The Naval Research Enterprise and Plasma Physics Research at NRL

Michigan Institute for Plasma Science & Engineering
University of Michigan

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A WORLD-CLASS LABORATORY

- Idea followed the sinking of the Lusitania in 1915
- Secretary Josephus Daniels Established Naval Consulting Board with Edison Chair, meeting October 7, 1915
- August 29, 1916 Congress appropriates funds to establish the Lab
- Delayed by WW-I, Assistant Secretary of the Navy, Theodore Roosevelt, Jr. Commissions the Lab at Bellevue site on July 2, 1923

Primarily In-house Research to support Navy and Marine Corps needs
• MISSION is to conduct a **broadly based multidisciplinary program** of scientific research and advanced technological development directed toward maritime applications of new and improved materials; techniques; equipment; systems; ocean, atmospheric, and space sciences; and related technologies.

• Primary **in-house research** for the physical, engineering, space, and environmental sciences

• Broadly based applied research and advanced technology development program in **response to identified and anticipated Navy and Marine Corps needs** and support to the Naval Warfare Centers
Plasma Physics is one of 18 NRL Research Divisions

Assistant Secretary of the Navy (Research, Development & Acquisition)

Chief of Naval Research

NRL

Commanding Officer
CAPT Paul Stewart, USN

Director of Research
Dr. John Montgomery

Business Operations
Mr. D. Therning

Systems Directorate
Dr. G. Borsuk

Materials Science and Component Technology
Dr. B. B. Rath

Naval Center for Space Technology
Mr. P. G. Wilhelm

Ocean and Atmospheric Science & Technology
Dr. E. Franchi

Radar
Electronic Warfare
Optical Sciences
Information Technology

Chemistry
Materials Science & Technology
Comp. Phys & Fluid Dynamics
Plasma Physics
Electronics Science & Tech.
Biomolecular Science & Eng.

Space Systems Dev
Spacecraft Engineering

Acoustics
Remote Sensing
Oceanography
Marine Geosciences
Marine Meteorology
Space Science
NRL has world-wide recognition in plasma physics & related technologies
Naval S&T Strategic Plan

Naval S&T Vision: Sponsor scientific research and technology to:
• Pursue revolutionary, game-changing capabilities for Naval forces of the future,
• Mature and transition S&T advances to improve existing Naval capabilities,
• Respond quickly to current Fleet and Force critical needs, and
• Maintain broad technology investments to hedge against uncertainty and to anticipate and counter potential technology surprise.
ONR TechSolutions Process

Naval Research Enterprise

Technology Solutions

Warfighter Need

Subject Matter Experts
Interpret Technology Requirements

Industry Partners & Academia

Delivery to Fleet/Force
Naval Research Laboratory (Appropriations Act, 1916)  
“[Conduct] exploratory and research work…necessary …for the benefit of Government service, including the construction, equipment, and operation of a laboratory….”

Office of Naval Research (Public Law 588, 1946)  
“…plan, foster, and encourage scientific research in recognition of its paramount importance as related to the maintenance of future of naval power, and the preservation of national security…”

Office of Naval Research - London Office (1946)  
“…reporting on the latest developments and to assist visiting American scientists to make contact with their colleagues in Europe…”

Transitioning S&T (Defense Authorization Act, 2001)  
“…manage the Navy’s basic, applied, and advanced research to foster transition from science and technology to higher levels of research, development, test, and evaluation.”
Department of the Navy’s Research Enterprise
Principal Conclusion: The expanding scope of plasma research is creating an abundance of new scientific opportunities and challenges. These opportunities promise to further expand the role of plasma science in enhancing economic security and prosperity, energy and environmental security, national security, and scientific knowledge.

Major Topics
- Low-Temperature Plasma Science & Engineering
- Plasma Physics at High Energy Density
- The Plasma Science of Magnetic Fusion
- Space & Astrophysical Plasmas
- Basic Plasma Science

“The past decade has seen an acceleration of foreign research, investment, and discoveries in plasma physics. Increasing foreign participation testifies to the compelling scientific opportunities.”

