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High-power Tests of X-Band RF Windows at KEK

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Abstract Various RF windows comprising a short pill-box, a long pill-box, a TW (traveling wave)-mode and three TE11-mode horn types have been developed for an X-band high-power pulse klystron with two output windows for JLC(Japan Linear Collider). The output RF power of the klystron is designed to be 130 MW with a 800 ns pulse duration. Since this X-band klystron has two output windows, the maximum RF power of the window must be over 85 MW. The design principle for the windows is to reduce the RF-power density and/or the electric-field strength at the ceramic part compared with that of an ordinary pill-box-type window. Their reduction is effective to increase the handling RF power of the window.

To confirm that the difference among the electric-field strengths depends on their RF structures, high-power tests of the above-mentioned windows were successfully carried out using a traveling-wave resonator (TWR) for the horns and the TW-mode type and, installing them directly to klystron output waveguides for the short and long pill-box type. Based upon the operation experience of S-band windows, two kind ceramic materials were used for these tests. The TE11-mode $1/2\lambda g$-1 window was tested up to an RF peak-power of 84 MW with a 700 ns pulse duration in the TWR.

INTRODUCTION

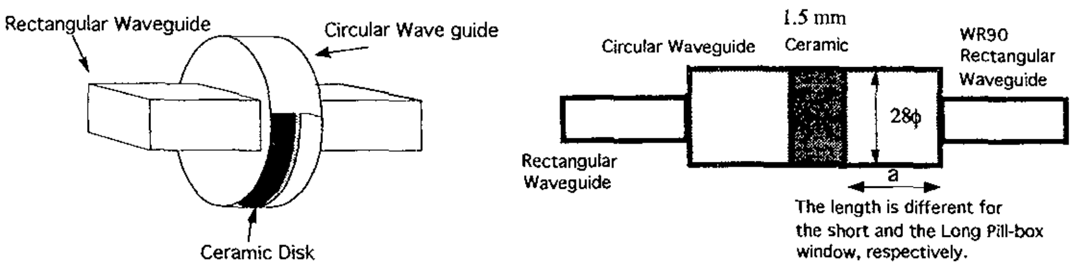
To realize the Tev-region beams of future linear colliders (LC), the development of an X-band high-power klystron with a pulsed RF output-power above 100 MW is necessary. KEK planed an R&D program for an X-band klystron having specifications of 11.424 GHz frequency, 130 MW RF output-power and 800 ns pulse width. It furnishes two output windows to reduce passing RF power. An output ceramic window is one of the important issues for developing high peak-power klystrons. The design criteria of the output window is handling an RF power of more than 70 MW with an 800 ns pulse width.

In accordance with the X-band klystron R&D program, ordinary pill-box-type windows were first evaluated in high-power tests[1] of the XB50K (30 MW class output) and 72K (100 MW class output) klystron series installing them directly. These tests showed that the maximum RF power passing through these windows was around 20 - 30 MW with a 200 ns pulse width, which was not sufficient to be employed in the above-mentioned klystron. We therefore started the development of a new type of a window.

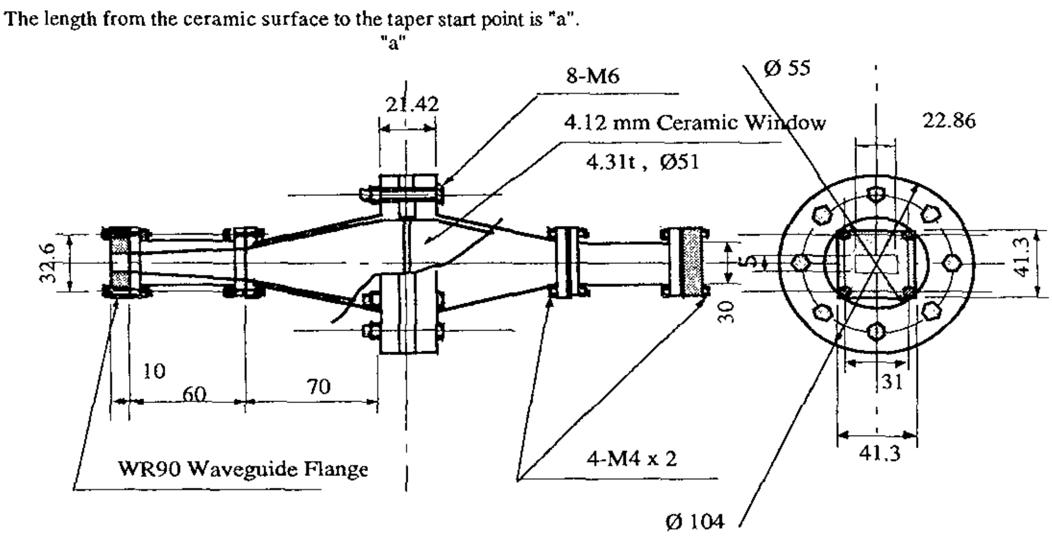
Generally, the electric-breakdown phenomena of an alumina ceramic depends on its surface electric-field strength. In a series of high-power tests of S-band ceramic windows by Y. Saito at KEK,[2] the maximum field strength on the ceramic surface was found to be 8 kV/mm (Peak value). Above this limit value, ceramics usually show a fatal destruction, such as blow holes, cracks and vacuum leaks.

