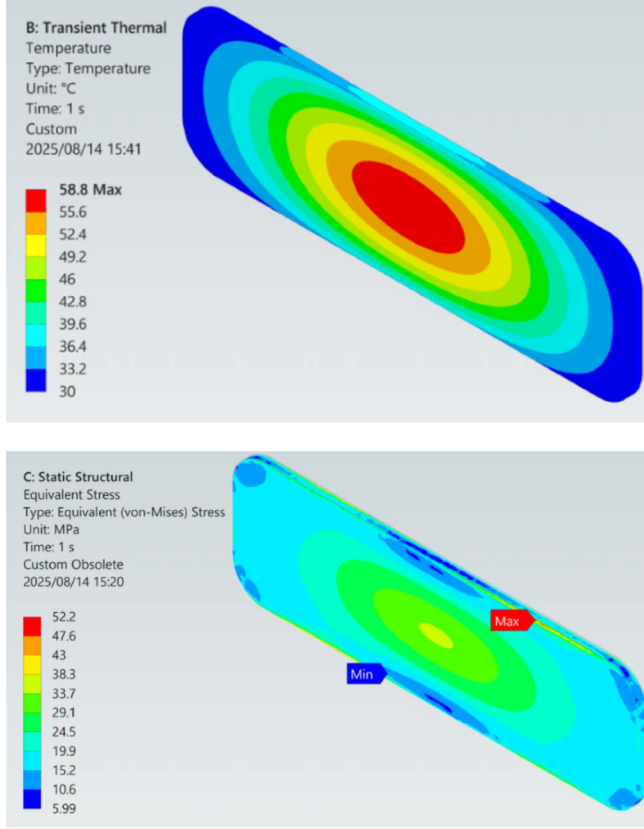


FIG. 8. Distributions of temperature rise (top) and stress (bottom) for the ceramic plate in the simulation at rf transmission of 250 kW and a ceramic loss factor $\tan \delta$ of 1×10^{-4} .

III. SCREENING THE CERAMIC PLATES

A. Ceramic plates cracked

In the high-power tests of the prototype rf windows, the temperatures around the center of the ceramic plate in the two cracked rf windows were 73 and 62°C at rf powers of 100 and 23.9 kW, respectively. The $\tan \delta$ of the latter cracked prototype was measured using an impedance analyzer, and the values were $(10\text{--}30) \times 10^{-4}$ at 500 MHz; the deviation was due to the measurement position. This was significantly higher than required. Then, it was concluded that the high $\tan \delta$ value caused overheating and excessive thermal stress sufficient to cause the cracks.

After the breakdown of the two prototypes, the ceramic manufacturer investigated the cause of their high $\tan \delta$ and identified it as an unoptimized molding process that resulted in alumina non-uniformity during manufacturing. Based on this analysis, the manufacturer improved the molding process. However, there were some ambiguities in $\tan \delta$ measurements below 1×10^{-4} . In $\tan \delta$ measurements using an impedance analyzer, the sample thickness should be less than 1 mm, whereas our ceramic plate was 5 mm thick. Therefore, the $\tan \delta$ of our ceramic plate could not be

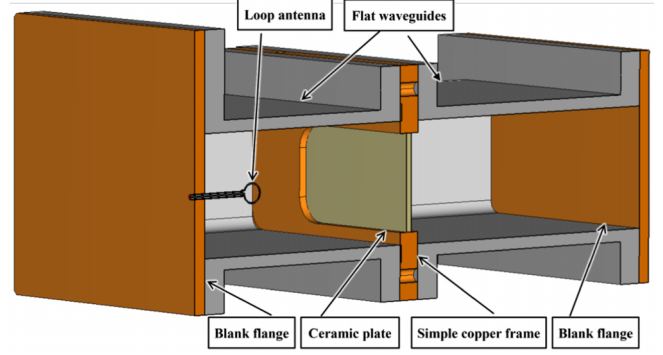


FIG. 9. Schematic cross-sectional view of the testbench for Q_0 measurement. The flanges sealed the bores of the waveguides to form a cavity whose Q_0 depends on the $\tan \delta$ of the ceramic plate.

precisely measured without being destroyed. To verify the $\tan \delta$ of the ceramic plate against the requirement, we built two setups to measure it non-destructively. The first is a loss estimate based on the unloaded quality factor (Q_0) of a resonator with the plates and waveguides as cavities. The ceramic plate with a large $\tan \delta$ ($> 10 \times 10^{-4}$) calculated from a low Q_0 value could not proceed to the second step. The second method is the rf high-power irradiation test. Using these measurements, we were able to determine whether the ceramic plate satisfied the required $\tan \delta$. The methods are described in the following sections.

