Present Status of High Power CW Klystrons

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Abstract

In the KEK B-Factory (KEKB), high power CW klystrons of 1MW and 1.2MW that have been developed for TRISTAN are to be used at a little bit higher frequency, 508.887MHz instead of 508.58MHz, without drastic changes in other specifications. Various improvements and modifications have been given so far, however, to both tubes to get characteristics upgrading and higher stability. Difficulties, like positive and negative spikes of anode current, Side Band Oscillation (SBO) and Fast Self-recovery Breakdown (FSB) in particular, that are caused by improper arrangement of gun structure and/or back streaming electrons have been extensively studied and solved by finding causes and remedies. In this paper the present status of R & D is reviewed including new findings on these tubes and the most updated summary of operation in TRISTAN.

1 Introduction

TRISTAN MR was terminated in December 1995, and was disassembled by the end of March 1996. It is now being rebuilt as KEKB composing of two rings installed side by side, the 3.5-GeV low energy ring (LER) for positrons and the 8-GeV high-energy ring (HER) for electrons. In TRISTAN two types of high power CW klystrons have been developed: one is 0.8MW/1.0MW tube called YK1302/YK1303 (Philips) and the other is 1.2MW tube called E3786/E3732 (Toshiba).

They are to be successively used in KEKB in almost the same frequency region (508.887MHz). Until now the operational time of transmitters has totaled 1,413,000 h (161 years) in filament hours: 55 years for 0.8MW/1.0MW tubes and 106 years for 1.2MW ones. Five tubes of the latter have been continuously operated over 40,000 h. Heater-on time of the top runner exceeded above 51,267 h. Figure 1 summarizes the klystron age and life distribution in 1,000-hour increments just at the time of shutdown of TRISTAN MR.

Not all klystrons delivered to KEK worked completely well. Typical difficulties met with are modulation-anode-involved instabilities: increased background level and positive spikes of anode current and Side Band Oscillations (SBO) in 0.8MW/1.0MW tubes [1]-[4], and negative spikes of anode current and Fast Self-recovery Breakdown (FSB) in 1.2MW tubes [5]-[8]. Both are related to excess barium evaporation from cathode directly or indirectly [9]. From Fig.1 one can notice that the main cause of tube's death is modulation anode involved instabilities shown as Anode (the dotted boxes). The marked tubes, including Leak, categorized as alive are repaired in-house and aged in the test field both by the author, and still in active service.

Shown in Fig.2 are the numbers of times of klystron replacement versus year, excluding replacement due to studies, rotations, acceptance tests and rearrangements for power balance, etc. As the number of stations, for 1.2MW tubes in particular, has increased, the smallness of the replacement frequencies in last several years is remarkable.

