UNM SCHOOL of ENGINEERING

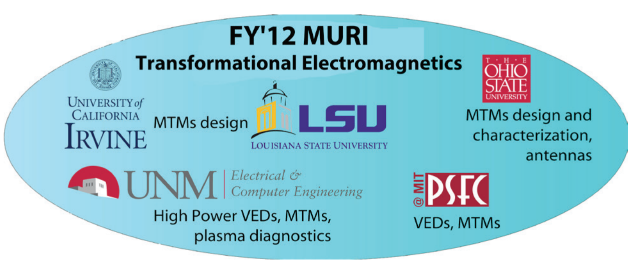
Department of Electrical & Computer Engineering

AFOSR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Consortium Overview, Programmatic Goals, Advisory Board

Edl Schamiloglu, PI

August 21, 2012



Preamble - I

2.2 ROLE OF THE DOD IN BASIC RESEARCH

United States Air Force General Hap Arnold, an aviation pioneer during World War II, once said that "the first essential of Air Power is pre-eminence in research" [3]. More recently, a current leader in the development of future technology for the DoD commented on the United States' military strategy for maintaining its capability into the twenty-first century. He said: "Long-range research in the basic sciences provides the foundation for our nation's technological strength" [4]. This comment echoes the rationale behind Vannevar Bush's visionary report, *Endless Frontier* [5].

[3] Arnold, General H. Memo to Dr. Theodore Von Karman. Subject: AAF Long Range Development Program. November 7, 1944.

[4] Beason, J. D. *DoD Science & Technology Strategy for the Post-Cold War Era*. Washington, DC: National Defense University Press, 1997.

[5] Zachary, G. P. *Endless Frontier: Vannevar Bush, Engineer of the American Century*. New York: Free Press, 1997.

From *High Power Microwave Sources and Technologies,* R.J. Barker and E. Schamiloglu, Eds. (IEEE Press/John Wiley and Sons, New York, NY, 2001), Chap. 2.

Preamble - II

AFOSR and the DoD are interested in Directed Energy Microwaves for these reasons:

- Speed-of-light, all-weather attack of enemy electronic systems.
- Area coverage of multiple targets with minimal prior information on threat characteristics.
- Surgical strike (damage, disrupt, degrade) at selected levels of combat.
- Minimum collateral damage in politically sensitive environments.
- Simplified pointing and tracking.
- Deep magazines (meaning long operating time without replenishment) and low operating costs.

From *High Power Microwave Sources and Technologies,* R.J. Barker and E. Schamiloglu, Eds. (IEEE Press/John Wiley and Sons, New York, NY, 2001), Chap. 2.

Preamble - III

- The U.S. Air Force has taken a lead role in the development of Directed Energy, including HPM. In fact, the Air Force has been designated lead service for Directed Energy.
- The Air Force Weapons' Laboratory (AFWL – predecessor to AFRL, Kirtland AFB, NM) begins HPM source research in late 1970s.

From *High Power Microwave Sources and Technologies,* R.J. Barker and E. Schamiloglu, Eds. (IEEE Press/John Wiley and Sons, New York, NY, 2001), Chap. 2.

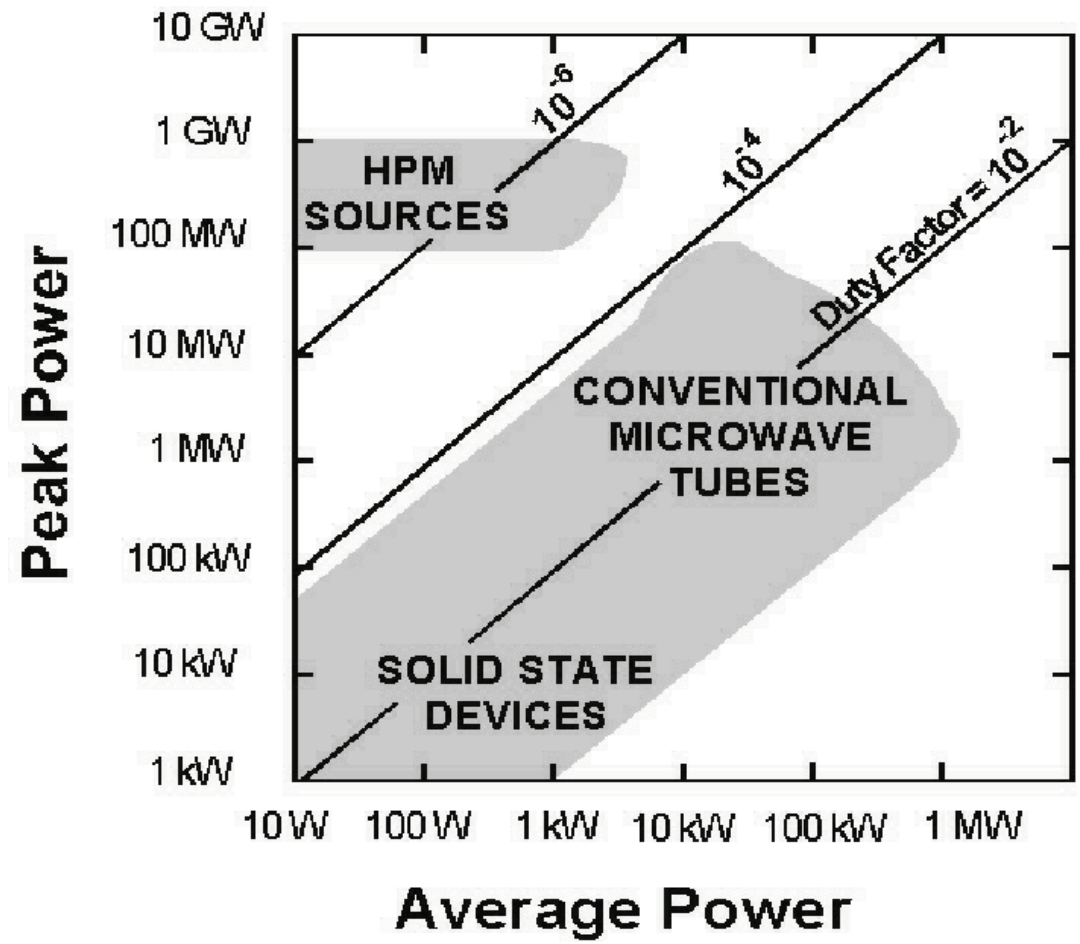
Introduction

High Power Microwaves – imprecise term, usually denotes sources of coherent radiation spanning 1 GHz - >100 GHz at power levels scaling as Pf^2 driven by high-perveance, relativistic electron beams. Can also connote: a) can mean high average power sources. b) can mean high power ultra-wideband (mesoband) microwave sources (incoherent, broadband). c) can connote nonlinear transmission line (NLTL) sources.

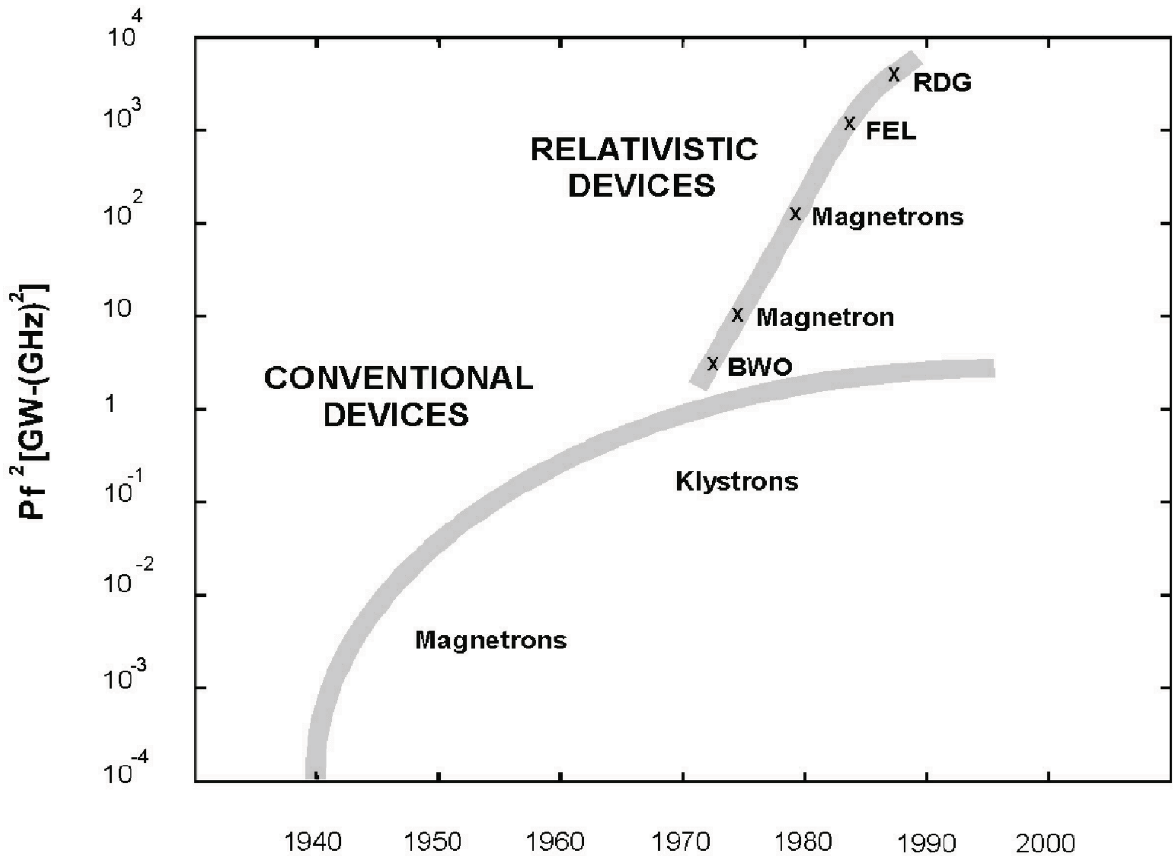
Electrons radiate because they are accelerated in some periodic fashion. The radiation can be coherent (stimulated emission), or incoherent (spontaneous emission). The contribution from electrons reinforce original EM radiation.

Beam bunching at the proper wavelength enforces coherency of radiation (spatial bunching, phase bunching). Vacuum devices are inherently more efficient than solid state devices since the electrons are free electrons!

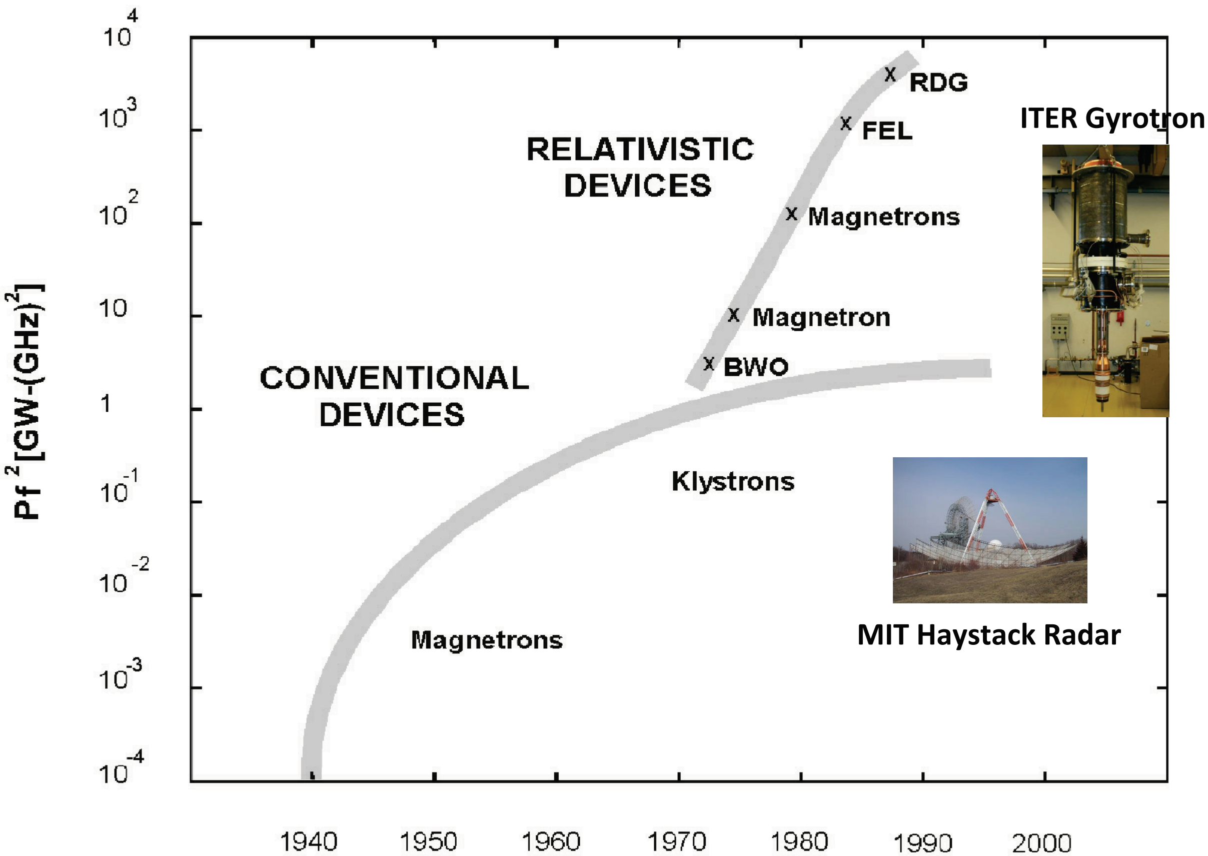
HPM vs. Other Microwave Sources



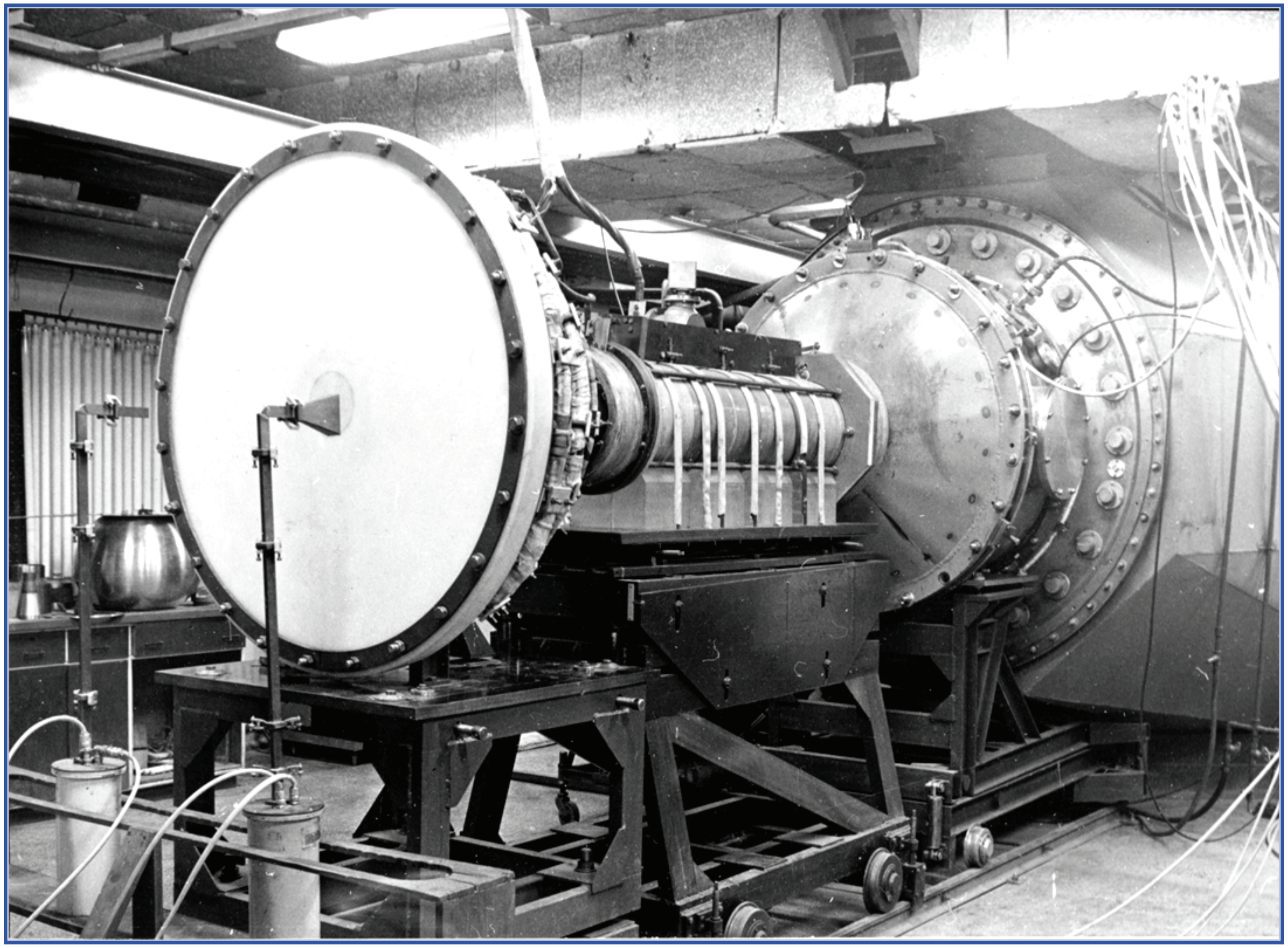
Historical Development Of HPM (mainly oscillators)



What About Amplifiers?



