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RF WINDOWS USED AT S-BAND PULSED KLYSTRONS IN KEK LINAC

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ABSTRACT
Breakdown of the alumina rf-windows used in high-power klystrons is one of the most serious problems in the development of klystrons. This breakdown results from excess heating of alumina due to multipactor bombardment and/or localized rf dissipation. A statistical research of window materials was carried out, and high-power tests were performed in order to develop rf windows having high durability for the KEKB klystrons. The breakdown mechanism of rf windows is being considered. An improved rf window installed in a KEKB klystron is also being tested.

Breakdown of alumina rf windows

Forty eight S-band pulsed klystrons (2856 MHz, 30 MW at maximum, 3.5 μs, 25 pps) are operated at the KEK 2.5-GeV linac. An rf window is installed in the output portion in order to isolate the vacuum from the atmosphere, and to pass rf power. The window comprises a pill-box housing and a brazed alumina ceramic. Although studies concerning rf windows have been made [1-3], the breakdown of rf windows during rf operation is one of the most serious problems. In KEKB, higher-power klystrons [4] are necessary and an improvement of the rf windows should be made.

Operation of the KEK linac started in 1981, and more than 180 klystrons have been used at the klystron gallery. The cumulative status of the klystrons is given in Table 1. Failure due to internal arcing between the electrodes of the electron gun was most frequent for oxide cathodes (~1987). Although the use of barium-impregnated (BI) cathodes suppressed internal arcing due to less electrode contamination (1987~), the breakdown of rf windows still remained.

Table 1 Failure analysis of klystrons. Living klystrons are those which have been used (working) or had been used and can be used again (stand-by).

Year of production	Cathode	No. of living klystrons	Average operation time (hours)	No. of failed klystrons	Causes: arcing	Causes: window	Causes: others	Mean age (hours)	MTBF (hours)
1979-1987	oxide	5	8,558	106	72	13	21	10,783	11,187
1987-1993	BI	52	18,719	24	0	18	6	11,176	51,734

The breakdown of rf windows is mainly due to localized surface melting caused by multipactoring and/or localized rf dissipation, leading to punctures. Multipactoring is a resonant multiplication of secondary electrons due to the high secondary electron emission coefficient (δ) of alumina. The breakdown mechanism is considered to be as follows [2,3]:

(1) Localized surface heating induces F-center oxygen-defect generation.

(2) Electrons trapped in F-center defects contributes to ohmic losses.

(3) Ohmic losses enhance the surface heating ("run-away").

Multipactoring can be suppressed by TiN coatings having a low δ. Localized rf dissipation depends on both the ceramic purity and the structure.

In this paper, window breakdown is discussed from the view point of a temperature increase of the rf windows in the gallery and high-power tests using a resonant ring. Flashover phenomena at higher power are also reported.

Window-housing temperatures (ΔT)

In order to estimate surface heating, the temperature increase at the window housing (ΔT) was measured during rf operation (~25 MW, 3.5 μs, 25 pps) at the klystron gallery of the KEK linac. Figure 1 shows the ΔT increase with the operation time for broken windows. All of these windows showed localized surface melting, indicating that the alumina ceramics gradually deteriorate along with the operation time, which probably depends on the alumina materials. It has been confirmed that measuring ΔT is an effective way to estimate surface heating.

At the KEK linac, three kinds of alumina ceramics have been used. The physical properties of the ceramics are summarized in Table 2. Ceramics 'A' and 'B' include many voids. The rather high tanδ values of ceramics 'A' and 'B' are probably caused by impurities and their voids. Ceramic 'C' has a low tanδ (rf losses).

