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Application of M-Type cathodes to high-power cw klystrons

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Abstract

Two types of high-power cw klystrons have been widely used at KEK in both TRISTAN and KEKB e^+e^- collider projects: one is a 0.8 MW/1.0 MW tube, called YK1302/YK1303 (Philips); the other is a 1.2 MW tube, called E3786/E3732 (Toshiba). Normally, the dispenser cathodes of the 'B-type' and the 'S-type' have been used, respectively, but for improved versions they have been replaced by low-temperature cathodes, called the 'M-type'. An Os/Ru coating was applied to the former, whereas an Ir one was applied to the latter. Until now, all upgraded tubes installing M-type cathodes, 9 and 8 in number, respectively, have worked successfully without any dropout. A positive experience concerning the lifetime under real operation conditions has been obtained. M-type cathodes are, however, more easily poisoned. One tube installing an Os/Ru-coated cathode showed a gradual, and then sudden, decrease in emission during an underheating test, although the emission could fortunately be recovered by aging at the KEK test field. Once sufficiently aged, the emission of an Ir-coated cathode proved to be very high and stable, and its lifetime is expected to be very long. One disadvantage of this cathode is, however, susceptibility to gas poisoning and the necessity of long-term initial aging. New techniques, like *ion milling* and *fine-grained tungsten top layers*, were not as successful as expected from their smaller scale applications to shorten the initial aging period. A burn-in process at higher cathode loading was efficient to make the poisoned cathode active and to decrease unwanted Wehnelt emission. On top of that, the *emission cooling*, and thus *thermal conductivity*, near to the emitting layer could play an important role in such large-current cathodes as ours.

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1. Introduction

At KEK, TRISTAN was terminated in December, 1995, and disassembled by the end of March, 1996. It is now being rebuilt as a new e^+e^- collider, KEKB, comprising two rings installed side by side. Research on B-physics will start after machine commissioning in October, 1998. High-power cw klystrons of the UHF band that have been developed for TRISTAN are to be successively used in KEKB in almost the same frequency region (508.887 MHz) [1]. Until now, the operational time of the transmitters has totaled 1,413,000 h (161 years) in filament hours: 55 years for 0.8 MW/1.0 MW tubes and 106 years for 1.2 MW ones. Five tubes of the latter have been continuously operated for over 40,000 h. The heater-on time of the top runner has already exceeded 53,220 h.

In the early stages, a tungsten dispenser cathode of the '*B-type*' was normally installed in Philips (Valvo), while that of the '*S-type*' was installed in Toshiba tubes. The tungsten pores are filled with a mixture of barium oxide, calcium oxide and aluminum oxide with a molar ratio of 5:3:2 and 4:1:1, respectively. The disadvantage of these cathodes is the relatively high ($1040\text{--}1050^\circ\text{C}_\text{B}$) operating temperature. The tube performance is directly or indirectly affected by an unwanted coating of barium on the electrodes, insulation ceramics and drift tubes. Typical difficulties encountered are modulation-anode-involved instabilities. To improve the stability over the lifetime it is essential to reduce barium evaporation by adopting a low-temperature cathode, called the '*M-type*', whose operation temperature could be reduced to ($975\text{--}980^\circ\text{C}_\text{B}$) [2].

2. Os/Ru-coated cathodes in Philips cw klystrons

In the case of YK1302/1303, barium plays a key role in almost every aspect: 1) primary electron emission from the anode as well as the focus electrode (Wehnelt) [3,4]; 2) flaking of condensed barium from the modulation-anode under electrical forces [5]; 3) side-band oscillations (SBO) on the output signal along with an irregular increase in the modulating anode current caused by secondary and back-streaming electrons [5,6].

Ba-adhesion to the anode is rather poor probably due to its combined structure. To reduce Ba evaporation and to suppress the primary emission from wrong places, a "cold gun" and then a "warm gun" instead of the "hot gun" design was adopted together with a low-temperature cathode made of osmium (Os)/ruthenium (Ru) metal coating of about $1\mu\text{m}$ thickness. The cathode operating temperature could be decreased from $1040^\circ\text{C}_\text{B}$ for standard B-type to $975^\circ\text{C}_\text{B}$ for M-type, as the turning point between the temperature-limited zone and the space-charge limited region was shifted to lower temperatures. This decrease of about 65K in cathode operating temperature can produce a remarkable reduction of Ba evaporation down to about 25%, as shown in Fig. 1.

