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STATUS OF HIGH EFFICIENCY KLYSTRON DEVELOPMENT IN TETD

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Abstract

TETD (Toshiba Electron Tubes and Devices Co., Ltd.) has been developing a high efficiency klystron improved bunch quality by the multi-stage of core oscillation design. For feasibility study, an S-band 7.5 MW klystron has been designed with the efficiency of more than 60% at 1.8 micro perveance. The first prototype was fabricated by modifying the interaction section of a commercial model to enhance the efficiency from 45% to 60%. The klystron was tested in June 2017, and 57% of efficiency at 6 MW output power was demonstrated. We are developing the second prototype which has the improved design for the higher efficiency at 7.5 WM output power. The design details and the test results of the first prototypes are presented.

INTRODUCTION

Klystrons have been widely used as RF source of particle accelerators in science and industry applications. The klystron efficiency is one of the important parameter regarding power consumption at large accelerator projects, especially future big projects, such as CLIC [1], ILC [2].

The efficiency of the recent commercial klystrons are around 40 - 60%, and some studies are carried out to increase the efficiency from this level. One of the approach for the high efficiency is a multi-beam klystron (MBK) which has several low perveance beams of a conventional interaction design. MBK technic can achieve the efficiency of more than 70% with the lower operating voltage. Another approach is changing scheme of bunching cavities to improve the quality of bunch, as this technic, the COM (core oscillation method) and the BAC (bunching - alignment - collection) technic are proposed [3, 4]. Simulation result by the design with the multi-stage COM is reported that the efficiency of 90% is achievable [5].

TETD has started the high efficiency klystron development by the new bunching approach since 2016 [6]. In the first prototype, the interaction section of a commercial model was replaced into a new cavity scheme to study feasibility of the new method.

DESIGN

Outline

In the klystron, cavities in the interaction section are arranged the electron bunches become tight at the output cavity, where RF output is generated by deceleration of the electrons. For the higher efficiency, good quality of bunch and uniform deceleration at the output cavity are required to reduce the energy remains after the deceleration. Required conditions for the bunch and the cavity field are:

(a) short bunch length with no electrons in accelerator phase of the output cavity field,

(b) low energy spreads in the bunch, and

(c) uniform electric field distribution in radial at the output cavity.

By a rough estimation of the energy remains after decelerations, efficiency is expressed as follows:

$$\eta \approx B(l)\cdot\left(1-\frac{\Delta V_{beam}}{V_k}\right)\cdot G(r_d,r_b), \qquad (1)$$

where $B(l)$ is the deceleration factor due to finite length of the bunch, ΔV_{beam} is the maximum potential spread in the electron bunch, V_k is the beam voltage, and $G(r_d,r_b)$ is the deceleration factor stemming from distribution of electric field in the output cavity.

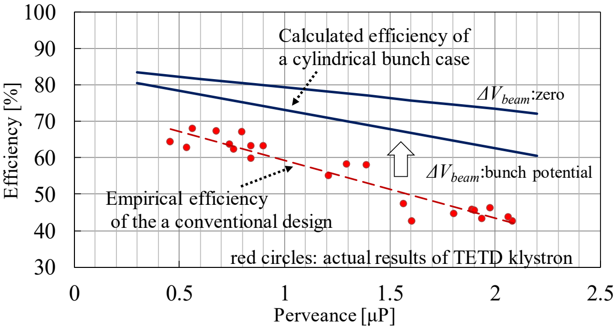

Figure 1: Relation between the perveance and the expectable efficiency of a cylindrical bunch shape.

