Collaborative Research on Novel High Power Sources for, and Physics of Ionospheric Modification
Point of Contact: Prof. Thomas Antonsen  
University of Maryland  
Departments of Electrical and Computer Engineering and Physics and Institute for  
Research for Electronics and Applied Physics College Park, MD

Participating Universities:

Institute for Research in Electronics and Applied Physics (IREAP), University of Maryland  
Space and Plasma Physics (SPP), University of Maryland  
Texas Tech University  
University of California, Los Angles

DOD Points of Contact:

Dr. Kent Miller - AFOSR  
Dr. John Luginsland – AFOSR  
Dr. Jason Marshall - AFOSR
The AFOSR MURI Challenge

Utilize new concepts of sources and antennas operated at high power to replace the large collection of sources and antennas in current ionospheric heaters.

- Our goal is to develop a path towards a mobile high-power heater at the required HF frequencies
- Mobile, inexpensive sources will revolutionize the science and operations of ionospheric modification

Objective

- Assemble team of physicist and engineers from space science, ionospheric modification (IM), plasma modeling and HPM to re-examine the coupling of EM energy to the ionosphere under different geomagnetic latitudes and conditions
- Outline research program to:
  - Determine the key properties of the EM source (frequency, ERP, Power, waveform, phase, modulation,..) required to explore EM-Plasma coupling and other critical physics questions as a function of geomagnetic location and ionospheric conditions
  - Define and design modern, efficient, powerful, tunable EM sources for IM and provide hardware testing under typical university HPM laboratory conditions (vacuum loads and/or anechoic chamber)
  - Develop theoretical tools to design feasibility lab experiments and use to demonstrate and test the results of the IM research.
Consortium Structure

PHYSICS

Papadopoulos
UMD
Theory/Modeling
IM Research Status

Gekelman
UCLA/LAPD
Laboratory Experiments

• High Power RF Source Technology
• Antenna Engineering

Antonsen
UMD
Development of High Efficiency Inductive Output Tubes (IOT)

Neuber Mankowsy
TTU
Laser Triggered RF Switches (PCSS)
Electrically Small Antennae

Specification of Radiated Power, ERP, frequency Polarization

ENGINEERING

Specification of Radiated Power, ERP, frequency Polarization
Teams

UMD SPP
Dennis Papadopoulos
Gennady Milikh
Xi Shao
Alireza Mahmoudian
Bengt Eliasson

Students
Aram Vartanyan
Chris Najmi
Kate Zawdie
Blagoje Djordjevich

Texas Tech
Andreas Neuber
John Mankowski
James Dickens
Ravindra Joshi

Students
Daniel Mauch,
Jacob Stephens,
Sterling Beeson,
David Thomas,
John Shaver,
Anthony Meyers,
Paul Gatewood,
Benedikt Esser

UMD CPB
Thomas Antonsen
Brian Beaudoin
Gregory Nusinovich
Tim Koeth

Graduate Students
Amith Narayan
Jay Karakad

Undergraduate Students
Quinn Kelly
Connor Thompson
Charles Turner
Nikhil Goyal

Advisors
Irv Haber
John Rodgers
Edward Wright

UCLA
Walter Gekelmann
Yuhou Wang
Space Plasma Physics (UMD) Objectives

• Identify and Explore the Ionospheric Modifications (IM) Physics Areas impacting the design of Mobile Ionospheric Heating sources (MIHs) where
  • No heating experiments were performed (e.g. equatorial regions)
  • Heating experiments were performed using low power heaters (e.g. mid-latitude)
  • Important new high latitude experiments with incomplete or controversial understanding (e.g. artificial ionization)
  • New concepts requiring mobile sources (e.g. monitor Coronal Mass Ejections)
• Design and, in collaboration with UCLA, conduct PoP experiments of the new physics concepts
• Collaborate with the Arecibo, HAARP, SURA and EISCAT experimental programs
• Provide design input to the source development teams
## Existing Heaters

