The Naval Research Enterprise and Plasma Physics Research at NRL

Michigan Institute for Plasma Science & Engineering

University of Michigan

Dr. Tom Mehlhorn
Plasma Physics Division
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7 Dec 2011

US NAVAL RESEARCH LABORATORY
The Navy and Marine Corps Corporate Laboratory

NRL has a distinguished history

THOMAS A. EDISON

"GOVERNMENT SHOULD MAINTAIN A GREAT RESEARCH LABORATORY TO DEVELOP GUNS, NEW EXPLOSIVES AND ALL THE TECHNIQUE OF MILITARY AND NAVAL PROGRESSION WITHOUT ANY VAST EXPENSE."

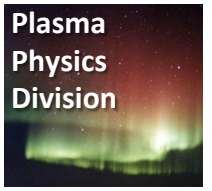
THOMAS A. EDISON,
THE NEW YORK TIMES MAGAZINE
SUNDAY, MAY 30, 1915

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

NRL: Navy's designated corporate laboratory by SECNAV 1991

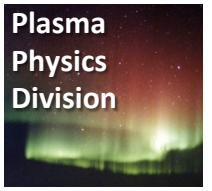


- MISSION is to conduct a broadly based multidisciplinary program of scientific research and advanced technological development directed toward maritime applications of new and improved materials; techniques; equipment; systems; ocean, atmospheric, and space sciences; and related technologies.

- 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

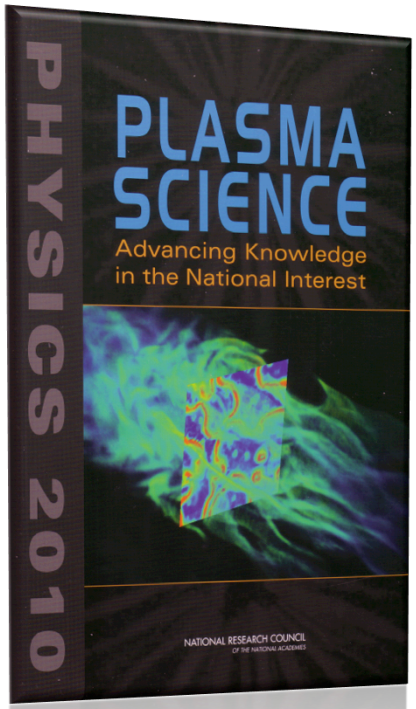
Commanding Officer
CAPT Paul Stewart, USN

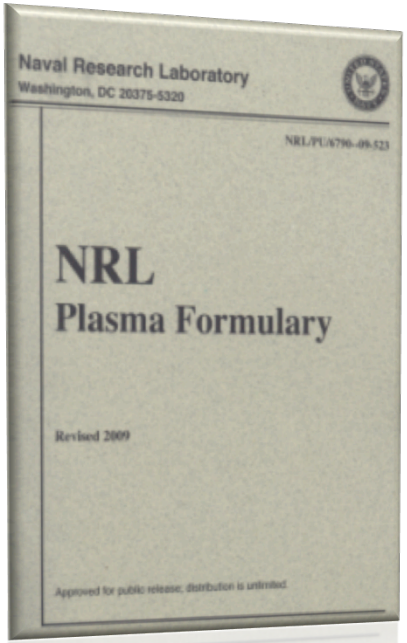
Director of Research
Dr. John Montgomery

Business Operations	Systems Directorate	Materials Science and Component Technology	Naval Center for Space Technology	Ocean and Atmospheric Science & Technology
Mr. D. Therning	Dr. G. Borsuk	Dr. B. B. Rath	Mr. P. G. Wilhelm	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

Plasma Physics Division



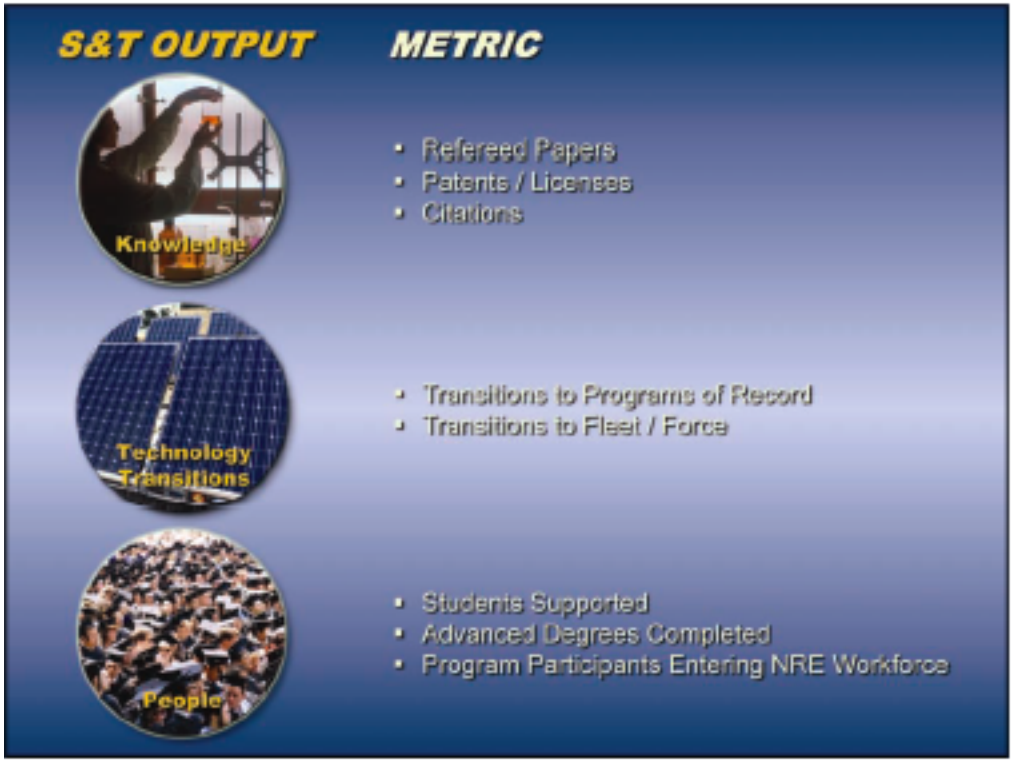


Naval S&T Strategic Plan

Plasma Physics Division

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

Plasma Physics Division

Warfighter Need

TECH SOLUTIONS

Subject Matter Experts
Interpret Technology Requirements

Naval Research Enterprise

NAVSEA WARFARE CENTERS
NAVAIR
NAVFAC
NAVSUP
SPAWAR
PENNSTATE ARL
APL
APPLIED RESEARCH LABORATORIES

Industry Partners & Academia

DIRECTOR OF INNOVATION
ONR

Technology Solutions

Delivery to Fleet/Force

NRL & the Office of Naval Research

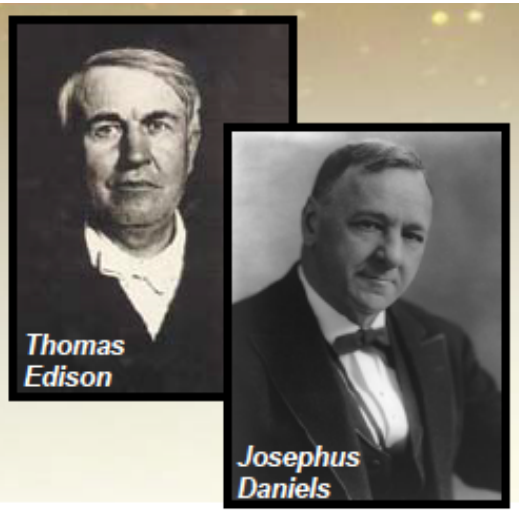
Plasma Physics Division

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…"



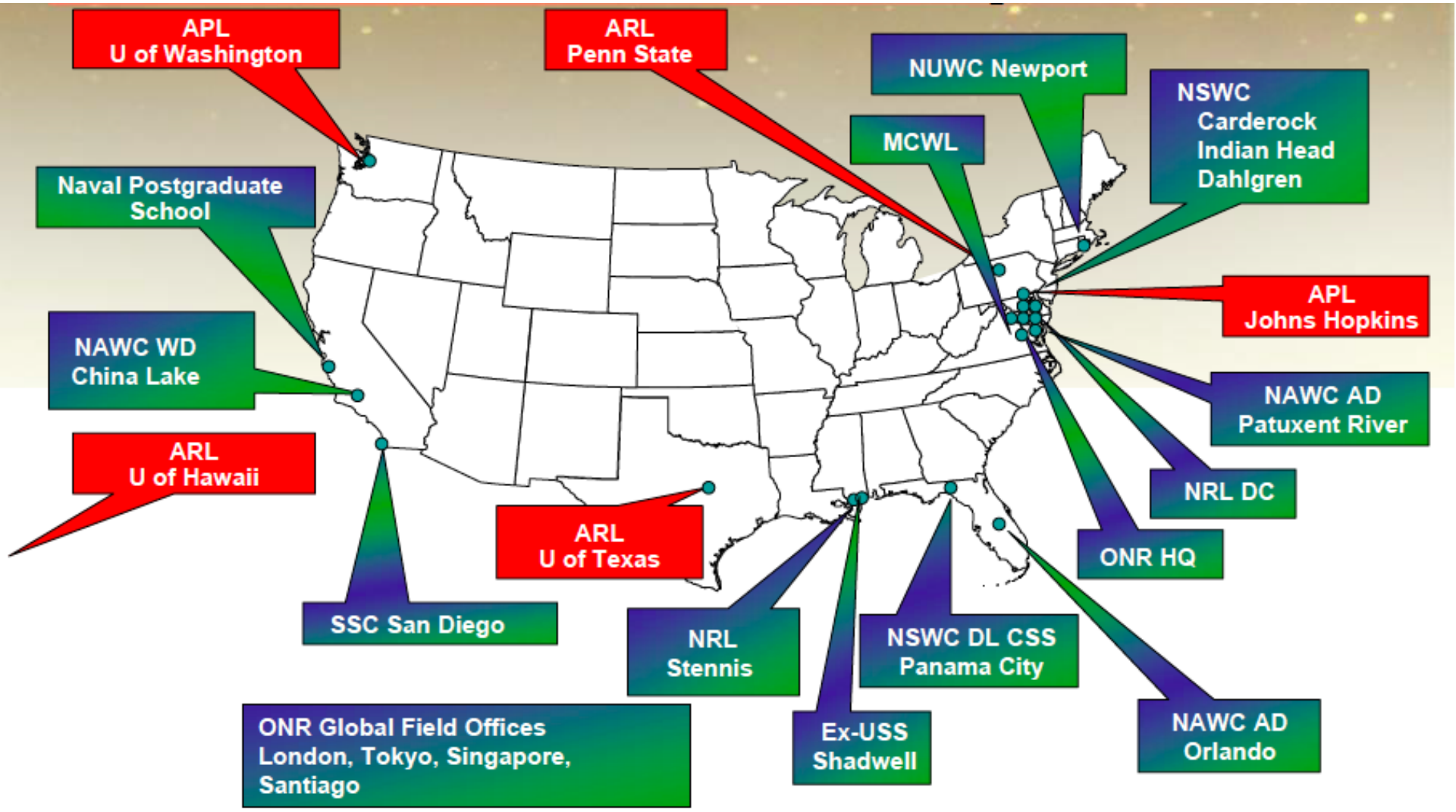
Office of Naval Research - London Office *(1946)*

"…reporting on the latest developments and to assist visiting American scientists to make contact with their colleagues in Europe…"

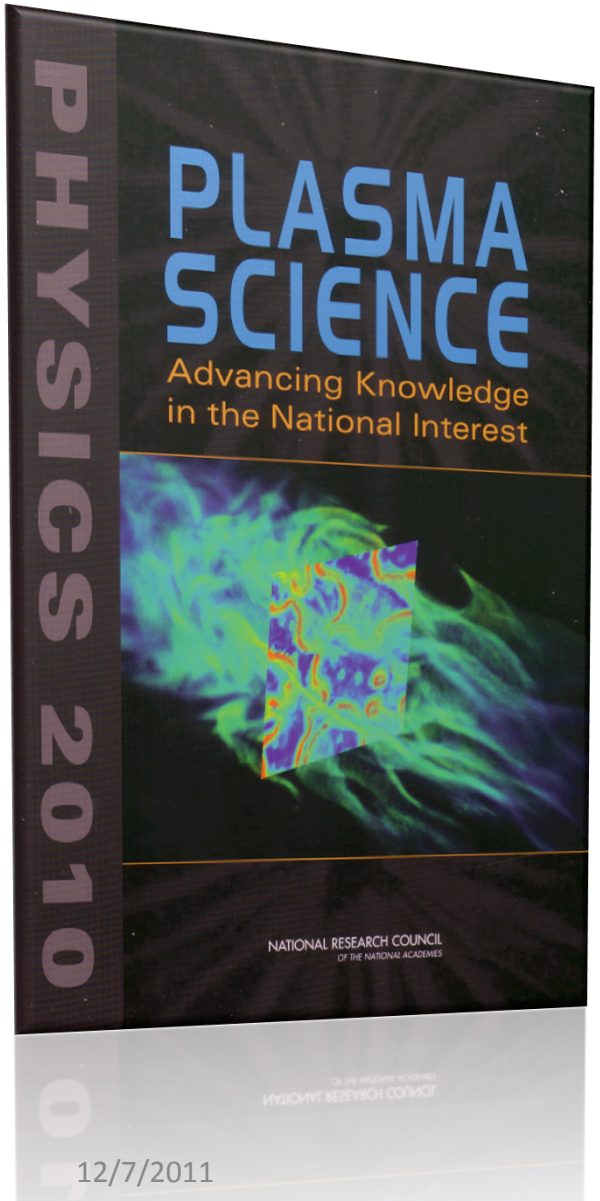
Transitioning S&T *(Defense Authorization Act, 2001)*

"…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



The 2010 NRC decadal assessment of Plasma Science identifies opportunities & challenges



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*

Code 6700 Senior Management

PLASMA PHYSICS DIVISION
Dr. THOMAS A. MEHLHORN, SUPERINTENDENT
Code 6700

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Dr. Richard F. Hubbard
Code 6701

Senior Scientist for Directed Energy Physics
Dr. Phillip Sprangle
Code 6703

Senior Scientist for Radiation Phys & High Energy Density Mat'ls
Dr. Jack Davis, Code 6705

Senior Scientist for Intense Beams & Plasma Processes
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Code 6709

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Dr. John Giuliani *
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Laser Plasma Branch
Dr. Stephen Obenschain
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Charged Particle Physics Branch
Dr. Robert Meger
Code 6750

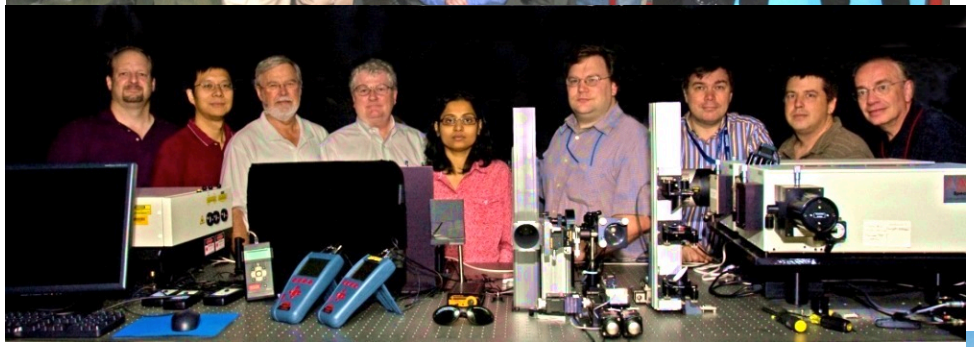
Pulsed Power Physics Branch
Dr. Joseph Schumer
Code 6770

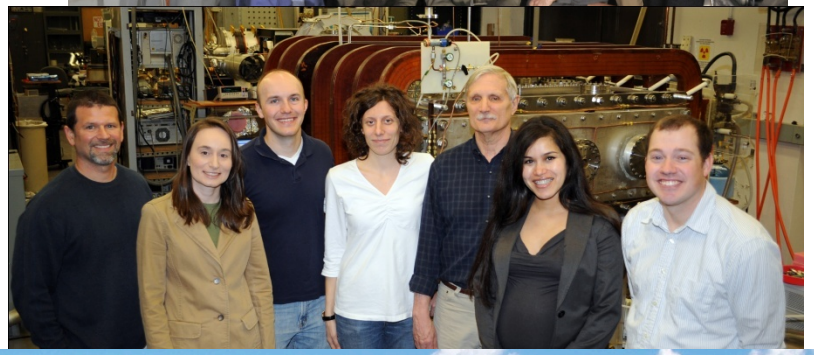
Beam Physics Branch
Dr. Joseph Peñano *
Code 6790

* Acting

Our individual and team researchers are our greatest asset (62 of 85 have PhDs)

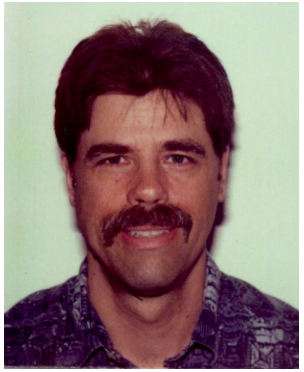
Plasma Physics Division





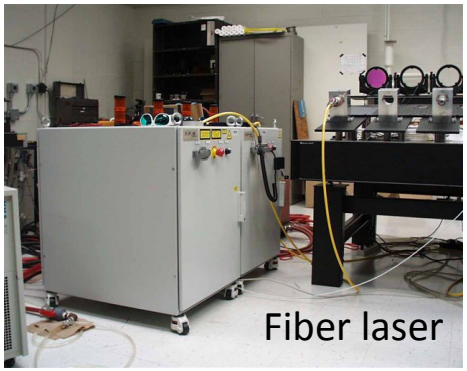
The University of Michigan is well represented in the Plasma Physics Division

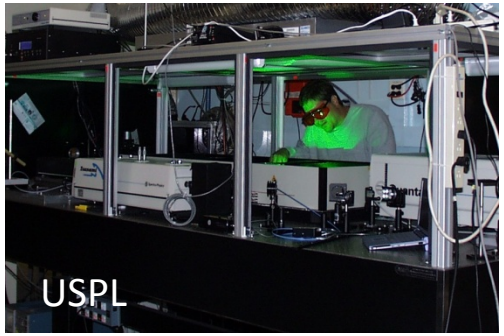
- Tom Mehlhorn (BS'74, MS'76, PhD'78 – Jim Duderstadt)
- Joe Schumer (MS '94, PhD '97 – James Holloway)
- Steve Swanekamp (PhD'90 – Terry Kammash)
- Andy Schmitt (BS'77, MS'79, PhD'82 - Jim Duderstadt)
- Ward Thornhill (PhD'85 – Jim Duderstadt)
- Young Chong
- Jacob Zier (PhD'11 – Ron Gilgenbach & YY Lau)
- Ken Grabowski (BS'74, MS'76, PhD'80 - John King)
- Ken Whitney (BS Physics)
- Jack Davis (Adjunct Professor)
- John Tucker

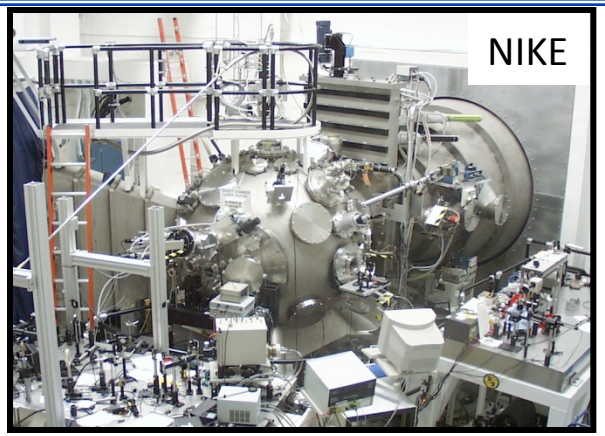


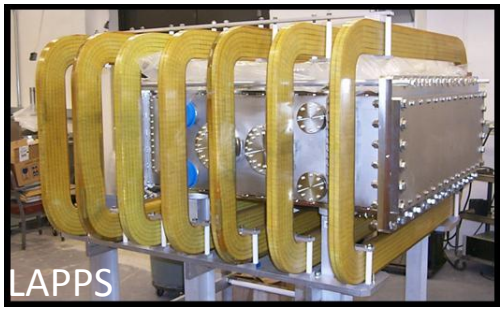
Code 6700 has an impressive array of unique experimental facilities

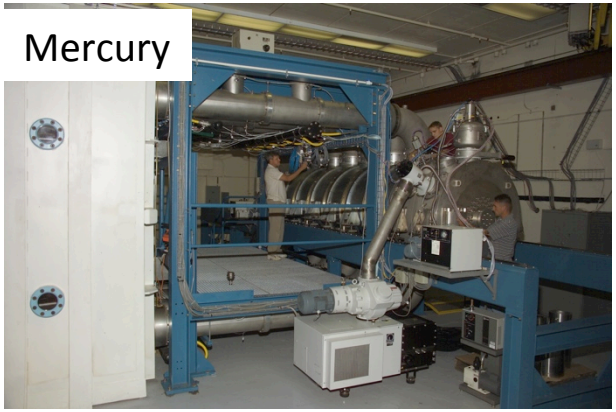
Plasma Physics Division

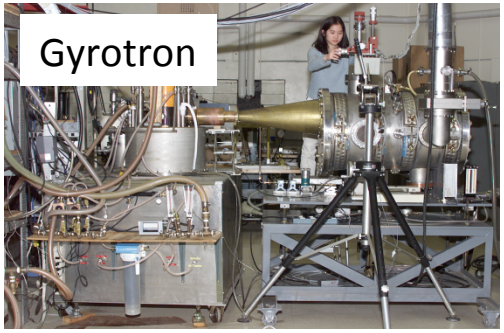


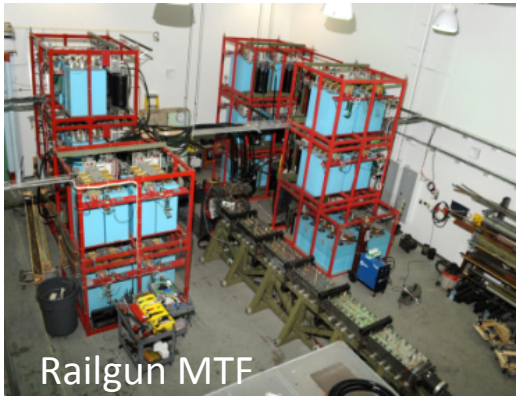


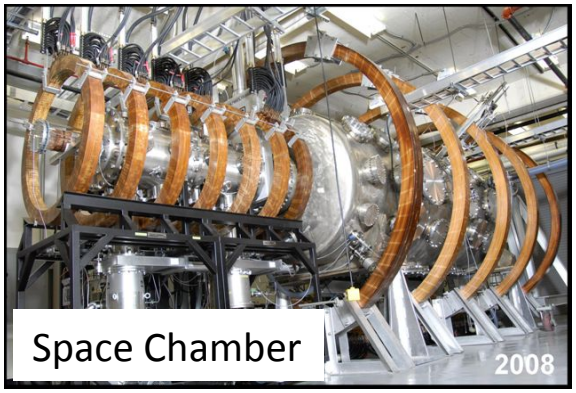


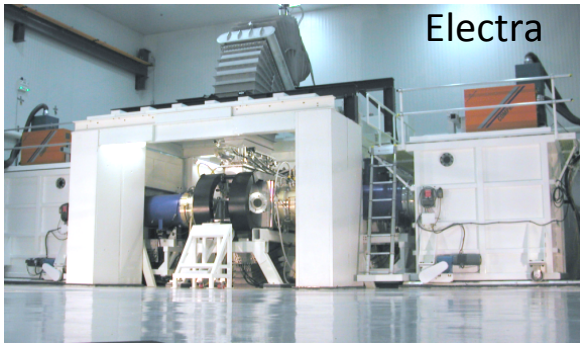








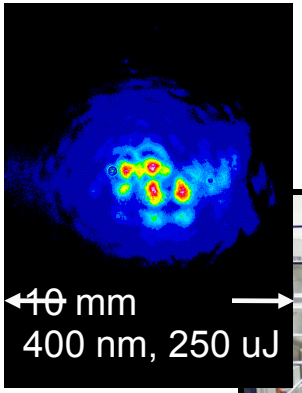




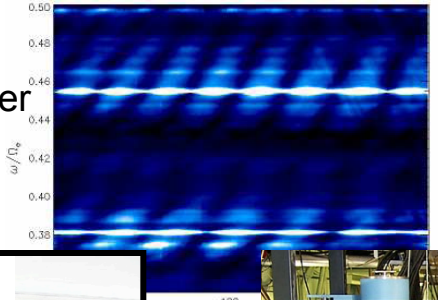
We develop and use state-of-the-art plasma diagnostics

