KLYSTRON DEVELOPMENT BY TETD

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Abstract

This article describes recent development status of klystrons and input couplers for high-power RF accelerator systems including a 324-MHz and a 972-MHz klystrons for J-PARC, 1.3-GHz vertical and horizontal MBKs for DESY and a 1.3-GHz TTF-type input coupler for EURO-XFEL. Development of a 5-GHz, 500-kW CW klystron for KSTAR and a 170-GHz quasi CW gyrotron for ITER are also presented as an application to fusion experimental devices.

KLYSTRONS FOR PROTON ACCELERATORS

TETD (Toshiba Electron Tubes & Devices Co., LTD.) developed a 324-MHz long-pulse klystron for J-PARC in collaboration with KEK and JAEA. Twenty klystrons were installed in the J-PARC linac last summer and were tuned individually for beam acceleration. The proton beam energy of 181 MeV was successfully achieved last January [1]. We are also in the final stages of developing a 972-MHz klystron used at some later point in the linac.

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

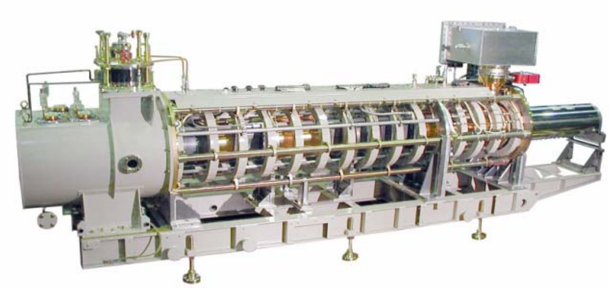

Figure 1: 324-MHz, 3-MW klystron E3740A.

Both the klystrons output 3 MW with a pulse duration of 0.62 ms at a repetition frequency of 50 pps as listed in Table 1. 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 klystrons have a different output structure optimized for the operating frequency.

The 324-MHz klystron, 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 two major problems were solved. One was oscillation caused by reflected electrons from the collector, and the other was instability probably due to slow electrons trapped by mirror-shaped magnetic field distribution. A derivative of E3740A , which operates at 325 MHz with a diode-gun mode, was developed for FNAL.

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.

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

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

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MULTI BEAM KLYSTRONS AND INPUT COUPLERS FOR EURO XFEL

TETD has been developing 1.3-GHz, 10-MW MBKs (multi-beam klystrons) for Euro XFEL 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 last summer. Its design parameters are listed in Table 2. The MBK has six low-perveance beams operated at a relatively low voltage 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 discrepancy between the numerical calculations and the experimental data at high voltage region is probably due to selecting a lower external Q factor of the output cavity than the optimum 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.

We designed and fabricated a horizontal version of the MBK and have started a factory test. This MBK has basically the same RF and electron beam structure as the vertical version.

TETD is on contract with LAL (Orsay - France) for the industrialization studies of the XFEL power couplers [3]. We have proposed some expertise and know-how on the basis of our rich experience developing couplers for KEK, SP-8 and SNS. Figure 5 shows the external view of the our power coupler, which is based on the TTF-3 coupler.

In order to achieve competitive cost and high reliability for volume production, we adopted all vacuum-brazed metallic joints and reduced parts and junctions of the bellow assemblies by analyzing the RF transmission characteristics. We are investigating fatigue strength of annealing bellows and TiN diffusion into ceramic. Two prototypes will be delivered next February.

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

APPLICATIONS TO FUSION EXPERIMENTAL DEVICES

A prototype of the 5-GHz, 500-kW CW klystron for KSTAR was completed. The klystron E3762, the external view of which is shown in Fig. 6, 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.

Figure 7 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.

JAEA(Japan Atomic Energy Agency) and TETD have been jointly developing the 170-GHz, 1-MW CW

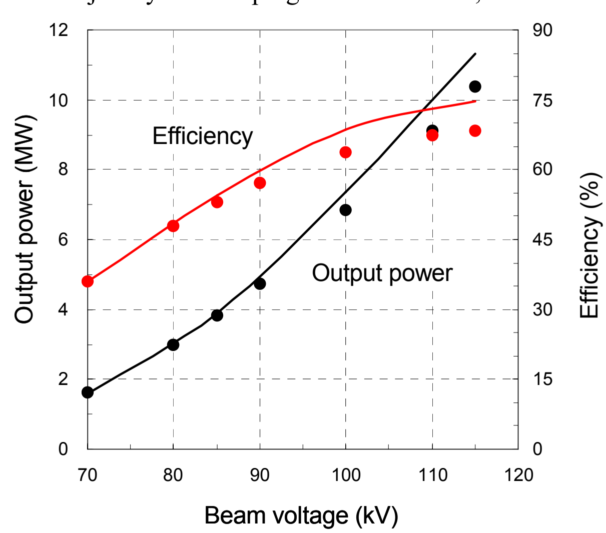

Figure 4: Output characteristics of E3736.

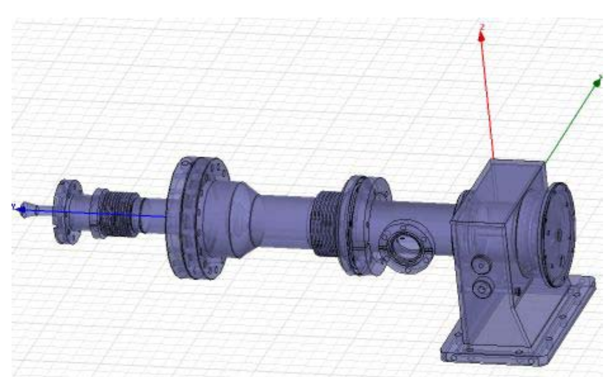
Figure 5: Power coupler for Euro XFEL.

gyrotron for ITER, which is shown in Fig. 8. Test is currently proceeding into the demonstration of high-power and long-pulse operation at the JAEA's test bench. JAEA has achieved a 1-MW, quasi-CW operation with an efficiency of 55%. Such a high efficiency was obtained by active control of the electron-beam parameters during the oscillation [4].

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)

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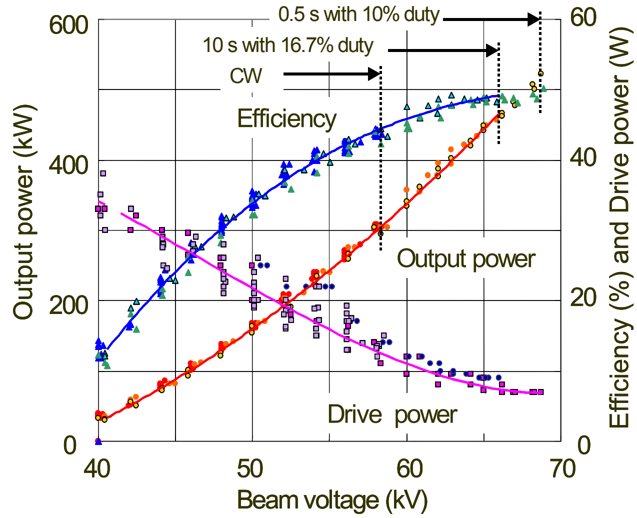

Figure 7: Output characteristics of E3762.

Figure 6: 5-GHz, 500-kW klystron E3762.

Figure 8: 170-GHz, 1-MW gyrotron E3993.