# Experimental Demonstration of a W-Band Sheet Beam Klystron

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**Abstract:** *As an important proof experiment for further developing a compact sheet beam klystron with the multi-cavity, multi-gap interaction circuit, we have designed and built a uniform magnetic focusing prototype tube, where a simulated 55 kV, 2.2 A sheet beam transports an interaction length of about 100 mm. A water-cooled solenoid is used to produce the field with a maximum value of 4,000 Gauss. To improve the characteristic impedance and efficiency, the HF circuit is composed of four multi-gap cavities, and each cavity includes a multi-layered membrane to finely tune its working frequency. Meanwhile, to simplify the structure, a single-port scheme is applied in the input and output cavities, the adverse influence of which on the field uniformity is reduced to a minimum level. The latest hot test shows the maximum output power attains to 2.57 kW at 95.025 GHz and the bandwidth is about 100 MHz when the output is over 1 kW. The self-oscillation has not been observed in this experiment.*

**Keywords:** W-band; sheet beam klystron; solenoidally focusing; electron optics; multi-gap cavity; hot test.

## Introduction

In the narrow bandwidth, high power, millimeter-wave applications, such as imaging, communication and accelerator driver, sheet beam klystrons (SBK) are the key candidate for its distinct advantage in power handling capacity, which is owed to its large tunnel size. With the increase of the beam power and the heat dissipation, SBKs' peak and/or averaged powers will conservatively be one magnitude larger than the situation in the traditional cylindrical scheme. In the latter one, to keep a reasonable electronic efficiency, the round tunnel radius is roughly one tenth of the operation wavelength. Contrarily, the rectangular tunnel in SBKs is theoretically unrestricted in the transverse dimension. However, in practical devices, an oversized aspect ratio of the beam and tunnel's section should be carefully evaluated for depressing high order non-working modes.

A three-cavity narrow band SBK has been reported by Naval Research Laboratory, where all the cavities have the same structure and the intermediate cavity is tuned to a slightly higher frequency. In this work, using a long enough drift distance that can contain a more complicated circuit, we utilize four stagger-tuning multi-gap cavities to further check the interaction stability, which is vital to expand the bandwidth in the successive design. The multi-layered elastic membrane is brazed on the cavity and serves as a movable side wall. Until now, two prototype tubes have been built. The relevant researches began at the end of 2015. They were separately hot-tested on January 2018 and December 2019. The following sections will briefly describe the design, manufacturing, and experiments.

## Electron Optics System

An elliptical shape cylindrical cathode is used to produce the required sheet beam with the cross-section of 6 mm × 0.5 mm. The compression ratio in the narrow dimension is about 8:1. The M-type impregnated cathode is chosen and its averaged surface current density is about 12.2 A/cm$^2$. In the electrostatic state, the electron gun perveance is 0.178 μp and the beam throw is 18 mm. Figure 1 is the complete electron optics model including the external solenoid. The bore diameter of the solenoid attains to 115 mm, which is large enough to insert an experimental tube even if the tuning apparatus is installed. There are three separate water-cooled coils in the solenoid inner space, and, in order to optimize the magnetic field transition in the beam injection region, a reverse coil is mounted on the pole piece plane. The excited maximum field can reach 0.4 T. Figure 2 shows the beam can smoothly pass through the tunnel of about 100 mm with a nearly constant wide size. In the experiments, the coils' currents can be independently changed to enhance the interaction under the condition of sustaining a favorable transmission.

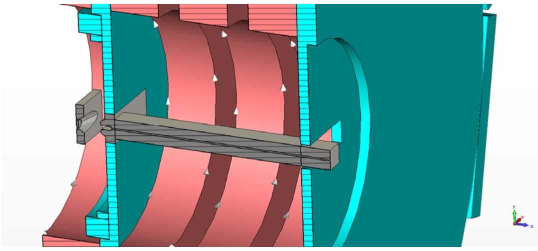

**Figure 1.** The electron optics model with external solenoid.

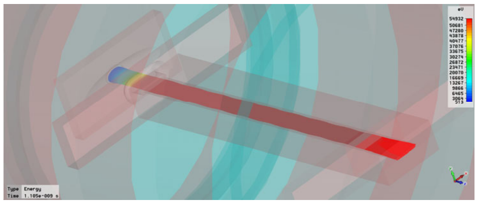

**Figure 2.** The simulated 3D beam trajectories.

## High Frequency System

In SBKs, to better match the sheet beam, the barbell-like cavity is used as the HF circuit unit. When operating at W-band, the single gap barbell cavity just provides a small characteristic impedance of 10-20 Ω. This drawback can be compensated by using the multi-gap cavity, which has high impedance and coupling and will be helpful for improving the

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This research was sponsored by the National Natural Science Foundation of China (Contract No. 61671431).

breakdown threshold and the power capacity. Through carefully optimizing the multi-cavity, multi-gap circuit parameters, the power bandwidth product in such a device can also be obviously enhanced. The HF circuit is composed of a triple-gap input cavity, two triple-gap bunching cavities and a five-gap output cavity, and all of them choose 2π mode as the working one. For the output cavity, a smaller gap period of 1.9π is adopted to further improve the energy extraction efficiency. Due to the same reason, the distance between the output cavity and the penultimate one is observably shortened. To check the tuning effect, the simulation exhibits the influence of the unilateral wall, that locates in the transverse dimension relative to the beam translation, on the output cavity, which corresponds to the frequency decrease of 324 MHz and the external quality factor increase of 110.8, when the side wall moves outwards 0.25 mm. Figure 3 demonstrates a typical beam bunching state in the interaction circuit.