In the case of the Os/Ru type, sufficient emission can be obtained soon after about 100 hs of aging in a factory. The cathode performance improves further with the life because the work function goes

through a minimum at 80% W concentration on the surface [7]. Underheating tests thus showed a slight increase in emission until about 5,298 LVh (filament hours). It also corresponds to a gradual improvement in the vacuum in a young tube showing a residue of Ar used during the coating process. We found, however, a gradual, and then sudden, decrease of emission in underheating data of one tube (V23) after about 8,500 hs of heater-on time at KEK. Data were taken by first decreasing the heater current down to the minimum level, increasing it in steps of 1 A, and waiting at each step for 1 h under fixed beam/anode voltage conditions of 72 kV/55 kV, where beam voltage is the potential of the body referenced to the cathode.

Emission slumps observed between 12,044 and 12,161 LVh were typical gas poisoning. An obvious correlation was found between the decrease in emission current, the heater power, and the ion-getter pump current. The lower was the heater power and the larger was the IGP current, the deeper was the emission slump. M-type cathodes are more sensitive to poisoning by gas than normal B-type ones. There is also ample room for doubt that poisoning was caused by the underheating process (cathode efficiency test with reduced heater current), itself. The time to reach the minimum in the work function at 975°C_B is expected to be more than 100,000 hs on this Os/Ru cathode [7]. Compared with it, the time for degradation in this case was too short, indicating that this emission slump was not due to intrinsic degradation but to accidental gas poisoning.

Fortunately, in this case, the emission could be mostly recovered by a cathode aging process, as shown in Fig. 2. This was accomplished at a test field of KEK for about 260 h without any special thermal flushing procedure. The total operation time of this tube is now over 16,200 LVh. The best emission characteristic at around 5,298 LVh has, however, never been obtained. In total, nine 1 MW tubes equipped with Os/Ru-coated M-type cathodes are working trouble-free at KEK. No flaking of Ba has occurred until now.

3. Ir-coated cathodes in Toshiba cw klystrons

In the case of E3786, insulation between the electrodes was a severe problem during the early stage of tube development [8]. Barium evaporation was one of the main causes of such phenomena. Since improvements were made on the gun design, material selection and pretreatment-and-baking process, however, serious electrical breakdown, like flaking of condensed Ba, has not yet been observed. The adhesion of Ba to the body or to the modulation anode is good probably owing to geometrical and material factors. In a few other tubes hysteresis appeared in the dynamic characteristic behavior, indicating multipactoring along the 1st or 2nd drift gap. The intended omission of the crown cut (biperiodically toothed edge) and stacking of the BaO layer on drift cones definitely induced such a phenomenon. It was thus easily repelled out by suppressing Ba evaporation and re-adopting the crown structure [4].

The most difficult problem often observed in this tube has been a *Fast Self-recovery Breakdown (FSB)* between the modulation anode and the body. Full discharging between the two electrodes or partial discharging of local electrical stress stored in a contaminating layer, such as Cu_2O on the anode ceramic, is a direct cause. Indirectly, however, Ba evaporation eases sputtering of the copper through Cu-Ba alloy formation, and triggers electrical breakdown [3,9,10]. Therefore, suppressing Ba evaporation by using an M-type cathode is also one of the essential remedies for *FSB*.

Among the many choices of M-type cathode, iridium (Ir) was selected as a coating material due to following reasons: 1) Ir is not as poisonous as other rare-earth materials. 2) A dramatic reduction in the work function, almost the same as other M-type cathodes, can be achieved. 3) By an alloying process, performed in a hydrogen atmosphere at 1285°C , Ir and W make a stable intermetallic compound layer (what is called the " ϵ_{II} " phase), which guarantees a long life of this cathode [11]. As for E3786, the use of this cathode was tried for the first time in the repair tube, T34C, and then in another repair tube, T47A. Figure 3 shows the underheating behavior of the tube T34C as compared with that of the tube T56 with a normal S-type cathode made by Semicon Associates. The cathode/anode voltages were fixed at 72 kV/55 kV. Data were taken at 0.5 h and 1 h after setting the heater current by 0.5 A and 1 A steps, respectively. Although initially the emission was not as high as expected, it became clearly superior to that of the S-type after 3,509 h's operation with a heater current of 23.0 A. At what stage the emission became good was not clear, because we could take these data only when TRISTAN was in a long shutdown period. A round edge in Longo's curve, found at an early stage, may be due to an inhomogeneity of the work function over the dispenser/emitting surface. Generally speaking, the M-type cathode is believed to be more easily poisoned by residual gas than the S-type. This inhomogeneity may be caused by ion attacks during the initial fabrication process performed at rather higher gas levels.