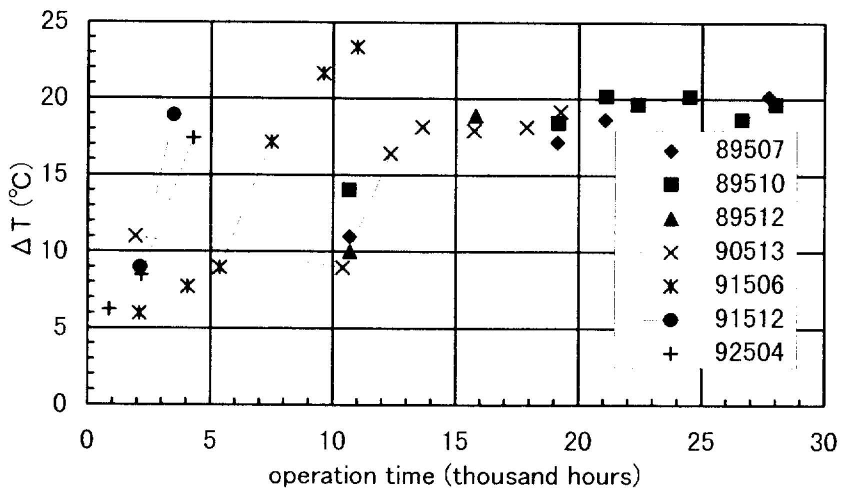

Figure 1 Increase in ΔT with the operation time. The legend is the klystron number.

Table 2 Physical properties of the window materials.

materials	purity (%)	grain size	ε	tan δ (10^{-4})	pre-existing defects
A	97.6	50 μm	9.0	3.2	F^+,F
B	99.5	50 μm	9.3	3.0	F^+
C	99.7	20 μm	9.95	0.4	F^+

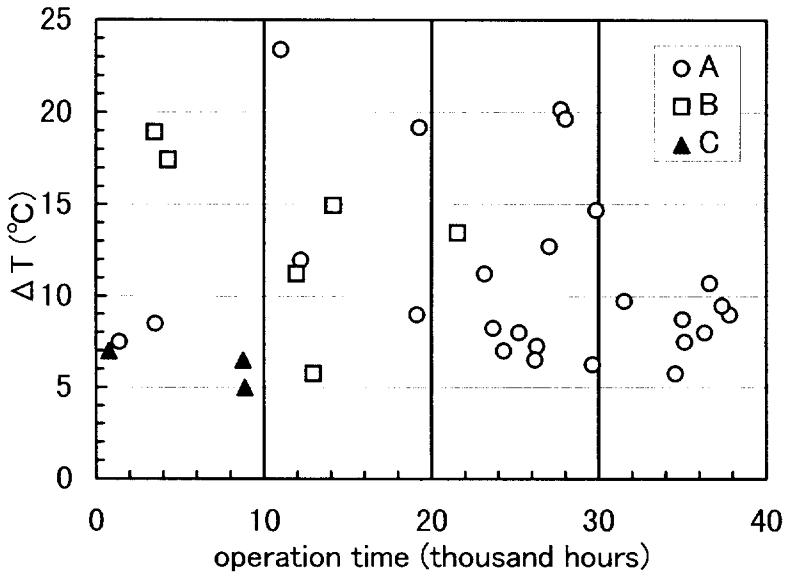

Figure 2 ΔT of window materials 'A', 'B' and 'C' during rf operation (~25 MW,3.5 μs, 25 pps) measured at the KEK linac on May, 1995.

Figure 2 shows ΔT (so surface heating) from the view point of the window materials. It is found that the ΔT of ceramics 'A' and 'B' is from 5° to 25°; on the other hand, the ΔT of ceramic 'C' was from 5° to 7°.

The difference in ΔT between the window materials is related to the feasibility of localized surface heating.

Window materials and breakdown

High-power tests of the alumina ceramics were carried out using a resonant ring [2]. In the resonant ring, the rf output power from a pulsed-klystron (30 MW, 2856 MHz, 2 μs, 20 pps or 50 pps) was transmitted through an input directional coupler and resonated in the ring. An rf window could be examined at a maximum power of 220 MW in this experiment.

