Plasma and Electro-energetic Physics

07 March 2012

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Integrity ★ Service ★ Excellence

Report Documentation Page

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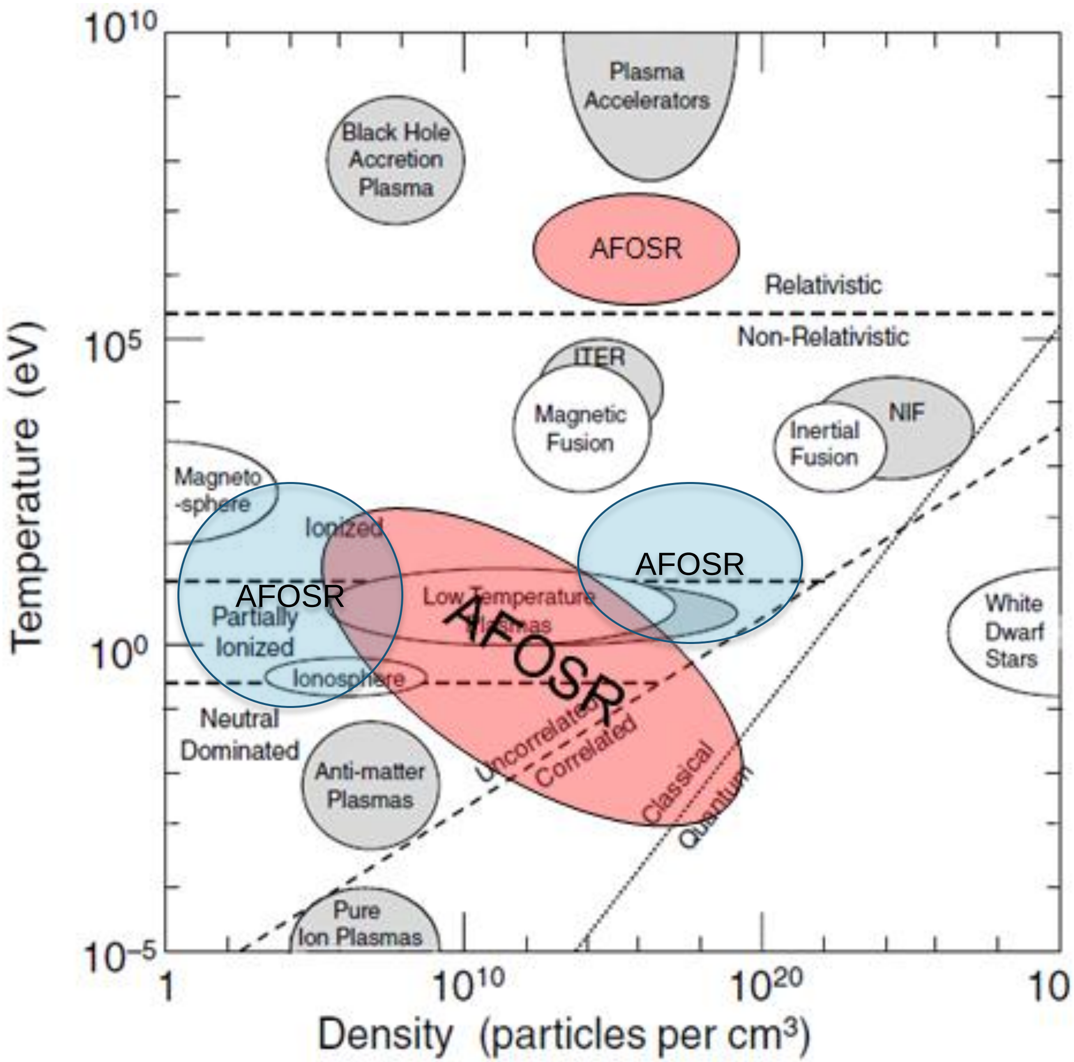
Plasma and Electro-Energetic Physics

NAME: John Luginsland , Plasma and Electro-energetic Physics

<u>BRIEF DESCRIPTION OF PORTFOLIO</u>: Explore scientific opportunities in plasmas and electro-energetic physics where *<u>energy-dense objects</u>* powered by electromagnetic energy can provide new vistas in high-power electronics, plasma-enabled chemistry, and fluid/turbulence dynamics arenas

<u>Sub-area</u>: High Power Microwave (HPM) sources, non-equilibrium plasmas, and pulsed power

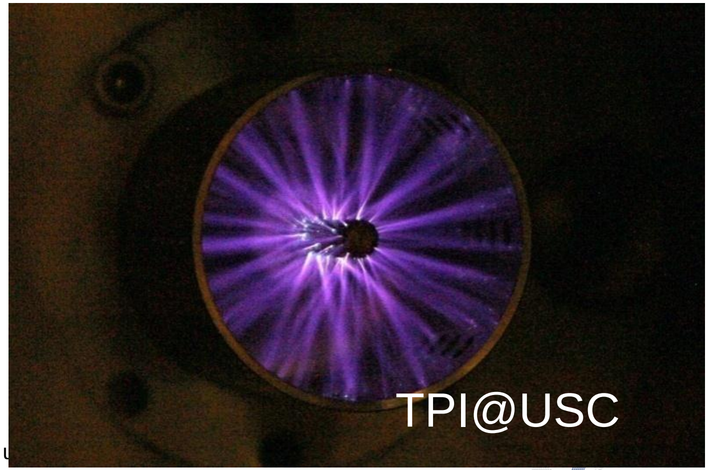


Plasma and Electro-Energetic Physics

WHY PLASMA?

Fundamental science to support AF needs in multiple applications:

- **Electronic attack & non-lethal weaponry**
- **Electronic warfare**
- **Long range, high resolution radar**
- **Long range, large bandwidth communications**
- **Compact chemical reactors (e.g. ozone, nanoparticle production)**
- **Plasma combustion (higher fuel efficiency, lower emission)**
- **Counter-directed energy**
- **Flight dynamics**
- **Turbulence control**
- **Ionosphere science (heaters)**



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Plasma - why it's hard…

Maxwell's Dynamical Equations (with complex surfaces):

$$\nabla \times E = -(1/c)\partial B / \partial t$$

$$\nabla \times H = (4\pi / c)\underline{J} + (1/c)\partial D / \partial t$$

Subject to the initial value constraints:

$$\nabla \cdot B = 0$$

$$\nabla \cdot D = 4\pi\underline{\rho}$$

With macroscopic media (complex, dispersive):

$$D = \varepsilon E$$

$$B = \mu H$$

Relativistic Lorentz Force Law for relativistic momentum *p* and velocity *u*:

$$dp / d\tau = (q/c)\left[\gamma c E + u \times B\right]$$

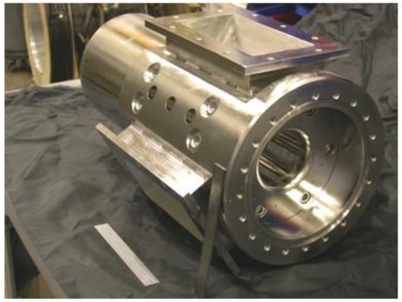
Source ρ,J

"7D," nonlinear, electro-dynamics & statics, relativistic statistical mechanics, self-DC and AC fields, and QM

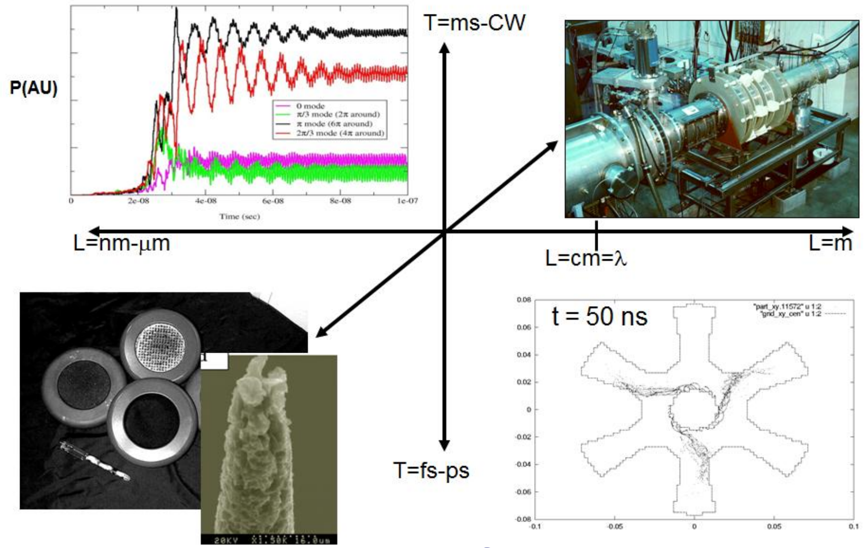
Plasma and Electro-energetic Physics

Physics Far From Equilibrium

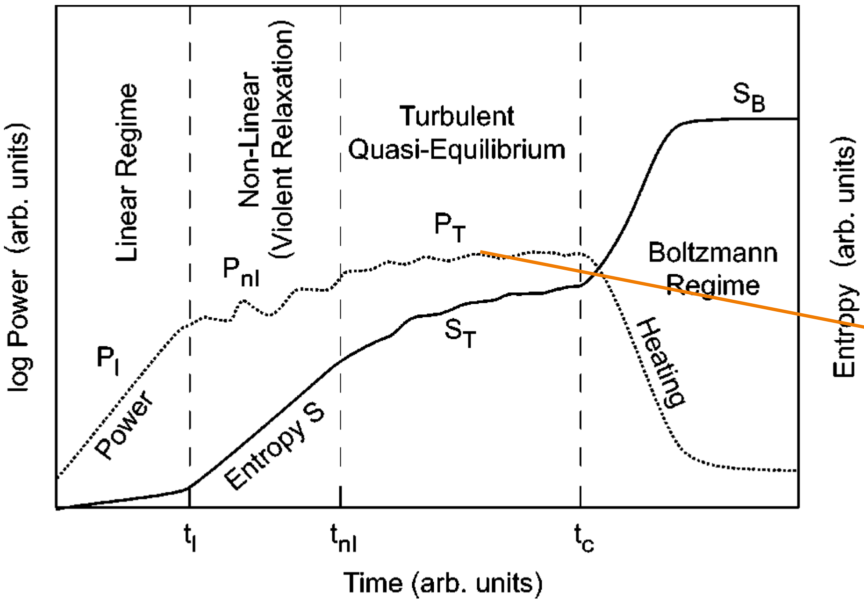
We strive to understand, predict, engineer, and invent high-energy density systems and quantify "performance" using fundamental *experimental, mathematical, computational, and diagnostic methods*