Aiming to obtain homogeneous emission from the very beginning, the tube T47A was treated slightly differently. The objective cathode temperatures in a vacuum treatment and in an activation process during evacuation were set higher, at $1100^\circ\text{C}_\text{B}$ and $1070^\circ\text{C}_\text{B}$ for T47A, compared with $1080^\circ\text{C}_\text{B}$ and $980^\circ\text{C}_\text{B}$ for T34C, respectively. As shown in Fig. 4, however, the results were again unsatisfactory. A long cathode aging time seemed to be necessary to obtain sufficient emission characteristics in this tube, too.

An aging was performed with a heater current of 26 A between stages ① and ② and ② and ③, but even with 29 A between ④ and ⑤ and ⑤ and ⑥. Although this is contradictory to the original idea to suppress Ba evaporation, a burn-in (lighting and aging) process at relatively higher cathode loading was efficient to make the poisoned cathode active and decrease the unwanted Wehnelt emission. The higher was the aging temperature, the more efficiently was the burn-in process advanced.

The cathode efficiency, shown by the uppermost curves in Figs. 3 and 4 is, however, astonishingly good. We can now operate the tubes T34C and T47A with a heater current/power of as

low as 21.5 A/206 W, compared with 24 A/280 W of the typical S-type, which is very effective to decrease Ba evaporation, to avoid anode current spikes and to extend tube life, itself. Once such characteristics are obtained, all are well. The operating temperature can be reduced by at least 70K (e.g., from 1050°C_B to 980°C_B).

4. Lifetime estimation of Ir-coated cathodes

Two 1.2 MW tubes, T34C and T47A, have been under special lifetime observations at KEK. Beam-current measurements were carried out periodically during the shutdown periods of TRISTAN. The behaviors of these two tubes, mainly after the zeniths of their emission characteristics, are shown in Fig. 5 and 6, respectively. T34C was aged with a heater current of 23 A, and continuously operated with the same current until 3,509 LVh, when the current was decreased to 21.5 A. On the other hand, T47A was initially aged with a heater current higher than 24 A, even up to 29 A, until 569.1 LVh (Ⓔ in Fig.4) and has thereafter been operated with 21.5 A from the time of 1,733 LVh.

When one evaluates the cathode performance, itself, the end-of-life is generally determined as the time when the emission decreases after operation to its 90% of the initial optimal value. An index, T_{90} , was thus introduced for lifetime prediction. Here, T_{90} is defined as the cathode temperature at which the beam current decreases to 90% of the stable space-charge limited current. From Figs. 5 and 6 one can assume that two tubes, T34C and T47A, were at the zenith of their emission characteristics at 3,509 LVh and 1,733 LVh, respectively. Using the known relationship between the heater power and the cathode temperature (°C_B) we can estimate T_{90i} of each tube at this time as being 918°C_B and 905°C_B, respectively. T_{90i} means the initial value of T_{90} . For each tube and each operating time (LVh), T_{90} was estimated from Figs. 5 and 6 and changes ΔT_{90} in temperature T_{90} , which is defined to be $\Delta T_{90} = T_{90} - T_{90i}$, were plotted versus the operating time t (LVh) in Fig. 7. The straight lines show that ΔT_{90} is roughly proportional to $t^{1.07}$ in our case. According to this ΔT_{90} method [12], one can obtain the life expectancy of each tube.

In the case of an Ir-coated M-type cathode, it is empirically admitted that the cathode must have a margin of operation temperature, preferably 80 K, for T_{90i} [13]. In our case of a high-power cw klystron, too, the operation is performed at such a temperature prepared by a heater power about 250 W. Therefore, the end-of-life can now be defined as the time at which T_{90} becomes equal to this operation temperature. In other words, the cathode lifetime is the time when ΔT_{90} reaches the horizontal line at 80 K in Fig. 7. The lifetimes could thus be estimated to be 70,000 h and 200,000 h for two 1.2 MW tubes, T34C and T47A, respectively. (See Fig. 7.)