The results are summarized in Table 3. F-center oxygen defects, which could contribute to surface heating, were observed at ceamics 'A' and 'B', where localized surface melting took place. On the other hand, ceramic 'C' was not liable to F-center defects due to a low tanδ.

Table 3 Properties and results of high-power tests.

Materials	defects after 220 MW operation	Coloring after rf operation	Comments
A	F^+,F	yellow	surface melting
B	F^+,F	slightly yellow	surface melting
C	F^+	no colorings	no breakdown

After high-power tests, coloring was observed on the surfaces on ceramics 'A' and 'B', which was probably caused by X-ray radiation due to electron bombardment. Such coloring was not observed on ceramic 'C' after high-power tests, which indicates that the ceramic was durable under X-ray radiation. This coloring was considered to be some kind of oxygen defect, since it vanished with time in the atmosphere. Although the relation between the coloring and breakdown is not well known, it is better for window materials to have durability against coloring because oxygen defects have played important roles for window breakdown.

Optimization of TiN coatings

Ti [5], Cr_2O_3 [6], particularly TiN coatings [3,7,8] having a low δ (secondary electron emission coefficient), are available for suppressing multipactor effects. TiN films with various thicknesses (1-20 nm) have been used, corresponding to the operating frequencies and powers. Very thin films could not sufficiently reduce δ; however, thick films probably cause excessive heating due to ohmic losses in the rf field because of good electric conductivity. It is thus necessary to optimize the film thickness coated on windows for practical use.

In order to estimate the suppression of multipactoring, δ was measured for TiN coatings on alumina ceramics using modified scanning electron microscopy (SEM) involving a pulsed-beam method (100 pA, 1 ms). Secondary electrons were captured by a biased (+40 V) Faraday cup, and δ was obtained from the ratio of the number of secondary-to-primary electrons. It was found that δ decreases with the film thickness, and has an almost constant value of less than unity for films of 0.5 nm or greater at 10 keV, as shown in Figure 3. This energy was estimated to be about the same as that of multipactor electrons at a power of 30 MW [9]. Thus, such films are expected to suppress multipactoring. Figure 4 shows the optical emission due to multipactoring during rf operation. All quarters had TiN coatings with a thickness of 0.2, 0.5, 1.0, 2.0 nm, respectively. No luminescence was observed on the alumina surface, except for the upper-left region where the thickness of the film is 0.2 nm. It was confirmed that multipactoring is suppressed by TiN coatings with a thickness of 0.5 nm or greater.

The total rf losses of TiN-coated alumina ceramics were measured using an rf cavity [3] in order to estimate the ohmic losses during rf operation. The total rf losses (P_{loss}) were expressed using the effective-loss-tangent ($\tan\delta'$),

$$P_{loss}=P_{ceramic}+P_{TiN}=\int \varepsilon\tan\delta\omega E^2 dV+\int \sigma\omega E^2 dv=\int \varepsilon\tan\delta'\omega E^2 dV$$

