Operational Experience and Recent Upgrading of TRISTAN High Power cw Klystrons

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Abstract

The rf system of TRISTAN MR required 525 MV of Vc to accelerate e^+e^- beams up to 32 GeV. This was achieved by 104 units of 9 cell APS cavities as well as 32 units of 5 cell superconducting cavities. Every 4 units is driven with a high power cw klystron which can provide rf power of 508.58 MHz up to above 800 kW. At present 34 klystrons are installed in MR, 12 of which, including 8 for superconducting cavities, are 0.8 MW/1 MW tubes called YK1302/1303 delivered from Philips and 22 of which are 1.2 MW tubes called E3786 delivered from Toshiba. Although the performance of the latter tube is rather very stable, some of them still suffer from unwanted instability due to pulse AM. Efforts have been continuously made to eliminate this instability.

1. INTRODUCTION

A new era of high power UHF klystron in Japan was inaugurated with a tube E3774 which was developed for the use of the synchrotron radiation facility (PF). The frequency was chosen to be 500.1 MHz and its rated rf output power was 200 kW. The design objective of the tube E3786 for TRISTAN was, however, set much higher than this as follows: 1.2 MW cw output rf power with an efficiency higher than 60 percent; 508.58 MHz with a − 1 dB instantaneous bandwidth at 1 MW power level wider than 0.7 MHz; stable operation for a VSWR as high as 1.15 at any phase angle; dc beam voltage and current less than 95 kV and 20 A, respectively; oil insulation for the gun; equipped with a modulation anode; one electromagnet for beam focusing; two 8 l/s ion pumps; vertical mounting position with a vapour cooled collector with dissipation larger than 1 MW without rf.

Although many difficulties were encountered, the design goal shown above was reached and specifications have been routinely fulfilled now[1]. The highest rf output power of 1.25 MW with efficiency above 66.7 percent and gain above 55 dB has been obtained, which seems not to be limited by the tube but to be limited by the klystron power supply.

The tube performance is generally very nice and stable. Operation of the tube is rather easy owing to the points as follows: simpleness of beam focusing without bucking and collector coils; insensitiveness to the field changes up to above ± 10 percent of the optimum value; the large collector dissipation above 1.3 MW without rf; absence of positive anode current spikes and side band oscillations; high gain without self oscillation; easy assembling and easy replacing due to simple structure which only needs a hoist crane; etc.

One of the drawbacks of this tube is, however, the pulse AM caused by intermittent negative spikes in anode current, I_a. If it happens, it generates much amount of side band components. As the accelerating cavity reflects back such components, driving power to the klystron is tripped via reflection interlock. The frequency of the spike varies between about 1 Hz and a few times a week, and it interrupts the operation of TRISTAN especially at the injection period[2].

In this paper, the operation of TRISTAN high power klystrons is first reviewed and then the recent upgrading of the klystrons is reported with special emphasis on Toshiba tube E3786, in particular dealing with the R&D to eliminate the instability of pulse AM. The upgrading of other tubes (Philips) is reported elsewhere in this conference[3].

2. OPERATIONAL EXPERIENCE OF KLYSTRONS

The construction of the accumulation ring, AR, began in 1981 and finished in 1983. Installation of prototype E3786 klystrons in the transmitter system started firstly at the east and the west power stations of AR early in 1983. In the initial stage, much improvement in the design was implemented. Then failures were concentrated on rf ceramic windows as the output power level increased. These difficulties have been gradually overcome after our many struggling joint efforts. The important modifications included: winding of heater wire; material changes of antenna and wehnelt; internal cavities; vacuum treatment of cathode and cathode subassemblies before installing; changing from cylindrical ceramic window to coaxial disk type one; coating of TiN on both ceramics and coaxial conducting parts to suppress temperature rise by multipactoring. In particular the last three techniques were essential to get rf cw output above 800kW stably[1].

