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OPTIMIZATION OF KLYSTRON EFFICIENCY WITH MOGA*

C. Meng†, O. Z. Xiao, S. L. Pei, S. C. Wang, Z. S. Zhou, X. He,
Institute of High Energy Physics, 100049, Beijing, China

Abstract

As the very important element of accelerator the klystron provide power to cavities for accelerating. Considering the accelerator cost of construction and running, the improvement of klystron efficiency is one developing hotspot of klystron research. In this paper the optimization method of klystron efficiency with MOGA based on 1D simulation program is proposed and the influences on klystron efficiency will be discussed.

INTRODUCTION

As the very important facility of accelerator the klystron provide power to cavities for accelerating. The increase in efficiency of RF power generation for future large accelerators, such as Circular Electron Positron Collider (CEPC), Future Circular Collider (FCC-ee), Compact Linear Collider (CLIC), International Linear Collider (ILC), European Spallation Source (ESS), and others, is considered a high priority issue. The required RF Power of above projects is in the 10-200 MW range. Due to the significant increase in RF power, it is advantageous to increase the efficiency of the RF source, in order to reduce costs of construction and running. One consensus of scientists is that all future (large) accelerators must consider energy efficiency.

Klystron is a very complicated RF source, especially in technology, machinery and physics design. There are several key parameters, such as stability, frequency, output power and efficiency, which need a lot of experience for design, construction and operation. Most high-power RF klystrons operates in the electronic efficiency range between 40% and 55%. Only a few klystrons can deliver a maximum of approximately 65%. With the demand of future accelerators, the high efficiency klystron design and development is more and more important and is listed as key technology research and development in many institutions. At IHEP there is a compact and methodical plan for high efficiency klystron design and construction form one general klystron case.

In order to maximise the efficiency of the klystron, the spatial and phase profile of the bunch should be that each electron has identical velocity after deceleration by the output gap, which is impossible because of the action of space charge force. The klystron beam perveance, $K = I\,V^{-3/2}$, is normally used as the measure of space charge forces: the smaller the perveance, the weaker the space charge and consequently the stronger the bunching. High-efficiency klystrons therefore require a low perveance. With the development of the core oscillation method (COM) [1,2], bunching-alignment-collection (BAC) [3], using third harmonic cavity [4,5] and multi-beam klystron [6], the efficiency of klystron can be improved greatly.

The design of klystrons has long been a manual process guided by experience. By now with the study of bunching mechanisms and simulation software, sufficiently rapid simulation method is a good process for klystron design. Generally, in the design of klystron, one use 1D simulation tool to find the high efficiency case and then use 2D or 3D software to examine and simulate the dynamic results.

As the first part of the klystron design, mathematical simulation based on computer programs, is a very troublesome and costly problem, especially for high efficiency klystron design. For example, a seven cavity klystron has six drift tubes, seven frequencies, input Q_e, output Q_e and some Q factor—at last 15 parameters. To reach a maximal efficiency, it is necessary to optimize the design in all parameters, which implies an enormous amount of computation. In this paper genetic algorithm was introduced based on 1D simulation program AJDISK [7]. In the klystron design, we concern the efficiency and the total length both. So Multi-Objective Genetic Algorithm (MOGA) was introduced for optimization and preliminary result will be presented in this paper.

MOGA OPTIMIZATION

GA optimization is a promising technique to find the optimal solution in a multi-dimensional, which is an example of a probabilistic, parallel, black-box search technique. Like many optimization methods, they work from a population of individuals (simulation inputs) and solutions (simulation outputs) characterizing the search space. In the design of klystron, the efficiency and total length both are the optimized objective, so MOGA based on NSGA-II [8] is introduced. NSGA-II has a better sorting algorithm, incorporates elitism and no sharing parameter needs to be chosen a priori, so it is a suitable algorithm as black-box search technique in our case. Once the population in initialized the population is sorted based on non-domination into each front and each individual is assigned rank value. In addition to rank value crowding distance is calculated for each individual. Large average crowding distance will result in better diversity in the population.