<table>
<thead>
<tr>
<th>Heater</th>
<th>Angle – B Degrees</th>
<th>L-Shell</th>
<th>f MHz</th>
<th>$P_R$ MW</th>
<th>Gain dB</th>
<th>ERP W</th>
<th>ERP dBW</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAARP- A</td>
<td>14.5</td>
<td>4.9</td>
<td>2.7-10.</td>
<td>3.6</td>
<td>30</td>
<td>3.6 GW</td>
<td>95 dBW</td>
</tr>
<tr>
<td>EISCAT B</td>
<td>12</td>
<td>6.1</td>
<td>3.9-8.0</td>
<td>1.2</td>
<td>30</td>
<td>1.2 GW</td>
<td>91 dBW</td>
</tr>
<tr>
<td>SURA C</td>
<td>19</td>
<td>2.6</td>
<td>4.5-9.0</td>
<td>.75</td>
<td>26</td>
<td>300 MW</td>
<td>85 dBW</td>
</tr>
<tr>
<td>PLAT D</td>
<td>22</td>
<td>2.3</td>
<td>2.7-10.</td>
<td>1.4</td>
<td>19</td>
<td>110 MW</td>
<td>80 dBW</td>
</tr>
</tbody>
</table>
## Heater Requirements

<table>
<thead>
<tr>
<th>Application</th>
<th>Region</th>
<th>Frequency</th>
<th>Power</th>
<th>ERP</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual Antenna</td>
<td>Equator</td>
<td>4-10 MHz</td>
<td>&gt;1 MW</td>
<td>&gt;75dBW</td>
<td>O,X</td>
</tr>
<tr>
<td>FAS SSS clouds for GHz ground-to-ground channel</td>
<td>Equator</td>
<td>4-12 MHz</td>
<td>&gt;2 MW</td>
<td>&gt;85dBW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mid latitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial Plasma Layers</td>
<td>Mid latitude</td>
<td>4-12 MHz</td>
<td>&gt;2 MW</td>
<td>&gt;85dBW</td>
<td>O, X</td>
</tr>
<tr>
<td>CME detection</td>
<td>Mid-latitude</td>
<td>10-30MHz</td>
<td>&gt;2 MW</td>
<td>&gt;85dBW</td>
<td>O</td>
</tr>
<tr>
<td>Substorm effects</td>
<td>Polar</td>
<td>4-8 MHz</td>
<td>&gt;2 MW</td>
<td>&gt;80dBW</td>
<td>O, X</td>
</tr>
</tbody>
</table>

**HAARP – 3.6 MW, ERP 85-96 dBW**

Other requirements:

- Polarization control
- Essentially CW
- Frequency Tuning 1MHz/min
Antenna Parameters

HAARP Element

- Gain: ~ 3 – 8 dBi [1]
- Size: 21 x 21 x 16 m
  - Area: 441 m² (0.1 acre)
  - Volume: 7056 m³
- Excitation: 10 kW
- ERP of array: 3.6 GW

TTU ESA

- Gain: 2.2 – 3 dBi
- Directivity: 3 – 4 dB
- Size: 3 x 2.5 x 1.5 m
  - Area: 7.5 m²
  - Volume: 11.25 m³
Technology Challenge – Mobile Heater

Array size 30 m by 30 m ????
Size Comparison (all same ERP)

• **Blue**: HAARP – 180 elements (3.6 MW)
  • \( \frac{3}{4} \lambda \) spacing between centers
  • 320 x 400 m

• **Green**: TTU – 180 elements (12 MW)
  • \( \lambda/2 \) spacing between element sides
  • 201 x 248 m (12.3 acre)

• **Orange**: TTU – 180 elements (12 MW)
  • \( \lambda/4 \) spacing
  • 4.2 acre (119 x 143 m)

• **Red**: TTU – 180 elements (12 MW)
  • \( \lambda/10 \) spacing
  • 1.4 acre (69 x 80 m)

• **Yellow**: TTU – 25 elements (85 MW)
  • 30 x 30 m array (0.2 acre)
  • \( \lambda/10 \) spacing
Polarization

- Controllable polarization will be possible by orienting ESA’s as shown
- May also reduce coupling between elements, and could make closer spacing possible
- Ongoing research
Technology Drivers - IOT

- Small footprint places premium on power, thereby to high efficiency
  - Operate IOT in class D with modulated e-beam on at full current for ¼ of cycle
    - Develop pulse modulator with short rise time
    - e-gun modulation by varying potential on control anode not intercepting beam current to avoid heating load –Tests with gridded Gun
  - Low loss tunable resonant cavity providing constant impedance over frequency

MICHELLE Code Simulations

Annular Beam Cathode – Non-gridded Gun
No Current Intercept

Solenoid Field

Cross sectional view of beam

Cathode and mod-anode potentials

Gridded Gun - Current Intercept
Decelerating Gap

0 V
-16 V

Solenoid Field surrounding decelerating Gap

Beaudoin et al., Proc. IPAC 2015
Technology Drivers
Experimental Test Stand

Prototyping
Gridded Gun & Modulator

HWE8-128

Beam
Parameters
20kV 5.7A

Grid modulator coaxially mounted around gun to eliminate transmission line effects

IXYS Boards with FETs capable of 1 kV at 20 A within 5 ns.

