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# Multi-stream Traveling Wave Tube (TWT)

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The project goal was to study instabilities associated with multi-stream electron beam devices. In Year 3 when studying fundamental properties of the dispersion relations, in particular the points of the transition to instability, we have discovered simple electric circuits with EPDs (exceptional points of degeneracy), which are, in fact, the points of the transition for stability to instability.


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# Annual Progress Report for Year 3 (2021-2022)

**A. Figotin and E. Schamiloglu**

**Subject:** Annual Progress Summary Report

Contract/Grant Title: Multi-stream Traveling Wave Tube

AFOSR Contract/Grant #: FA9550-19-1-0103

**Reporting Period:** April 1, 2021 – March 31, 2022.

## I. Summary of objectives and achievements of Year 3

The project goal was study instabilities associated to multi-stream electron beam devices. In the Year 3 when studying fundamental properties of the dispersion relations, in particular the points of the transition to instability, we have discovered simple electric circuits with EPDs (exceptional points of degeneracy), which are, in fact, the points of the transition for stability to instability. These circuits can be used for enhanced sensing.

- ***The UNM group led by Prof. Schamiloglu has succeeded in designing a cathode capable to generate two electron beams with two different energies (of about 10-20%) by using a single pulsed power driver. The developed design has been thoroughly tested by a number of PIC simulations which are in an excellent agreement with the developed by them analytical theory***.
- We have found a way to obtain a frozen mode in a SWS based on the serpentine waveguide commonly used to realize TWT at millimeter waves. The finding can be used to conceive regimes of interaction between an electron beam and three electromagnetic degenerate modes to improve the performance of TWT amplifiers.
- We carried out comprehensive studies of high-sensitivity in various gyrator-based circuits with EPDs.
- We have analyzed different approaches to achieve EPDs in coupled resonators using a gyrator or PT-symmetry. We have compared the three general ways to get EPDs in circuits: (i) using the conventional PT symmetry, i.e., using two coupled resonators, one with loss and one with gain; (ii) using a single resonator with a time varying component; (iii) using gyrators.
- We developed a comprehensive perturbation theory for our circuits near an EPD. Using this theory we advanced an approach to sensing, allowing to benefit from the proximity to an EPD on the one hand when providing for stable operation.
- ***We have filed two patent applications, the US and the international one, titled "Sensing circuits".***

## II. Publications.

- Figotin A. Exceptional points of degeneracy in traveling wave tubes, J. Math. Phys., **62**, 082701, (2021).
- Figotin A. Perturbations of circuit evolution matrices with Jordan blocks, J. Math. Phys., **62**, 042703, (2021).
- Figotin A., Circuit Synthesis based on Prescribed Lagrangian, (accepted), 2022.
- K. Rouhi, A. Nikzamir, A. Figotin, and F. Capolino, "High-Sensitivity in Various Gyrator-based Circuits with Exceptional Points of Degeneracy," *European Physics Journal (EPJ) Applied Metamaterials*, 2022. Accepted: 01/02/2022
- A. Nikzamir, K. Rouhi, A. Figotin, and F. Capolino, "How to Achieve Exceptional Points in Coupled Resonators Using a Gyrator or PT-symmetry, and in a Time-Modulated Single Resonator: High Sensitivity to Perturbations," *European Physics Journal (EPJ) Applied Metamaterials*, 2022. (Invited Paper) Accepted.
- K. Rouhi, A. Nikzamir, A. Figotin, and F. Capolino, "Exceptional point in a degenerate system made of a gyrator and two unstable resonators," *Phys. Rev. A,* Vol. 105, 032214, 2022.
- A Nikzamir, K Rouhi, A Figotin, F Capolino, "Demonstration of Exceptional Points of Degeneracy in Gyrator-Based Circuit for High-Sensitivity Applications," arXiv:2107.00639, 2021.
- K Rouhi, A Nikzamir, A Figotin, F Capolino, "Enhanced Sensitivity of Degenerate System Made of Two Unstable Resonators Coupled by Gyrator Operating at an Exceptional Point," arXiv:2110.01860. 2021 Oct 5.
- K Rouhi, R Marosi, T Mealy, AF Abdelshafy, A Figotin, F Capolino, "Exceptional degeneracies in traveling wave tubes with dispersive slow-wave structure including space-charge effect," Applied Physics Letters, 2021 Jun 28;118(26):263506

# Part I: Studies at UCI

## I. Studies of serpentine and helical TWTs.

We have conducted thorough studies of frozen modes in three-way slow-save structure (SWS) for three-mode synchronization. We have found a way to obtain a frozen mode in a SWS based on the serpentine waveguide commonly used to realize TWT at millimeter waves. The developed approach can be used to conceive regimes of interaction between an electron beam and three electromagnetic degenerate modes to improve the performance of TWT amplifiers

We have also studied a model of helical TWTs accounting for the SWS dispersion characteristics and space-charge effects. This model is a generalization of the Pierce method that accounts for the dispersion of the cold mode in the SWS. It is based on the dispersive value of the cold mode characteristic impedance. The model is in a very good agreement with the gain results obtained from PIC simulations. It is also useful for finding the dispersion diagram of the "hot" modes in TWTs.

