DEVELOPMENT OF HIGH-POWER MICROWAVE DEVICES IN TOSHIBA

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Vacuum microwave devices continue to be essential for high-power RF accelerator systems and plasma heating or current drive systems for fusion experimental devices. Klystrons are suitable for use in amplification at the frequency ranges from 300 MHz to X band, while gyrotrons are mainly utilized in the millimeter wave range. Input couplers also play an important role in the building of acceleration cavity systems. TETD (Toshiba Electron Tubes & Devices Co., LTD.) has been developing these vacuum microwave devices in collaboration with some Japanese research institutes.

Two kinds of long-pulse klystron for the J-PARC project were developed in collaboration with KEK and JAEA, which each have their operation frequencies, 324 MHz and 972 MHz as listed in Table 1. Both tubes output 3 MW with a pulse duration of 0.62 ms at a repetition frequency of 50 pps. They have a triode-type electron gun and the same beam parameters and operate with an anode-modulating mode to reduce the cost of the power supply system. The tubes have a different output structure optimized for the operating frequency.

The 324-MHz tube, E3740A is horizontally oriented as shown in Fig. 1. Its weight was trimmed by 35% compared with the same size klystron by unifying it with the focusing solenoids. The maximum power of 3.03 MW was achieved with an efficiency of 57% for a beam voltage of 110 KV after some problems such as oscillation caused by reflected electrons from the collector and instability probably due to the magnetic field distribution like mirror field were solved. Twenty of the tubes were already installed in the J-PARC linac system and successfully completed acceptance testing.

Table 1: Design parameters of klystrons for J-PARC

	E3740A	E3766
Frequency (MHz)	324	972
Output Power (MW)	3	
Efficiency (%)	50	
Gain (dB)	55	
RF Pulse Length (ms)	0.62	
Beam Pulse Length (ms)	0.7	
Repetition Rate (Hz)	50	
Beam Voltage (kV)	110	
Anode Voltage (kV)	94	
Beam Perveance ($I/V^{1.5}$)	1.37×10^{-6}	
No. of cavities	5	6
Window	Coaxial	Pillbox
Output Flange	WR-2300	WR-975
Tube Length (m)	4.55	2.93

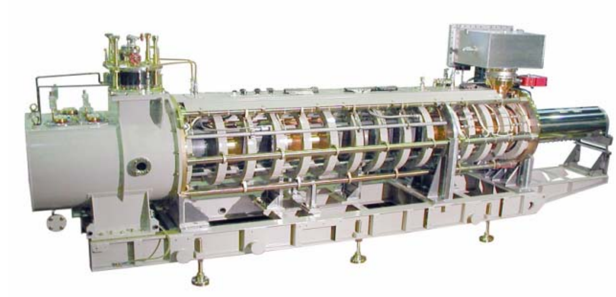

Figure 1: 324-MHz, 3-MW klystron E3740A

Figure 2 shows the 972-MHz tube, E3766. The second cavity incorporated in the first two prototypes had a relatively wide gap to meet a bandwidth of 10 MHz, and in addition, its RF electric field in the gap was symmetric with respect to the gap center, leading to TM011 and TM021-mode monotron oscillations. The 3-MW stable operation was obtained in the third tube with a new RF structure aimed at mass production.

TETD has been developing 1.3-GHz, 10-MW MBKs (multi-beam klystrons) for the Euro XFEL project in collaboration with KEK. A vertically-oriented MBK, E3736, the external view of which is shown in Fig. 3, already completed acceptance testing at DESY. Its design parameters are listed in Table 2. The MBK has six low-perveance beams operated at a relatively low voltage

Figure 2: 972-MHz, 3-MW klystron E3766

Figure 3: 1.3-GHz, 10-MW, MBK E3736

Table 2: Design parameters of 1.3-GHz, 10-MW MBK

Frequency	1.3 GHz
Peak Output Power	10 MW
Average Output Power	150 kW
Beam Voltage	115 kV
Beam Current	132 A
Efficiency	more than 65%
RF Pulse Duration	1.5 ms
Repetition Rate	10 pps
Gain	47 dB
Number of Beams	6
Number of Cavities	6
Cathode Loading	2.0 A/cm^2

of 115 kV and six ring-shaped cavities to enable a higher efficiency than a single-beam klystron for a similar power.