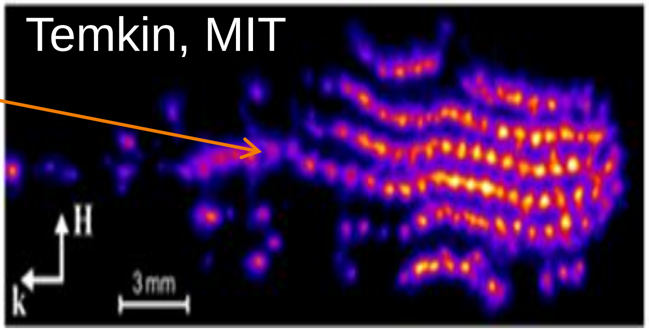


~GW for *short* periods



"Tyranny of scales"

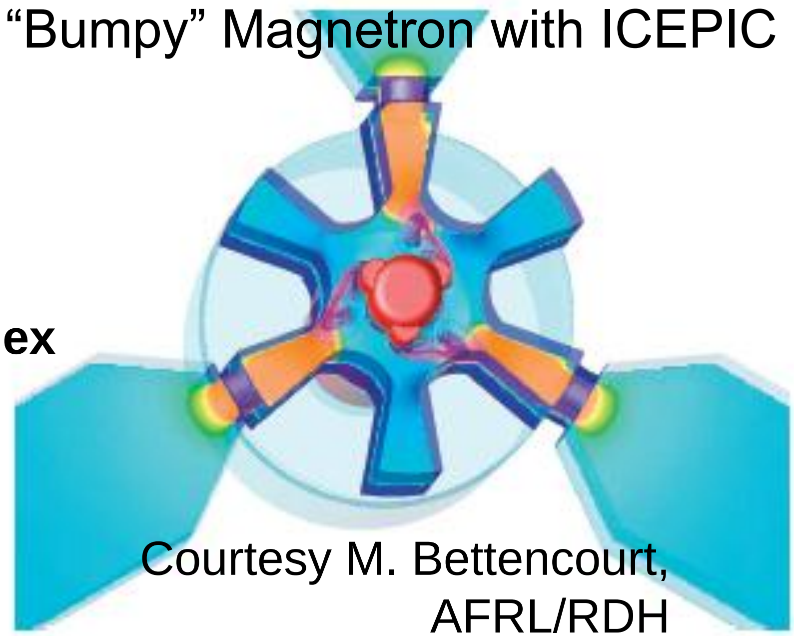




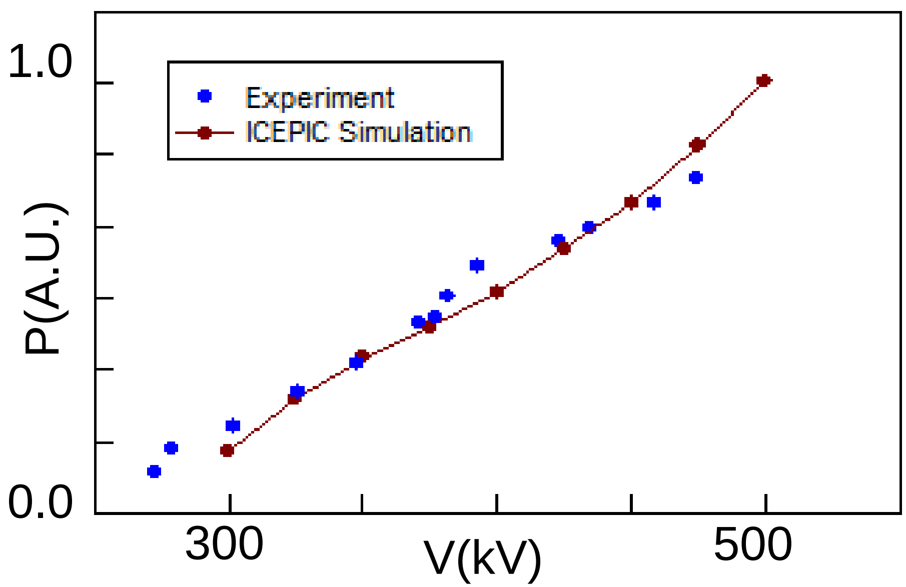
High Power Microwaves

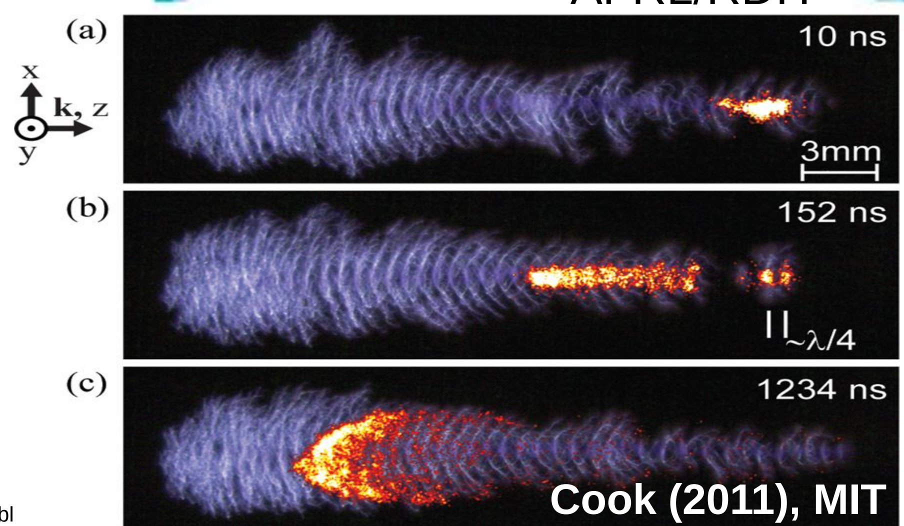
- **HPM and vacuum electronics has demonstrated Pf² (energy density) doubling every 26 month since 1930**
  - **MW-GW, ~30-40% efficient, 0.1-1 μs**
- **3D, high-fidelity, parallel modeling of high energy density fields and particles in complex geometry with <u>some</u> surface effects**
- **Regularly reach the limit of air breakdown**

"Bumpy" Magnetron with ICEPIC



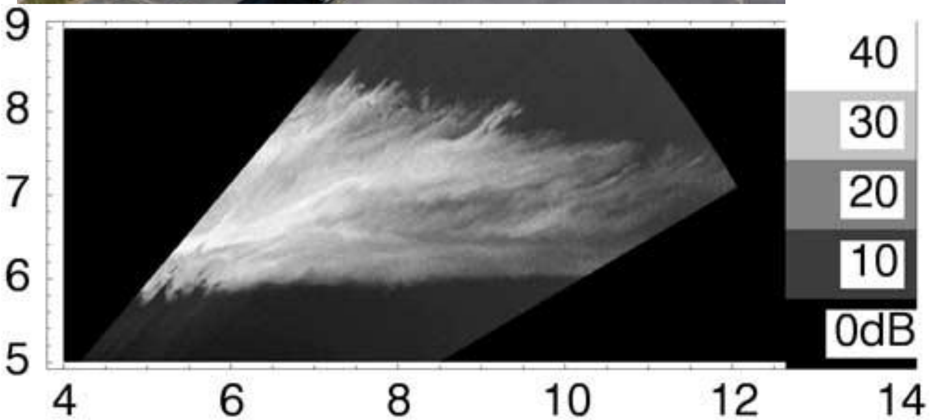
Courtesy M. Bettencourt, AFRL/RDH



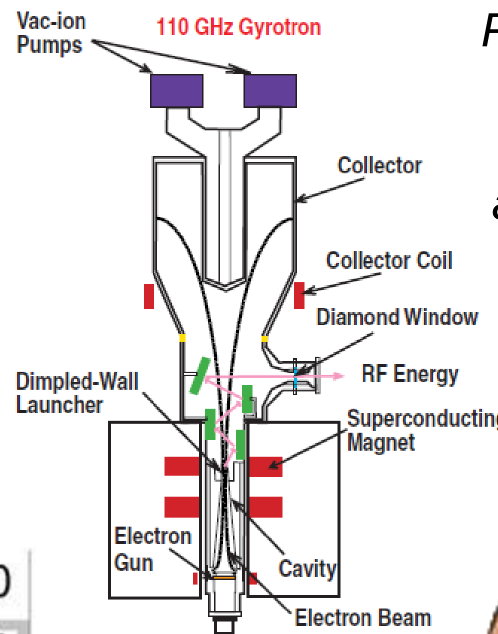


Cook (2011), MIT

Amplifiers vs Oscillators
A Grand Challenge

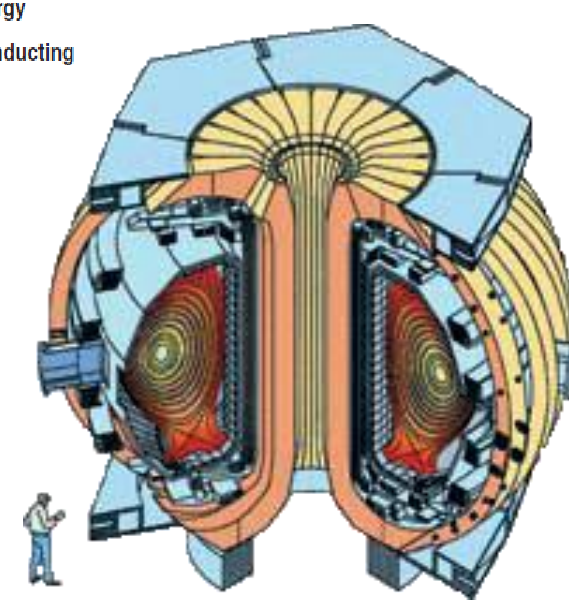


94 GHz, 80kW (10kW ave),
700MHz BW



Fundamental challenge in mating high power (nonlinearity) and amplification (linearity)

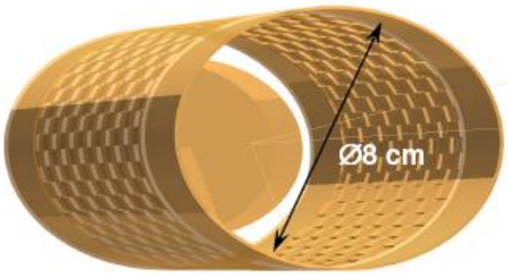
ITER/D3D

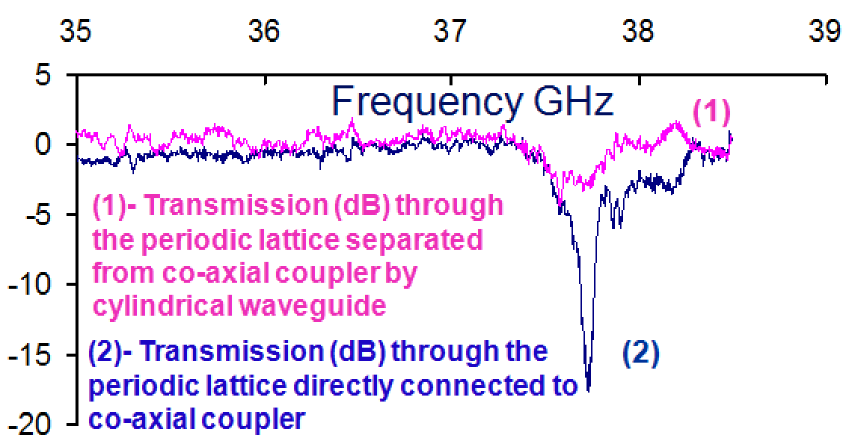


110 GHz, 1MW (10s pulse),
1.1 MHz BW

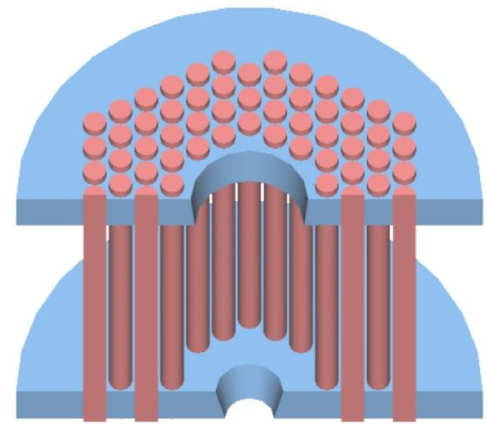
Single Modes in 3D Devices
(Science for Dispersion Engineering)

