FCI SIMULATION ON 100MW CLASS KLYSTRON AT X-BAND

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Abstract

A 100MW X-band pulsed klystron named XB72K was designed by the use of a 2-1/2-D particle-in-cell code FCI. The designed efficiency was about 45% while the high power operations of this tube showed a measured efficiency of 30%. The main cause for this efficiency discrepancy was an inadequate simplification of the interaction region geometry used for the calculations. Additional corrections for the simplified geometry were made and the efficiency calculated after these corrections turned to be consistent with the high power measurements.

Introduction

In a future linear collider such as Japan Linear Collider (JLC)[1,2], accelerating gradients of 50 to 100MV/m at the X-band (11.424 GHz) are being considered. In order to achieve such high gradients, it is necessary to develop klystrons with a very high peak output power. In 1991, a 100MW class klystron named XB72K was designed in order to satisfy such a power requirement. High power tests of the first tube were carried out in 1992~93[3,4]. This tube has achieved a peak power output of 93MW with a 50ns pulse duration. There was, however, a large discrepancy between the design efficiency and observed one. Therefore, revised simulation work was undertaken in order to understand the cause of this discrepancy. The results are described in the following section.

Design of XB72K

The design parameters of XB72K are listed in Table 1. A very small beam is required for klystrons operating at such a high frequency as the X-band. Therefore, the beam should be compressed to a very small cross section compared to the cathode area even with a relatively high cathode loading design. A simulation code EGUN[5] was used to determine the gun geometry and focusing field profile which provide a good beam formation. Figure 1 shows the gun geometry. Figure 2 shows a beam trajectory together with the focusing field profile. A simulation code FCI[6] was used to optimize RF parameters in the interaction space.

TABLE 1
Design Parameters of XB72K Klystron

Operating Frequency	11.424 GHz
Peak Output Power	120 MW
Efficiency	45 %
Saturated Gain	53~56 dB
DC Beam Parameters	
Voltage	550 kV
Current	490 A
Perveance	1.2×10^{-6} AV$^{-3/2}$
Diameter	~ 7 mm
Beam Area Compression	~110 : 1
Cathode Loading(Max.)	17 A/cm^2
Magnetic Focusing Field	
at the Cathode	42 Gauss
on the Axis(Max.)	~7000 Gauss
Number of Cavities	5

Figure 3 shows the optimized positions of the cavities. The code calculates also the beam scallop, which becomes larger as the bunching process develops. Therefore, the beam hole radius was increased from 4.6 mm at the upstream side to 4.8 mm at the downstream side and finally 5.2 mm after the output cavity. Table 2 summarizes RF parameters of cavities. A "nose-cone removed pillbox cavity[7]" was adopted except for the input cavity in order to reduce electric fields on the surface of the cavities. The geometry of the output cavity designed with this concept is shown in Fig. 4.

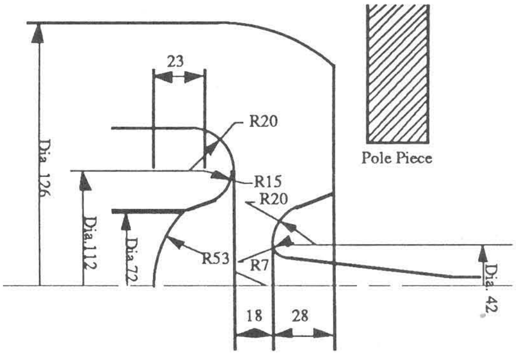

Fig.1 Gun Geometry (in mm)

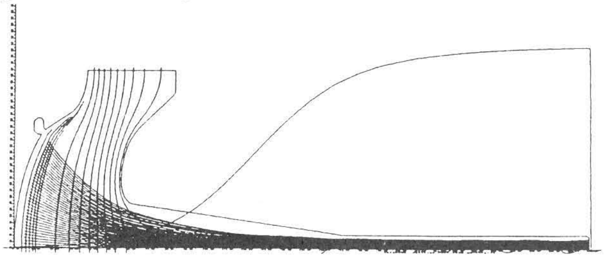

Fig.2 Electron Beam trajectory calculated by the use of EGUN-code (Vb = 550 kV, Ib = 490 A)

Results of High Power Tests

The magnetic field profile was set as calculated during high power tests. It was impossible to measure body currents. But this tube left no apparent traces of beam interceptions when it was cut half after tests. Table 3 summarizes beam conditions when the tube was operated at the highest ratings. The maximum DC voltage reached 600 kV with a beam current of 550 A. The maximum output power was 93 MW at a beam voltage of 580 kV. Measured efficiencies are shown in Fig. 5 together with calculated ones. The measured efficiencies were less by about 15% than the calculated as this figure indicates. More details of high power tests are described elsewhere[3,4].

