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Design Consideration of 650-MHz Circular Electron–Positron Collider Klystron and Simulation of Its Beam Tester *

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We present the first phase R&D for the 800 kW cw, 650 MHz klystron for the future circular electron–positron collider (CEPC) project in China. The CEPC requires 192 klystrons and it is desired to be designed in the Institute of High Energy Physics, CAS, and manufactured domestically. Therefore, we present the manufacturing schedule of this project; the three-stage development from the beam test tube to the klystron having a high efficiency structure. Design of the beam test tube that comprises electron gun and collector is presented. First, gun simulation having a modulating anode is performed using DGUN software. The uniform beam trajectories with a beam perveance of 0.64 $\mu A/V^{3/2}$ are simulated. We employ a Ba-dispenser cathode of radius 35 mm with $\phi 10$ hole at the center and obtain a current density on cathode less than 0.45 A/cm^2. The beam trajectories are also simulated over beam test tube of length about 2 m with a magnetic field of 213 Gauss. Thermal analysis of the collector is performed using the ANSIS-CFX code and hence the cooling structure is determined. Mechanical design is almost carried out and it is in manufacturing stage.

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The interest for the large electron–positron colliders such as proposed ILC and FCC has been increased due to many exciting discoveries in particle physics. Recently the future plan of a circular electron–positron collider (CEPC) was proposed by the Institute of High Energy Physics (IHEP), CAS, in China. For the success of these linear colliders, one of the key points is the efficient and reliable generation of rf power. The klystron is the key component of rf power for such a project. For the CEPC project, many high-power klystrons with frequency of 650 MHz and output power of 800 kW are required.[1] In this project, acquisition of high efficiency of the klystron is the key challenge. Since this is the first large project in China, it is desired that the IHEP would design the klystron and manufacture it domestically. Our first goal is to achieve the efficiency of klystron higher than 70%. A general plan is presented in Ref. [2]. We are planning to start from a single beam klystron. As the choice of an optimized perveance is deeply related to the klystron efficiency, thus its value is tentatively chosen to be 0.64 $\mu A/V^{3/2}$ compromising the applied voltage and possible efficiency as predicted by the empirical formula.[3] The development of klystron is to be performed by several experts in IHEP and will be manufactured in collaboration with a domestic company. Preliminary design of this tube is presented that includes the plan of the project, design of the beam tester comprising an electron gun, the focusing magnet and the collector. The interaction region design was presented in Ref. [4].

There are some difficulties for the development of klystrons in China. Though designing and simulation of the klystron are basically similar, special skills, infrastructures and experiences are required for manufacturing such a large klystron as desired in accelerator physics. According to the tentative design, the whole klystron from the gun to the collector would be about 4.5 m in length. If the klystron could be manufactured in an industrial company of China in partnership with IHEP, a large brazing furnace and vacuum baking furnace are required, and so far such an infrastructure is not available. Therefore we need the collaborative work to introduce these manufacturing devices. Processing and evaluation of the tube also require experience. Since design and simulation are insufficient and immature, we need to proceed gradually. On the other hand, to save money and time, a suitable choice is a demountable structure as illustrated in Fig. 1. The first step is to manufacture a beam tester to verify gun and collector design[5,6] and hence the gun design and collector capability are evaluated.

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The next step is to add the interaction region part that comprises the cavities based on the classical efficiency tuning design. The one-dimensional disk model simulation predicted the klystron efficiency of about 74%.[4] Finally the drift tube section is replaced with cavity layout of the higher efficiency design which is recently developed using the concept of bunch core oscillation and the BAC technology.[7,8] So, we can try to check the design exactness. However, full power rating evaluation is not always required. Pulse operation can confirm the part of this design feasibility.

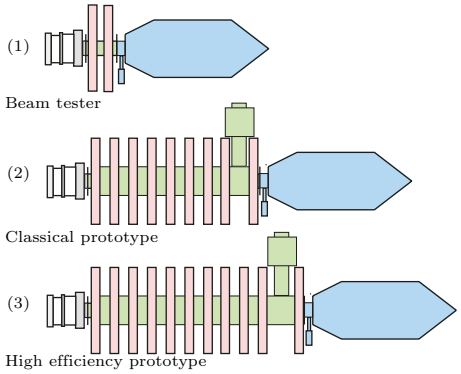

Fig. 1. Klystron development plan. These structures are demountable and reusable by taking apart the gun and collector.