Plasma Physics Division

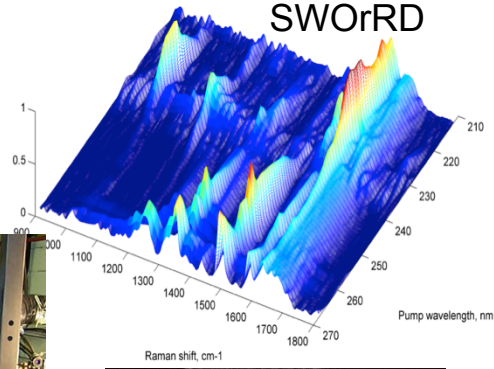
Femtosecond filament

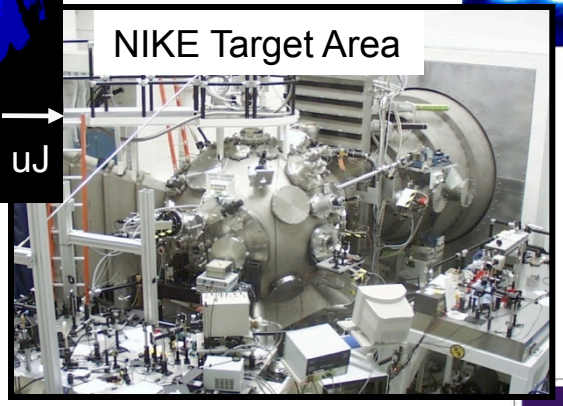


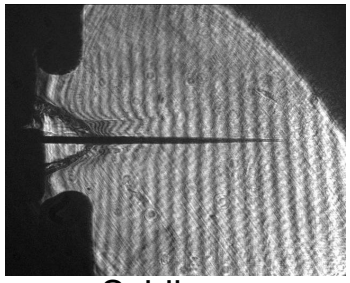
Whistler Wave



SWOrRD

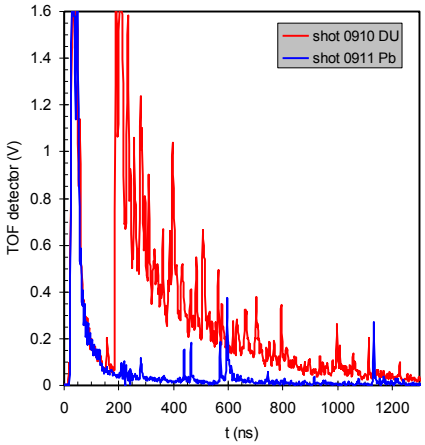




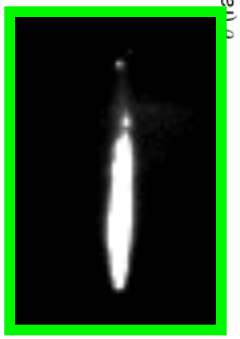


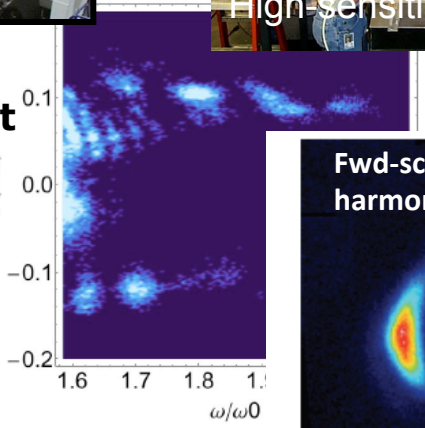
Schlieren

Prompt neutrons

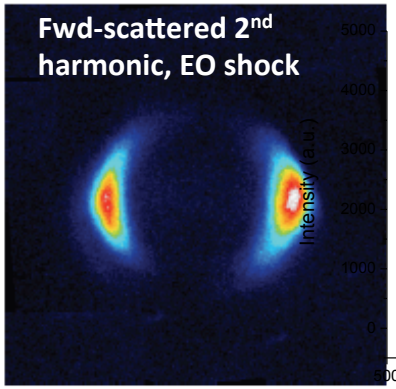


Laser filament in water

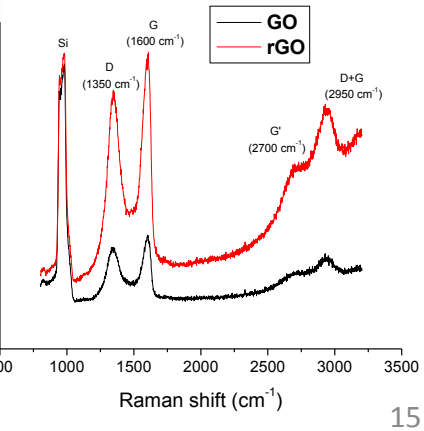




Fwd-scattered 2nd harmonic, EO shock

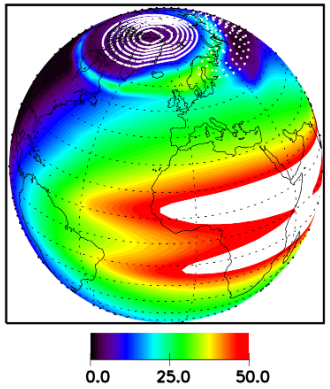


Graphene oxide reduction



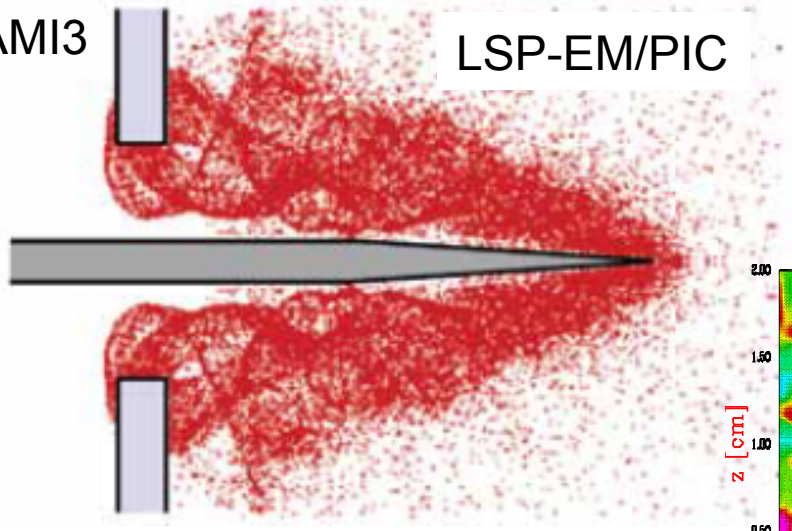
We develop & use state-of-the-art plasma EM, & atomic physics codes

Plasma Physics Division

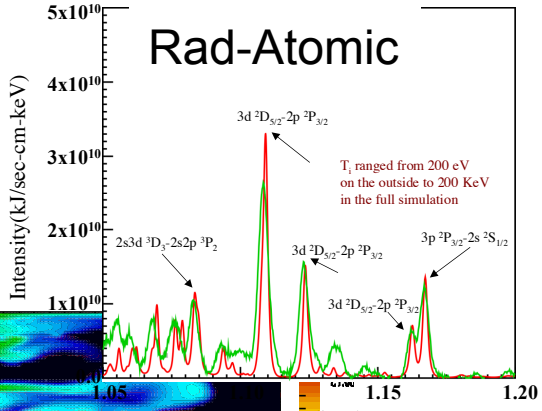


SAMI3

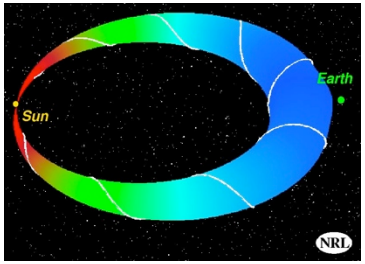
LSP-EM/PIC

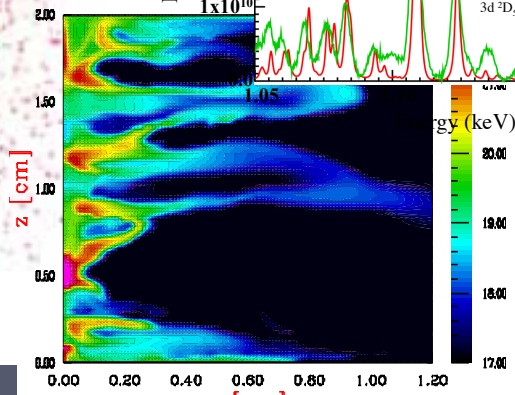


Rad-Atomic



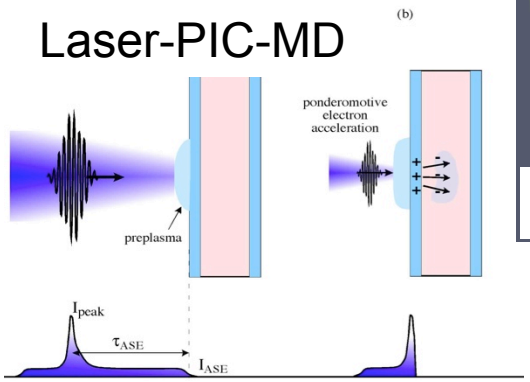
EFR

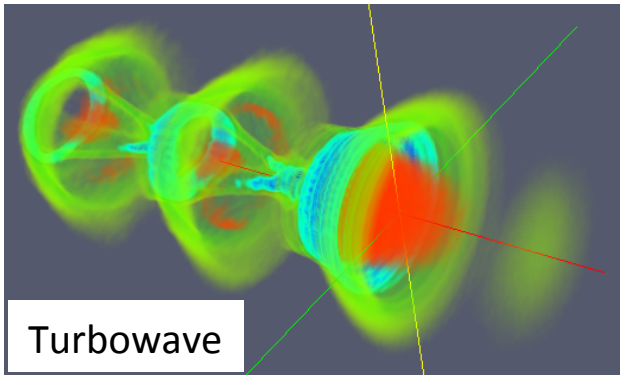


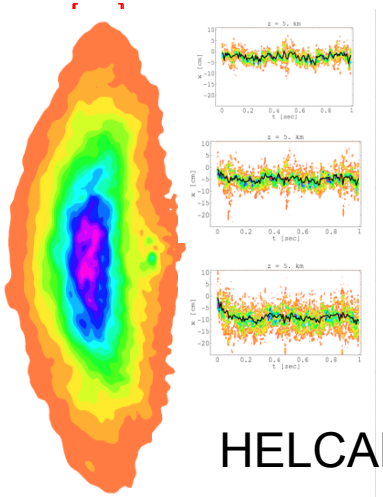


MHD

Laser-PIC-MD





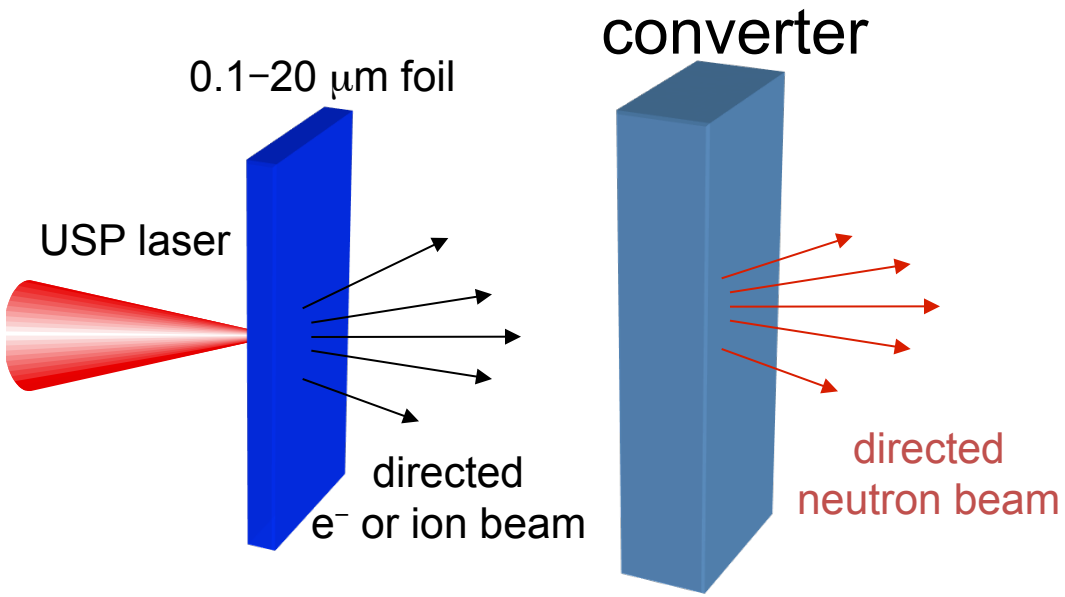


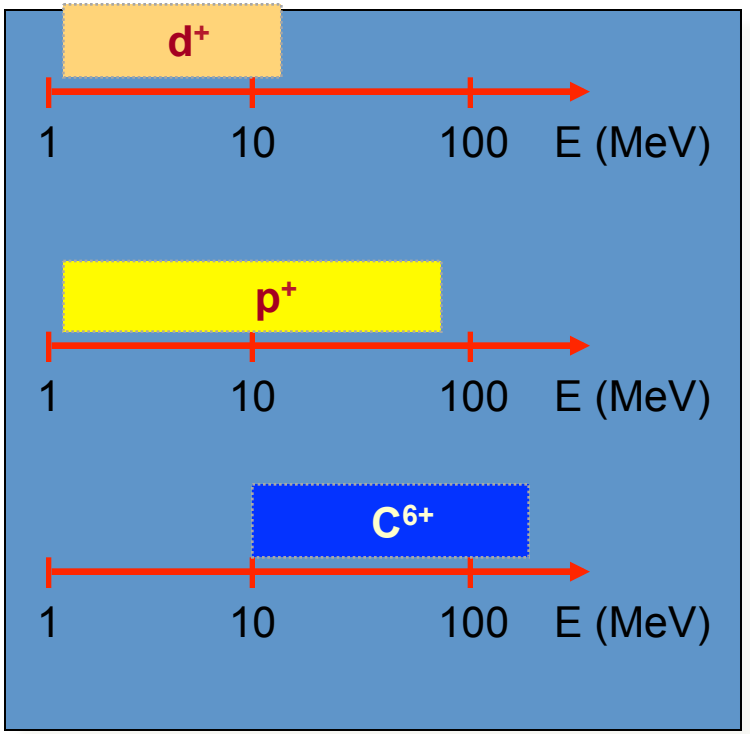
HELCAP

Power Projection and Integrated Defense

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





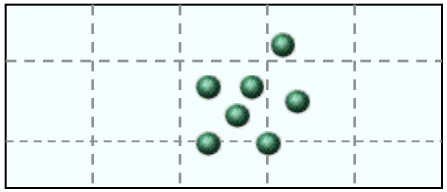
Typical ultrashort pulse lasers parameters

Laser intensity	**10^{18} – 10^{22} W/cm^2**
Laser pulse duration	**30 fs – 1 ps**
Laser wavelength	**0.8 – 1 μm**
Laser energy	**1 J – 1 kJ**

Numerical capabilities developed at NRL

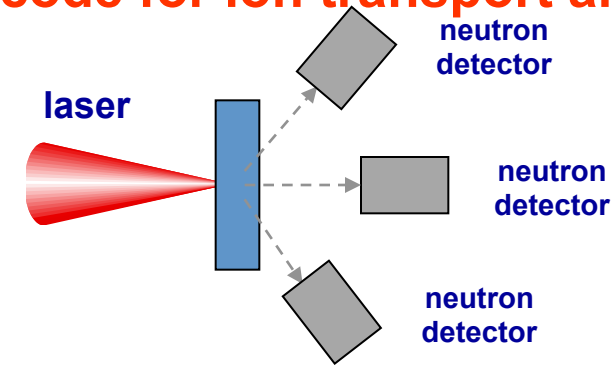
Plasma Physics Division

2D relativistic PIC code for laser-target interactions



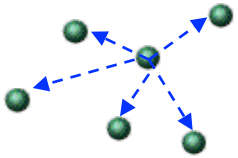
Ideal for modeling laser-target interactions and HEDP.

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, thermodynamcs 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).

NRL Radiation Hydrodynamics Code 6720

Numerical approach for laser-target interaction & neutron production

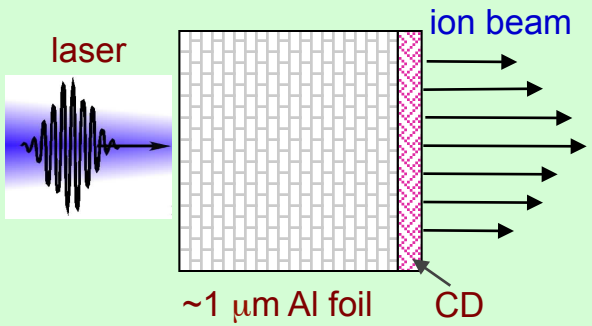
Plasma Physics Division

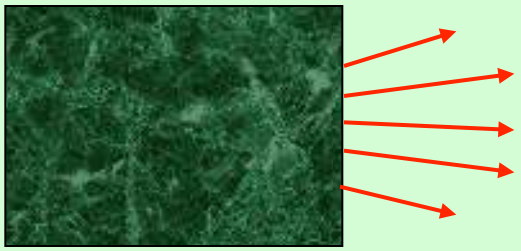
Laser-target interaction model: 2D PIC

Model the interaction of intense ultra short laser pulses with thin foils using a 2D electromagnetic **particle-in-cell (PIC) model**.

Ion beam-target interaction model: 3D MC

Utilize data output from the PIC model as input for a **3D Monte-Carlo model** simulating the production and scattering of neutrons





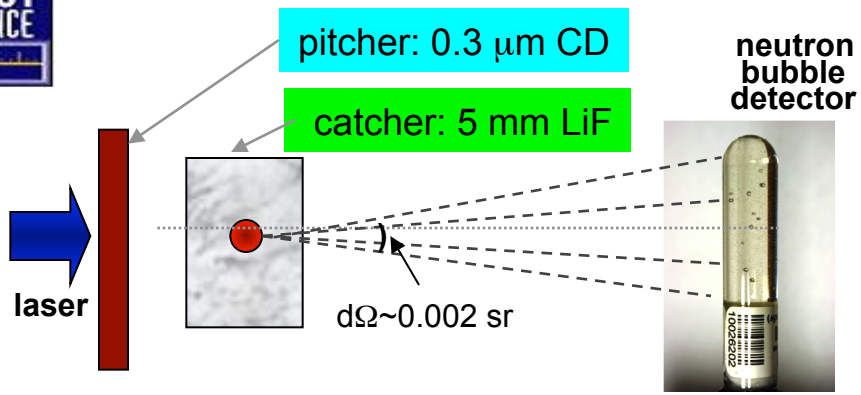
PIC model → ion beam parameters (E,θ) → 3D Monte-Carlo → neutron beam parameters (E,θ)

NRL Radiation Hydrodynamics Code 6720

Collaborative research with U. Michigan on laser-target interaction

Plasma Physics Division

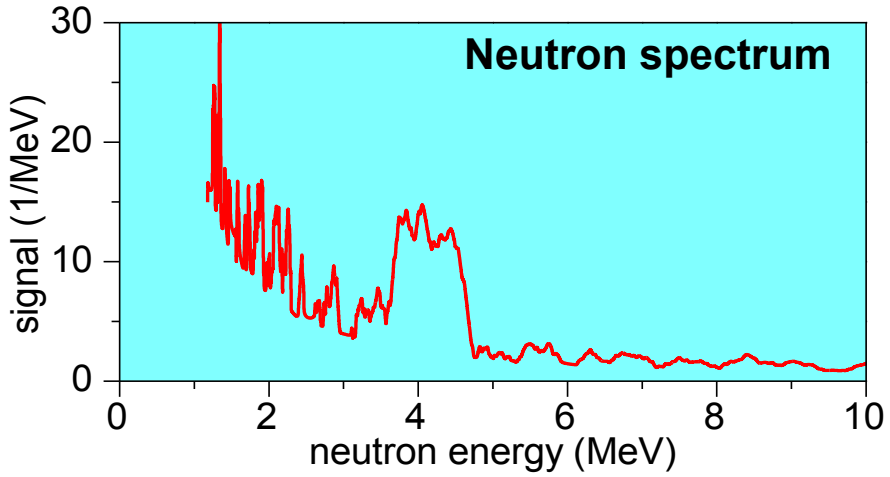
Experiments on HERCULES at CUOS



Y~4x10^5 neutrons
dΩ~2x10^{-3} sr

=>

$$\frac{dY}{d\Omega} \cong 2\times10^{8}\ \frac{neutrons}{sr}$$



Bubble detector

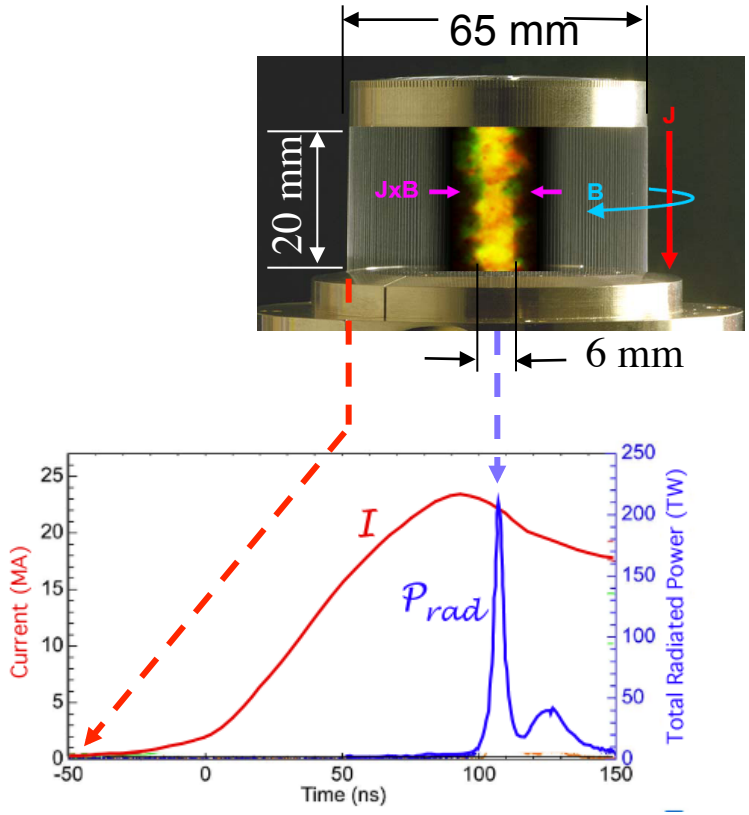
- dimensions: 10x1 cm^2
- sensitivity: 1-15 MeV
- conversion factor: 10^5 n/bubble

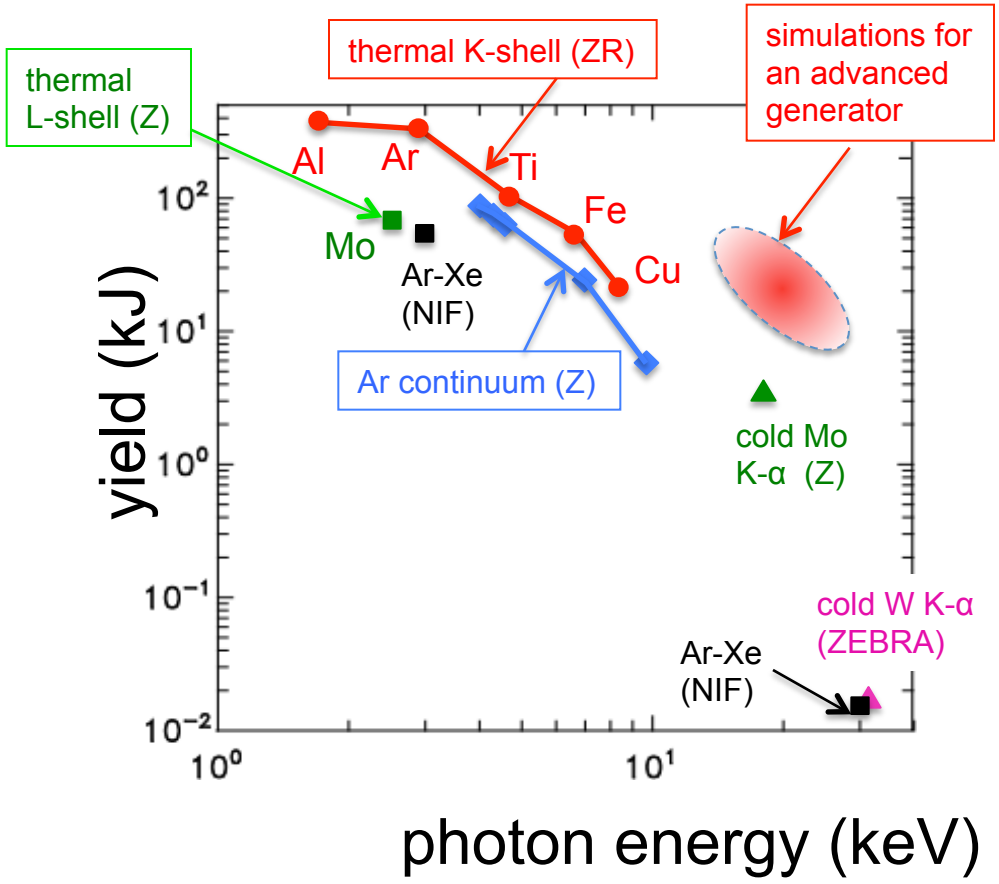
Laser parameters:

E_{laser}	2 J
I_0	5x10^{21} W/cm^2
τ_{FWHM}	30 fs
D_{FWHM}	1 μm
P	50 TW
λ	0.8 μm
ps contrast	10^{-7}