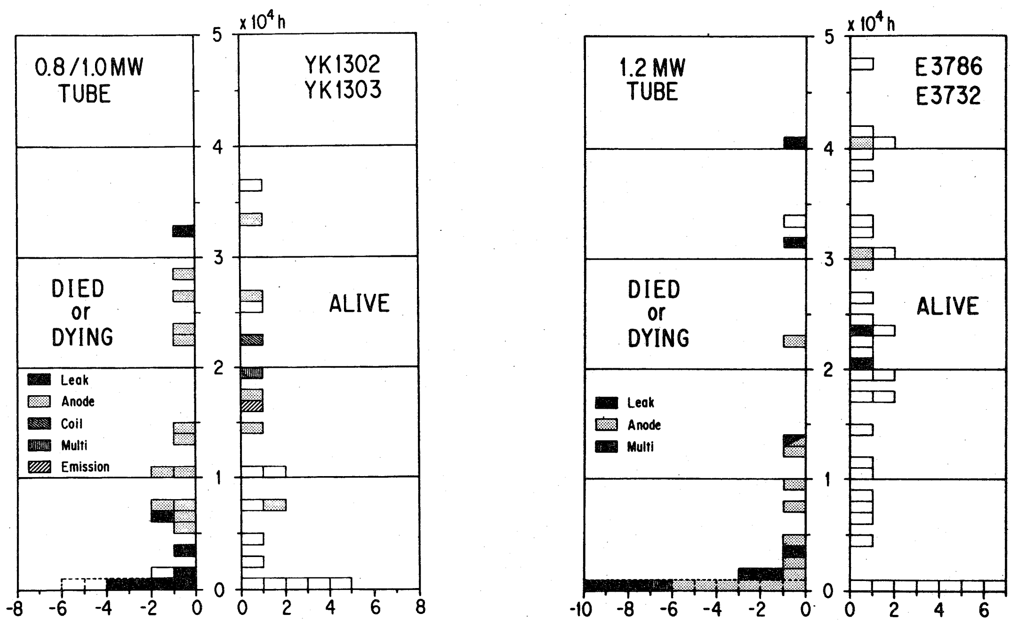

Fig. 1 The number of klystron in each LV age category. Multi means difficulties of multipactoring at relatively lower power levels. Marked tubes, including Leak, categorized as alive are in-house repaired and still usable ones. Boxes surrounded by dotted lines represent unaccepted tubes due to initial troubles or poor performance.

The descending hatch in the graph means that tubes developed troubles of various I_a related instabilities in YK1302/1303 and negative I_a spikes and FSB in E3786, respectively. Main efforts for improvement have been, therefore, concentrated on such troubles and difficulties.

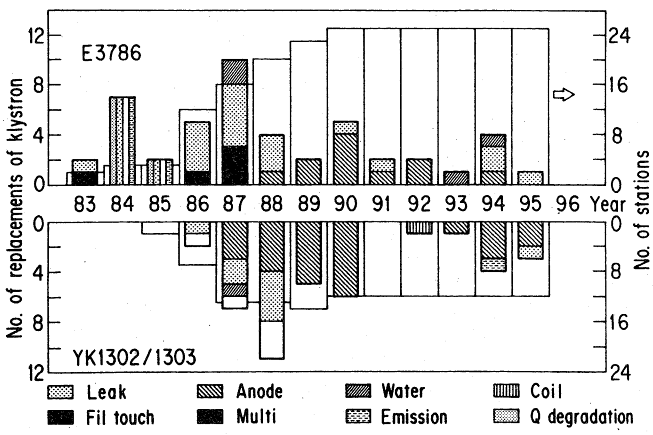

Fig. 2 The number of tube replacement versus year. In the causes of replacement, Multi means multipactoring, Water denotes the leakage of body or boiler water, Emission is the emission slump and Coil is the trouble in focusing coil.

2 Positive Anode Current Spikes and Back Streaming Electrons

High efficiency high power CW klystrons tend to show instabilities near saturation due to electron feedback mechanism through back streaming electrons. They can originate from collector and/or output rf region and can be influenced by rf power level, load mismatches, focusing fields and secondary electron coefficient of drift gaps, etc. The last factor well accounts for the time dependent effect of the instabilities. Irregular anode current (positive anode current spikes) and spurious rf output (S B O) can be observed often simultaneously. If this behavior happens, it may lead to beam loss in the storage ring accelerator, and thus a severe problem for its rf system.

In case of YK1302/YK1303 instabilities of this kind have been observed above 900kW below saturation under some combinations of focusing and prefocusing fields. The stability range often decreases with time and tubes become unstable even under matched operation after about 3000 h. Remedies can be obtained and tube's performance has been improved by some measures as reported before [4].

A strong interest concerning this instability is why such a phenomenon can never be found in 1.2MW tubes that are stable over whole range of output power level despite a higher efficiency (≥63%) and a higher power gain (≥50dB). The probable absence of back streaming electrons due to geometry has long been believed as a reason, but the simulation with FCI code has always shown their presence in these tubes, too [10]. A recent experiment on a 1.2MW tube well accounted for this discrepancy as follows.