In cw operation, many parameters should be lower than the pulsed case, such as an applied voltage and a cathode emission as known empirically in Ref. [9]. We started using a modulating anode (MA) gun structure for CEPC klystron to evaluate various parameters' feasibilities. Therefore, the CEPC klystron with the MA gun is expected to investigate the design ambiguity. In MA klystron, a current is determined by the voltage between an MA and a cathode (gun perveance), and a tube perveance is derived by the voltage between an anode and a cathode (a beam perveance). Therefore the MA gun is said to be one of variable perveance gun. Using the MA klystron, we investigate the following items: (1) perveance simulated by the various gun codes has some errors and the MA gun can correct this ambiguity. In fact, empirically EGUN and DGUN predict the perveance of about 5% lower. Furthermore, the gun assembly expands thermally when it operates and if we do not know this variation exactly, an operating perveance deviates from the designed value. We may make this point clear using the MA gun. (2) Availability for a maximum electric field and a current density in cw operation should be cleared by comparing a pulse voltage with a cw voltage on the modulating anode. (3) Concerning the heating capability of collector and rf window, it is useful to evaluate them by changing the pulse duty.

Figure 2(a) shows the perveance with a function of an MA voltage using the gun layout as shown in Fig. 4(a). If the manufactured gun has different performances, it is possible to obtain the design value by slight change of MA voltage because gun perveance is more sensitive to MA voltage. Figure 2(b) shows the relation between perveance and MA distance from the cathode. This situation indicates the possibility of adjusting the perveance if it deviates from expected value between the manufactured dimensions (cold dimension) and operating dimension (hot dimension). At the same time, we can estimate the difference between the model dimension and the real manufactured dimension, by investigating this correction factor. Rectangular box in Fig. 2(b) indicates that the possible region of ambiguity comes from the hot-cold dimension difference.

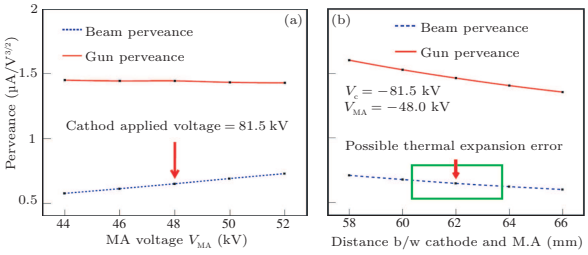

Fig. 2. The perveance as a function of an MA voltage. If the manufactured gun has different performances, it is possible to obtain the design value by slight change of MA voltage (a), and the relation between perveance and MA distance from the cathode (b).

For designing the high-power cw klystron, temperature rise due to the power dissipation in the tube including in the collector, rf window and other internal structure possibly induces various failures. We introduce the appropriate criterion, while the direct experimental confirmation is desired. If MA klystron is operated in the pulse mode, we can experimentally check the parameter which is linked with the power by changing the pulse duty. Conceptual pulse operation in the MA gun is shown in Fig. 3(a). Figures 3(b) and 3(c) show the conceptual testing setups in pulse and usual modes. The pulse modulator as shown in Fig. 3(b) does not need power supply for its operation, instead we just need to apply the potential and operate in various duty rates. Required power is all supplied by the dc power supply.

The MA gun with the Pierce gun design[10] is achieved by using the various simulation codes such as DGUN,[11] EGUN,[12] and CST.[13] Main work was carried out by DGUN and then reliability of the results was checked with other codes. The parameters of the electron gun with spherical cathode are summarized in Table 1. We designed the electron gun with beam of current 15.1 A operating at voltage 81.5 kV, which are the requirements of the rf design.[4] For cathode loading we chose the conservative value, a cathode radius of 35 mm having a current density less than 0.45 A/cm^2. There are examples of Toshiba 1.2 MW cw klystron and SLAC BFK of 1.25 MW cw klystron.

