DESIGN AND HIGH-POWER TEST OF A TE11-MODE X-BAND RF WINDOW WITH TAPER TRANSITIONS

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A TE11-mode X-band RF window capable of passing RF power above 70 MW with 500 ns duration has been developed for installation to a pulse high-power klystron. The window comprises: a) TE10(WRJ-10) - TE11-mode (WC-5) converters, b) circular-waveguide tapers and c) an alumna ceramic with a circular-waveguide frame. This paper describes its design and high-power performance. The basic design concept is to reduce the RF field strength on the ceramic surface by increasing the diameter of its ceramic part compared to an ordinary pill-box-type window. The design of its RF structure was achieved by using a circuit model, and was confirmed by numerical simulations. The dimensions of the window necessary to obtain good RF transmission were found by changing the length of the circular-waveguide frame. A high-power test using a traveling-wave resonator has been successfully carried out up to a circulating power of 100 MW with a 300ns pulse width. The tests showed that the break-down limit of the electric-field strength on the ceramic surface was about 8 kV/mm. This limit was the same as in the case of S-band pill-box window experiments.

I. INTRODUCTION

In high-energy physics institutes, such as KEK, SLAC and BNIP, the development of 100MW-class X-band klystrons is underway for future linear colliders. For realizing klystrons, the alumna-ceramic RF window is one of the key-technologies. Therefore, the development of a window capable of passing RF power above 100 MW is necessary.

Ordinary pill-box type windows have been evaluated in high-power tests of the XB50K(30MW class output) and 72K(100MW class output) series in accordance with an X-band klystron R&D program.[1] These tests have shown that the limitation of its peak RF-power is around 20 - 30 MW with a 200 ns pulse width.

Generally, the electrical-breakdown phenomena of an alumna ceramic depends on its surface electric-field strength. In a series of experiments concerning S-band ceramic windows by Y, Saito of KEK,[2] the maximum field strength on the ceramic surface was found to be 8 kV/mm(Peak value). Above this field strength, ceramic showed fatal destruction, such as blow holes, cracks and vacuum leaks. In order to reduce the ceramic surface-field strength, an over-size TE11-mode ceramic window with tapered transitions was designed and tested. The window is shown in Fig. 1.

II. DESIGN AND LOW-POWER MEASUREMENTS

The basic criteria for designing the TE11 window are as follows: a circular ceramic-disk was chosen for easy machining and brazing; furthermore, a large-diameter ceramic-disk, compared with the wavelength of the window operation frequency(11.424 GHz), was adopted. The cut-off frequency(1.125GHz) of the ceramic part is far lower than the operation frequency. In some cases, higher-order mode RF-signals generated by the ceramic surfaces, the mode-converters and the taper transitions could be trapped in the ceramic and between the tapers(so-called trapped-mode resonance); this may cause a local higher field or heat up of the ceramic. Therefore, the mode selection of the window becomes important and the trapped-mode resonances must be separated from the operating frequency. The TE11-mode was chosen for simplicity of mode-conversion from the TE01-mode.

The TE11-mode circular-ceramic window with taper transitions is divided in to 3-parts: a) mode-converters from a rectangular-waveguide mode(TE01) to a circular-waveguide mode(TE11); b) two circular-waveguide tapers and c) a 51ϕ circular-waveguide frame(WC-5) installing an about 0.8nm TiN coated ceramic-disk(NITOKU, UHA-99 & HA-997, 4.1 mm thickness).

In the design stage of the window, the RF characteristics, such as the frequency responses, of this type over-size window were not clear. The dimensions of the window must be chosen in order to avoid any trapped-mode resonance. For this reason, the following 4 design steps were carried out: a) impedance matching using a circuit-model method[3] was used and determines roughly the S-parameter behavior; b) the trapped-modes of the ceramics and the susceptance components of the taper transitions were analyzed by a field-matching method;[4),5)] c) numerical simulations using RF-structure analysis codes, such as "MAFIA" and "HFSS", were carried out in order to confirm the results of the analysis above mentioned and d)

