Design Study of X-band High Efficiency Klystrons for CLIC

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Abstract: *The design of two X-band high efficiency (HE) Klystrons are presented in this paper. Based on Core Oscillation Method (COM) and coupled-cell output structure topology, 8MW Klystron for Xbox test stand can yield 58% output efficiency with beam perveance of 1.6uP. Scaling and post-optimization method is used for 50MW Klystron for CLIC accelerating structures design, which can provide 65% output efficiency with beam perveance of 0.75 uP. The peak electric field is lower than 100kV/mm for both cases, which is purposely optimized to avoid RF breakdown. The parameter optimization is done with KlyC1.5D simulation and results are verified by CST PIC simulations.*

Keywords: High efficiency Klystrons; Core-oscillation method; Coupled-cell structures

Introduction

The High Efficiency (HE) International Klystron Activity was initialed at CERN in 2014. Since then, the different klystron bunching technologies such as COM, BAC and CSM have been put forward and evaluated for the application to the large-scale scientific projects such as CLIC and FCC [1,2,3]. To facilitate the fast and accurate study and optimization of HE klystrons, large signal code KlyC has been developed at CERN [4]. The new HE, high power X-band Klystrons for CLIC high gradient program have been designed and communicated to the industry. In these tubes, the large ratio between tunnel aperture and microwave wavelength has to be adopted in order to accommodate high beam current. That makes the use of harmonic cavities (BAC and CSM methods) impractical due to their small transverse dimension. COM bunching method is the natural choice for X-band High efficiency high power Klystron, in which the prolonged bunching circuit length could be mitigated due to the high frequency. In such tubes, the coupled-cell output structure is also a mandatory choice because of the large beam tunnel that reduces the effective impedance $R/Q*|M|^2$. The coupled-mode model for such RF circuits has been implemented into KlyC to facilitate the optimization and analysis [5]. RF circuit of the 8MW X-band Klystron was optimized in KlyC and further benchmarked using CST PIC simulations. In these simulations, the 58% efficiency has been achieved for the tube with large ($1.6\mu AxV^{-1.5}$) beam perveance [6]. This retrofit design employed the optics of existing 6MW Canon X-band tube and is considered as a prominent upgrade, when compared with available commercial product [7]. The bunching circuit for the 50MW X-band Klystron was scaled from the 8MW Klystron, using the General Parametric Scaling procedure developed at CERN [8]. Combined with new design of the 6-cell tapered output structure, such a Klystron showed extraction efficiency of ~65% in the PIC simulation.

8MW Klystron for Xbox test stand

Beam voltage (154kV) and current (90A) are fixed as in original design to enable direct replacement of the tubes and to preserve the design of the cathode. Initially, RF bunching circuit and the multi-cell output coupler been designed separately. At this stage, the artificial output cavity with large beam coupling (|M|=0.9) has been used to optimize the frequencies and positions in the 8-cavities COM bunching circuit. The saturated efficiency of 65% with artificial output cavity has been achieved. The coupled cell output structures alone were optimized in KlyC using the internal module with idealized pre-bunched beam option. Frequencies, locations, external quality factors and number of the cells were all optimized to enhance the efficiency whilst keeping the maximum surface field in a coupler at a reasonable level (<100mV/m). Finally, the 4-cell output structure was selected with output efficiency of 61% for the idealized bunched beam. Combining the COM bunching circuit and 4-cell output structure, the whole tube was re-optimized in KlyC, predicting 60% efficiency with maximum electric surface field of 70 MV/m. The KlyC design was next benchmarked in CST PIC simulation, which showed the efficiency of 58% and maximum electric field of 82 kV/mm. The beam dynamics in the proximity of the output structure are shown in Fig. 1. In these simulations, the magnetic solenoidal filed was chosen to be 2.5 times of Brillouin magnetic field. The total length of RF circuit is about 300 mm.