Both have used 70 mm diameter cathodes with total current of 21–26 A corresponding to current density 0.55–0.67 A/cm^2. Both used the similar M-type dispenser cathodes and their lifetimes are more than 50000 h.[14,15] A Ba-dispenser cathode having a ϕ10 hole at the center is used to avoid the possible damage induced by the ion bombardment which is harmful in the cw operation. This effect was known but recently such emission slump by ion bombardment was also clearly simulated.[16] Since we employ the demountable structure and proceed by possibly reusing gun and collector, residual gases tend to increase, and it may be more harmful to the cathode operated in cw than the one operated in pulse operation. This makes the choice of cathode with a hole adequate. The focusing magnetic field and electric field are simulated by the POISSON code.[17]

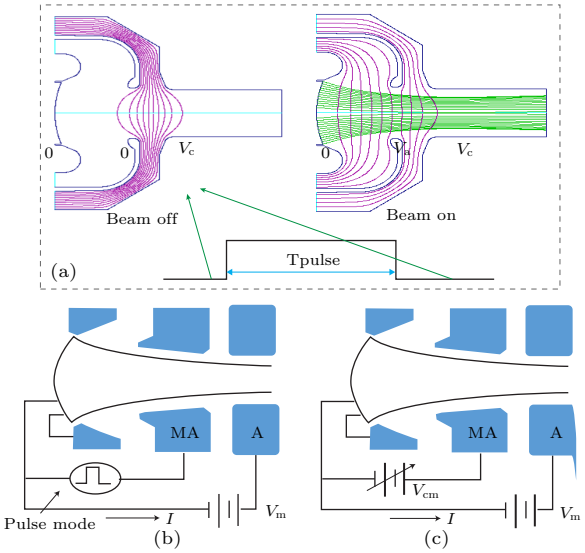

Fig. 3. Concept for pulse operation of modulating anode gun. (a) The relationship with the beam and pulse applied voltage. (b) The voltage feeding diagram for pulse operation. (c) The usual MA gun operation diagram. By using this method, it is possible for klystron to be performed from a small duty of pulse to cw operation.

Table 1. Calculated parameters of the CEPC Gun.

Applied voltage on cathode	kV	−81.5
Applied voltage on MA	kV	−48.0
Beam waste diameter	mm	35.6
Beam/gun perveance	μA/V$^{3/2}$	0.64/1.45
Max field on BFE/MA	kV/mm	3.94/2.51
Av. cathode density (given)	A/cm^2	0.45
Cathode uniformity		1.24

Figure 4 illustrates the simulation results of the MA gun using the DGUN code along with the maximum field on the electrode and the current density on the cathode. The ratio of a beam radius to a drift tube radius is 0.64 and is the same as the required value from the rf simulation. From this design, a cathode uniformity of 1.24 is obtained. Since the gun is subjected to high electric field where the breakdown and arcing phenomena tends to occur, electric field on the electrode and HV ceramic seal are set under the allowed value as given in Ref. [9]. A simulation and a design of HV gun envelope of CEPC klystron has been checked by the POISSON code. The obtained maximum electric field on the beam focusing electrode, modulating anode electrode and anode electrode are 3.90 kV/mm, 2.51 kV/mm and 1.77 kV/mm, respectively, which are all less than the acceptable experimental values of electric fields of starting breakdown in cw.

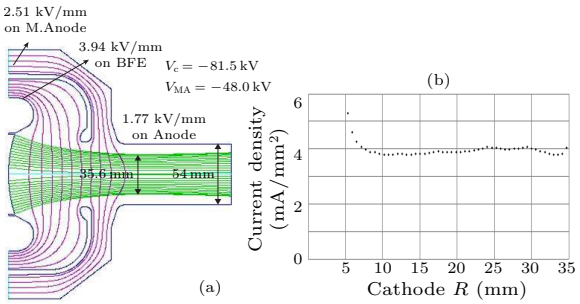

Fig. 4. Simulation results for MA gun of 800 kW CEPC klystron is shown. (a) The beam trajectory and maximum electric field on electrode, and (b) the current density on cathode.