In the optimization, we only need to set the population, generation number, variable range and edit the objective function, then the rest work goes to computer. Of course there are some issues should be considered.

Search Space

In the optimization generally there is a total length limit from the construction or some else, so at the population initialization stage, one need to screen the population meet-

* Work supported by NSFC (11705214)
† mengc@ihep.ac.cn

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ing the limit of total length. In the definition objective function stage, one total length cut-off point is defined. Individuals below the cut-off value have their fitness unchanged, but individuals above this point are defined as less fit.

MOGA is intended to target short, efficient klystrons. However, there exists a lot of cases result in a short, very inefficient klystron. This causes the algorithm to waste time on areas of the solution space that are of no interest. So one cut-off efficiency curve is defined, one example is shown in Fig. 1, the cut-off efficiency is changing with generations because the expected efficiency is higher and higher with generations. Individuals above the cut-off efficiency in the efficiency objective have their fitness unchanged, but individuals below this point are defined as less fit. Application of this technique cause the algorithm to ignore the short, inefficient klystrons and increase the search space efficiently.

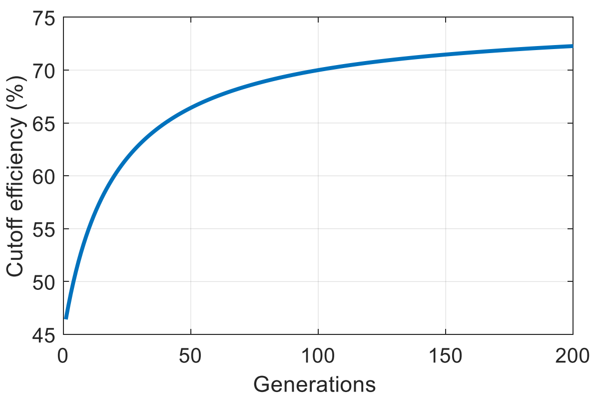

Figure 1: Cut-off efficiency curve.

Reflected Electrons

The reflected electrons may create a feedback mechanism and cause oscillation, which limit output power and efficiency, even can make the klystron cannot work. Here we set the velocity of the slowest electron as a cut-off condition. This value should be set carefully and some experience is need. Here we set the cut-off point to zero that means good population should have no reflected electrons.

Bandwidth

The algorithm calculated the efficiency at the default frequency (f_0). However, most case we need to consider the bandwidth. If individuals can meet all above cut-off condition, then we can calculate the results at the upper (f_+) and lower bandwidth points (f_-). We define the parameter D_{gain} as following:

$$D_{gain} = 2G_{f_0} - G_{f_+} - G_{f_-} \quad . \tag{1}$$

We set the cut-off value of D_{gain} and below this value the fitness will not be unchanged. This cut-off condition can be introduced after some generations to avoid all initial cases be discarded.

OPTIMIZATION TEST

At first we test the 6-cavity klystron at 650 MHz with normal perveance electron gun (K=6.5×10^{-7}, V=81.5 kV, I_0=15.1 A). There are 11 variables: 5 distance variables and 6 frequency variables. The distance range is 0.2 m to 1 m. The third cavity is second harmonic cavity. The total length is composed of the distances and additional 0.2 m. In this case the cut-off length value is 2.2 m, the cut-off efficiency is 55%, and the cut-off gain is 1.8 with ±0.5 MHz bandwidth. The evolution results with 100 generations are shown in Fig. 2. The total length of klystron is in the range from 1.2 m to 2 m, the efficiency is fitted as:

$$\eta(\%) = 79.4 - 17.8(L - 0.2)^{-3} \,. \tag{2}$$

According to the simulation results, the efficiency will be more higher than the fitting curve when the total length is larger than 2 m.