The Era of Big Machines – 1970s – 1990s!



The "GAMMA" accelerator, High Current Electronics Institute, Tomsk, Russia

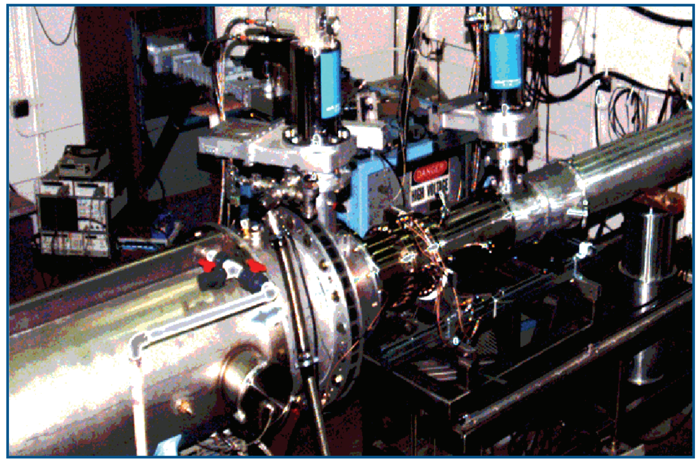
The Era of Big Machines – 1970s – 1990s!

The "GAMMA" accelerator, High Current Electronics Institute, Tomsk, Russia

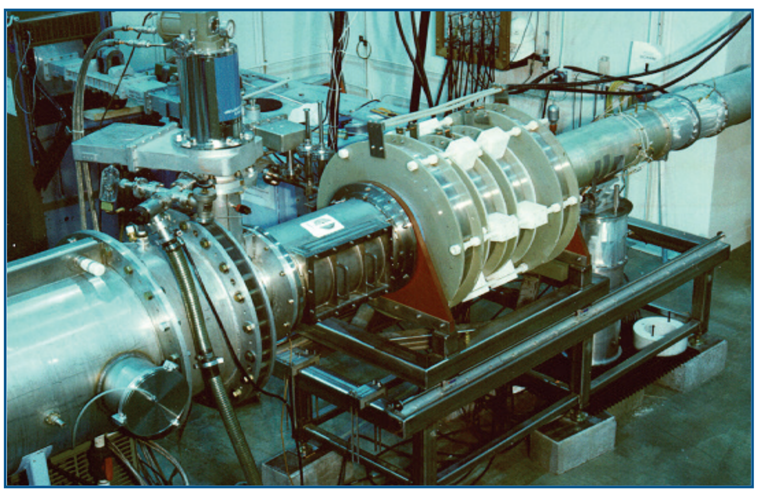
The Era of Big Machines – 1970s – 1990s!

The ORION HPM test facility – the premier facility of its kind in the world. (Built in the U.S. by Physics International – now part of LMC – for the UK MoD in mid 1990's – based on tunable relativistic magnetrons.)

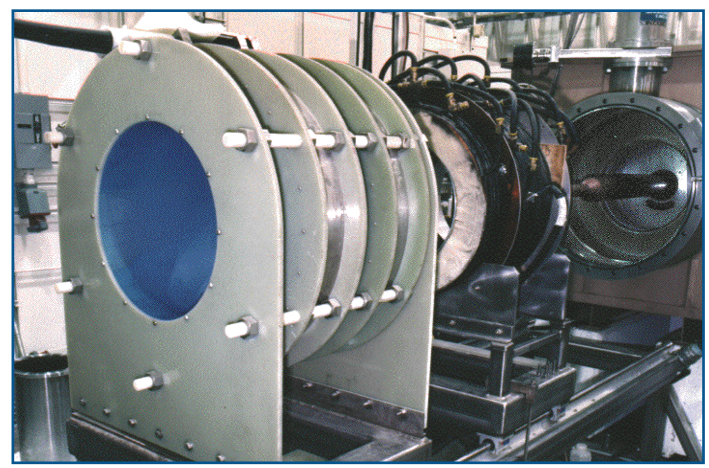
Some HPM Sources at AFRL, mid- 1990s



Magnetically Insulated Line Oscillator (MILO)



Relativistic Klystron Oscillator (RKO)



Gyro-BWO (High Power & Frequency Agile)

History Of Narrowband HPM Revisited

HPM Power Derby* 1970's to mid-1990's – New sources, greater radiated powers

Sober Realization, mid-1990's to present – Pulse shortening, few new source configurations, diminishing resources.

*Power Derby used by J. Benford and J. Swegle, *High Power Microwaves* (Artech House, Norwood, MA, 1992), p. 398.

Future Of HPM – From 1991

HPM Power Levels of 10 – 100 GW and radiated energies of 10 kJ and greater were to be routinely achieved by now!**

**See Table 12.2 in J. Benford and J. Swegle, *High Power Microwaves* (Artech House, Norwood, MA, 1992).

AFOSR-Sponsored International Workshop

The Seventh Special Issue on High Power Microwave Generation

ACKNOWLEDGMENT

The Guest Editors wish to thank all referees, as several received multiple papers, for their efforts in reviewing the papers. They would also like to thank S. Gitomer for his encouragement, patience, and support.

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Fig. 1. Group photograph taken at the International Workshop on High Power Microwave Generation and Pulse Shortening, Edinburgh, U.K., 12 June 1997.

What Went Wrong? - Realization

• Pulse shortening will limit radiated HPM to about 100 ns (old goal was 1 GW power for 1 μs, yielding 1 kJ energy)

• Move away from the “flame-thrower” mentality

• HPM power is sufficient; work on higher repetition rate

• Be smarter – tailor HPM waveforms to optimize effects

• Focus on developing broadband HPM amplifiers (generate a desirable waveform at low power, then amplify to high power)

• Need advances in compact pulsed power so that these can leave the laboratory and fit on mobile platforms!

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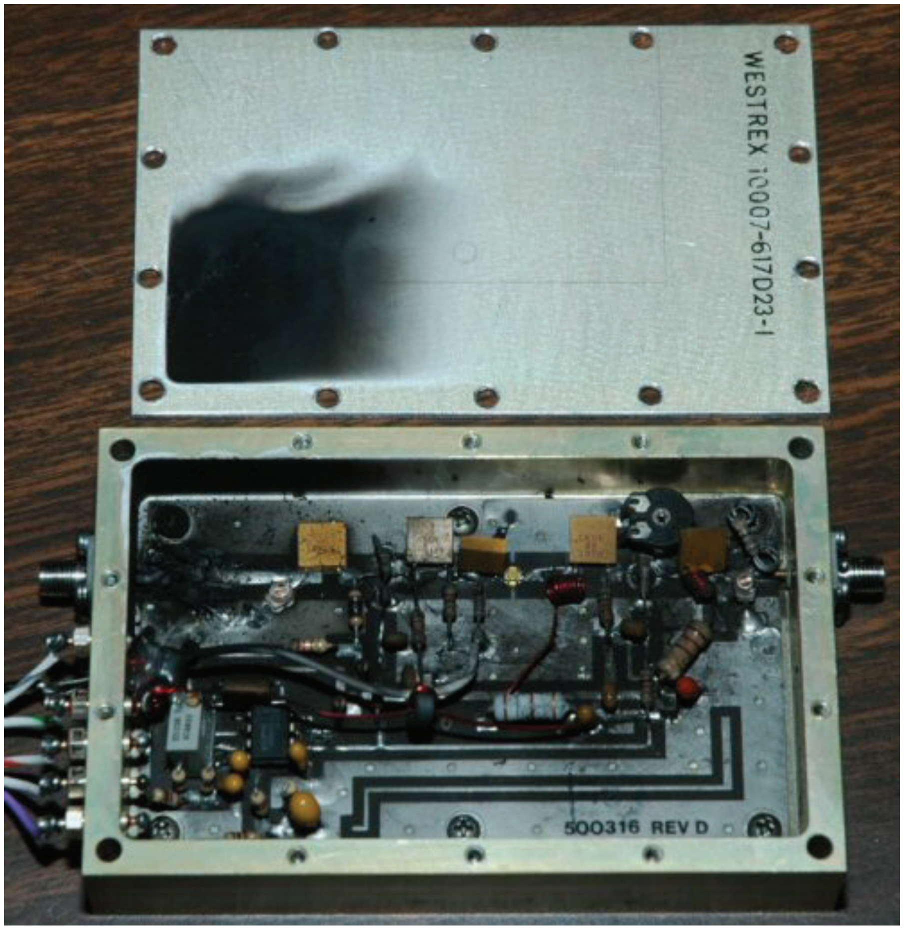
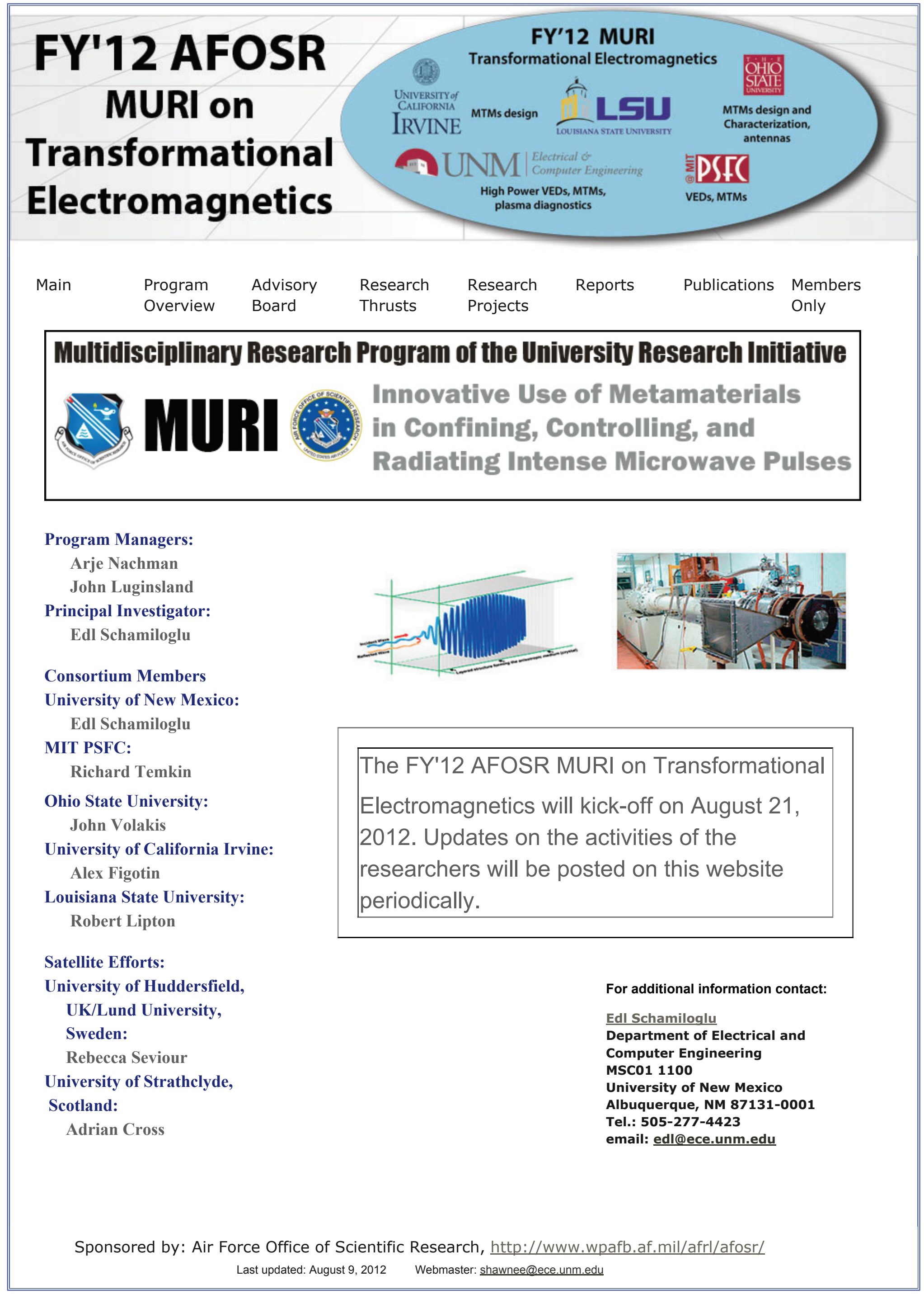
Effects-Driven HPM Source Research – Waveform Diversity



Courtesy, Sameer Hemmady, TechFlow Scientific (formerly University of Maryland)

… and here we are!

http://ece.unm.edu/FY12MURI/



FY'12 AFOSR MURI on Transformational Electromagnetics

FY'12 MURI
Transformational Electromagnetics

University of California Irvine — MTMs design
LSU Louisiana State University
The Ohio State University — MTMs design and Characterization, antennas
UNM Electrical & Computer Engineering — High Power VEDs, MTMs, plasma diagnostics
MIT PSFC — VEDs, MTMs

Main | Program Overview | Advisory Board | Research Thrusts | Research Projects | Reports | Publications | Members Only

Multidisciplinary Research Program of the University Research Initiative

MURI

Innovative Use of Metamaterials in Confining, Controlling, and Radiating Intense Microwave Pulses

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Satellite Efforts:
University of Huddersfield, UK/Lund University, Sweden:
Rebecca Seviour
University of Strathclyde, Scotland:
Adrian Cross

The FY'12 AFOSR MURI on Transformational Electromagnetics will kick-off on August 21, 2012. Updates on the activities of the researchers will be posted on this website periodically.