B. Q_0 measurement

For the $\tan \delta$ measurement as a non-destructive method, we assembled a cavity using two waveguides, two blank flanges to close the waveguides, and a ceramic plate embedded in a simple copper frame, as shown in Fig. 9. The ceramic plate was inserted into the copper frame but not brazed. The copper frame also had two cooling channels. A loop antenna was inserted through one of the blank flanges and connected to a network analyzer. The Q_0 of this cavity depended on the $\tan \delta$ of the plate, and the correlation between Q_0 and $\tan \delta$ was estimated using CST Studio Suite [9] as shown in Eq. (1),

$$\tan \delta = 10^{(-8.54 \times 10^5 \cdot Q_0 - 2.78)}. \quad (1)$$

This equation did not account for the surface electrical resistance of the waveguides and blank flanges. After the Q_0 measurement, Q_0 was converted to $\tan \delta$ using Eq. (1). Following the ceramic manufacturer's modification of the alumina molding process, eight ceramic plates were produced and labeled LOT 1 through LOT 8. Their measured Q_0 and $\tan \delta$ values using Eq. (1) are listed in Table II. The measured $\tan \delta$ were approximately 1×10^{-4} . However, the precision of $\tan \delta$ in this measurement was approximately 1×10^{-4} due to the surface

TABLE II. Measured Q_0 and $\tan \delta$ calculated using the correlation between Q_0 and $\tan \delta$ in the simulation, in Q_0 measurements for the eight ceramic plates (LOT 1–LOT 8). The $\tan \delta$ specified in the datasheet was less than 1×10^{-4} . The $\tan \delta$ of the cracked ceramic plate, measured by an impedance analyzer, is also shown.

Ceramic ID	LOT 1	LOT 2	LOT 3	LOT 4	LOT 5	LOT 6	LOT 7	LOT 8	Cracked plate
Measured Q_0	13,200	13,100	13,200	13,200	13,200	13,200	13,000	13,000	
Calculated $\tan \delta$	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.2×10^{-4}	$(10-30) \times 10^{-4}$

electrical resistance of the waveguide bores. Though the precision of this measurement was limited, we could exclude ceramic plates with high $\tan \delta$ ($> 10 \times 10^{-4}$). After screening, the temperature rise of the ceramic plates was measured using high-power rf tests, as described in the next section.

C. Temperature measurement of the ceramic plates

Because the $\tan \delta$ of the ceramic plates was approximately 1×10^{-4} according to the Q_0 measurement, their temperature rise was measured under irradiation at an rf power equivalent to 400 kW. The experimental setup is illustrated in Fig. 10. The blank flange with the antenna was removed from the resonator, as shown in Fig. 9, and the cavity was connected to a WR-1500 waveguide using a step transformer. The cavity was fed with an incident rf wave from the klystron. A standing wave was formed by the traveling and reflected waves, and a ceramic plate was placed at the antinode position. As a result, the amplitude of the electric field at the ceramic plate was twice that of

the traveling wave, which is equivalent to four times the traveling power.

For this measurement, 100 kW of rf power was fed into the cavity, corresponding to a transmitted power of 400 kW, to measure the temperature increase above the rf transmission requirement of 250 kW. The interior of the waveguides was maintained at atmospheric pressure. The frame was cooled with water at 28°C and a flow rate of approximately 5 ℓ/min. The temperature of the ceramic plate was measured using a thermographic camera through a port on the E-bend waveguide, and the temperatures of the frame and cooling water pipes were measured using thermocouples. The temperature rise of the plate was evaluated by simulation using ANSYS by transmitting an rf power of 100 kW through the ceramic plate, assuming a $\tan \delta$ of the ceramic between $(0.1-1.0) \times 10^{-4}$. The estimated temperature rise (ΔT) was proportional to $\tan \delta$ as:

$$\Delta T[\text{K}] = 2.6 \times 10^5 \cdot \tan \delta. \quad (2)$$

The measured temperature increases for each ceramic plate are listed in Table III. In these tests, none of the plates showed an abnormal temperature increase after the alumina ceramic molding process was improved. The temperature rises were 12–18 K, corresponding to $\tan \delta = (5-7) \times 10^{-5}$. Therefore, it was concluded that the modification to the alumina molding process successfully produced ceramics with a $\tan \delta$ of less than 1×10^{-4} .

