Plasma and Electro-energetic Physics

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

Sub-area: High Power Microwave (HPM) sources, non-equilibrium plasmas, and pulsed power
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)
Plasma - why it’s hard…

Maxwell’s Dynamical Equations (with complex surfaces):
\[ \nabla \times E = -(1/c) \partial B / \partial t \]
\[ \nabla \times H = (4\pi/c) J + (1/c) \partial D / \partial t \]

Subject to the initial value constraints:
\[ \nabla \cdot B = 0 \]
\[ \nabla \cdot D = 4\pi \rho \]

With macroscopic media (complex, dispersive):
\[ D = \varepsilon E \]
\[ B = \mu H \]

Relativistic Lorentz Force Law for relativistic momentum \( p \) and velocity \( u \):
\[ dp / d\tau = (q / c) \left[ \gamma c E + u \times B \right] \]

“7D,” nonlinear, electro-dynamics & statics, relativistic statistical mechanics, self-DC and AC fields, and QM
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 $P_f^2$ (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 some 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

Haystack

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

ITER/D3D

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

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
High Power Metamaterials
(AFLR/RD)

D. Smith, Duke
Beam-Wave Interaction (Plasmon Mode and Beam-loading)

Current density nonlinearly detunes the structure

- 300kV, AFRL MM
- 500kV, SLAC MBK
SEM image of the dual carbon fiber cathodes (500 μm separation)

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

Equipotential lines of the dual carbon fiber cathodes

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)
ICEPIC simulations: Results

Black Curve: Exp. Data
Red Curve: ICEPIC Fit
A potentially new direction for plasma synthesis

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

**Microplasma “jet”**
- Microscale, continuous
- High pressure (10-1000 Torr)
- Non-thermal [> 10,000 K]
- Collisional, but no arc...
Microplasmas: A new class of atmospheric-pressure plasmas

- Microscale: $d_{\text{hole}} \sim 100 \, \mu\text{m}$
- Non-thermal: $T_g \sim 100\text{s} \, \text{deg} \, \text{C}$
  $T_e \sim 1 \, \text{eV}$ or higher
- High electron densities: $10^{13}-10^{16} \, \text{cm}^{-3}$
- Stability at high pressures: $1 \, \text{atm}$ 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
Nanoparticle growth

Highly versatile scheme for nanoparticles
Multiple metals with precise size control (safety)
Bimetallic (e.g. intermetallics)
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, $\text{C}_2\text{H}_4$-air at 1 atm, $\phi=1.1$, 300 $\mu$s exposure

- **Spark Ignition**
  - Flame Diameter = 74 mm
- **Arc**
  - Flame Diameter = 93 mm
- **Transient Plasma Ignition**
  - Flame Diameter = 93 mm

Discharge: 10 $\mu$s, 15 kV pulse (105 mJ)
Electrode: Spark plug, 1 mm gap

Discharge: 12 ns, 42 kV pulse (70 mJ)
Electrode: 3.2 cm anode, 6 mm gap

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

**Gundersen, USC**
Transient Plasma Ignition

Combustion of Stoichiometric CH$_4$-air at 1 atm

- 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

<table>
<thead>
<tr>
<th>Pulse Generator Switch Type</th>
<th>Peak Voltage (kV)</th>
<th>Pulse Width (ns)</th>
<th>Energy Per Pulse (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thyratron (1998)</td>
<td>50</td>
<td>150</td>
<td>1000</td>
</tr>
<tr>
<td>Pseudospark (2003)</td>
<td>90</td>
<td>85</td>
<td>1500</td>
</tr>
<tr>
<td>IGBT (2006)</td>
<td>60</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td>SCR (2008)</td>
<td>65</td>
<td>12</td>
<td>200</td>
</tr>
</tbody>
</table>

![Graph showing pulse characteristics of different switch types](image)
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.

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 ($\varepsilon$)
  - Breakdown Dielectric strength ($E$)
  - Engineered non-linearity (Ferro- and Anti-Ferro-Electric)
  - Low loss

- Novel Circuits
  - Scales to 100kV, 10s MW

INPUT PULSE

OUTPUT PULSE

10’s kV, 10’s ns

1 GHz, >50kV, 30ns

Seaquest DFT

DISTRIBUTION A: Approved for public release; distribution is unlimited.
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)

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

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
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