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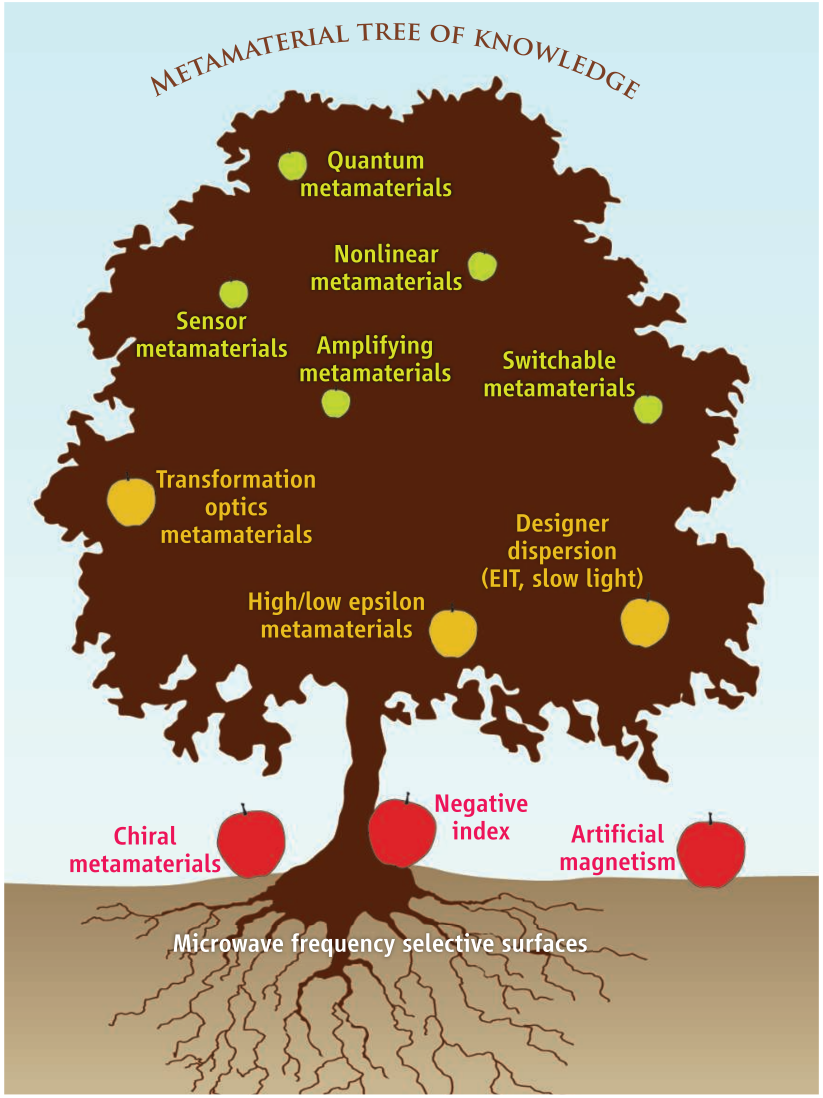
Our Vision

DIRECTED ENERGY COMMUNICATIONS FUNDAMENTAL SCIENTIFIC RESEARCH DEFENSE & CIVILIAN RADAR ACCELERATOR RESEARCH
Innovative use of Metamaterials in Confining, Controlling, and Radiating Intense Microwave Pulses
Facilitating the rapid transition of research outcomes to the Air Force Research Laboratory
Integrated Technologies
DIRECTED ENERGY DEFENSE & CIVILIAN RADAR
COMMUNICATIONS ACCELERATOR RESEARCH
FUNDAMENTAL SCIENTIFIC RESEARCH
Charging & Damage
Waveform Diversity
Technology Base
Significant Losses
Superior Results
Knowledge Base
UNIVERSITY of CALIFORNIA IRVINE
MTMs design
LSU
LOUISIANA STATE UNIVERSITY
THE OHIO STATE UNIVERSITY
MTMs design and characterization, antennas
UNM Electrical & Computer Engineering
High Power VEDs, MTMs, plasma diagnostics
@MIT PSFC
VEDs, MTMs



APPLIED PHYSICS

The Road Ahead for Metamaterials

Nikolay I. Zheludev

Metamaterials enable us to design our own "atoms" and thus create materials with new properties and functions.

The Road Ahead for Metamaterials
Nikolay I. Zheludev
Science **328**, 582 (2010);
DOI: 10.1126/science.1186756

The term "Metamaterials" was first coined in 1999 by Rodger Walser, University of Texas. His definition is as follows:

> Metamaterials are macroscopic composites having man-made, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation.

He chose "meta" as the prefix from the Greek work *meta* meaning *beyond*.

(From B. Munk, *Metamaterials: Critique and Alternatives* (John Wiley and Sons, New York, NY, 2009), p. vi.)

Recap of "Metamaterials"

Taxonomy of Metamaterials is a problem. It seems that there is no one satisfactory definition that does not restrict a class of worthy Metamaterials. The "beyond-nature" definition of Metamaterials clearly fails!

PHYSICAL REVIEW E **74**, 021922 (2006)

Gleaming and dull surface textures from photonic-crystal-type nanostructures in the butterfly *Cyanophrys remus*

Krisztián Kertész,[1] Zsolt Bálint,[2] Zofia Vértesy,[1] Géza I. Márk,[1] Virginie Lousse,[3,4] Jean Pol Vigneron,[3,*] Marie Rassart,[3] and László P. Biró[1,†]

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(Received 27 March 2006; published 31 August 2006)

Recap of Metamaterials

FIG. 1. (Color online) The butterfly *Cyanophrys acaste* is shown here in a resting position, when the hind wing overlaps the forewing. The ventral faces of the wings are displayed, with a cryptic dull green color. *Cyanophrys remus* displays identical resting position.

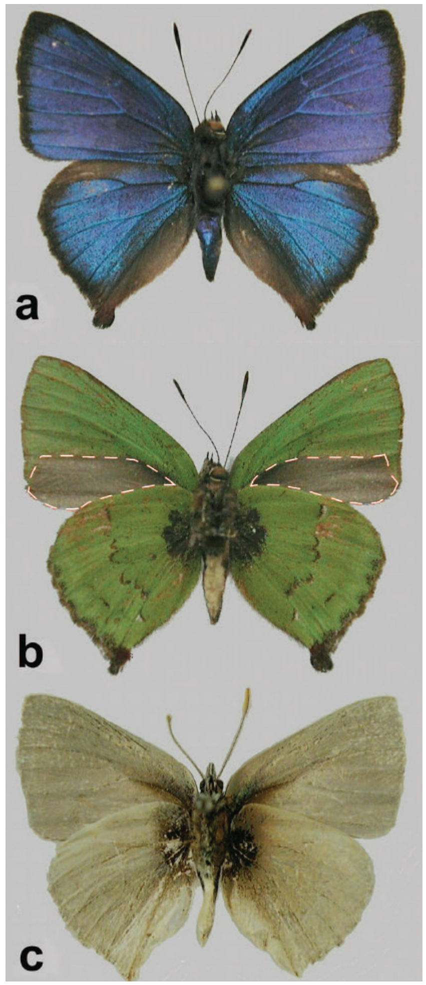


FIG. 2. (Color online) (a) Dorsal surface and (b) ventral surface of the butterfly *Cyanophrys remus* showing their structural colors. The region of the forewing delineated by dashed white lines is covered by the hindwings in resting position. It is worth pointing out that there are no scales producing structural colors along the ventral fore wing anal area. In (c) the ventral side of a bleached butterfly is shown (see text for details). All the specimens in this figure are males.

Recap of Metamaterials

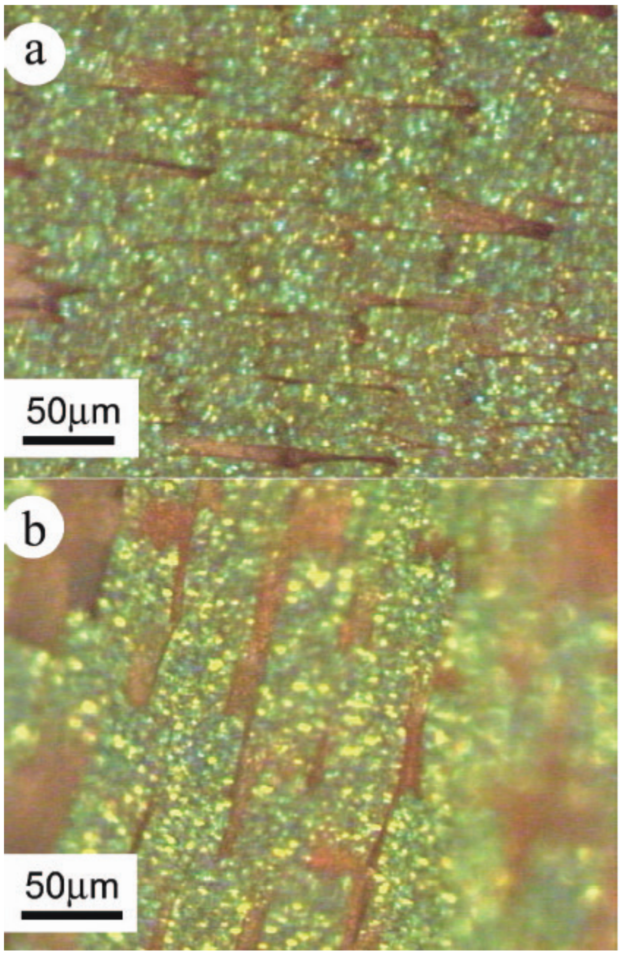


FIG. 3. (Color online) Ventral surface of the wing under two different conditions of illumination. One may remark the occurrence of bright spots colored blue, green, and yellow, which light up with different intensities as the illumination and observation conditions change.

Recap of Metamaterials

Sihvola (Helsinki University of Technology) suggests that *emergence* is a property that needs to be associated with Metamaterials (in that the Metamaterial gains its properties from its structure)…from:

A. Sihvola, "Metamaterials: A Personal View," *Radioengineering,* vol. 18, pp. 90-94, 2009.

Abstract. *This article discusses fundamental properties of metamaterials. Firstly, it is argued that the defining property of metamaterials is emergence and not that they should display properties not observable in nature. In addition, the regime where matter can be assigned effective properties will be quantified using concepts of metamaterialization period and number of generations.*

Recap of Metamaterials

Wegener and Linden (Karlsruhe Institute of Technology and University of Bonn, respectively):

A "metamaterial composed of submicron gold helices arranged into a square lattice." … "can be used as a compact circular polarizer with more than one octave bandwidth – between wavelengths of about 3.0-6.0 μm – and is the circular analogue of the wire-grid polarizer used in Heinrich Hertz's 1887 pioneering experiments…"

M. Wegener and S. Linden, "Shaping Optical Space with Metamaterials," *Physics Today,* October 2010, pp. 32-36.

Our point of view on "Metamaterials"

- Our consortium will not restrict our research on materials with periodicity $d \ll \lambda$. Periodic structures with periodicity $d \sim \lambda/2$ are of equal interest to us.

- Recent work by Seviour, French *et al.* has demonstrated that metamaterials can handle only 80 W of continuous power before melting.

2P-65 High Power Metamaterials for Radiation Sources

R. Seviour[1], E. Luchinskaya[2], D. Shiffler[3], J. Luginsland[3], D. M. French[3]
[1]*Huddersfield University, Huddersfield, Sweden*
[2]*Lancaster University, Lancaster, UK*
[3]*AFRL, Dayton, OH, USA*

The 39th IEEE International Conference on Plasma Science

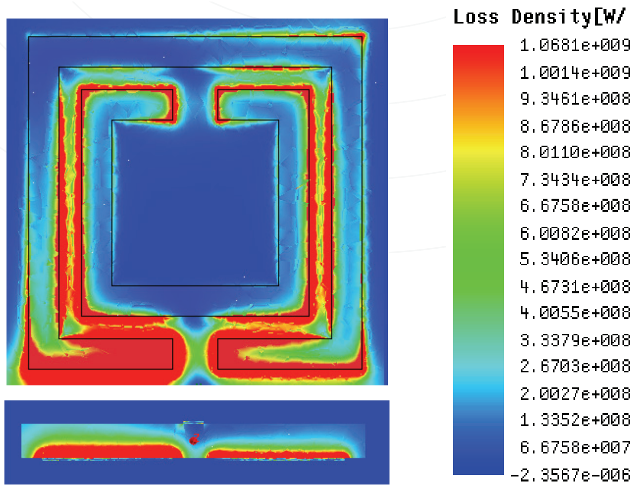
Conference Program

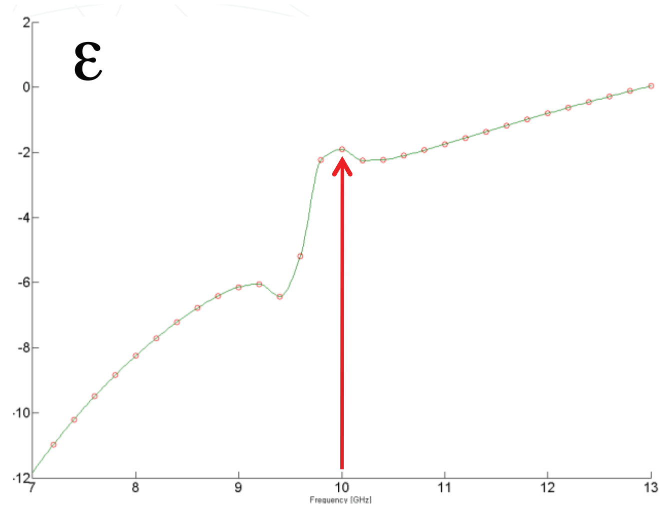
July 8-12, 2012
EICC - Edinburgh, Scotland

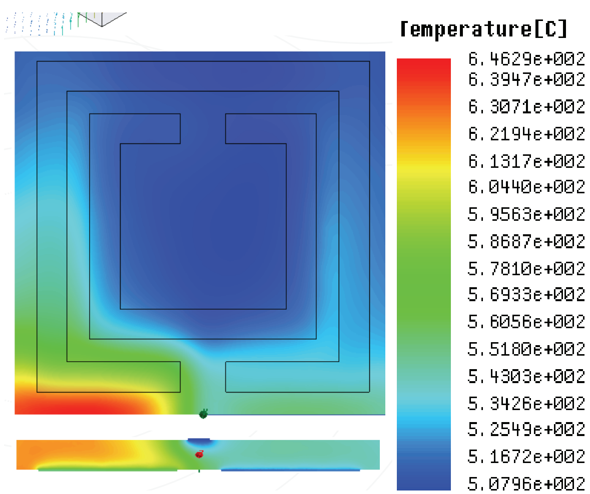
Melting is a Serious Concern

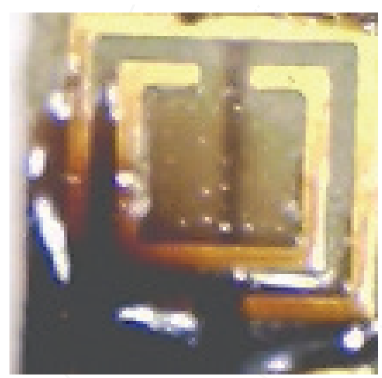
Seviour and French (in preparation)