Until 1986 two companies, Philips (Valvo) and Toshiba, have succeeded in fabricating the 1 MW tubes and suppling them to KEK. Since then these two companies have shared the super high power klystrons for TRISTAN whose beam energy has been

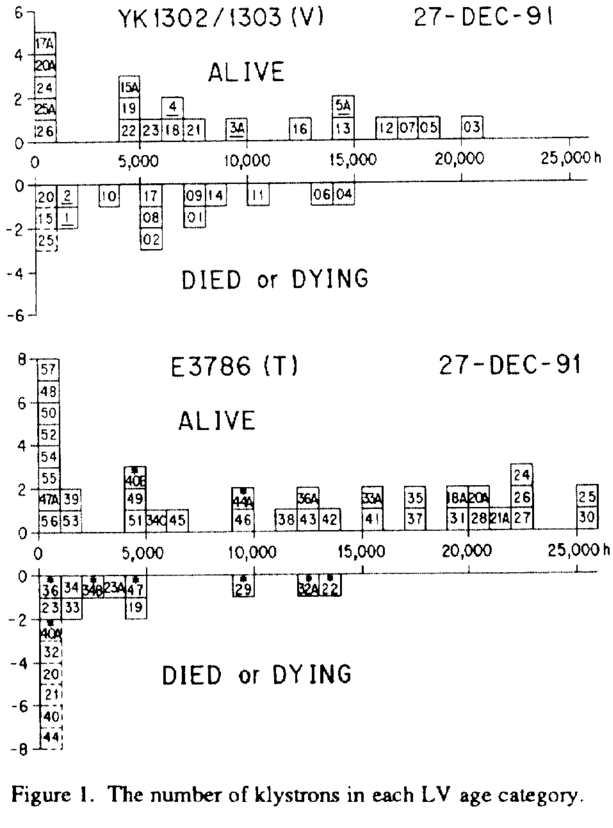

Figure 1. The number of klystrons in each LV age category.

increased in several steps with growing numbers of the cavity structures and thus of the transmitters. During the summer shutdown of 1989, the last 16 units of 5 cell superconducting cavities were installed in D10 and D11, and the construction of totally 34 rf transmitter stations were completed. After getting the world record of the beam energy, 32 + 32 GeV, in 1989 with the accelerating voltage of 525 MV, TRISTAN in 1990 entered into the high luminosity run period (phase II) of rather lower beam energies, 29 + 29 GeV, necessitating the accelerating voltage about 386 MV. It demands the more stable and the more efficient operation of klystrons at medium power levels rather than operation near full power above 800 kW. Until now (the beginning of 1992) operation time of MR transmitters totalled 19,000 to 23,500 h in TSUKUBA (D1 and D2), 22,500 to 23,000 h in FUJI (D7 and D8), 15,900 to 20,900 h in OHO (D4 and D5) and 9,000 to 13,000 h in NIKKO (D10 and D11) straight sections, respectively. That of AR transmitters reached above 28,200 to 31,100 h in the east and the west power stations. There have been over 712,000 low voltage operating hours (equivalent to over 81 years) accrued in all transmitters in KEK.

Shown in Fig. 1 are numbers of living and failed klystrons of Philips (Valvo) and Toshiba in each low voltage (filament time) age category, respectively. Numerals in the graph denote the tube serial numbers in KEK. Underlined tubes of Philips show the 800 kW model YK1302 or its version modified to 900 kW output power. Alive tubes of YK1302/1303 include the deteriorated ones only available at D10 and D11 for superconducting cavity use.

Once accepted E3786's run well. The earliest of the disk window type, T18A, installed in the Oho (D5) gallery, for example, is now approaching 20,000 hours of filament (LV) time and two tubes T25 and T30 in AR, are still being operated without troubles over 25,000 hours. Only deteriorated are the tubes marked with an asterisk which are out of service due to frequent negative I_a spikes. Tubes without showing I_a instabilities are working well. Due to poor statistics, however, life time expectation is still impossible. On the other hand, most failures encountered by Philips tubes are related to anode over current, positive anode current spikes and side band oscillations.

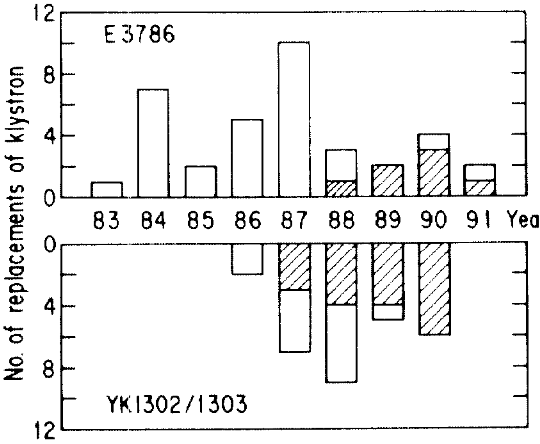

Figure 2. The number of klystron replacements vs year.