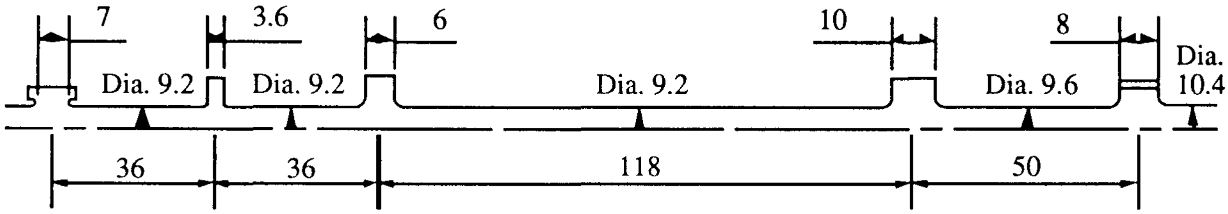

Fig.3 Interaction Space Geometry (in mm)

TABLE 2

RF Parameters of Cavities (Design Value)

Cav. No.	R / Q (Ohm)	Q_L	f0 (MHz)
1 (Input)	163	110	11424
2 (Gain)	75	4370	11436
3 (Gain)	126	6390	11450
4 (Penult.)	209	8780	11800
5 (Output)	181	15	11424

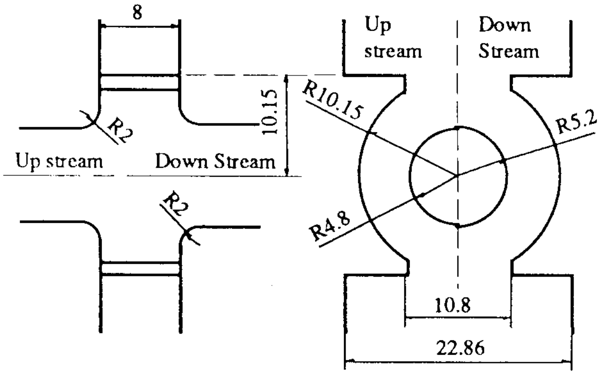

Fig. 4 Output Gap Geometry (in mm)

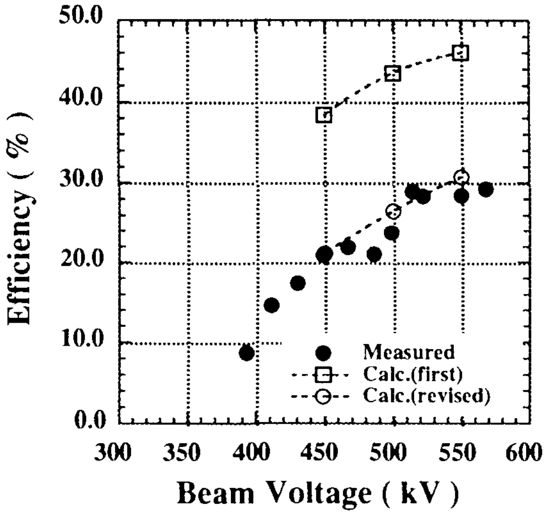

Fig. 5 Measured(Calculated) Efficiency versus Beam Voltage

TABLE 3

Summary of High Power tests (Max.)

Beam Voltage	600 kV
Beam Current	550 A
Beam Power	330 MW
Peak Power Output	93 MW @ 580 kV
Efficiency	29 % @ 580 kV

Discussion of Efficiency Discrepancies

In order to find out causes of the discrepancy, input parameters for the FCI-code were examined again. The FCI-code can not take in an actual cavity shape. It must be simplified as shown in Fig. 6. The cavity length G can be varied for each cavity. As a beam aperture radius, however, only one input parameter R is allowed for all cavities in the interaction space. The nose-coneless cavity has round corners as shown in Fig. 3. But they can not be included in the input parameter set.

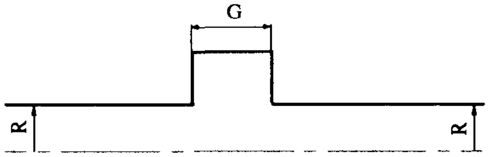

Fig 6 Simplified Geometry for the Cavity Field Calculation in the FCI -code

At first simulations, R was chosen to be 4.8 mm and G's were the same as those shown in Fig. 3. However, field distributions calculated by the FCI-code were found to be different from those calculated by the SUPERFISH-code which takes into account the round corners and differences of the beam aperture radius. As an example, Fig. 7 shows two types of output for the Ez on the axis of the output cavity. It is clear that the SUPERFISH calculates a broader distribution due to the round corner and a larger beam aperture radius at the downstream side. This might indicate that the FCI-code calculates a shorter transit time and hence a better efficiency.