These lifetimes are both sufficiently long compared with the longest life (53,220 h) ever recorded by one tube (T30) installing an S-type cathode that died due to water leakage outside the vacuum. The lifetime of each tube seems, however, to be very much different. For what reason such a difference was made is not obviously clear. During the production stage the cathode of the T47A was vacuum

treated and activated at higher temperatures than that of T34C. At the initial aging stage at KEK, too, T47A was operated at a relatively higher heater current, even up to 29 A. (See Fig. 4.) Owing to such a total history of tube treatments, the best emission of T47A appeared sooner (1,733 LVh) than that of T34C (3,509 LVh), which made it possible to then decrease the heater current from 23 A to 21.5 A sooner in the former than in the latter. The large difference in the life expectancy of the two tubes may be attributed to this initial small variation in the tube treatments. A more effective burn-in could be realized at higher temperatures. Although the initial evaporation rate of Ba increased, the total quantity of its evaporation during its life could be saved by making the aging period shorter. As a result, the lifetime could also be made longer simultaneously.

5. Techniques of ion milling and fine-grained tungsten top layer

One disadvantage of the Ir-coated M-type cathode is susceptibility to gas poisoning and the necessity of long-term initial aging [9,10]. The same type, but much smaller, cathodes have been, however, extensively used in TV CRTs very successfully without necessity of such long term initial aging. This suggests that in our klystron use gas poisoning may be promoted by a larger and much open structure of the cathode. Among many gases, Ar, H₂O, O₂, air and SO₂ are poisonous, while CO, CH₄, N₂ and H₂ are not so poisonous to this cathode. In order to cope with this gas poisoning problem at the initial stage, various modifications were attempted in the fabrication process, including using a thinner coating thickness (2286 Å) of Ir, a longer alloying time (3 h) in H₂, an additional heat treatment *in vacuo* (1 h) in addition to that in H₂ (2 h), both at 1285°C, and venting with N₂ instead of air after an alloying treatment. The situation seemed to be improved but only slightly[10].

The last, but most promising, techniques which we have recently tried were: 1) *Argon-ion milling* of the tungsten surface and 2) dispenser cathode with a *fine-grained tungsten top layer*, both of which were originally developed by Toshiba [14]. Argon-ion milling is a technique used to sputter-etch a mechanically crushed surface-layer of the W cathode matrix, and to expose the inner natural W layer abundant in pores. The milling conditions were as follows: the ion gun was a 30 mmφ Ar-ion source of COMMONWELTH SCIENTIFIC Corp; the flow rate and pressure of Ar gas were 3.5 SCCM and 3×10^{-4} Torr, respectively; the distance between the gun and cathode surface was 210 mm; the beam current was 15 mA under an applied voltage of 750 V and the milling time was 2.5 h. In our firing (annealing and degassing) process, taken after alumina potting, the cathode was heated up to 1820°C *in good vacuo*. Argon ions impinged upon the W surface during the ion milling process, could thus be mostly removed out. A roughened surface can deliver high density of Ba-supplying pores and give Ba a suitable shelter from ion bombardment. (See Fig. 8.)

In order to improve the emission stability under ion bombardment, a fine-grained tungsten top layer was applied on the substrate body of porous tungsten before emitter impregnation. A top layer of about 3 μm in thickness was prepared by a spin-coating technique. The average particle size of the

fine-grained tungsten was 1 μm , compared with 4.5 μm (porosity 20%) of the substrate. The fine-grained layer was sintered to the tungsten body by firing at 1900°C for 30 min. The cathode was also impregnated with the same 4:1:1 emitter, cleaned lightly and then coated with Ir by a sputtering process in Ar. This method proved quite successful in smaller cathodes for, e.g., CRT guns [14]. Combining with the argon-ion milling technique, it was applied on two E3786 tubes (T18C and T23B) for the first time as a large-scale application. (See Fig. 9.)