HV ceramic seal design is important for reliable operation of electron gun. It relates an outer layout of a socket tank with a magnet design (existence of extra coil in gun region). Therefore, a consistent design is required. We carefully chose the design with no extra coil near the gun region in the oil tank. Average (maximum) field on the ceramic was 0.32 (0.52) kV/mm (cathode to MA) and 0.25 (0.47) kV/mm (MA to anode) along the length (about 150 mm) of ceramic.

Beam optics over the structure along with the magnetic field is simulated by using EGUN and DGUN. We assume the semi-confined flow of magnetic field to be 26 Gauss at the cathode and 180 Gauss on the drift tube region (Brillouin field of 111 Gauss). For this simulation, it is difficult to introduce the proper beam forming magnetic field near the cathode because there is not enough space to put the coil to adjust this beam-forming field except inside of an oil tank. Finally we solved this problem by introducing the pole piece of the magnet very near to the anode structure. Instead we cannot obtain perfect matching and there is small scalloping in the interaction region. When beam trajectory was simulated for full length of structure including the cavity section and collector, 100% beam transmission has been established as shown in Fig. 6, and resultant scalloping is not a serious problem. To check the results, simulations of the gun including the magnetic field are performed using different codes, and all the results show 100% beam transmission. For the ripple rate, there are discrepancies of about 10–20% among the codes.

Figure 5 shows the simulation results of the beam

tester and the whole klystron structure using the DGUN code. In this case, the cathode has a $\phi 10$ hole at the center and trajectories show the annular shape which has an area with no electron near the center. For the collector design, we assumed the capability of full beam energy dissipation and chose the design criterion for the surface dissipation power density as to be conservative value of 200 W/cm^2 initially. First, analysis was performed using the universal spread beam trajectory and analytical formula of collector power dissipation. Maximum dissipation appears at the location where the beam rim hits the wall and the radius of the collector changes. A choice of surface dissipation power density less than 200 W/cm^2 results in a large collector having the large bore diameter and a long size. Then we changed the collector dissipation to 500 W/cm^2, which is also an acceptable value.[18] To add magnetic field is a better choice to cool the collector. We can see the beam divergence difference with and without magnetic field in Figs. 5(a) and 5(b), respectively. Short magnetic coil with stronger magnetic field of 213 Gauss is added for quick beam divergence of beam tester having a reduced sized collector, i.e., shorter than 2 m as shown in Fig. 5(b). The total layout of the CEPC klystron from the gun, cavity section and collector is shown with the beam trajectories in Fig. 5(c). The whole length of the CEPC klystron layout with reduced size of collector is reached up to about 4 m.

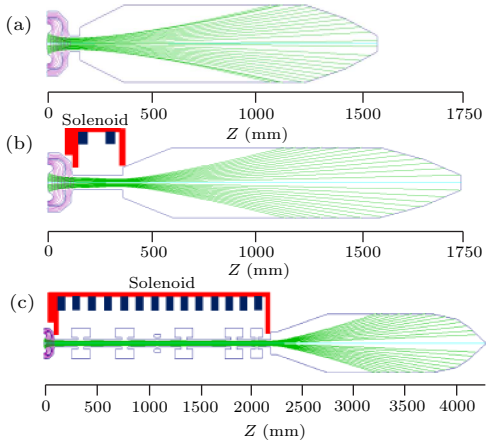

Fig. 5. (a) Beam tester without coils. (b) Beam tester with coils. (c) The total CEPC klystron layout.

