ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS038

THERE-DIMENSIONAL SIMULATION OF A C-BAND 32-BEAM KLYSTRON

Zening Liu[1,2], Hao Zha[1,2], Jiaru Shi[1,2,†], Huaibi Chen[1,2]
[1]Department of Engineering Physics, Tsinghua University, Beijing 100084, PR China
[2]Key Laboratory of Particle and Radiation Imaging of Ministry of Education, Tsinghua University, Beijing 100084, PR China

Abstract

A 32-beam klystron working at 5.712 GHz has been designed with efficiency of 70% and output power of 3.4 MW. Core oscillations method (COM) is chosen to bunch electrons. The code KlyC is used for 1-D and 1.5-D calculation and a series of parameters are given after optimizing, including the position, frequency, R/Q, Q_0 and Q_e of cavities. CST/PIC is used to make the final design and coaxial cavities are used. This paper describes 1-D, 1.5-D and 3-D beam dynamics of the klystron, compares their differences, and analyses effect of these differences on efficiency.

INTRODUCTION

Klystron, the microwave generating device, is widely used in the field of particle accelerator. There are increasing demands for the klystron with the development of large accelerators such as Compact Linear Collider (CLIC) and Future Circular Collider (FCC). The klystron is not only required to produce a high radio frequency (RF) power but also have a high efficiency [1]. Therefore, there is increasing research on the klystron [1-4].

The development of the klystron depends on enhancing computer codes. 1-D codes such as AJDisk [5] which have a short simulation time are usually used to make an optimization. 2-D codes such as TESLA [6] which have a high simulation accuracy are usually used to predict the efficiency. KlyC which is a 1-D/1.5-D large-signal klystron simulator is recently developed at CERN as an efficient and fast enough tool [7]. However, these codes use different approximations to economize on computation time [7] and high order modes which are likely to results in high order mode oscillation are ignored in these codes. Consequently, 3-D codes such as CST/PIC is still necessary for designing and building a klystron, especially a multi-beam klystron (MBK).

A 32-beam klystron which has shown advantages such as low operating voltage, broad bandwidth and high efficiency [8] is designed in this paper. KlyC is used for 1-D and 1.5-D calculation and CST/PIC is used for 3-D calculation. The electron model, beam dynamics, including bunching and decelerating process, and the efficiency of 1-D, 2-D and 3-D calculation are compared.

A CASE OF A MULTI-BEAM KLYSTRON

A C-band klystron has been designed in 2017 with AJDISK [9]. Some parameters have been modified as the initial design of this paper, including the voltage, the radii of each beam and each tube, the beam number and input power. The design in 2017 has used core oscillations method (COM) which has shown a potential of achieving 90% efficiency [1] to obtain a high efficiency of 80%. Therefore, this method is used to bunch electrons in this paper.

Parameters Selection

The voltage is set to 55 kV, and the single-beam current is set to 2.8 A. The operation frequency is 5.712 GHz. Each beam has a radius of 1.8 mm and the tube has a radius of 3 mm. Taking account for the MBK which has 32 beams, the input RF power of each beam is set to 0.78 W to insure a low total input RF power, which is also ordered to obtain a high gain.

A series of parameters of cavities including the R/Q and M are calculated by CST/Eigenmode and they are used as the 1-D and 1.5-D input parameters. The other parameters need to be optimized for obtaining a high efficiency.

Parameters Optimization

KlyC has an optimizer that automatically optimizes efficiency. After optimization, the efficiency and gain reached 75% and 52 dB respectively in a 1-D calculation result. Optimized parameters are shown in Table 1.

1.5-D results will be obtained if the layer number is set to be more than 1. Taking into account the calculation time and accuracy, the value is set to 4. The efficiency and gain reached 70% and 51 dB respectively in this situation.

Table 1: Some Parameters After Optimizing

Cavity ID	Q_e	Frequency	Position
1	511	5712.2 MHz	0 mm
2		5729.8 MHz	70.7 mm
3		5778.6 MHz	193.6 mm
4		5765.7 MHz	316.9 mm
5		5800.0 MHz	397.3 mm
6		5781.0 MHz	481.0 mm
7		5767.3 MHz	517.2 mm
8	224	5708.2 MHz	545.1 mm

Cavity Configuration

There are 14 beams in the inner circle and 18 beams in the outer circle. The inner circle and outer circle have a radius of 19 mm and 26 mm respectively. Coaxial cavities in the TM_{010} mode should be chosen to obtain accepted R over Q and M and adapt the multi-beam configuration. The 3-D

† shij@mail.tsinghua.edu.cn

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS038

structure of the high frequency part of klystron is shown in Fig. 1.

