OPERATION OF THE UHF CW KLYSTRON AT THE WORLD'S HIGHEST POWER LEVEL

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Abstract

One of the leaked KEKB CW klystrons was repaired in-house and aged at the klystron test field to recover its original rf function. At 508.887 MHz the world's highest power level of 1.3 MW was reached. The coaxial rf window cooled by a hybrid system using air and circulated water, its titanium nitride coating and the improved version of slanted-tube water load proved to work normally and stably under such super-high power rf conditions. This paper describes a performance and high power characteristics of this tube. The tube shows a tendency, however, to lose its aged memory after some standby periods. Limitations of such in-house repairing are also discussed.

IN-HOUSE REPAIRING

In KEKB 24 high power CW klystrons are now being used, of which 4 are 1 MW ones from Philips and other 20 are so-called 1.2 MW ones from Toshiba. Both tubes have been developed and improved originally for TRISTAN in close collaboration between KEK and each industry. The MTBF of the latter is for example 34,636 h and, even 46,917 h, if initial failures during the period below 1,000 LVh are not included, considering *Infant Mortality*. The heater-on time, LVh, of five tubes exceeded 50,000 h and that of top runner (T27 installed in D7-B station) has almost reached 70,000 h. Stable, reliable and long life performances have been assured, which contributed much to KEKB's success.

Until now many leaked klystrons, irrespective of 1 MW or 1.2 MW ones, have been repaired in-house by brazing (hard soldering) and by the treatment with vacseal®. They have then been aged in test fields [1] and returned to active service. The leak test was based only on 8 l/s ion pumps. Freon, butane, ethanol and water were used as leak hunting probes. Leakage of one klystron (E3786, T41) occurred while stored on standby and its mode was unique. Two of three stainless steel sealing members, 0.5t / 0.5t and 5 mm in diameter, around the output coaxial line were located as leak sources. They play roles to seal the holes that are used to align an inner conductor during the shrinkage fit process [2]. One leak was on the welding bead but another was located about 1 mm below the bead, indicating leaks were caused by sensitization although parts made of low carbon stainless steel (SUS304L 0.5t / 0.5t) must have been used.

The leaks were sealed with vacseal® resin. Leak points were further localised by removing the sealant with acetone and again sealed with it as small quantity as possible. After curing in warm atmosphere the tube was dc- and rf-aged at the klystron test field [1]. Application of high voltage was, however, very difficult even with a reduced beam current, because the beam voltage of our klystron power supply (KPS) cannot be lowered below 47 kV. Initially, about 110 times' switch-on trials were needed, which extended over 3 calendar days. Then afterwards, the tube was firstly operated in diode mode by using another low voltage power supply (e.g. 1 kV, 50 mA). After decreasing the background gas pressure sufficiently, switching on the tube with KPS in triode mode showed no difficulties. Owing to the beam pumping effect vacuum in the tube was made better and better. Then the rf ageing smoothly progressed up to 1.3 MW with neither serious gas bursts nor abnormal arcs.

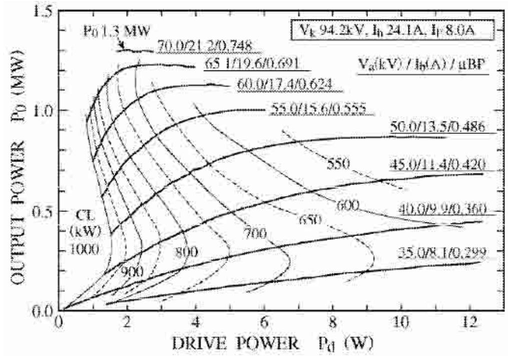

Figure 1: Klystron characteristics at KEKB frequency, 508.887 MHz. Constant collector loss curves (in kW) are shown up to 1000 kW. The highest rf output is 1.3 MW.

TUBE PERFORMANCE

CHARACTERISTICS AT KEKB FREQUENCY

Klystron characteristics at KEKB frequency, 508.887 MHz, are illustrated in Fig. 1. This tube, T41, works with high efficiency (64-67%) and large gain (53-58 dB). The highest rf output was 1.3 MW, which is the world record in the UHF CW klystrons. Constant collector loss curves (in kW) are shown up to 1000 kW. This tube belongs to the category of Type 2, which shows more collector loss on the way of increasing the modulating anode voltage [3].

GENERAL RF PERFORMANCE

Figure 2 shows the measured saturation output power, the efficiency and the phase shift as a function of the beam voltage with the modulating anode voltage adjusted for a μbeam perveance of 0.75. The maximum efficiency is 65.5% at a beam voltage of 85.2 kV for a beam current of 18.3 A. The highest rf output power is 1.3 MW for a beam voltage of 94.1 kV with an efficiency of 64.8%. A four port

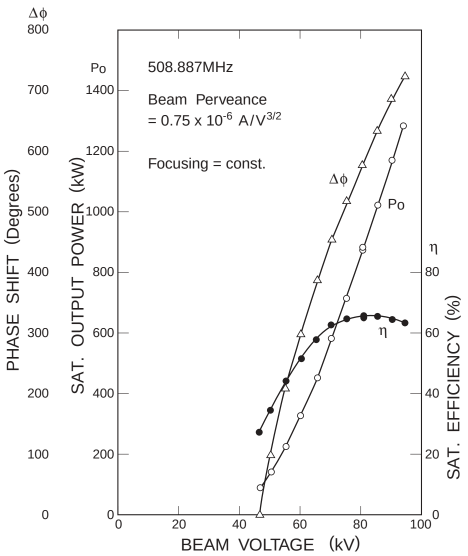

Figure 2: Performance of T41 as a function of beam voltage.

