DESIGN OF A C-BAND HIGH-EFFICIENCY MULTI-BEAM KLYSTRON

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Abstract

A multi-beam klystron at 5.712GHz has been designed with efficiency of more than 80%. It can generate a pulse with output power of about 3MW and a pulse length of 5 μs. Space charge effect and large signal theory, which both increase the accuracy theoretically, are considered in the simulation. A series of parameters of cavities are given after optimizing, including the frequency, *R/Q*, Q_0 and Q_e. This paper describes the beam dynamics design of the klystron as well as a preliminary mechanical design.

INTRODUCTION

The efficiency of the klystron which is used to generate RF power has attracted increasing attention. Improving efficiency is considered a high priority issue for future large accelerators[1]. There are few C-band high-efficiency klystrons available on the market. The commercial C-band klystrons have a typical efficiency of 50%, such as Toshiba klystrons with an efficiency of 47%, CPI klystrons with an efficiency of 48%, and IECAS klystrons with an efficiency of 47%. Some theories are developed to increase the efficiency of the klystron and they have shown potential to obtain the efficiency above 80%[1, 2]. It is quite useful to develop a high-efficiency klystron for reducing cost and operating cost.

The multi-beam klystron has shown obvious advantages such as low operating voltage, high bandwidth, high efficiency, and high gain[3] compared with the single-beam klystron. It is a trend to develop the multi-beam klystron. A one-quadrant version of 6-beam klystron for ILC has been built, which is expected to produce 2.5 MW at 1.3 GHz in a 1.6 ms[4]. Another L-band multi-beam klystron has been designed for a future electron-ion collider, which yields high efficiency (above 70%) for the power output of 125 kW at 952.6 MHz[5]. An S-band MBK which has an efficiency above 60% has been build[6]. A C-band 18-beam klystron has been designed which producing 125 kW pulse power[7]. SLAC has developed a 5 MW X-band MBK[8].

A multi-beam klystron with an efficiency above 80% is designed in this paper. A single-beam klystron is designed first and then it is extended to a multi-beam klystron. AJDISK is used to design the single-beam klystron and the design process is described after some parameters are selected. At last the optimization results of the single-beam klystron are shown.

SINGLE BEAM DESIGN

To begin with, a single-beam klystron was designed with AJDISK which is a 1-D large signal klystron simulator developed at Stanford Linear Accelerator Center[9]. And then it could be extended to a 40-beam MBK.

Parameters Selection

There are two classes parameters in the klystron[1]. The first class can be completely defined according to our need, and the seconds need to be optimized to obtain a high efficiency.

The voltage is set to 50 kV for avoiding using an oil tank, and the single-beam current is set to 2.5 A. The operation frequency is 5.712GHz. Each beam has a radius of 1 mm and the tube has a radius of 1.5 mm. It is assumed that the unloaded Q-factors of all cavities are 10000.

Some class B parameters can also be estimated according to specific requirements. For instance, taking account for the MBK has 40 beams, the input RF power of each beam is set to 2 W to insure a low total input RF power, which is also order to obtain a high gain. In addition, *R/Q* is estimated at 35 in the C-band situation.

The other parameters need to be optimized for obtaining a high efficiency.

Configuration Design

Taking account for the target of efficiency above 80%, we cannot use traditional bunching methods. Core oscillations mothed (COM) which is a new bunching technique has shown potential of achieving 90% efficiency[1]. Therefore, this method is used to bunch electrons in this paper.

However, it is difficult to know in advance the positions where cavities can make electrons oscillate around the bunch center. It is suggested to design a traditional configuration to begin with, which means finding positions where the first harmonics current reaches the maximum. And then gain cavities and output cavity should be moved back to leave electrons enough space to oscillate, which causes that the length of the klystron increases about 20%.

There are about five stages in this klystron, which means there are at least 6 cavities. Actually, the electrons cannot bunch efficiently because of the low input power and the low *R/Q* of input cavity. Two extra gain cavities have to be placed in the first stage to accelerate bunching. In other words, there are eight cavities in this klystron.

Amplitudes of RF current the first and the second harmonics with traditional bunching method and COM are respectively shown in the Fig. 1 and Fig. 2.