## II. Simple circuits for enhanced sensing.

We carried out comprehensive studies of high-sensitivity in various gyrator-based circuits with EPDs. We have also analyzed different approaches to achieve EPDs in coupled resonators using a gyrator or PT-symmetry and compared the three general ways to get EPDs in circuits: (i) using the conventional PT symmetry, i.e., using two coupled resonators, one with loss and one with gain; (ii) using a single resonator with a time varying component; (iii) using gyrators.

We developed a comprehensive perturbation theory for our circuits near an EPD. Using this theory we advanced an approach to sensing, allowing to benefit from the proximity to an EPD on the one hand when providing for stable operation.

***We have filed two patent applications, the US and the international one, titled "Sensing circuits" have been submitted to the patent offices***.

## III. Faculty and Graduate Students Involved

**PIs:** Prof. Alexander Figotin. Prof. Edl Schamiloglu.

**UCI PhD Students:** Ahmed F. Abdelshafy, Kasra Rouhi.

**Collaborators**: Prof. Filippo Capolino, UC Irvine.

**UNM PhD Students:** Khandakar Nusrat Islam.

**UNM Research Assistance Professor:** Ahmed Elfrgani.

# Part II: UNM team contributions

### Generating Two Beams with Different Energies from a Single Cathode Using a Single Pulsed Power Source

The goal of this project is to generate two electron beams with two different energies (of about 10-20%) by using a single pulsed power driver. The challenge in doing this is that the two cathodes we would employ would be at the same potential so that explosive emission nested cold cathodes will not have different energies. In this second year we studied the possibilities in detail. What we have concluded is that generating two electron beams with different energies from a single cathode stalk is not possible for the low energies and low currents (comparable to commercial communications traveling wave tubes – TWTs) considered in this project. However, we find that at relativistic energies with larger currents, two beams with 10-20% energy difference can be produced. This conclusion was reached following analytical derivations and particle-in-cell (PIC) simulations with experiments ongoing. The geometry is shown in Fig. 1 and the parameters are summarized in Table 1.

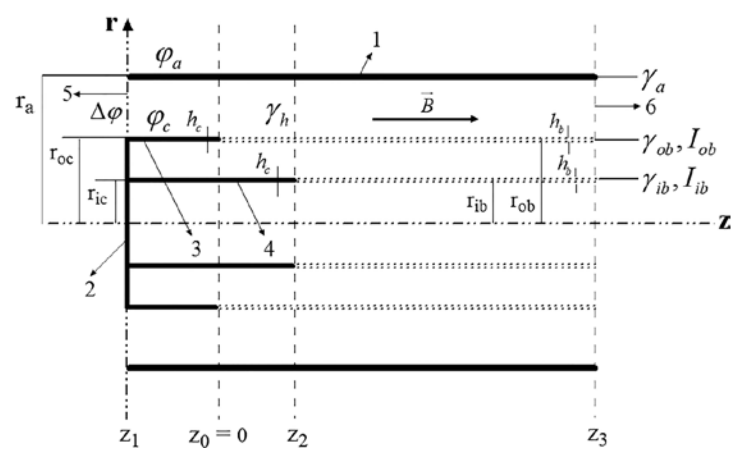


**Figure 1: Geometry for the analytical calculations (from [1]).**

The parameters are summarized in Table 1.

**TABLE I.** Design parameters of two nested MICDs in a vacuum tube.

| Inputs<br>Design parameters | Symbols | Values | Units | Outputs<br>Parameters | Units |
|---|---|---|---|---|---|
| Anode potential | $\phi_a$ | 100–500 | kV | $I_{ib}$ [a] | A |
| Cathode potential | $\phi_c$ | 0 | kV | $I_{ob}$ [b] | A |
| Anode radius | $r_a$ | 2.5 | cm | $\gamma_{ib}$ [c] | Unitless |
| Anode length | $z_1$ to $z_3$ | 16.5 | cm | $\gamma_{ob}$ [d] | Unitless |
| Outer cathode radius | $r_{oc}$ | 0.9 | cm | $Ek_{ib}$ [e] | keV |
| Outer cathode length | $z_1$ to $z_0$ | 4.9 | cm | $Ek_{ob}$ [f] | keV |
| Cathode thickness | $h_c$ | 0.02 | cm | | |
| Inner cathode radius | $r_{ic}$ | $r_{ic} < r_{oc}$ | cm | | |
| Inner cathode length | $z_1$ to $z_2$ | $l_{ic} < l_{oc}$ | cm | | |

[a]Inner electron beam current.
[b]Outer electron beam current.
[c]Relativistic factor at the external boundary of the inner electron beam.
[d]Relativistic factor at the external boundary of the outer electron beam.
[e]Inner electron beam energy.
[f]Outer electron beam energy.