Constant
Impedance Cavity

Lumped Parallel LC Circuit operating at approximately 1-2 MW at 1-10MHz.

Maintaining a constant gap impedance across the frequency range of interest with a fixed turns ratio, will require that the quality factor vary over that range.

Source and Antenna Development

**ESA** – Electrically Small Antenna to interface with UMD 50 Ohm impedance rf source.
- Factor of several smaller than dipole
- Frequency tunability demonstrated

**Highly repetitive light sources**
- Driver for PCSS
- Modulated UV narrowband light source with high power (~100 W) at rf frequencies

**PCSS** – Photoconductive Semiconductor Switching
- Achieved 700 kV/cm switching field
- Demonstrated repetition rates of up to 65 MHz at 20 kV switching amplitude
- Direct rf drive approach

**Challenges**
- Optimize tradeoff between antenna efficiency/size/tunability
- Improve PCSS photonic efficiency
- Increase output power of light source

**Direct Drive Concept**

**1 MHz light pulse train**

**PCSS die for size comparison**
Collaborative Research on Novel High Power Sources for and Physics of Ionospheric Modification

Agenda

<table>
<thead>
<tr>
<th>Time (EDT)</th>
<th>Topics</th>
<th>Speakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:00 PM</td>
<td>Greetings</td>
<td>Tom Antonsen</td>
</tr>
<tr>
<td>2:05 PM</td>
<td>Agency Perspectives</td>
<td>Kent Miller/John Luginsland</td>
</tr>
<tr>
<td>2:10 PM</td>
<td>Collaboration Overview/Technical Challenges/Straw Man Numbers</td>
<td>Tom Antonsen UMD/IREAP</td>
</tr>
<tr>
<td>2:30 PM</td>
<td>The Physics of Ionospheric Modifications - Issues and Impact on the Source Design</td>
<td>Dennis Papadopoulos UMD-SPG</td>
</tr>
<tr>
<td>3:00 PM</td>
<td>Experimental Measurements</td>
<td>Yuhou Wang/Walter Gekelman - UCLA</td>
</tr>
<tr>
<td>3:15 PM</td>
<td>Prospects for a PCSS based RF generator</td>
<td>Andreas Neuber James Dickens – Texas Tech</td>
</tr>
<tr>
<td>3:45 PM</td>
<td>Tunable Electrically Small Antennas</td>
<td>John Mankowski – Texas Tech</td>
</tr>
<tr>
<td>4:00 PM</td>
<td>Prospects for an Inductive Output Tube (IOT) based source</td>
<td>Brian Beaudoin – UMD CPB Students</td>
</tr>
<tr>
<td>4:30 PM</td>
<td>Discussion of critical issues</td>
<td>All</td>
</tr>
<tr>
<td>5:00 PM</td>
<td>Closing Comments/Adjourn</td>
<td></td>
</tr>
</tbody>
</table>
Goals/Objectives

Develop prototypes of EM sources for mobile, reconfigurable ionospheric heaters based on:

(i) Comprehensive understanding of the current status of IM research and applications;

(ii) Combination of theoretical/modeling with laboratory experiments scaled to simulate ionospheric plasma parameters at different geomagnetic latitudes and diurnal variation and solar cycle;

(iii) Understanding of modern high power RF source technology and antenna engineering including meta-materials.
Estimate Antenna Gain for 30m by 30 m “array”

\[ G_{\text{max}}(5 \text{ MHz}) = 7 \text{ dB} \]

\[ 85 \text{ dBW} - 7 \text{ dBW} = 78 \text{ dBW} = 63 \text{ MW} \]
Rough Numbers

Power Requirement – 63 MW

If array has roughly 100 elements

630 kW/element  -  70 kW/m²