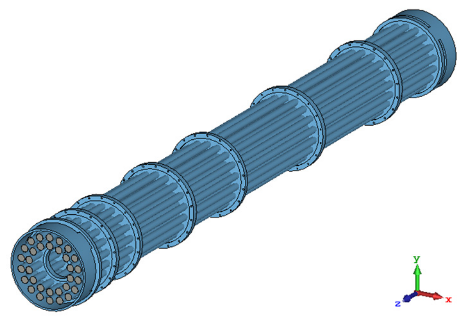

Figure 1: The 3-D structure of the high frequency part of klystron in CST.

CST/PIC RESULTS

In order to obtain the results consistent with the 1-D and 1.5-D calculation, eight cavities must be placed and tuned to frequencies as shown in table 1. Moreover, the longitudinal magnetic field should be set to be strong enough to be equivalent to an infinite magnetic field. The input power is set to be 25 W and the klystron has an output power of 3.4 MW and the efficiency has reached 70%.

COMPARISON OF KLYC/1-D, KLYC/1.5-D AND CST/PIC CALCULATION

Electron Model

Electrons are considered as a series of discs in the 1-D model and the electric field and space charge field experienced by the electrons on a disk are the same, which means the beam dynamics is the same at different radii on a disk. However, the electric field in a cavity and space charge field are differenced at different radii on a disk, which is considered in the 1.5-D model.

In a disc, electrons are considered as a series of rings with different radii in the 1.5-D model. The beam dynamics of different rings are different, but the dynamics of the same ring are the same, which means it cannot describe the electric field with uneven angular direction in a cavity.

In addition, both 1-D and 1.5-D model neglect high order modes of cavities. Finally, they have an assumption that there is an infinite magnetic field, which means they ignore the horizontal movement of electrons.

Unlike them, CST/PIC can describe complex electric field and high order modes in a cavity. Electrons are treated as uniformly distributed macro particles in this situation. Consequently, both the lateral and longitudinal movement can be considered in CST/PIC.

Beam Dynamics

The phase trajectories and the first order current harmonics by KlyC/1-D and KlyC/1.5-D are shown in Fig. 2 and Fig. 3 respectively. There are four layers in a beam in KlyC/1.5-D calculation.

The beam dynamics of 32 beams are the same in KlyC, but they are different in CST/PIC. 32 circular sources are defined and 'lines' is set to be there. The phase trajectories and the first order current harmonics of a beam are shown in Fig. 4.

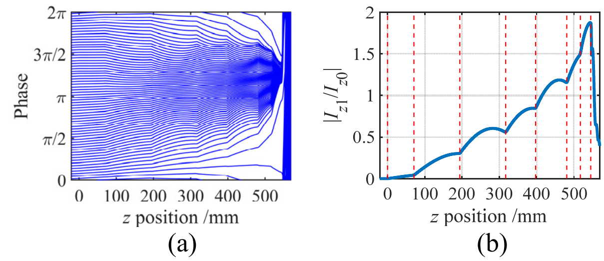

Figure 2: Phase trajectories and the first order current harmonics with KlyC/1-D.

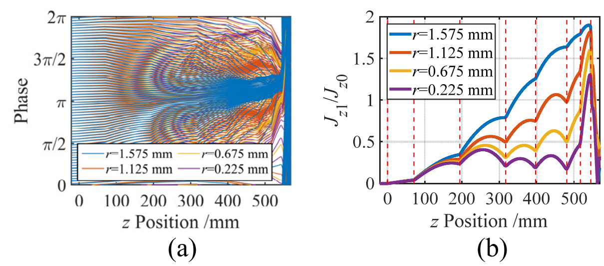

Figure 3: Phase trajectories and the first order current harmonics at different radii calculated by KlyC/1.5-D.

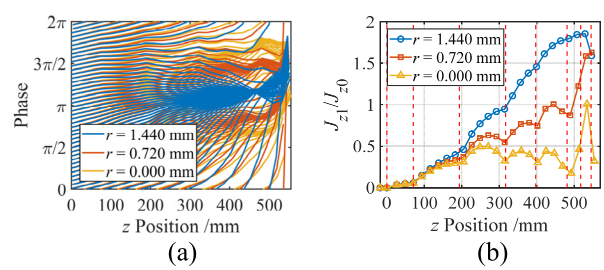

Figure 4: Phase trajectories and the first order current harmonics at different radii calculated by CST/PIC.

