DEVELOPMENT OF HIGH POWER CW KLYSTRONS FOR TRISTAN

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Abstract

At the initial stage of operation of the TRISTAN MR, 16 high power klystrons are used to deliver an RF power over 0.8 MW per tube to accelerating cavities of an alternating periodic structure (APS) operating at 508.58 MHz. In close cooperation between KEK and tube industry, extremely high power klystrons (E3786) have been successfully developed after overcoming several technical difficulties. The highest RF output power of 1.25 MW with efficiency above 66.7 percent and gain above 55 dB has been reached. Half of the RF power stations are being occupied with this type of tubes.

Introduction

The main features of the design objectives of the tube for TRISTAN were: 1 MW CW output power with efficiency higher than 60 percent; 508.6 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; modulating anode providing easy control of the beam current and thus the output power level; vertical tube position with a vapor cooled collector having a dissipation larger than 1 MW without RF.

Since 1981 the fundamental design study of the 1 MW tube has been started in Toshiba to fulfill the above specifications with the help of the CAD covering the optimization of the gun geometry, analysis of the beam dynamics by disk model simulation, the optimization of the collector geometry and the total thermo-structural analysis (ADINA) by a finite element method. At that time the state of the art in high power UHF tubes was represented by E3774 for the use of the synchrotron orbital radiation facility (PF) in KEK[1]. Although its RF output power is 200 kW, the basic technological problems as related to cathodes, material treatment, joining and processing techniques as well as window design proved to be the same. The experience of the production and the use of this tube offered us a significant starting point for higher power designs. On the other hand, larger dimensions (total length: 4.35 m), higher operating voltage and power dissipation have made necessary new approaches to the design and to manufacturing techniques and have required the development and installation of new production and test facilities.

Several prototype tubes have been built, tested and analyzed extensively. The first failure occurred with water leaking through the welded parts, Q degrading of the external cavities and breaking down between the gun electrodes. Finally failures were concentrated on RF windows as the output power level increased. These difficulties including the fabrication control problems have been overcome step by step in a KEK-Toshiba joint effort[2-3]. Design modifications and improvements were fed back to the new production of E3774 as well as E3786, and this approach also contributed significantly to other high power tubes like E3778.

Development of TRISTAN Klystron E3786

In E3786 a barium impregnated cathode of type S made by Semicon Associates is used. Its diameter is 70 mm which means the maximum cathode loading of 0.52 A/cm^2. The barium is generated in an internal cavity by reaction between barium oxide and tungsten and diffuses out through a porous tungsten plug, thus constantly replenishing the supply of Ba monoatomic layer on the emissive external surface. Excess BaO impregnated in the cathode, however, is rather harmful as it accumulates on the other electrodes like wehnelt and anode and/or ceramic insulators, which results in the degradation of the breakdown voltage as was often the case with early tubes. Excess barium evaporation in the initial stage of the cathode life must be avoided. This has been done by pre-activation process which consists of keeping the cathode button at 1160°C for 6 hours and then the mounted gun assembly at 1015°C for about half an hour both in a UHV induction furnace with an oil-free pumping system. This treatment can decompose $BaCO_3$ which is formed through CO_2 absorption by $Ba(OH)_2$ and will desorb much quantity of CO during operation. Release of CO may cause the local vacuum degradation around the gun assembly and trigger the glow discharge and sputtering of the electrode materials.

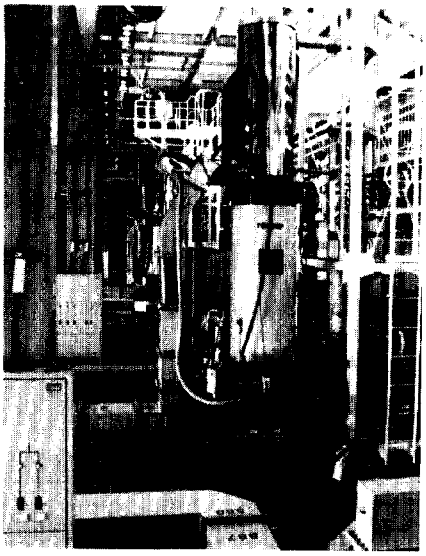

Fig. 1
Klystron E3786
for TRISTAN.