*Support provided by DOE, NSF, and NASA*
Our individual and team researchers are our greatest asset (62 of 85 have PhDs)
The University of Michigan is well represented in the Plasma Physics Division

- Tom Mehlhorn (BS’74, MS’76, PhD’78 – Jim Duderstadt)
- Joe Schumer (MS ’94, PhD ’97 – James Holloway)
- Steve Swanekamp (PhD’90 – Terry Kammash)
- Andy Schmitt (BS’77, MS’79, PhD’82 - Jim Duderstadt)
- Ward Thornhill (PhD’85 – Jim Duderstadt)
- Young Chong
- Jacob Zier (PhD’11 – Ron Gilgenbach & YY Lau)
- Ken Grabowski (BS’74, MS’76, PhD’80 - John King)
- Ken Whitney (BS Physics)
- Jack Davis (Adjunct Professor)
- John Tucker
Code 6700 has an impressive array of unique experimental facilities.
We develop and use state-of-the-art plasma diagnostics

Femtosecond filament

NIKE Target Area

Prompt neutrons

Laser filament in water

SWOrRD

Schlieren

Graphene oxide reduction

12/7/2011
We develop & use state-of-the-art plasma EM, & atomic physics codes
Vision: Enhance extended-range power projection capabilities and integrated layered defense by improving manned and unmanned Naval platforms, enabling forces to complete missions in hostile environments by avoiding, defeating and surviving attacks. Demonstrate improvements in standoff indirect precision fires on time-critical targets, while limiting collateral effects through the use of electromagnetic kinetic projectiles, hypersonic missile propulsion, scalable weapons effects, directed energy and hypervelocity weapons.
Directed ion/neutron beams using ultrashort pulse lasers

**Typical ultrashort pulse lasers parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser intensity</td>
<td>$10^{18} - 10^{22}$ W/cm²</td>
</tr>
<tr>
<td>Laser pulse duration</td>
<td>30 fs – 1 ps</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>0.8 – 1 µm</td>
</tr>
<tr>
<td>Laser energy</td>
<td>1 J – 1 kJ</td>
</tr>
</tbody>
</table>
Numerical capabilities developed at NRL

2D relativistic PIC code for laser-target interactions

Ideal for modeling laser-target interactions and HEDP.

3D MC code for ion transport and neutron production

Neutron spectrum from nuclear fusion reactions can be calculated for an array of neutron detectors located around the target and compared to experimental data.

3D MD code for laser-cluster interactions

Perfect for modeling the nano-world: small clusters, thermodynamics and transport properties of matter, etc.

Strong numerical capabilities with in-house developed codes for three widely used simulation techniques: particle-in-cell (PIC), molecular dynamics (MD) and Monte Carlo (MC).
Model the interaction of intense ultra short laser pulses with thin foils using a 2D electromagnetic particle-in-cell (PIC) model.

Utilize data output from the PIC model as input for a 3D Monte-Carlo model simulating the production and scattering of neutrons.
Collaborative research with U. Michigan on laser-target interaction

Experiments on HERCULES at CUOS

- Bubble detector
  - dimensions: 10x1 cm$^2$
  - sensitivity: 1-15 MeV
  - conversion factor: $10^5$ n/bubble

Laser parameters:
- $E_{\text{laser}} = 2$ J
- $I_0 = 5 \times 10^{21}$ W/cm$^2$
- $\tau_{\text{FWHM}} = 30$ fs
- $D_{\text{FWHM}} = 1$ µm
- $P = 50$ TW
- $\lambda = 0.8$ µm
- ps contrast $= 10^{-7}$

Neutron spectrum

$Y \sim 4 \times 10^5$ neutrons
$d\Omega \sim 2 \times 10^{-3}$ sr

$\frac{dY}{d\Omega} \approx 2 \times 10^8 \frac{\text{neutrons}}{\text{sr}}$
Z pinches:: intense plasma radiation source of photons hν>10 keV

Plasma Physics Division

simulations for an advanced generator

cold Mo K-α (Z)
cold W K-α (ZEBRA)

thermal K-shell (ZR)
Ar continuum (Z)
Ar-Xe (NIF)
thermal L-shell (Z)

yield (kJ) vs. photon energy (keV)

Current (MA) vs. Time (ns)

Total Radiated Power (TW) vs. Time (ns)
Advanced simulations of Z-pinch loads require an integrated physics approach

- atomic physics
  - energy structure
  - rate coefficients
  - emissivity & opacity

- rad transport
  - non-local photo-pumping
  - emission line profile
  - spectral output