The essential results are summarized in Fig. 2. The agreement between analytical theory and simulations is extraordinary. Details of the analytical theory can be found in [1]. The theory basically extends Fedosov's theory for a single magnetically insulated coaxial diode (MICD) to two nested MICDs.

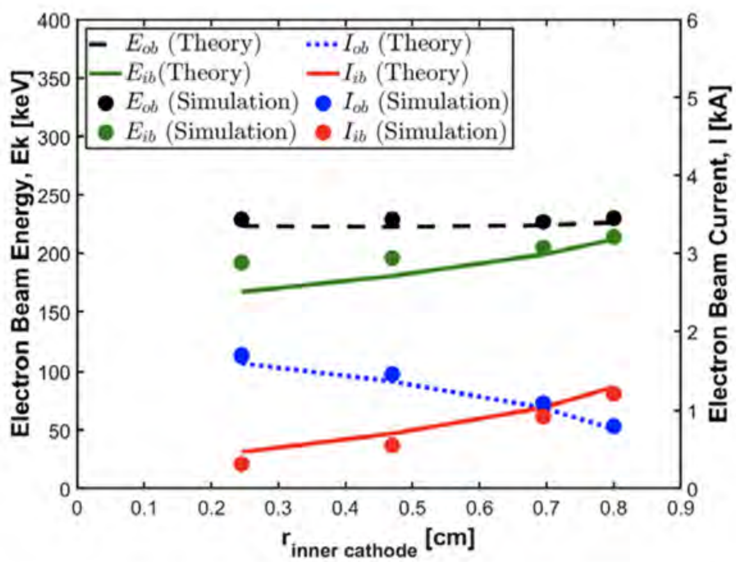


**FIG. 2.** Analytics and simulations of outer (blue) and inner (red) electron beam currents and analytics and simulations of outer (black) and inner (green) electron beam energies as a function of the radius of the inner cathode $r_{ic}$.

This research is the first study of multi-electron beam generation with different energies from a single cathode at a single potential, demonstrating the generation of two beams with comparable currents and with an energy difference of about 6%–27% with applications to a multi-stream TWT. A combination of comprehensive quantitative and qualitative approaches is used to analyze the data from both simulation and analytical theory. One of the significant findings to emerge from both analytical theory and PIC simulation results is that at a certain value of inner cathode radius and a certain axial extent of the inner cathode compared to the outer cathode, the beam "currents" for both inner and outer electron beam are comparable and that greater than 10% energy difference can be achieved. This is highly important for the multi-stream TWT amplifier concept [3]. Experiments are ongoing to validate these findings.

It should be noted that this technique for generating two electron beams with ~10% difference in energies and comparable currents from two MICDs on a cathode stalk at a single potential is most effective when the beams have a significant space charge. This restricts the parameter range of feasibility to, roughly, voltages > 100 kV and currents > 1 kA.

Two publications thus far have appeared based on this work and are listed in the References.

## References


1. K.N. Islam and E. Schamiloglu, "Multiple electron beam generation with different energies and comparable currents from a single cathode potential for high power traveling wave tubes (TWTs)," J. Appl. Phys., vol. 131, 044901-1-15 (2022).
2. K.N. Islam, L.D. Ludeking, A.D. Andreev, S. Portillo, A.M. Elfrgani, and E. Schamiloglu, "Modeling and Simulation of Relativistic Multiple Electron Beam Generation with Different Energy from a Single Cathode Potential for High Power Microwave Sources," IEEE Trans. Electron Dev., vol. 69, 1380-1388 (2022).
3. A. Figotin, *An Analytic Theory of Multi-Stream Electron Beams in Traveling Wave Tubes* (World Scientific, 2020).


We are expecting two more to be published. In addition one invention disclosure has been submitted:

1. K.N. Islam, E. Schamiloglu, and STC.UNM, "Multi-Stream Traveling Wave Tube and Methods Thereof," Provisional Patent Filed 24 June 2021.

## Personnel

Khandakar Nusrat Islam defended her Ph.D. in Spring 2022 and is currently a PostDoc at UNM while she decides on a position to take Summer 2022.