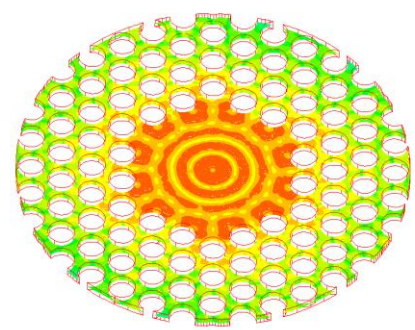
Ka-Band Maser@Ustrathclyde (Cross)

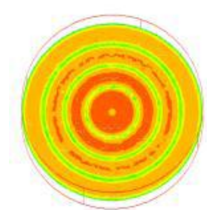




140GHz Gyrotron@MIT (Temkin)







Modern EM structures to provide single mode operation

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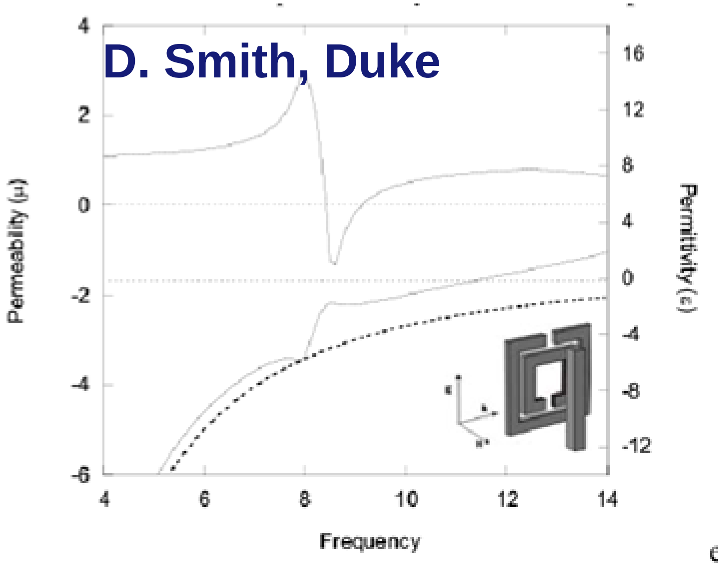
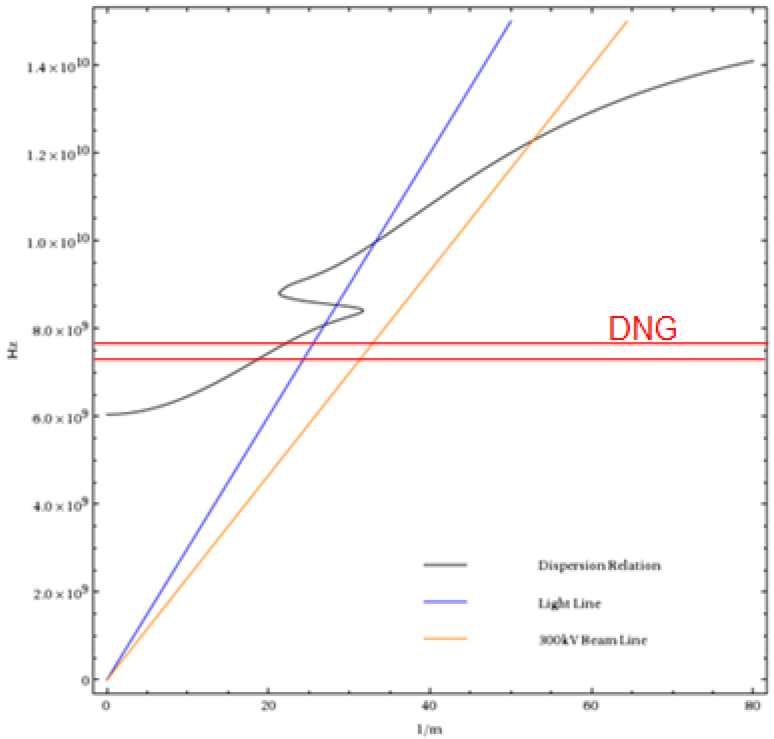
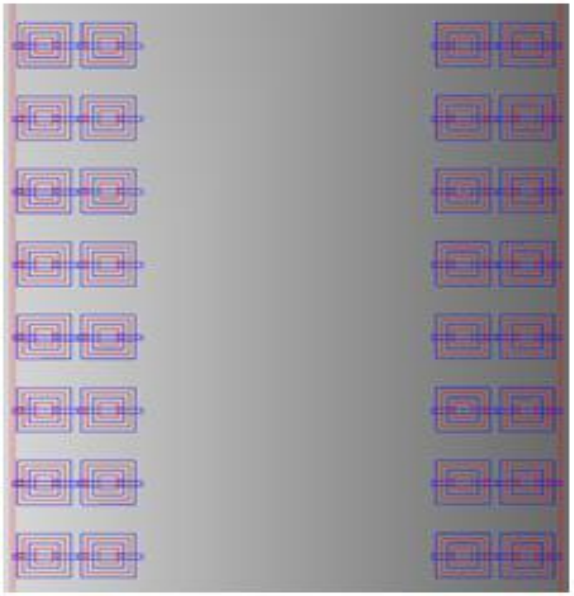
High Power Metamaterials (AFLR/RD)







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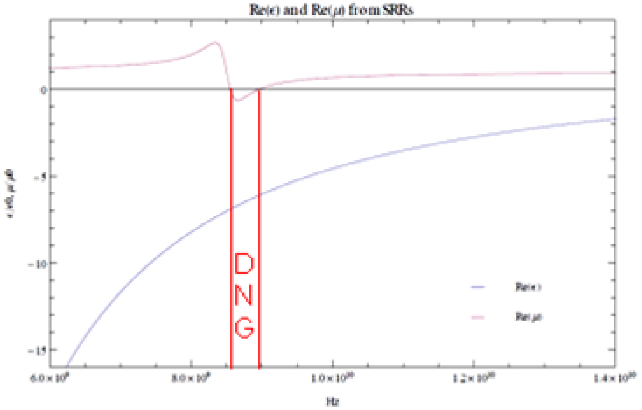
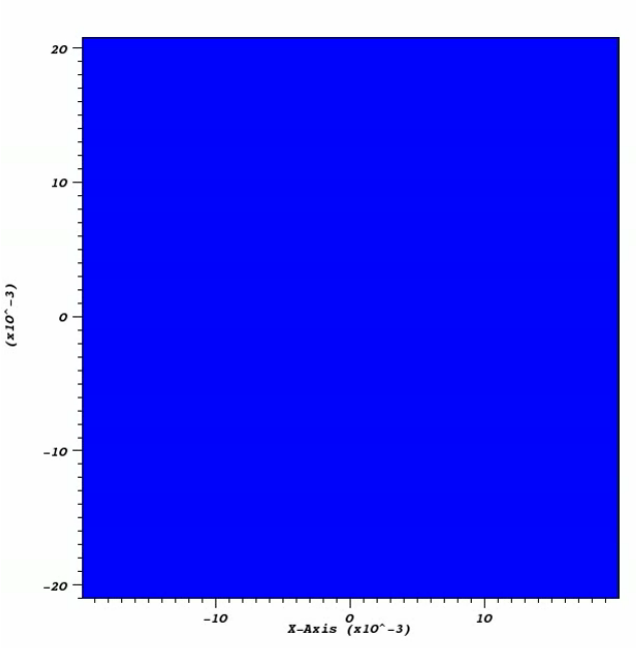
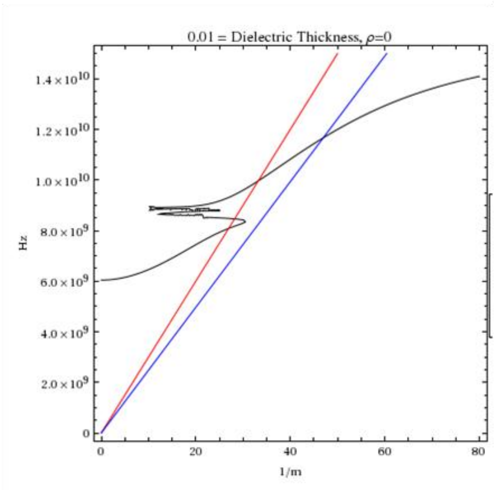
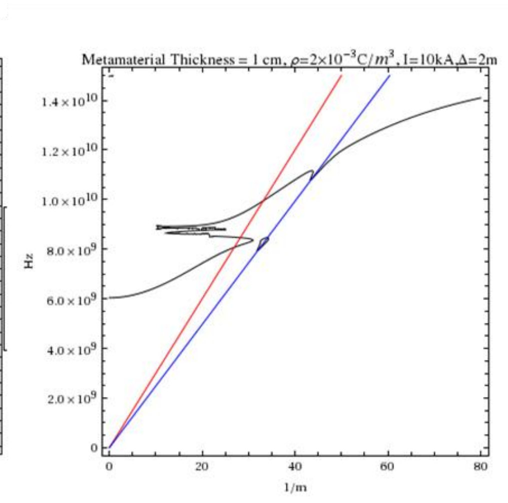
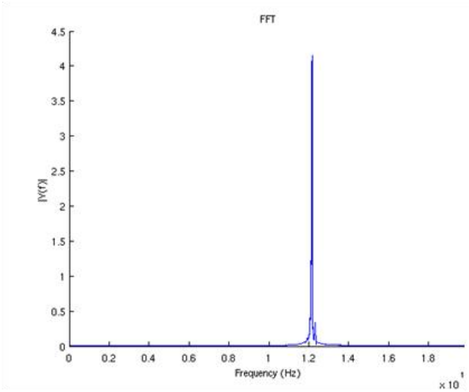