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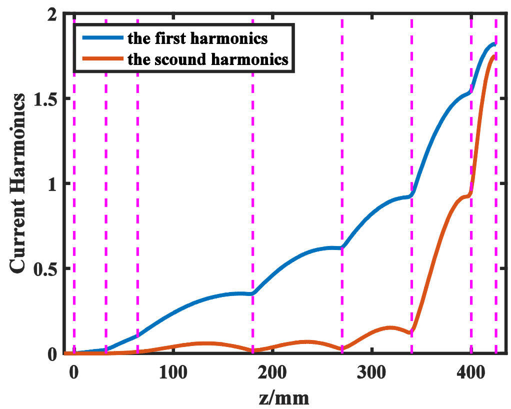


Figure 1: Amplitudes of RF current the first and the second harmonics with traditional bunching method.

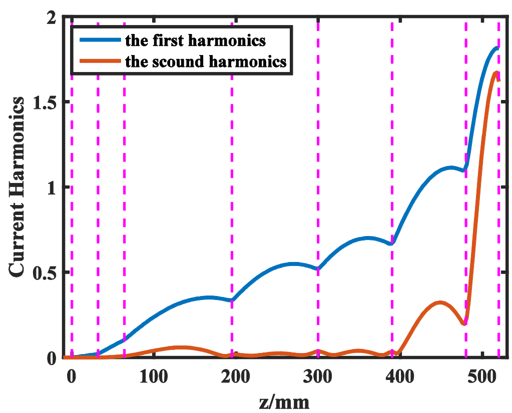


Figure 2: Amplitudes of RF current the first and the second harmonics with COM.

Parameter Optimization

Remaining parameters are the frequencies of cavities and Q_e. The bunching effect depends on the frequencies and it is quite important to obtain a high efficiency. Complete energy transfer is also important to obtain a high efficiency. We have to increase Q_e to promote energy transfer because of low *R/Q*. Cavities should also be adjusted to the proper positions in this process.

However, we could see overlap which we do not like in the process. Even though it usually appears with a higher efficiency, we have to change parameters to eliminate it. Phase trajectories with overlap and without overlap are respectively shown in Fig. 3 and Fig. 4.

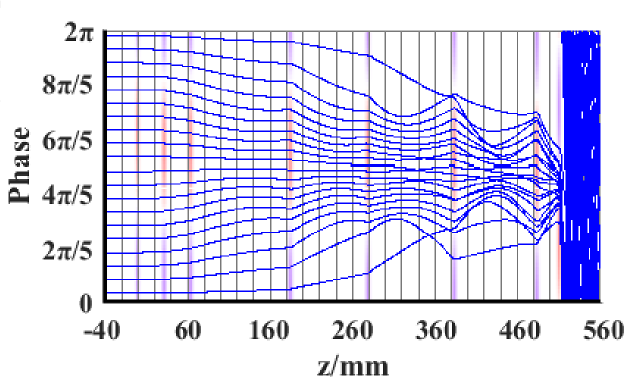


Figure 3: Phase trajectories with overlap.

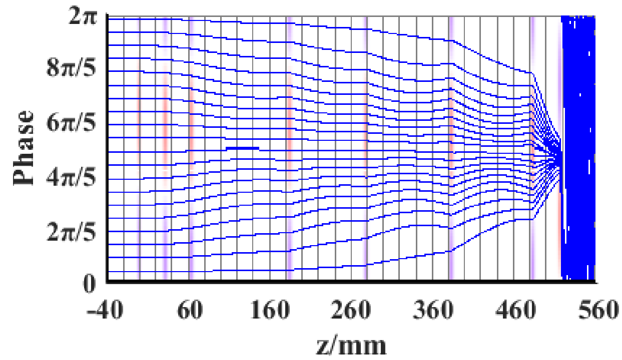


Figure 4: Phase trajectories without overlap.

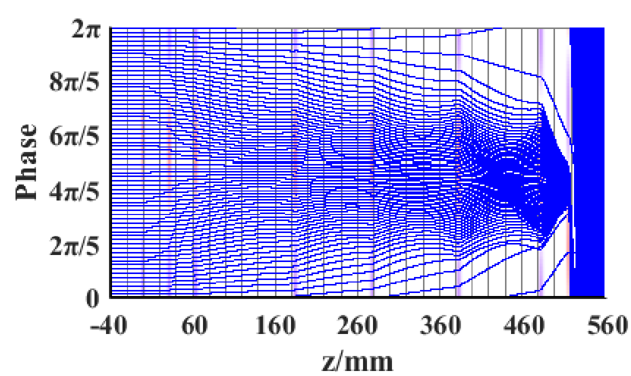
Optimization Results

A 1-D design result with efficiency of over 80% has been obtained after optimizing parameters which are shown in Table 1. The phase trajectories and RF current harmonics are shown in Fig. 5. The klystron has an efficiency of 81% and a gain of 47 dB. Although the efficiency is not the highest and there is still a little overlap in the phase trajectories, it is acceptable to us.