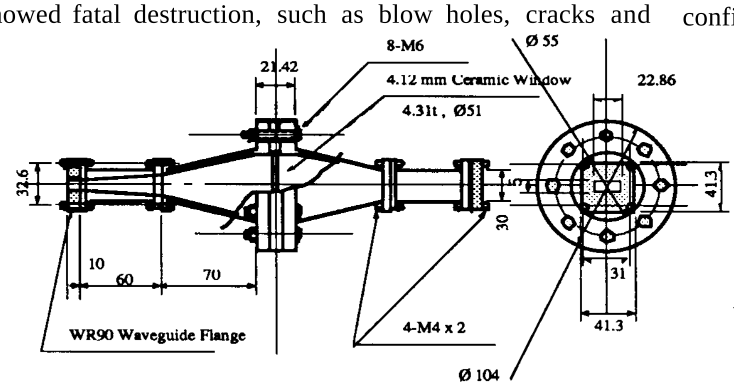


Fig. 1: Schematic diagram of the TE11 window

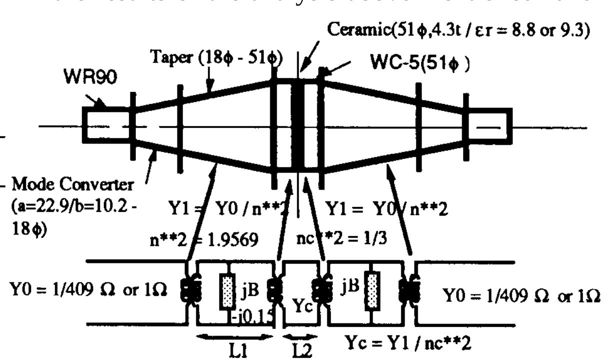
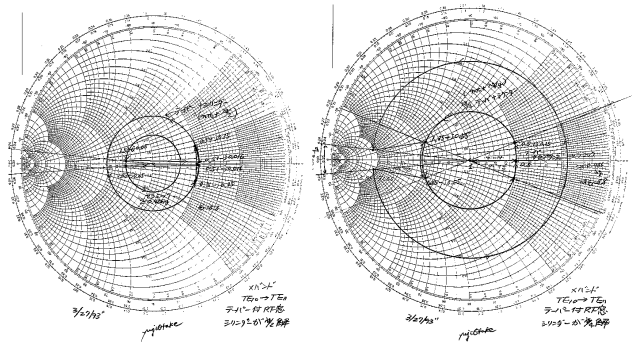


Fig. 2: Circuit model of the window



1/2λg case 1/4λg case

Fig. 3 Admittance transformation of the window

to also confirm the results obtained above and to determine the final dimensions of the window, several cold models were tested.

A. Circuit model and electromagnetic field analysis

The circuit model of the window was constructed as shown in Fig. 2, and used for the analysis. The definition of a waveguide characteristic-admittance is "$Y_0 = P/V^2$", which Schelkunoff defined,[6] where the Vs are the values integrated along the maximum electric-field lines of the circular and rectangular waveguide cross sections; P is their transmitting power. The frequency response of the window using the circuit model and the characteristic admittance(Y_0) defined above was solved using the equation

$$\frac{Y_{in}}{Y_0} = \frac{Y(L) + jY_0 \tan \beta L}{Y_0 + jY(L) \tan \beta L},$$

where Y_{in} is the input admittance of the window and β is the propagation constants of the waveguides; L is the length measured along their RF propagation direction. The susceptance components of the taper transitions to be used in the circuit model were calculated by field-matching[5] and "HFSS" and, measured by the cold model. Electromagnetic-field analyses were also performed by "HFSS" and "MAFIA".