- magnetohydrodynamics
  - dimensionality
  - Implosion & stagnation
  - circuit or laser deposition

- non-LTE population kinetics

- internal energy, ionization, resistivity, thermal conduction

**product:**
- Verification tests for non-LTE radiation & MHD codes.
- Validation of simulations through yields & synthetic spectra.
- Interpretation of plasma conditions from spectral & imaging diagnostics.
- Development of shot matrices.
- Predictions for next generation pulse power machines.
2D (R-Z) MACH2-TCRE simulations compare well with SS K-shell ZR yields

Nested double SS wire array load ($M_{tot} = 2.5$ mg, $R = 55$ mm) on refurbished Z (Z1860/61)

Include model for wire ablation & initial inhomogeneities. Matching radiation data requires a ~25% current loss at final feed.
The simulated and experimental K-shell spectra reveal plasma conditions in the emitting region are $T_e \sim 3.5$ keV and $n_e \sim 3 \times 10^{22}$ cm$^{-3}$.
Future gas puff experiments will examine novel neutron sources

Heavy (Ar) gas outer liner imploding on an inner D$_2$ annulus

- Injected supersonic annular and/or cylindrical gas jet(s)
- Single or multiple-shell D$_2$, Ne, Ar, Kr
 Beam Physics Branch - 6790
Laser Facilities

High Energy Laser Lab

- Used with scalable incoherent beam combining architecture –
- Direct energy weapon applications
- Power beaming application – persistent surveillance

TFL Ultrashort Pulse Laser (USPL)

- Laser wakefield accelerators
- Underwater acoustic sources
- Laser-guided discharges
- Detection of explosives and nuclear material
- Atmospheric propagation

Development of gated RF thermionic electron source for Navy FEL INP
NRL Kilowatt Fiber Laser (IPG)

\[ P > 1 \text{ kW}, \text{CW}, \quad M^2 = 1.03, \quad \Delta \lambda/\lambda = 0.07\%, \quad \eta_{\text{wall plug}} \sim 30\% \]

\[ P_{\text{fiber}} = 10\text{ kW}, \text{ single mode} \]

Random polarization

7 kW power supply

Volume of optics
\[ \sim 0.03 \text{ m}^3/\text{kW} \]
Incoherent Combining of Fiber Lasers for Long-Range DEW Applications

- U.S. Patent # US 7,970,040 B1, issued on June 28, 2011

\[ 2R_{BD} \approx 2\sqrt{NR_o} \]
Laser Propagation in Presence of Turbulence

- Laser spot size on target at range $L$
  $$R(L) = \left( \Theta_{\text{diff}}^2 + \Theta_{\text{turb}}^2(L) + \Theta_{\text{jitter}}^2 \right) L^2 + R_o^2 \left( 1 - \frac{L}{L_{\text{focal}}} \right)^2 \right)^{1/2}$$

- Diffraction angle (diffraction + beam quality)
  $$\Theta_{\text{diff}} = M_o^2 \frac{\lambda}{\pi R_o}$$
  $M_o^2$: intrinsic BQ
  $R_o$: initial laser spot size

- Spreading angle due to turbulence
  $$\Theta_{\text{turb}}(L) = M_{\text{turb}}^2(L) \frac{\lambda}{\pi R_o} = \frac{1.6 \lambda}{\pi r_o(L)}$$

- Transverse coherence length (Fried parameter)
  $$r_o(L) = 0.184 \left( \frac{\lambda^2}{C_n^2 L} \right)^{3/5}$$
  $C_n^2$: structure constant
  $C_n^2 \sim 10^{-15} - 10^{-13} \text{ m}^{-2/3}$
NRL Beam Director
Incoherent Beam Combining

NRL: Antonio Ting, Richard Fischer, Greg DiComo (Ph.D. Student, UMD)
NSWC Propagation Range - 1.2 km Four Incoherently Combined SM Fiber Lasers

3 kW transmitted, 2.8 kW on target
SOR Propagation Range 3.2 km

- Perform field experiments at 3.2 km range using incoherently combined high-power lasers (6.2 kW, $M^2 \sim 1$)
NRL Fiber Laser Field Field Experiments at SOR Propagation Range 3.2 km