For this reason, the electric-field strength at the ceramic part of the short pill-box type window was calculated using numerical-simulation code "HFSS".[3] This calculation showed that the field strength is almost 8 kV/mm at 30 MW. Based on this fact, we decided what method was necessary to obtain a low electric field in the ceramic part as the RF design direction of the next windows. One is that a solution to be a traveling wave in the ceramic disk should be employed. Second is that, in order to increase the electric-field level of ceramic destruction, a fine ceramic having voids and structure defects as small as possible should be also selected, as is apparent from the experimental results in the S-band case.[2,4]

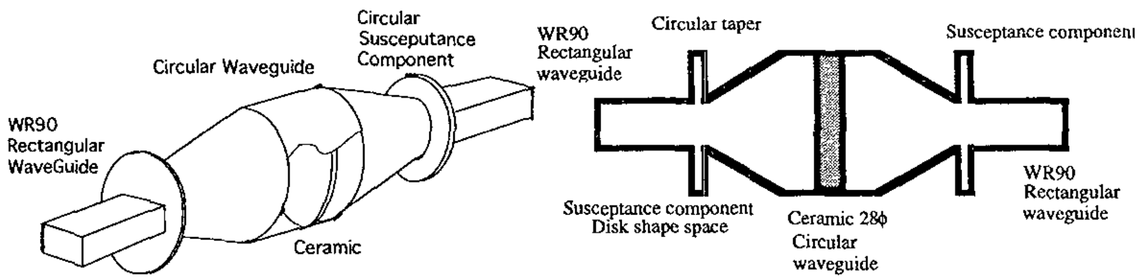
This paper gives brief explanations of the window structures (RF and mechanical) developed by the collaboration group between KEK and BINP as well as summary of their high-power tests and, the process and results of a high-power test of the TE11-mode horn window (1/2λg-1 solution).



A: Short and long pill-box windows



B: TE11-mode horn type window



C: TW-mode type window

Fig. 1. Schematic diagrams of the X-band RF windows

Table 1. Comparison of the maximum electric-field strengths on the ceramic surfaces and the bandwidths of the windows.

Type	Field strength*	Band width**
Pill-box	0.868	500 MHz
Long pill-box	0.414	300 MHz
TE11 1/4λg	0.424	250 MHz
TE11 1/2λg-1	0.400	300 MHz
TE11 1/2λg-2	0.369	700 MHz
TW-mode	0.362	300 MHz

* Normalized to the electric field of the TE10 rectangular-waveguide (WR90).
** Below S11 = -20 dB.

THE WINDOW STRUCTURES AND A COMPARISON OF THE ELECTRIC-FIELD STRENGTH AT THE CERAMIC DISK

We designed 2 pill-boxes and 3 TE11-mode horns as well as a TW-mode type window. The simplified drawings and the key-dimensions (a) for RF tuning variables are shown in Fig. 1. The pill-boxes are of the short and long type; the length of its circular waveguide and the thickness of the ceramic disk mainly differ. The horn-type windows have 3 different (a) to be different RF structures, which are called in the 1/4λg, 1/2λg-1 and 1/2λg-2 solution. The TW-mode type has 2 RF structures having a slightly different shape, depending on the ceramic material.