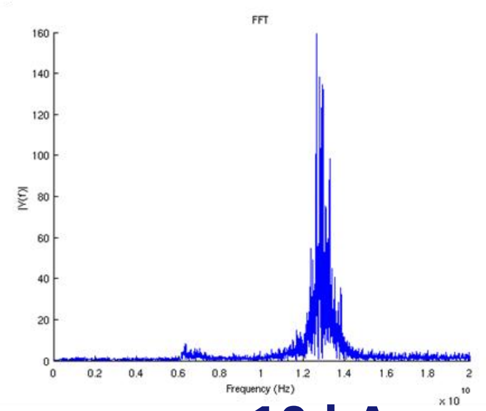
Beam-Wave Interaction (Plasmon Mode and Beam-loading)



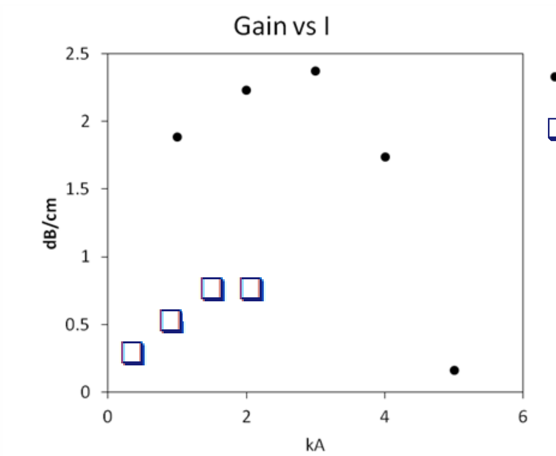








1A **10 kA**



- **300kV, AFRL MM**
- ❑ **500kV, SLAC MBK**

Current density nonlinearly detunes the structure

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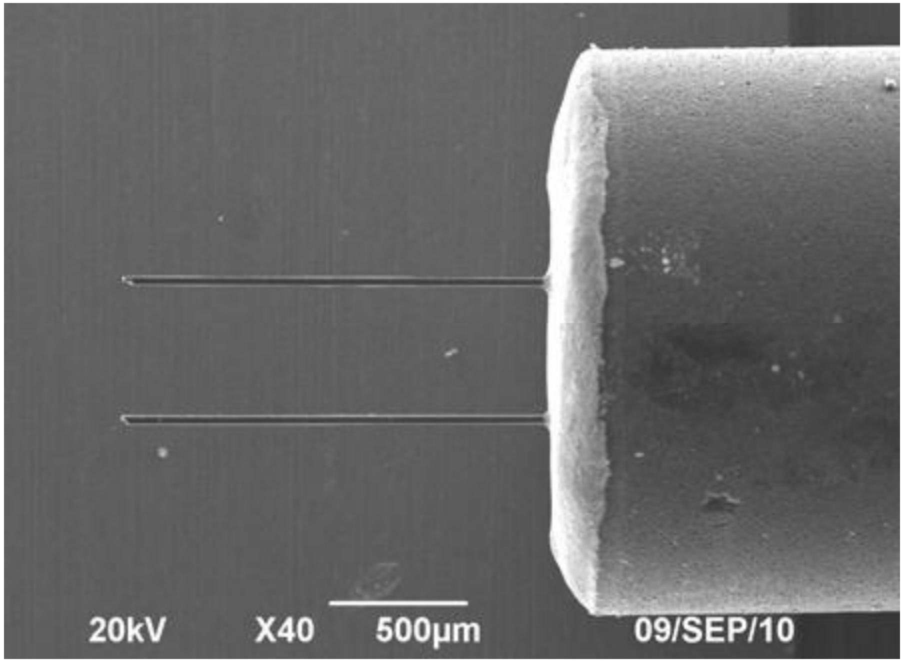
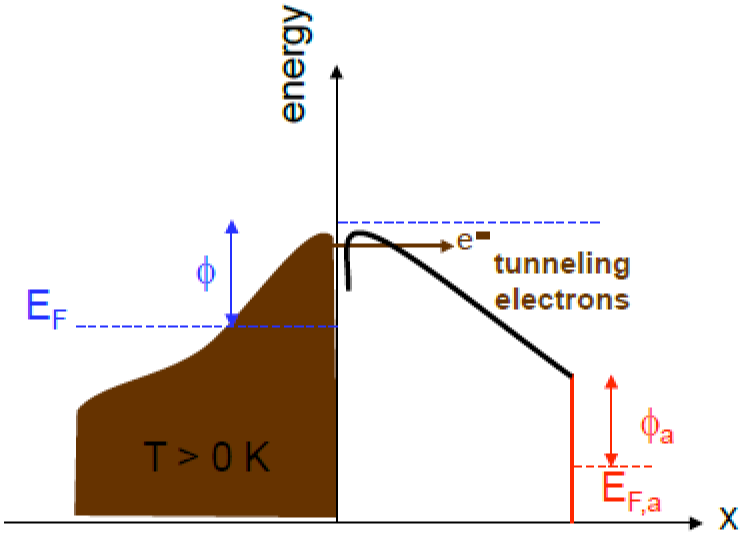
Field Emission Physics



SEM image of the dual carbon fiber cathodes (500 µm separation)



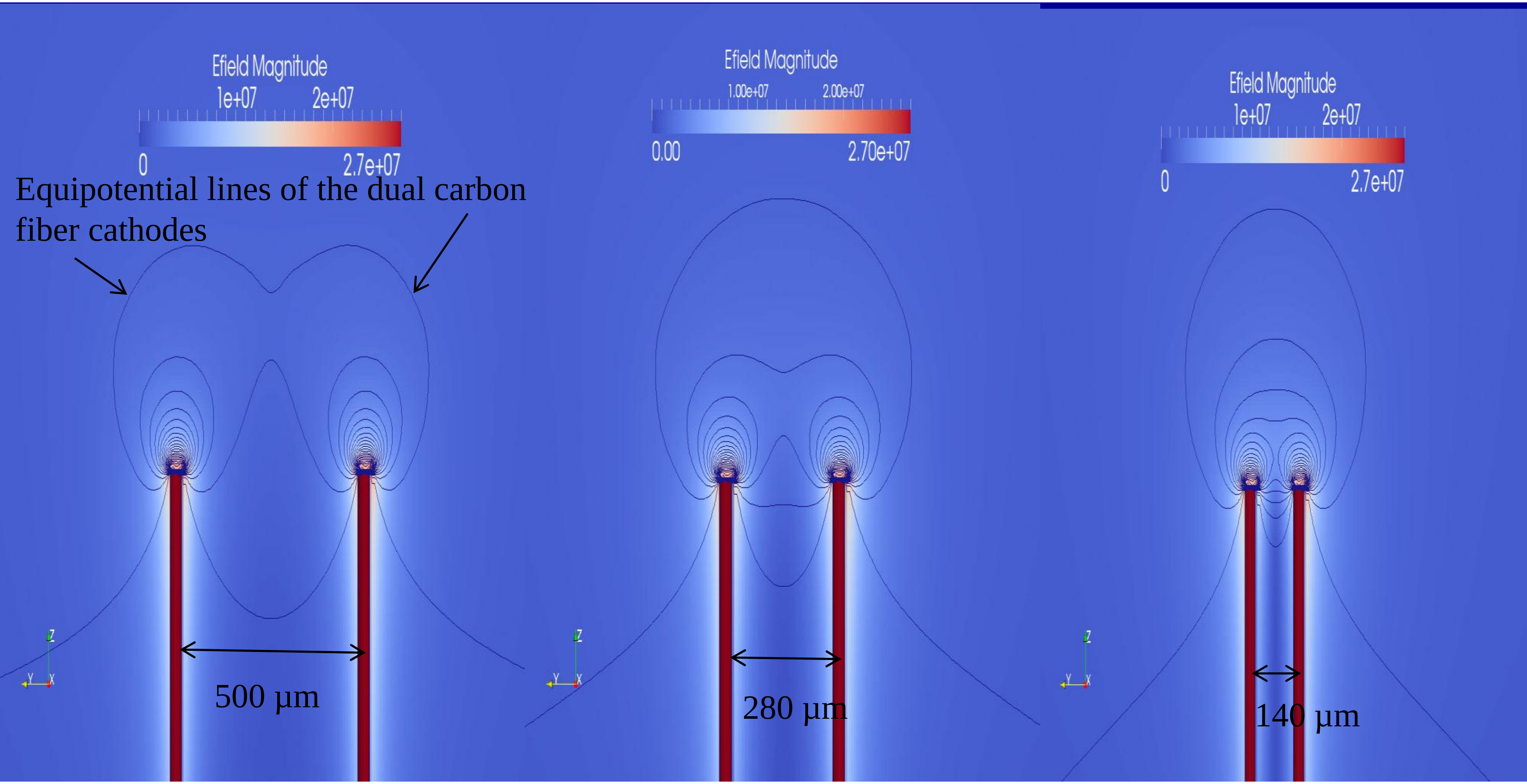
Fowler-Nordheim Equation (1928):

*theoretically require fields ~1000 V/µm

Cathode diameter: 35 µm
Cathode length: 1.5 mm
Center to Center spacing: 500 µm (or 280 µm or 140 µm)

Tang, AFRL/RD

ICEPIC simulations



Electric field data showing the equipotential lines of the dual carbon fiber cathodes with 500 µm, 280 µm, and 140 µm center to center separation, which compares to AFRL's analytic conformal mapping model (Tang, APL 2011)