Figure 2 shows a 1-D COM bunching process, while Fig. 3 shows that inner electrons and outer electrons do not experience COM bunching, which is similar to Fig. 4. Because there are weak space charge field and strong electric field in the cavity at radius of 1.44 mm whereas there are strong space charge field and weak electric field in the cavity at the radius of 0.00 mm. The distribution of macro particles before a bunch enters the output cavity is shown in Fig. 5.

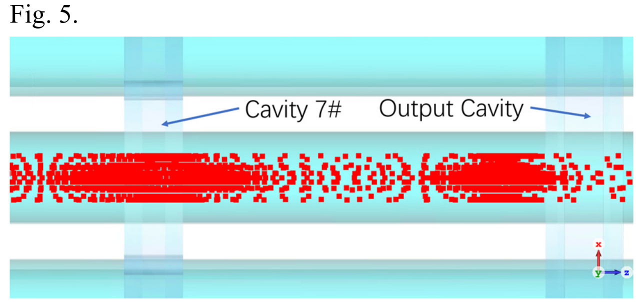

Figure 5: The distribution of macro particles before a bunch enters the output cavity.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS038

The ratio of electron velocity (v_e) to the speed of light (c) at different positions when the minimum velocity occurs calculated by KlyC/1-D, KlyC/1.5-D and CST/PIC is shown in Fig. 6, Fig. 7 and Fig. 8 respectively.

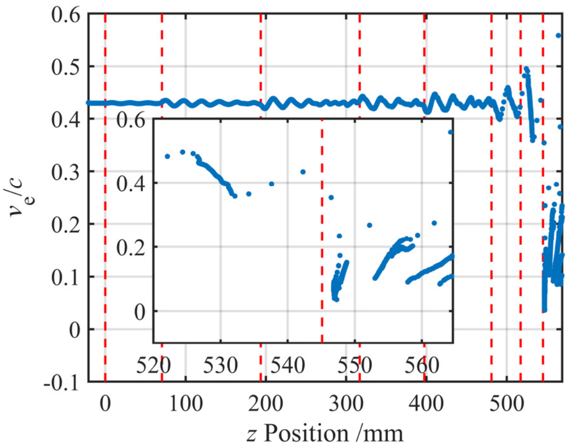

Figure 6: Electron velocity trajectories calculated by KlyC/1-D.

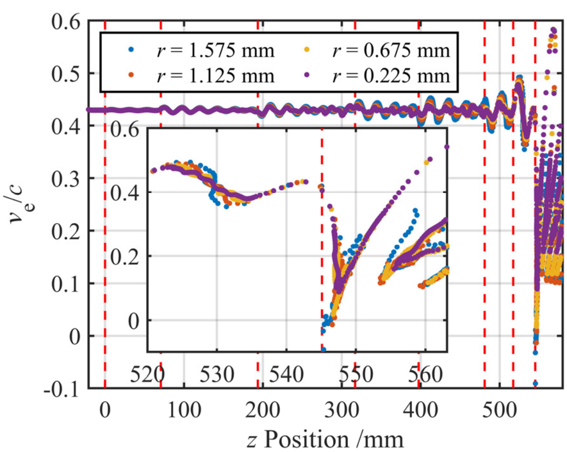

Figure 7: Electron velocity trajectories at different radii calculated by KlyC/1.5-D.

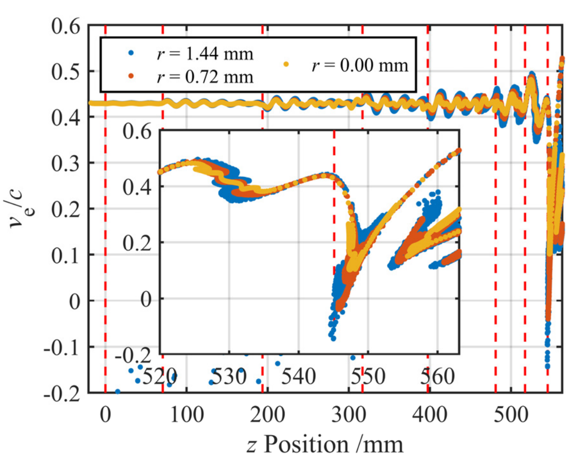

Figure 8: Electron velocity trajectories at different radii calculated by CST/PIC.

One can see the minimum velocity of 0.04c and -0.09c in Fig 6 and Fig. 7 respectively, and there are no reflected electrons. However, reflected electrons occur in Fig. 8. The klystron has the minimum electron velocity of -0.15c.

The klystron calculated by CST/PIC usually has a lower minimum electron velocity than that calculated by KlyC does. Reflected electrons are more likely to occur in CST/PIC even though the KlyC has no reflected electrons at all, especially when the minimum electron velocity is below -0.1c according to experience. Therefore, the 3-D calculation is necessary for designing and building a klystron.