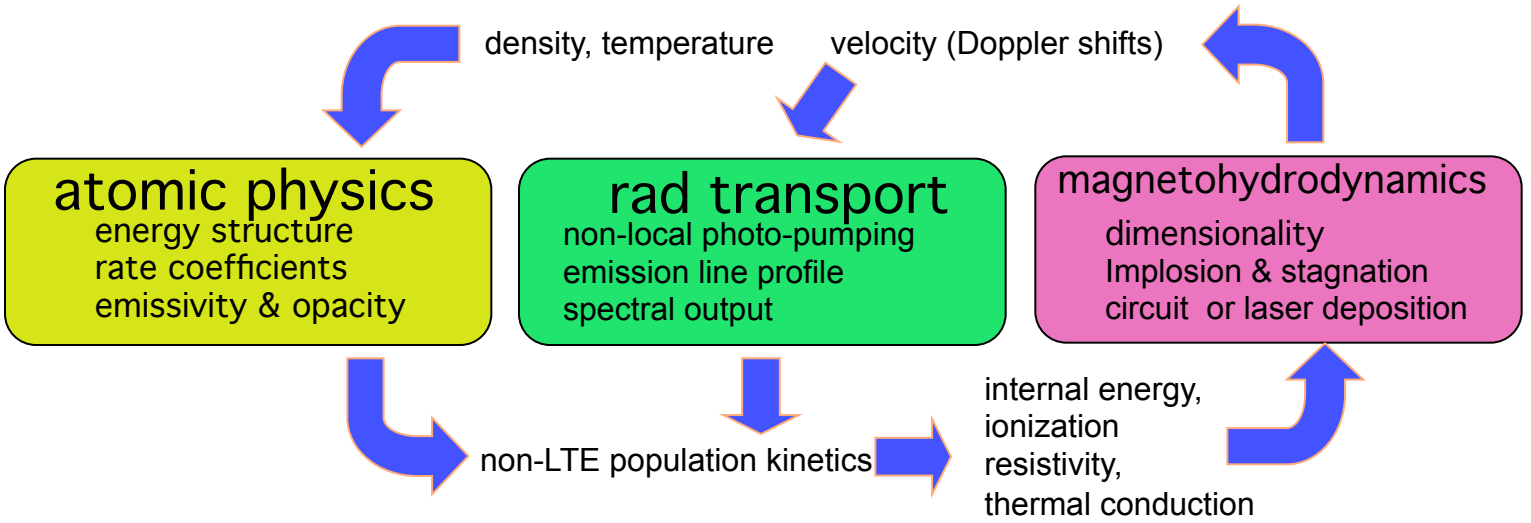
NRL Radiation Hydrodynamics Code 6720

Z pinches:: intense plasma radiation source of photons hv>10 keV





Advanced simulations of Z-pinch loads require an integrated physics approach

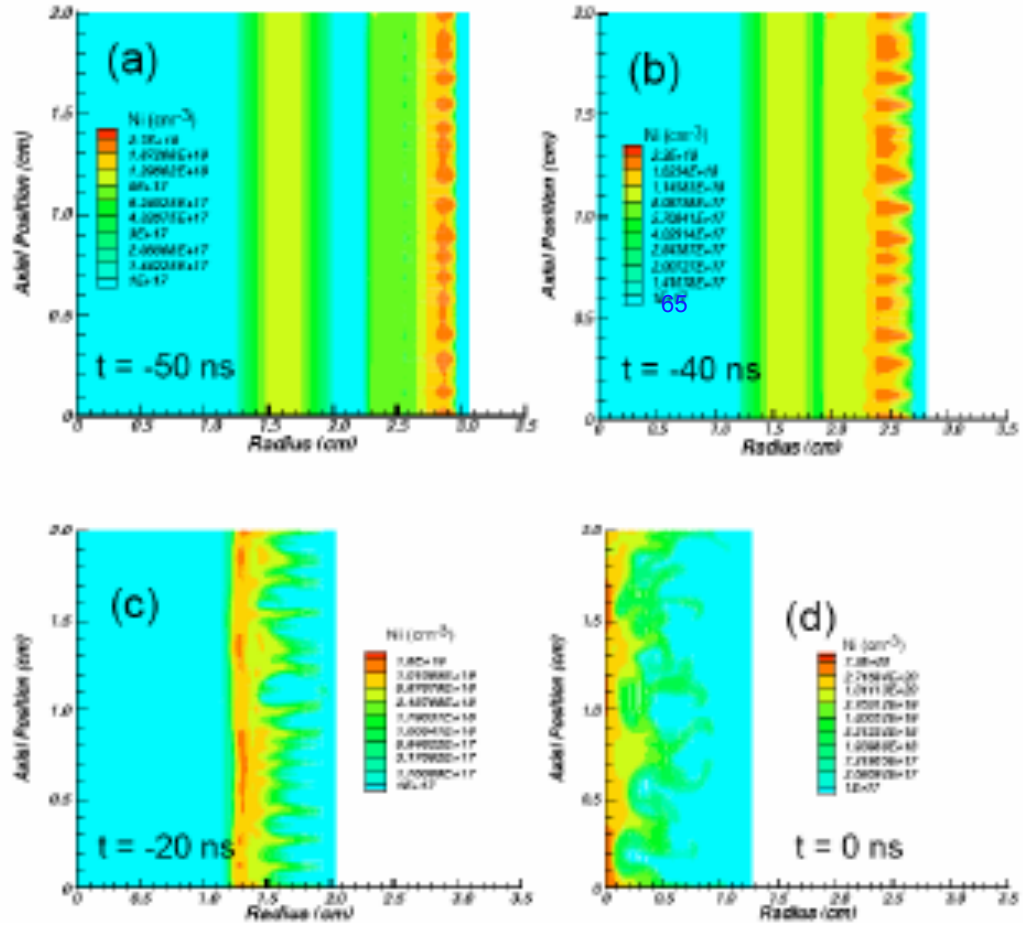


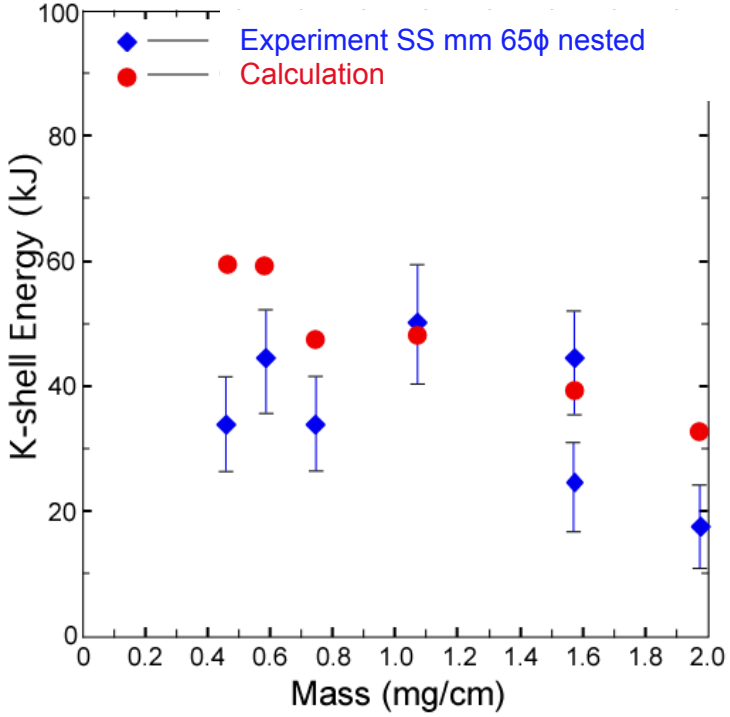
product:

- ❑ 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)

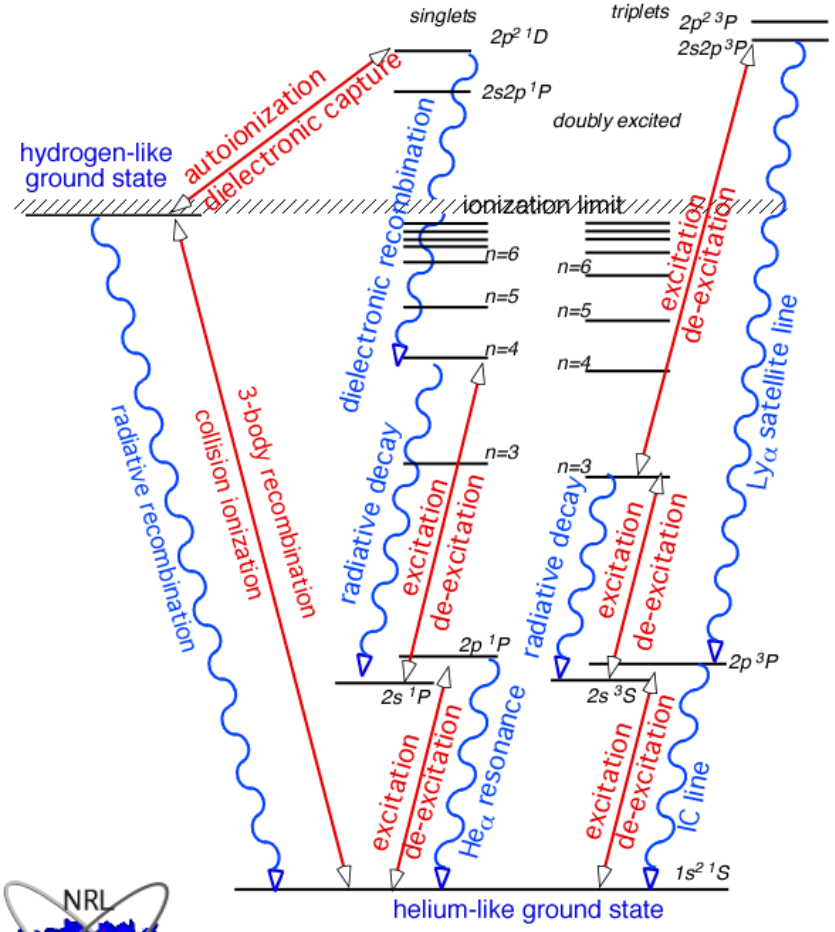


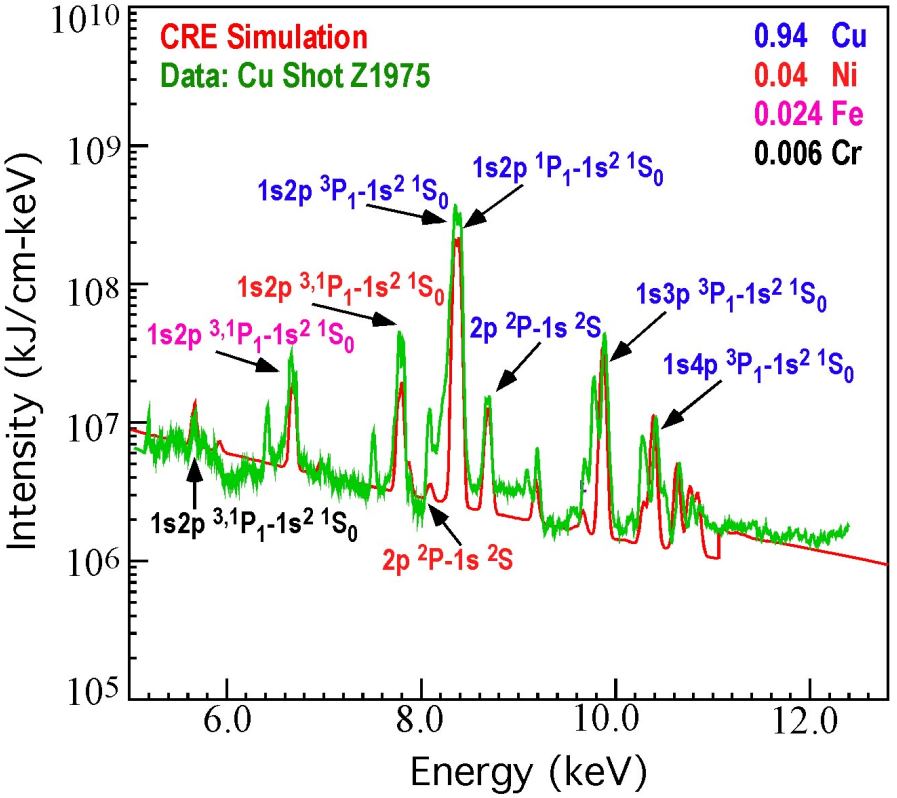


Include model for wire ablation & initial inhomogeneities. Matching radiation data requires a ~25% current loss at final feed.

NRL Radiation Hydrodynamics Code 6720 Plasma Physics Division

Detailed atomic physics + CRE + non-local radiation transport provide synthetic spectra





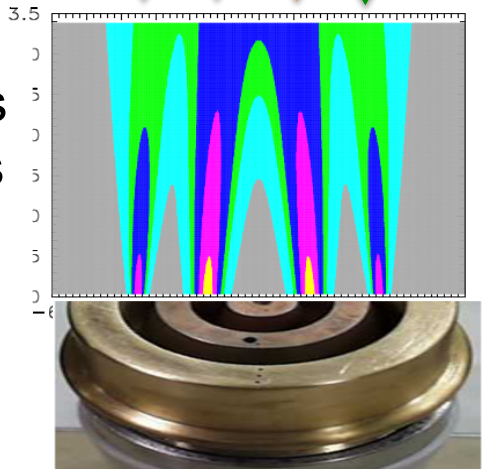
The simulated and experimental K-shell spectra reveal plasma conditions in the emitting region are T_e~3.5 keV and n_e ~ 3x10^{22} cm^{-3}.

Future gas puff experiments will examine novel neutron sources

Plasma Physics Division

Heavy (Ar) gas outer liner imploding on an inner D_2 annulus

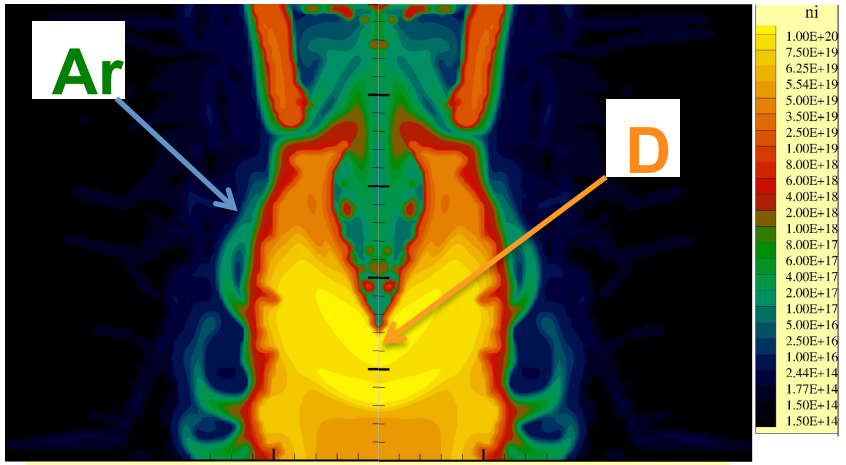
Ar D D Ar



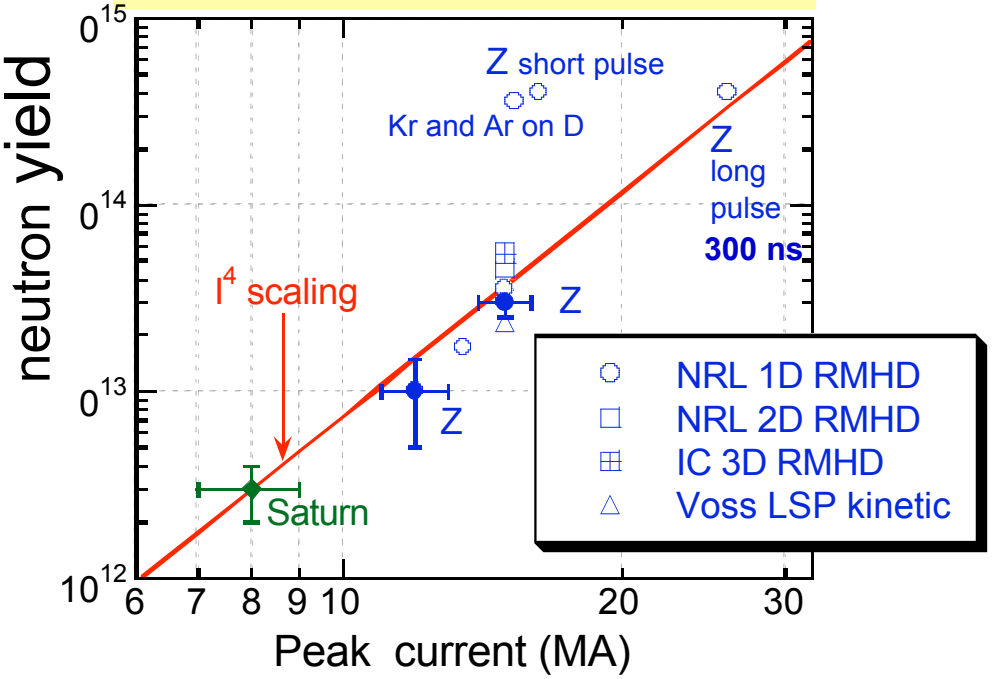
gas jets

nozzle

- **Injected supersonic annular and/or cylindrical gas jet(s)**
  - **Single or multiple-shell**
  - **D_2, Ne, Ar, Kr**



Ion density contour at t=144 ns for Ar-on-D Z-pinch load



NRL Radiation Hydrodynamics Code 6720
Plasma Physics Division

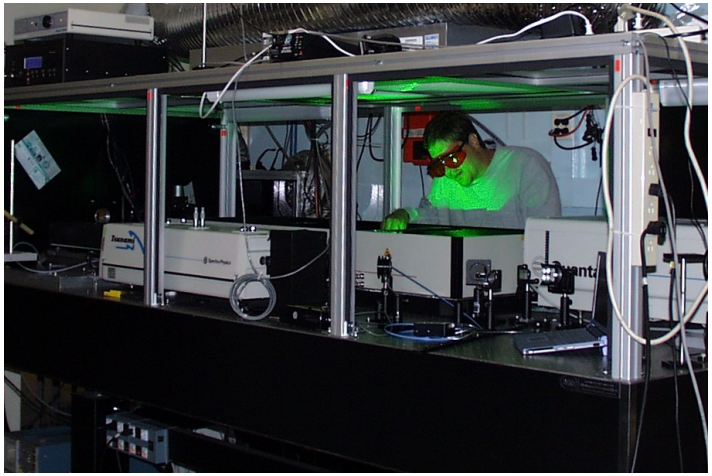
Beam Physics Branch - 6790
Laser Facilities

Plasma Physics Division

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)

Plasma Physics Division

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

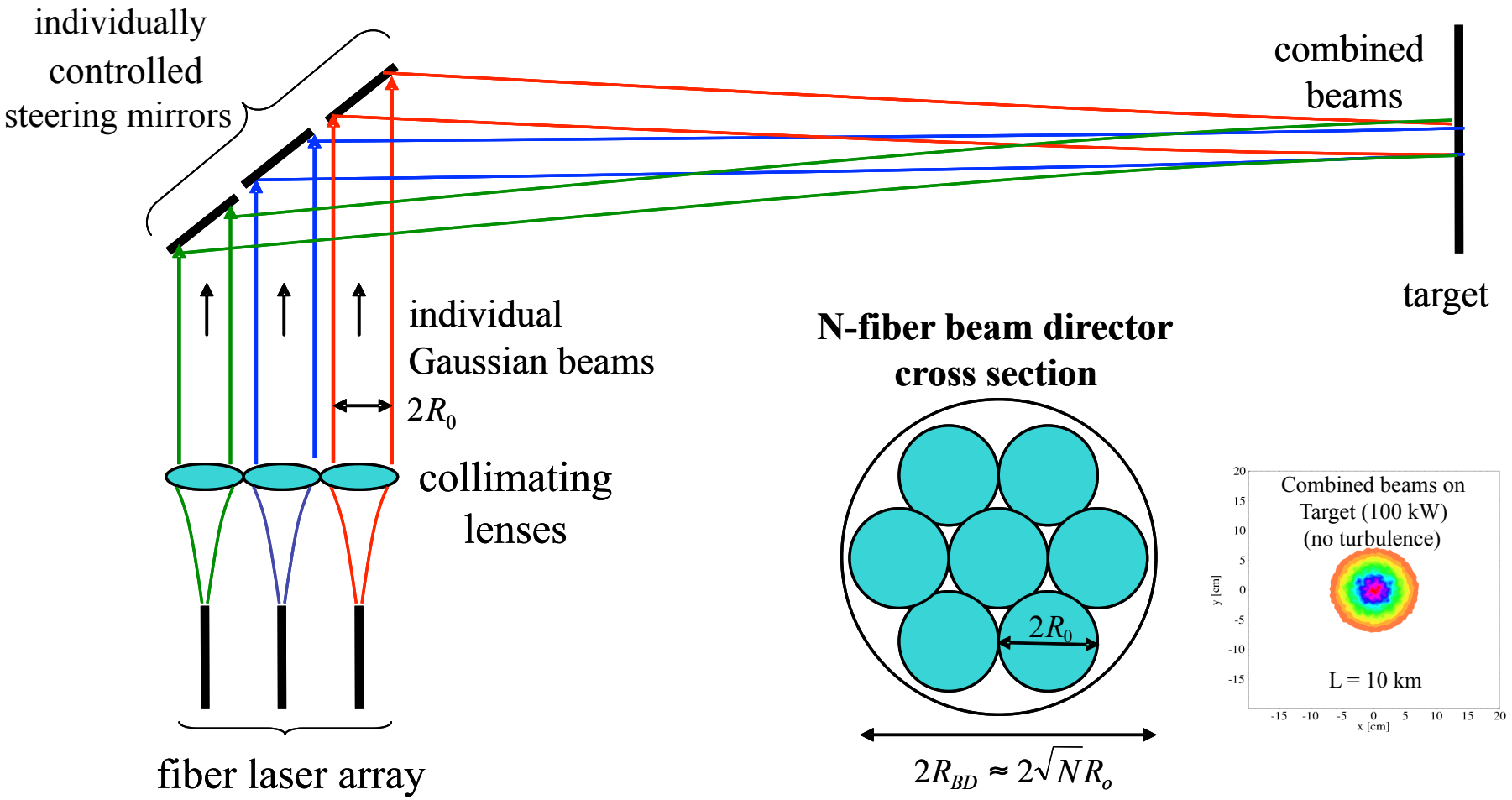
$P_{fiber} = 10\,\text{kW}$, single mode

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*



- **NRL** Memorandum Report -6790-06-8963 (2006) ; also **JDE 2,** 273 (2007)
- **U.S. Patent** # US 7,970,040 B1, issued on June 28, 2011
- **IEEE Journal of Quantum Electronics, 45,** No. 2, February (2009)

Laser Propagation in Presence of Turbulence

- **Laser spot size on target at range *L***

$$R(L) = \left(\overbrace{\left(\Theta_{\text{diff}}^2 + \Theta_{\text{turb}}^2(L) + \Theta_{\text{jitter}}^2\right)}^{\Theta_{spread}^2} L^2 + R_o^2 \left(1 - \frac{L}{L_{\text{focal}}}\right)^2 \right)^{1/2}$$

diffraction & beam quality — turbulence — jitter — focusing

- **Diffraction angle (diffraction + beam quality)**

$$\Theta_{diff} = M_o^2 \frac{\lambda}{\pi R_o}$$

M_o^2 : intrinsic BQ

R_o : initial laser spot size

- **Spreading angle due to turbulence**

$$\Theta_{turb}(L) = M_{turb}^2(L) \frac{\lambda}{\pi R_o} = \frac{1.6\lambda}{\pi r_o(L)}$$

- **Transverse coherence length (Fried parameter)**

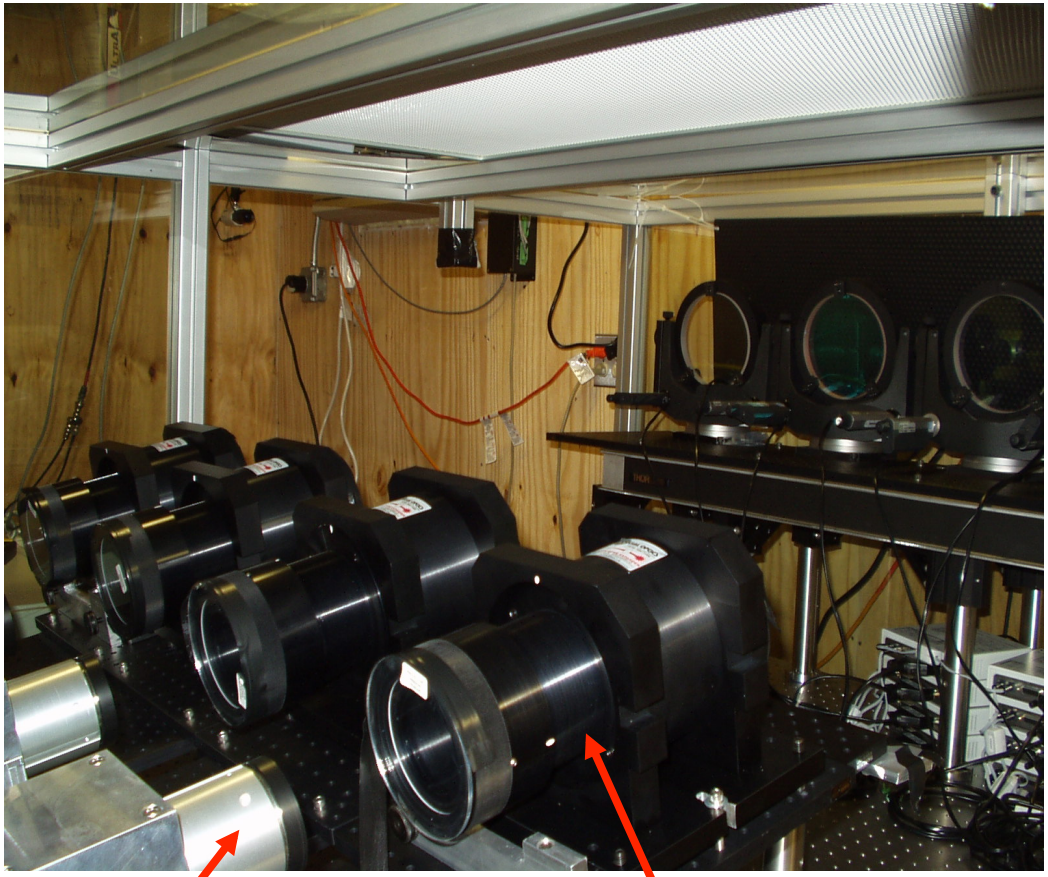
$$r_o(L) = 0.184 \left(\frac{\lambda^2}{C_n^2 L}\right)^{3/5}, \quad C_n^2 : \text{structure constant}$$

$$C_n^2 \sim 10^{-15} - 10^{-13}\ \text{m}^{-2/3}$$

NRL Beam Director Incoherent Beam Combining

Plasma Physics Division

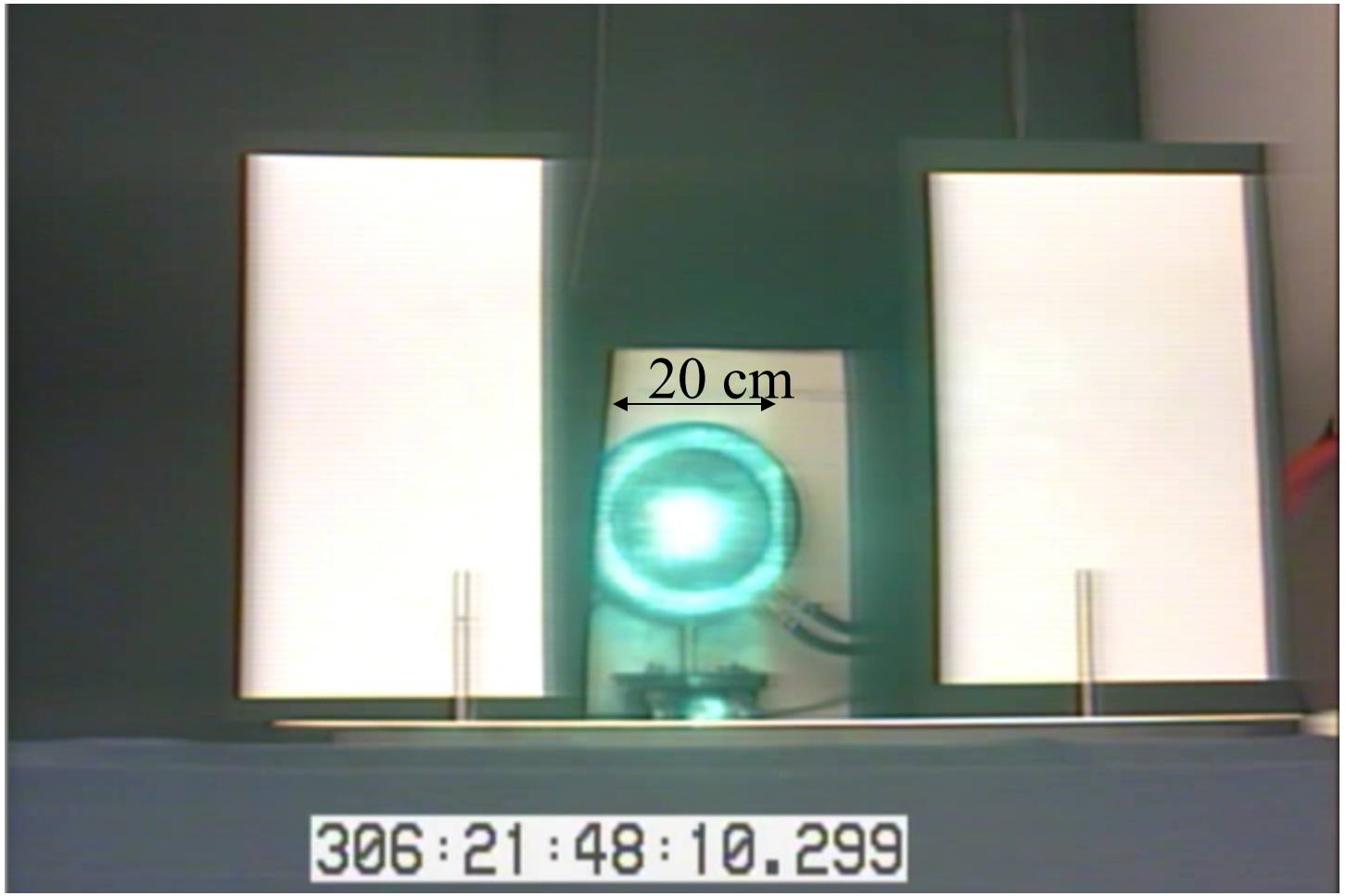
NRL : Antonio Ting, Richard Fischer, Greg DiComo (Ph.D. Student, UMD)