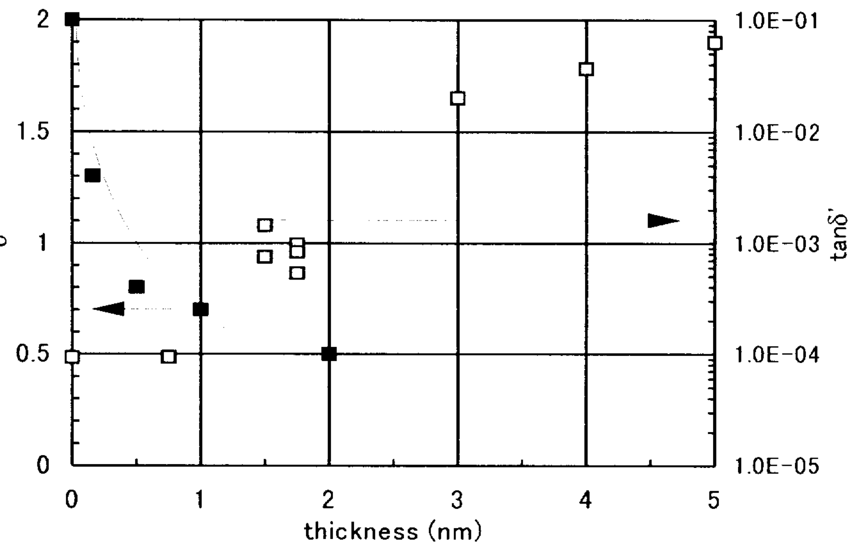

Figure 3 Secondary electron emission coefficient (δ) at 10 keV electron irradiation and effective loss tangent (tanδ') with various coating thickness.

where σ is the conductivity of the film, ω is the operation frequency, and V and v are the volume of the ceramic and TiN coatings, respectively. Since tanδ of the alumina ceramic is about 1×10^{-4}, the ohmic losses of TiN films are larger than the dielectric losses when the coated film is thicker than 1 nm, as shown in Figure 3. From high-power tests, a localized "going-away" of TiN coatings was observed for coatings having a tanδ' of more than 7×10^{-4} (corresponding to a film thickness of 1.5 nm). It is considered that the localized excessive heating of the coatings caused the "going-away". The threshold thickness is 1.5 nm where excessive heating takes place.

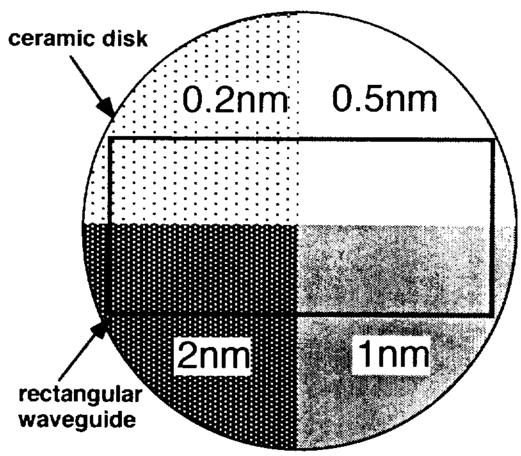

Figure 4 The optical emission due to multipactoring during rf operation (30 MW).

Windows for KEKB klystrons

It has been found that 50 MW klystrons capable of a 4 μs pulse width at 50 pps are required for the KEKB project [4]. The specifications of the KEKB klystrons are shown in Table 4. Ceramic 'C' has been adopted for the window material as well as TiN film coatings for multipactor suppression.

The window installed in a 50-MW klystron was tested. Figure 5 shows the ΔT of the 50-MW klystron. ΔT was suppressed by about 10% compared to an rf window with ceramic 'A'. Also, ΔT of ceramic 'C' at the linac had a small distribution.

Table 4 Specifications of KEKB klystrons

	maximum rf power	pulse width	pulse repetition	average power	window materials
existing	33 MW	2 μs	50 pps	3.3 kW	A,B,C
KEKB	50 MW	4 μs	50 pps	10 kW	C