The waveguide parts of all the windows are made by oxygen-free copper and are joined by a blazing technique. High-purity ceramics of 99% and 99.7% (UHA-99 and HA-997, respectively, supplied by NGK Spark Plugs Co. Ltd) have been selected in accordance with the operation experience of S-band RF windows.[2] To suppress the secondary-electron yield on the ceramic surface, a TiN coating was applied by an RF-sputtering method (coating thickness shown in Table 2).

Table 1 summarizes the electric-field strengths at the ceramic surface and the bandwidths of the windows. The strengths were calculated by "HFSS". The RF structures of the long pill-box and the TW-mode type employ quasi and pure TW-mode solutions.[5] The TW-mode solution is able to achieve a pure traveling-wave in the ceramic disk by a matching mechanism with a standing wave between the ceramic surface and an RF susceptance element apart for a length of more than 1/4λg. The TE11-mode horn type with the 1/4 λg solution uses an over-size waveguide with tapered transitions to reduce its RF power density.[6,7] The 1/2λg-1 and 1/2λg-2 solutions of the horn type use a hybrid solution of the over-size waveguide and the quasi TW-mode solution.

SUMMARY OF THE X-BAND RF-WINDOW HIGH-POWER TESTS

Table 2 summarizes the results of the high-power tests, giving the window category, test methods, RF power conditions, ceramic materials and coating thicknesses. As a first step, a test of the short pill-box-type window was carried out by installing it directly to the klystron outputs. The result has already been explained in Introduction. The long pill-box was also tested up to passing a power of 48 MW, 80 ns by the klystron outputs. However, the window did not still show its own maximum handling RF-power because of the limitation of the klystron output power. After the 1st experiment of the long pill-box, the TWR was developed and became available for using to a high-power window test. We started a high-power test series of the TE11-mode horn type windows. At first, the window of the 1/4λg solution was evaluated. Then, the RF power of the TWR was stably circulated until 72 MW, 700 ns. The window of the 1/2λg-1 solution was

Table 2, Summary of the X-band RF window high-power tests.

Pill-box		
	Tested by the klystron outputs,	
	Power limitation	20 - 30 MW
	Pulse width	200 ns
	Ceramic	UHA99
	(NGK Co. Ltd.)	
	TiN coating thickness	6 nm
Long pill-box		
	Tested by the klystron outputs,	
	Power limitation	More than 48 MW
	Pulse width	80 ns
	Ceramic	UH997
	(NGK Co. Ltd.)	
	TiN coating thickness	6 nm
TE11-mode	1/4λg solution	
	Tested by the TWR,	
	Power limitation	72 MW, (100 MW)
	Pulse width	700 ns, (300 ns)
	Length "a"	≅ 9 mm.
	Ceramic	UHA99
	TiN coating thickness	4 nm
TE11-mode	1/2λg-1 solution	
	Tested by the TWR,	
	Power limitation	84 MW, (133 MW)
	Pulse width	700 ns, (300 ns)
	Length "a"	≅ 12 mm.
	Ceramic	UHA99 (tested) HA997 (will be tested)
	TiN coating thickness	0.8 nm
TE11-mode	1/2λg-2 solution	
	Will be tested by the TWR.	
	Length "a"	≅ 14 mm
	Ceramic	HA997
	TiN coating thickness	0.8 nm
TW-mode #1		
	Test by the TWR.	
	Power limitation	30 MW,
	Pulse width	300ns,
	Ceramic	Russian Ceramic
	TiN coating thickness	0.8 nm
TW-mode #2		
	Will be tested by the TWR.	
	Ceramic	HA997
	TiN coating thickness	0.8 nm

successively tested; the result of a power-limitation test was 84 MW, 700 ns.

Recently, the TW-mode type #1 was tested, which has a Russian ceramic just finished by the TWR. The final circulating power reached around 30 MW, 300 ns and the conditioning time of the low-power region at less than 10 MW was about two- or three-times longer than other X-band window high-power tests. After the final circulating power, the window was destroyed by a heavy flashover of the ceramic surface.

Usually, the conditioning necessary to reach the operation power of the X-band RF window is within 20 - 30 hours, which is shorter than that of the usual S-band components. However, the other features of conditioning such as light from a ceramic surface by multipactoring, is not so much different from the S-band case.[2,4]

In the series of high-power tests tabulated in Table 2, the power limis have some relation to the electric-field strengths on the ceramic surface. The difference in the limitation between the 1/4 λg and the 1/2 λg-1 solutions is related to the difference in their field strengths.[6,7] Apparently, reducing the electric field on the ceramic surface is effective for achieving high power.

