Investigations of Non-Linear Spectral Behavior in Multi-Toned Helix Traveling Wave Tubes

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Purpose of Investigation

The custom-modified experimental test TWT will allow for experimental determination and verification of currently-unavailable multi-tone wave spectra details and beam-phase-space evolution. The collected experimental data will indicate opportunities for TWT modifications that will improve tube linearity, efficiency when simultaneously amplifying multiple signals (with both analog and digital modulation) and evaluate the accuracy of several numerical tools including CHRISTINE [1], CTLSS [2], MAGIC2D and –3D [3], etc.

Initial Work

Initial experiments will include measurements of the circuit’s loaded and unloaded phase velocity. These data allow for unique comparisons with theoretical models of a typically unavailable parameter. Such comparisons will provide interesting insights into the computational models and fundamental interaction physics.
Advanced Investigations of Traveling Wave Tube (TWT) Physics
Using a Custom-modified Experimental Test Device

Custom-modified experimental TWT.

TWT with gun optics and vacuum gate.
Advanced Investigations of Traveling Wave Tube (TWT) Physics
Using a Custom-modified Experimental Test Device

Device Details:

- Wideband (1.5 octaves) 2-6 GHz.
- Multi-stage (2 with sever).
- Vane-controlled dispersion, focus-electrode current control.
- Multiple RF output ports along helix.
- Gate-valve on exit for in-situ spent beam analysis.
- Solenoid focusing-compatible, for experimental flexibility.
- Short or long pulse operation using new water cooled collector.
Advanced Investigations of Traveling Wave Tube (TWT) Physics Using a Custom-modified Experimental Test Device

- Investigate beam-wave interaction and spent beam distribution using custom-fabricated, wideband TWT with unprecedented diagnostic access.

- The 1.5-octave, 2-6 GHz TWT has multiple output taps to reveal the nonlinear time and space evolution of the carrier(s), harmonics and intermodulation products.

- Correlation between exit beam energy & electromagnetic wave evolution will be revealed.

- New understanding will identify optimal strategies to maximize linearity and efficiency in TWTs.
Intermodulation Products in Multi-toned Ultrawideband Traveling Wave Tube Amplifiers

- New multioctave TWTs offer unprecedented opportunities for high-speed, multichannel wireless data transfer and sat-com.

- Problem: The intermodulation products generated due to non-linearities inherent in the operation of the TWT are now within that same TWT’s gain regime. This leads to an increase in the “noise” of the system.

- An understanding of the non-linearities and how they affect the intermodulation products is needed to deal with this problem.

Output spectrum illustrating unequal gain (at $f_1$, $f_2$) and unwanted IMPs/harmonics for unequalized, two-toned wideband TWTA
Advanced Investigations of Traveling Wave Tube (TWT) Physics
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PC-controlled H.V. pulse modulator and microwave diagnostics equipment.

Water-cooled collector for long-pulse experimental flexibility.
Advanced Investigations of Traveling Wave Tube (TWT) Physics
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External solenoid and test instrumentation rack.

Agilent 8565E spectrum analyzer used with gating feature to capture pulsed-signal spectra.

Example of multi-tone TWT output spectrum with intermodulation products visible.
Schematic of Circuit for Phase Measurements

This circuit will allow direct measurement of the phase shift between two closely spaced taps along the helix of the experimental TWT. From knowledge of the spacing and phase shift, the beam loaded phase velocity and dispersion relation may be extracted.

Measured Phase Curve @ 2GHz

Phase Delay (deg) vs. Volts

-6

-4

-2

0

2

4

6

0 30 60 90 120 150 180

Volts

Phase Delay (deg)

Measured Phase Curve @ 2GHz

(Phase extracted from DC voltage)
Experimental Gain Characterization of Custom-modified TWT

- **Graph 1:**
  - **X-axis:** Frequency [GHz]
  - **Y-axis:** Gain [dB]
  - **Note:** Pin=1mW

- **Graph 2:**
  - **X-axis:** Power In (mW)
  - **Y-axis:** Power Out (W)
Comparison of Growth Rates vs Frequency

Pierce: 1D linear code based on Pierce analysis
td-sim: 1D non-linear time domain code
Christine: Christine code
exp: Experimental data (preliminary)
Preliminary Investigation of Spectral Evolution along TWT Helix

![Graph showing spectral evolution along TWT Helix](image-url)
Modeling the Custom-modified Tube

- This custom modified tube gives us the ability to take measurements of the waveform at various points along the tube as well as measure spent beam energy. To make the most of this opportunity we wish to compare such unique data with different numerical models.

- For example, we have started modeling using the code CHRISTINE, developed by Antonsen and Levush in collaboration with the Naval Research Laboratory.

- Presented here are some preliminary CHRISTINE modeling results of the custom TWT.

Parameters of the custom-modified tube:

- Operation Frequency Range: 2-6 GHz
- Beam Current: 0.212 Amps
- Beam Voltage: 2900 Volts
Modeling the Custom-modified Tube

Taps 2, 3, and 7 allow measurement of waveforms at various positions along the tube. As can be seen in the model, we expect significantly different measurements at each of the tap points. Matching these measurements with model data at these points will allow extrapolation of the waveforms at other points in the tube.
Modeling the Custom-modified Tube

Comparing the results of the single and multi-tone drives together and with experiments will allow a better understanding of the growth rates of intermodulation products and what causes them.
Custom-modified TWT Project Status

• Beam optics, vacuum system and high-voltage modulation functioning.
• Magnetic solenoid is configured and field has been mapped.
• TWT gain has been characterized with respect to frequency and drive power.
• Preliminary multi-tone spectra have been measured at output and along helix.
• Homodyne circuit used to measure loaded vs. unloaded wave phase velocity is calibrated.
• Preliminary CHRISTINE modeling has been initiated.
• Completed design and fabrication of spent beam diagnostic manipulation stage.
• Water cooled collector has been designed and fabricated for long-pulse flexibility.
Summary

Use of a custom-modified TWT will allow us to obtain previously-unavailable experimental details.

Experimental Apparatus Include:

- Multiple output taps, allowing the measurement of the evolution of electromagnetic wave spectra as well as beam-loaded phase velocity
- A Retarding Field Energy Analyzer is being built to measure time averaged electron kinetic energy distributions.
- External Solenoid Magnetic fields, allowing adjustment of the fields to determine the effects of beam parameters on TWT operation.

We will examine the effect of the electron beam, magnetic focusing, and helix circuit on nonlinear phenomena and intermodulation products of the TWT.