Shown in Fig. 2 are the number of times of klystron replacements vs year. As the socket for E3786 has increased year by year in number, the smallness of the replacement frequencies in last few years is remarkable. Hatching in the graph means that tubes developed troubles of negative I_a spikes in E3786 and various I_a related instabilities in YK1302/1303, respectively. Thanks to joint efforts between KEK and both makers, these troubles have been favorably diminished and during the last one year only 2 tubes had to be replaced, one of which was merely socketed out for inspection and still alive.

3. UPGRADING OF KLYSTRONS E3786

3.1 AM due to Negative Spikes in Anode Current

The klystron E3786 behaves very good only except for a problem of pulse AM. The phenomenon is caused by 'fast self-recovery breakdown' along the anode ceramic between the modulation anode which is at the negative high voltage and the body at the earth level[2]. The typical signal of the negative spike of I_a and side band components produced are shown in Fig. 3. Two countermeasures: reinforcing the shielding ring; making grooves inside the ceramic; proved to be ineffective, as three tubes modified in this way still have shown the same spike phenomena.

Figure 3. The negative spike of I_a and side band components. 0.04mA/div vs 20ms/div (left). 500kHz/div (right).

The anode ceramic of the troubled tube is very often contaminated with copper and/or copper compounds typically taking the isolated round shape of 10 to 30 mm in diameter. If not, the surface analysis (ESCA) shows that even clean-looking area of such a ceramic is contaminated mainly with copper which is sputtered from the anode electrode. It is now believed that main cause of the negative spike is relaxation by partial discharging of local electrical stress stored in semiconducting layer of Cu_2O[4]. Protecting the anode ceramic from copper depositing is postulated as the most promissing way to solve this problem of intermittent negative I_a spikes.

3.2 Ir Coated M-type Cathode

By overcoating the impregnated tungsten surface with either osmium, iridium or rhenium, a dramatic reduction in work function to about 1.8 eV can be achieved. This means that this type of cathode called M-type can deliver the same emission density as the S-type cathode at approximately 100°C lower temperature. This fact gives us a very effective countermeasure to prevent various faulty phenomena caused by barium adhesion inside the klystron tube. Moreover as the barium evaporation loss is suppressed, the cathode life is extended longer.

Among many choices of M-type cathode, iridium is considered to be one of the best ones as follows: operative at 1000°C or below with a current density of at least up to 2.5 A/cm^2; longer cathode life than the Os-Ru-coated M-type; forming of stable emission centers without retarded alloying process; nontoxicness presenting no safety problem during cathode production[5]. According to factory's life test, the Ir-coated cathode, operating with a current density of 0.8 A/cm^2, for example, is estimated to have a life of 150,000 h before the emission decreases by 4 %. Such a long life can be attributed to the Ir-W alloy layer (called the "ε_{II} phase") formed by alloying between the Ir coating layer and the W substrate during the manufacturing process. This ε_{II} phase was proven to be extremely stable without substantial degradation during the cathode life[6].

As for E3786, the first trial use of this cathode was made to the repair tube, T34C, and the second one was made to another repair tube, T47A, in combination with the first application of nickel coating to the copper anode. Figure 4 shows the underheating behaviour of the tube T34C as compared with that of

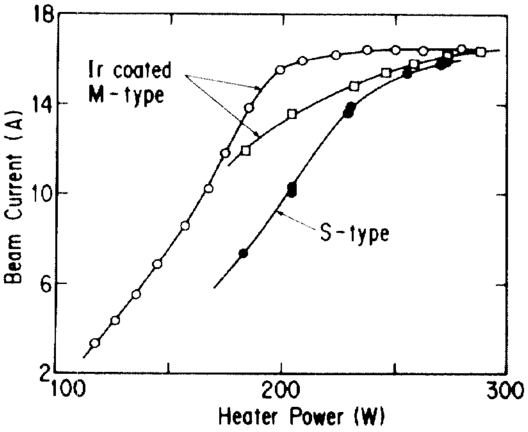

Figure 4. Underheating curves of T34C(M-type) and T56(S-type). Empty circles denote the data after 3,400 h's operation.

the tube T56 with a normal S-type cathode made by Semicon Associates. The cathode/anode voltages were fixed at 72 kV/55 kV. Although initially the emission was not so high as expected, it became clearly superior to that of the S-type after about 3,400 h's operation with the heater current of 23.0 A. At what stage the emission became good was, however, not clear because we could take these data only when TRISTAN was in long shutdown period. A round edge in Longo's curve found at an early stage may be due to the inhomogeneity of the work function over the dispenser/emitting surface, which may be caused by ion attacks during initial aging process performed in rather higher gas levels.