(Spot Size on Target at Low Power)
How Railguns Work

- A railgun is basically a linear electric motor
- Current through a sliding short or armature reacts with its own magnetic field generating a JxB force
- Acceleration relies on maintenance of the sliding contact
- High velocity and kinetic energy requires high current passing through the slider
- **Force (F=ma)** depends on current density (J), magnetic field (B), and area (A) or total current (I)

\[ F = ma = \int J \times B \, dA \equiv \frac{1}{2} IBA \]
MTF Railgun Operation

Modern railguns use high energy density caps and solid state switches.
Sliding Contacts

- High current sliding contacts dominate railgun physics
- High pressure metal-metal contact
- Time and velocity dependent current distributions
- Velocity comparable to field (current) penetration times
Primary Damage Mechanisms

Rails
- Edge Grooving – high current erosion of sliding contact
- Gouging – shock generation at high velocity contact
- Mechanical rail wear – high velocity heating of sliding interface
- Post Transition erosion – arc damage to metal electrodes
- Cyclic fatigue – repetitive extreme stress of materials
- Mechanical deformation – extreme stress

Armatures
- Erosion – material melted from slider
- Fracture – cracking of legs, liquation cracking
- Action – exceed melt energy of body

Insulators
- Thermal flux - high temperature gas
- Molten metal - hot debris

10 GW Input Power
NRL MTF Facility

- 6-m long railgun, 5 cm bore diam.
- Low L’ solid SS containment
- 22 – 0.5 MJ Cap. Banks
- SS Switches
- 54 mm Round, Flat, Fi, G2 and G2i
- 1.55 MA, Action ~ 7\times10^9 A^2-s
- L’ ~ 0.3-0.4 \mu H/m
- I^2v peak ~ 3\times10^{15} A^2-m/s
- Over 1000 shots fired to date
- 26 distinct shot campaigns in FY10

G10 Insulators
304 SS Containment

Liner
Backing Rail

MTF Shot 791, RB Rev L w/Sn

Current (200 kA/d)
Muzzle Voltage (200 V/d)
Velocity (500 m/s/d)
I^2v (5e14)
Action (1e9 A^2-s)
Railguns: fiction & fact
Railguns: fiction & fact
The Free Electron Laser (FEL) weapon system will provide U.S. ships with speed-of-light fire capability for a range of missions and threats, a key element of a future future shipboard layered defense.

An Innovative Naval Prototype program for the FEL technology began in 2010. It will demonstrate scalability of the necessary FEL physics and engineering for an eventual megawatt-class device. The program will focus on the design, development, fabrication, integration and test of a 100-kilowatt class FEL device. Future needs for ship integration and beam control are being considered.

This revolutionary technology provides multiple payoffs to the warfighter. The ability to control the frequency of the laser beam allows for operation in the maritime environment. The variability of the beam strength provides graduated lethality with minimum collateral damage and a low cost per engagement when compared to the projectile and logistics support costs of conventional explosive munitions. Against low value targets it is an effective alternative to the use of expensive missile systems. The FEL provides speed of light and precision engagement of both high speed, sophisticated anti-ship missiles, as well as swarming, slow speed, unsophisticated small craft.

Research Challenges and Opportunities:
- FEL weapons
- Injectors
- Accelerators
- Amplifier/oscillator designs
- Beam control
- Modeling and simulation
- Scalability

What will it accomplish?
- FEL will equip U.S. ships that have high depth-of-fire with speed-of-light delivery, seconds dwell time and a deep magazine for a more powerful means of self-defense. It is a revolutionary weapon that will transform how the Navy fights future battles.

What is it?
The Free Electron Laser (FEL) provides naval platforms with a highly effective and affordable defense capability against surface and air threats, future antiship cruise missiles and swarms of small boats. Utilization of FEL also allows an unlimited magazine with speed-of-light delivery.

How does it work?
- FEL generates high-intensity laser light by utilizing the energy from unbound accelerated high-energy electrons. This technology is commonly used in the Department of Energy’s particle colliders for basic subatomic research. The FEL program is an investment by the Office of Naval Research to transition the accelerator technology from particle colliders to a future ship self-defense weapon system.