After the tests, rf windows were manufactured using these ceramic plates, and none of the windows cracked during rf operation.

IV. DISCHARGE ON THE CERAMIC SURFACE

After resolving the abnormal temperature increase, rf transmission tests were conducted at 250 kW. The setup is shown in Fig. 11 except the ferrite magnets. The two rf windows were mounted on both sides of a vacuum waveguide connecting the klystron and dummy load. The rf windows and vacuum waveguide were not baked to avoid thermal damage. The pressure inside the vacuum waveguide was maintained below 1×10^{-5} Pa using a scroll pump, turbomolecular pump, and sputter ion pump. The interlock system monitored three parameters: vacuum pressure using a cold cathode gauge with a 5×10^{-5} Pa threshold, arc light via optical sensors on the

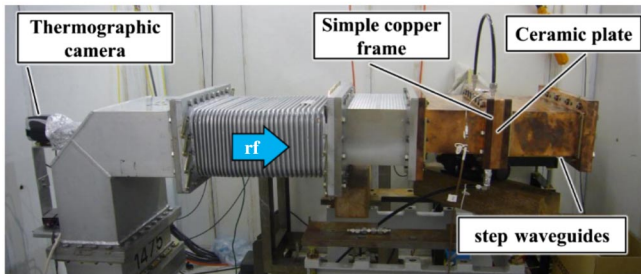
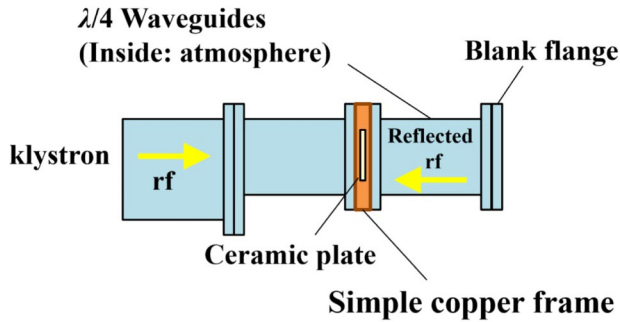


FIG. 10. Schematic (top) and photograph (bottom) of the configuration for the high-power rf test used to measure the temperature rise of ceramic plates. The temperature of each ceramic plate was measured using a thermographic camera.

TABLE III. Measured temperature rise (ΔT) of the eight ceramic plates in the high-power rf test in a configuration described in Figure 10 with 100 kW. The temperature rises corresponded to $\tan \delta \sim (5-7) \times 10^{-5}$.

Ceramic ID	LOT 1	LOT 2	LOT 3	LOT 4	LOT 5	LOT 6	LOT 7	LOT 8
Measured ΔT	13 K	12 K	13 K	12 K	13 K	12 K	18 K	17 K

vacuum waveguide ports, and excessive rf reflection through directional couplers in the waveguides. When a discharge occurred, at least one of the sensors detected it and terminated the rf operation.

However, the discharges were observed on the ceramic surfaces on the vacuum side in the test, and the operation was halted approximately once per day. This frequency was insufficient for stable rf operation. The discharge appeared to result from the multipactor effect. This problem was solved using two methods: (1) applying vertical magnetic fields to the ceramic plates and (2) coating the ceramic plate with a material having an SEY lower than that of TiN. These two methods are described in the following sections.

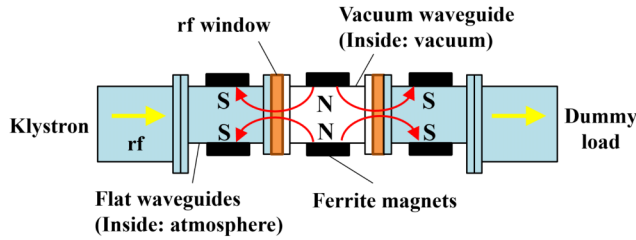


FIG. 11. Schematic of a high-power rf test configuration for evaluating the performance of the rf windows. The vacuum waveguide was evacuated to a pressure below 1×10^{-5} Pa using a scroll pump, a turbomolecular pump, and a sputter ion pump. The magnetic fields on the surfaces of the ferrite magnet were 380–400 mT.