Figure 1 illustrates relationship between the perveance and the expectable efficiency. Dashed line shows the empirical efficiency by the actual data of a conventional design. Solid lines are calculated efficiency by Eq. (1) in the case of ideal bunch shape of cylindrical. In the calculation, it is assumed that the length of bunch is a quarter of the electron wavelength, all electrons are uniformly distributed in the bunch, potential spreads of the electrons in the bunch are lower than the space charge potential of bunch edge and the drift tube of the output cavity has regular size in response to the frequency and the perveance. It is predicted that the klystron efficiency can be enhanced by improving the bunch quality, especially in the case of the high perveance. On the other hand, one of anticipated issues of the high efficiency klystron is instability due to high RF current by the tight bunch and/or oscillations by the arrangement of many cavities, particularly the high perveance design would have the high risk of instabilities. The first prototype was developed to evaluate the efficiency and the stability at the high perveance. In this development, S-band pulsed klystron E3772A was chosen for the base model. E3772A is 2856 MHz, 7.5 MW pulsed klystron, which has small drift tubes enabling to adopt 2nd harmonic cavities which could keep the body length same.

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The new klystron was replaced only the interaction section into the new design based on the multi-stage COM.

Details

The design parameters of the base model and the new klystron are shown in Table 1. In the new design, the interaction section except the output cavity was modified on condition of keeping the same body length. Figure 2 shows the phase diagram of the beam simulation results at the rated beam voltage by the FCI code [7]. The interaction section of the current klystron is a standard five cavity design which has a single core oscillation section. The new design consists of a gain cavity section, a double core oscillation section and a bunching section with three cavities for the tight bunch. The total cavity number is ten and two 2nd harmonic cavities are inserted to the COM section to shorten the tube length. In the core oscillation process, electrons outside of the bunch are collected to the main bunch and electron velocity in the main bunch is aligned by the oscillation. Bunching by the multiple-cavities enables to form the tight bunch with low energy spread due to smooth modulation by the lower cavity voltage and the space charge effect in the bunch core. Figure 3 shows the beam profile of the beam simulation at the rated beam voltage. As seen in the profile, the amount of accelerator phase electrons at the output cavity is thinner than the conventional design.

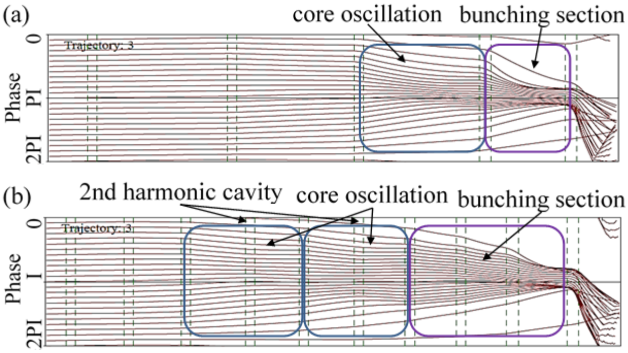

Figure 2: Phase diagrams of medium radius beam by FCI simulation. The upper (a) is the conventional, the lower (b) is the new design.

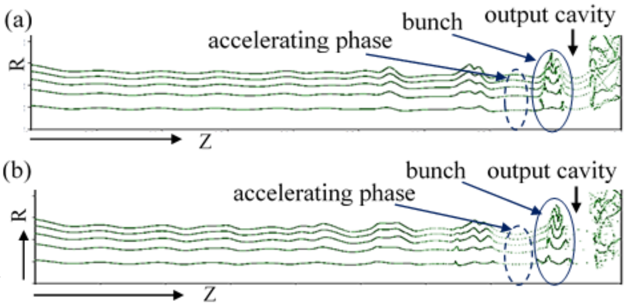

Figure 3: Beam profile of FCI simulation results. The upper (a) is the conventional, the lower (b) is the new design.

The simulation result is shown in Table 1. The FCI code predicted that the power efficiency as high as 62% could be obtained at the beam voltage of 145 kV. Enhanced efficiency of 13% was expected. Against stability issues, the power gain dependence on the frequency was designed that the gain was maximum around the operating frequency and no backward electrons from the output cavity were observed up to 155 kV in the simulation.