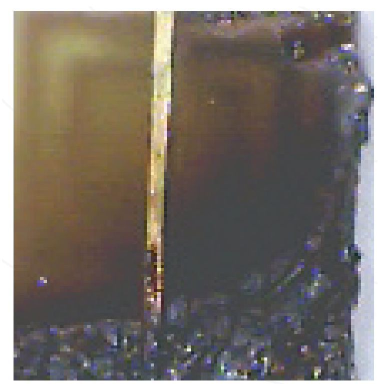
SRR @ 10 GHz 1 W forward power



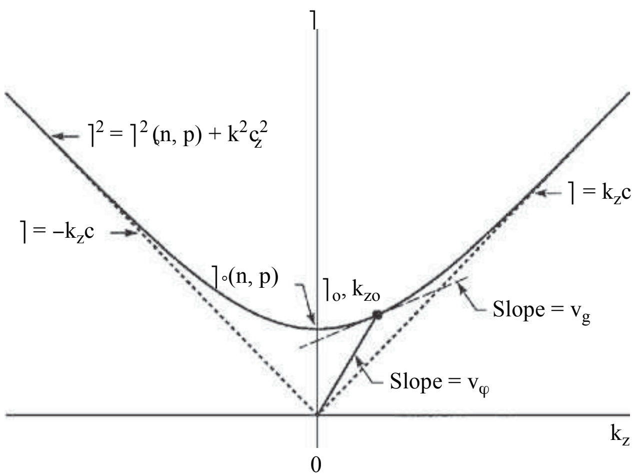


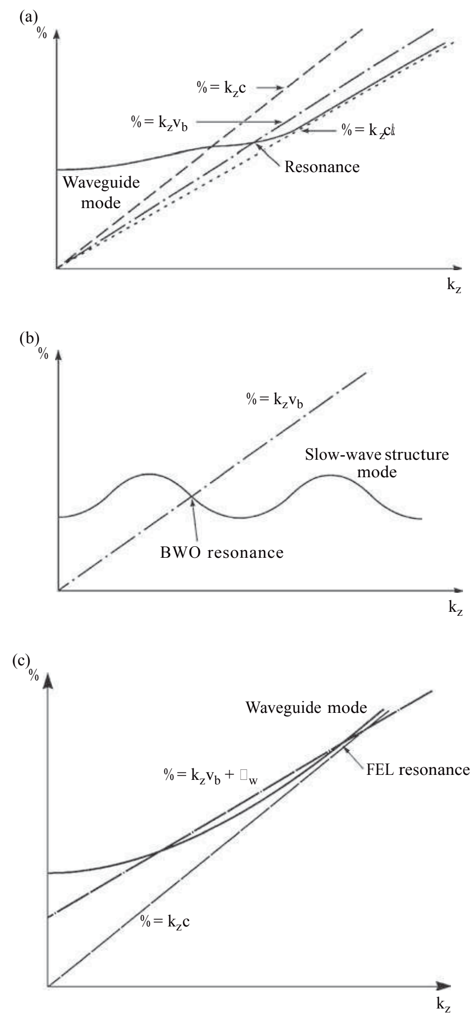






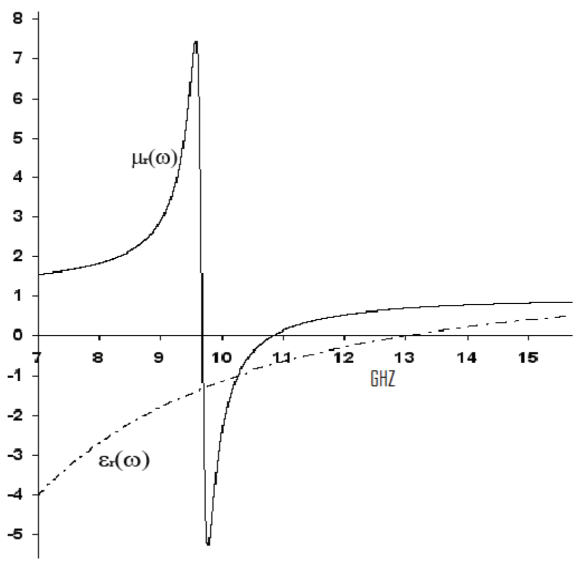
The Importance of Dispersion Engineering

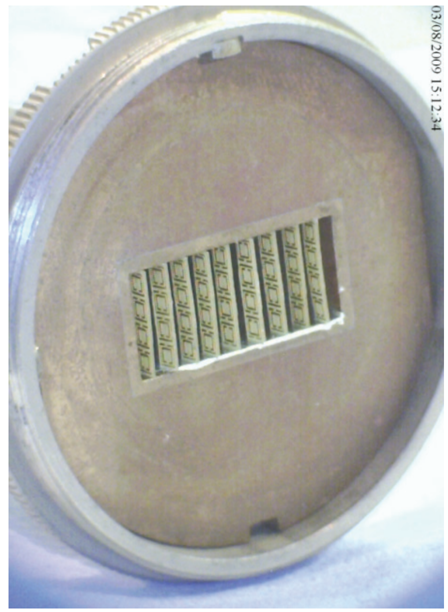


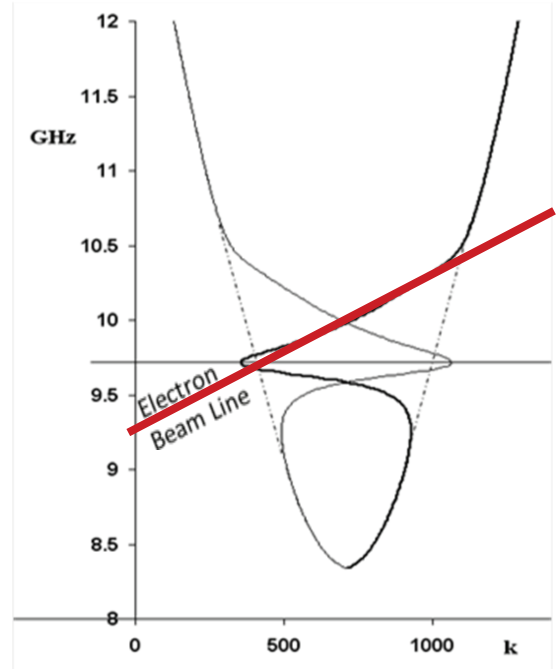


(From J. Benford, J. Swegle, and E. Schamiloglu, *High Power Microwaves, 2nd Ed.*, 2007.)

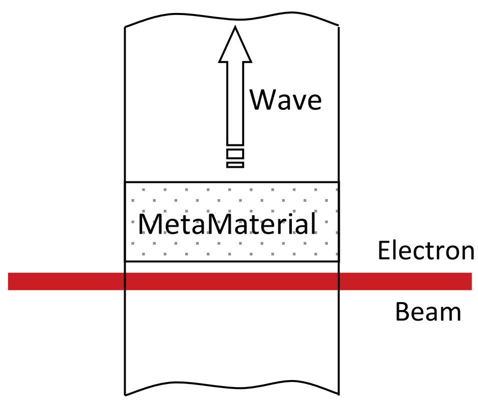
Dispersion Engineering to Study Novel Beam-Wave Interaction Structures



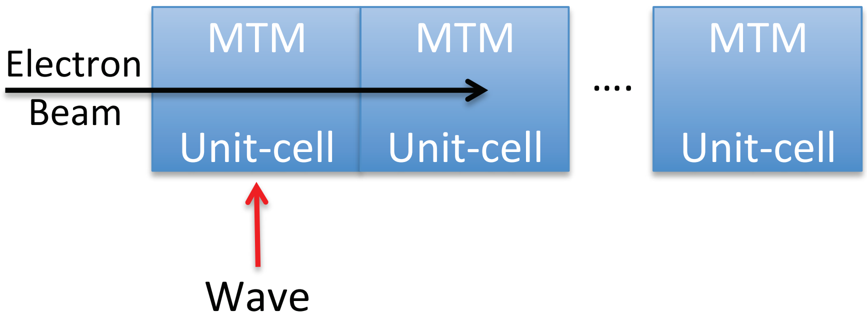


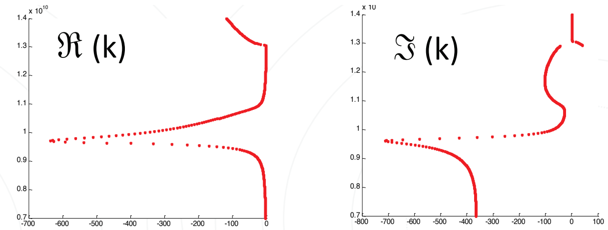


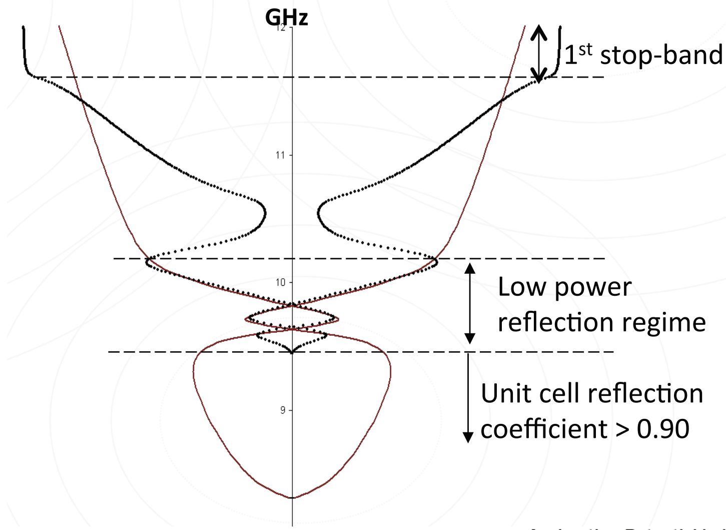
(Courtesy Rebecca Seviour, University of Huddersfield, UK/Lund University, Sweden.)



Novel MTM/Beam Interactions



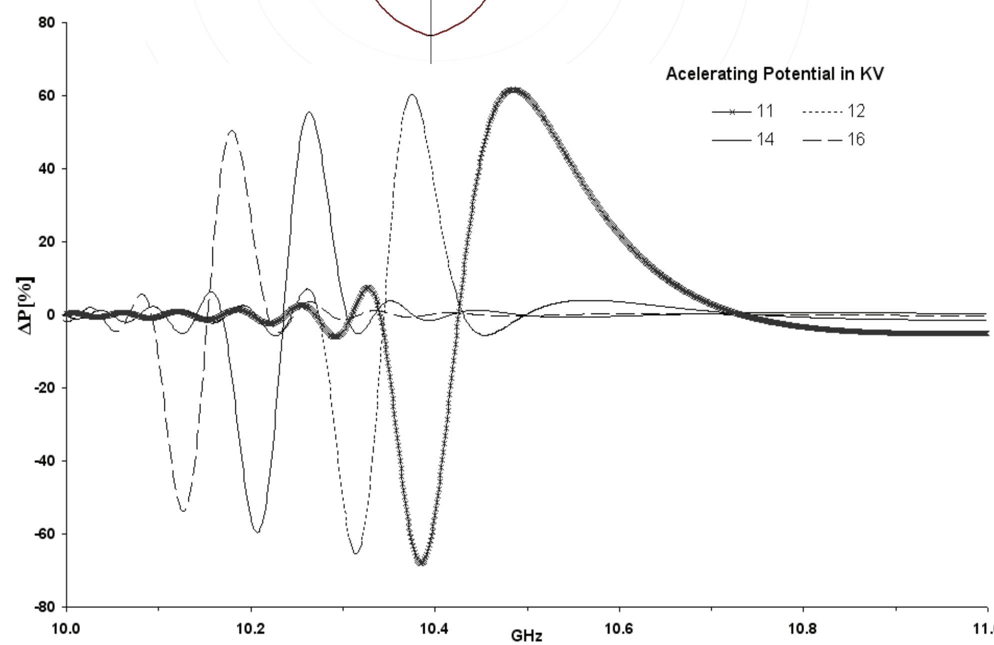




$$\beta_{mm}(\omega) = c^{-1}\sqrt{\omega^2\epsilon_r(\omega)\mu_r(\omega) - \omega_c^2}$$

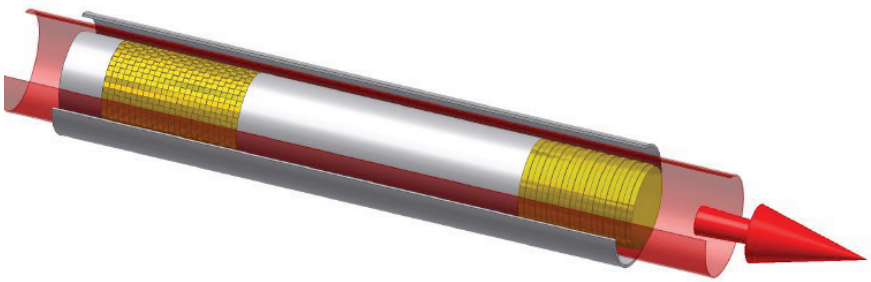
$$\Delta P = \frac{\omega^2\mu}{\beta_0}\frac{L^3}{2ab}Z^2\frac{\mathrm{d}}{\mathrm{dX}}\left(\frac{\sin^2(\mathrm{X})}{\mathrm{X}^2}\right)\frac{\mathrm{c}}{\gamma^3}\frac{1}{\mathrm{v_e^3}}\left(\mathrm{mc^2 I_b/e}\right)$$

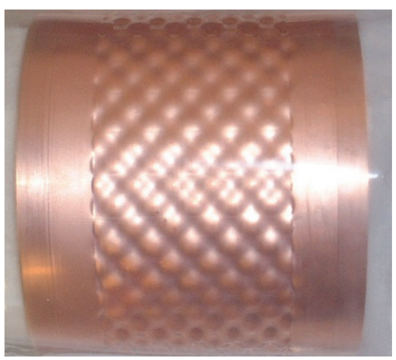
→ **Inverse Cherenkov Accelerator**
→ **Compact Amplifier**

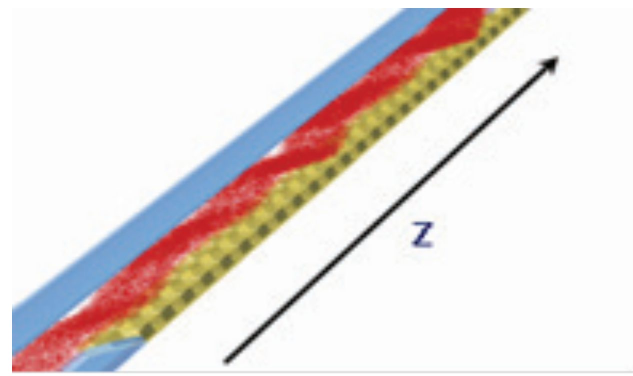


Wave energy amplification in a metamaterial-based traveling-wave structure.
Europhysics Letters, 87(3):34005, 2009.
Y. S. Tan and R. Seviour

Dispersion Engineering to Study Novel Beam-Wave Interaction Structures



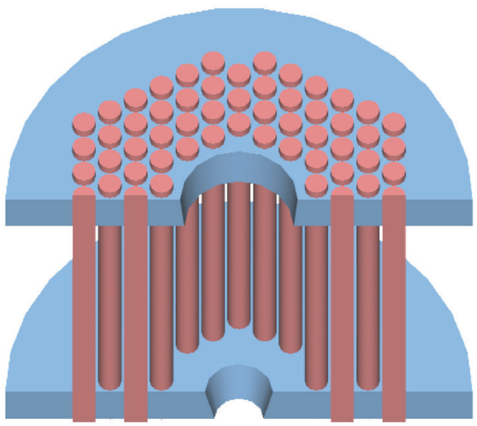




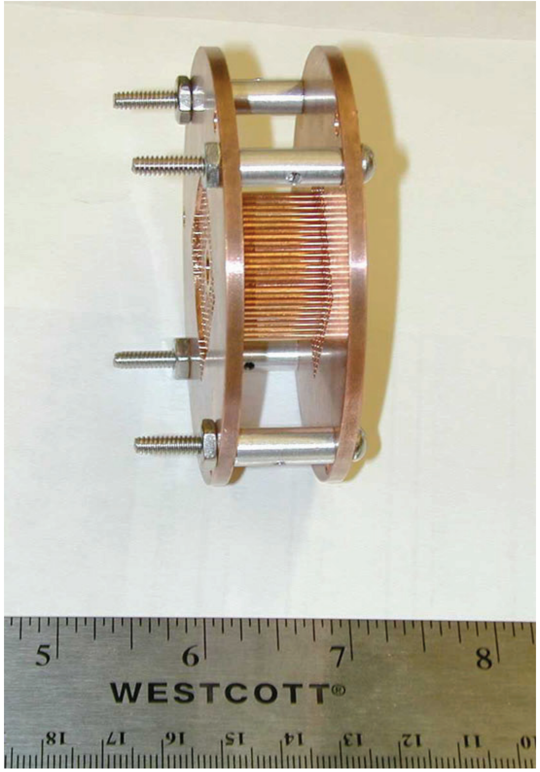
Schematic diagram of the 2D-1D FEM (top left).
Diagram (generated by PIC code MAGIC) of the FEM (section) driven by annular electron beam (red dots) (top right).