Point of Contact
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(703) 696-2594
quentin.sauter@navy.mil
The Free Electron Laser is a new ONR Innovative Naval Prototype program.
NRL RF-Gated Thermionic Electron Gun Experiment

HV Modulator

HV Modulator Controls

16 GHz Oscilloscope

Dual Frequency RF Drive

Electron Gun

Fast Faraday Cup
**Vision:** Increase Naval forces’ freedom of action through energy security and efficient power systems. Increase combat capability through high energy and pulsed power systems. Provide the desired power where and when needed at the manned and unmanned platform, system and personal levels.
Nike Laser Target Chamber

Electra 5 Hz electron-beam-pumped KrF laser

- Laser facilities
  - NIKE: 3 kJ KrF laser (0.25 μm, 4 ns) S. Obenschain
  - Electra KrF laser development facility (700 J, 5 Hz) J. Sethian
- Research activities:
  - ICF Target physics – Laser plasma interactions, RT instabilities, shock ignition
  - Laser Science – High power KrF, repetitive KrF and solid-state pulsed power
- Vision:
  - Contribute to future US Inertial Fusion Energy program
The NRL Laser Fusion Energy Program

Prospects & Payoff for both the Navy and the Nation

- Fusion energy available sooner.
- New clean & abundant supply of energy.
- U.S. could be world leader in a valuable new technology.
- Provide power for Naval bases & synthetic fuel production.

Spinoffs:

- Durable high energy pulsed power.
- Directed energy weapons.
- Materials processing with Electron beams

Program History

- 1972  world leader in high energy Nd:glass lasers. (technology exported to LLNL for ICF)
- 1995  Completed Nike, worlds largest krypton-fluoride (KrF) laser – a deep UV gas laser.
- 1999  Started National program to develop reactor grade laser fusion components.
- 2002 – 2009  Developed robust target designs with more than enough energy gain for power plants.
- 2006- Identified “Fast Track” staged development path to fusion energy.
- 2009  Electra facility demonstrates long duration high-energy KrF operation.
Nike is employed for studies of hydrodynamics and LPI.

Orthogonal imaging of planar targets with monochrome x-rays.

Collision with low density foam foil.

Areal density ringing after short laser pulse.

44 overlapped ISI-smoothed KrF laser beams.
Nike has accelerated target to 1000 km/sec to explore Impact Ignition

Joint experiment with U. Of Osaka, ILE
KrF has significant advantages for achieving the high gain needed for fusion

Shortest wavelength (248 nm)
  Better coupling to pellet
  Higher threshold for Laser Plasma Instabilities (experiments)

Smoothest laser profile (< 0.2% non-uniformity)
  Minimizes laser perturbations on target (demonstrated)

Predict power plant class gains with modest lasers

"Conventional" Direct Drive:  Gain: 160 @ 2.4 MJ laser

"Shock Ignition" Direct Drive:  Gain: 200 @ 1 MJ laser
                       Gain: 300 @ 2 MJ laser
KrF Progress- NRL Electra Laser

2.5 to 5 Hz
300-700 Joules
10 hours continuous 90,000 shots
400,000 shots total
Predict > 7% total efficiency
Pulsed power demonstrator: 11.5 M shots continuous @ 10 Hz
Developed credible solutions for the other key components for laser IFE

Target Fabrication:
Mass produced foam shells
Estimated cost $0.16 each

Target Engagement:
Bench test: 34 micron accuracy

Final Optic (Grazing Incidence Mirror)
10,000,000 shots at 3.5 J/cm²

Chamber Wall (nano-scale tungsten)
may have lifetime of several years
NRL proposed Fusion Test Facility: Demonstrate/integrate science & technologies
Develop
durability and validate materials

500 kJ laser
Gain = 100
5 Hz
Fusion Power: 150-200 MW
Could be operating 2022
Code 6770 pulsed power facilities are used for PFD and HEDP research

Gamble II (2 MV, 1 MA, 100 ns)

- Oil-insulated Marx
  - 0.5 MJ, 5 MV
- Water Switch
- Oil Switch
- Vacuum load region
- 65 ft

Hawk (0.7 MV, 0.7 MA, 1 μs)

- 17 ft

- PFRP basic physics
- Diagnostics for HEDP
  - High resolution K-line spectrometer
  - Image-plate/scanner for x-ray imaging
  - Electrical and x-ray monitors
- Computer codes
  - ITS (radiation transport)
  - LSP (EM PIC/Monte Carlo code)
  - MACH (MHD plasma dynamics)

- PFD development for future applications
  - Long-pulse PFD source for active detection of fissile materials

12/7/2011
MIPSE Seminar - 7 Dec 2011
MERCURY, completed in late 2004, is used for active detection and flash radiography.