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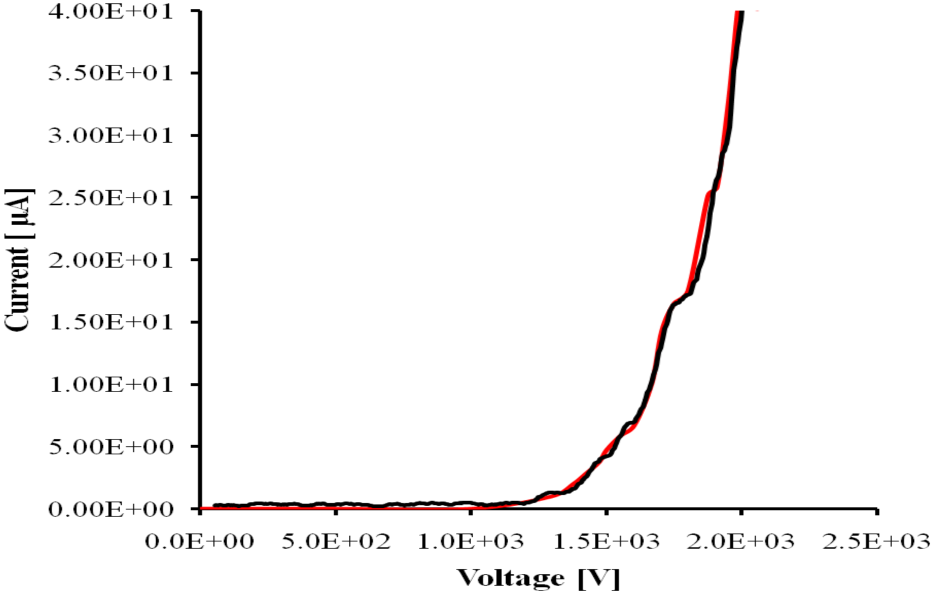
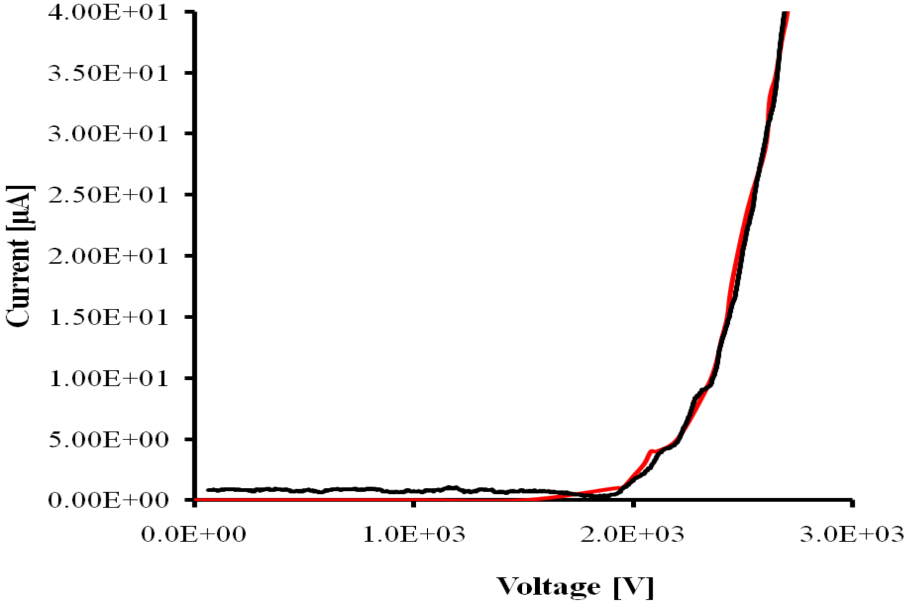
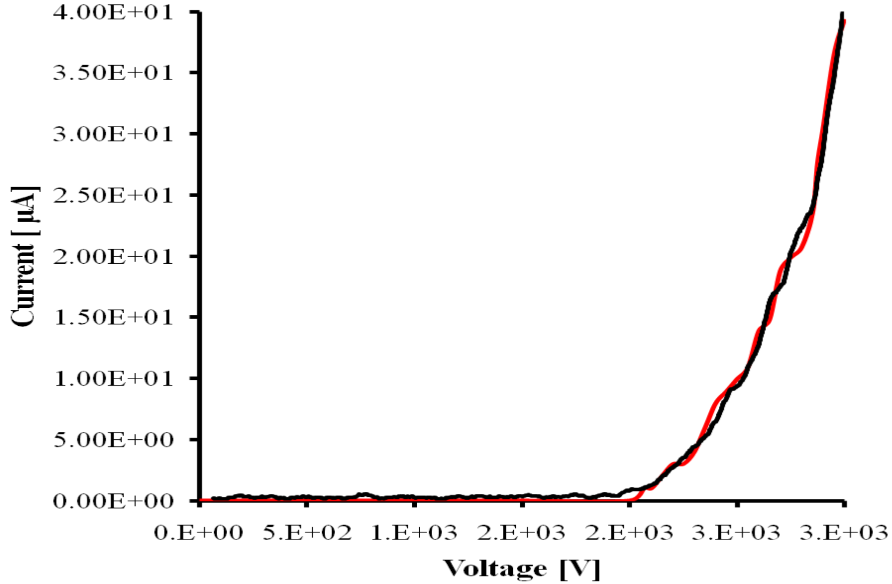
ICEPIC simulations: Results



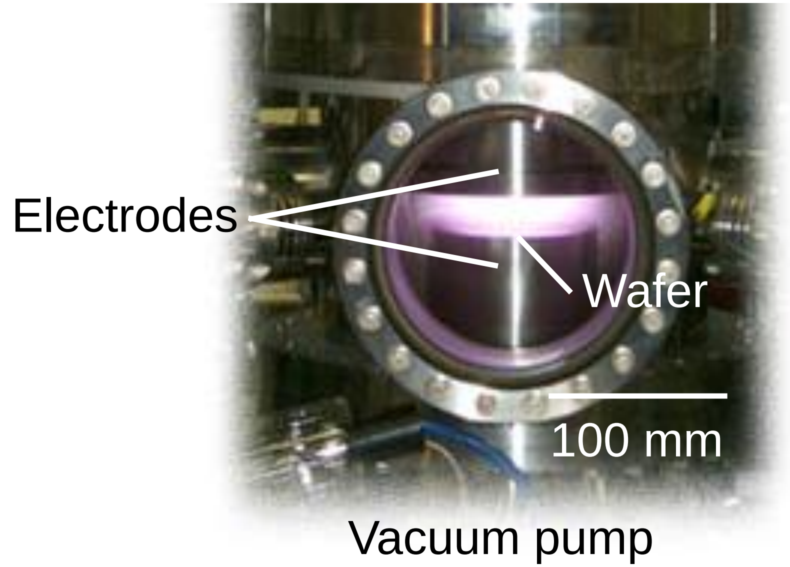




Black Curve: Exp. Data
Red Curve: ICEPIC Fit

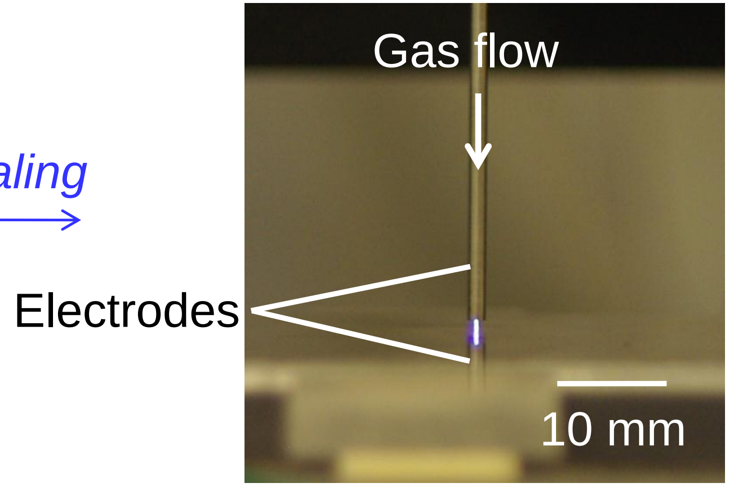
A potentially new direction for plasma synthesis

Conventional plasma



pd scaling ⟷

Microplasma "jet"



- Large volume, batch
- Low pressure (10^{-5}-10^{0} Torr)
- Non-thermal [> 10,000 K]
- Collisionless

- Microscale, continuous
- High pressure (10-1000 Torr)
- Non-thermal [> 10,000 K]
- Collisional, but no arc…

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<u>Microplasmas: A new class of *atmospheric-pressure* plasmas</u>

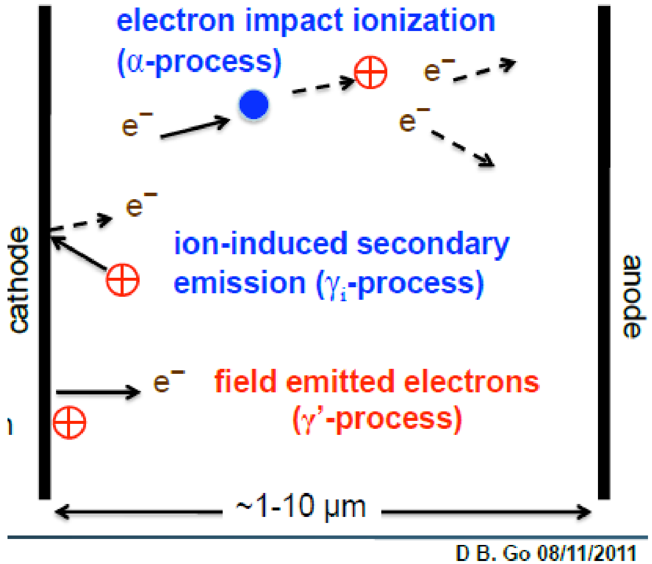
- Microscale: d_{hole} ~ 100 µm
- Non-thermal: T_g~100s deg C

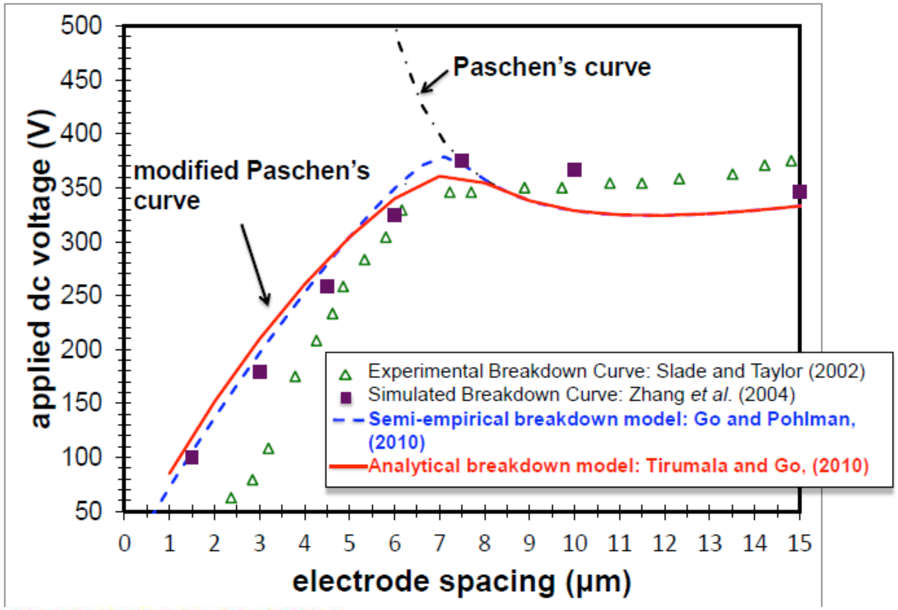
  T_e~1 eV or higher
- High electron densities: 10^{13}-10^{16} cm^{-3}
- Stability at high pressures: 1 atm or higher
- Flow (jet)

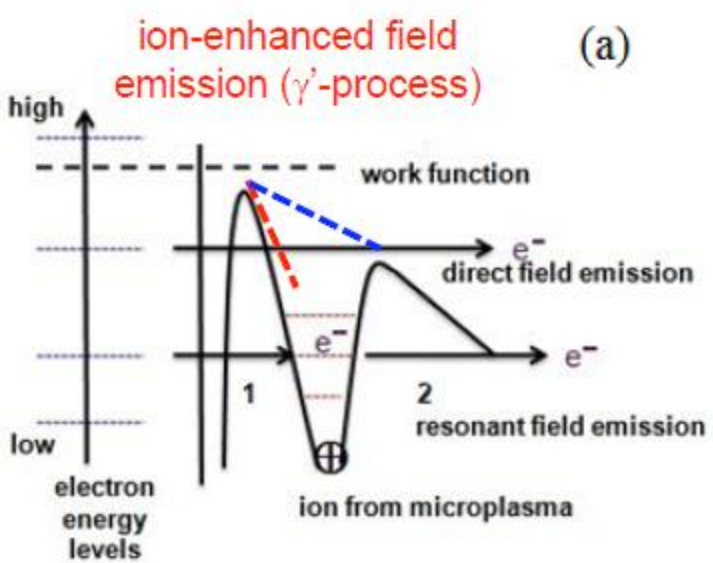
Offers key advantages for (nano)materials synthesis and ties to AFRL needs in material development