(Courtesy Adrian Cross, University of Strathclyde, Scotland)

Dispersion Engineering to Study Novel Beam-Wave Interaction Structures

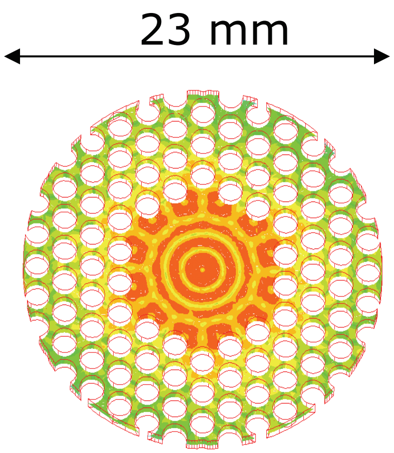


Design Parameters:
V = 65 kV
I = 5 A
f = 140 GHz
B = 5.4 T

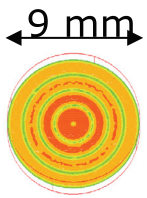


PBG resonator used in the experiment

Note that resonator has no outer wall



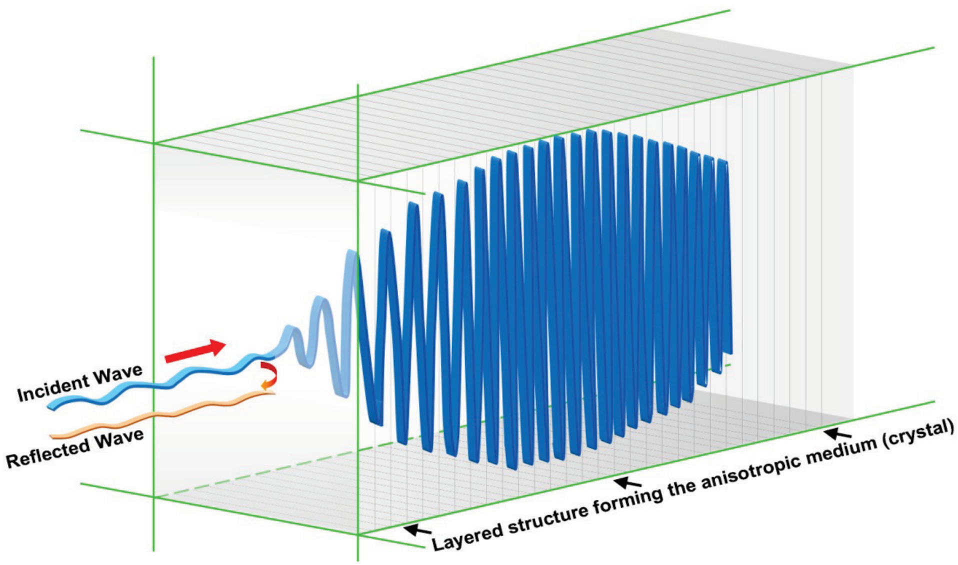
TE_{04} mode at 139.8 GHz



Cylindrical cavity with a TE_{04} mode at 139.8 GHz

(Courtesy Rick Temkin, MIT)

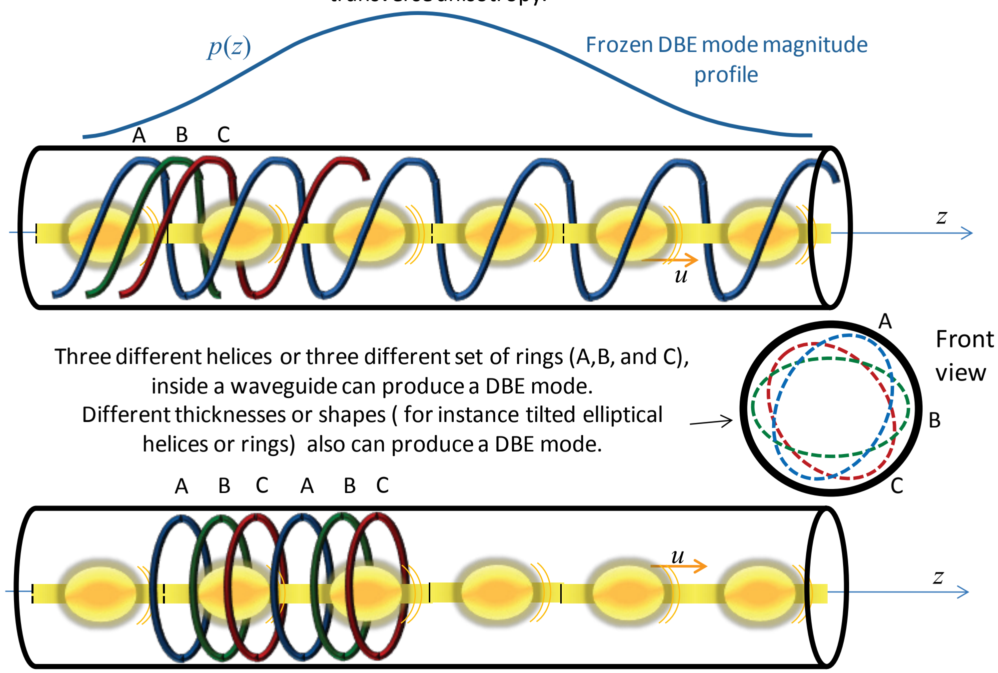
Dispersion Engineering to Study Novel Beam-Wave Interaction Structures



Depiction of wave slow down and amplitude growth (amplification) as the wave propagates within the MTM structure (to the right) formed by DBE crystals. (Courtesy John Volakis, OSU.)

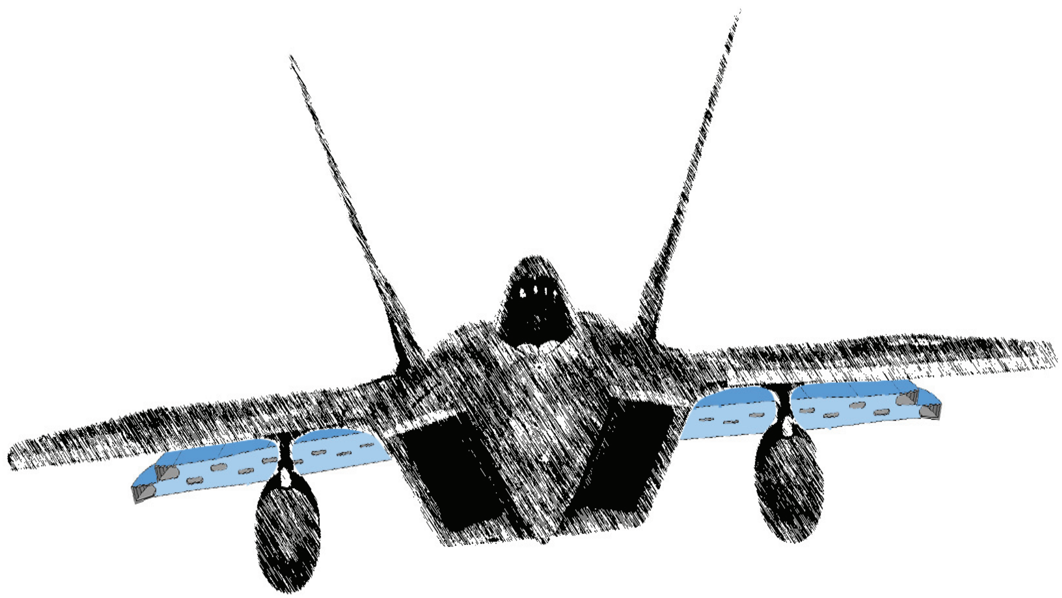
Dispersion Engineering to Study Novel Beam-Wave Interaction Structures

TWT with super amplification via the DBE mode. Examples for creating the special transverse anisotropy.



Basic principle of operation. The electron beam transfers energy to the frozen DBE mode. The frozen DBE mode allows for greater amplification compared to the RBE mode. (Courtesy Alex Figotin, UCI.)

Metamaterials are not only of interest for sources, but also components (antennas, phase shifters, *etc.*)



Our Goals

- **Sources –** Rely on dispersion engineering (all members) to propose novel beam/wave interactions (MIT – Shapiro, Ohio State – Volakis, UC Irvine – Figotin, LSU – Lipton), to exploit in experimentation (at UNM and MIT)

- **Characterization -** Characterize survivability of proposed structures in experimentation using plasma diagnostics (UNM – Gilmore)

- **Exploit Metamaterials for Passive/Reconfigurable Structures –** UNM – Christodoulou, UC - Irvine Capolino, Ohio State - Volakis

Management Plan

AFOSR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Dr. Arje Nachman | Dr. John Luginsland

Advisory Board:

Dave Abe
Carter Armstrong
Bruce Carlsten
Charles Chase
Chuck Gilman
John Petillo
Don Shiffler
Don Sullivan
Pravit Tulyathan

University of Huddersfield — Inspiring tomorrow's professionals

University of Strathclyde Glasgow

Edl Schamiloglu, Consortium PI

PSFC Plasma Science & Fusion Center @ MIT

Rick Temkin, PI

The Ohio State University

John Volakis, PI

University of California · Irvine

Alex Figotin, PI

LSU

Robert Lipton, PI

Our Advisory Board

- Dr. Dave Abe, Naval Research Laboratory
  (represented today by Dr. John Pasour)
- Dr. Carter Armstrong, L-3 Communications
- Dr. Bruce Carlsten, Los Alamos National Laboratory
  (unable to join us today)
- Mr. Charles Chase, Lockheed Martin, Palmdale, CA
- Mr. Chuck Gilman, SAIC Albuquerque, NM
- Dr. John Petillo, SAIC Boston, MA
- Dr. Don Shiffler, AFRL/RD
- Dr. Don Sullivan, Raytheon-Ktech, Albuquerque, NM
- Dr. Pravit Tulyathan, Boeing, Seal Beach, CA

Management Plan

- Communicate amongst ourselves and with the outside world through:
  http://www.ece.unm.edu/FY12MURI/

- Kick-off meeting August 21, 2012 - UNM
- Year 1 Review August/September, 2013 – MIT
- Year 2 Review August/September, 2014 – Ohio State
- Year 3 Review August/September, 2015 – UNM
- Years 4 and 5 contingent on Year 3 Review

Management Plan

- Monthly graduate student presentations (30 minutes each) either *via* internet conferencing with video, or teleconferencing
- Quarterly teleconferences among PI's
- Annual meeting with Advisory Board (coincides with annual review meeting)
- Periodic updates to Program Managers
- Satellite meetings with select consortium members at annual conferences (IEEE Antennas and Propagation Society, ICOPS, IVEC, *etc.*)

Management Plan

Emphasize:

- Collaboration
- Transitions
- Publications
- Presentations
- Student placement

THE UNIVERSITY of NEW MEXICO

AFOSR AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

KICK-OFF MEETING - FY12 AFOSR MURI ON TRANSFORMATIONAL ELECTROMAGNETICS
August 21, 2012
Stamm Room, Rm. 1044, Centennial Engineering Center
University of New Mexico

AGENDA

08:30	Shuttle bus leaves from Parking and Transportation Services to Centennial Engineering Center
08:30	Coffee
09:00	Welcome – Edl Schamiloglu introduces UNM Administration
09:15	Opening Remarks – Arje Nachman, John Luginsland
09:30	Consortium Overview, Programmatic Goals, Management Plan – Edl Schamiloglu
10:00	MIT Perspective and Plans – Rick Temkin
10:30	UNM Perspective and Plans – Edl Schamiloglu, Mark Gilmore, Christos Christodoulou
11:00	Ohio State Perspective and Plans – John Volakis
11:30	UC Irvine Perspective and Plans – Alex Figotin/Filippo Capolino
12:00	LSU Perspective and Plans – Robert Lipton
12:30	Closing Remarks – Edl Schamiloglu, then Arje Nachman and John Luginsland
12:45	Working Lunch (provided) – Discussions
2:00	Tours of UNM Laboratories

UNM SCHOOL *of* ENGINEERING

Department of Electrical & Computer Engineering

AFOSR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

University of New Mexico Perspective and Plans

Edl Schamiloglu, PI

August 21, 2012

FY'12 MURI
Transformational Electromagnetics

University of California Irvine — MTMs design

LSU Louisiana State University

The Ohio State University — MTMs design and characterization, antennas

UNM Electrical & Computer Engineering — High Power VEDs, MTMs, plasma diagnostics

PSFC @ MIT — VEDs, MTMs

Who we are

Dr. Edl Schamiloglu, UNM PI
Dr. Christos Christodoulou, UNM Co-PI
Dr. Mark Gilmore, UNM Co-PI

Dr. Mikhail Fuks, Research Professor
Dr. C. Jerald Buchenauer, Research Professor
Dr. Alan Lynn, Research Assistant Professor
Dr. Sarita Prasad, Research Assistant Professor
Dr. Mehmet Su, Research Assistant Professor

Dr. James Carroll, Sandia National Laboratories (Materials Science)

Who we are – my group

Edl Schamiloglu, UNM PI

Mikhail Fuks, Research Professor
C. Jerald Buchenauer, Research Professor
Sarita Prasad, Research Assistant Professor

Ph.D. Students – Christopher Leach, Kimberly Nichols, Brock Roberts

Undergraduate Students – Artem Kuskov, Matthew Dill

Our Goals

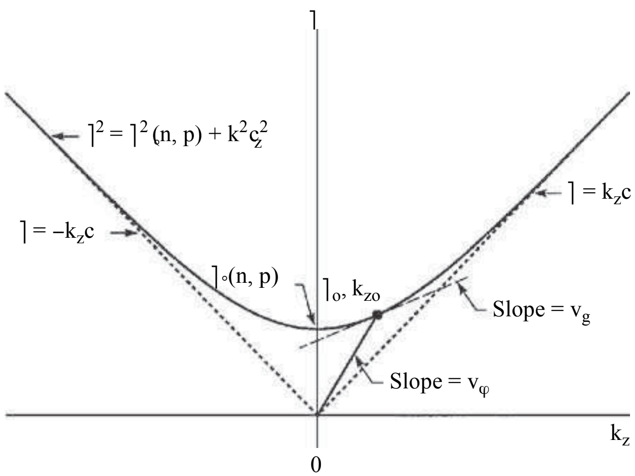
- **Sources –** Rely on dispersion engineering (all members) to propose novel beam/wave interactions (MIT – Shapiro, Ohio State – Volakis, UC Irvine – Figotin, LSU – Lipton), to exploit in experimentation (at UNM and MIT) – Edl Schamiloglu
- **Characterization -** Characterize survivability of proposed structures in experimentation using plasma diagnostics (UNM – Gilmore)
- **Exploit Metamaterials for Passive/Reconfigurable Structures –** (UNM – Christodoulou, UC - Irvine Capolino, Ohio State – Volakis)

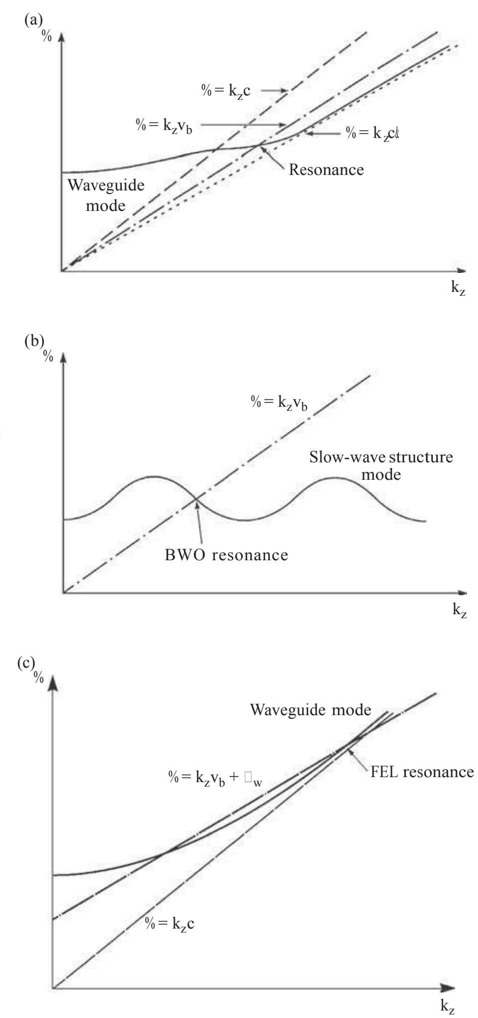
Our Goals

- **Sources –** Rely on dispersion engineering (all members) to propose novel beam/wave interactions (MIT – Shapiro, Ohio State – Volakis, UC Irvine – Figotin, LSU – Lipton), to exploit in experimentation (at UNM and MIT) – Edl Schamiloglu

- Will identify all modulators, pulsers, electron beams available to the consortium. These are at MIT and UNM, but could also be at AFRL, NRL, LANL. The parameters of all available electron beams will then inform the MTM thinkers and allow them to propose preliminary structure designs. Manufacturability and survivability are critical factors.