Thermal design of the collector is performed using the ANSYS-CFX code[19] under these conditions. All beam power of 1.2 MW is dissipated in the collector, forced water cooling is employed, and the maximum power dissipation density is chosen to be 500 W/cm^2. Outer surface of the collector has a grooved structure, where cooling water is forced to flow with a high Reynolds number. Employing a fluid flow and a coupled heat transfer simulation, the groove number was optimized by keeping the water flow rate constant. In this case, the water flow velocity was chosen to be 4 m/s. So far, the analysis involving the vapor cooling and related flow has not been performed. The groove dimension (the width to height ratio) of 1:2 was employed by compromising the cooling efficiency and geometrical factors. Through simulation, we obtained the CFX result for the maximum temperature inside the collector with a function of a groove number, and the same result was also found by using water flow rate function. The 180 grooves and 1400 L/min water flow rate were finally chosen by compromising the fin size limit and water in the case of a large collator case. The whole collector structure with the grooves is shown in Fig. 6(a). The CFX result was checked by ANSYS-Multiphysics as shown in Fig. 6(b), the results have 3% discrepancy for analytic calculation for coefficient of wall heat transfer on the interface of water–copper, which are slightly lower than CFX's prediction in Fig. 6(c). Due to the current manufacturing limitation of furnace in China, we made re-analysis in which the whole length is shorter than 2 m as shown in Fig. 5(b).

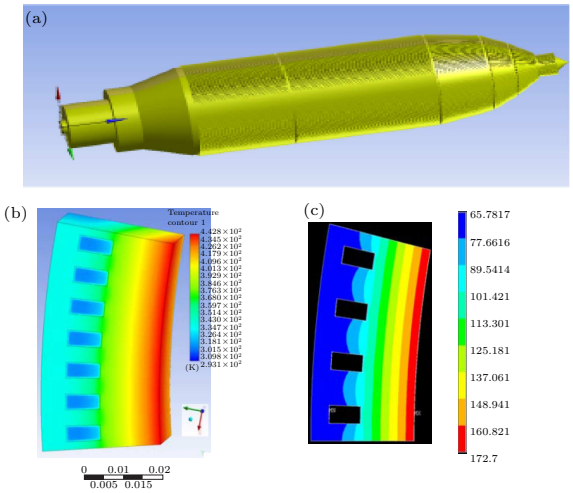

Fig. 6. (a) The whole collector structure with grooves, and contours of temperature in (b) ANSYS/CFX and (c) ANSYS/Multiphysics.

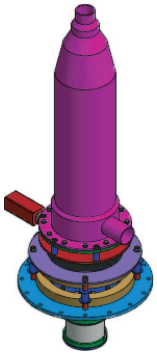

Fig. 7. Mechanical design of the beam tester.

After finishing the simulation, we started to make the mechanical drawing of the beam tester. We have already procured the cathode. Since the collector is

large, it is divided into four parts which are then brazed using class 1 oxygen free copper. In the collector groove, we made thermocouple installation holes each 250 mm apart, to measure the temperature rise distribution of the collector because of operation of the beam tester. Mechanical design of the electron gun requires detailed procedures to assemble and to align every component in the assembling stage. Short drift tube section having the evacuation port is welded to the gun assembly and the collector. The collector has an integrated ion pump, which is reused along with the collector. In Fig. 7, the dimensional beam tester structure drawn by the Autodesk Inventor is shown. Currently maximum available baking furnace used for the beam tester is about 2 m long, while we are proposing to a collaborative company in China to invest on a larger baking furnace to be installed with full length klystron. We expect to finish manufacture of the beam tester within 3–4 month, since IHEP has a test facility of ADS which processes the 324-MHz MA klystron that can be used to process the beam tester.

In summary, a plan of manufacturing the CEPC 650-MHz, 800-kW cw klystrons and the design of the beam tester have been described. The electron gun with the modulating anode has been designed. Using the computer simulation tools such as DGUN, EGUN and CST, the design of the electron gun and beam optics for the whole structure have been achieved successfully. It is shown that the perveance adjustment is possible by changing the modulating anode voltage. This enables us to check the perveance ambiguity and dimension difference of gun electrodes. It is also shown that pulse operation helps us to evaluate the thermal rating of the collector. Collector design for cw operation is calculated using the ANSYS-CFX code and the cooling structure is successfully determined. We will start manufacturing a beam tester within 3–4 months to evaluate the basic parameters. The next step will be to introduce the larger furnace and to replace the interaction region with the current short drift tube.

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