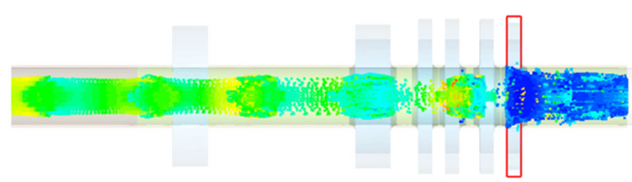

Figure 1. Beam dynamics in 8MW X-band HE Klystron.

Field distribution in one RF frame is plot in Fig. 2. It is worth to mention that the field pattern in output cells is a mixture of the traveling wave and standing wave. The -1dB bandwidth in this Klystron is about 60MHz.

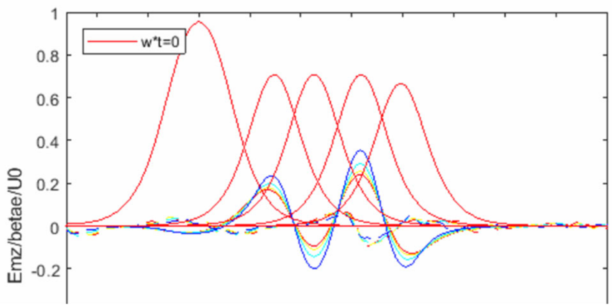

Figure 2. Normalized field distribution in output structures by KlyC.

Next, the collector, magnetic system and output coupler 3D topology have adjusted to fit the klystron RF circuit. The average power dissipation density in collector wall is below 0.05kW/cm^2. The all-in-one simulation results are shown in Fig. 3, in which the electron beam is generated and convergent by electron gun, bunched and power-extracted by RF circuit and finally deposited on the collector wall. No reflected electrons have been observed.

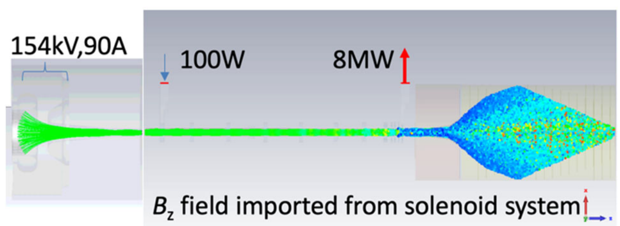

Figure 3. All-in-one PIC simulation for 8MW Klystron

50MW Klystron for CLIC main-accelerators

Parametric scaling method was used to scale the COM circuit of 8MW Klystron to the 50MW Klystron. The new coupled-cell output coupler was specifically designed for this high-power Klystrons to accommodate even higher beam voltage and current. Tapered 6-cell output coupler was finally adopted to efficiently extract the power from bunched beam and to avoid the beam interception. For this coupler, KlyC showed that extraction efficiency can be as high as 70% with maximum electric field of 90kV/mm. The whole tube simulation in KlyC showed efficiency of 68% with maximum surface electric field of 85MV/m. The phase space diagram in output section is shown in Fig. 4.

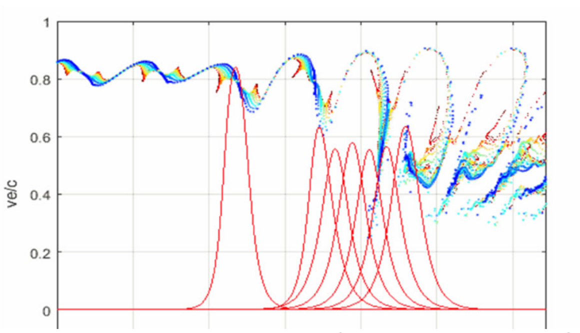

Figure 4. Phase space diagram for 50MW tube by KlyC.

The preliminary CST PIC simulations confirmed that the output efficiency is of the order of 65% and maximum electric field in the last cell is about 100 MV/m. Further optimization to shortening the bunching circuit is undergoing for both 8MW and 50MW X-band Klystrons.

Conclusion

The 8MW and 50MW X-band high efficiency Klystron have been optimized and designed by CERN home-made code KlyC and benchmarked with CST PIC simulation. COM method for bunch circuit and couple-cell structure for output cavity are utilized for both Klystrons to achieve high efficiency while keeping a reasonable peak electric field. Both of the Klystrons are considered to be prototyped in the near future.

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