Magnetically-insulated inductive voltage adder designed to produce a 50-ns pulse with a load voltage of 6 MV, 360 kA to 8 MV, 250 kA (360 kJ at 95-kV Marx charge).

800 R@1m at 8 MeV could service many of SNL’s Hermes users.
Intense Pulsed Active Detection (IPAD) uses a single intense radiation pulse for SNM interrogation

**advantages**

- Single intense radiation pulse →
  - 100-ns illumination time
  - seconds for entire inspection
  - high signal/natural background, or lower dose
- Single pulses → access prompt signature
- Same technology drives many irradiation sources
  - brems or beam-target ($\gamma_0$, n, $\gamma_0 + n$)

**issues**

- Compact, reliable pulsed power with modest repetition rate (~TW, several shots/min)
- Sensitive detectors with fast recovery and response to gammas & neutrons (operate in harsh environment)
NRL is remaining involved in the development and utilization of LTD for radiography, etc.

Six-fast brick cavity assembled & tested
Ktech Contract # N00173-10-C-2019

Six-slow brick cavity procured
NRL Capital Procurement

57-kV, 400-kA, 220-ns rise

50-kV, 135-kA, 50-ns rise-time

4' x 8' x 7.5" per cavity

LCR Applet, by R.J. Allen

Courtesy Ktech, R. Spielman
Unambiguous detection of DU by delayed gammas achieved in < 1s

- 6-detector bismuth germanate (BGO) array fielded 2.65 m from DU
- 5-cm-dia × 5-cm-thick scintillators collimated by lead & borated polyethylene
- Similar results from HPGe detector observing >1700 kV photons for 20 s
Long-Range Power Beaming using High-Power CW Fiber Lasers

**Objective:**
Evaluate long-range power beaming capabilities using high-power cw fiber lasers and advanced laser power converters.

**Payoff:**
Laser power beaming can be used to increase the flight duration and operational capabilities of UAVs.

**Approach:**
Conduct laboratory experiments to characterize laser power converters and beam directors using high-power cw fiber lasers. Perform long-range (3 km) power beaming field tests with stationary collectors. Conduct power beaming experiments with dynamic platforms, such as a UAV, and design a system for transition to TEW division.
Maximum Power of Vacuum Electronic, Solid State, and Quantum Electronic Devices

- Need for “compact and mobile” sources has spurred interest in scaling slow-wave vacuum devices to THz regime, i.e., DARPA HiFIVE Program
  Goal: $P \sim 100 \text{ W} @ 220 \text{ GHz}$ with 500 W-GHz BW ($\ast$)

- Gyrotrons offer higher power for some DoD applications

- Fast-wave interaction scales well to short wavelengths

Terahertz Gyrotron Project Equipment

Cryomagnetics
12 T Cryogen-free Superconducting Magnet

Rockwell
Hard-Tube Modulator
70 kV, 10 A, 1–1000 Hz, 0.5–20 μs

CW gyrotron power supply, cooling and control systems
550 GHz $\text{TE}_{15,2}$ Gyrotron Experiment

- Trim Coil
- Magnet Dewar
- Main Coil
- Cavity ($D \approx 7\lambda$)
- Helical Launcher
- Flat mirrors
- Collector (cm)
- Quasi-parabolic Reflector
- Window
- 3-in. dia. Warm Bore

12/7/2011
**Vision:** Achieve an integrated hybrid Force of manned and unmanned systems with the ability to sense, comprehend, predict, communicate, plan, make decisions and take appropriate actions to achieve its goals. The employment of these systems will reduce risk for Sailors and Marines and increase capability.