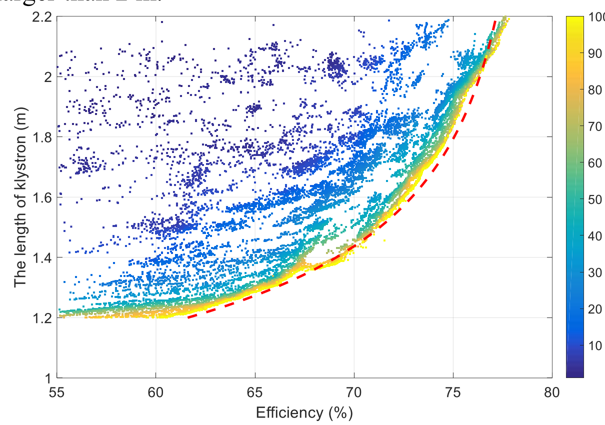

Figure 2: The evolution results for 6-cavity klystron with normal perveance electron gun.

Then we test the 7-cavity klystron at 650 MHz with low perveance electron gun (K=2.5×10^{-7}, V=110 kV, I_0=9.1 A). There are 15 variables: 6 distance variables, 7 frequency variables, input Q_e and output Q_e. The distance range is 0.2 m to 1 m between the second and the fifth cavity in each other and 0.18 m to 1 m for else cavity distance. The third cavity is second harmonic cavity and the fourth cavity is third harmonic cavity. The total length is composed of the distances and additional 0.2 m. In this case the cut-off length value is 3 m, the cut-off efficiency curve is shown in Fig. 1, and the cut-off gain is 2 with ±0.5 MHz bandwidth. The evolution results with 300 generations are shown in Fig. 3. The total length of klystron is in the range from 1.4 m to 2.8 m, the efficiency is fitted as:

$$\eta(\%) = 86.4 - 48.7(L - 0.2)^{-6} \,. \tag{3}$$

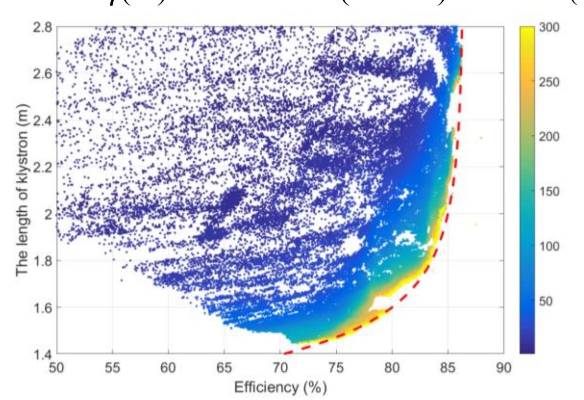

Figure 3: The evolution results for 7-cavity klystron.

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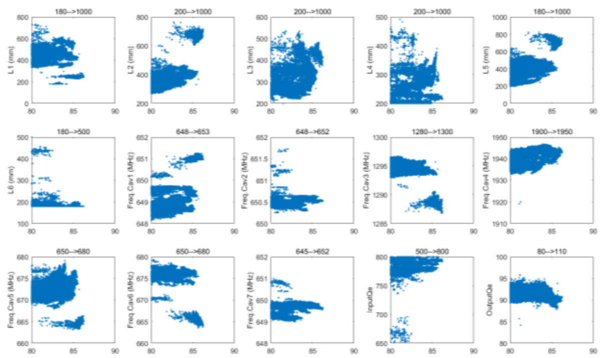

Figure 4: Variables distribution with efficiency larger than 80%.

The efficiency depend on variables are analysed. Figure 4 shows the variables distribution with efficiency larger than 80%. From the results one can get that the distance between the last two cavities is as short as possible to get high efficiency. The frequency of the second cavity is very sensitivity that means frequency error tolerance is small.

We chose one case with efficiency about 85%. The efficiency with input power and the gain with frequency is shown in Fig. 5.