What we are good at:
The Importance of Dispersion Engineering





(From J. Benford, J. Swegle, and E. Schamiloglu, *High Power Microwaves, 2nd Ed.,* 2007.)

UNM was a Leader in a Paradigm Shift

• Prior to early-mid 1990s experimentalists tinkered, modeling and simulation tried to match results. Absolute agreement was poor.

• Today, no metal will be cut until simulation demonstrates optimal performance!

• Particle-in-cell (PIC) codes revolutionized the field. Developed by plasma physicists, these are 3D finite-difference-time-domain (FDTD) fully electromagnetic field solvers that incorporate relativistic dynamics. ICEPIC is a parallelized 3D development at AFRL and is the state-of-the-art in PIC. University community uses MAGIC (ATK/Mission Research, sponsored by AFOSR). Result – virtual prototyping!

• UNM, in a collaboration with AFRL and Sandia National Laboratories, led the way in understanding why PIC simulations were not in absolute agreement with experimental results (had to do with numerical damping of grid noise).

PIC Codes Rule …

Plasma physics and HPM sources

HPMs are generated from the resonant interaction of intense relativistic electron beams with electromagnetic cavities. The interaction transforms electron kinetic energy into electromagnetic energy. Mathematically analyzing the electromagnetic cavities is relatively straightforward—even for complex cavities—because of the linearity of Maxwell's governing equations. Analyzing the natural modes of the electron beam's oscillation, however, is more difficult.[3]

In principle, we could compute each individual electron's motion using the electromagnetic fields that other electrons generate—subject to the boundary constraints that the electromagnetic cavity imposes. An exact formulation yields the Klimontovich equation for the evolution of electron number density through phase space. However, directly solving the Klimontovich equation is too expensive, because the number of required computations per unit time scales at least as the square of the number of particles, and there is an unreasonably large number of particles for macroscopic physical systems. Therefore, we use the large number of particles in a realistic HPM device to justify our use of statistical mechanics, and we can describe the physics in terms of the Boltzmann transport equation together with the full Maxwell equations.[4]

The particle-in-cell method for numerically formulating these governing equations is a well understood, reliable approach, if we can assume that short-range collisional effects are, on average, small. Over the past several decades, many researchers, beginning with Oscar Buneman, have developed the PIC technique to a high degree of sophistication. In this technique, finite-sized charged particles interact with the average electromagnetic field distribution (supported on a discrete grid).[5,6] We can also include particle collisions in the PIC formulation using Monte Carlo collision models.[7]

The PIC method solves for the time advance of the magnetic and electric fields (**B** and **E**) with Faraday's law and Ampere's law (in Heaviside-Lorentz units):

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}\,, \quad \frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - \mathbf{J}\,.$$

The PIC method implements these laws on a staggered Yee grid,[8] using the well-known methods of finite-difference time domain (FDTD),[9] where **J** represents the current density and c is the speed of light. The Maxwell divergence equations are initial value constraints, and the computational methods must preserve these constraints.[10] We close these equations by "pushing" particles due to the electromagnetic forces, according to the Newton-Lorentz force equation.[11] The moving charged particles collectively define **J**, which then serves as the source term in Ampere's law.

From R.E. Peterkin and J. Luginsland, "A Virtual Prototyping Environment For Directed-energy Concepts," *Computing in Science and Engineering,* March/April 2002, pp. 42-49.

Specifically, the relativistic Newton-Lorentz force equation

$$\mathbf{F} = m\frac{d\mathbf{u}}{d\tau} = q\left(\gamma\mathbf{E} + \frac{1}{c}\mathbf{u}\times\mathbf{B}\right),$$

determines a particle's relativistic velocity **u** in terms of proper time τ, where

$$\frac{d\mathbf{x}}{d\tau} = \mathbf{u} = \gamma\mathbf{v},$$

determines a particle's new position in response to the electromagnetic forces, and γ is the usual relativistic factor $(1 - \mathbf{v}^2/c^2)^{-1/2}$.

The charged particles are representative phase-space markers called *macroparticles*. These macroparticles have the same charge-to-mass ratio as the real particle (such as an electron) under study, but we can multiply both quantities by a factor N so that the macroparticle can be thought to represent N physical electrons at a given location in a phase-space of velocity and position. Because we preserve the charge-to-mass ratio, the macroparticle responds to forces in a physically accurate way. This lets us simulate kinetic plasma physics without relying on fluid approximations. It also lets us retain the full phase-space features of the distribution function. We can interpret the PIC method as a direct computational implementation of a Klimotovich formulation for macroparticles.[12]

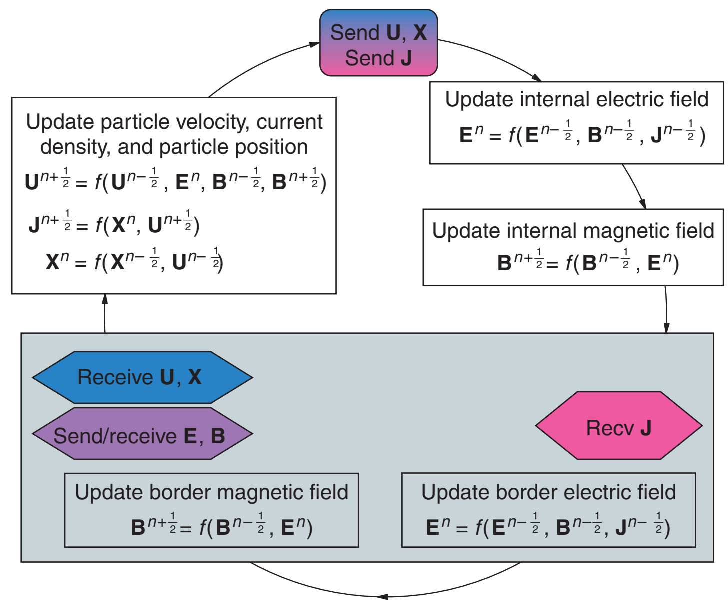


Figure 1. The modified particle-in-cell loop for the Improved Concurrent Electromagnetic Particle-In-Cell software. (J represents the current density, and B and E are the magnetic and electric fields.)

852 IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 24, NO. 3, JUNE 1996

Enhanced Frequency Agility of High-Power Relativistic Backward Wave Oscillators

Larald D. Moreland, Edl Schamiloglu, *Senior Member, IEEE*, Raymond W. Lemke, A. M. Roitman, S. D. Korovin, and V. V. Rostov

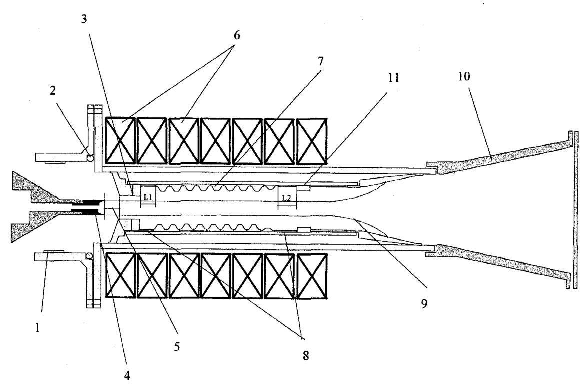
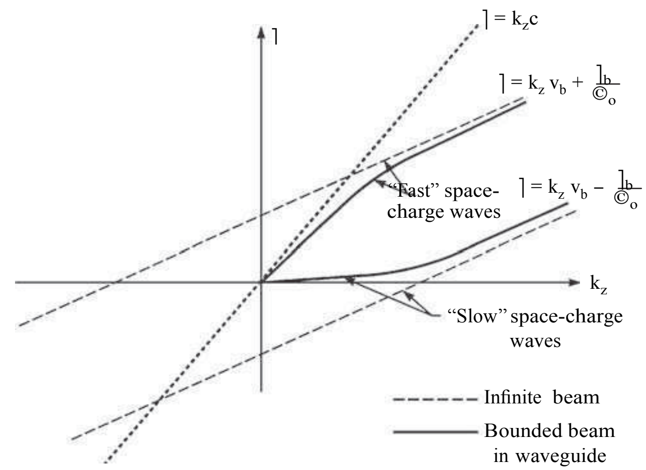


Fig. 1. Experimental setup for BWO experiments with forward and backward shifting. Shown in the diagram are (1) capacitive voltage divider, (2) Rogowski coil, (3) cutoff neck, (4) cathode, (5) A–K gap, (6) magnetic field coils, (7) slow wave structure, (8) smooth circular waveguide and shifting lengths L_1 and L_2, (9) electron beam, (10) output horn antenna, and (11) reflection ring.



PIC Codes Rule …

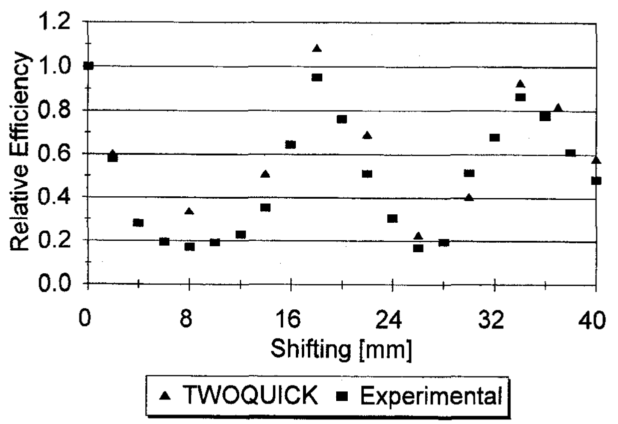


Fig. 2. Relative efficiency as a function of forward shifting as observed in experiment and TWOQUICK simulations.

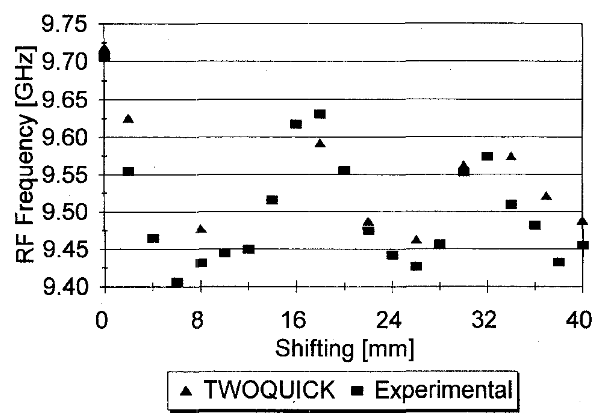


Fig. 3. RF frequency as a function of forward shifting as observed in experiment and TWOQUICK simulations.

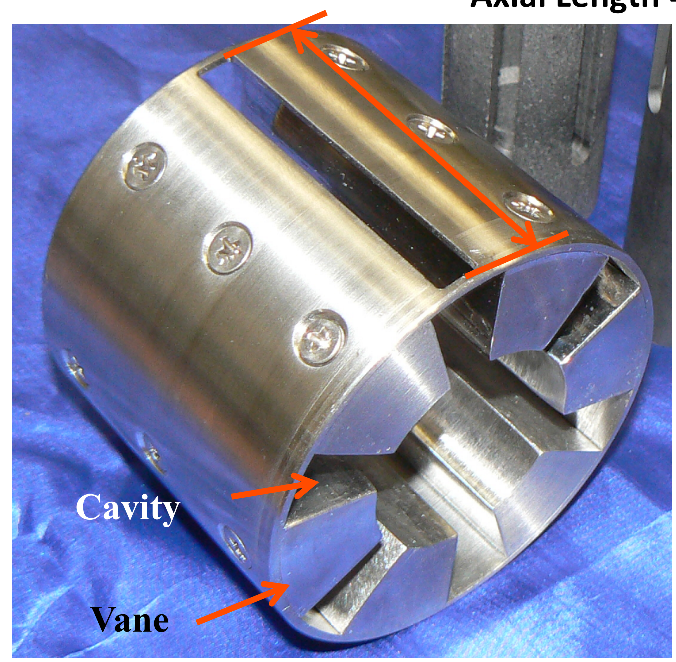
MAGIC PIC Code - Relativistic Magnetron

A6 Magnetron (G. Bekefi, MIT, late 1970s)

Radius of the Vane = 2.11 cm

Radius of the Cavity = 4.11 cm

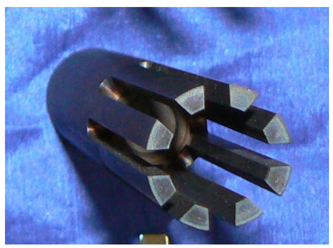
Radius of the Cathode = 1.58 cm

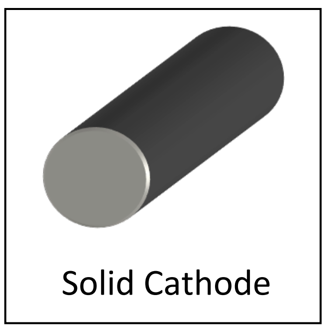


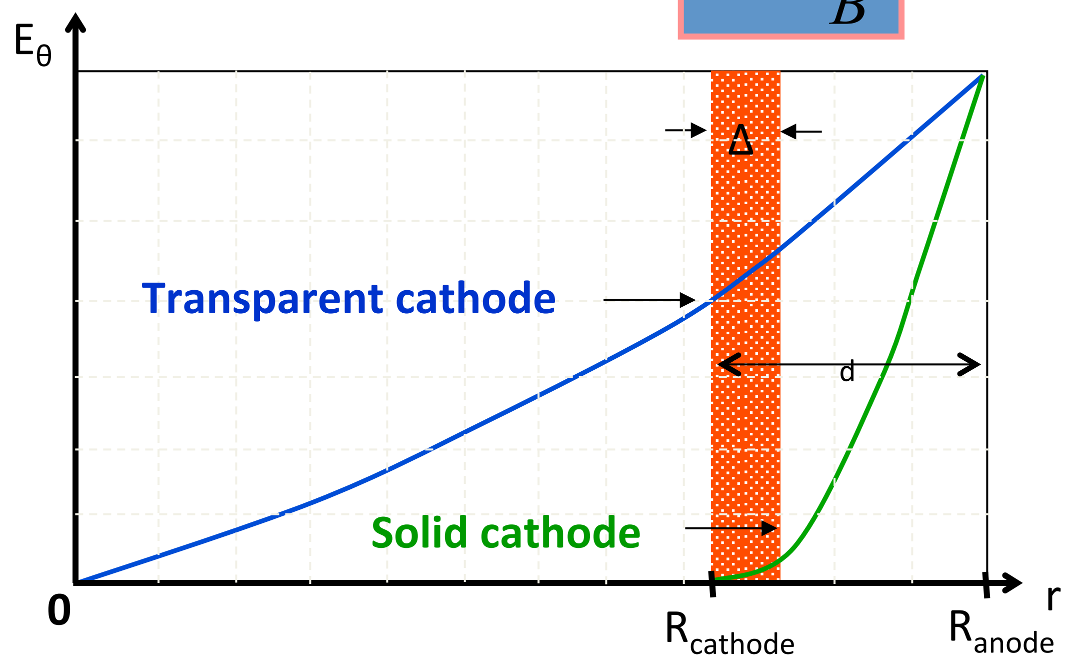
Relativistic Magnetron Driven by a Transparent Cathode