The focusing coil for 1.2MW tubes is composed of 8 pairs of inner and outer concentric coil elements. From the bottom to the top, the pairs are named as A to H, each of which could be driven independently but normally in series with a current I_f. The bucking coil is not used in this tube. In order to test the tube performance the top pair (H) was excited with a separate power supply with a current I_{fH}.

Figure 3 shows an example of the I_{fH} dependence of the anode current, I_a, and the body temperature increase, ΔT_B. The anode current is usually determined by small interception of the main beam and/or the wehnelt emission. In the case of Fig. 3, however, it changes with the local field made by the top coil, H, being apart farthest from the gun area. This fact clearly shows that in the 1.2MW tube, too, there exists a back streaming of electrons returning from collector and/or output rf region.

The difference of this tube from the 0.8MW/1.0MW one is that the background level of I_a is low and no astable change of I_a is found, indicating most returning electrons are interrupted by a drift body but a portion of them can reach tne modulation anode rather constantly.

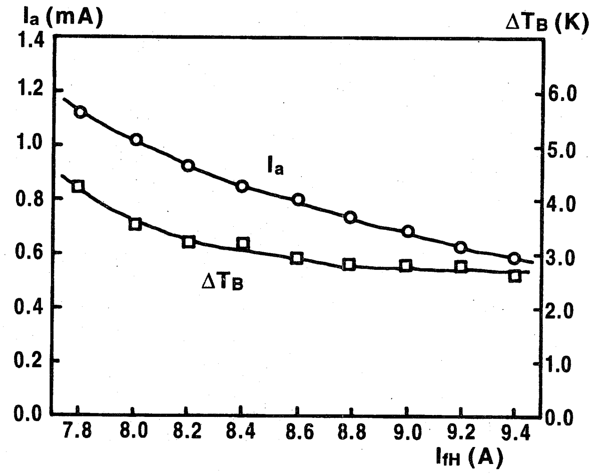

Fig. 3 The dependence of the anode current and the increase of body temperature of the tube T40B on the top coil current, I_{fH}. The main focusing current, cathode and anode voltages, the beam current, the micro beam perveance and the rf power output were 8.0A, 90kV, 62.1kV, 18.8A, 0.702μBP and 1060kW, respectively.

Phenomenologically another distinct difference can be observed between 0.8MW/1.0MW tubes and 1.2MW tubes in characteristic curves of rf output vs. drive powers, with the anode voltage as a parameter. In the former, I_a generally has a maximum at a shoulder of the curves, about 0.5dB below saturation. The increase of I_a closely relates to the I_a irregularities. In one of the latter tubes (T23B), on the contrary, the place where I_a is the largest locates far below, e.g., 250~300kW, only weakly depending on the anode and cathode voltages. Not absence but constancy of the returning electrons may be the main reason for the complete freedom from instabilities of positive anode current spikes and SBO in 1.2MW tubes.

3 Negative Anode Current Spikes and Fast Self-recovery Breakdown

Another instability of negative I_a spikes and FSB is, on the other hand, unwanted phenomena typical of 1.2MW tubes. As repeatedly reported, however, this kind of instability can be practically avoided in the most advanced version, E3732, by adopting Ir coated M-type cathode, $Cr+CrO_x$ coated Cu modulation anode and conical shape of anode ceramics [6]-[9]. Fundamental study on the mechanism of this phenomenon is being continued by making a special type of socket as well as a gun tube.

M-type cathode coated with Ir thin layer is one of the essential techniques to suppress insulation breaking between electrodes and FSB [8]. The disadvantage of Ir, that is susceptibility to gas poisoning and necessity of long term initial aging, is, however, still open question, as the new techniques, like *ion milling* and *fine-grained tungsten top layer*, proved to be unsuccessful to shorten the initial aging time [8][9].

Compared with other parts, 0.8MW/1.0MW tubes are designed to have larger margin for gun ceramics in size. This fact, together with the use of sandwich structure of Cu and stainless steel for a modulation anode, has long been believed to be the reason of absence of this insulation breaking in 0.8MW/1.0MW tubes.