Aiming to get a homogeneous emission from the early beginning, the tube T47A was treated a little bit differently. The objective cathode temperatures in vacuum treatment and in activation process during evacuation were set higher as 1100°C_B and 1070°C_B for T47A as compared with 1080°C_B and 980°C_B for T34C, respectively. As shown in Fig. 5, however, the results were unsatisfactory. Long cathode aging time seemed necessary to get sufficient emission characteristics. Aging was performed with a heater current of 26A between stages 1 and 2, and, 2 and 3, but even with 29A between 4 and 5, and, 5 and 6. Although this is contradictory to the original idea to suppress Ba evaporation, the higher the better the aging temperature was to proceed the cathode aging process effectively. The cathode efficiency shown by the uppermost curves in Fig. 4 and 5 is, however, astonishingly good. We can now run the tube T34C with a heater current/power of as low as 21.5 A/206 W as compared with 24 A/280 W of the typical S-type tube, which is very effective to decrease Ba evaporation, to avoid anode current spikes and to extend tube life itself.

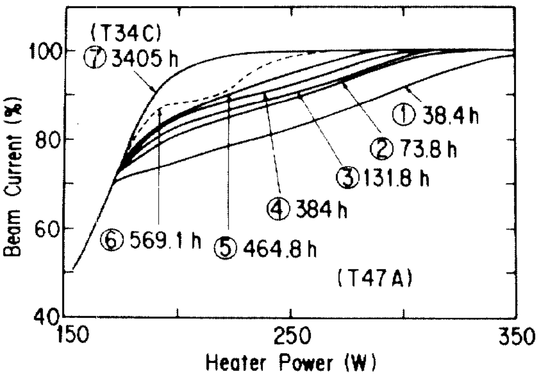

Figure 5. Underheating curves of T34C and T47A. Data taking time of 6 is different from others.

3.3 Ni Coating on Anode Surface

Coating the outer side of anode with a material that is harder to be sputtered than copper is expected to prevent Cu coating on insulator ceramic. Nickel, chromium oxide or titanium nitride can be a candidate to fulfil the requirements. As nickel can be coated more easily than others by electroplating in the production line, it was tried first by making a test bench in which insulation of small gap ($\gtrsim$ 0.2 mm) between copper and SUS balls, 1 3/16 inches in diameter, was tested in high vacuum. Balls covered with barium layer were also examined in the same test bench. The result was fed back to the tube production line and the anode electrode of one real klystron (T47A) was coated with nickel[7].

As the klystron experiences several heat cycles during the brazing process, nickel, 1.0 – 1.5 μm thick, diffuses into OFHC copper (Hitachi class 1) to make cupronickel. As Ni and cupronickel have higher melting points and lower sputtering yield than pure copper, the sputtering of copper on to the ceramic must be suppressed. Forming of undesirable semiconducting phase of Cu_2O may be blocked owing to the coexistence of Ni. Focusing conditions will not be modified by the ferromagnetism of Ni, because the layer is so thin and Ni forms cupronickel whose Curie point is low. Both bench test and a real tube test were very satisfactory. F-N plots and breakdown voltages showed small differences between nickel coated copper and pure copper no matter whether they were coated with Ba overlayer or not. Ni coating showed no deterioration and no bad effects on insulation between electrodes and on vacuum in the tube. Although the leak current, when 90 kV was applied between anode and body, was about twice as much as that (~ 0.05 mA) of most other klystrons, insulation of the tube T47A was still sufficiently good, the gas burst was not frequent and high potting time to get 90 kV was even shorter than other klystrons[7].

4. SUMMARY

Of late years, owing to KEK-Toshiba joint efforts, the super high power klystrons E3786 have been improved and operated very well. One of the problems remaining yet to be solved is the fast self-recovery breakdown which induces pulse AM in rf output. Nickel coated anode and M-type cathode have been applied to one real tube (T47A) after a bench test on ball gaps. Although further investigations, more statistics and longer running periods are required, new modifications are expected to suppress the breakdown effectually. Until now the tube T47A with both M-type cathode and Ni coated anode has been operated very well over 1,640 h without showing any signs of instability. The 1st M-type cathode tube (T34C) also has been operated well over 6,500 h without any troubles. The authors gratefully acknowledge the contributions of all the members of the KEK TRISTAN rf group, the Toshiba High Power Klystron group and the Toshiba Electronic Material Engineering group to this joint effort.

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