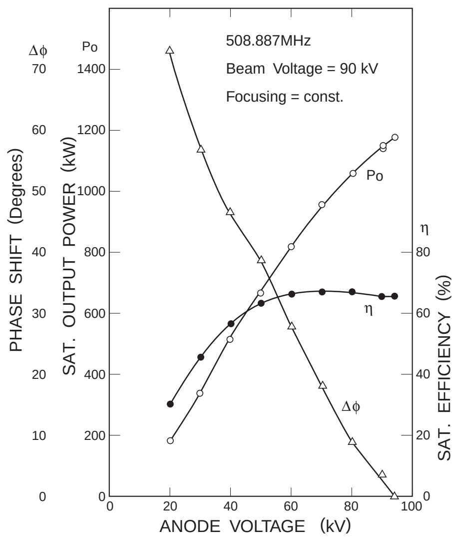

Figure 3: Performance as a function of anode voltage.

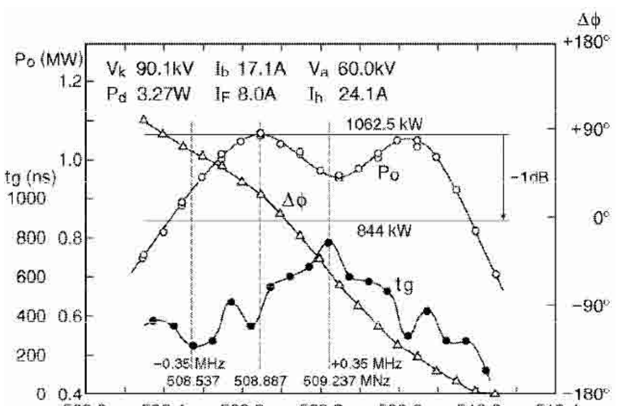

Figure 4: An example of instantaneous bandwidth characteristics of T41. The beam voltage, V_k, is 90.1 kV.

phase-shift circulator and an improved version of slanted-tube water load [1] have performed well (VSWR 1.07) under such super-high power rf conditions. Figure 3 shows the variation of the saturation output power, the efficiency and the phase shift as the modulation anode voltage is varied. An example of the frequency dependence of the output power, the phase shift and the group delay, $t_g = -\, d\phi/d\omega$, are shown in Fig. 4 for the beam voltage of 90.1 kV.

HYBRID COOLING OF OUTPUT WINDOW

Ceramic windows now adopted for 1.2 MW tubes are of disk type made of 95% aluminum oxide. Both inner and outer peripheries of the disk are cooled by water and the flat face is by filtered forced air. The vacuum-side surface of the disk and the 152D part of the coaxial waveguide are coated with titanium nitride about 10 nm thick to avoid abnormal temperature rise due to multipactoring [2,4-6]. In the test field 10% ethylene glycol water is used as a coolant, which is circulated by a chiller, CFT-75. The pressure drop Δp across a known disk-type iris in a sufficiently long straight pipe (DIN 1952) was measured by using a U-tube manometer containing water or silicon oil. The flow rate of air can be obtained as a function of Δp by using a working curve Q = f (Δp). Strictly speaking, the temperature difference ΔT of air depends on the air inlet temperature, Tin. To eliminate the changes due to this dependence, a regression line was induced by way of regression analysis and 47.1˚C was selected as a base air inlet temperature. In the plots, this compensated temperature rise is used.

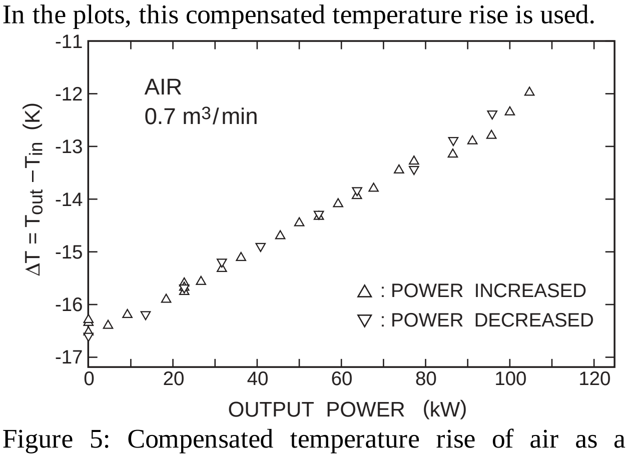

Figure 5: Compensated temperature rise of air as a function of klystron output power.