A. Applying a vertical magnetic field to the ceramic

A single-surface multipactor is assumed to be excited by repeated collisions between electrons and a material that emits secondary electrons via rf electric and magnetic fields. The primary electrons are initially accelerated along the y axis in Fig. 4 by the TE₁₀ mode electric field in the waveguide. The rf magnetic field along the x axis then drives the primary electrons along the z axis, perpendicular to the ceramic plate and the copper flange. As a result, the primary electrons collide with these surfaces and generate secondary electrons. Therefore, the multipactor can be disturbed when a magnetic field is applied vertically to the ceramic surface, causing the electron trajectory to spiral and preventing the primary electrons from accelerating along the z axis.

Ferrite magnets with a residual magnetization of 380–400 mT were installed on the top and bottom sides of the waveguides, producing a magnetic field of 20–30 mT on the ceramic surface. The configuration of this rf high-power test is shown in Fig. 11, during which rf waves up to 250 kW were transmitted through the two rf windows. The trends in rf power, vacuum pressure, temperature of the ceramic plate in the rf window, and alarm history during the test are shown in Fig. 12. In the test, slow gas emissions were initially observed, followed by an increase in rf power. When the vacuum deteriorated to 1×10^{-5} Pa, the increase in rf power was paused until the vacuum improved. After the slow gas emission ceased,

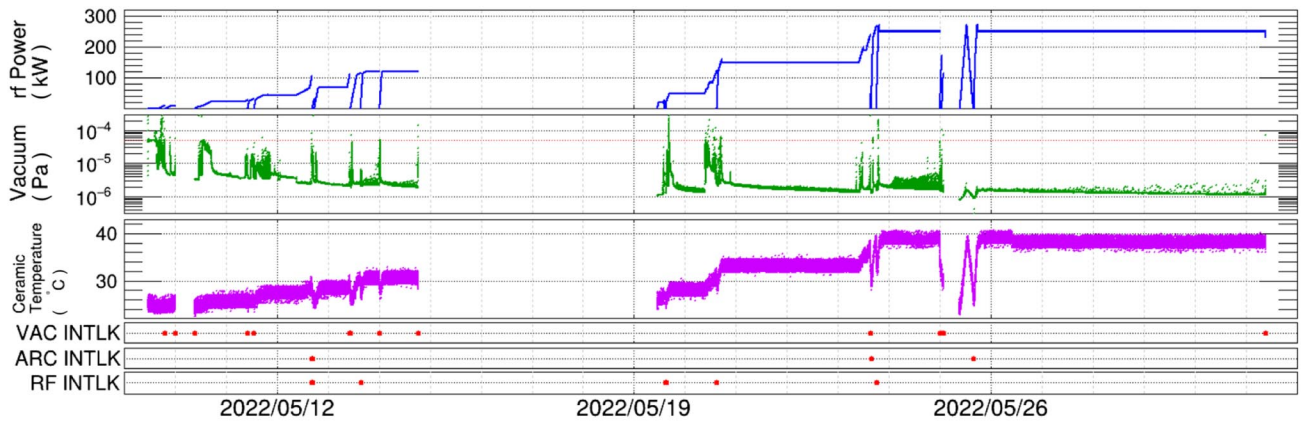


FIG. 12. Trend graph of the rf power, vacuum pressure, temperature of the ceramic plate in the rf window, and alarm (interlock) history due to vacuum pressure, arc, and rf reflection during the high-power conditioning test for the rf windows with the magnetic field. The horizontal axis shows the elapsed time (Year/Month/Day).

TABLE IV. Number of detections of the arc sensors to observe the arcing light coming from the rf windows in NanoTerasu storage ring.

	Beam commissioning	User operation
	(April 2023 to March 2024)	(April 2024 to March 2026)
rf window 1	14	0
rf window 2	7	0
rf window 3	4	0
rf window 4	6	0

discharge was no longer observed, and rf operation stabilized at 250 kW. Power transmission of 250 kW was maintained for over five days without any interlocks. This indicates that applying a magnetic field can suppress multipactor discharge.