Internal discharge of klystrons usually occurs at the concentrated electric field between wehnelt and anode or body and anode. With the heater off, the anode current representing mostly the wehnelt emission obeys very well the Fowler-Nordheim law of cold emission. Spot knocking (high potting) process in which dc high voltage is applied between these electrodes removes the protrusions, and remarkably enhances the breakdown field. In early stages, as wehnelt, gold plated molybdenum lightweight structure was used. Because the cathode heats up to ∿ 1050°C, the wehnelt becomes hot and the unwanted spurious emission occurs from the Ba or BaO layer sticked on the ridge. These electrons hit the drift tube or body and trigger the glow discharge which results in sputtering of metallic materials from the electrodes. According to the X ray fluorescence analysis Cu and Au as well as Ba were detected from the surface of the body facing to the anode and the inner surface of the ceramic of the 1st cavity whose Q was degraded. These phenomena were solved by lowering the wehnelt temperature, confining the heat to the cathode button with layered shields and making all cavities internal. One way tried was to make the wehnelt out of OFHC copper and to get good thermal conduction. Wehnelt emission drastically decreased by more than one order of magnitude and showed again the Fowler-Nordheim law of cold emission even during operation. At 1.8 MW dc input, the modulation anode current was only 0.2 mA. Copper and barium, however, tend to form a binary alloy with a low melting point (minimum 458°C) and hence temperatures of wehnelt and anode should be kept low enough. For new versions, vacuum-melted, low carbon stainless steel, SUS316L is used instead of copper as a wehnelt material. The excellence of stainless steel over copper is in the mechanical strength and endurance at the higher operating temperature when covered with excess barium layer.

In early tubes, copper plated stainless steel was used as the material of an antenna type probe in cylindrical output windows. As it was welded, baked at rather high temperature (above 500°C) for such a long period of 165 hours and then constantly drenched with cooling water from inside, it often showed a delayed corrosion and leak through 'sensitization'. Halogen ions in water like chlorine and fluorine promote this process. In new tubes brazed copper was used instead of welded stainless steel and no trouble have been found hereby. When the use of stainless steel is indispensable from the mechanical reasons, material with very low carbon content such as SUS304L and 316L should be used.

The last but the most important developments have been made on the output window in respect of surface treatment of ceramic, cooling method and design of coaxial to rectangular waveguide transition. Although the thermal conducting of the ceramic is rather good and the dielectric losses are never very large ($\sim 6 \times 10^{-5}$), temperature gradients can become inacceptable due to the very large RF fields the ceramic encounters. A poreless and uniform material as well as a homogeneous distribution of the electric field are most preferable. Sufficient care must be taken to metallizing, brazing and cooling designs of ceramic partition which is in our case made of 95 percent pure alumina. Dielectric and ohmic loss as well as yield strength of ceramic closely relate to pore densities and impurity contents in a ceramic[2].

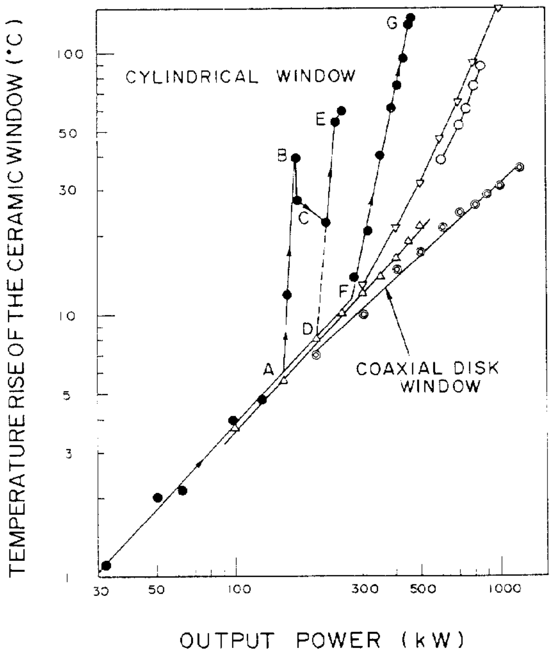

Fig. 2 Temperature rise of ceramic vs. output power.