NSWC Propagation Range - 1.2 km Four Incoherently Combined SM Fiber Lasers

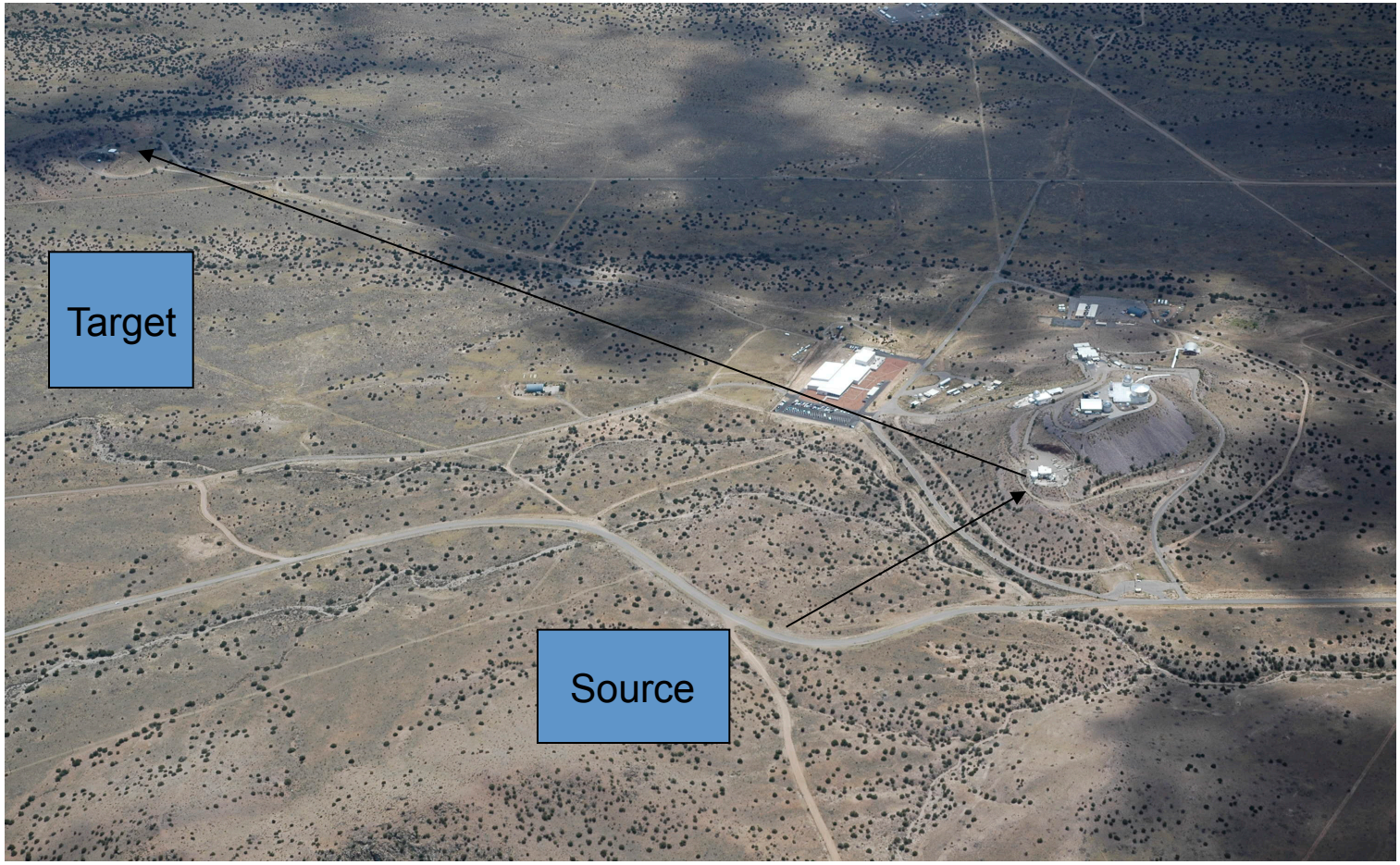
Plasma Physics Division

3 kW transmitted, 2.8 kW on target



SOR Propagation Range 3.2 km

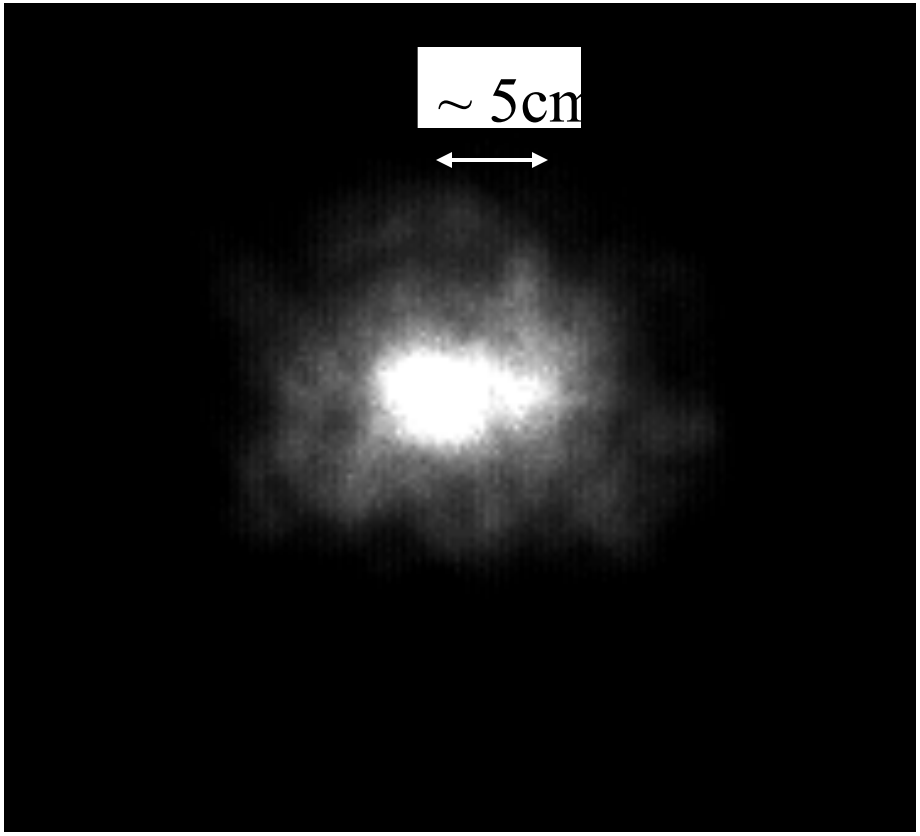
- Perform field experiments at 3.2 km range using incoherently combined high-power lasers (6.2 kW, M^2 ~1)



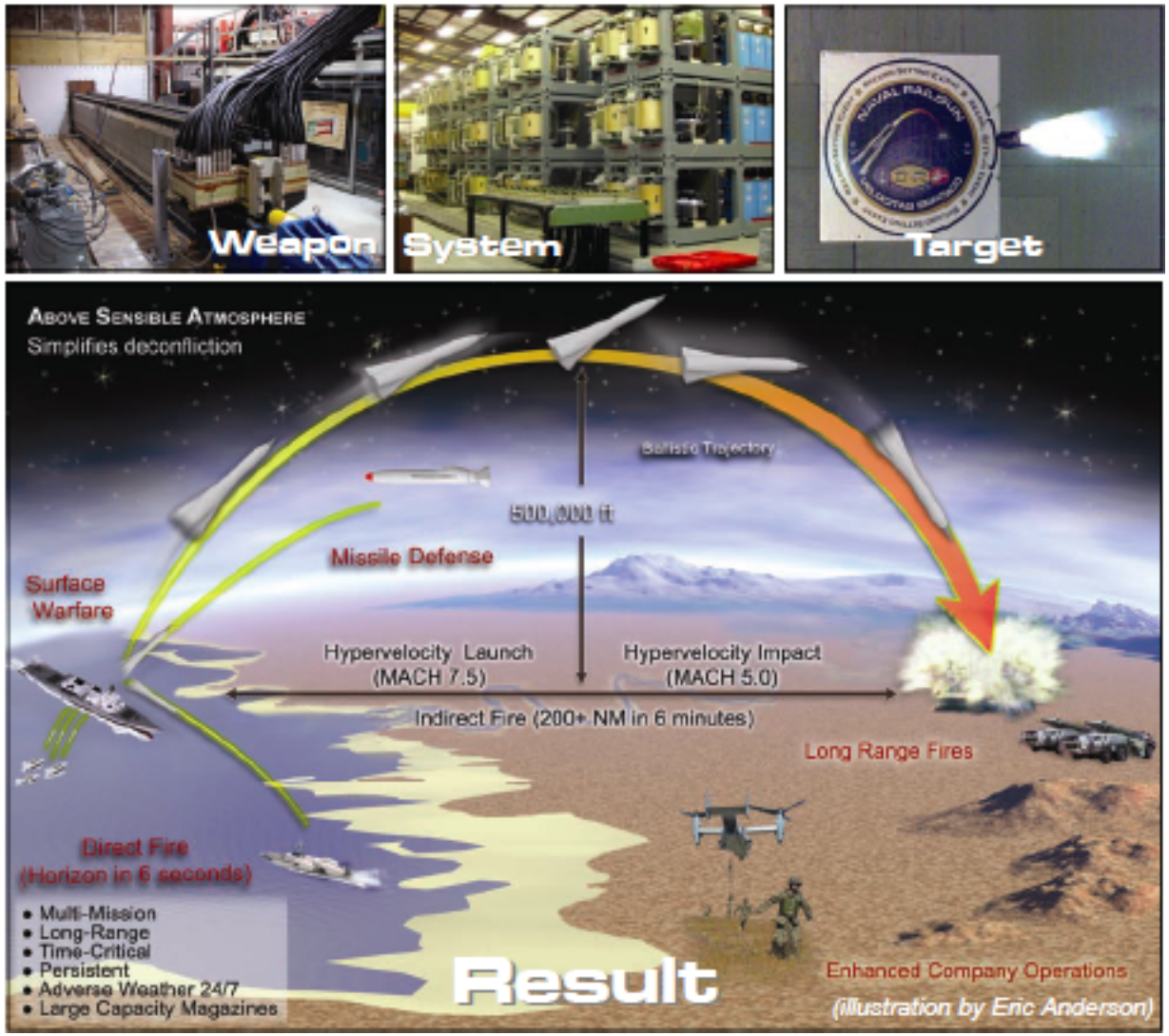
NRL Fiber Laser Field Experiments at SOR Propagation Range 3.2 km

Plasma Physics Division

(Spot Size on Target at Low Power)



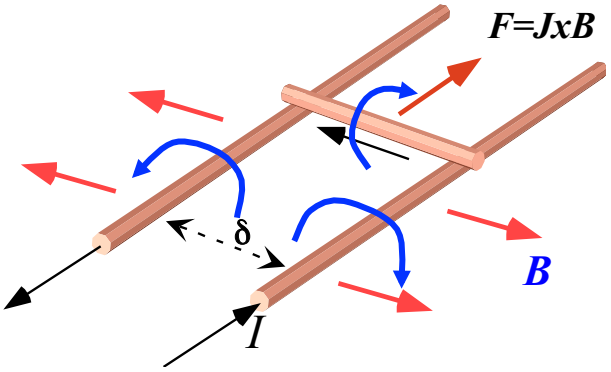
ONR Railgun Innovative Naval Prototype

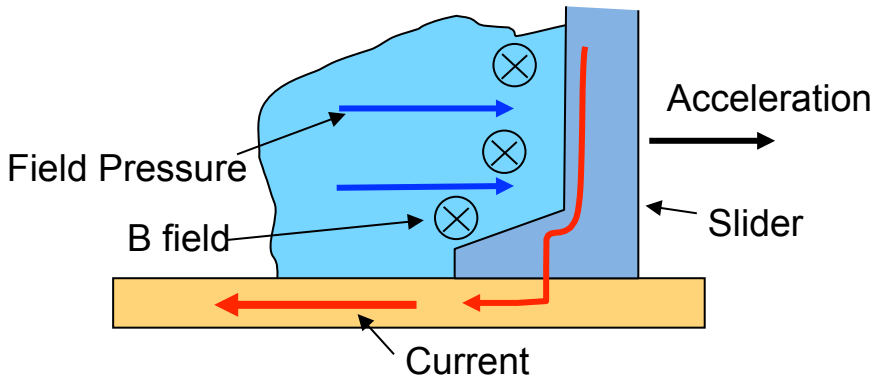


How Railguns Work

- 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*)**

$$F = ma = \int J \times B dA \cong \frac{1}{2} IBA$$

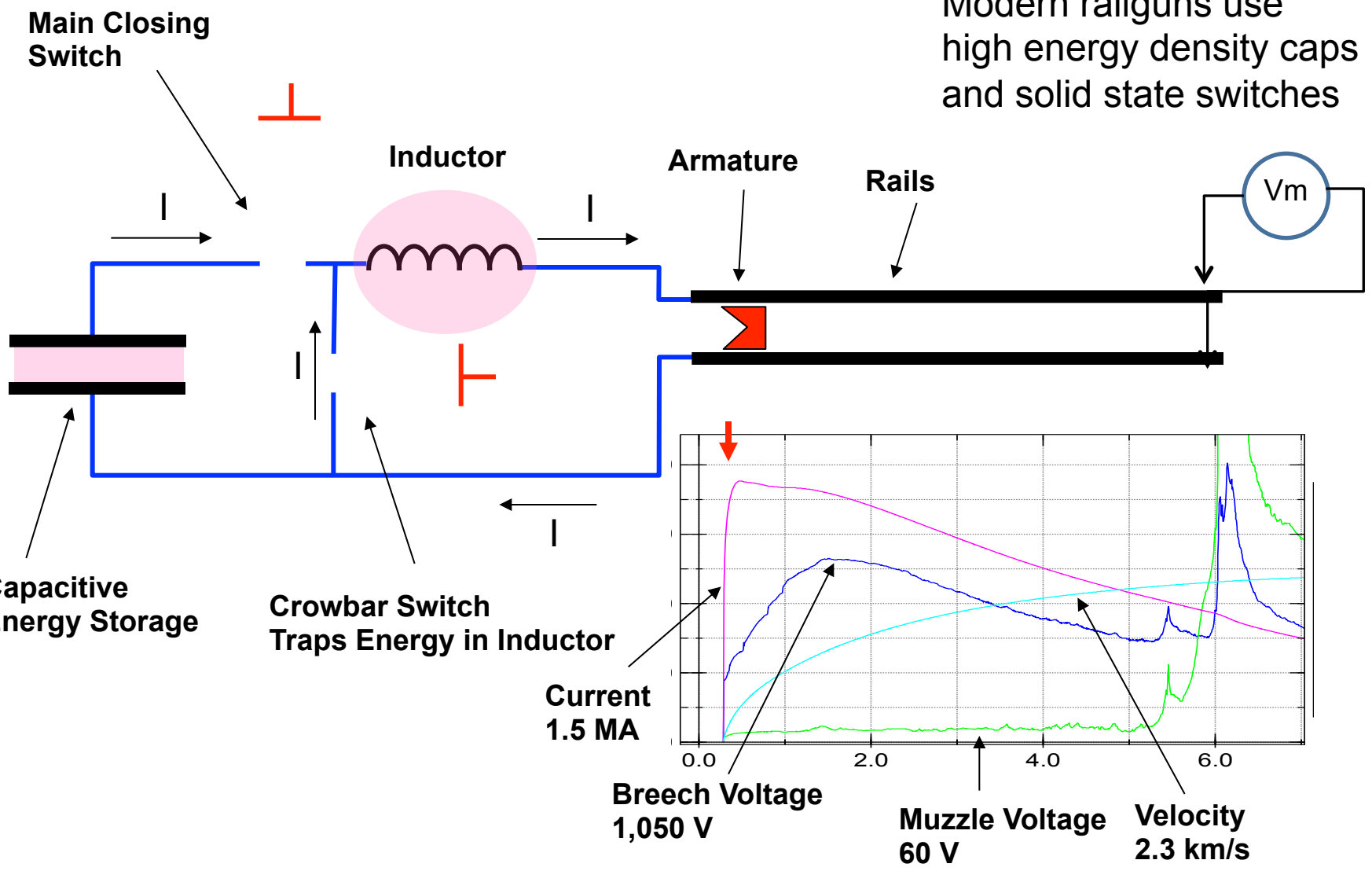




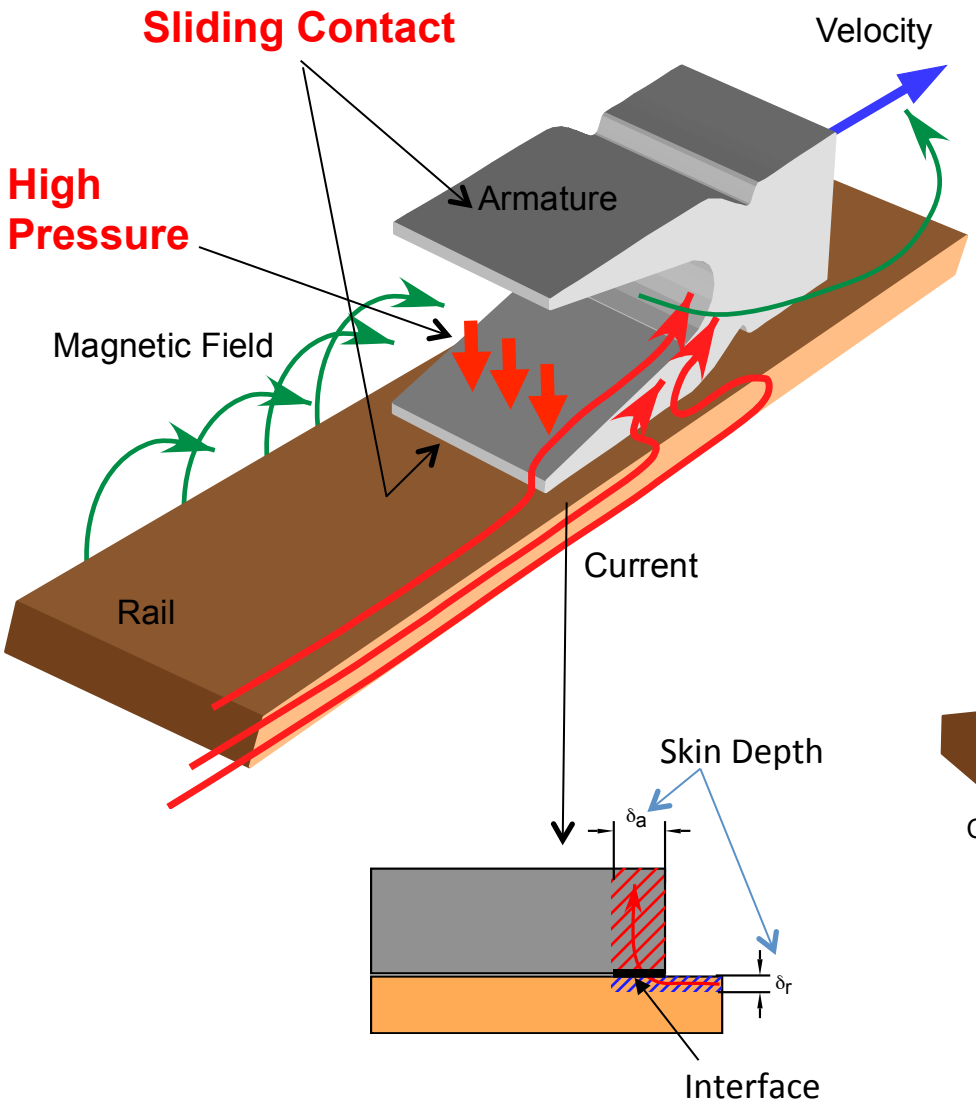
MTF Railgun Operation

Plasma Physics Division

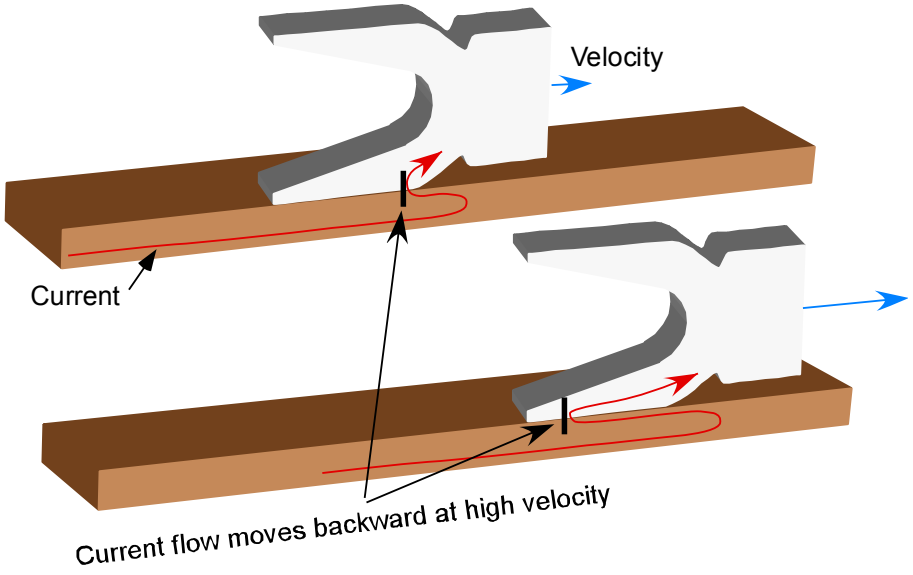
Modern railguns use high energy density caps and solid state switches



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

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Rails

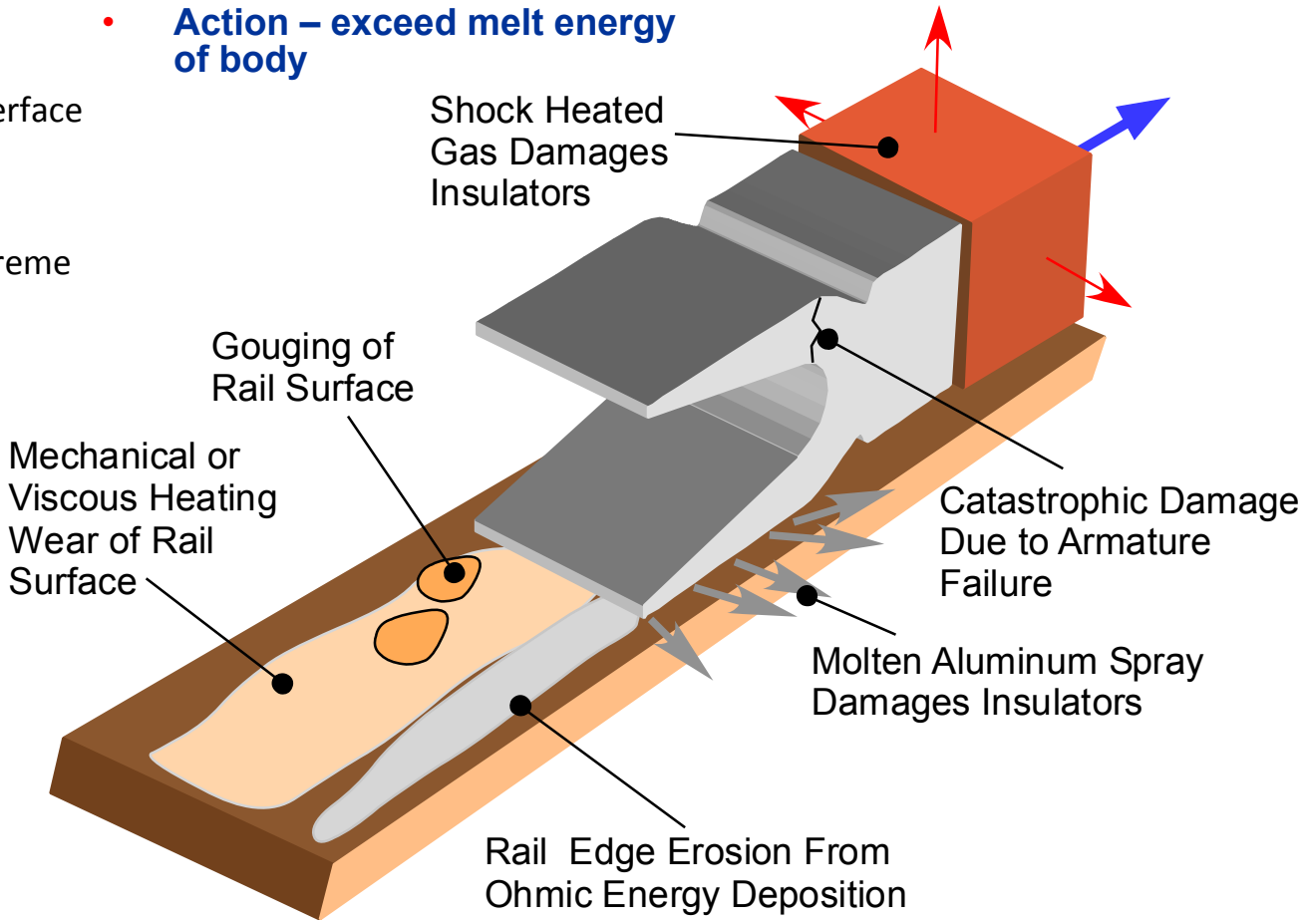
- Edge Grooving – high current erosion of sliding contact
- Gouging – shock generation at high velocity contact
- Mechanical rail wear – high velocity heating of sliding interface
- Post Transition erosion – arc damage to metal electrodes
- Cyclic fatigue – repetitive extreme stress of materials
- Mechanical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