**Description:** Autonomy and unmanned systems will be used in all operating domains, performing multiple missions, and will be developed into numerous platforms.
Environmental Profiling using Swarming UUVs

Each agent maintains a local model

Optimal decentralized data fusion

Consensus control predicts global model

Lynch, KM; Schwartz, IB; et al IEEE TRANSACTIONS ON ROBOTICS, 24 (3): 710-724 2008

Best IEEE paper finalist
**Vision:** More effective point of injury care for Sailors and Marines. **Enhanced health and warfighter performance both afloat and ashore.** Highly efficient and effective human-system performance aided by new technologies created through the exploitation of biological design principles. Enhanced warfighter and system performance with reduced personnel costs as a result of the right information being provided to the right people with the right skills at the right time in the right jobs.
SWOoRD
Swept-Wavelength Optical resonance Raman Device

HMX

Escherichia coli

Chemical detection
Biological detection
Nuclear Forensics (?) Uranophanes

J Grun
Plasma Facilities - 6750

Large Area Plasma Processing System
S. Walton

- Uses moderate energy (few kV) sheet electron beam for ionization
- Unique low temperature (0.5 eV) plasma suitable for treating delicate materials (polymers, organic semiconductors)

Space Plasma Simulation Chamber
W. Amatucci

- Large volume permits scaled laboratory simulations of space plasma processes
- Plasma wave generation and instabilities, plasma flows, pitch angle scattering, etc.
- Supports efforts on radiation belt remediation concept
- Space hardware RDT&E
A plasma source based on electron beam ionization

**Typical Operation:**
CW & Pulsed e-beam ~ 2 keV beam
Period = 2 - 60 ms, Duty = 10% - 100%
B = 150 - 200 Gauss (for beam collimation)
P = 5 - 150 mTorr

**Typical Plasma Source dimensions:**
thickness ~ 1 cm
Width (hollow cathode length) ~ 25 - 50 cm
Length (beam distance) ~ 50 - 100 cm

* US patent no. 5,874,807 (Feb. 1999)
Plasma generation with high-energy electron beams

• In discharges,
  – small fraction of electrons ionize gas
  – most energy is used to excite the gas

• The injection of a 2 keV beam into the background gas will directly ionize and dissociate the gas.
  • more efficiently ionize
  • no threshold determination
  • ionize all species equally
  • density controlled by beam current

• The plasma (or secondary) electrons have much a lower energy
  • are not required to sustain the plasma
  • cooled electrostatically and through inelastic collisions

The resulting high $n_e$ and low $T_e$ are key attributes
Diagnostics

Unique species generation

High density/localized

Low $T_e$

Low ion energies


Access to new operating parameters opens up new opportunities in plasma processing

Processing of “energy sensitive” materials

Materials where roughening or etching is not good ...

Polymers - *surface roughening is an issue*
- In the development of organic transistor devices (Materials Today 10(3) 2007).
- In new 193 nm photoresists.
- In the development of thin, multi-stack capacitors.
- In biosensor development, presentation can be adversely impacted

Graphene (or other 2-D materials) - *etching is not an option*
- Single monolayer of sp² bonded carbon with some of the best thermal and electrical properties known
- Carbon-based nanoelectronics is the best candidate to replace CMOS technology in the future. ITRS (July 2008)
- However, to realize its full potential, its chemistry needs to be managed ...

In the processing of either material, we aim to impart functional groups to the surface to improve their performance in a variety of applications.
Vision: Assure access to the global ocean and littoral reaches and hold strategic and tactical targets at risk. Sense and predict environmental properties in the global ocean and littorals to support tactical and strategic planning and operations. Improve operational performance by adapting systems to the current and evolving environment.
Laser pulse, plasma & shock characterization
• High-resolution, intensified, gated ($\tau_{\text{res}} \geq 0.8 \text{ ns}$) CCD cameras
• Fiber-coupled & imaging spectrometers
• Sub-ns-resolution streak cameras
• High-pressure (kbar) gauges
• Dark-field shadowgraphy (schlieren) imaging of shock propagation

Test Chambers:
Underwater Laser Plasma Chamber
• Volume $\approx 1 \text{ m}^3$
• Multiple optical quality access ports for laser beams & imaging

Laser Filament Imaging Chamber
• Variable length water tube with high-resolution beam profile imaging

Portable nanosecond 532 nm Lasers:
• 1) 2 J, 6 ns; 2) 450 mJ, 9 ns; 3) 60 mJ, 4 ns

Portable picosecond 532 nm Lasers:
• 125 mJ, 100 ps

Laboratory femtosecond 400 nm Lasers:
• 1) $\sim 0.5$ J, 50 fs @ 10 Hz; 2) 7 mJ, 35 fs @ 1 kHz
NRL Remote Underwater Laser Acoustic Source (RULAS)  
P.I. Dr. Ted Jones

- **Acoustic communications**
  - Transmit from airborne laser platform to submarine or UUV
  - Dynamically change instructions as mission & data change
  - Optically penetrate thermocline