The next RF characteristics of the window became clear through the studies mentioned above: a) The ceramic thickness which produces a good RF transmission is slightly less than 1/2λg for compensating the susceptance components. b) There are three optimum solutions for the cylinder length from the ceramic surface to the taper. The Smith-chart in Fig. 3 shows these solutions, which are for cylinder lengths of 1/4λg(8.625mm) and 1/2λg; the 1/2λg solutions have two slightly different cylinder lengths (11.7mm, 13.845mm). The example of the window frequency response simulated by the circuit model is shown in Fig. 4. c) Where the admittance of the ceramic part transforms to the near center on the Smith-chart as in the 1/2λg case, the solution has a wider frequency band-width in order to obtain a good transmission and a lower ceramic surface-field than in the 1/4λg case. d) The solutions for the TE11 window are periodic with every 1/2λg wavelength step. e) By using "HFSS" the field distributions for the 6-types of RF-windows were determined. The relative field strength of the ceramic surface and their band-width are summarized in Table 1. The results show that one of the 1/2λg solutions of the TE11 window has almost the same performance as the "KAZAKOV" type, and can reduce the maximum surface electric-field to about 37% of the rectangular-waveguide field.

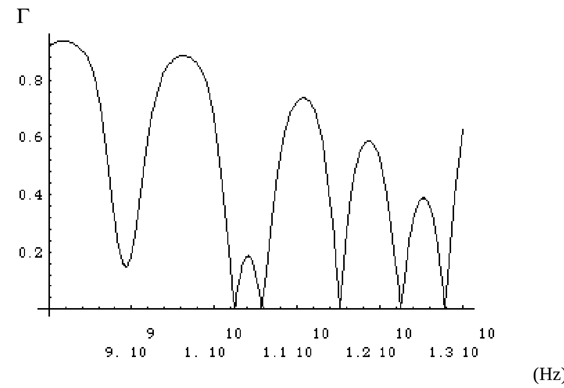


Fig. 4: Frequency response of the window using the circuit model(1/4lg solution)

Table 1: Comparison of the electric-field strengths on the ceramic surfaces and the band widths among 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
KAZAKOV	0.362	300 MHz

*Normalized to the TE10 rectangular-waveguide. $E = \sqrt{ExE^*}$

B, Trapped-mode resonance

In the design stage trapped-mode resonances were expected at the ceramic part (generally called the ghost-mode in the case of a ceramic) and between both tapers. They were calculated in order to obtain the frequencies and modes by "MAFIA". However, the electromagnetic field strengths of the ghost-modes which were found by low-power measurements were at a very low-level. In this case the "MAFIA" calculations did not have sufficient accuracy. For this reason, another calculation method, such as field-matching, was employed in order to obtain more accuracy. The method was used in order to find mode transmitting only in the ceramic while maintaining continuity of the electromagnetic fields of the circular-waveguide part and the ceramic part at the ceramic surface. The ghost-mode observed in the low-power measurements were all confirmed in the MAFIA and the field-matching calculations. Experiments to pick up the ghost-modes were carried out by setting the ceramics in to the circular-waveguide frame with antennas.[4] To find the trapped-mode between the tapers, "MAFIA" was used; the results coincide with the low-power measurements shown in Fig. 5. The trapped and the ghost modes are tabulated in Table 2.

Table 2: Trapped modes around 11.424GHz

	Calculated	Measured
Between tapers	≈10.5GHz	≈10.9GHz
	≈11.3GHz	≈11.23GHz
	≈11.7 GHz	≈10.65GHz
In Ceramic	≈10.1GHz(TE221 like)	≈10.8GHz
	≈11.5GHz(TE131 like)	≈11.3GHz

C, Low-power measurements of the cold

In a previous step for the high-power model, a cold model window of brass was produced according to the dimensions determined from the design. However, a calculation of the TE11 window was not sufficiently accurate because of its over-size. Therefore, the center frequency of the pass-band was adjusted by changing the length of the circular-waveguide frame. The frequency shift of the length was measured as being 50MHz/mm; this value was in good agreement with the circuit models and MAFIA calculations. Fig. 5 shows the measurement results of the cold model having the 1/2λg-2 solution. As the 1st stage of a comparison among the three solutions of the TE11 window in a high-power RF, a high-power model with the 1/4λg cylinder and the UHA-99 ceramic has been made of oxygen-free copper (OFC, Class 1, HITACHI).