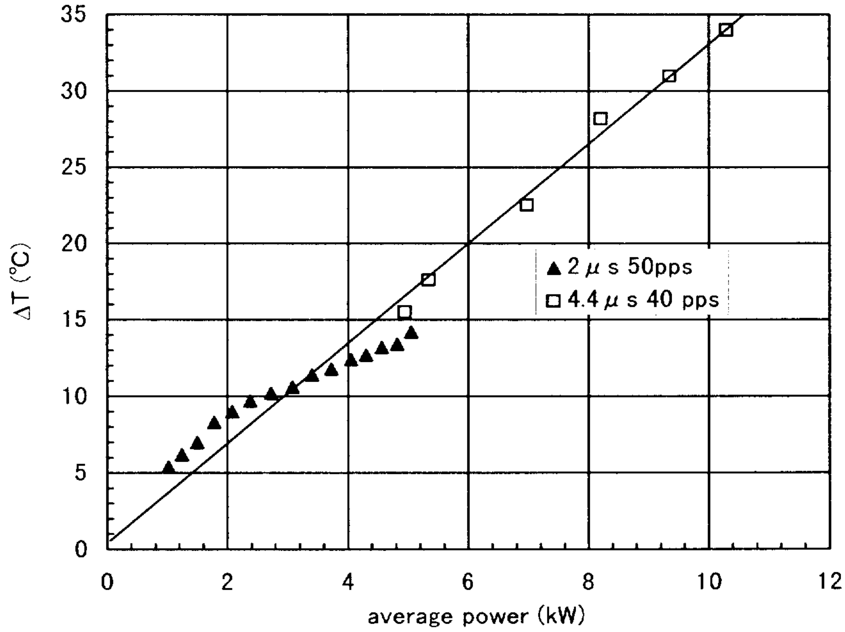

Figure 5 ΔT of the 50 MW klystron during rf operation.

Flashover of the windows

Flashover [10,11] took place at a higher power (more than 200 MW), as shown in Figure 6. The threshold transmission power of a flashover depends on the material, surface treatment and coating. Though a TiN coating can suppress multipactoring, the secondary electrons emitted from alumina are accumulated in TiN coatings. The flashovers are probably a discharge of the accumulated charges in the TiN coatings. The threshold depended on the surface finish, such as polishing and annealing. High-power tests of different surface-finished ceramics were carried out. The results are summarized in Table 5. The number of accumulated charges were considered to be higher for polished ceramics due to mechanically introduced defects, which could contribute to electron-emission sites. On the other hand, an annealed ceramic probably has lower electron-emission sites so that the threshold power is higher. It is concluded that the elimination of surface charging is important to increase the threshold of a flashover.

It is desirable to measure not only the surface distribution, but also the depth distribution of charges and the electric potential, which is probably related to a flashover.

Figure 6 Observed flashover during rf operation at the transmission power of more than 200 MW.

Table 5 Polishing and annealing effect on the flashover threshold.

Materials	finish	treatment	threshold power	comments
C	unpolished	none	>230 MW	no breakdown
	polished	annealed	230 MW	local melting
		none	230 MW	pin-hole
sapphire	unpolished	none	160 MW	local melting
	polished	annealed	100 MW	
		none	80 MW	

Conclusions

The breakdown of the rf window is due to localized excess heating. Actually, rf widows with a large ΔT (temperature increase from room temperature) show localized surface melting, or sometimes punctures, leading to vacuum leaks. Since breakdown is related to the feasibility of the F-center of alumina ceramics, ceramics having a low $\tan\delta$ (such as ceramic 'C') are durable.

The thickness of TiN coatings for multipactoring suppression must be optimized in order to avoid excessive ohmic heating. In our system, 0.5 nm - 1.5 nm coatings are the optimized thickness.

At the KEKB project, since 50 MW klystrons will be used, an improvement in the rf windows became necessary. An rf window with ceramic 'C' was chosen for the KEKB klystron, and ΔT was suppressed by about 10% compared to that of a window with ceramic 'A'.

Flashovers observed at more than 200 MW are a serious problem for higher power operation. It is considered that such flashovers have been due to electron accumulation on a TiN coated area, where electrons emitted from the ceramics were trapped due to the low δ of TiN coatings. The annealed ceramics, which probably have lower electron emission sites, have a higher threshold power. The breakdown (flashover) thresholds of the polished disks were lower than that of annealed or unpolished disks due to the larger accumulated charges on the TiN coated surface, probably released from dislocations and/or micro-cracks of alumina caused by polishing. It is concluded that the elimination of surface charging introduced by mechanical polishing is effective to increase the threshold of a flashover.

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