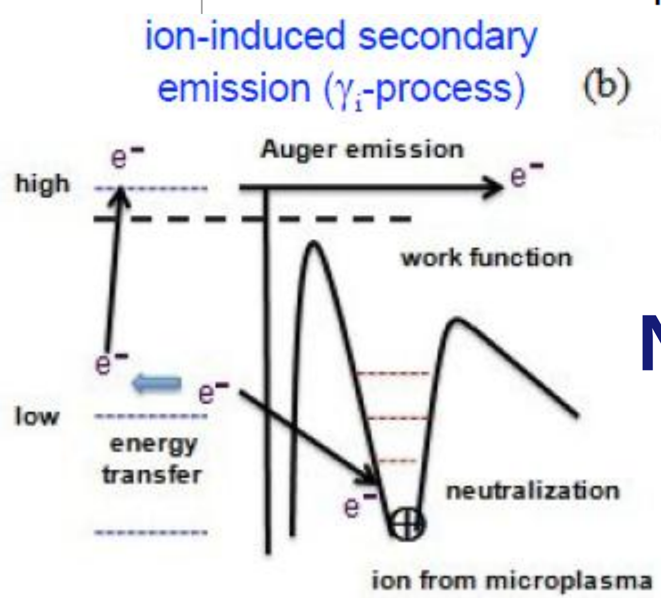
National Research Council called microplasmas one of the most exciting areas in plasma science

Coupling to electrode results in fundamental change in plasma production



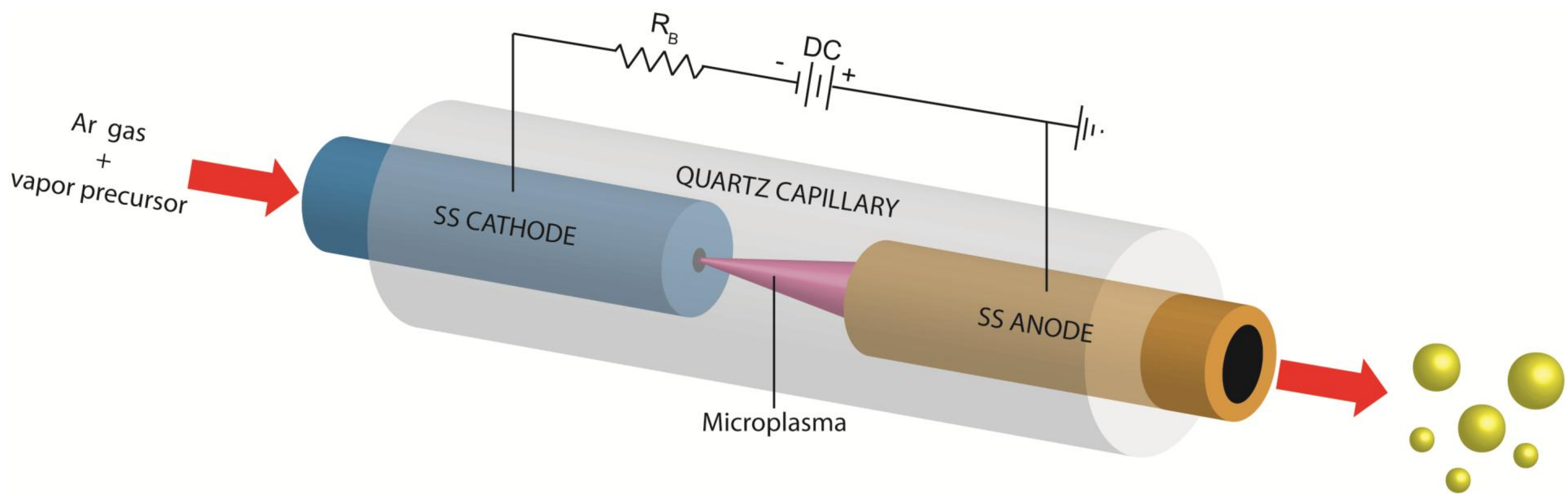






Go, Notre Dame

Continuous-flow microchemical reactors based on microplasmas



Characteristics of process

- Non-thermal dissociation of reactive precursor molecules (EID)
- Short residence times (10^{-3}-10^{-6} seconds)
- *In situ* monitoring (aerosol size classification)
- Generic – precursor can be chosen to grow different materials (Si, Fe, Ni, Pt, Cu, NiFe)

Sankaran, CWRU

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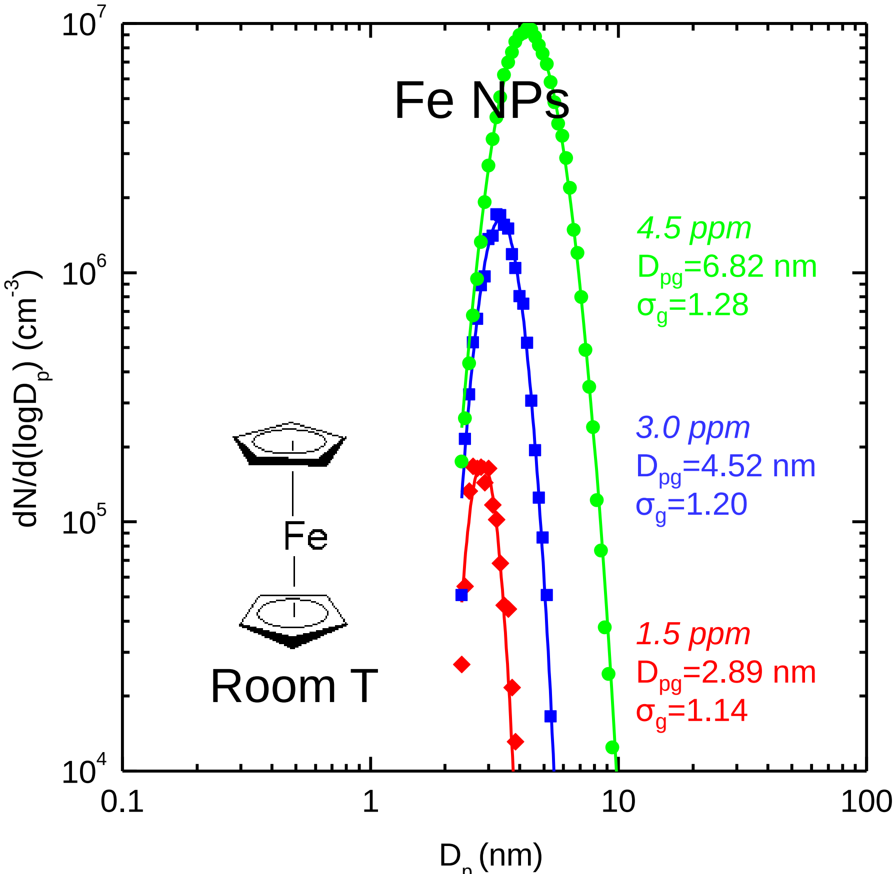
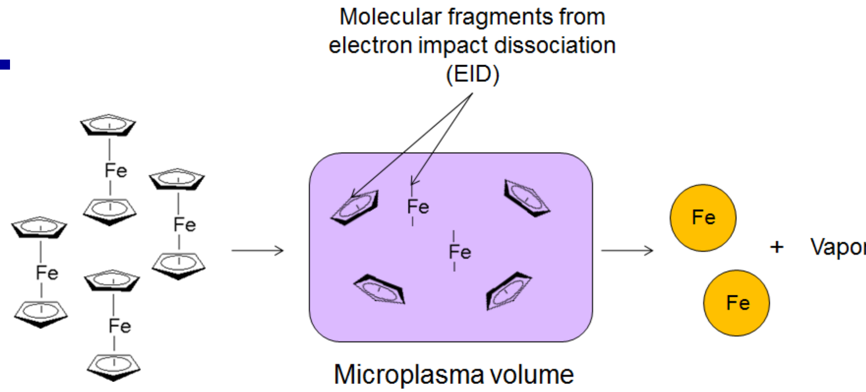
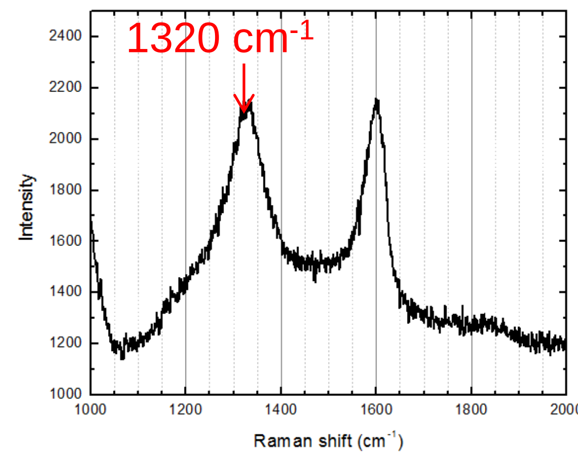
Nanoparticle growth