- **Virtual acoustic beacon array for UUV navigation** (analogous to GPS)
  - Airborne laser generation of acoustic pulse trains with encoded location and time

- **SONAR applications**
  - Detect and identify mines & other underwater targets
  - Map sea floor topography
  - Laser acoustic imaging
Space Experiments and Projects

• CARE – CARE II
• PERCS
• Radiation Belt Remediation
• Orbital debris
• Shuttle burns
• HAARP
• Space Chamber Expts
Large volume, steady-state, space-like plasmas

2-m diameter by 5-m main vacuum chamber

2 m of plasma column source chamber section

Steady-state magnetic fields ranging from 0 to 1000 G levels.

Variable plasma conditions simulate many regions of near-Earth space

Experiments include:
- radiation belt dynamics,
- broadband ionospheric ion-cyclotron wave generation,
- wave and Joule heating of ionospheric plasma,
- magnetotail particle and wave dynamics.

Spacecraft diagnostic development and hardware testing/qualification
**NRL Space Physics Simulation Chamber**

**Experimental Parameters**

- Plasma Species: Argon (A=40)
- Plasma Density ($n_e$): $10^9$ - $10^{11}$ cm$^{-3}$
- Electron Temperature ($T_e$): 3 - 5 eV
- Ion Temperature ($T_i$): $\sim$ 0.07 eV
- Ion Cyclotron Frequency ($f_{ci}$): 11.5 kHz

**Dimensionless Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ionosphere</th>
<th>SPSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{pe}/\Omega_e$</td>
<td>0.1-10</td>
<td>0.01-50</td>
</tr>
<tr>
<td>$\rho_i/L_E$</td>
<td>0.01-0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>$E/B$</td>
<td>&lt; 30 km/s</td>
<td>&lt; 20 km/s</td>
</tr>
<tr>
<td>$\beta = nkT/(B^2/2\mu_0)$</td>
<td>$10^{-7}$-$10^{-4}$</td>
<td>$10^{-7}$-$10^{-4}$</td>
</tr>
</tbody>
</table>
Research Questions

• How do artificial radiation belts form in the post-HAND environment?
  – What wave characteristics are important for pitch-angle scattering?
  – How do the various plasma wave modes interact and transition?

Experimental Tasks

• Characterize the Shear-Driven EMIC Wave-Vector Spectrum
• Develop antennas for launching EMIC waves
• Investigate EMIC wave energetic electron pitch-angle scattering
• Investigate transitions between EM wave modes (Option Years)
The NRL Ionosphere Model & the Heart of ISES-OE (Plasma Physics Division).

Comprehensive: multi-ion dynamic
Neutral species input:
1) theoretical model: TIEGCM, or
2) empirical: such as
NRLMSISE00/HWM93/HWM07
EUV model: EUVAC empirical model
Magnetic latitude range (+/- 60°)
Nonorthogonal, nonuniform fixed grid
Self-consistent potential solver
Tilted Dipole Field

12/7/2011
Space Weather Modeling

Plasma simulation models
- SAMI-2 and SAMI-3 (Ionosphere)
- LFM (Magnetosphere)
- RCM: Ring current

Predicted Total Electron Content Map

• Electron density isosurfaces from SAMI-3 simulation code
• First fully 3-D simulation of equatorial spread F (ESF)
• Plasma bubble can affect communications
NRL Rapid Remediation Concept

CONCEPT:
Inject massive amount of energy over a short period

APPROACH:
Release neutral gas from a satellite moving perpendicular to the magnetic field and convert the orbital kinetic energy of the neutrals into free energy for sustaining EM waves that pitch-angle scatter electrons from belts
Objective:

1) Develop the concept of artificially generating and maintaining a dust layer in the near-earth plasma environment to induce enhanced drag on space debris
2) Develop proof-of-principle experiments to validate the novel concept
3) Design a detailed blueprint for a space demonstration experiment

Approach:

1) Determine requirements for inducing enhanced drag on space debris by artificially creating and maintaining a dust layer in space.
2) Choose orbits of space debris and calculate the minimum drag necessary for forcing their orbits to decay into the atmosphere.
3) Determine the volume, dust size, and duration necessary for a stable dust layer to produce the necessary drag enhancement
Thank you for your attention

Are there any questions?