This method was applied to the rf windows in the NanoTerasu. The four TM020-mode cavities and the rf windows were installed in the NanoTerasu storage ring. The multipactor discharges are detected by arc sensors, which monitor the arcing light in each rf window through the H-bend waveguide. The number of detections at the arc sensors is summarized in Table IV. Since the user operation in April 2024, multipactor discharges have not been observed at the rf windows.

B. DLC coating on the ceramic

The ceramic surface of the rf window in the NanoTerasu was coated with TiN. If the ceramic plate is coated with a material that has an SEY lower than that of TiN, multipactor discharge can be further reduced. DLC is a candidate for ceramic coatings [10]. DLC is formed from mixed lattices of graphite and diamond and is used to coat metal cutting tools, automobile parts, and other components, taking advantage of its hardness, strength, and slickness properties.

However, it has been reported that DLC is weak at high temperatures and detaches from the base material when the temperature exceeds 300°C in air. It is considered that if DLC is heated above 300°C by discharge, the SEY in the damaged region may increase and fail to suppress multipactor. We therefore compared the SEY of DLC samples, including those that were heated. Ceramic pieces (cylinder: $D19 \times L5$ mm, or cuboid: $19 \times 19 \times 5$ mm) coated with a 1- to 2- μm -thick DLC layer were prepared. Some DLC-coated pieces were baked at 300 or 500°C for more than 3 h under vacuum at a pressure lower than 1.1 Pa. The DLC-coated pieces looked unchanged before and after the baking; however, the DLC on the baked piece was detached upon wiping with ethanol. After coating and baking the ceramic pieces, we measured the SEY using a scanning electron microscope (SEM)-based device according to the procedure described in Refs. [11,12]. First, the

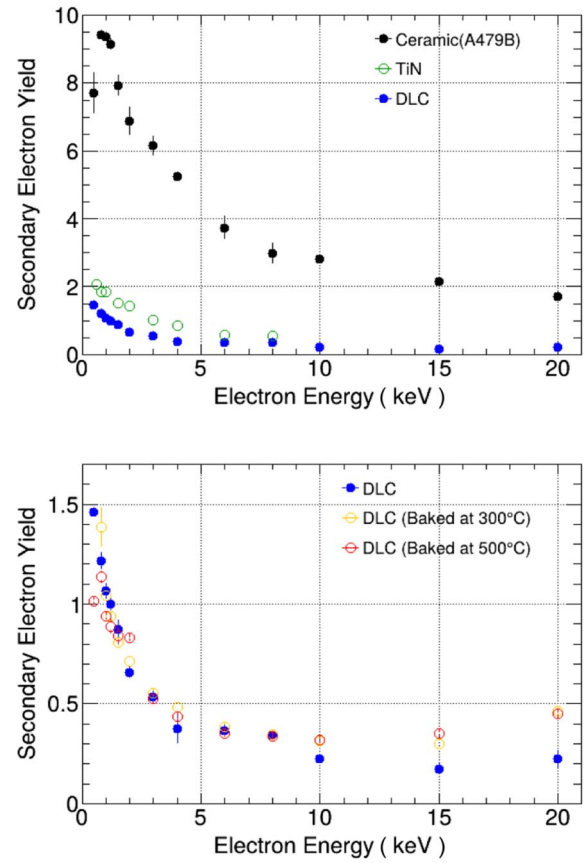


FIG. 13. SEY distribution as a function of the incident energy of the primary electron for ceramic samples without coating, with TiN coating [11,12], and with DLC coating (top). The bottom figure also shows the SEY distributions of the DLC coated sample, baked at 300°C for 3 h and 500°C for 5 h. The error bars indicate only statistical uncertainty.

charge of the primary electrons was measured by shooting them toward a carbon target, a conductive material placed on the stage in the SEM. Second, a ceramic piece coated with the DLC was replaced on the carbon target, and the charge of the secondary electrons was also measured.



FIG. 14. Photograph of the rf window coated with the DLC on the vacuum side.