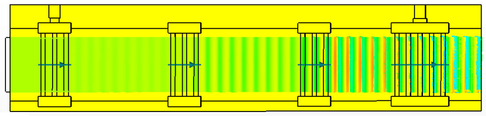

**Figure 3.** The typical beam bunching state in the circuit.

In order to reflect the measured cavity intrinsic quality factor of about 910, the oxide-free copper conductivity intentionally takes a lower value of $2.0\times10^7$ s/m in the beam-wave interaction calculations. In the other hand, a limited uniform magnetic field is used by considering the user-defined beam is directly injected. According to the PIC simulations, when a drive power of 18 W at 94.5 GHz is introduced, the output power can reach 4.98 kW with the gain of 24.4 dB, where a 55 kV, 2.2 A electron beam passes through the 8 mm × 0.7 mm tunnel.

## Manufacture and Test

The cathode and focusing electrode are manufactured and assembled with high precision. The extension lengths of these two electrodes are measured at the working temperature, and these data are used to amend the design values during the assembling phase. In the gun, with the aim of improving the beam quality, the focusing electrode is independently applied a potential being several hundred volts lower than the cathode's one. To ease the fabrication, the HF circuit is halved as two same parts along the symmetrical plane parallel to the beam transverse direction. The simulation shows the cavity frequency is very sensitive to the gap height, for instance, about 500 MHz per 10 μm in the triple-gap case. Hence, a membrane must be set to compensate the cavity frequency offset besides rigorously controlling the structure sizes through precision CNC machining. To simplify the structure and leave space to install the tuning apparatus, the input and output cavities use the single-port scheme to connect with the waveguide, and they have been optimized to minimize the adverse influence on the cavity field uniformity. The intermediate cavities' coldtest is very important. The first thing is to discriminate the working mode from the peaks on the measured S-parameter curve by using the perturbation method, and then it will be possible to adjust the desired mode frequency by moving the membrane. Figure 4 is the structural section of the prototype tube and its photo after baking.

The W-band SBK prototype tube in test is shown in Figure 5, and it is driven by an extended interaction klystron with the output capacity of over 500 W. The applied high voltage square wave is with the amplitude 57 kV, the repetition rate 25 Hz, and the pulse width 10 μs. The measured beam transmission is over 90% in the HF state. In the hot test, the maximum output power of 2.57 kW is obtained at the frequency of 95.025 GHz with the gain of near 20 dB and the efficiency of about 2.2%. The bandwidth can reach about 100 MHz for the output being over 1 kW. During the test, the indicator power is stable and the self-oscillation has not been observed. Here, the weaker interaction is due to a larger tunnel height in real structure. The working frequency change is attributed to the cavity tuning during the coldtest phase.

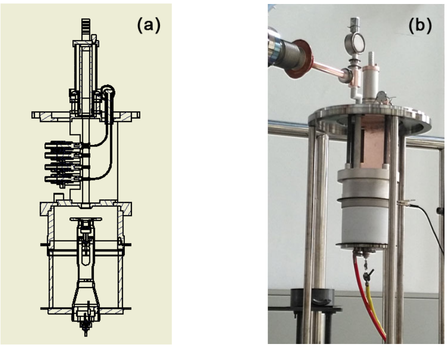

**Figure 4.** The section of the prototype tube (a) and its photo after baking (b).

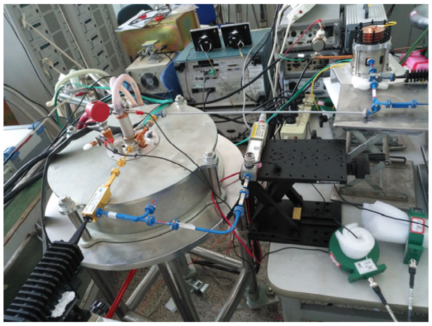

**Figure 5.** The W-band SBK prototype in test.

## Summary

For further validating the multi-cavity, multi-gap circuit, we have built and tested W-band sheet beam klystron prototype tubes. Through this work, the HF circuit manufacturing, the cavity coldtest, and the frequency tuning techniques have been proof-tested. It should be noted that the electric parameters and the structure of the SBKs are not optimal, which unavoidably restricts the device performance. On this basis, a newly designed W-band SBK will be developed in future.

## References

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