Suppression of multipactoring was, however, the most important key factor to get high RF output power. Two types of ceramic windows were tried in our developmental work. The shape first tried was a cylinder which encloses a probe antenna at the end of the WR1500 waveguide. As the power level is raised, the window temperature first rises linearly with the applied power. Then a critical field is reached, above which the window temperature rises very rapidly. Blue or purple glow is observed above this level, too. This is so-called a one side multipactoring[4] which relates not to the bulk but to the surface properties such as the high secondary-electron-emission coefficient δ of alumina. Due to this phenomenon and the severely inhomogeneous field around the surface, the limit of power output of this type of tubes was determined by failure of window caused by thermal cracking. In Fig. 2 examples of the ceramic temperature rise ΔT, monitored by an infrared thermometer are shown. Without coating, a threshold level is around $p_0 = 200$ kW above which $\Delta T \propto p_0^n$ ($n \sim 10$) (A - B). Linear rise of temperature below this level corresponds to the dielectric or ohmic heating of the ceramic. The threshold level can be increased and the slope n can be decreased by RF aging like B → C, D - E and F - G. This process, however, took an impractically long time. Furthermore, according to the surface analysis, a small amount of Cu was detected, indicating that the aging process is equivalent to the coating process of such metallic films which can also reduce δ. The situation was drastically improved by artificial coating with titanium nitride on the inner surface of ceramic windows as shown by triangular plots in Fig. 2. The coating was done by dc reactive sputtering method in N_2 + Ar mixture almost the same way as shown in the literature[5]. The optimum thickness (around 60 to 150 Å) and condition were determined by small sample tests performed in the quartz vacuum tube which was placed at an antinode position of the WR1500 waveguide[6]. Temperature rise due to multipactoring was found to be very sensitive to the magnetic field applied to the output coaxial line. It also depends on the cooling conditions imposed by water and air flow. Speeding up the velocity of the wind around the ceramic by guided forced air can suppress the ΔT growth as represented by unfilled circles. By all these means, ΔT at 1 MW could be reduced to 95°C. In any case, however, as the RF field distribution is not so uniform, the temperature distribution is not so balanced in this type of ceramics. Light spots due to fine particles or protrusions were often observed on inner wall of the ceramic. These spots, some of which disappeared during RF aging, were apt to be collected on the lower side of the tilted cylinder probably due to the gravity, and could be acracking center by becoming white-hot. The CW power safely transmitted by this type of window has been 850 kW at most.

The ceramic windows now adopted for 1.2 MW tubes are of a disk type shown in Fig. 3. Dimensions of the doorknob and other electrical parts were determined carefully by matching tests of cold assembly. This type of ceramic has much more uniform field distribution and then no abnormal temperature gradient was expected. Both inner and outer peripheries of the disk are cooled by water and the flat face is cooled by air flow of ~ 1 m^3/min. As electrons bombard a ceramic surface with a lower angle, δ is enhanced and the threshold of multipactoring is rather lower (~ 20 kW) for a disk ceramic without coating. The impact energy loaded by electrons are, however, also smaller and the slope n of temperature rise seems to be lower. In our tubes the vacuum-side surface of the disk is coated with titanium nitride (~ 100 Å) in the same way. The typical window glow could not be observed and the multipactoring was almost completely suppressed. As shown in Fig. 2, at the maximum CW output of 1.2 MW ΔT was only 30 $\sim$ 40°C.

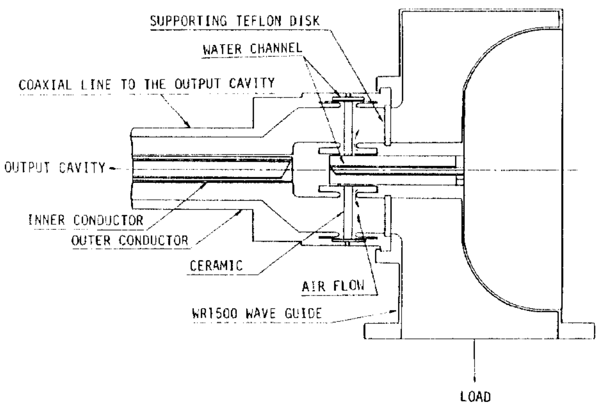

Fig. 3 Disk type window.

