Coating Techniques and Improvement of High Power CW Klystrons for TRISTAN

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Abstract

Throughout R&D of 1.2MW cw klystrons, three key coating techniques have played important roles to get reliable and stable tubes. One is TiN coating on rf window ceramics to suppress multipactoring and abnormal increase of ceramic temperature. Another is Ir coating on the impregnated tungsten to get M-type cathode. Excess Ba evaporation can be suppressed by reduced heater power, which decreases the HV breakdown probability. The other is CrO_x coating on Cu anode to improve insulation and protect anode ceramic from contamination with copper and/or copper oxide. Such contamination can be one cause of *fast self-recovery breakdown*. Together with enlargement of anode ceramic, all these techniques were applied to the most advanced version of 1.2MW tube, E3732. Although unexpectedly long aging time was needed initially to get sufficient emission, the tube has worked in excellent manner without showing any instabilities.

1. INTRODUCTION

In total twenty-four 1.2MW klystrons including 2 in AR, have been operated in TRISTAN. The top runner (T25) has already recorded an accumulated operational time over 40,000 h. There have been over 780,000 low voltage operating hours accrued in all 1.2MW tubes. No leakage has been encountered during operation due to cracks on ceramic windows. It is owing not only to the optimized design of matched coaxial-to-doorknob transitions but also to the special coating of anti-multipactoring layer of TiN on ceramic windows [1]. Coating procedure, thickness optimization and surface characterization are reported in the next section.

During operation, however, some tubes showed negative anode current spikes inducing reflections from cavities. This phenomenon is caused by *'fast self-recovery breakdown'* between the modulation anode and the body [2]. Partial discharging of local electrical stress stored in contaminating layer such as Cu_2O on anode ceramic is a main cause of the phenomenon [3]. Protecting the anode ceramic from copper depositing is the most promising way to solve this problem.

Four countermeasures have been tried initially. One is reinforcing the inner corona ring on the body. Another is making grooves inside the anode ceramic. A third is nickel coating on the body side of the anode [4]. The fourth is the use of Ir coated M-type cathode that reduces the temperature of the anode and suppresses the deposit of barium onto the anode. These countermeasures except for the fourth one, however, proved ineffective, as a couple of tubes modified in this way still have shown the same spike phenomena [5].

To overcome this situation two new countermeasures have been taken recently: chromium oxide instead of Ni coating on anode; and enlarging the diameter of anode ceramic as well as inner corona ring [5]. Until now three tubes made and modified in this way (E3732) have behaved excellently without showing any I_a instabilities. Progress and improvements are presented below in detail.

2. TiN COATING ON RF WINDOW

One of great difficulties in developing high power klystrons was an rf window. Due to the so-called one-side-multipactoring, the ceramic window showed abnormal temperature increase above a threshold level. The same phenomena happened in rf couplers used in both APS and superconducting cavities. A special coating procedure of titanium nitride on window ceramics was developed to suppress these phenomena. The coating was done by dc reactive sputtering method in Ar + N_2 mixture almost the same way as shown in the literature [6]. A conventional diffusion pump system made of iron was used together with a liquid nitrogen trap. Such a system is rather preferable to oilless UHV systems to get the ideal coating layer of TiN as mentioned below.

Bench tests were carried out to optimize the coating conditions [7]. The klystron output power was fed through a Y shaped circulator and 100% reflected by a waveguide short. Small ceramic samples were exposed to rf field in a quartz vacuum tube that was placed at an antinode position of the WR1500 (R6) waveguide. In parallel, measurements were also made on dc resistance of these samples. Important points about the anti-multipactoring coating are as follows:
1) Characteristics of the film depend on the equipment as well as the method of coating. 2) TiN (more precisely speaking,

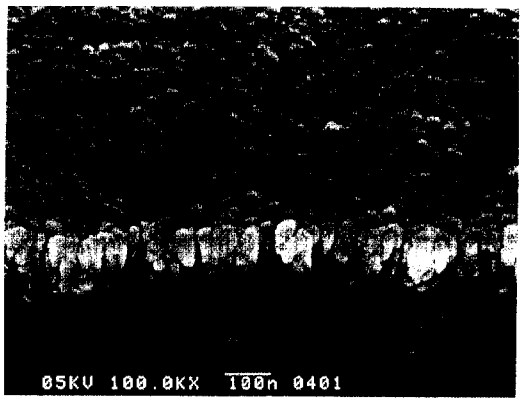

Figure 1. A SEM photo of columnar structure of TiN.

TiN_xO_y) is one of the best coating materials. The dc resistance of the film is very high and even increases with thickness and with exposure time to rf field. Pure TiN is rather worse because of its high metallic conductivity. 3)The optimum thickness for UHF is 50~300Å. The thicker, the better if it's below 150Å.