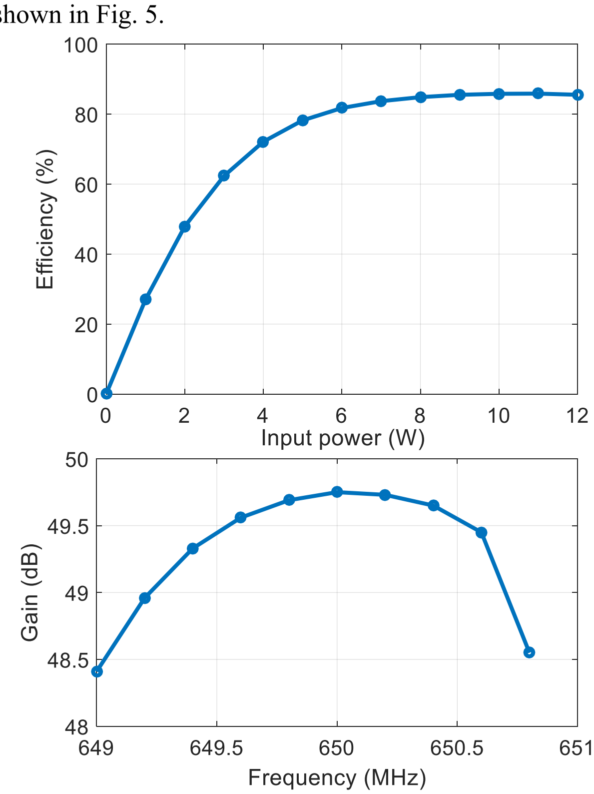

Figure 5: The efficiency Vs. input power (top) and gain Vs. frequency (bottom).

CONCLUSION

High efficiency klystron design is a very important issue and key point in the future accelerators. In this paper the klystron optimization based on 1D AJDISK with MOGA is presented. The optimization of 6-cavtiy klystron and 7-cavity klystron is presented and discussed.

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REFERENCES

[1] A. Yu. Baikov, O. A. Grushina and M. N. Strikhanov, “Simulations of conditions for the maximal efficiency of decimetre-wave klystrons”, *Technical Physics*, vol. 59(3), pp. 421-427, Mar. 2014.

[2] A. Yu. Baikov, C. Marrelli, I. Syratchev, “Toward highpower klystrons with RF power conversion efficiencies on the order of 90%”, *IEEE. Trans. Elec. Dev.*, vol. 62(10), pp. 3406-3412, Oct. 2015.

[3] I. A. Guzilov, “BAC method of increasing the efficiency in klystrons”, in *Proc. 10th Int. Vacuum Elec. Sources Conf. (IVESC ’14)*, Saint Petersburg, Russia, July. 2014.

[4] V. Hill, G. Burt, D. Constable, C. Lingwood, C. Marrelli, I. Syratchev, ‘Particle-in-cell simulation of second and third harmonic cavity klystron’, in *Proc. 18th Vacuum Electronics Conference (IVEC2017)*, London, England, April. 2017.

[5] D. A. Constable *et al.*, “HIGH EFFICIENCY KLYSTRON DEVELOPMENT FOR PARTICLE ACCELERATORS”, in *Proc. eeFACT2016*, Daresbury, UK, 2016.

[6] Z. N. Liu *et al.*, “DESIGN OF A C-BAND HIGH-EFFICIENCY MULTI-BEAM KLYSTRON”, in *Proc. IPAC2017*, Copenhagen, Denmark, May 2017.

[7] A. J. Jensen et al., “Developing sheet beam klystron simulation capability in AJDISK”, IEEE Trans. Elec. Dev., vol. 61(6), pp. 1666-1671, Jan. 2014.

[8] Kalyanmoy Deb et al., “A Fast Elitist Multi-objective Genetic Algorithm: NSGA-II”, IEEE Transactions on Evolutionary Computation, Vol. 6(2), pp.182 -197, April 2002.