Table1: The Parameters of Design Target and Design Result

Parameter	E3772A	High efficiency		Unit
	results	target	result	
Output power	8.1	>7.5	8.9	MW
Frequency	2856	2856	2856	MHz
Beam voltage	155	145	145	kV
Perveance	1.8	1.8	1.8	$\mu A/V^{3/2}$
Drive power	80	< 160	130	W
Efficiency	48	≥ 60	62	%

TEST RESULTS

The first prototype was tested in July 2017. Table 2 shows the experimental results. The klystron achieved 57% of efficiency at 6 MW output power and 55% efficiency at 7.5 MW output by optimizing the focusing magnetic field respectively. In 7.5 MW operation of the condition 2, the focusing magnetic field strength was increased to prevent instabilities. Figure 4 shows waveforms and Fig. 5 shows transfer characteristics at these conditions. The output waveforms were steady and stable in 4.5 µs rf pulse operations and no unstable phenomena was observed in the transfer characteristics.

Table 2: Test Result

Parameter	Cond. 1	Cond. 2	Unit
Operating frequency	2856	2856	MHz
Beam voltage	131.1	144.8	kV
Beam current	83.4	95.2	A
Output power	6.2	7.5	MW
RF pulse width	4.5	4.5	µs
Pulse repetition rate	100	100	pps
Drive power	60	90	W
Power efficiency	56.9	54.7	%
Power gain	50.5	49.0	dB
Beam perveance	1.76	1.73	$\mu A/V^{3/2}$
Solenoid coil power	2.6	6.5	kW

Figure 6 shows the test results of the saturated output power as a function of the beam voltage. The maximum efficiency of the new klystron was 58% at 7 MW output in the condition 1, while 46% in E3772A at 7.5 MW output, the increase was 12%. The maximum output power in the condition 2 was 8.5 MW at 150 kV of beam voltage and 56% of efficiency.

One of issues of the first prototype was instability in high output power range with operation of lower focusing magnetic field strength. The efficiency of the klystron was limited due to setting of the focusing field. By analysing the data of the stability related to conditions of the focusing field, the instability seems to be caused by backward electrons from the collector. The second prototype was modified the design of collector and tuning of cavities in the gain section to improve the stability for 60% of the target efficiency. The tube has been fabricated in March 2018, and will be tested in April 2018.

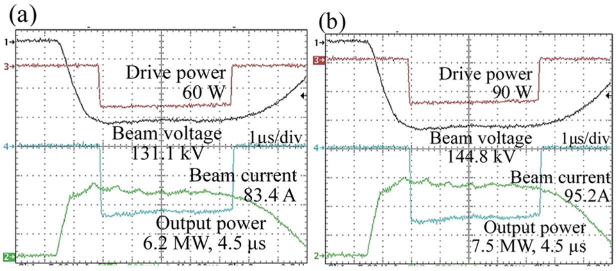

Figure 4: Output power and Beam voltage waveform. The left (a) is 6.2 MW output of the cond. 1, and the right (b) is 7.5 MW output of the cond. 2.

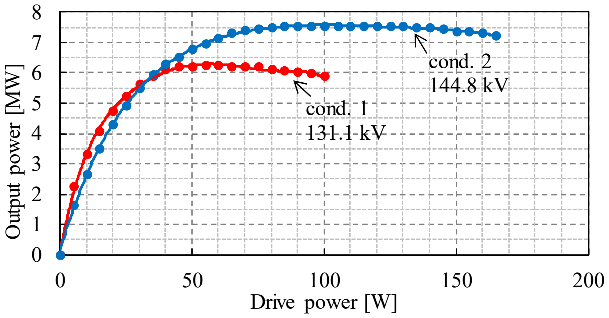

Figure 5: Transfer characteristics of the new klystron.