A detailed example of the tests will be given in the next paragraph.

Process and Results of a High-Power Test of the TE11-Mode Horn Window(1/2λg-1 solution)

As the typical process and results of a high-power test by the TWR, we describe the case of the TE11-mode horn window with the 1/2 λg-1 solution, which showed the highest handling power. Figs. 2 and 3 show the experimental set-up of the window in the TWR and the history of the high-power conditioning.

As the first step, the input RF pulse width to the TWR and its pulse repetition-rate were fixed at 400 ns and 25 pps, respectively. In 10 hours of conditioning, the circulating power reached 20 MW. After this point, the RF pulse-width was shortened to 300 ns for a comparison with the results for the 1/4λg case shown in Table 2. The circulating power was increased up to 133 MW during conditioning for 20 hours(net). When the circulating power was around 60 MW, a discharge showing ordinary uniform blue light from the ceramic surface was observed by a CCD camera. This power level of 60 MW under which the first light was observed was higher than about 40 MW in the case of the 1/4 λg solution window. The power difference of 20 MW between the 2 cases can not be simply explained by the difference in their electric-field strength at the ceramic surface. There were probably some additional effects, such as a difference in the TiN coating on the ceramic surface (the ceramic disk of the 1/4 λg was coated outside of KEK and the 1/2 λg-1 case was by the KEK staff). The light continued in RF power from 60 MW to 133 MW; no significant RF reflections or bright-spots due to the discharge was observed. After this conditioning, the circulating power was fixed at 84 MW and the RF pulse width was gradually expanded from 300 ns to 700 ns; the repetition rate was kept at 25 pps. During this power level, the 700 ns operation remained rather stable without any heavy flashovers.

Fig. 4 shows a picture of the RF power in the TWR with 84 MW, 700 ns; the light spectra is also shown in Fig.5. The wavelength of the peak in the graph is 694 nm of Cr^{34}. Unfortunately, the ultra-violet (UV) region of the spectra could not be observed, because the material of the view-port was the usual glass that absorbs UV light.

While the circulating power reached 84 MW, bright-spot discharges appeared on the ceramic surface; the flashovers and steady bright spots had increased at over 84 MW. Finally, additional RF power could not build up due to big reflections from the window. The window was broken with cracks of the ceramic due to serious flashovers during the final process of the test. Fig. 6 shows cracks in the ceramic disk installed to the circular waveguide frame.

During the test, the temperature of the window was gradually increased from about 30 deg. without any RF to about 80 deg. during the final process. The basic vacuum pressure in an RF-off condition was gradually decreased from 1.8×10^{-5} pa (the start of the test) to 9×10^{-6} pa (the end of the test) due to the conditioning effect.