Efficiency and Simulation Time

If the input power is scanned from 0 W to 25 W, the power transfer curve will be obtained as shown in Fig. 9. KlyC results and CST/PIC results agree well even though there are some differences in beam dynamics.

It took 2.7 min and 51.3 min to simulate a 1-D case and a 2-D case respectively using an Intel Core 2.5-GHz CPU with 8 GB of RAM, while it took about 33 h to simulate a 3-D case using two Intel Core 1.7-GHz CPUs with 128 GB of RAM and a Tesla 20 GPU.

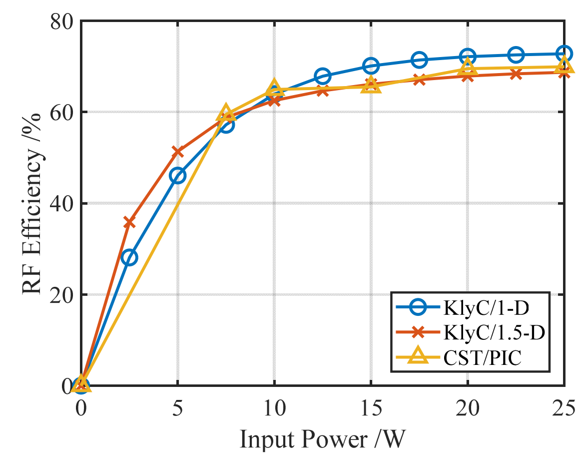

Figure 9: RF power production efficiencies calculated by KlyC/1-D, KlyC/1.5-D and CST/PIC.

CONCLUSION

A design of a C-band 32-beam klystron whose efficiency is up to 70% calculated by KlyC/1-D, KlyC/1.5-D and CST/PIC has been represented in this paper. The bunching process and efficiency calculated by KlyC/1.5-D are in good agreement with CST/PIC. Taking account for the high accuracy of KlyC and the large time/resources consuming of CST/PIC, the 1-D and 2-D codes is indispensable to efficiently design a klystron. At the same time, CST/PIC usually has a lower minimum electron velocity and can predict reflected electrons in the output cavity, which is necessary for designing and building a klystron.

ACKNOWLEDGMENT

The authors would like to thank J. Cai and I. Syratchev for the KlyC code.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS038

REFERENCES

[1] A. Y. Baikov, C. Marrelli, and I. Syratchev, "Toward high-power klystrons with RF power conversion efficiency on the order of 90%", *IEEE Trans. Electron Devices*, vol. 62, no. 10, pp. 3406–3412, 2015.

[2] I. A. Guzilov, "BAC method of increasing the efficiency in klystrons", in *Proc. 2014 IEEE Int. Vacuum Electron Sources Conf. (IVESC)*, St. Petersburg, Russia, June-July 2014, pp. 1-2.

[3] V. C. R. Hill, C. Marrelli, D. Constable and C. Lingwood, "Particle-in-cell simulation of the third harmonic cavity F-Tube klystron", in *Proc. 2016 IEEE Int. Vacuum Electron Sources Conf. (IVESC)*, Monterey, CA, USA, April 2016, pp. 1-2.

[4] J. Cai, I. Syratchev and Z. Liu, "Scaling Procedures and Post-Optimization for the Design of High-Efficiency Klystrons", *IEEE Trans. Electron Devices*, vol. 66, no. 2, pp. 1075-1081, 2019.

[5] G. Caryotakis, "High power klystrons: Theory and practice at the stanford linear accelerator center", SLAC, Menlo Park, CA, USA, Rep. SLAC-PUB 10620, Aug. 2004, pp. 91–97.

[6] I. A. Chernyavskly, "Advanced large-signal modeling of Multiple-beam Klystrons using generalized impedance matrix approach", in *Proc. 2018 IEEE Int. Vacuum Electron Sources Conf. (IVESC)*, Monterey, CA, USA, April 2018, pp. 3-4.

[7] J. Cai and I. Syratchev, "KlyC: 1.5-D Large-Signal Simulation Code for Klystrons", *IEEE Trans. Electron Devices*, vol. 47, no. 4, pp. 1734- 1741, 2019.

[8] C. Bearzatto, A. Beunas, and G. Faillon, "Long pulse and large bandwidth multibeam klystron", in *AIP Conference Proceedings*, VELIZYMay 1999, pp. 107-116.

[9] Z. Liu, J. Shi, H. Chen and M. Peng, "Design of a C-Band High-Efficiency Multi-Beam Klystron", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 4221-4223.