Armatures

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

Insulators

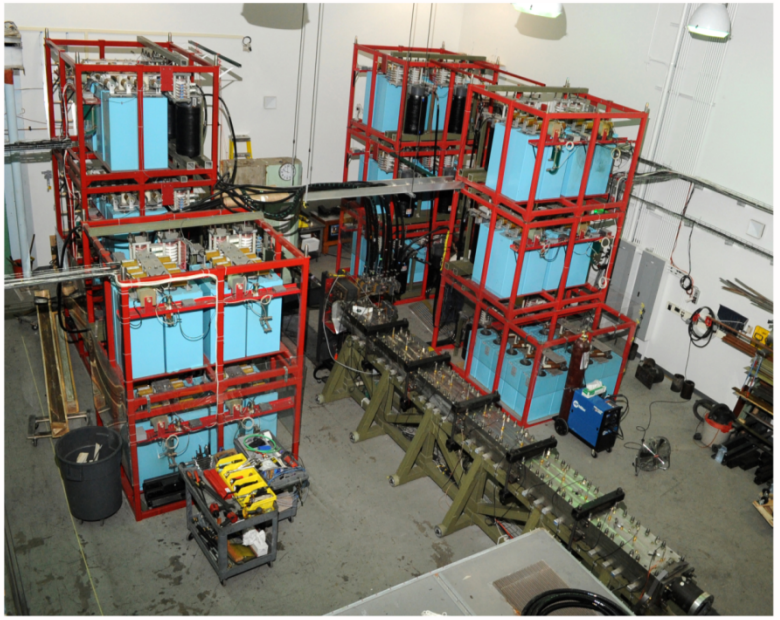
- **Thermal flux - high temperature gas**
- **Molten metal - hot debris**

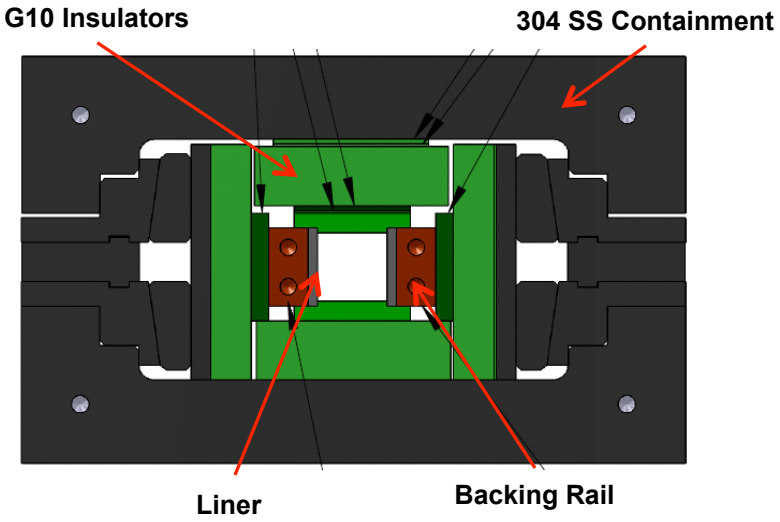


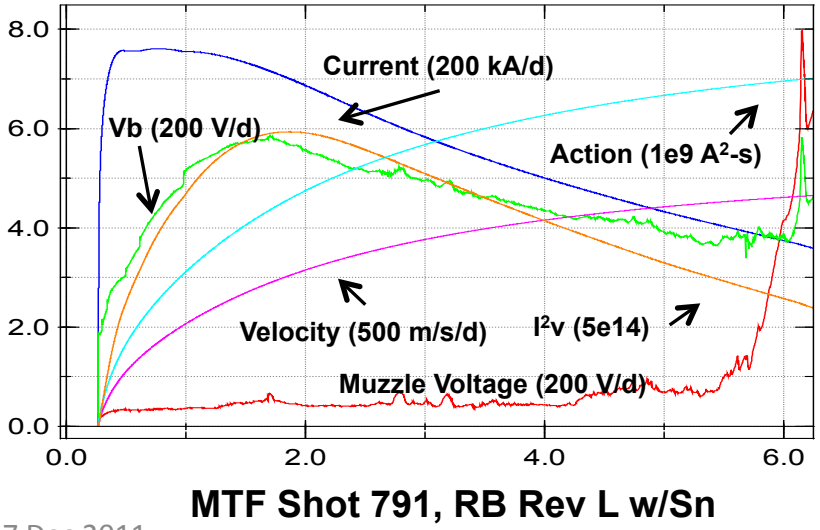
10 GW Input Power

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 ~ 7×10^9 A^2-s
- L' ~ 0.3-0.4 μH/m
- I^2v peak ~ 3×10^{15} A^2-m/s
- Over 1000 shots fired to date
- 26 distinct shot campaigns in FY10





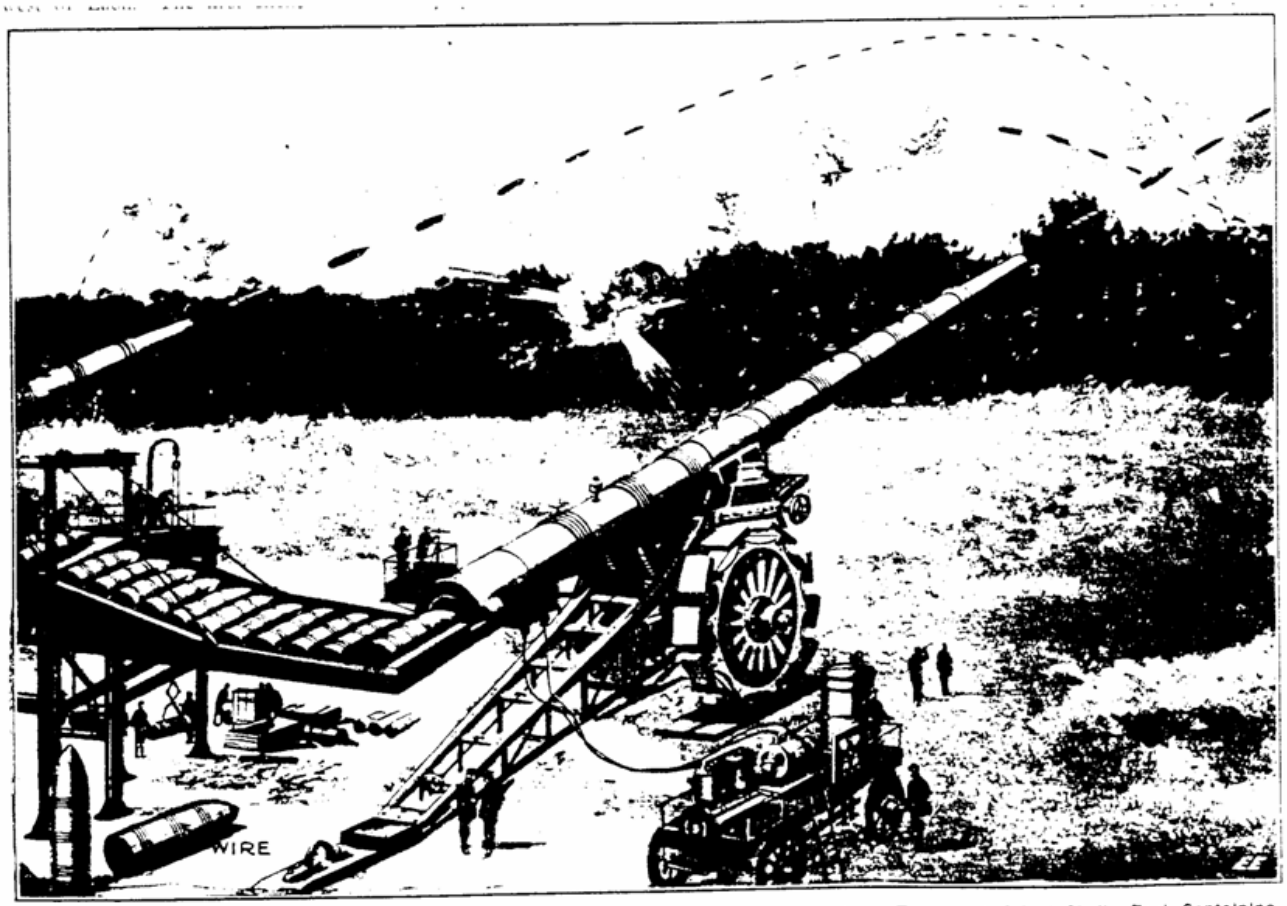


MTF Shot 791, RB Rev L w/Sn

Railguns: fiction & fact

80 ELECTRICAL EXPERIMENTER June, 1918

A 100 Mile Electro-Magnetic Gun



The Illustration Herewith Shows a Mighty 90-Foot Electro-Magnetic Gun, Capable of Hurling a Torrent of 19-Inch Shells, Each Containing a Charge of High Explosives. It Would Be Noiseless and Smokeless, Besides Being Mobile Enough to Permit Its Transportation From Place to Place At Short Notice. There Would Be No Wear and Tear On This Gun As Is the Case Now With the Cannon Using Explosive Charges to Expel the Projectile From the Barrel. First Described in This Journal For November, 1915.

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Railguns: fiction & fact

Free Electron Laser

ONR Program Code 35 — November 2010

At a Glance

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.

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.

Point of Contact

Quentin Saulter
(703) 696-2594
quentin.saulter@navy.mil

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 missles, 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

The Free Electron Laser is a new ONR Innovative Naval Prototype program

Plasma Physics Division

FEL Technology Baseline

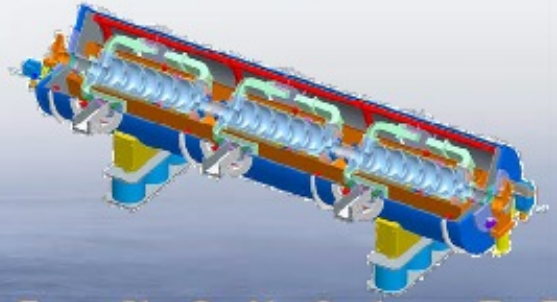
High Power Optics

NISUS Amplifier Wiggler

Electron Transport Magnets

High Current RF Gun

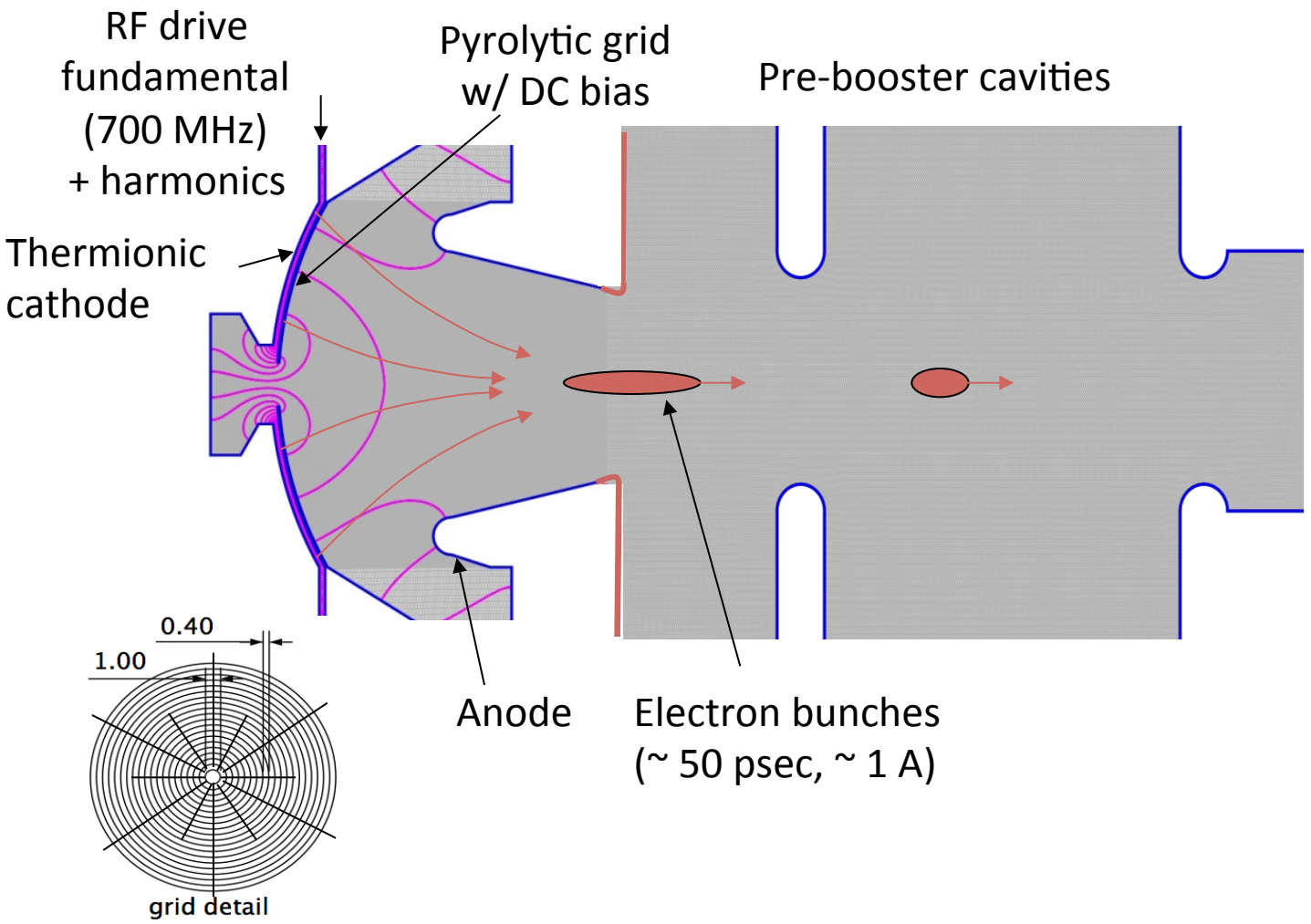
Superconducting ERL Cryomodule



High Power Beam Dump

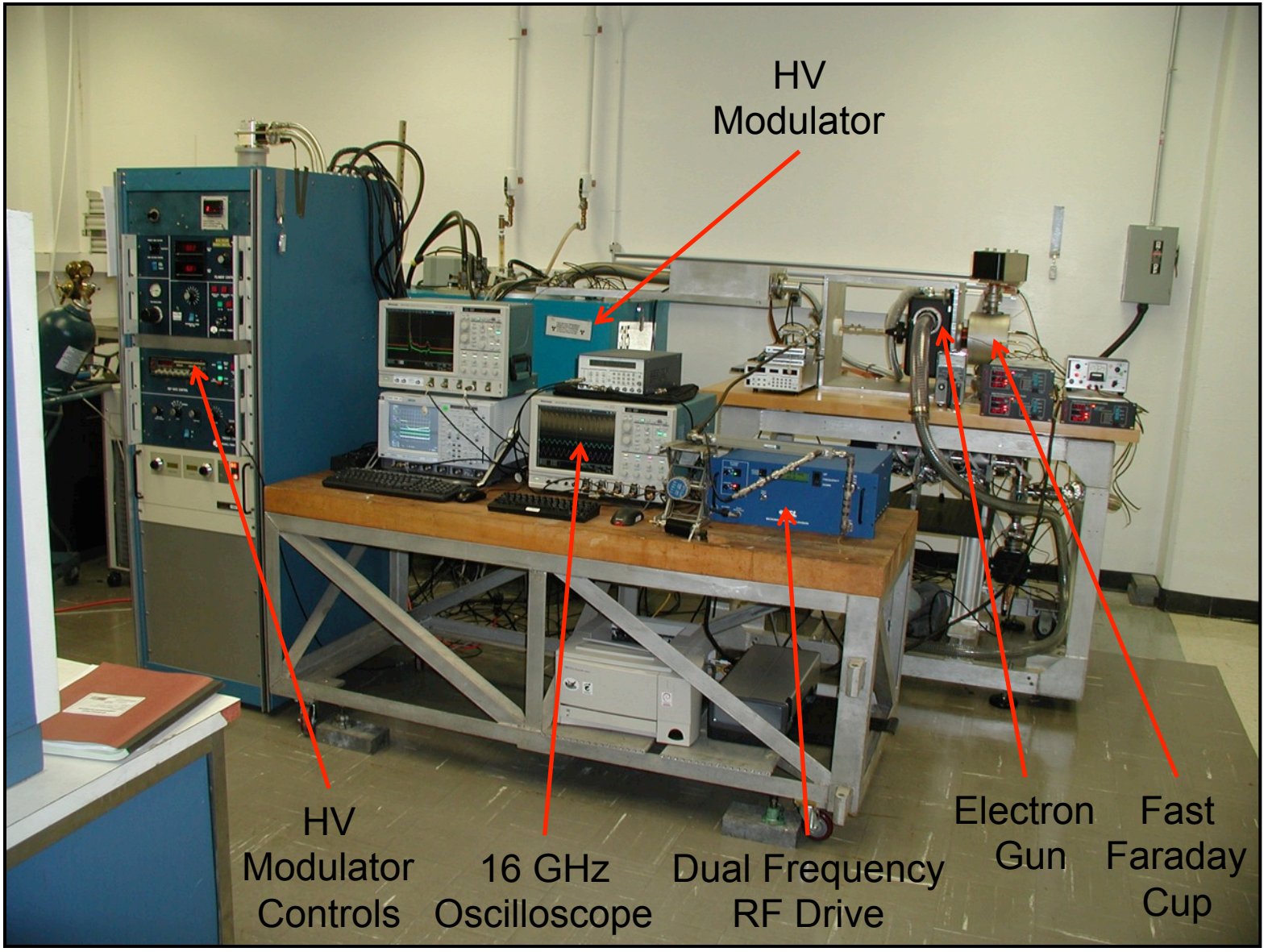
OFFICE OF NAVAL RESEARCH

RF Gated Gridded Thermionic Injector*



* "High Average Current Electron Guns for High-Power FELs", P. Sprangle, J. Penano, B. Hafizi, D. Gordon, S. Gold, A. Ting and C. Mitchell, Phys. Rev. Special Topics Accelerators and Beams, 14, 020702 (2011).

NRL RF-Gated Thermionic Electron Gun Experiment



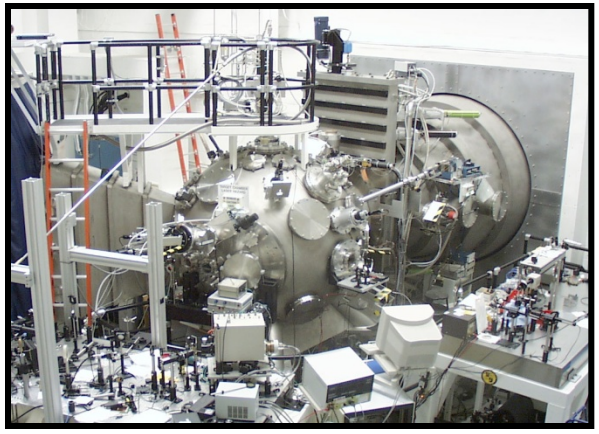
Power and Energy

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.

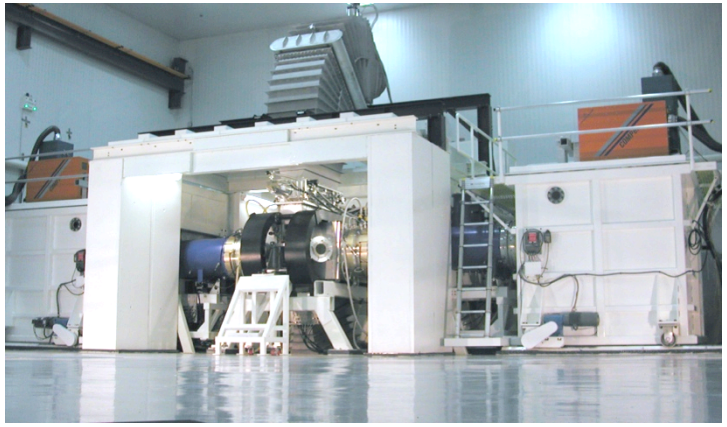
Laser Fusion Branch - 6730

Plasma Physics Division

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

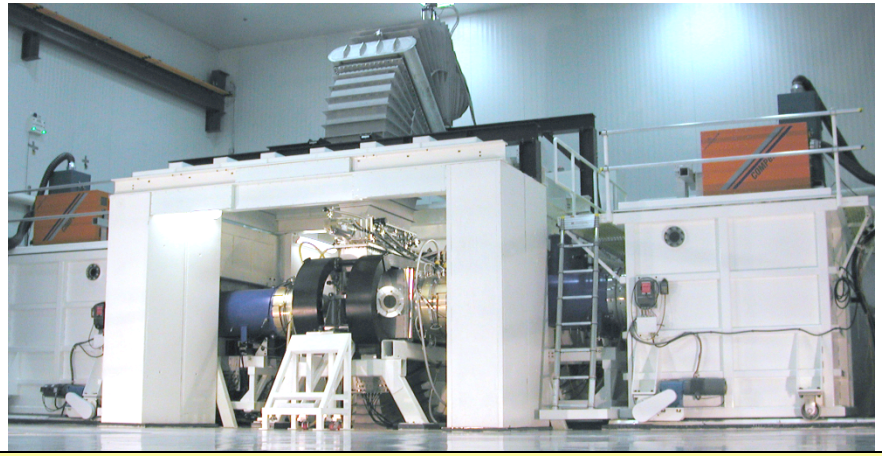
Prospects & Payoff for both the Navy and the Nation

- 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 eams

NRL Nike target chamber optics



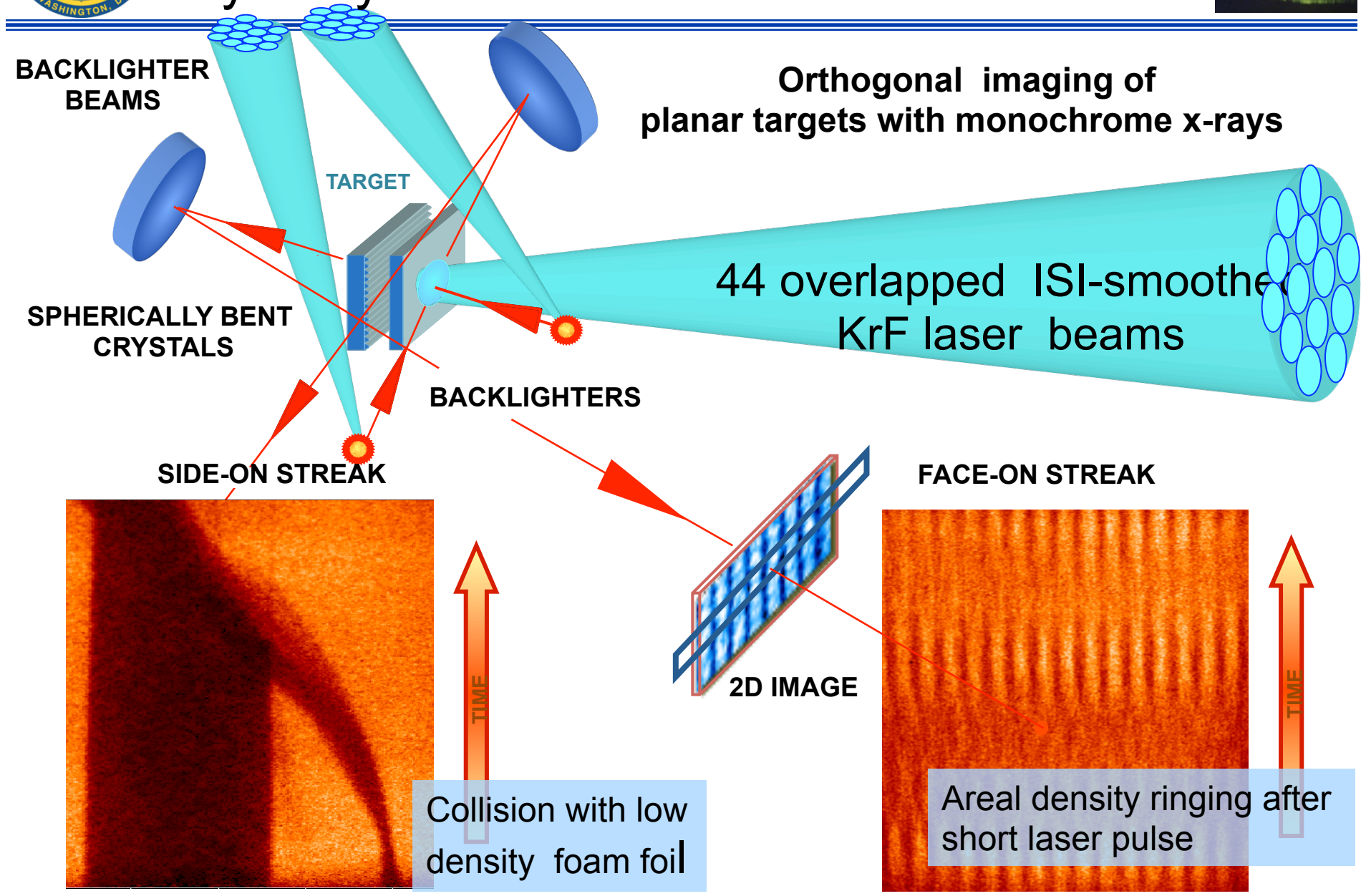
Electra 5 Hz electron-beam-pumped KrF laser