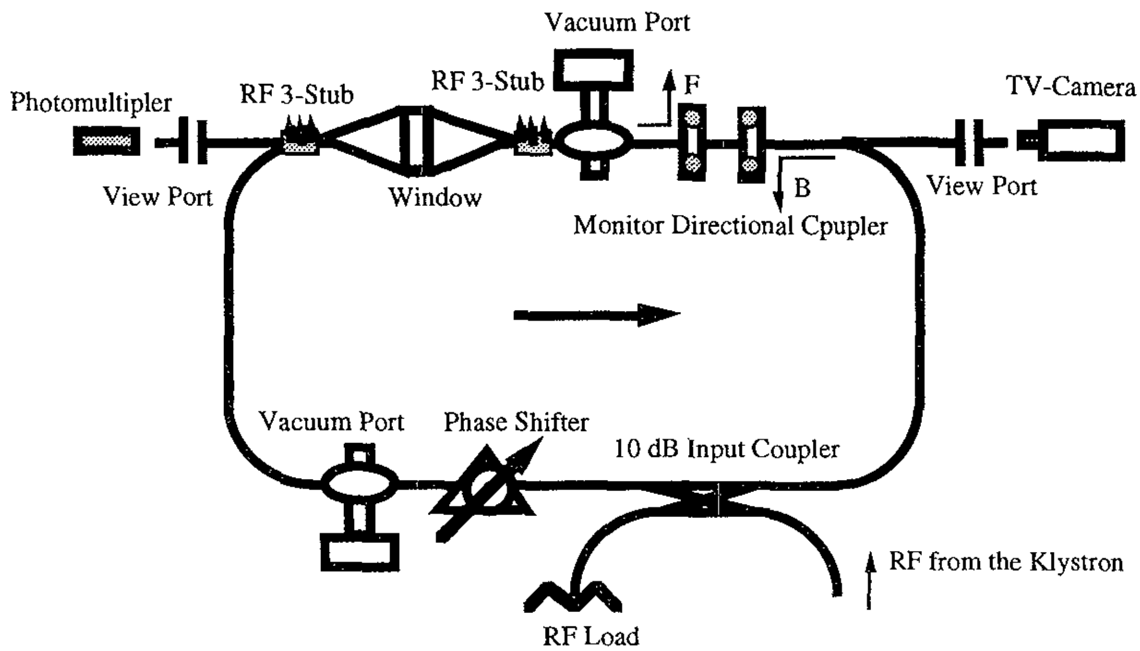


Fig. 2, Experimental set up of the TWR

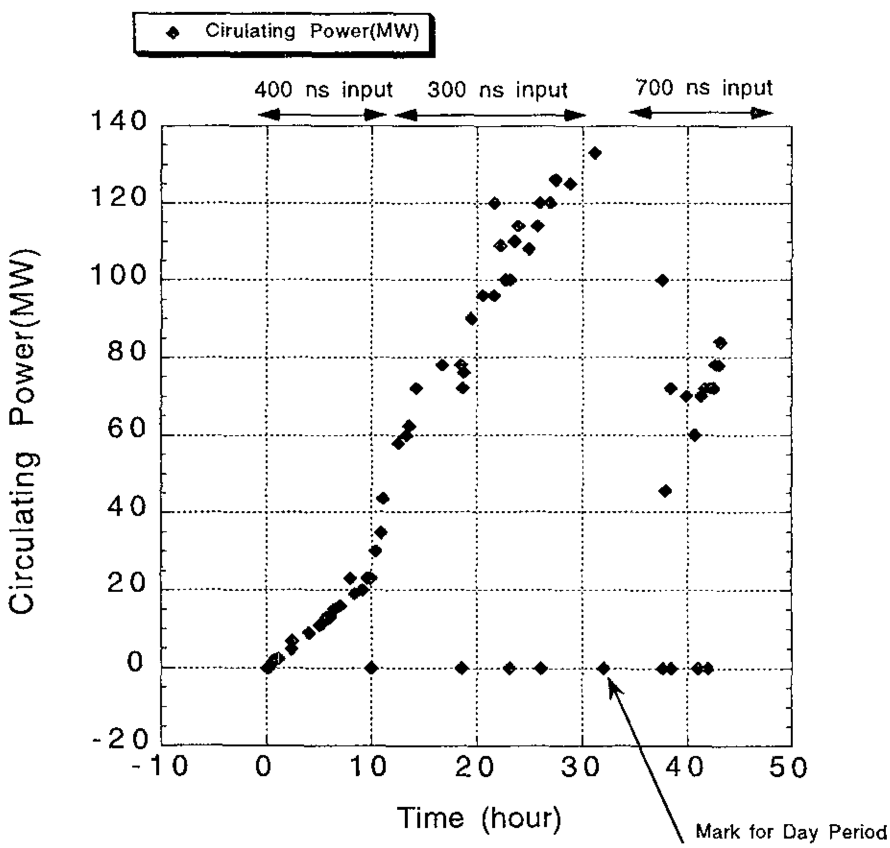


Fig 3, Conditioning plot of the high-power test for the TE11-mode horn window (1/2 λg-1 solution)