Micro Raman spectroscopy of carbon nanoparticles

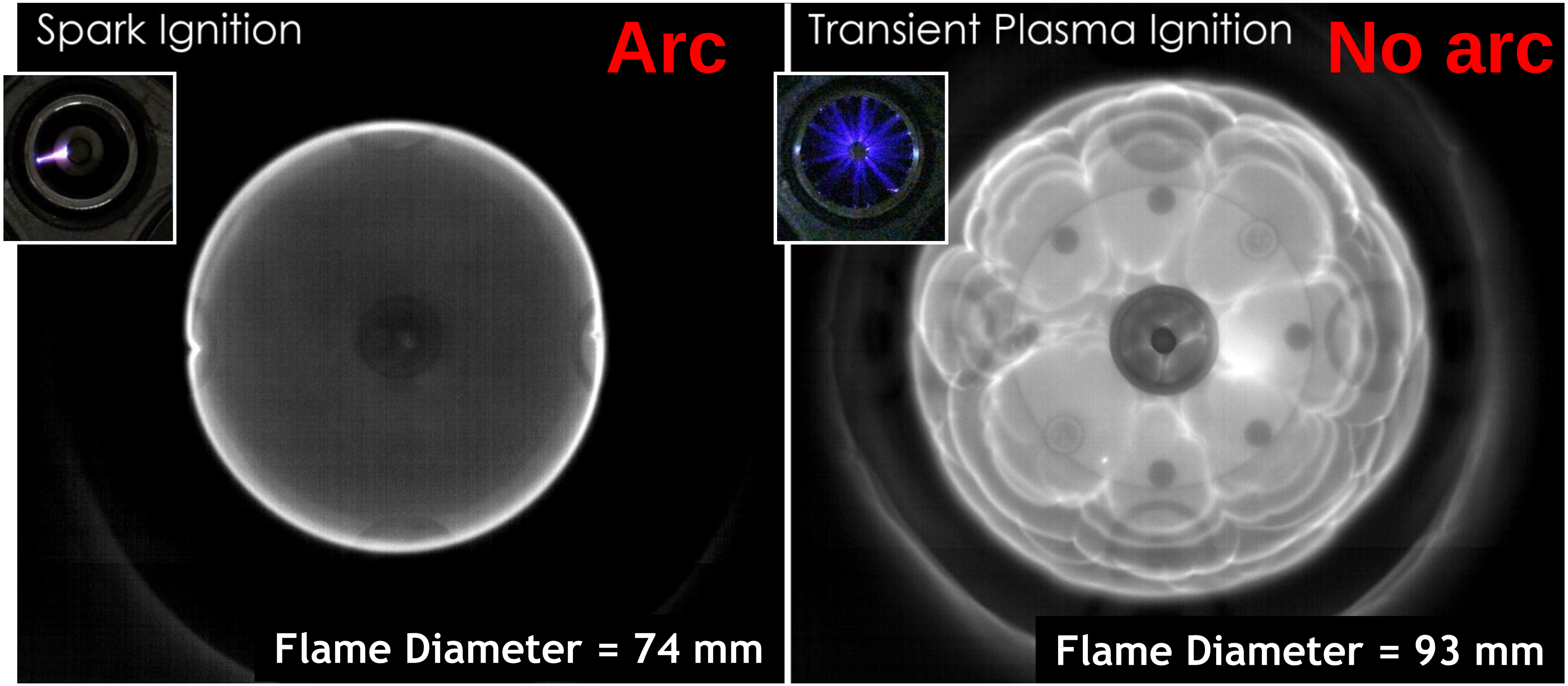


Highly versatile scheme for nanoparticles
Multiple metals with precise size control (safety)
Bimetallic (e.g. intermetllics)
Carbon particles/films, including diamond at room temp (late 80s prediction of diamond stability at nanoscale)

Sankaran, CWRU

Transient Plasma

Flame propagation 6.0 ms after ignition, C_2H_4-air at 1 atm, ϕ=1.1, 300 μs exposure



	Spark Ignition	Transient Plasma Ignition
Discharge:	10 μs, 15 kV pulse (105 mJ)	12 ns, 42 kV pulse (70 mJ)
Electrode:	Spark plug, 1 mm gap	3.2 cm anode, 6 mm gap

Average increase in flame speed of 15% TPI compared to spark ignition

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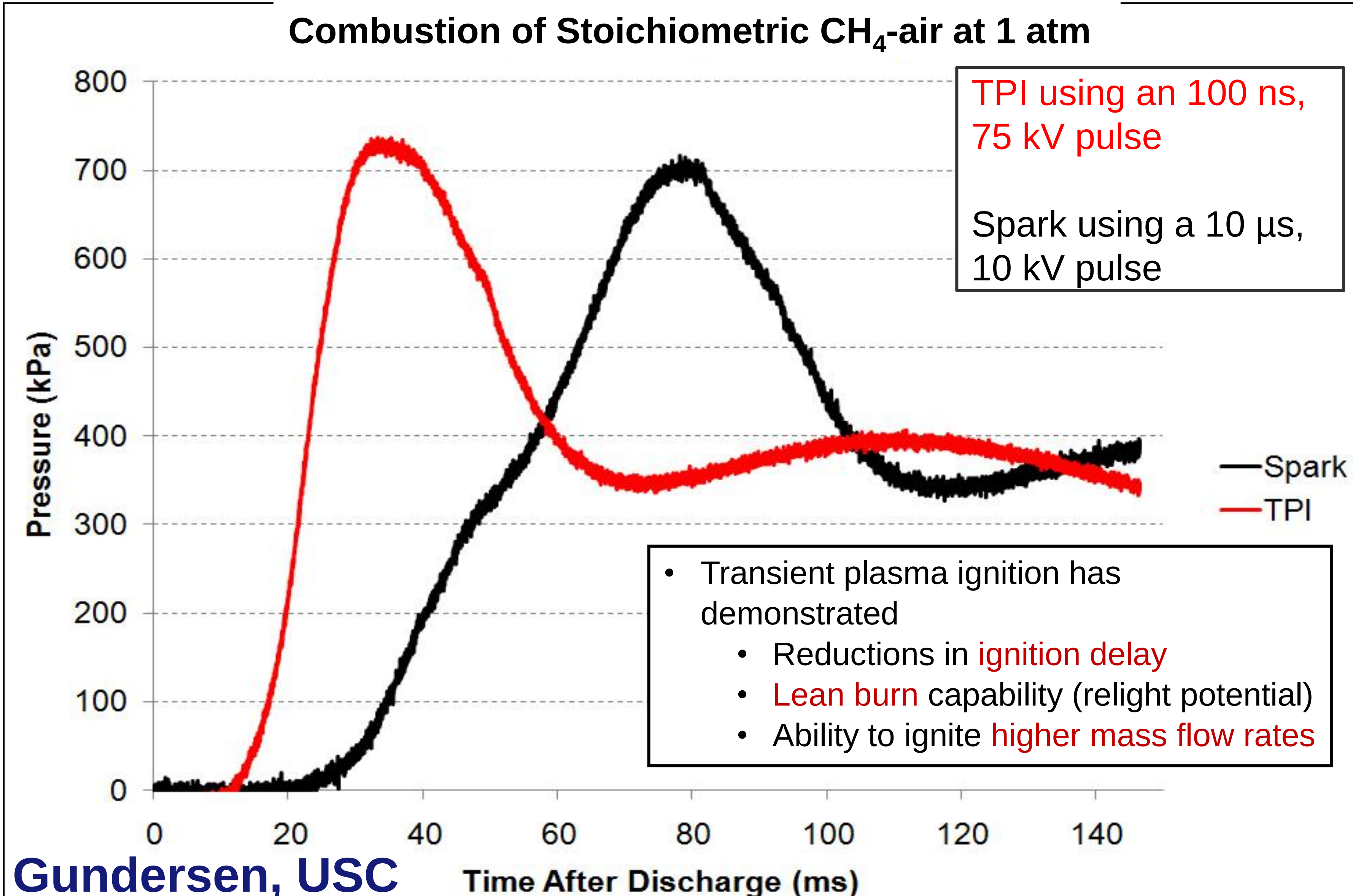
Transient Plasma Ignition

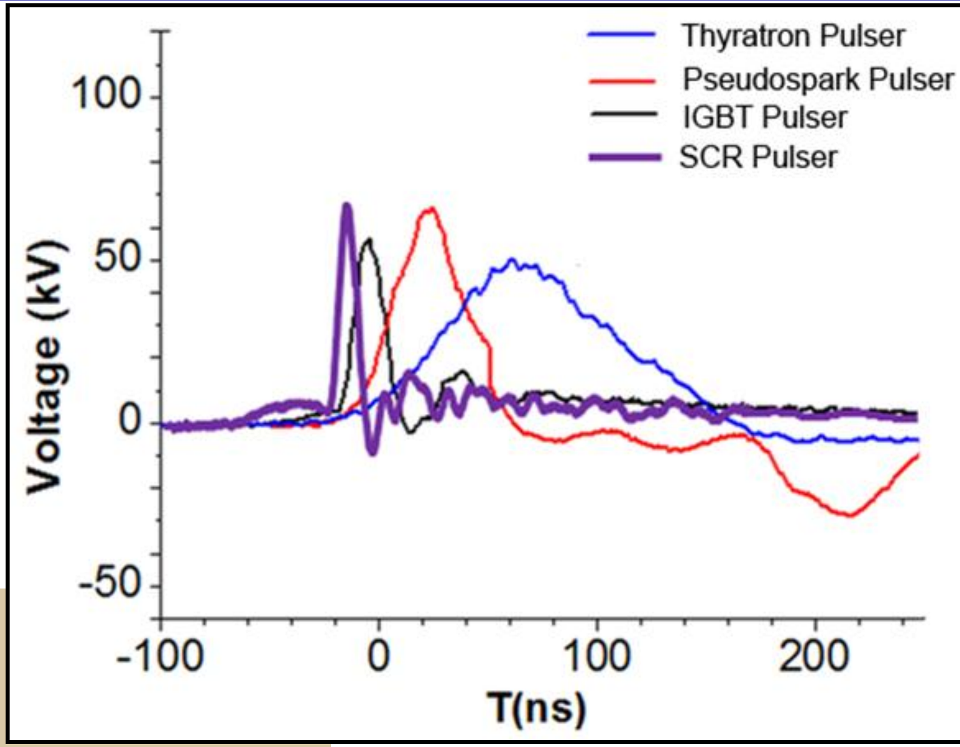


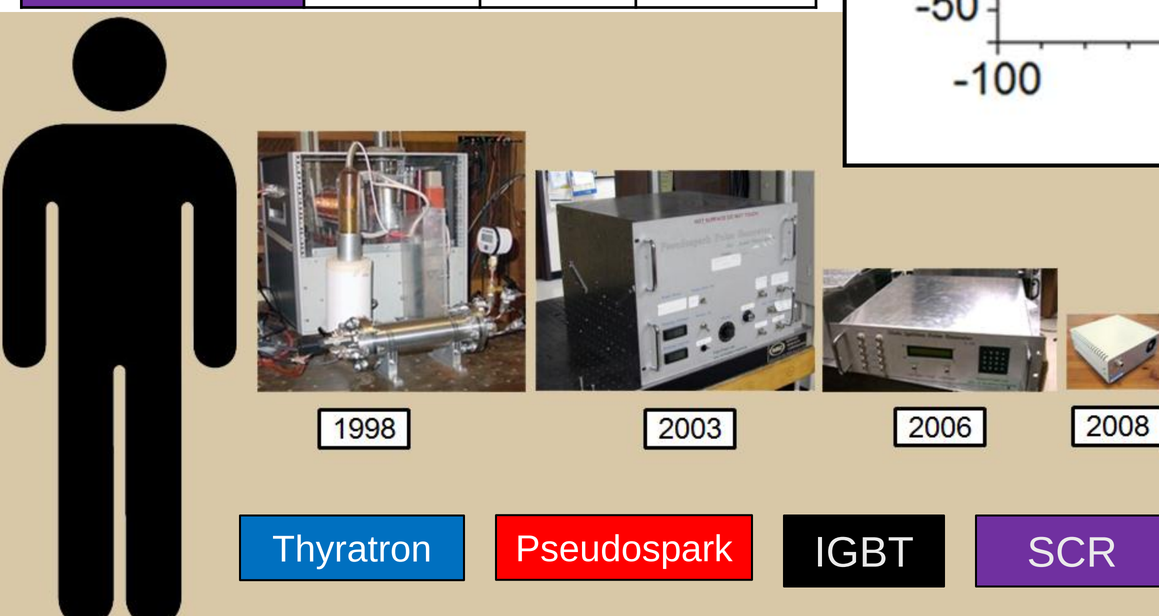
- Transient plasma ignition has demonstrated
  - Reductions in ignition delay
  - Lean burn capability (relight potential)
  - Ability to ignite higher mass flow rates