6. Discussion and concluding remarks

M-type cathodes are essential to suppress excess barium evaporation and to obtain a reliable performance and insulation of high-power klystrons. Two types of M-type, Os/Ru and Ir coatings have been applied to two types of tubes, YK1302/1303 and E3786/3732, respectively. In the case of the former, for example, the heater power could be reduced by about 17%, and thus the barium evaporation rate could be suppressed to approximately 25% of that for the B type [6,7]. In the case of the latter, the heater power could also be saved, even by as much as 100 W, which affected the design philosophy of the oil tank for the electron gun [9]. Until now, all upgraded tubes installing M-type cathodes have shown sufficiently good insulation and dynamic behaviors without any dropout. A positive experience concerning the lifetime under real operation conditions has been obtained.

M-type cathodes are, however, more easily poisoned. One 1 MW tube having an Os/Ru-coated cathode showed a gradual, and then sudden, decrease in emission during an underheating test, although, fortunately, the emission could be partly recovered by a cathode-aging process. The emission slumping was strongly correlated with the vacuum in the tube, and thus it was clearly gas poisoning. Initial poisoning of Ir-coated cathodes of 1.2 MW tubes is, however, difficult to understand. The vacuum in tubes installing Ir-coated cathodes is, in general, very good, since they are mostly repair tubes, and have experienced baking and aging processes several times. New techniques, which are called *argon-ion milling* and *fine-grained tungsten top layers*, have been attempted in our high-power cw klystrons. In conclusion, both techniques were not as successful as expected from the smaller scale applications to shorten the initial aging period. Statistically, however, as a distinct tendency, the former technique showed a relatively positive effect on the test stage emission characteristics in the factory. On the other hand, rather negative results were obtained by the latter one. In both cases (T18C and T23B), the initial emission was very poor and, to make matters worse, the initial Wehnelt emission determining modulation anode current grew sharply along with an increase in the heater power. In one case (T18C), the burn-in process at relatively higher cathode loading was efficient to make the poisoned cathode active and to decrease the unwanted Wehnelt emission; in the other case (T23B), however, burn-in took a ridiculously long time, and was technically difficult because the higher cathode loading was accompanied by heavier Wehnelt emission.

When one electron is emitted from a cathode, it carries out, as a net, the kinetic energy equivalent to ϕ (eV) and cool the emitting surface. A completely different conjecture can thus be made on the necessity of a long initial aging of 1.2 MW tube. The emission slump could not be mainly due to ion bombardment, but due to an *emission cooling effect*, because the cooling power of a high beam current of 20 A (the specification value) is very large, that is to say as an integral 36 W for a work function (ϕ) of 1.8 eV, compared with a heater power of about 206 W. From this point of view, long initial aging could be considered to be an improving process of the *thermal conductivity* of Ir, impregnated tungsten or their interface layers. In the case of small-scale as well as low-duty pulse applications, the emission cooling is negligibly small, and thus the emission can be good from the beginning [14]. Further, the thermal conductivity of a fine-grained tungsten top layer must be very bad and difficult to improve, due to loose binding with the tungsten body, which is very consistent to our experiences concerning two tubes, T18C and T23B. The lifetime of the Ir-coated cathode was proved to be sufficiently long compared with the total tube life. The only problem left yet to be solved is still the necessity of long initial aging. In order to obtain good performance of emission from the very beginning, an improvement will be made in the cathode processing, so that the thermal conduction near to the emitting layer may be promoted sooner. Further research and development will be continued along this line.

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Figure captions

- Fig. 1. Underheating plots for B-type ① and M-type cathodes after 765 h ② and 5,298 h ③ and the Ba evaporation rate ④ normalized to the B-type operation point.
- Fig. 2. Underheating characteristic plots of YK1303 (V23) during the life. The emission was recovered by cathode aging performed at a test field of KEK.
- Fig. 3. Underheating curves of T34C (M-type) and T56 (S-type). The squares and the empty circles denote the data after 93 h's and 3,509 h's operation, respectively.
- Fig. 4. Underheating curves of T47A. The data-taking time of ⑥ was different from the others.
- Fig. 5. Underheating characteristics during the life of E3786, T34C.
- Fig. 6. Underheating characteristics during the life of E3786, T47A.
- Fig. 7. Time dependence of ΔT_{90} in the case of the Ir-coated M-type cathode of the 1.2 MW cw klystrons, T34C and T47A. Lifetime can be expected to be 70,000 h and 200,000 h, respectively.
- Fig. 8. Secondary electron images obtained from the cathode surface; (left) before and (right) after Ar-ion milling treatment.
- Fig. 9. Secondary electron image of the cathode surface with a fine-grained tungsten top layer.

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