E3786 Performance

Figure 4 shows the measured CW saturation output power, conversion efficiency and the phase shift as a function of the beam voltage with the modulating anode voltage adjusted for a beam perveance of 0.71 × 10^{-6} A/V$^{3/2}$. The maximum efficiency is 66.7 percent at a beam voltage of 93 kV for a beam current of 20.1 A, which almost realizes the designed value by a one-dimensional large-signal computer calculation. A newly developed circulator and an RF waterload have performed satisfactorily during the operation. Figure 5 shows the variation of saturation output power, efficiency and phase shift as the accelerating anode voltage is varied. The magnetic field was held constant although the performance of this tube was very stable to field changes up to ± 10 percent of the designed value. For twelve 1.2 MW tubes the amount of scatter in efficiency at 1.2 MW output level is between 62.5 and 66.7 percent.

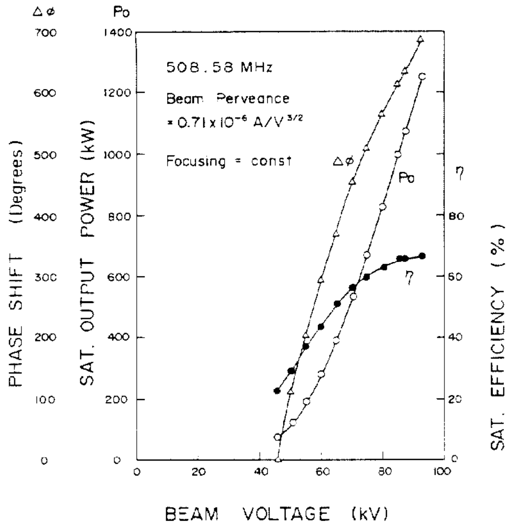

Fig. 4 E3786 performance as a function of V_k.

With RF drive reduced each klystron was tested up to a collector dissipation level of 1.2 MW for 15 minutes. This is a necessary mode of operation in the TRISTAN application, since the klystron output power is controlled by varying not only the anode voltage but also the RF drive. When arcs, RF drive is switched off fast, but the anode voltage supplied by a Cockcroft-Walton's apparatus can be decreased no faster than in 0.4 ∿ 0.6 sec. For one of the tubes, collector dissipation was tested above 1.3 MW with RF drive completely removed. The collector could withstand such a high power load with the collector temperature kept below 115°C. At the output power of 1.2 MW this tube shows the − 0.5 dB band width wider than 0.8 MHz. Hysteresis or fluctuation of the output power due to the thermal expansion etc. of tube components were scarcely observed. If the tube had been aged sufficiently, the pressure could be kept constantly lower than 10^{-8} Torr, and the operation could be continued without any serious gas burst. The body loss calculated from the temperature rise of the body cooling water was 11.3 kW at most. It is only 0.6 percent of the dc input power, which means the beam transmittance in the tube is very good as high as 99.4 percent.

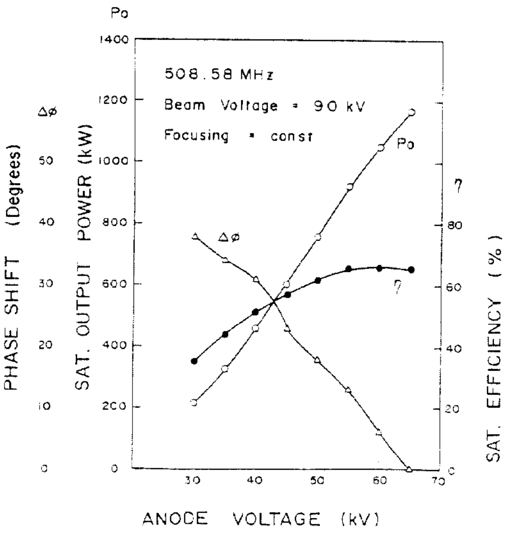

Fig. 5 E3786 performance as a function of V_a.

Conclusion

A super high power CW klystron has been developed for the TRISTAN storage ring at KEK. Collector can withstand the dissipation above 1.3 MW, the ultimate value may be near 1.5 MW. The average efficiency is about 65 percent with the maximum value obtained being above 66.7 percent. The highest RF output power is 1.25 MW for a beam voltage of 93 kV, while the highest beam voltage so far applied is 95 kV, which suggests that the output power about 1.4 MW might be possible for this tube. Because the temperature rise of the window ceramic is effectively suppressed by titanium nitride coating, the output power above 1.5 MW would not be beyond our reach if the efficiency kept the high value at the beam voltage up to 100 kV.

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