In order to get a better field approximation, G's were modified so that the FWHM of Ez on the axis calculated by the FCI-code becomes the same as that calculated by the SUPERFISH-code with actual dimensions of each cavity. However, the radius R was unchanged. The result is shown in Fig. 8 and Table 4 shows the effective cavity length obtained in this way.

TABLE 4

Modified Gap length (in mm)

Cavity	Input	2-nd	3-rd	4-th	Output
G	7.3	3.1	6.8	10.8	9.5

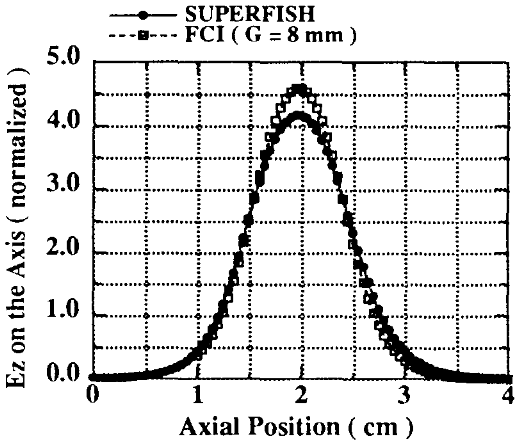

Fig. 7 Ez distributions on the axis calculated by the FCI-code with G=8 mm together with that calculated by the SUPERFISH-code for actual dimensions

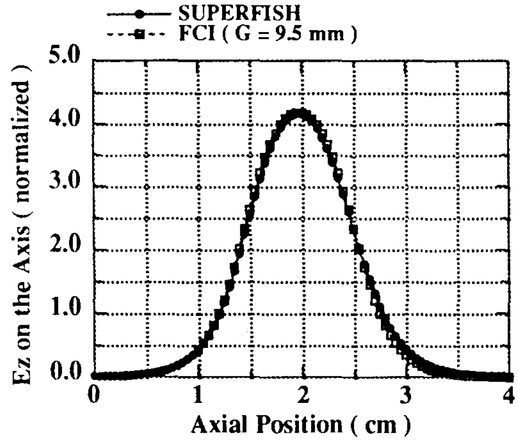

Fig. 8 Ez distributions on the axis calculated by the FCI-code with G=9.5 mm together with that calculated by the SUPERFISH-code for actual dimensions

Regarding R/Q values, those calculated by the SUPERFISH-code[8] were used in first calculations. But, since the output cavity has output irises, R/Q might be smaller than that calculated by SUPERFISH-code. This would be another cause for the efficiency discrepancy. In fact a reduction factor of 15% was observed for a 100 MW S-band klystron which has a similar output cavity configuration[9]. This reduction of R/Q reduced calculated powers about 5 %.

In many plasma simulation codes, various non-physical instabilities are observed. In the FCI-code, a small loss term is introduced into wave-equations of electromagnetic fields to suppress such a kind of instability[6]. The default value of this loss term is set to be 0.01. First calculations were executed with this default value. Several calculations were executed by varying this parameter from 0.5 to 0.0. These calculations revealed that the instability did not appear even if no damping was made. However, the calculated power was reduced roughly 10% compared to that calculated with default value. This would be also another cause.

Figure 9 shows a "beam snap-shot' and a beam energy profile along the axis calculated by the FCI-code.

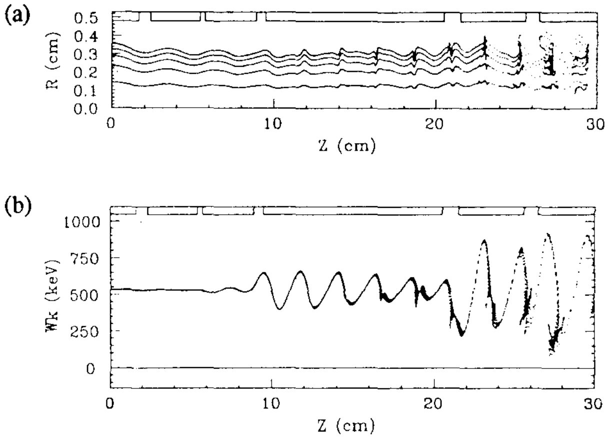

Fig. 9 Some Graphic Outputs of the FCI Simulation (revised) Vb = 550 kV, Ib = 510 A (a) "Beam Snap-shot" (b) Beam Energy Profile along the z-axis

Conclusion

The cause for the efficiency discrepancy was round corners of the cavities and differences of the beam hole aperture which were not taken into account in first calculations. Another causes would be a reduction of R/Q of the output cavity and a use of loss parameter to suppress a kind of instability in numerical calculations. After corrections for these problems were made, the efficiency calculated by the FCI-code turned to be consistent with the measured values.

Acknowledgment

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