According to the results, the klystron has a kinetic efficiency of over 85% but a total efficiency of 81% because Q_e of the output cavity is so high that the circuit efficiency is low. But we have to choose a high Q_e to obtain a high kinetic efficiency. Kinetic efficiency, circuit efficiency and total efficiency for different Q_e are shown in Fig. 6. In addition, the high Q_e of the output cavity causes a narrow bandwidth.

Table 1: Some Parameters after Optimizing

Cavity ID	Q_e	Frequency	Position
1	175	5712.0 MHz	0.0 mm
2		5717.0 MHz	32.0 mm
3		5739.0 MHz	64.0 mm
4		5735.0 MHz	185.0 mm
5		5742.0 MHz	279.0 mm
6		5733.0 MHz	384.0 mm
7		5724.1 MHz	484.1 mm
8	512	5712.0 MHz	517.1 mm



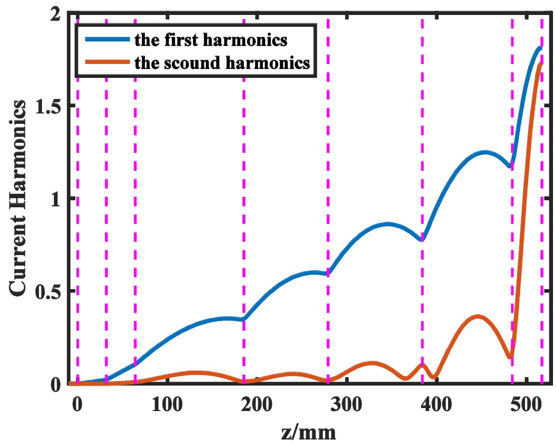


Figure 5: Phase trajectories and RF current harmonics after optimizing.

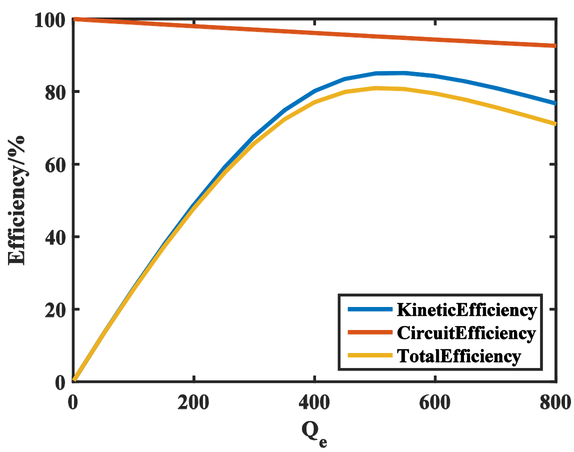


Figure 6: Kinetic efficiency, circuit efficiency and total efficiency for different Q_e.

MULTI BEAM DESIGN

Scaling Laws

The single-beam klystron could be extended to a multi-beam klystron according to a multiple to single beam equivalence concept[10]. These parameters of multi-beam klystron were shown in Table 2.

Table 2: Parameters of Multi-beam Klystron

Parameters	Value
Beam Voltage (kV)	50
Beam Current (A)	100
Frequency (GHz)	5.712
N_{beams}	40
P_{out} (MW)	4.1
Efficiency (%)	81
Gain (dB)	47

Beams Configuration

There are 40 electron beams in this klystron. There are 15 beams in the inner circle and 25 beams in the outer circle. TM_{020} should be chosen to adapt the multi-beam configuration.

In addition, each beam has a radius of 0.28 cm according to the cathode emission capability of 10 A/cm^2. Therefore, we should design an electron gun with a compression ratio of 8.

CONCLUSION

A design of a C-band 40-beam klystron whose efficiency is up to 81% has been represented in this paper. It has an operating voltage of 50 kV and a perveance per beam of 0.22 μP. The peak output power is 4 MW and the gain is close to 47 dB. The bandwidth and total length are not payed attention to in the design process. The loss of electrons which is ignored in the 1-D simulation could decrease the efficiency in the actual situation. 3-D simulation will be used to design the klystron later.

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