Gundersen, USC

Advances in Compact Pulsed Power at USC

Pulse Generator Switch Type	Peak Voltage (kV)	Pulse Width (ns)	Energy Per Pulse (mJ)
Thyratron (1998)	50	150	1000
Pseudospark (2003)	90	85	1500
IGBT (2006)	60	20	300
SCR (2008)	65	12	200

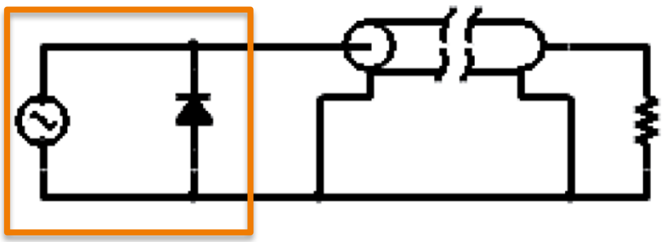




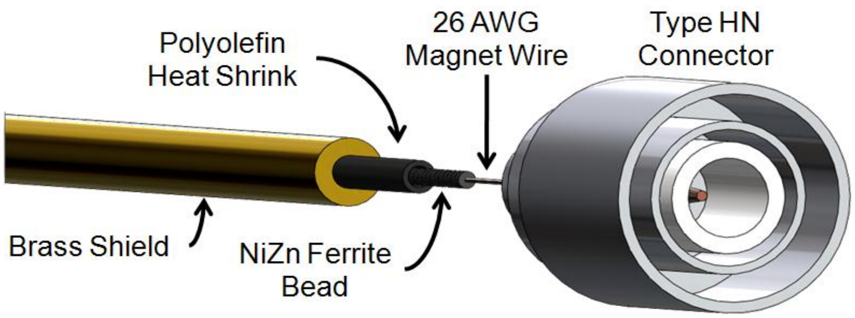
SCR (Enlarged View)

Emphasis on reducing pulse rise time

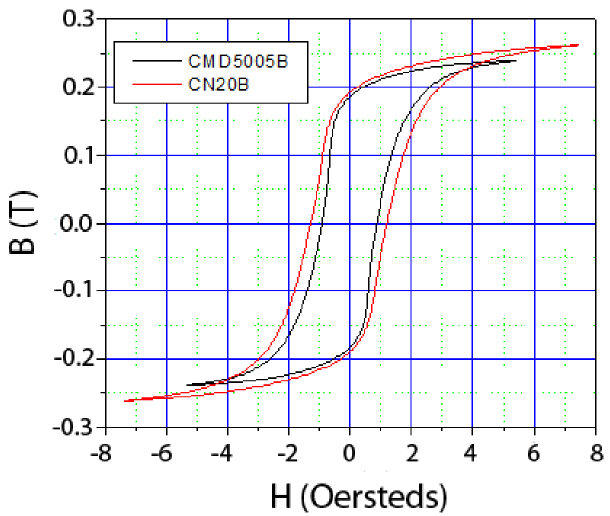
The nonlinear nature of ferrites can be utilized to generate a propagating electromagnetic shockwave that reduces the rise time of the wave as it travels.



Coaxial shockline made of ferrite



Nonlinearity of ferrite beads



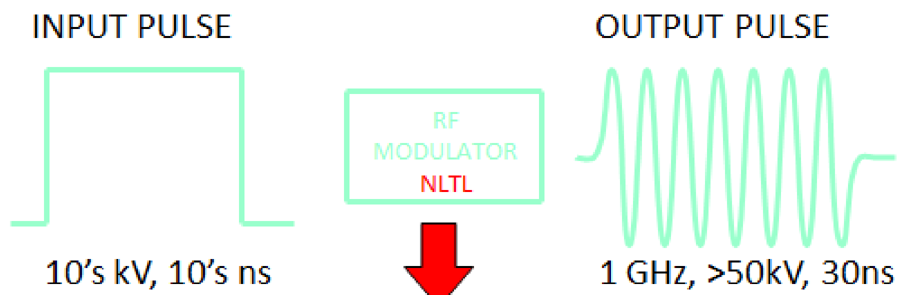
Shocklines are:

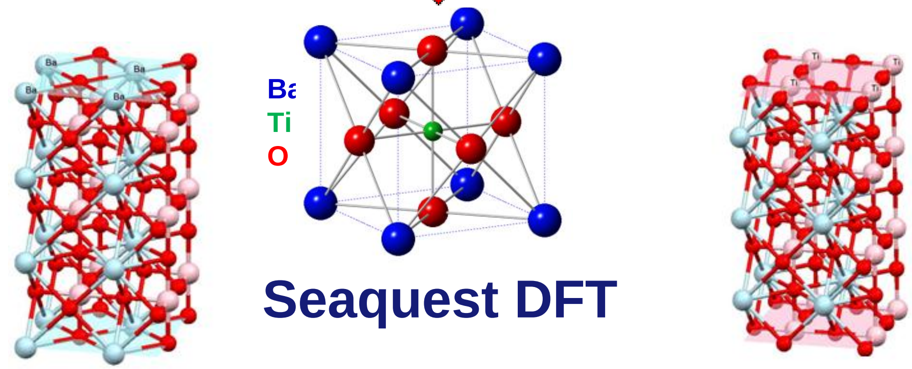
- Composed of either ferroelectric or ferro(ferri)magnetic material
- Driven by a High Voltage Pulse from a solid state pulse generator
- Capable of reducing pulse rise times
- Either two conductor or single conductor transmission lines

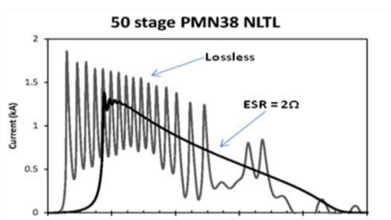
Sanders, USC

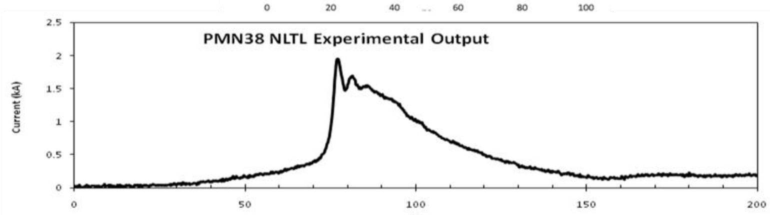
Nonlinear Dielectrics Science (Heidger, AFRL/RD with PNNL)

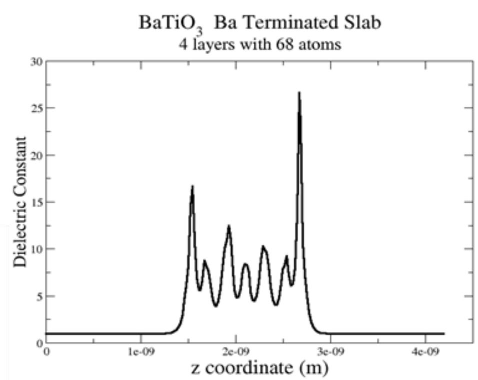
- Engineer materials to provide competing characteristics of
  - Energy density (ε)
  - Breakdown Dielectric strength (E)
  - Engineered non-linearity (Ferro- and Anti-Ferro-Electric)
  - Low loss
- Novel Circuits
  - Scales to 100kV, 10s MW

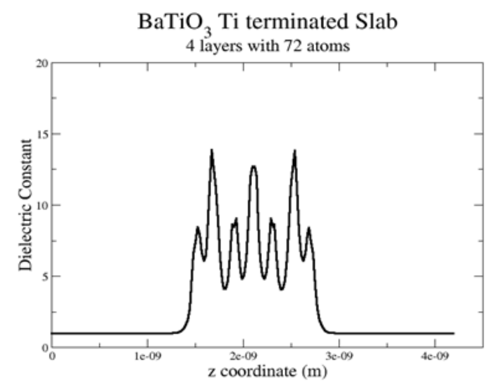












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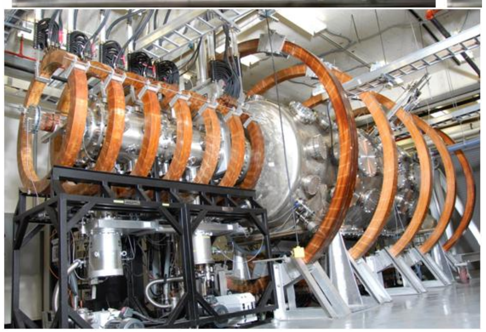
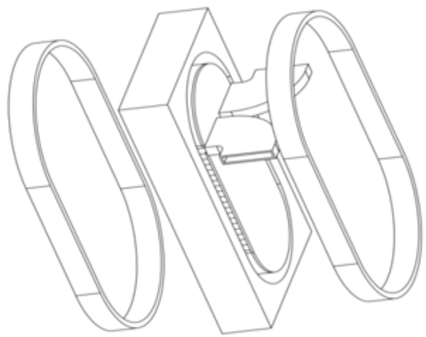
AFOSR is the leading DOD 6.1 organization for non-equilibrium plasma physics, especially for HPM/vacuum electronics EM sources



43 Active Basic Research Grants in FY12

- 1 IEEE Marie Curie Award winner
- 1 member of National Academy of Sciences
- 1 APS Maxwell Prize winner
- 7 IEEE PSAC award winners
- 1 APS-DPP Weimer Award nominee
- 4 Young Investigators
- 4 IEEE PSAC Outstanding Graduate Student
- Active academia/service lab research
  - 5 new hires from academia to service labs (3 AFRL / 2 NRL)

Cross-disciplinary

We need “7D”, nonlinear, electro-dynamics and statics, relativistic statistical mechanics, self-DC and AC fields, and quantum mechanics

- Physics
- Electrical Engineering
- Nuclear Engineering
- Applied Mathematics
- Chemistry
- Computer Science

Collaborators/Teammates

- **Active and close collaborations with AFRL, ONR, ARL, DTRA, DARPA, NSF, and DOE**
- **Joint project with DARPA in micro-plasmas**
- **Lead a joint AFRL/NRL effort in active EM fields in the ionosphere**

Plasma and Electro-energetic Physics

- **High Power Microwave Sources**
  - **High Power Amplifiers**
  - **High Power Metamaterials (New 2012 MURI)**
  - **Raw Peak Power Oscillators**
- **Non-equilibrium Plasma Physics**
  - **Modeling of dense, kinetic plasmas (New STTR)**
  - **Plasma Chemistry (transient/micro-plasma)**
  - **Ultracold/strongly coupled Plasmas (New 2012 BRI and STTR)**
  - **COTS PIC technology**
- **Pulsed Power Physics**
  - **Nonlinear dielectric Strength Physics**
  - **Compact, Portable Pulsed Power**

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