The rate of energy transfer from the electrons to the RF field

$$v_r = \frac{E_\theta}{B}$$





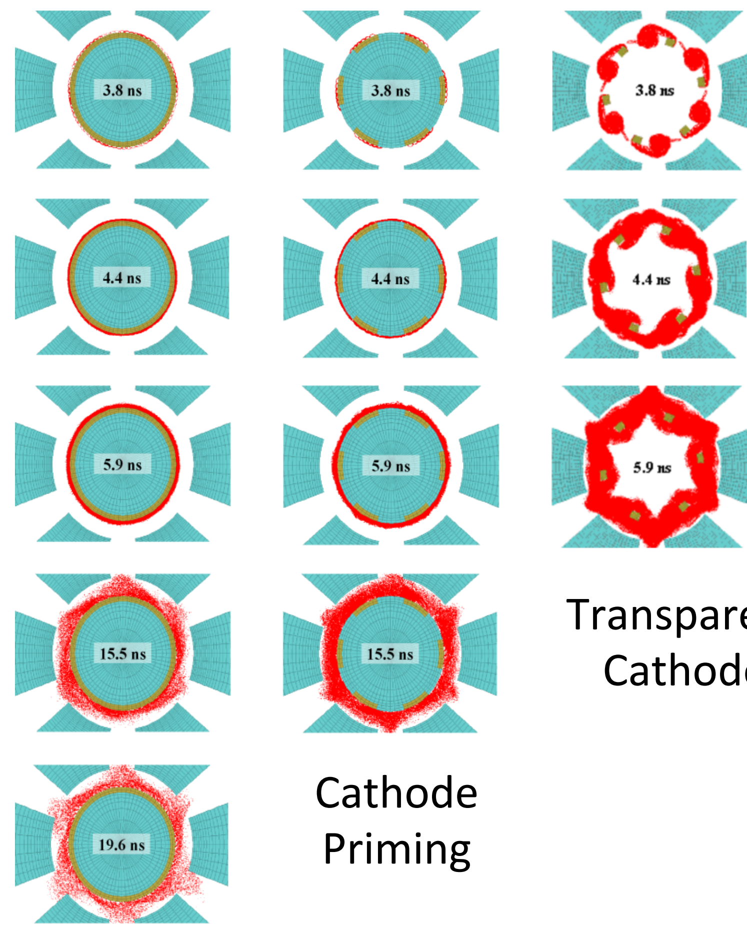


Azimuthal Electric Field Distribution

[1] M.I. Fuks and E. Schamiloglu, "Rapid Start of Oscillations in a Magnetron with a "Transparent Cathode"," *Phys. Rev. Lett.* vol. 95, 205101-1-4 (2005). Two patents have been issued (2010, 2011).

Relativistic Magnetron

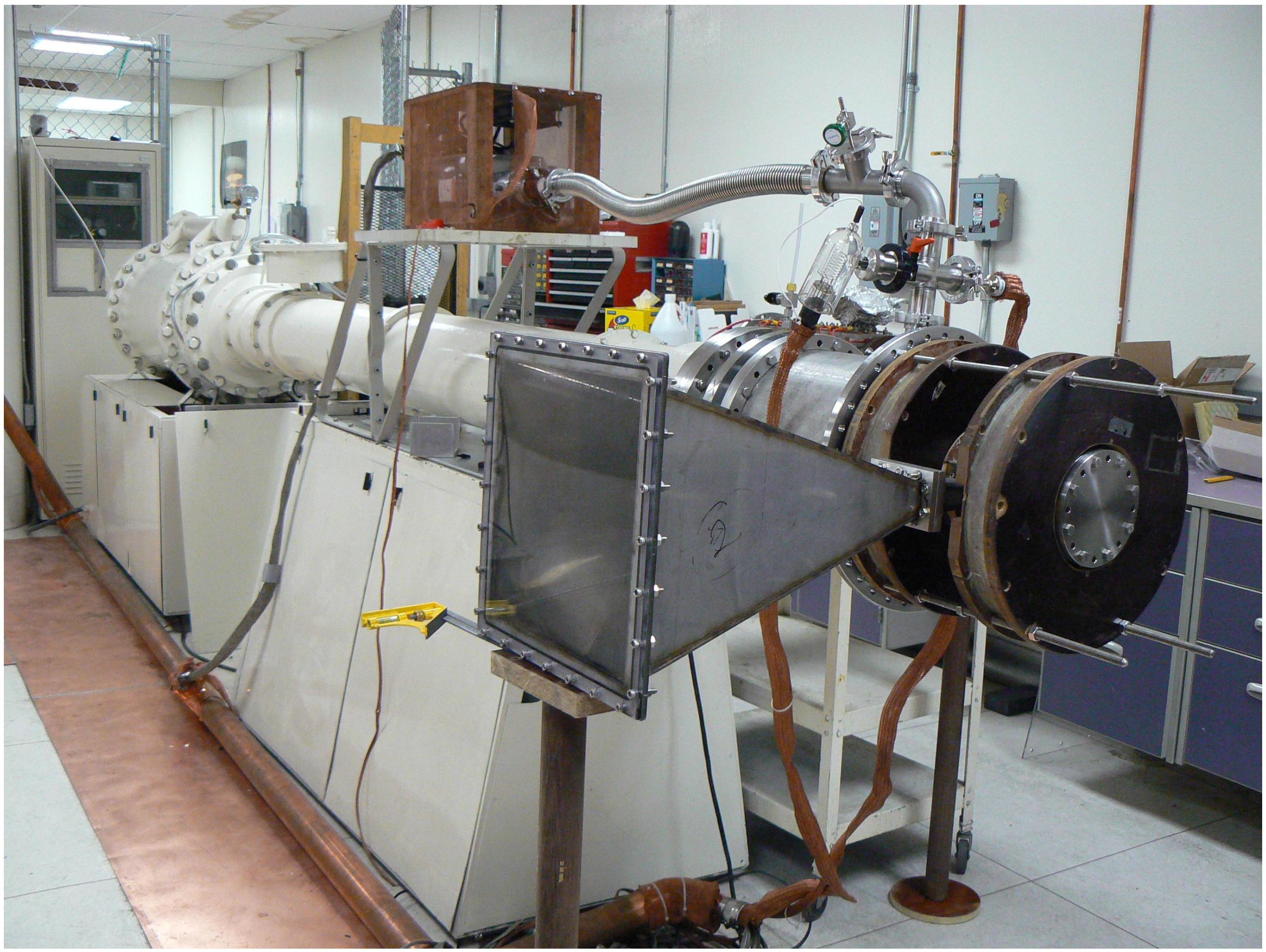
Comparison of electron spoke formation time for three different cathodes in an A6 magnetron. (From MAGIC particle-in-cell simulations.)



PIC Codes Rule …

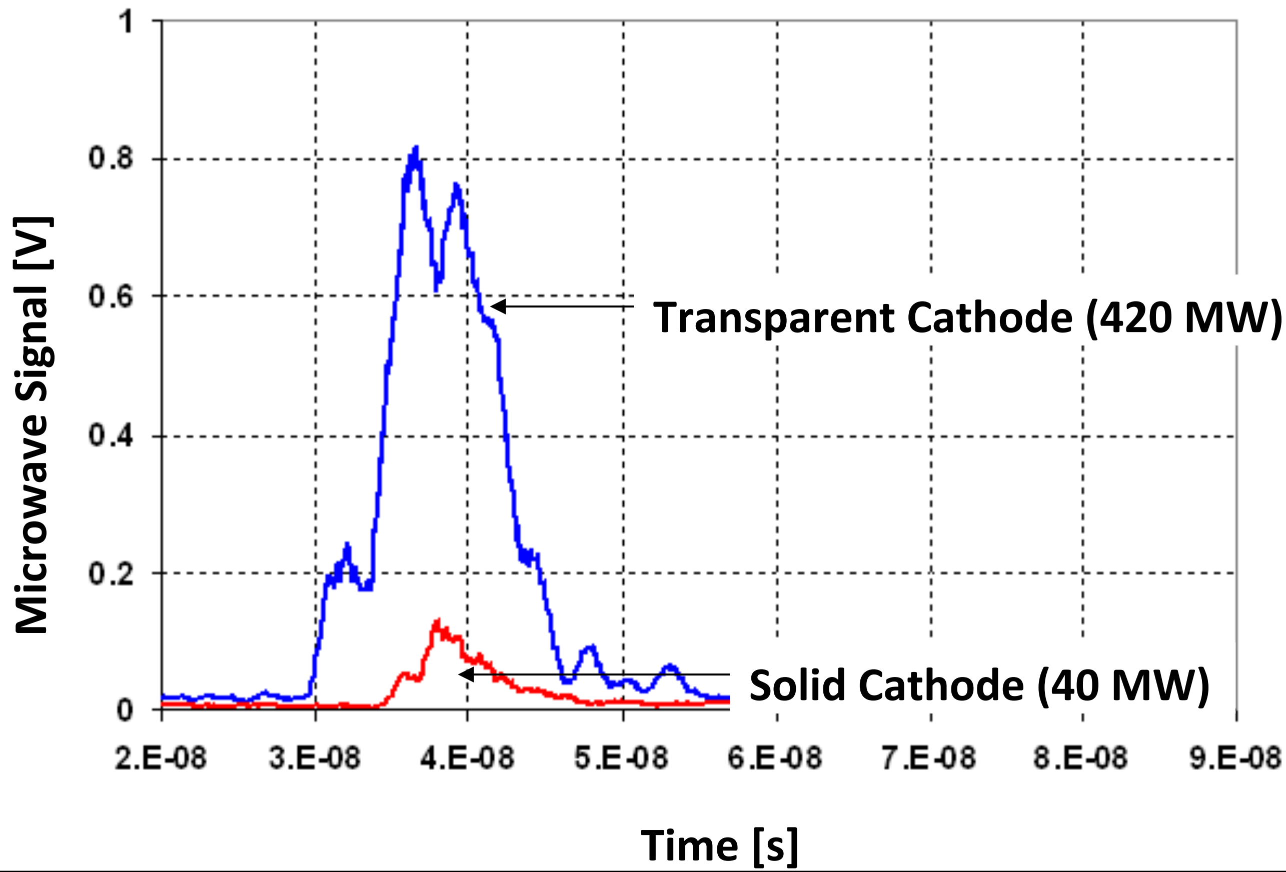
Relativistic Magnetron

UNM's SINUS-6 Configured for Relativistic Magnetron Experiments



Relativistic Magnetron

Experimental Result – Sarita Prasad's Dissertation

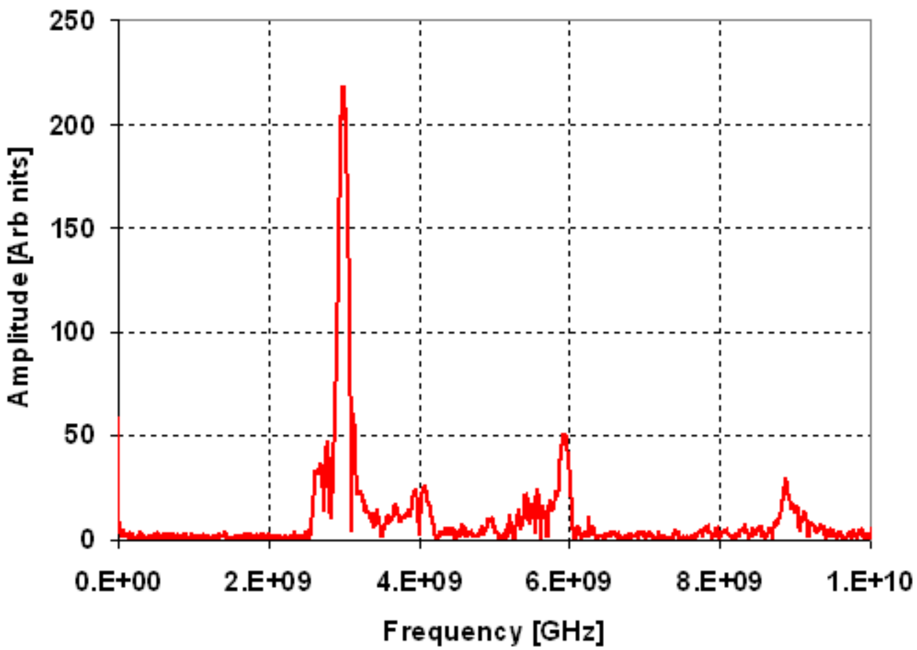


NOTE: Ratio of transparent cathode to solid cathode performance in experiments consistent with predictions. Absolute values are lower since available voltages in experiments lower than those used in simulations.

Relativistic Magnetron

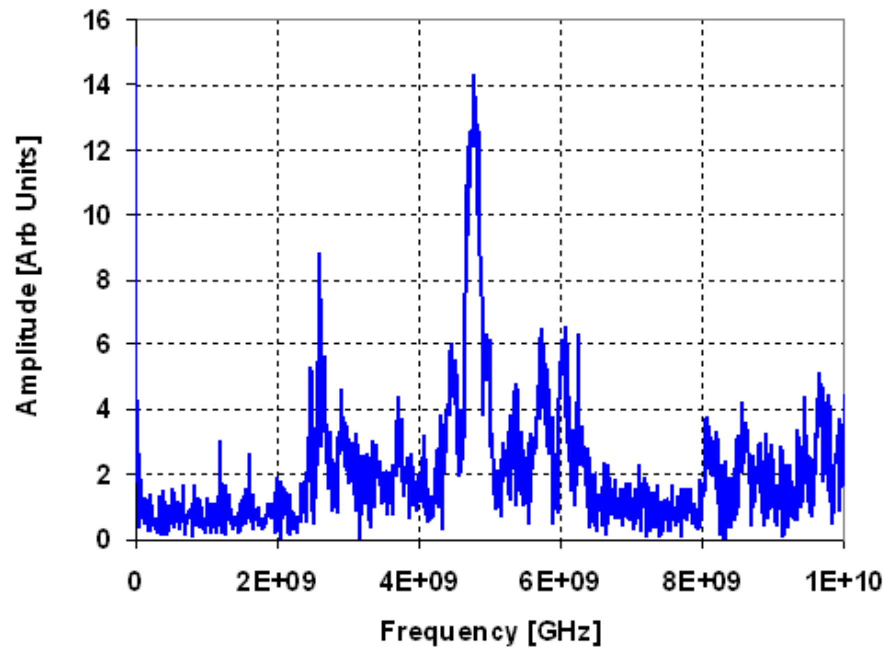
Sarita Prasad's Dissertation

Transparent Cathode



Frequency = 2.9 GHz
π-mode

Solid Cathode



Frequency = 4.8 GHz
4π/3-mode

Relativistic Magnetron with Diffraction Output Driven by Transparent Cathode

1302 IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 38, NO. 6, JUNE 2010

70% Efficient Relativistic Magnetron With Axial Extraction of Radiation Through a Horn Antenna