Figure 4 indicates dependence of the output power and the efficiency on the beam voltage, where the solid lines and the solid circles correspond to the design and the measured data, respectively. The difference between the two data at high voltage region is probably due to selecting a lower value than the optimum one obtained by calculation for an external Q factor of the output cavity to prevent instability from occurring for unmatched loads. We achieved a 10.2-MW average power over a 1.5-ms pulse with a repetition rate of 10 pps and demonstrated a stable 24-hour continuous operation under this condition. A horizontal version of the MBK has been designed. It will be tested this summer.

Figure 5: Test facility for E3762

Table 3: Specifications and Design parameters of 5-GHz klystron

	Specs	Design
Frequency (GHz)	5	
Output power (kW)	400	500
Pulse length (s)	10	CW
Beam voltage (kV)	< 70	68
Anode voltage (kV)	< 66	61
Beam current (A)	< 17.5	15.5
Efficiency (%)	> 30	> 50
Drive power (W)	< 30	< 20
Number of cavities		6
Dissipation (kW)	800	800
Length (m)	2.6	
Weight (kg)	800	
Number of windows	2	2 (BeO)

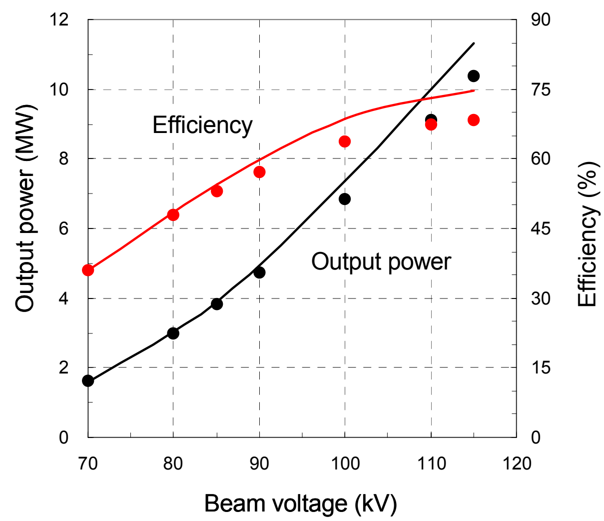

Figure 4: Output characteristics of E3736

A prototype of the 5-GHz, 500-kW CW klystron for KSTAR was completed. The klystron E3762 was designed with the aim of outputting continuous wave power of 500 kW with efficiencies above 50% as listed on Table 3. A 1.5-π three-cell output cavity was adopted to realize higher efficiency within an allowable heat load. Beryllium oxide disks, which have relatively high thermal conductivity and low tan delta, were selected to avoid window failure by thermal stress. Evaporative cooling was adopted as shown in Fig. 5.

Figure 6 shows dependence of the output power, the efficiency, and the drive power on the beam voltage. A maximum power of 510 kW with an efficiency of 50% was achieved for a beam voltage of 68 kV. We also demonstrated a continuous operation of 350 kW and a 10-s pulsed operation of 455 kW and confirmed that the measured losses of the body and the windows were similar as calculated. It can be expected from the test results that the continuous operation of 500 kW will be achieved in the next tube.

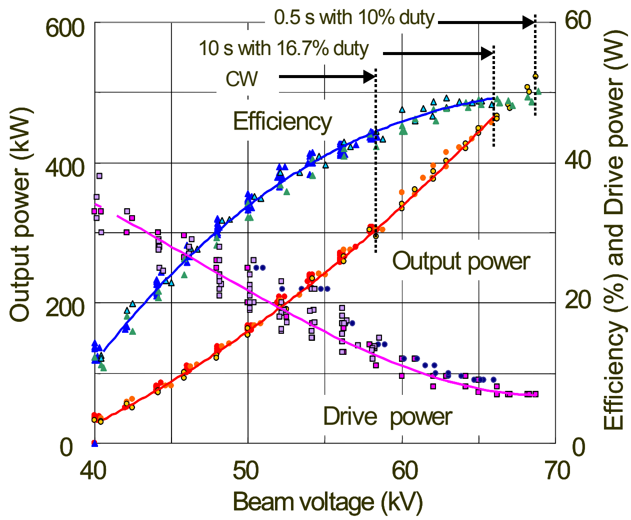

Figure 6: Output characteristics of E3762

JAEA and TETD have been jointly developing the 170-GHz, 1-MW long-pulse gyrotron for ITER, which is shown in Fig. 7. Tests is currently proceeding into the demonstration of high-power and long-pulse operation at the JAEA's test bench.

Figure 7: 170-GHz, 1-MW gyrotron E3993