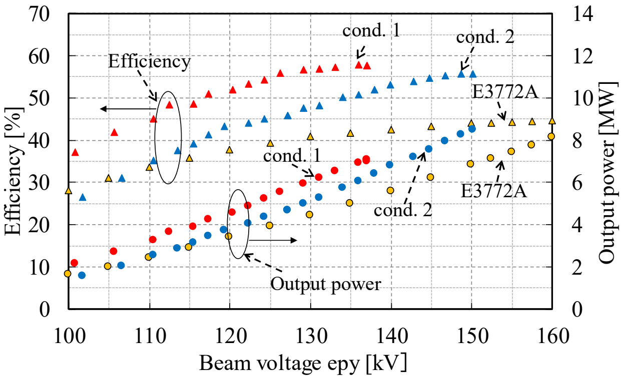

Figure 6: Measured saturated output characteristics of the new klystron and E3772A.

CONSIDERATION

The efficiency applying the double core oscillation and the smooth bunching technic was estimated from the trial beam simulations of different perveance. In the simulations in low perveance, the high efficiency design was applied to L-band 10 MW MBK on condition of the same beam voltage and different number of beams. Figure 7 shows relationship of the efficiency and the perveance. The empirical efficiency in conventional tubes, the simulation results applying the method, and the estimated efficiency corrected the results by empirical factor between the simulation result to actual efficiency are shown. Applying the improved bunch design, it is expected that the efficiency is increased by 10 - 15 % from the current level. The enhanced efficiency is estimated to be about 60% in pulsed klystron with the high perveance of around 2 μP, about 70% in CW or long pulsed klystron with the perveance of about 1 μP, and about 80% in MBK with the low perveance of less than 0.5 μP.

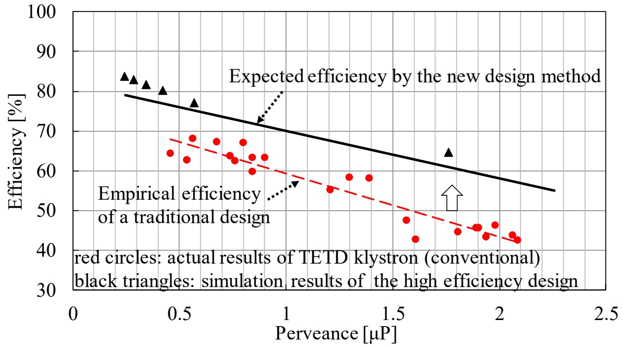

Figure 7: Relation between the perveance and the achievable efficiency by the new design method.

CONCLUSION

Availability of the multi-stage of core oscillation bunching design was demonstrated through the test of the first prototype which performed 58% of efficiency, increased by 12% from the conventional. One of issues in the test was instability which limited the efficiency in the high output range. The second prototype which has improved the design against the stability issues has been developed for the target efficiency of 60% or more, and the tube will be tested in April 2018. In the beam simulations of different perveance, the efficiency enhancement by this method is predicted to be about 10% at 0.5 μP and about 15% at 1.8 μP. Application of the method to scientific and industrial klystrons for reducing the power consumption or increasing the output power are expected.

REFERENCES

[1] CLIC collaboration. A multi-TEV linear collider based on CLIC technology: CLIC Conceptual Design Report. Volume 1. Technical report, CERN, Geneva, 2012.

[2] ILC Technical Design Report Volume 3 – Accelerator, 2013.

[3] A. Y. Baikov *et al*, "Simulation of conditions for the maximal efficiency of decimeter-wave klystrons." Technical Physics 59.3 (2014): 421-427.

[4] I. A. Guzilov, "BAC method of increasing the efficiency in klystrons", *Vacuum Electron Sources Conference (IVESC)*, 2014 Tenth International, IEEE, 2014.

[5] A. Y. Baikov *et al*, "Toward high power klystrons with RF power conversion efficiency on the order of 90%", *IEEE Trans. Electron Devices*, Vol. 62, No. 10, 2015.

[6] K. Suzuki *et al*, "High efficiency klystron design and test result in TETD", in *Proc. IVEC 2018*, 19th Int. Vacuum Electronics Conference.

[7] T. Shintake, "FCI-Field Charge Interaction Program for High Power Klystron Simulation", in *Proc. of the 1989 IEEE Particle Accelerator Conf. (PAC'89)*, Mar. 1989, Chicago, IL, USA, pp. 94-96.