# Novel Sawtooth Structure Loading to Mitigate Mode Competition in a 346 GHz Backward Wave Oscillator

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**Abstract:** *A novel approach to mitigate mode competition and improve stability in a 346 GHz Backward Wave Oscillator (BWO) by loading a copper sawtooth slow wave structure (SWS) is proposed. The effects of mode competition, and the sawtooth structure loading effects are discussed. CST simulation has been used to verify the analysis and test of the stability of those circuits.*

**Keywords:** backward wave oscillator; sawtooth structure; mode competition; slow wave structure

## Introduction

Backward wave oscillators (BWOs) are vacuum electron devices (VEDs) that can produce a comparatively high-power RF signal, which can be used as a frequency tunable power source [1] for applications including biomedical diagnostics and spectroscopy [2]. This paper discusses a double corrugated waveguide (DCW) [1] BWO high-frequency circuit, which has been designed and simulated to interact with a 22 kV, 30 mA pencil electron beam to produce 1 W of continuous wave (CW) output power at 346 GHz. The BWO is intended to serve as a local oscillator in an array of subharmonic mixers to study anomalous transport on the National Spherical Torus Experiment Upgrade (NSTX-U) [3]. As an oscillator, a BWO produces RF signals from white noise, but have been known to have issues with stability due to mode competition [4]. Traditionally, these instabilities would be mitigated by inserting lossy material to attenuate the competing modes, but it would also adversely affect the operating mode as well, leading to reduced output power [5]. Here, we propose a novel approach by loading a sawtooth structure of copper material into the BWO, which will only affect the dispersion characteristics of the higher-order, competition mode, thereby effectively mitigating mode competition, without altering the operating mode significantly.

## BWO Instability Analysis

Mode competition occurs when both the operating and parasitic modes are excited in an interaction circuit, and the adverse bunching of the electron beam by the parasitic mode reduces the transfer of energy to the operating mode [6]. Fig. 1 shows the unloaded BWO circuit and the dispersion diagram. Point A (~346 GHz) depicts the intersection with the 22 kV beam and the backward wave region (n = -1) of the operating mode. Points B (~ 390 GHz) and C (~700 GHz) are two other intersection points that may cause higher-order mode parasitic oscillations; however, the start-oscillation conditions must be satisfied to excite these higher-order modes.

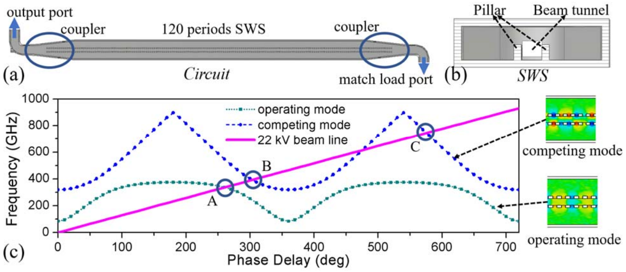

**Figure 1.** 140 period unloaded BWO: (a) top cross-sectional view (b) front-cross-sectional view (c) dispersion diagram.

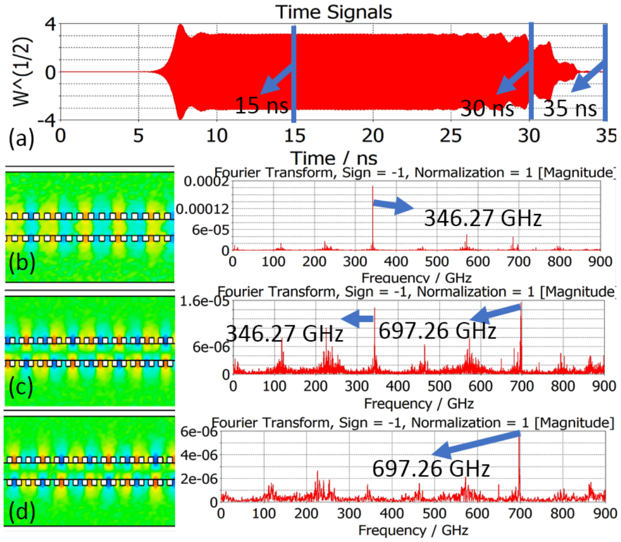

**Figure 2.** Output port signal of unloaded BWO. Ez field distribution (left) and Fourier spectrum (right) for (b) 15 ns (c) 30 ns (d) 35 ns.