III. HIGH-POWER TEST

A high-power test of the window was carried out using a traveling-wave resonator(TWR).[8] At first, the input RF pulse width of TWR and its pulse repetition-rate were adjusted to 300ns and 25pps. The conditioning of TWR and the window proceeded below a circulating power of 10MW for a net time of 5 hours. After conditioning, the power was increased up to 100MW with an input RF power of 15MW; this process was continued for 15 hours(net). Then, a discharge on the ceramic surface was ordinary uniform blue-light; no significant RF reflection or bright-spot due to the discharge was observed. After this operation, the leakage of the window was checked using a He leak detector; it did not show any problem, such as cracks of the ceramic. Next, the circulating power was set to 70MW and the RF pulse width was gradually expanded from 300ns to 700ns. The repetition-rate was also changed to 50pps. Then, steady blight-spots appeared on the ceramic surface, and the window became broken due to a flash-over. Fig. 6 shows a picture of the RF power in TWR with 100MW, 300ns.

IV. CONCLUSIONS

The design has almost been successfully completed. The electric field in the ceramic of the 1/2λg-2 solution is quiet low (about 37% of the rectangular-waveguide field), the same as the "KAZAKOV" type. Furthermore, the electromagnetic field adjacent to the ceramic is also low compared with that of the "KAZAKOV" type. We think that it has some advantage. The power capability shown in the high-power test is sufficient for our requirements. It is a great step for the 100MW X-band klystron development. However, the surface field of the ceramic surface was around 7kV/mm when the ceramic was broken in the 70MW case. This fact is similar to the situation in the S-band window experiments. The power could be thought of as the limit of this type of ceramic. For the next step of the high-power test, we will employ a finer ceramic, like HA-997(NITOKU), and the 1/2λg-2 solution.

Acknowledgments

The authors wish to thank Drs. T. Higo and H. Sakai, Y. Sito, S. Mitizono for their help and discussions.

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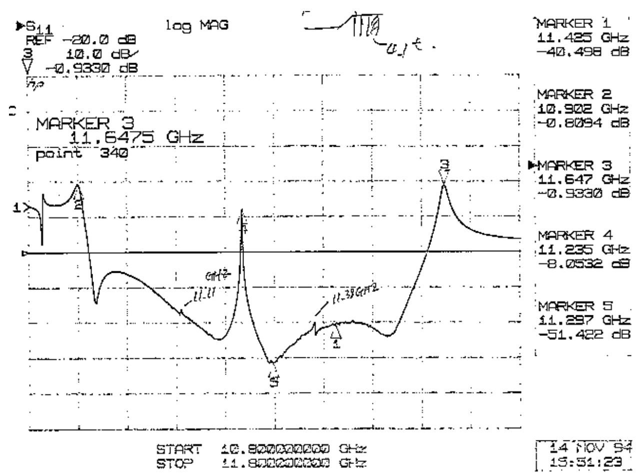

Fig. 5: Frequency response of the TE11 window (1/2λg-2 case)

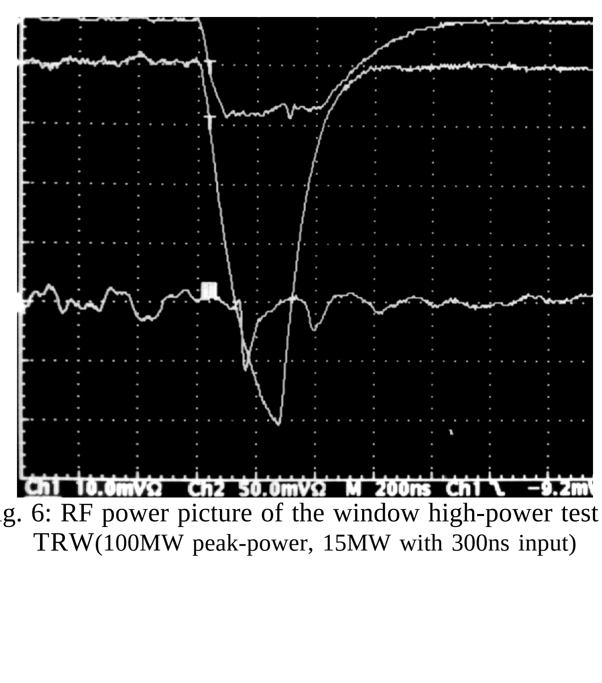

Fig. 6: RF power picture of the window high-power test in TRW(100MW peak-power, 15MW with 300ns input)