Recently, however, in one 0.8MW tube (v04) a similar kind of phenomena has been observed as illustrated in Fig. 4, showing this instability not unique to special tubes but more general to high power klystrons. This I_a spike normally accompanies increase of beam current, I_b, and seems dependent on V_K and to be avoidable by adjusting the prefocusing coil current I_{pf} and aging at relatively higher V_K.

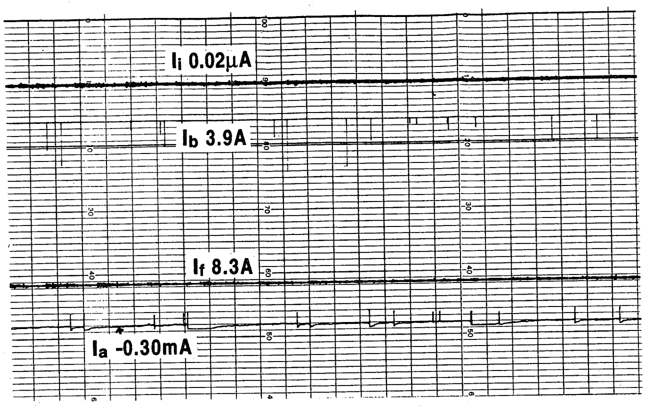

Fig. 4 Negative anode current spikes observed without rf for the first time in a 0.8MW tube. The operational conditions are as follows: V_h 21.8V, I_h 21A, V_K 90kV, I_b 3.9A, V_a 19.4kV, I_a~ 0.3mA, I_f 8.28A, and I_{pf} 5.38A. Time scale is 30min/div.

4 Efficiency of KEKB Tubes, E3732

When operating storage ring accelerators, stability is the most important requisite of klystrons. As the power cost is generally increased with the scale-up of the machine, however, the power efficiency becomes relatively important. To optimize the tube regarding efficiency we prepared a special focusing coil whose 8 elements can be excited separately, and closed water chiller systems that can control body and window water temperatures independently.

Efficiency of the 1.2MW tubes is in average 3~5% larger than that of the 0.8MW/1.0MW tubes. By adjusting the magnetic field profiles and body and output window temperatures, it could be increased even more. Although the optimum conditions are not universal, 66% and more has been preliminarily obtained in an average level tube (T40B) for 1MW output by good combination of these parameters, e.g. I_f 8.0A, I_{fH} 8.0A, window 21.7°C and body 18.3°C.

When used at lower V_K, say, 55.6kV, a good saturation efficiency above 39% has been obtained for 228kW power output at 508.887MHz. Owing to general reliableness and easiness of handling, we will use 1.2MW tubes for driving superconducting crab cavities at such lower power levels in KEKB.

5 Conclusion

Instabilities typical of 0.8MW/1.0MW (Philips) and 1.2MW (Toshiba) CW klystrons are irregular anode currents directed positive and negative as compared with stable values, respectively. They are normally accompanied by SBO and AM in the rf output, which eventually increase the power reflection from the accelerating cavities. Joint efforts have been made with each maker to improve the tube stability by modifying the original design. In the most advanced versions, both tubes behave very nicely [4][8].

New findings reported here are summarized as follows: 1) The 1.2MW klystrons (E3786/E3732) are uniquely stable tubes without irregular increase of anode current and SBO notwithstanding their high gain and high efficiency. This does not mean, however, the absence of back streaming electrons. Constancy as well as smallness in number of such electrons must be a key reason to account for this fact. 2) Negative anode current spikes and FSB were found for the first time in a 0.8MW tube. Although it is unclear whether the mechanism is completely identical or not, the FSB may be the more universal breakdown phenomena between anode and body electrodes. 3) New techniques, like *ion milling* and *fine-grained tungsten top layer*, were not so successful as expected [9] to shorten the initial aging period of the Ir coated M-type cathode. 4) By optimizing the magnetic field profile and body and output window temperatures of 1.2MW tubes, efficiency can be increased above 66% for 1MW output, although further studies for optimization are needed.

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