Apart from the dc reactive sputtering method, coating was done by ion plating in an oilless UHV pumping system. Samples made by the former process, however, always showed better results. It can be accounted for by the microscopic structure of our films. TiN grows up in island or columnar form. Very high resistivity is ensured by the oxygen rich grain boundary layers of TiN_xO_y. Such a situation is clearly shown in a SEM photo of Fig. 1.

3. Ir COATED M-TYPE CATHODE

Until now we have successfully used iridium coated M-type cathode in five modified klystrons. Working temperature can be about 980°C which is at least 70K lower than that of S-type. Lower operative temperature and less evaporation of barium are beneficial to keep insulation and to suppress unwanted depositing of Cu-Ba alloy on to the anode ceramic.

As we reported before [3,5], iridium coating has several advantages over other coating materials like Os-Ru. One of disadvantages of it, however, is susceptibility to gas poisoning and necessity of long term initial aging with rather higher heating power. In order to shorten the initial aging period, for a new modified tube (T31A), we tested a thinner coating thickness (2,700Å instead of 3,500Å) of Ir and double heat treatments (alloying process) *in vacuo* (1,285°C x 1h) as well as in hydrogen (1,285°C x 2h). Situation was improved but only a little as shown in Fig. 2.

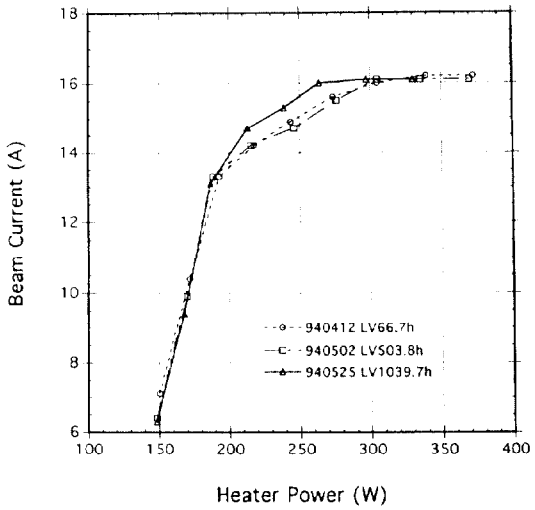

Figure 2. Underheating data vs. LV time of T31A.

On top of that, no further improvements were found by additional aging at 26A of I_h (335W) for 437.1hrs. It is probably because operation was continued during this period with rather lower beam current. Aging should be done at lower cathode temperature (e.g., I_h=23A) with higher beam current (e.g., I_b>15A). Nine days were necessary, however, to get only 0.3A emission gain as shown by a chain line in a schematic drawing of Fig. 3.

According to our experiment, the more efficient aging can be realized by current up and down mode in which higher emission is used at relatively lower gas level before slump. By repeating, e.g., 5 minute up and 5 minute down beam currents, the initial value of 16A was temporarily recovered after only several such cycles. After continuing this aging mode for about 150 hrs., the emission was much improved as shown in Fig. 3. As this aging method seems so effective, in the next tube it will be applied from the early beginning to avoid gas poisoning that must occur at the initial stage.

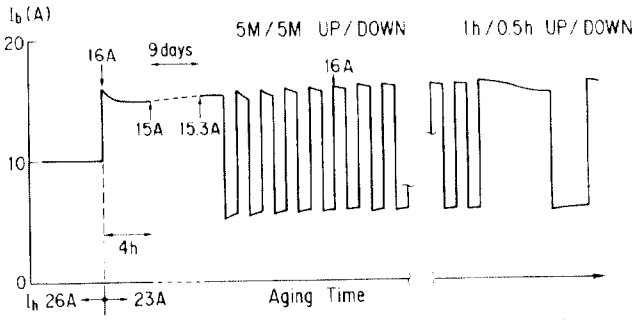

Figure 3. Heater aging in current up and down mode.

4. CrO_x COATING ON ANODE

Until now 9 klystrons showing I_a spikes have been opened and carefully inspected. The anode ceramics of such tubes were very often contaminated with Cu and/or Cu compound typically taking the isolated round shape of 10 to 30mm in diameter [4]. Discharge marks were sometimes found on the outside of the anode as well as on the inner corona ring [5]. What is interesting is that in two tubes (T47 and T31) neither discharge marks nor contamination could be found anywhere as summarized in Table I. The surface analysis (ESCA) showed that, however, even clean-looking area of such ceramics was microscopically contaminated mainly with copper that was sputtered from the anode surface. Coating the outer surface of anode with a material that is harder to be sputtered than copper is expected to solve this problem.