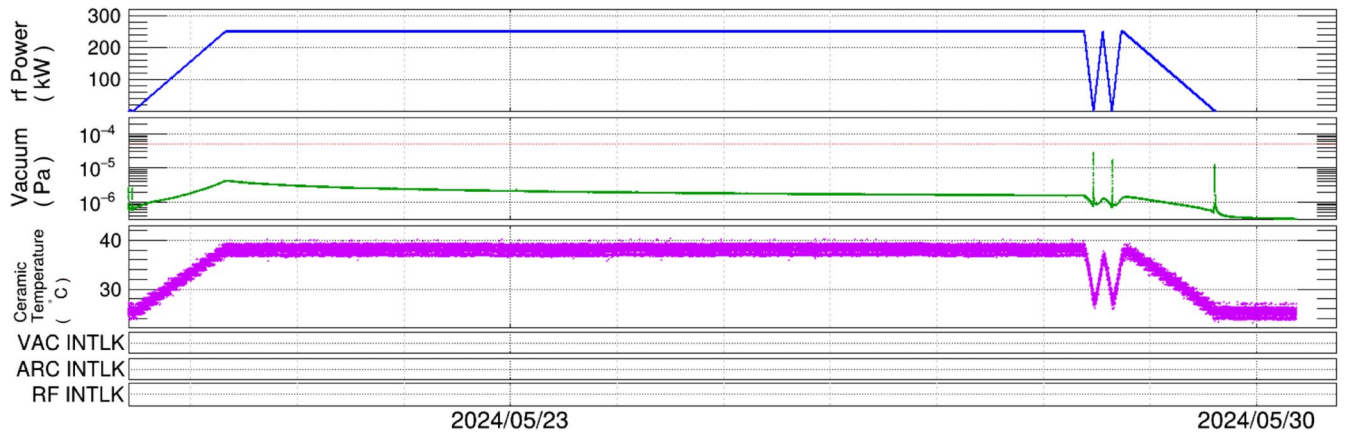


FIG. 15. Trend graphs of the rf power, the vacuum pressure, the temperature of the ceramic plate in the rf window, and the interlock due to the vacuum pressure, arc, and rf reflection during the high-power conditioning test for rf windows coated with the DLC applied magnetic field. The horizontal axis shows the elapsed time (year/month/day).

Consequently, the SEY can be calculated from the ratio of the charge of the primary electrons to that of the secondary electrons.

The SEY of alumina ceramic, TiN, and DLC as a function of the primary electron energy is shown in Fig. 13. The SEY of DLC was approximately three-fourths that of TiN. Figure 13 also shows the SEY of DLC baked at 300°C for 3 h and 500°C for 5 h under a pressure of 1.1 Pa. The difference in SEY between baked and non-baked DLC in vacuum was small. As a result, DLC suppressed multipactor discharge more effectively than TiN, and this effect remained even after the thermal damage up to 500°C in a vacuum.

To confirm the stable operation of the DLC-coated rf window, two rf windows were prepared to be coated with the DLC on a ceramic plate. The DLC-coated rf window is shown in Fig. 14. A high-power rf test was performed using the same procedure described in Sec. IVA and shown in Fig. 11. Magnetic fields from the ferrite magnets were applied to the rf windows during this test. The results are presented in Fig. 15. Although the vacuum degraded to a non-problematic level with an rf power below 5 kW, operation at 250 kW remained stable for seven days without any interlock halts. The results showed that the DLC-coated rf windows enabled more stable operation than TiN-coated rf windows. Therefore, we conclude that rf cavities sealed with the DLC-coated rf window under external magnetic fields can operate stably.

V. SUMMARY

A waveguide-type rf window was developed to seal an rf cavity in a vacuum and transmit 250 kW of rf power at 509 MHz. Because the rf window has a simple plate structure, it can be installed in a waveguide system and easily and quickly replaced with a spare in the event of ceramic puncture. Non-destructive screening methods were developed using a resonator embedded with the ceramic

plate for rf windows with a $\tan \delta$ higher than 1×10^{-4} . Regarding another problem, discharge on the ceramic surface on the vacuum side was suppressed by applying vertical magnetic fields. Furthermore, the surface of the ceramic plate coated with DLC was more effective than that coated with TiN in suppressing discharge. The rf windows coated with TiN and subjected to an external magnetic field were installed in the rf cavities of a NanoTerasu storage ring. The accelerator operated without any problems in the rf window.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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