Fig. 2 shows the CST® particle-in-cell (PIC) output port signal of the unloaded BWO. It can be seen that instabilities start to occur around 24 ns. To further study the instability, an analysis of Ez and the Fourier spectrum is carried out when the output is temporaly stable at 15 ns, when there are dense instabilities at 30 ns, and when the output is terminated at 35 ns. The Ez distributions are different at each of these three times. Also, at 15 ns, there is one distinct peak in the Fourier spectrum, which is the operating mode (346.27 GHz). As time progresses to 30 ns, a higher-order mode peak (697.26 GHz) appears, and at 35 ns, only the higher-order mode is apparent. This analysis shows that as time elapses, two modes are excited, which compete with each other. Eventually, the higher-order mode dominates, thereby reducing the interaction between the operating mode and the beam and, thus, reduces the output signal to zero. The relevant culprit for the mode competition is the couplers. The output port coupler is optimized to couple out the energy of the operating mode; therefore, the excited higher-order mode would be trapped within the SWS, and, as time progresses, the trapped higher-order mode will accumulate to a sufficient level to create instabilities.

## Copper Material Sawtooth Structure to mitigate mode competition effects

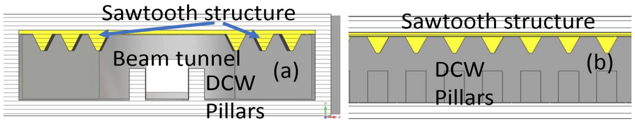

**Figure 3.** 140 period Loaded BWO (a) Front cross section (b) side cross section.

The loaded BWO presented in this paper can be seen in Fig. 3. The function of the sawtooth structure is to suppress the parasitic oscillation of the higher-order mode by altering the higher-order mode dispersion curve without affecting the operating mode dispersion curve. Fig. 4 shows the dispersion diagram of the unloaded and loaded BWO and includes the operating mode and higher-order mode dispersion curves for both unloaded and loaded cases and a 22 kV beam voltage line superimposed in the same figure.

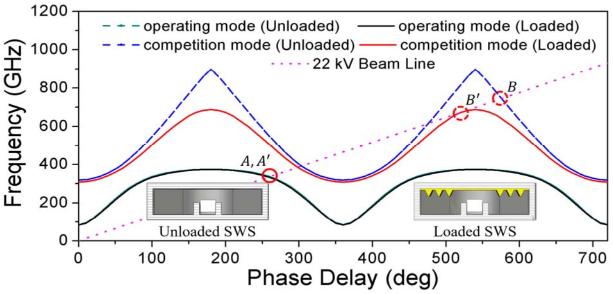

**Figure 4.** Unloaded versus loaded BWO Dispersion Diagram.

It can be seen that both the operating mode dispersion curves of unloaded and loaded BWO SWS are nearly identical, which means that the loaded sawtooth structure does not significantly affect the operating mode. The 22 kV beamline does not intersect with the loaded BWO dispersion curve over the original backward wave region (n = -2); however, the intersection occurs at the forward wave region (n = 1), so the chances of a higher-order mode excitation are limited. Fig. 5 shows the output signal of the loaded BWO and the Fourier spectrum of Ez at 35 ns. It can be seen that, during the 35 ns simulation time, the output signal is stable, and the Fourier spectrum is clean, which confirms that only the operating mode is excited and sustained within the loaded BWO. Thus, the stability of this high-frequency circuit significantly improved.

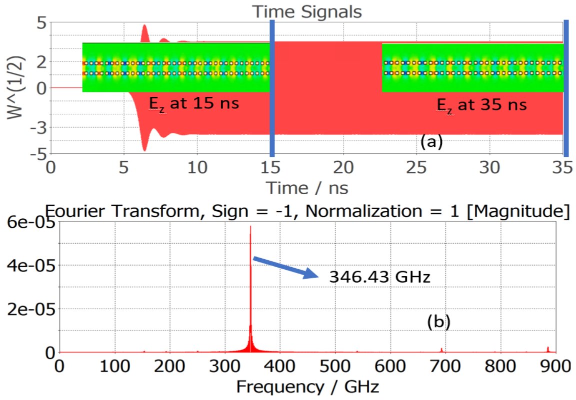

**Figure 5.** Loaded BWO (a) output signal (b) Fourier spectrum at 35 ns.

## Conclusion

To mitigate mode competition by the method of altering the dispersion curve of only the higher-order mode, a loaded BWO was designed and simulated. CST PIC has been employed to verify the analysis. The stable output power with a clean spectrum proves the effectiveness of this method.

## Acknowledgements

This work was supported by Department of Energy grant: DE-FG02-99ER54531 and DE-FG02-99ER54518

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