Table I

Tube No	Isolated round-shaped deposit of Cu and/or Cu compound on anode ceramic	Small contaminant on anode ceramic facing to SUS inner corona ring	Contaminant-free ceramic and discharge-mark-free anode surface
T36	Yes	Yes	No
T34A	Yes	Yes	No
T40A	Yes	Yes	No
T34B	No	Yes	No
T47	No	No	Yes
T32A	Yes	Yes	No
T58	No	Yes	No
T29	Yes	No	No
T31	No	No	Yes

As we reported before, Ni coating showed a promising behavior in several tubes [3,4]. T58 installed with a Ni coated anode, however, suffered from the typical anode current spikes. In case of Ni, as each part of the anode must be brazed at high temperatures in H_2, interdiffusion occurs between Ni and Cu, which leaves Cu rather than cupronickel on anode surface.

Meanwhile CrO_x is another good candidate for coating materials as it forms a very dense and stable passivated layer. Surface roughness of Cu can be not so changed. Cr has a higher melting point, a lower diffusivity and a lower sputtering yield than pure Cu and Ni. Less water can be adsorbed on and more easily desorbed out of CrO_x layer [8]. As reported elsewhere [5], sputtering was first applied to coat the anode surface of one tube (T32B) with $Cr+CrO_x$ of 200-500Å in total thickness. This tube behaved very well and has been operated in MR without any troubles over 1.5 years.

In case of new version, E3732, vacuum coating was adopted instead of sputtering to coat $Cr+CrO_x$ layer on Cu. Diffusion of Cr as well as Cu is suppressed to a smaller extent as the anode subassembly does not experience any brazing process after coating. The setup of vacuum coating is shown in Fig. 4.

The main pump was a cryopump background pressure of which was below $5x10^{-6}$ Torr. Prior to installation the anode subassembly must be degreased. Just before evaporation the anode surface was activated by Ar sputter cleaning.

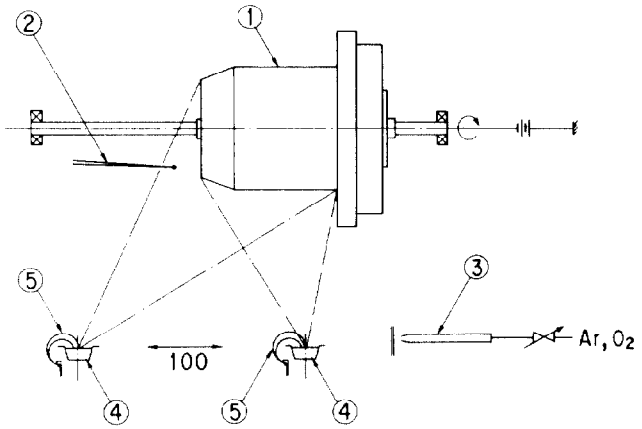

Figure 4. Setup of vacuum coating of $Cr+CrO_x$:
① substrate made of Cu; ② thermocouple;
③ gas nozzle; ④ material to be evaporated;
⑤ electron trajectory.

Three lamp heaters were used for heating substrate. Double electron bombardment heating sources as well as substrate rotation mechanism were also used to get uniform film thickness. Conditions of vacuum coating are as follows:

Substrate temperature:	≈280°C
Pressure during evaporation:	$1x10^{-4}$ Torr O_2
Deposition rate:	10 Å/s
Substrate rotation:	10 rpm
Target film thickness:	Cr 200 Å + CrO_x 300 Å

Adhesion of the film was checked by 90° bending test on small samples and proved very good. Auger electron spectroscopy showed that the composition factor x of CrO_x formed is very near to 1.3 rather than 1.5. Shown in Fig. 5 is a SEM photo of real anode surface coated with $Cr+CrO_x$. The $Cr+CrO_x$ layer vacuum coated on the copper electrode has shown no deterioration and no bad effects on the insulation and on vacuum in the tube.

Figure 5. A SEM photo of $Cr+CrO_x$ layer on Cu anode.

5. SUMMARY

Three coating techniques of TiN, Ir and $Cr+CrO_x$ worked very well in the most advanced version of 1.2MW klystron for TRISTAN, E3732. TiN coating is very effective to operate klystrons at high output power level as expected for transmitters in KEKB project. It can also play an important role to get reliable and stable rf input couplers for both normal and superconducting cavities in that project. Chromium oxide and iridium coatings must be very effective to suppress the anode current negative spikes that induce amplitude modulation in the klystron output and interrupt the operation of KEKB as well as TRISTAN. Although further investigation, more statistics and longer running period are required, these coatings in combination with reconstruction of anode ceramics [5] are highly anticipated to get rid of the *fast self-recovery breakdown* from our klystrons effectually.

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