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

Plasma Physics Division



Nike has accelerated target to 1000 km/sec to explore Impact Ignition

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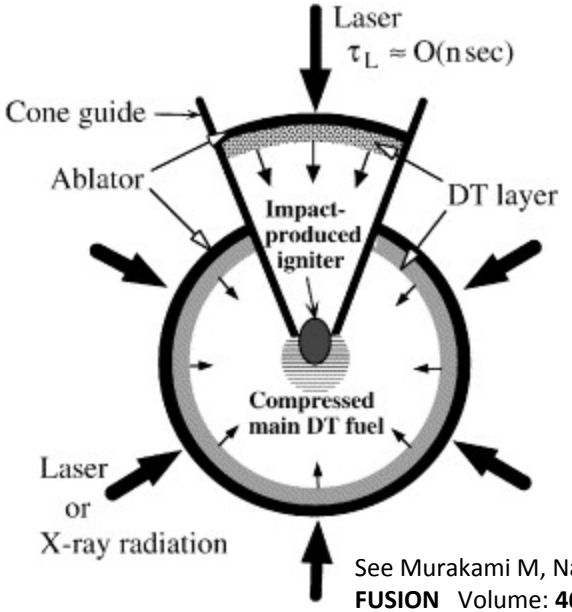
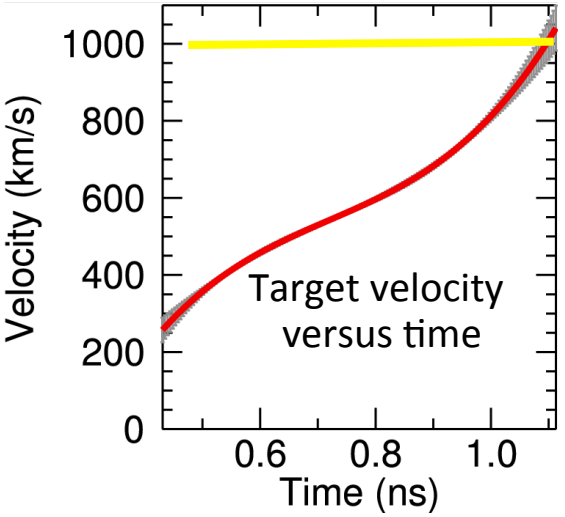
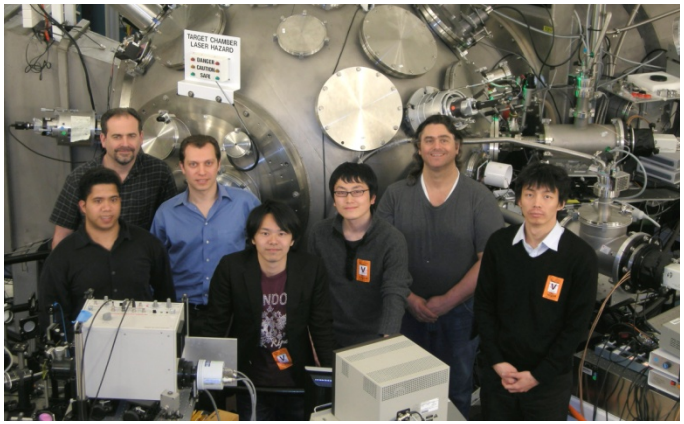
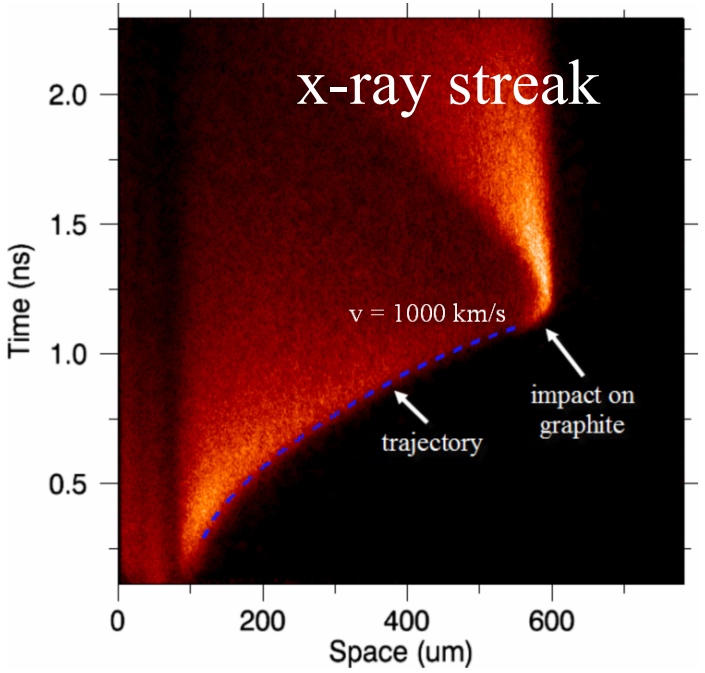


See Murakami M, Nagatomo H, Azechi H, et al.**NUCLEAR FUSION** Volume: **46** Issue: **1**





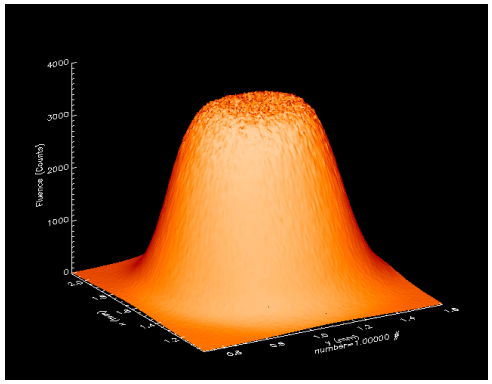


Joint experiment with U. Of Osaka, ILE

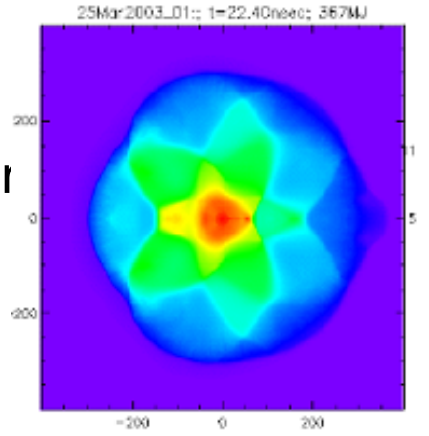
KrF has significant advantages for achieving the high gain needed for fusion

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)

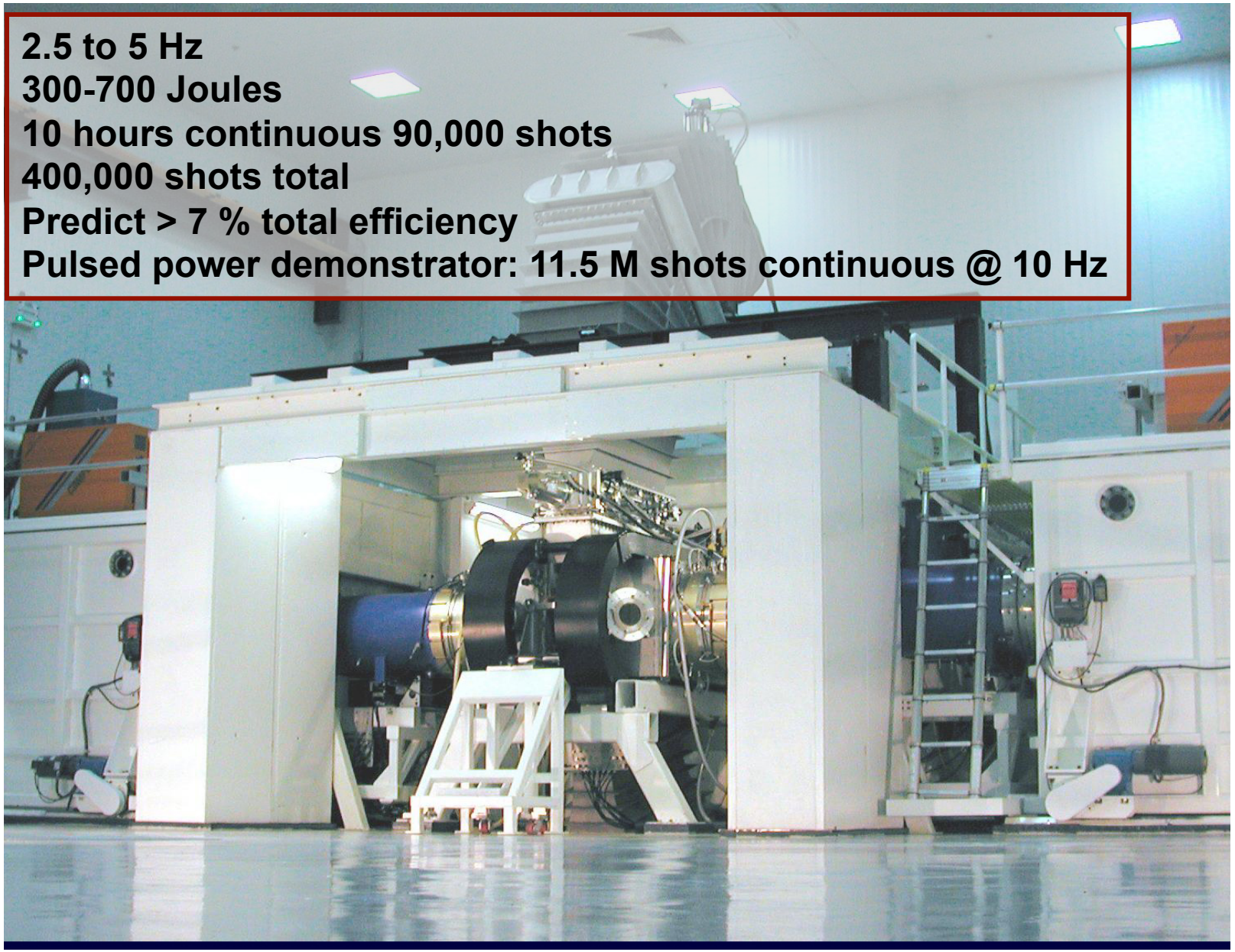


Predict power plant class gains with modest lasers
- "Conventional" Direct Drive: Gain: 160 @ 2.4 MJ laser
- "Shock Ignition" Direct Drive:
  - Gain: 200 @ 1 MJ laser
  - Gain: 300 @ 2 MJ laser



NRL

KrF Progress- NRL Electra Laser

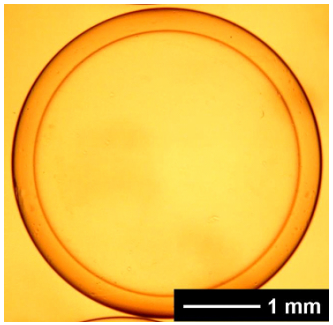


Developed credible solutions for the other key components for laser IFE

Target Fabrication:

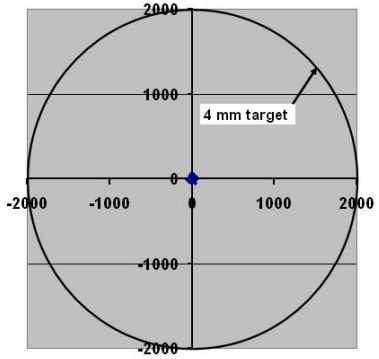
Mass produced foam shells

Estimated cost $0.16 each



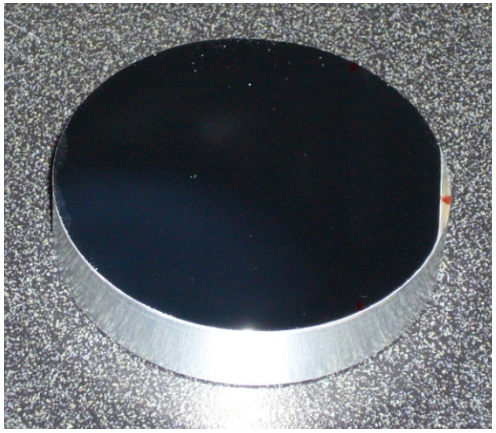
Target Engagement:

Bench test: 34 micron accuracy



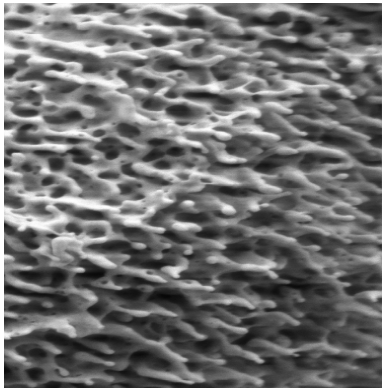
Final Optic (Grazing Incidence Mirror)

10,000,000 shots at 3.5 J/cm^2



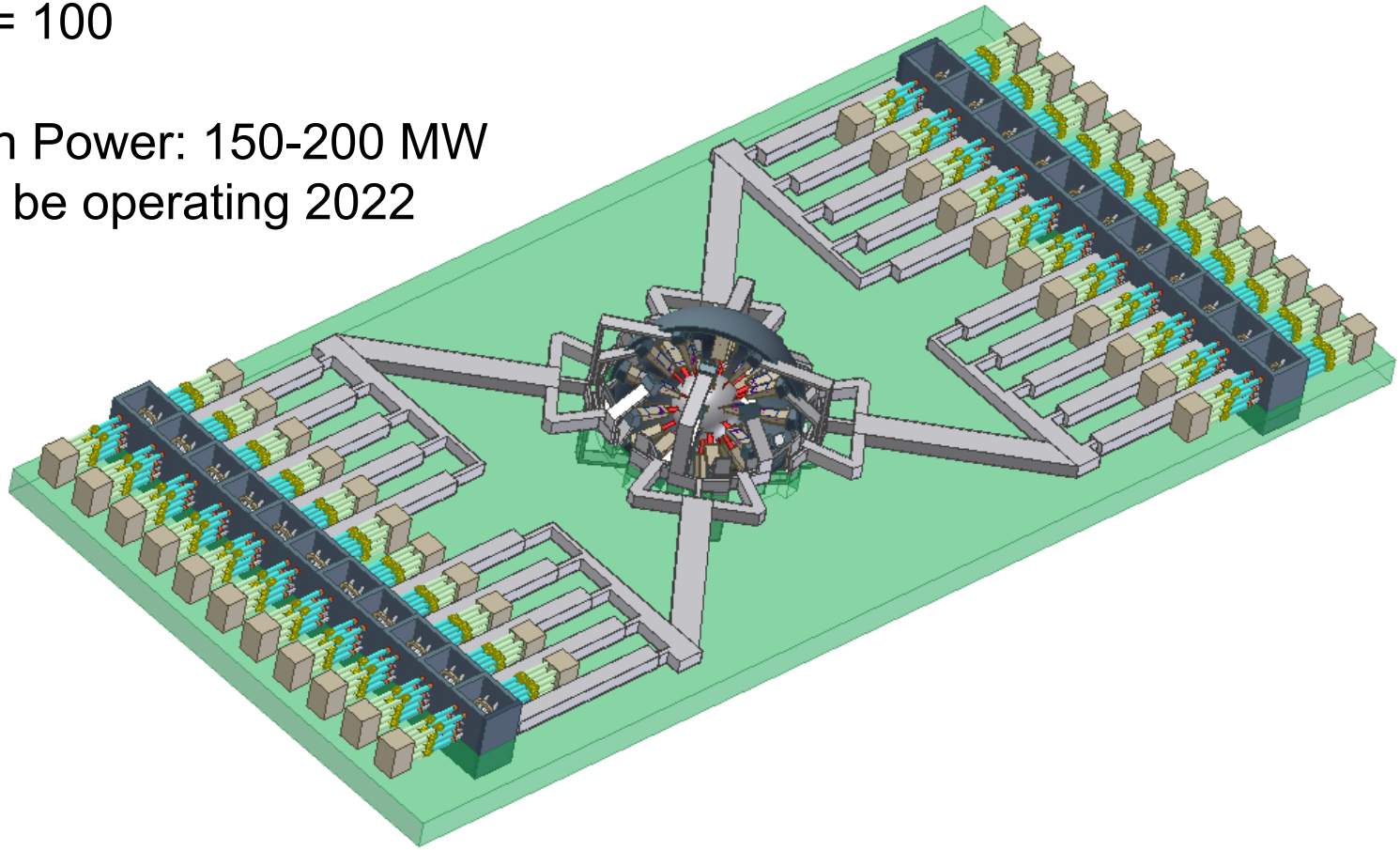
Chamber Wall (nano-scale tungsten)

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

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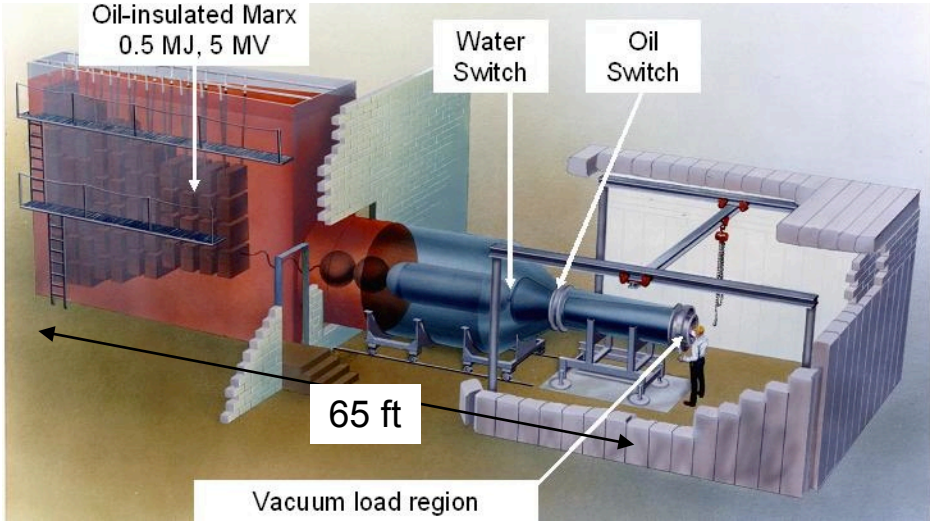
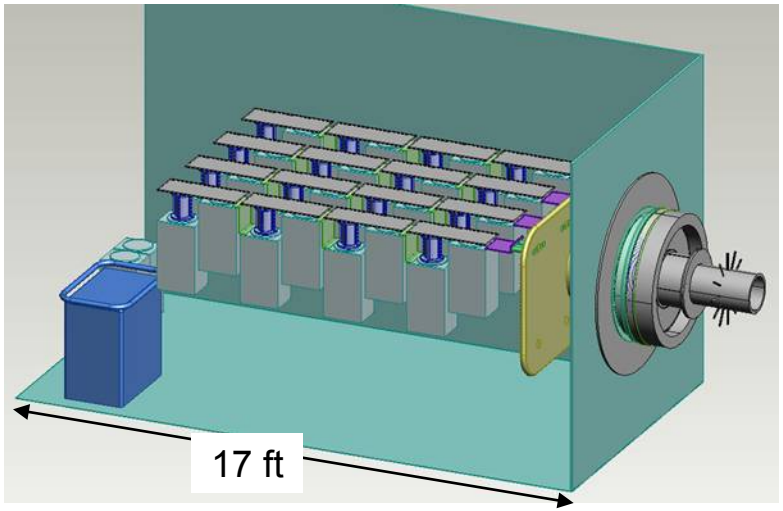
Gamble II (2 MV, 1 MA, 100 ns)



- 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)

Hawk (0.7 MV, 0.7 MA, 1 μs)



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

MERCURY, completed in late 2004, is used for active detection and flash radiography

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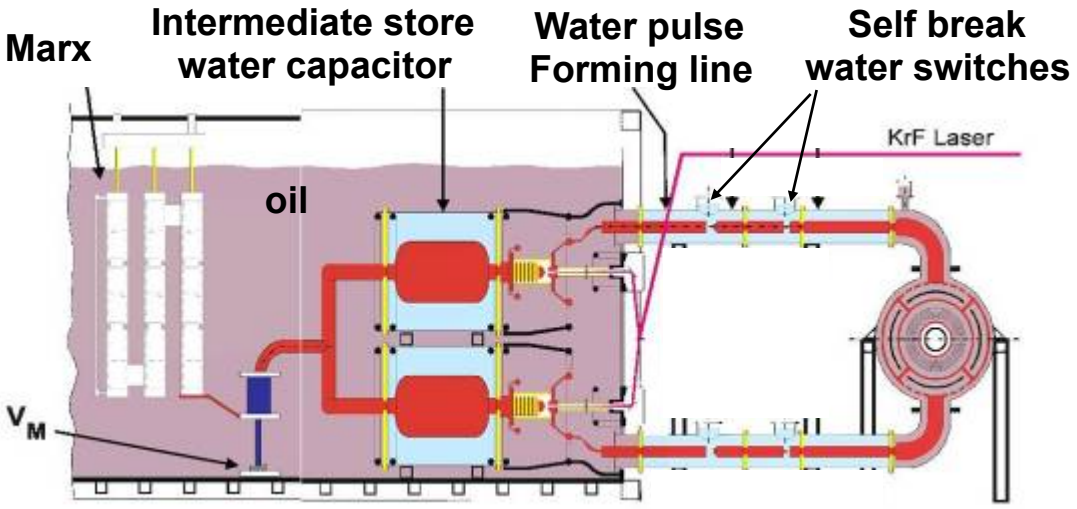
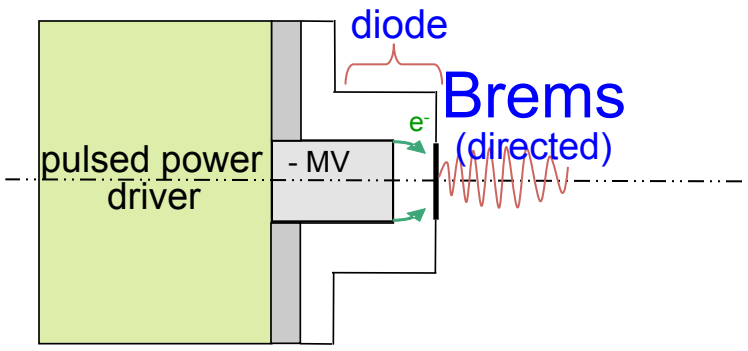
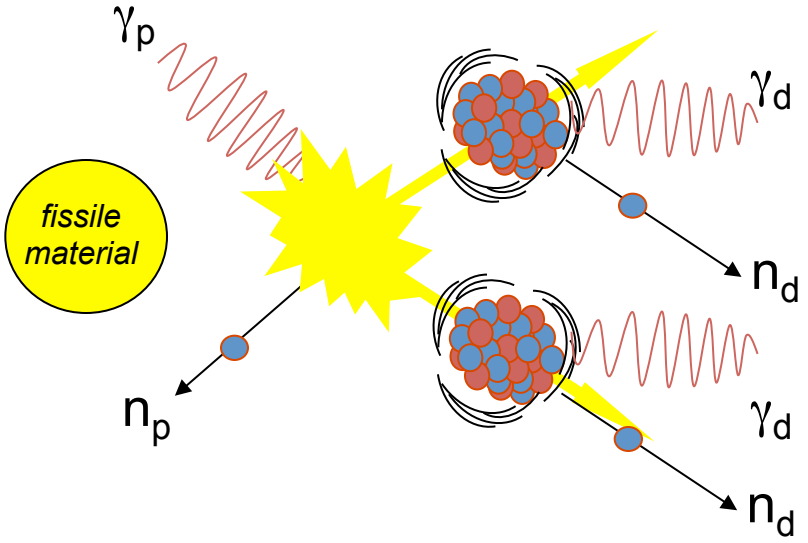
Magnetically-insulated inductive voltage adder designed to produce a 50-ns pulse with a load voltage of 6 MV, 360 kA to 8 MV, 250 kA
(360 kJ at 95-kV Marx charge)

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 (γ_0, n, γ_0 + n)

issues

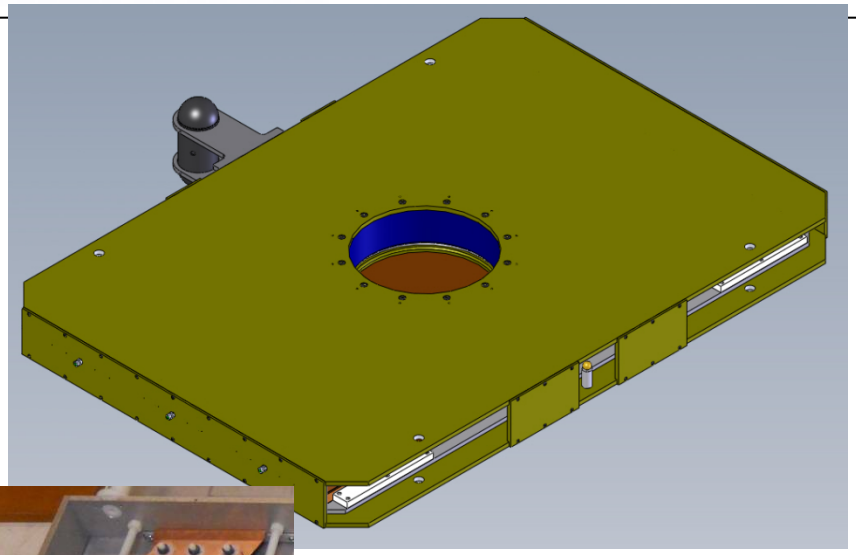
- Compact, reliable pulsed power with modest repetition rate (~TW, several shots/min)
- Sensitive detectors with fast recovery and response to gammas & neutrons (operate in harsh environment)

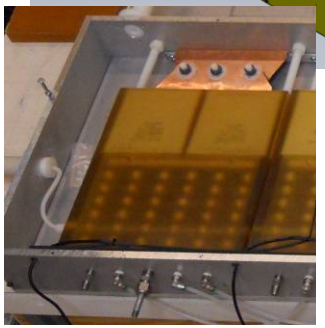
NRL is remaining involved in the development and utilization of LTD for radiography, etc.