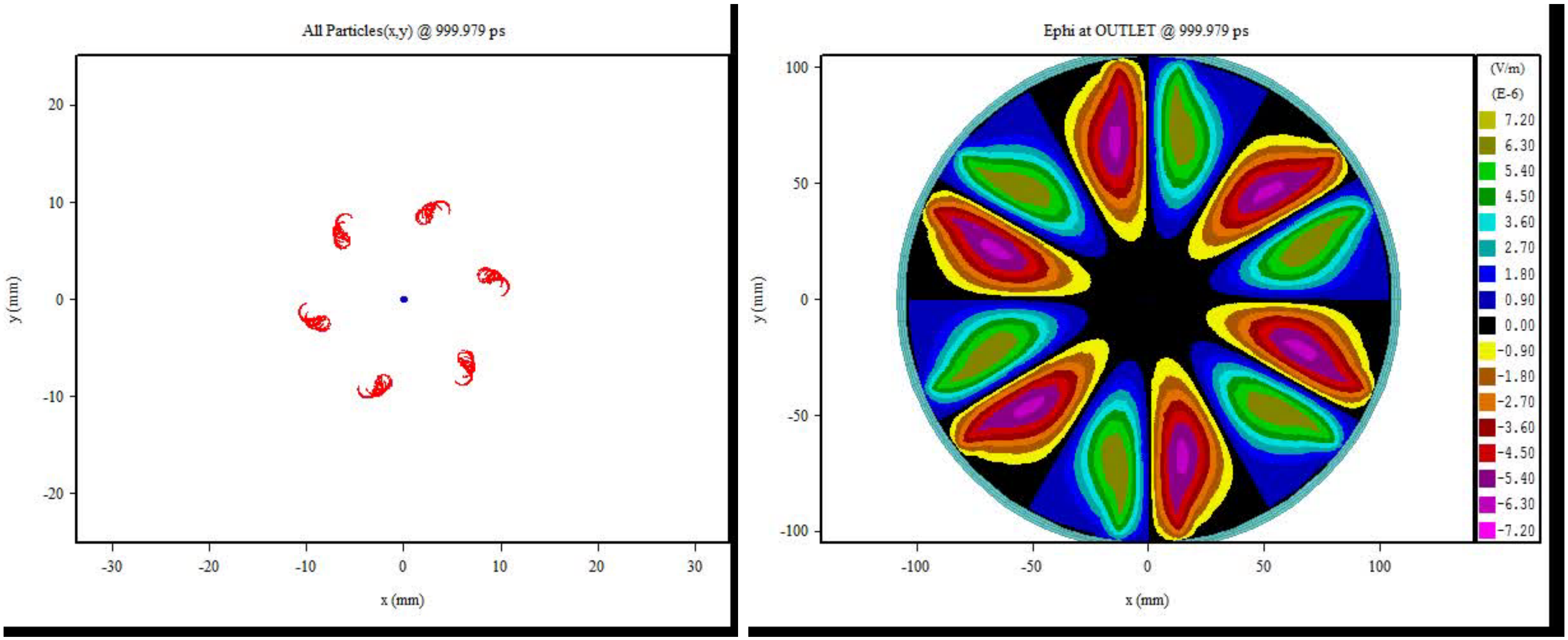
Mikhail I. Fuks, *Senior Member, IEEE*, and Edl Schamiloglu, *Fellow, IEEE*

***Abstract*—At the Nagaoka University of Technology (Japan), Daimon and Jiang used particle-in-cell (PIC) code simulations to demonstrate that the electronic efficiency of the A6 magnetron with axial extraction can be increased from 3% up to 37% applying different diffraction outputs, from tapered cavities in a conical horn antenna to modified expanded ones that improve magnetron matching with the antenna. This paper presents PIC code simulation results for the modified magnetron design using a transparent cathode, in contrast with Daimon and Jiang's simulations that used a solid explosive emission cathode. Furthermore, by further optimizing the magnetron parameters, we demonstrate an efficiency approaching 70% with gigawatt radiation power for an applied voltage of 400 kV. By maintaining a synchronous interaction of electrons with the operating wave, we found that the radiation power increases as the square of the diode voltage up to a diode voltage of 800 kV with short rise time that does not exceed 20 ns. In addition, we show that using a transparent cathode promotes avoiding the regime of hard excitation of magnetrons.**

***Index Terms*—Diffraction output (DO), mode conversion, radiation pattern, relativistic magnetron, transparent cathode.**

Fig. 1. The X-band magnetron used in experiments [1], [2].

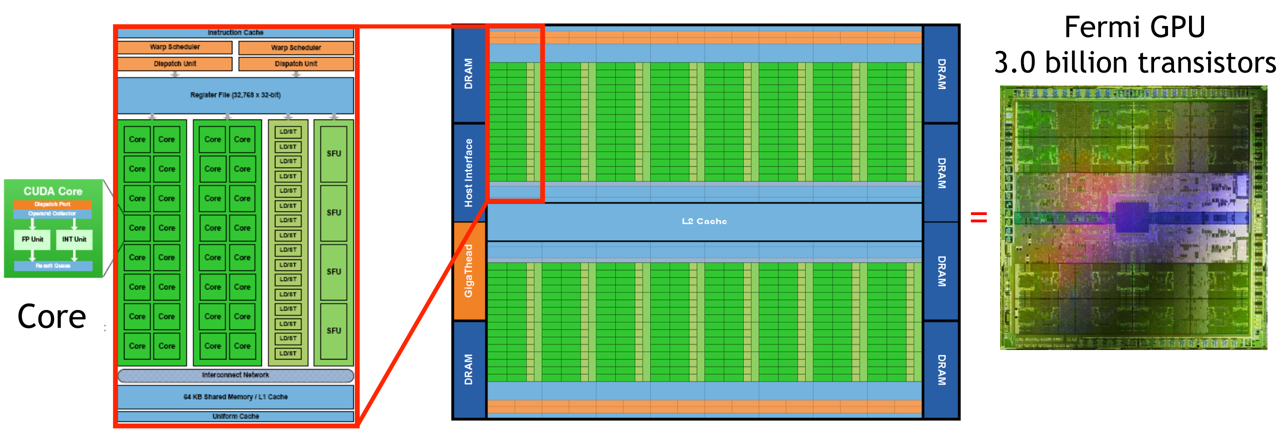
Relativistic Magnetron With Axial Extraction – 4π/3 Mode Operation



PIC Codes Rule … Except when d<<λ!

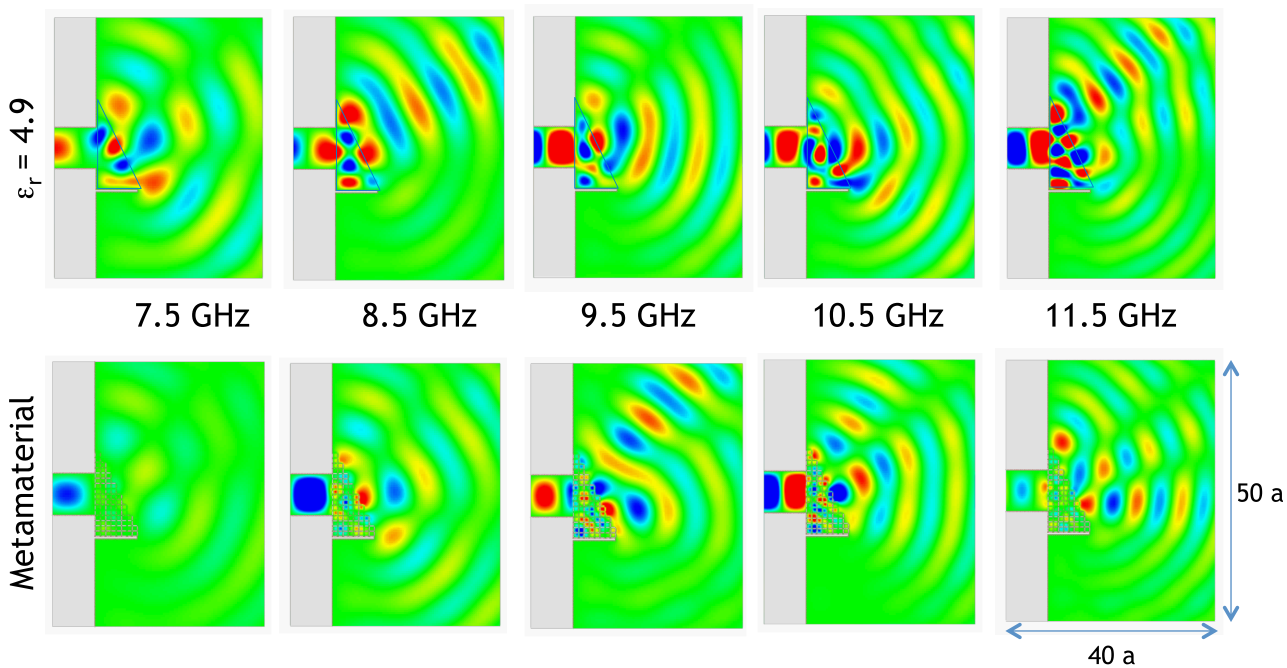
Need more powerful tools! Will collaborate with:

- AFRL – ICEPIC (Peter Mardahl *et al.*)
- NRL – NEPTUNE (Simon Cooke *et al.*)
  - Parallel computing hardware
    - ✓ Multi-core CPUs - Using Intel's Threading Building Blocks Library
    - ✓ Graphics Processing Units (GPUs) - Using Nvidia's CUDA library
    - – Cluster computing
  - GPU computing: 512 cores, 3Gb memory, $600



PIC Codes Rule … Except when d<<λ!

Metal inclusions significantly modify the effective material properties:



50x1x40 unit cells, 16x8x16 unit-cell grid → 800x8x640 ~ 4M cells

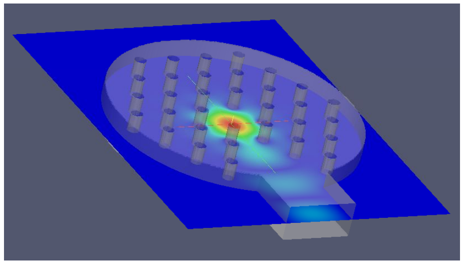
Neptune slides courtesy of Simon Cooke.

PIC Codes Rule … Except when d<<λ!

"MIT" Photonic Bandgap Cavity

Mode confinement in a photonic bandgap structure

CE-ADI-FDTD achieves very high simulation rate

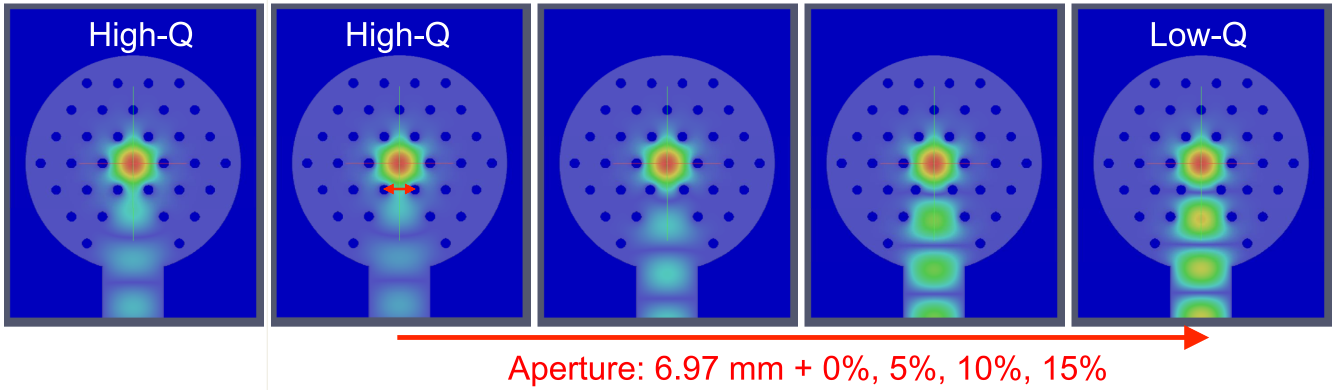


268 x 34 x 334 = 3.04 Mcells
200 rf periods

FDTD	CE-ADI-FDTD
cΔt=0.006 λ 94.6s	cΔt=0.25 λ 32.3s
	cΔt=1.00 λ 8.25s

```
94.538s / 33417 steps
   2.829 ms/step
1075.7   Mcell.steps/s
   6.43  Mcell.periods/s
```

```
 8.257s / 200 steps
41.288  ms/step
73.7    Mcell.steps/s
73.618  Mcell.periods/s
```



PIC Codes Rule … Except when d<<λ!

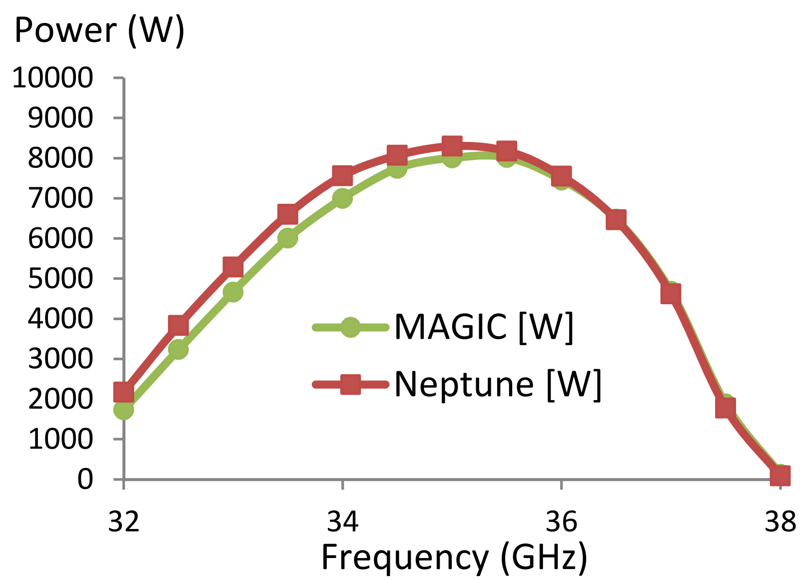


Figure 4. Comparison between MAGIC and Neptune simulations of large-signal CCTWT amplifier operation.

GPU-Accelerated 3D Large-Signal Device Simulation Using the Particle-in-Cell Code 'Neptune'

Simon J. Cooke, Igor A. Chernyavskiy, George M. Stanchev, Baruch Levush
Naval Research Laboratory, Code 6841,
4555 Overlook Ave. S.W., Washington, DC 20375
(simon.cooke@nrl.navy.mil)

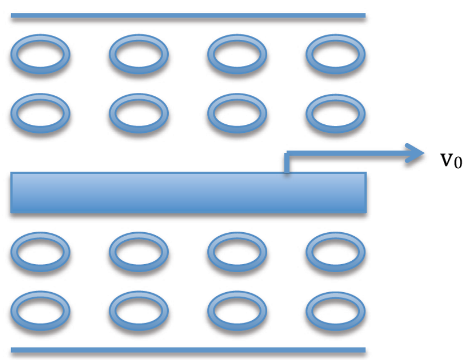
Thomas M. Antonsen Jr.
Science Applications International Corporation,
1710 SAIC Drive, McLean, VA 22102.

One path forward – Quadrupole Strong Focusing

(Kim Nichols Ph.D.)

Study of Beam with Interaction Circuit

- The transported beam will be studied for interaction in a TWT structure
- The beam characteristics could influence efficiency
- Optimization of gap shunt impedance (R/Q)
- A possible TWT structure for it to be studied in is an MTM (artificial dielectric) structure (to maximize gain and bandwidth) such as this electron beam in a circular waveguide surrounded by a sub-wavelength metal dielectric structure:



Next Portion of UNM Work:

- **Characterization -** Characterize survivability of proposed structures in experimentation using plasma diagnostics (UNM – Gilmore)

- **Exploit Metamaterials for Passive/ Reconfigurable Structures –** (UNM – Christodoulou, UC - Irvine Capolino, Ohio State – Volakis)