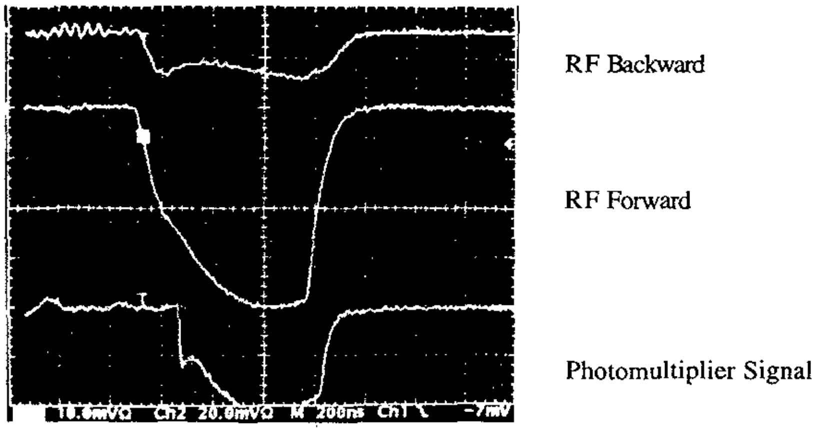
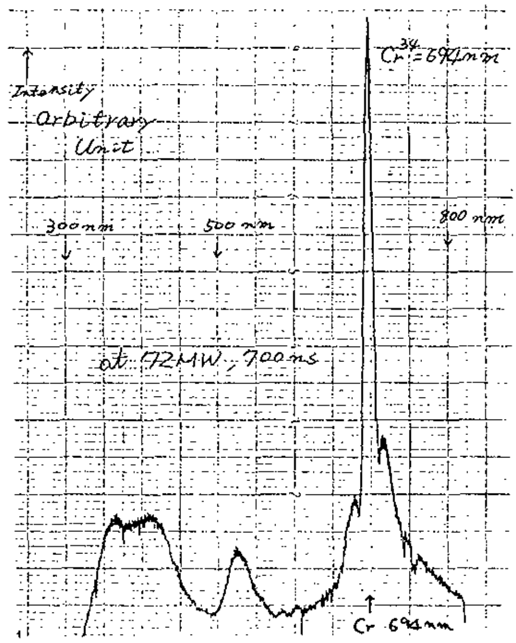


Fig. 4, RF-power waveforms of the window high-power test in the TWR (84 MW, 700 ns, Horizontal scale: 200ns/Div.)



(Horizontal: Wave Length, from 250 nm to 850 nm, 50 nm/Div.. Vertical: Intensity, Arbitrary Unit.)

Fig. 5, Spectra of the ceramic light at 72 MW, 700 ns

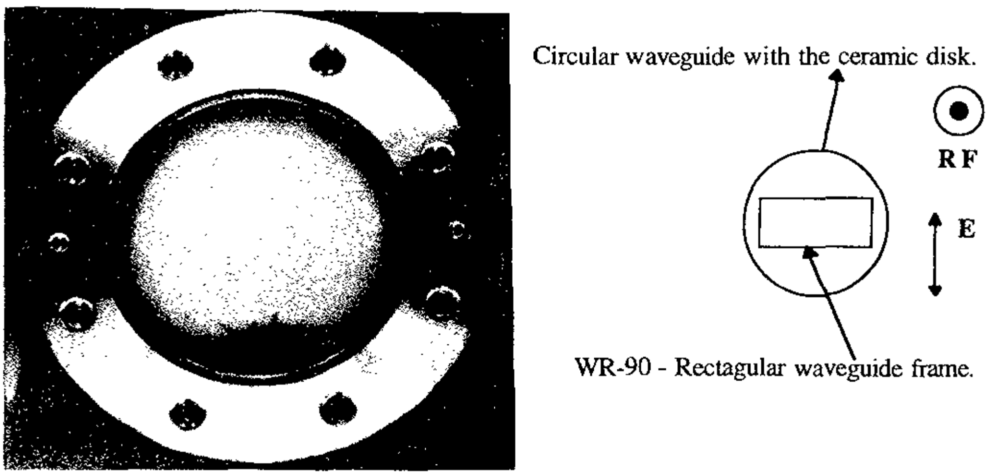


Fig. 6, Ceramic window with cracks after being tested

CONCLUSIONS

By the R&D work of the collaboration group between KEK and BNIP, several types of the X-band RF windows have been developed, and windows for a future JLC klystron have become a reality. Especially the TE11-mode horn type window has sufficient specifications (84 MW, 700 ns in the TWR) to be used with the klystron of a prototype RF power source system for the X-band linear collider being planed by KEK[8].

In a series of high-power tests, the following results were obtained.

(a) The low electric-field strength at the ceramic disk of the window is effective to increase its handling RF power.

(b) The final circulating power of the TWR, in which the TW-mode window with a Russian ceramic was installed, was lower than that of the TE11-mode horn type (even though the electrical-field strength at the ceramic disk between them did not differ much). In a prediction based on the results of S-band TW-mode window tests,[9] we believe that this fact could depend on the ceramic material.

(c) The other experimental results without considering the electric-field strength show no big difference to the S-band RF window tests.

ACKNOWLEDGMENTS

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