NRL

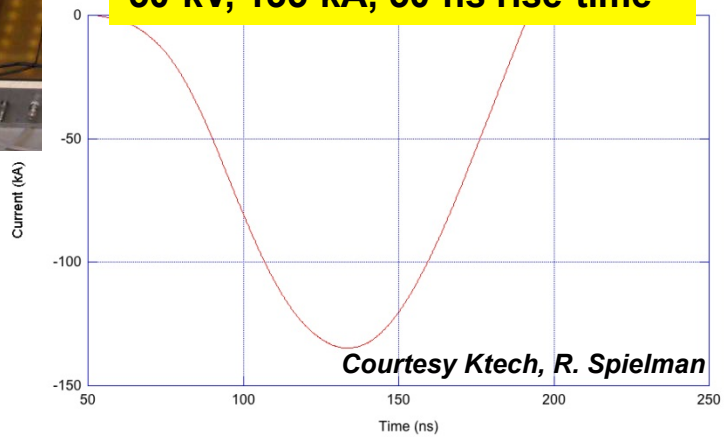
Six-fast brick cavity assembled & tested

Ktech Contract # N00173-10-C-2019



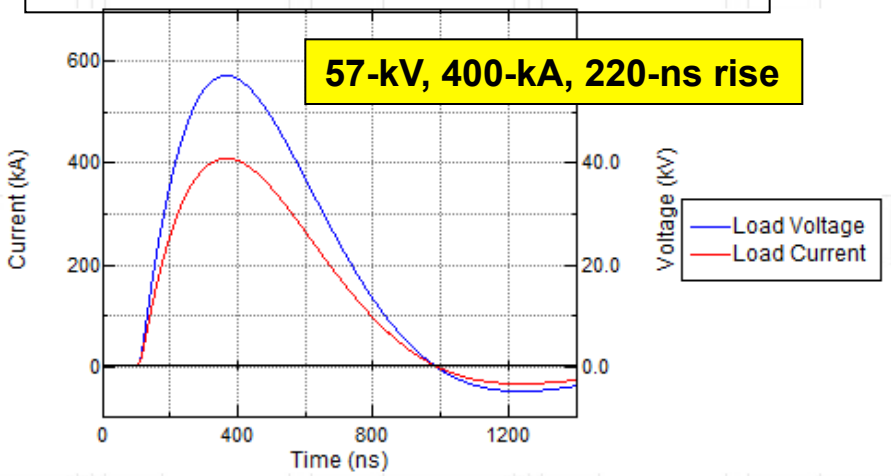


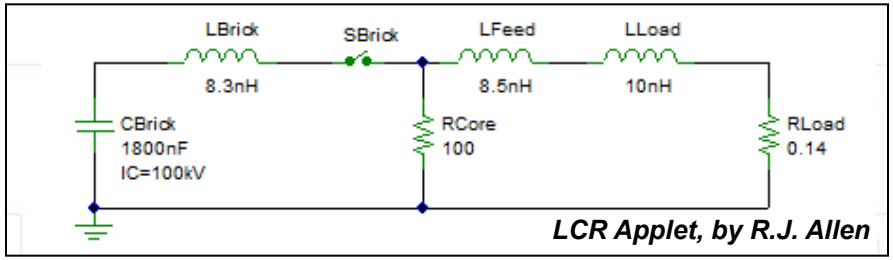
50-kV, 135-kA, 50-ns rise-time



Six-slow brick cavity procured

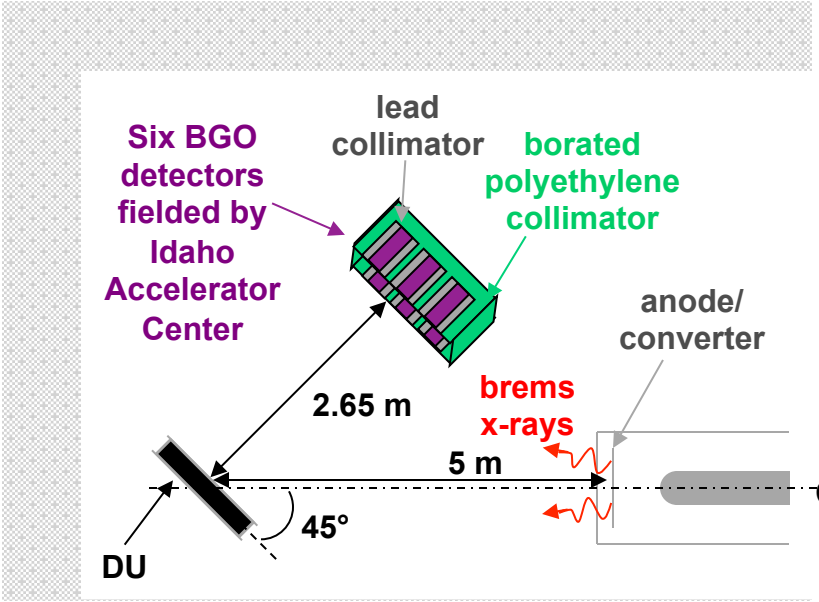
NRL Capital Procurement

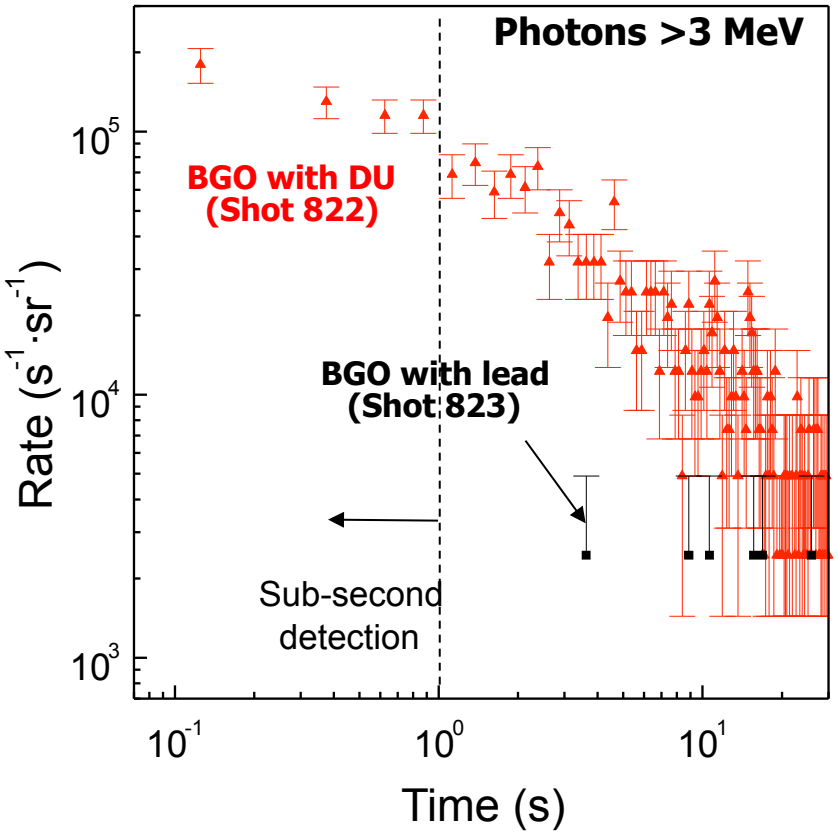




4' x 8' x 7.5“ per cavity

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

Plasma Physics Division

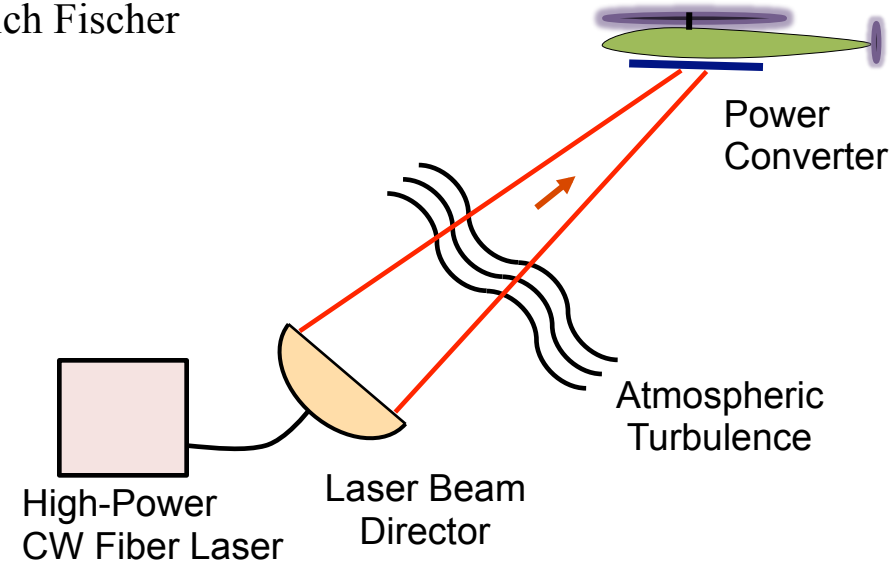
P.I. Dr. Rich Fischer

Objective:

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

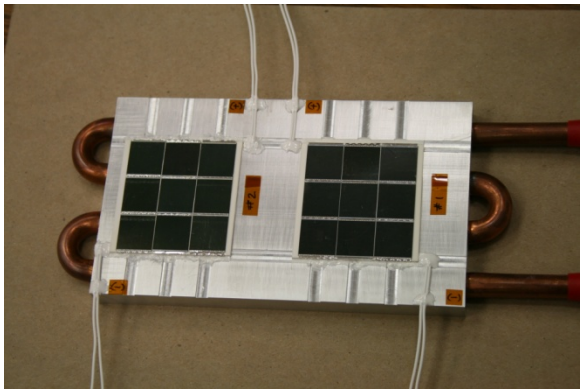
Payoff:

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



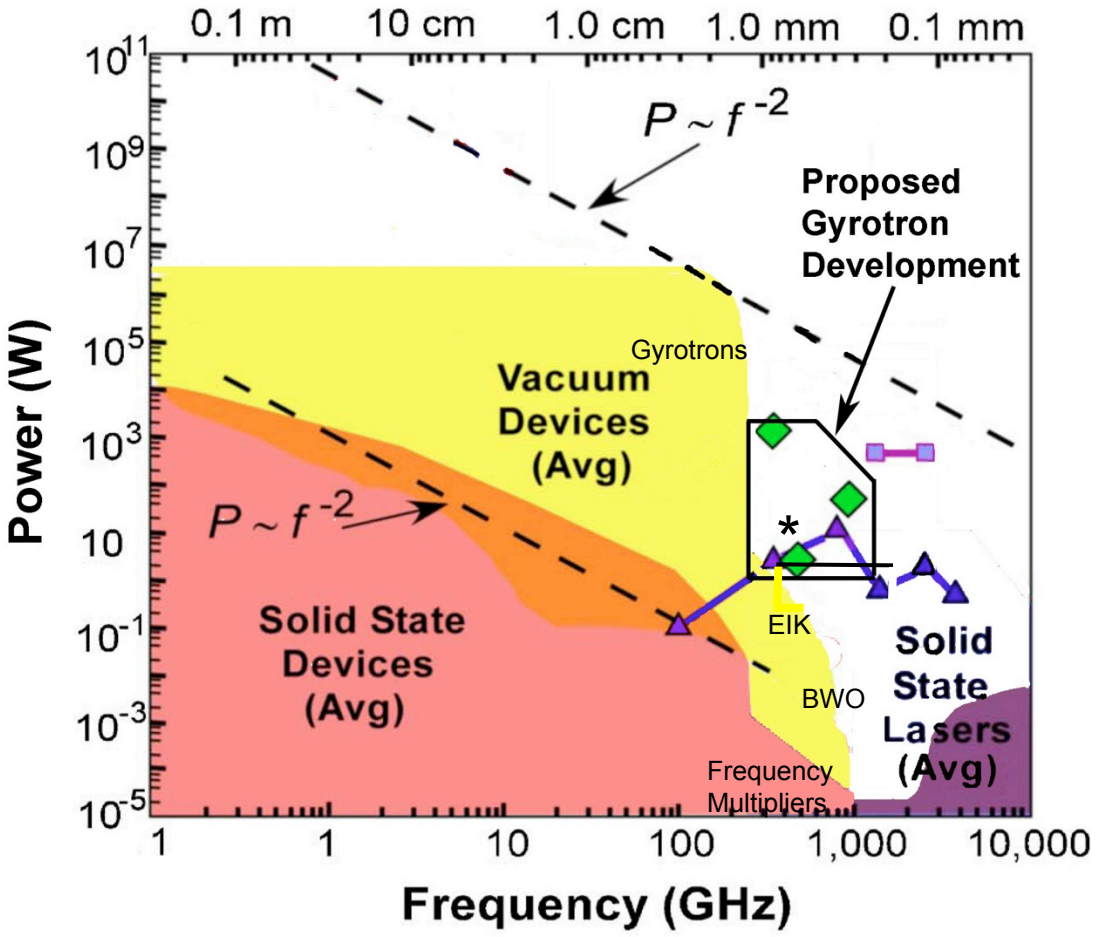
Approach:

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.



Laser Power Converter Prototype

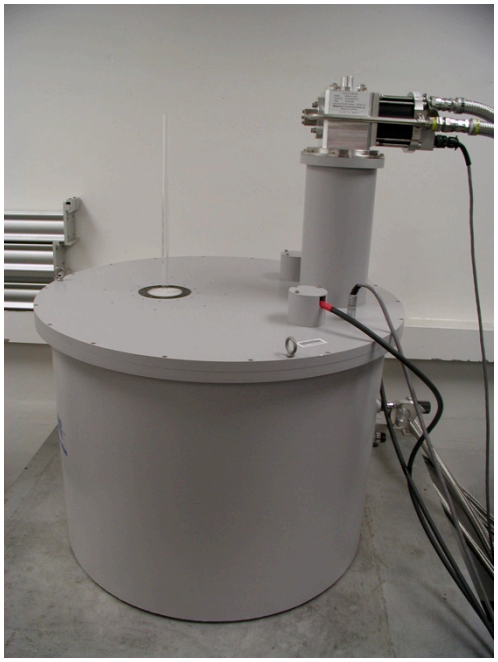
Maximum Power of Vacuum Electronic, Solid State, and Quantum Electronic Devices



- 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~100 W @ 220 GHz with 500 W-GHz BW (*)
- Gyrotrons offer higher power for some DoD applications
- Fast-wave interaction scales well to short wavelengths

Ref: J.H. Booske, Phys. Plasmas 15, 055502 (2008)

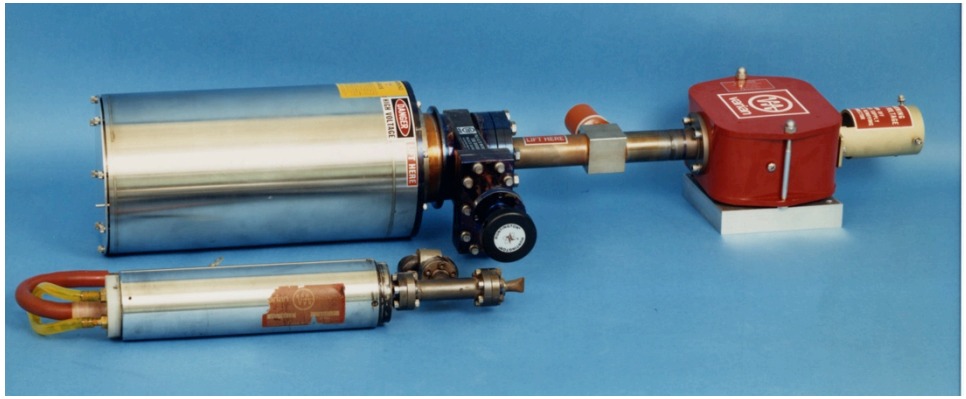
Terahertz Gyrotron Project Equipment



Cryomagnetics
12 T Cryogen-free Super-conducting Magnet

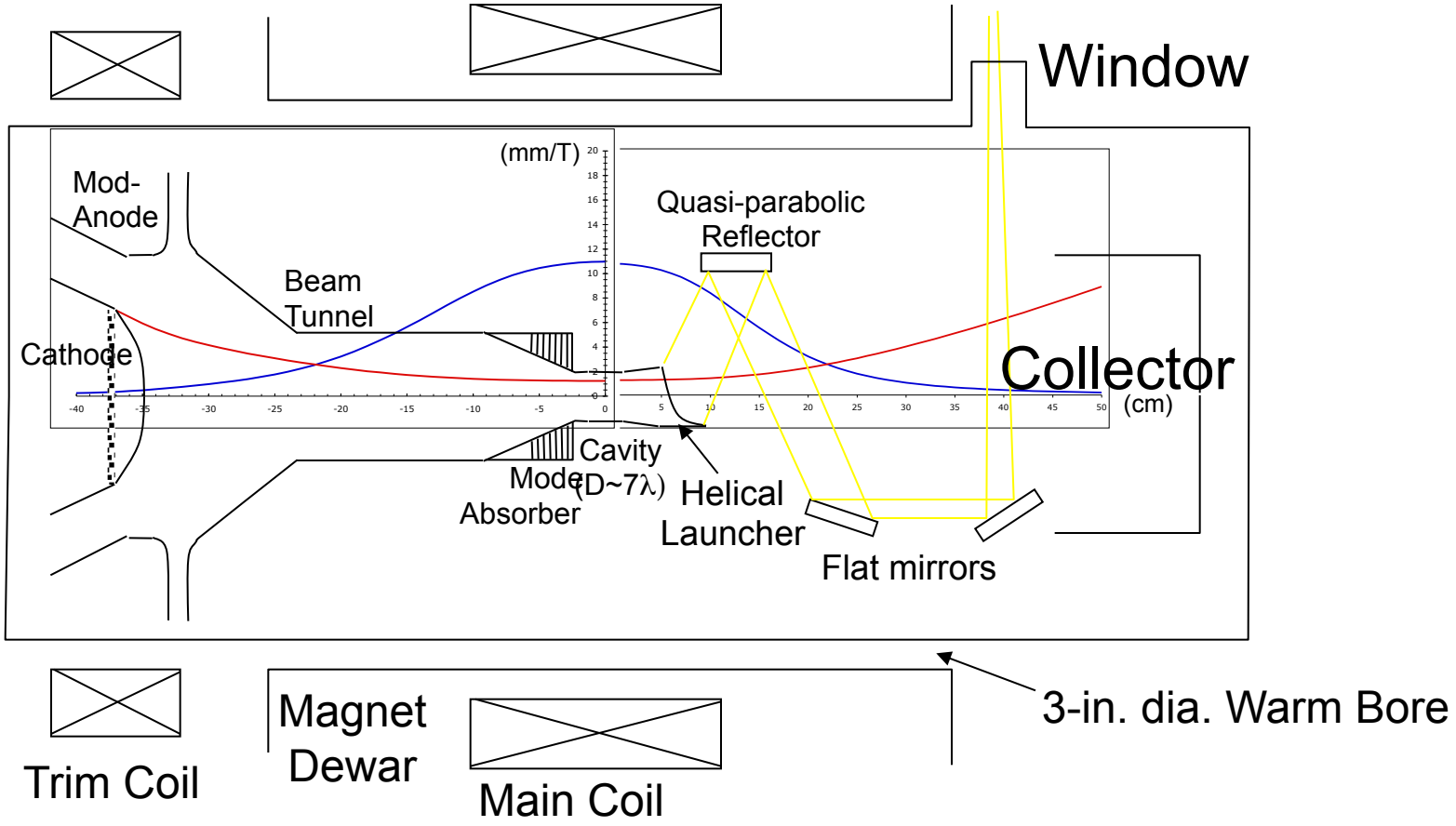
Rockwell Hard-Tube Modulator

70 kV, 10 A, 1–1000 Hz, 0.5–20 μs



CW gyrotron power supply, cooling and control systems

550 GHz $TE_{15,2}$ Gyrotron Experiment



Autonomy and Unmanned Systems

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.

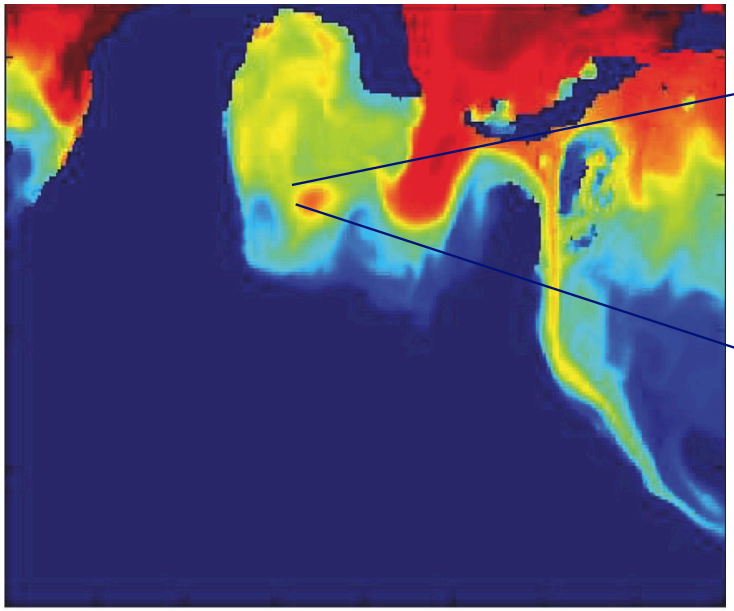
Description: Autonomy and unmanned systems will be used in all operating domains, performing multiple missions, and will be developed into numerous platforms.

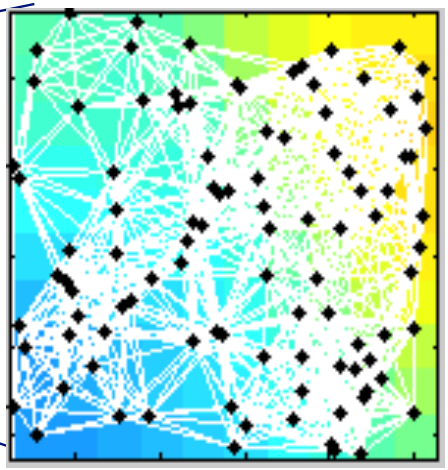
Coherent dynamics through delayed coupling architecture

Designing Cooperative Agents

Plasma Physics Division

Environmental Profiling using Swarming UUVs

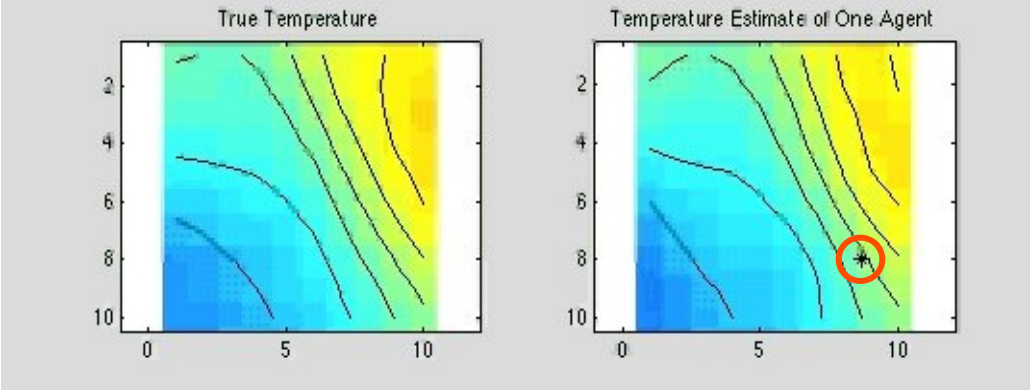




Random network between UUVs

Each agent maintains a local model

Global prediction of single agent



Optimal <u>decentralized</u> 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

Warfighter Performance

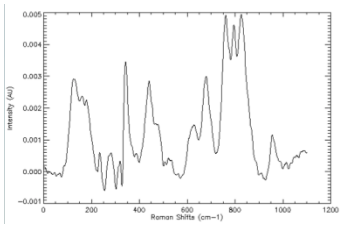
Vision: More effective point of injury care for Sailors and Marines. Enhanced health and warfighter performance both afloat and ashore. Highly efficient and effective human-system performance aided by new technologies created through the exploitation of biological design principles. Enhanced warfighter 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.