As shown in Fig. 5 and 6, the behaviour of the temperature rise is linear and no abnormal increase can be seen, indicating heating is caused mainly by dielectric loss and one-side multipactoring is suppressed by the titanium nitride coating. Around 800 kW one can see a slight decrease of slope the origin of which is for the time being not definitely clear. Possible explanations are as follows. With growing rf electric field, the effective total secondary electron yield; 1) gets smaller than unity; 2) gets limited by the finite dimension of the ceramic disc.

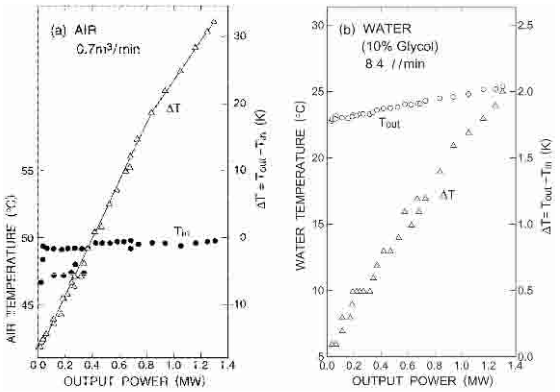

Figure 6: Temperature rise of (a) cooling air and (b) chiller cooling water containing 10% ethylene glycol as a function of klystron output power up to 1.3 MW.

From the flow rate Q (l/min) and the temperature rise ΔT (K) we can estimate the dissipated power P (kW) as follows:

$$P = Q \cdot \Delta T / \ (14.35 \cdot G),$$

$$G = \left[C \Big/ \tfrac{kcal}{kg \cdot K} \cdot \rho \Big/ \tfrac{kg}{\ell} \right]^{-1},$$

where C is the specific heat and ρ the specific weight. In our case, as the factor G, 1.02 was used for water and 3578 for air. Figure 7 summarises power balance of the system. At the klystron output of 1.3 MW the total power from the window is 1.63 kW, while the body loss amounts to 19.4 kW. About 26% of heat from the window is removed by air and 74% by water. The ratio by air increases with rf power.

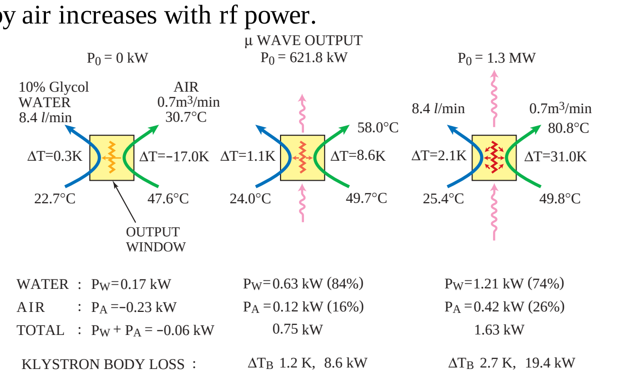

Figure 7:Hybrid cooling system of klystron output window.

DISCUSSION

Leak hunting, repairing, dc ageing and rf ageing were successfully done on one of the leaked KEKB tubes (T41). After cured, the tube could be operated continuously above 1 MW for 9 h, above 1.2 MW for 1.5 h, and above 1.3 MW for 15 minutes without any vacuum or rf troubles.

Gas bursts accompanying the multipactoring effects in the coaxial waveguide around the power levels of 36.5 kW, 132.4 kW and 267.3 kW, respectively, were carefully suppressed by long term on-site rf ageing. If stored, however, this aged tube showed a tendency to lose its memory of having been aged. Although we know the way to conquer large gas bursts happening at the early stage, it would take long ageing time. Even if the super-power as high as 1.3 MW is capable, such a tube could not be used for KEKB machine operation practically.

All these phenomena can be accounted for just by the existence of small quantity, 5.24 ppm by volume, of helium in the atmospheric air. If the leak hole is very narrow, only the helium can selectively diffuse into the tube owing to its smaller atomic dimension (1.95 Å in diameter) and higher permeability. The narrower the aisle, the higher the selectivity of helium. After a long-term storage, it can gradually concentrate and accumulate in the tube. Due to its weak binding to electrode surfaces helium can be easily desorbed with low energy electrons below 100 eV but never pumped out by getter ion pumps and can return back to gun and rf output area. For a complete repair, such a tube must be opened and baked in a furnace again. We could evacuate the residual inert gas like helium only by this process.

CONCLUSION

Small leak from air occurred in one of the high power klystron tubes. Grain boundary corrosion of welded parts made of stainless steel was the cause of that leak. The tube was successfully in-house repaired and aged to recover its original rf specification and even more. Continuous operation at the world's highest power level of 1.3 MW became possible. The hybrid cooling system for the rf output window worked well. This tube cannot be, however, used on active service as it soon loses the aged memory and emits a lot of gas again. Helium can be a most probable gas accumulated in such a tube. Selective diffusion and ease of desorption of this inert gas can account for the tube behaviour losing its dc- and rf-aged memory.

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