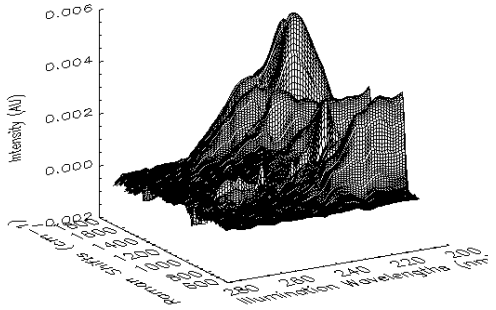
SWOrRD

Swept-Wavelength Optical resonance Raman Device

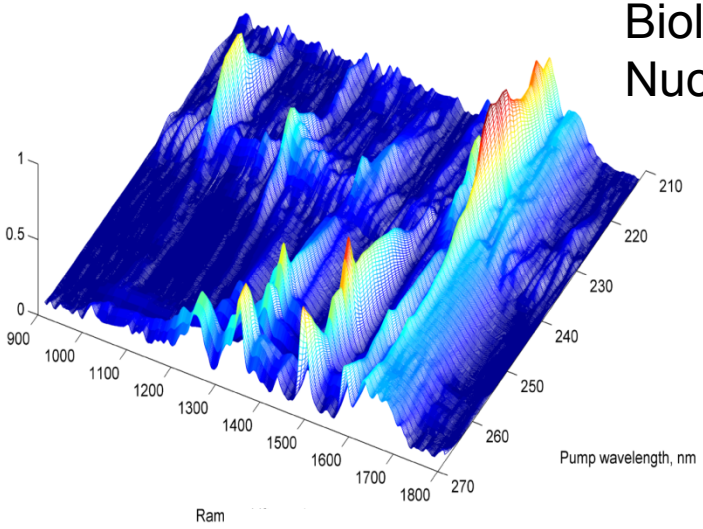
Plasma Physics Division

HMX

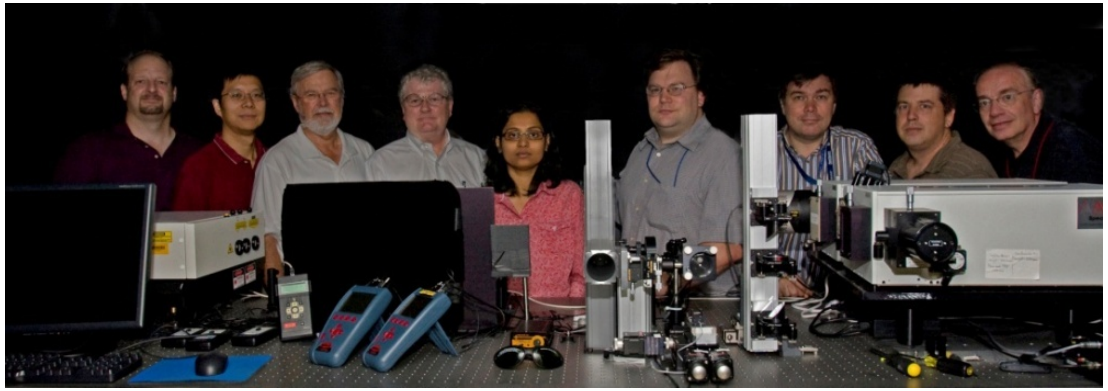




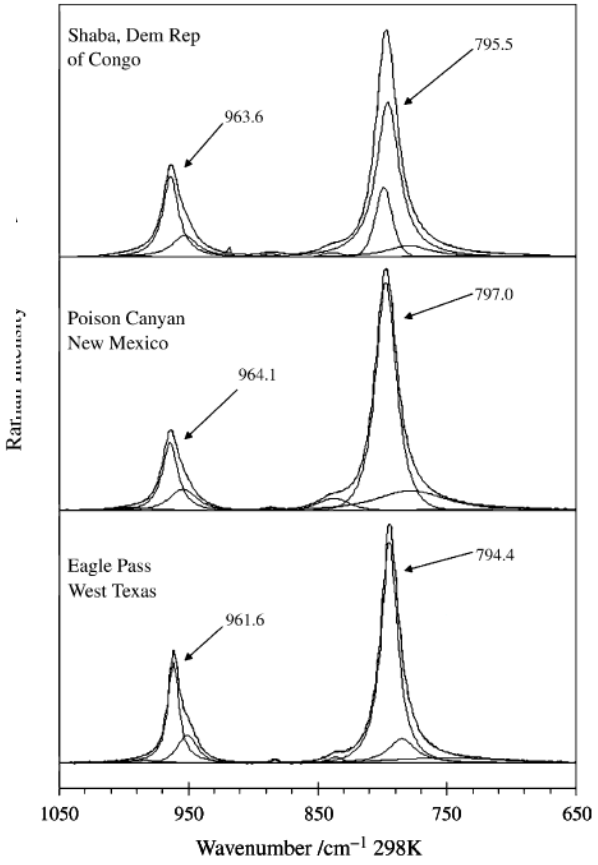
Escherichia coli



J Grun

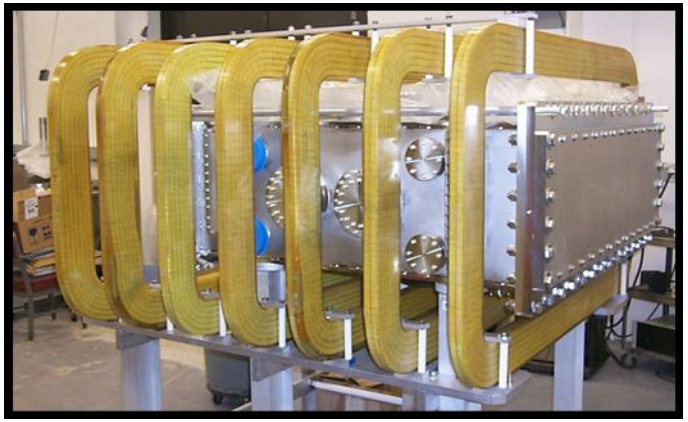


Chemical detection
Biological detection
Nuclear Forensics (?) *Uranophanes*



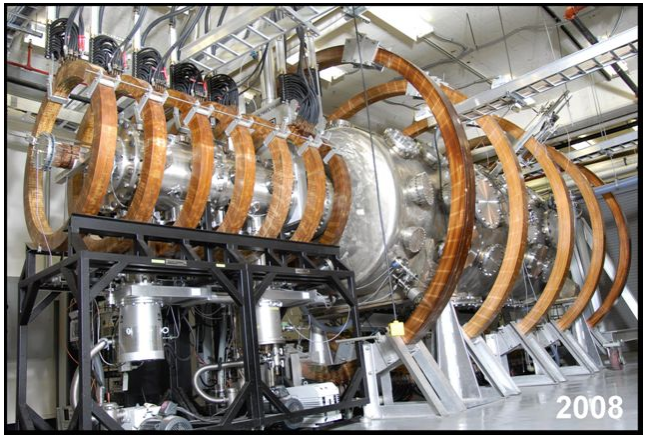
Plasma Facilities - 6750

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)

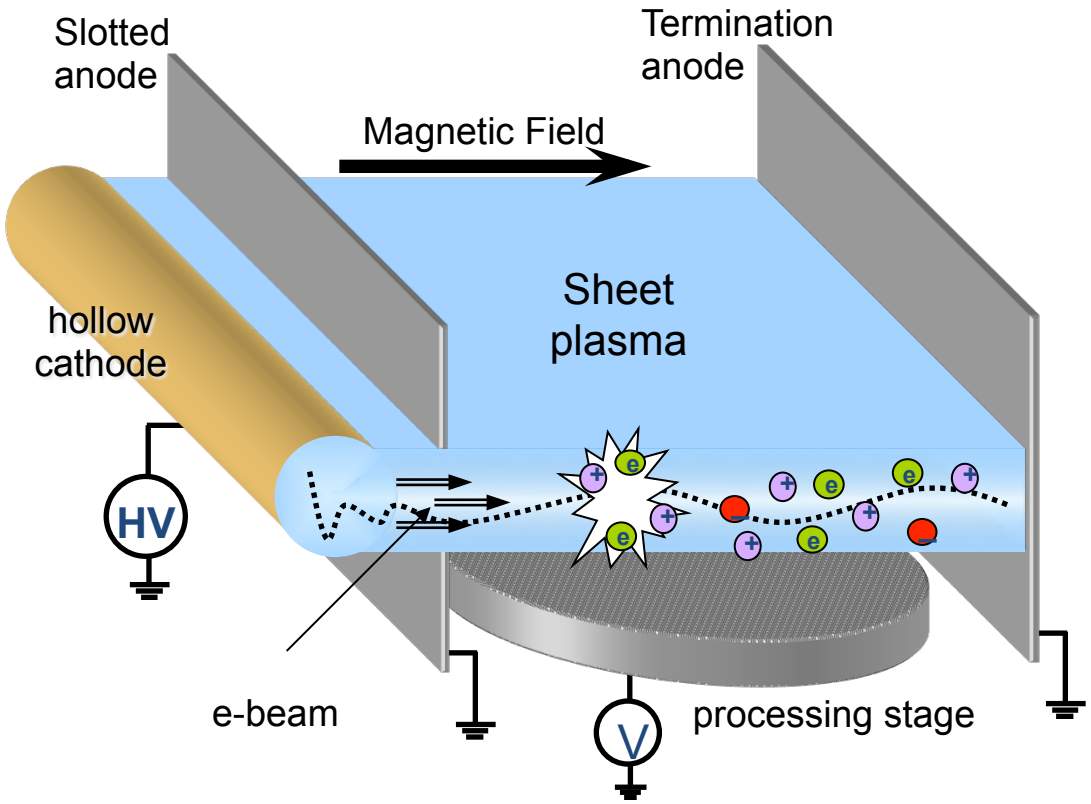
Space Plasma Simulation Chamber
W. Amatucci

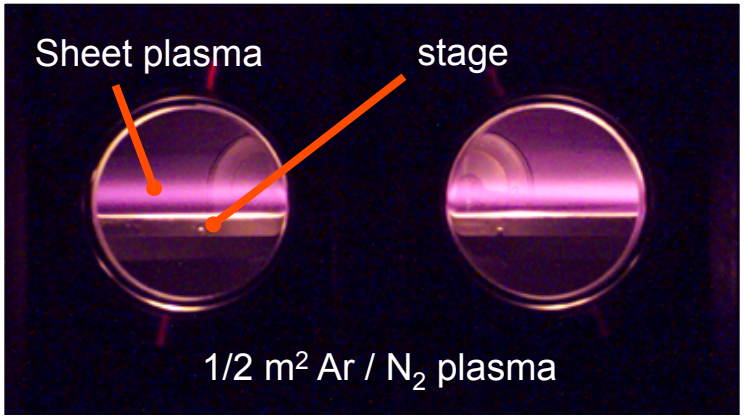


- Large volume permits scaled laboratory simulations of space plasma processes
- Plasma wave generation and instabilities, plasma flows, pitch angle scattering, etc.
- Supports efforts on radiation belt remediation concept
- Space hardware RDT&E

LAPPS: Large Area Plasma Processing System*

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 ~ 1cm

Width (hollow cathode length) ~ 25 - 50 cm

Length (beam distance) ~ 50 -100 cm

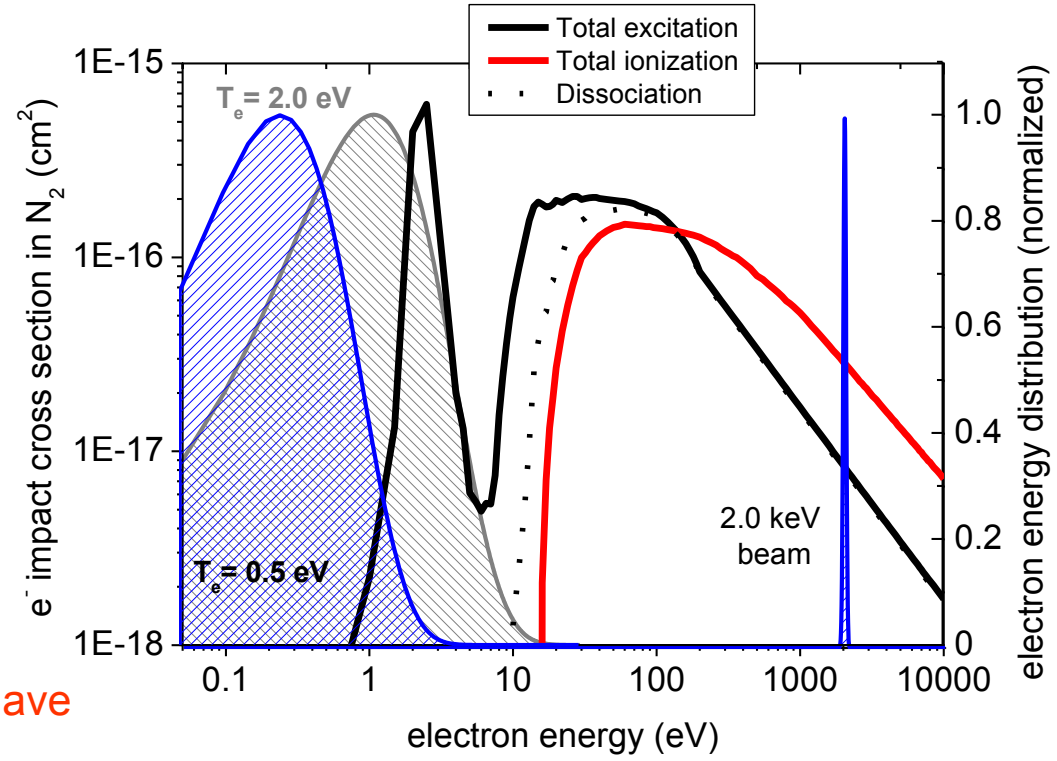
* US patent no. 5,874,807 (Feb. 1999)

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

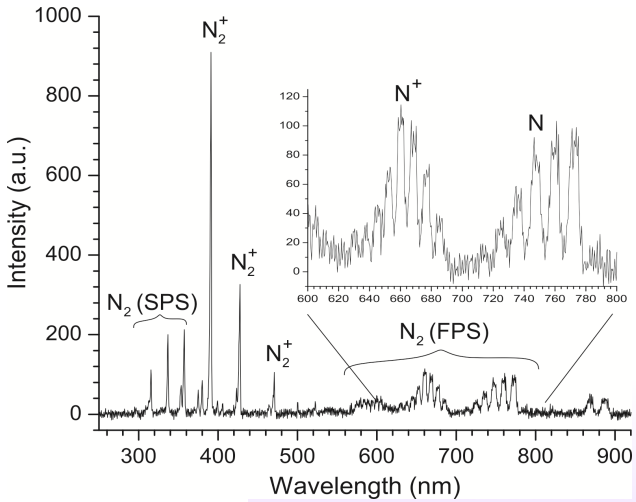


The resulting high n_e and low T_e are key attributes

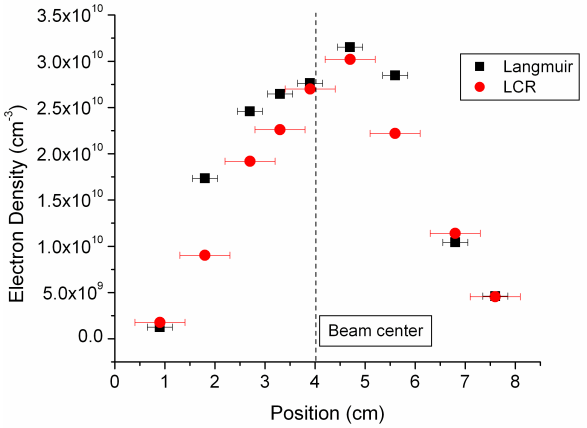
Diagnostics

Plasma Physics Division

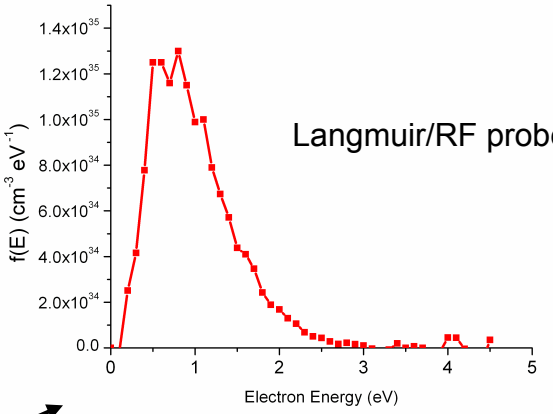
Unique species generation [1]

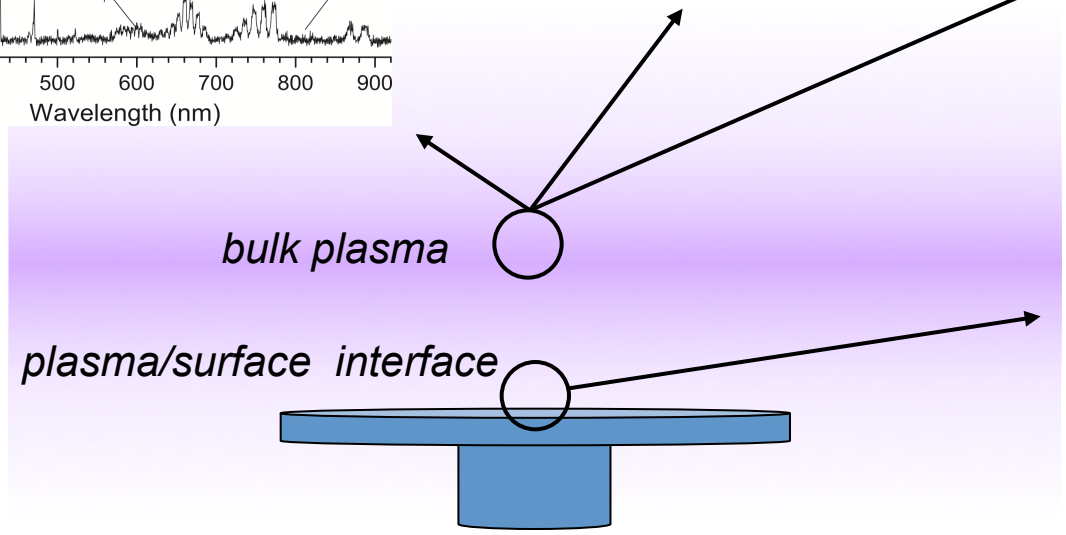


High density/localized [2]

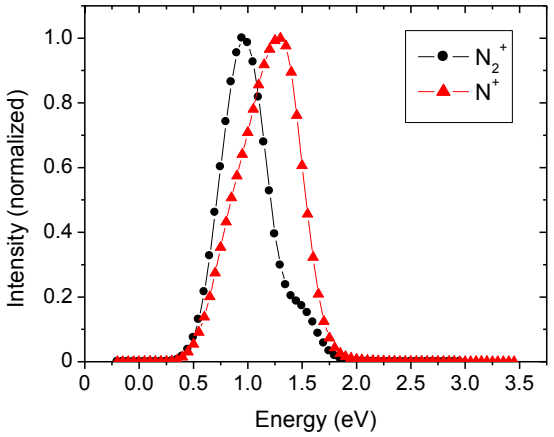


Low T_e





Mass spectrometry [3]



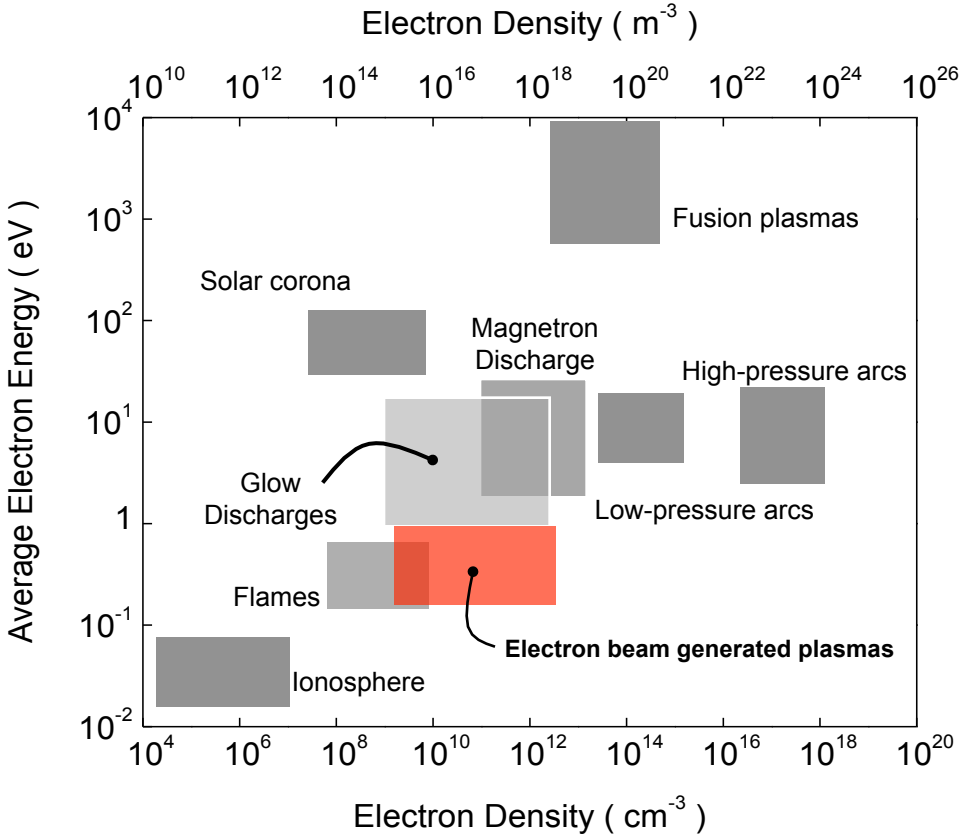
Low ion energies

[1] E. H. Lock, et al., NRL MR 6750-11-9333, May 13 (2011).

[2] D.R. Boris, et al, Plasma Sources Sci. Technol. 20, 025003 (2011).

[3] S.G. Walton, et al. Surf. Coat. Technol., 186 (1-2), 40 (2004).

Electron Beam-Generated Plasmas



Plasma sources (discharges) used in materials processing

Type	T_e (eV)	n_e (cm^{-3})
ICP	4	10^{11}
ECR	4	10^{11}
DBD	2 - 10	10^{13}
RIE	8	10^{10}
DC Diode	2 - 10	10^{10}
CCP	1 - 5	10^{9} -10^{10}
Electron Beam	**0.3 - 1**	**10^{9} -10^{12}**

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

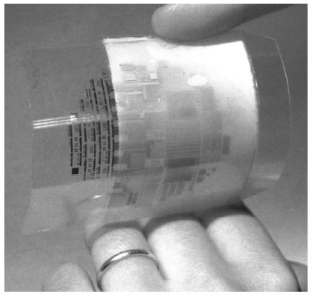
From: S.G. Walton and J.E. Green, "Plasmas in Deposition Processes," In *Handbook of Thin Film Deposition Technology: 3rd Edition,* ed. Peter Martin, Holland: Elsevier (2009).

Processing of "energy sensitive" materials

Plasma Physics Division

Materials where roughening or etching is not good …

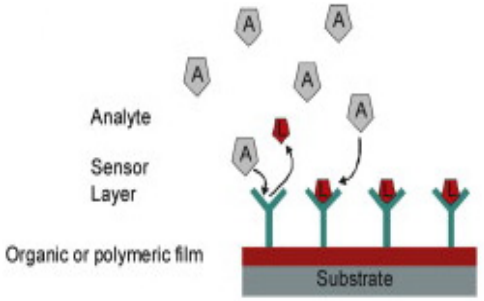
Flexible electronics



Polymers - *surface roughening is an issue*

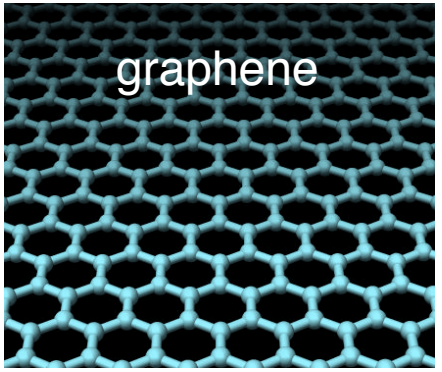
- In the development of organic transistor devices (Materials Today 10(3) 2007).
- In new 193 nm photoresists.
- In the development of thin, multi-stack capacitors.
- In biosensor development, presentation can be adversely impacted

Biosensors



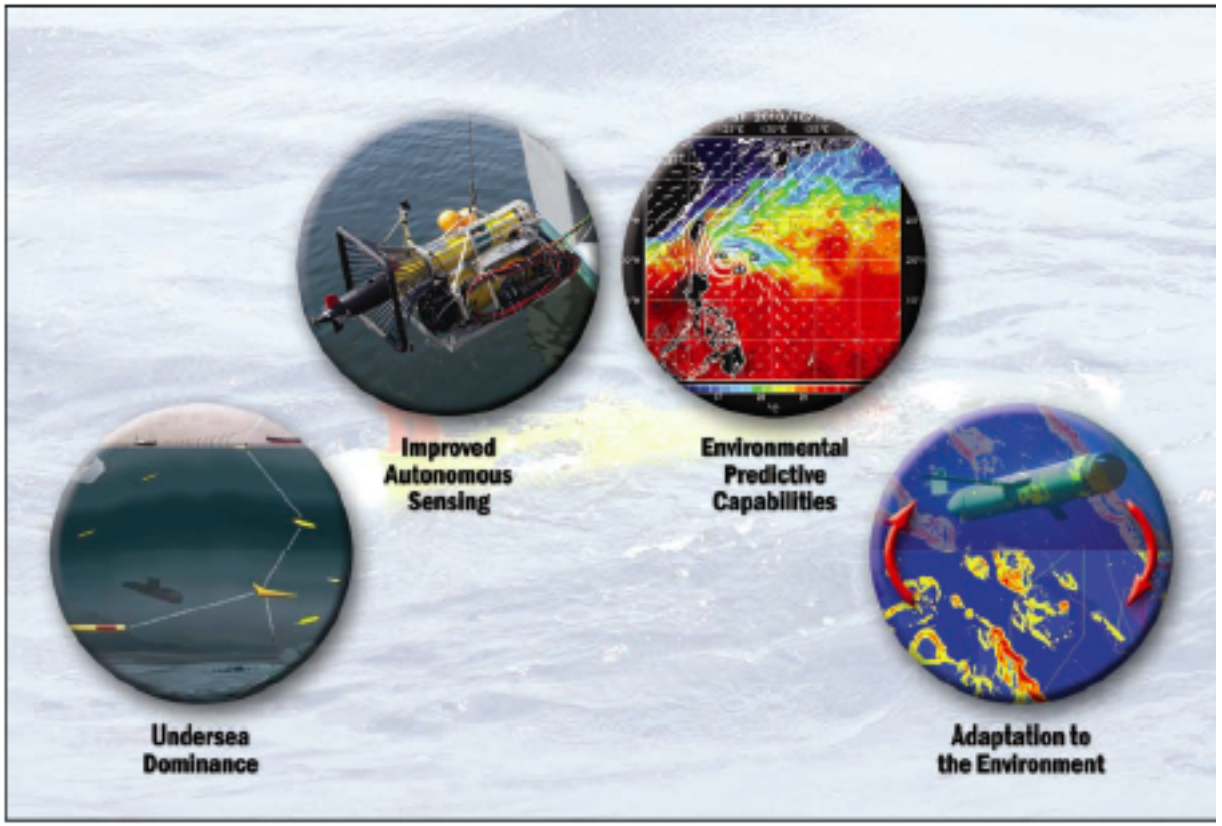
Graphene (or other 2-D materials) - *etching is not an option*

- Single monolayer of sp^2 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

Assure Access to the Maritime Battlespace



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.

6795 Intense Underwater Laser Lab
Unique Laser Facility & Diagnostic Suite

Plasma Physics Division

Laser pulse, plasma & shock characterization

- High-resolution, intensified, gated ($\tau_{res} \geq 0.8$ 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 ≈ 1 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:

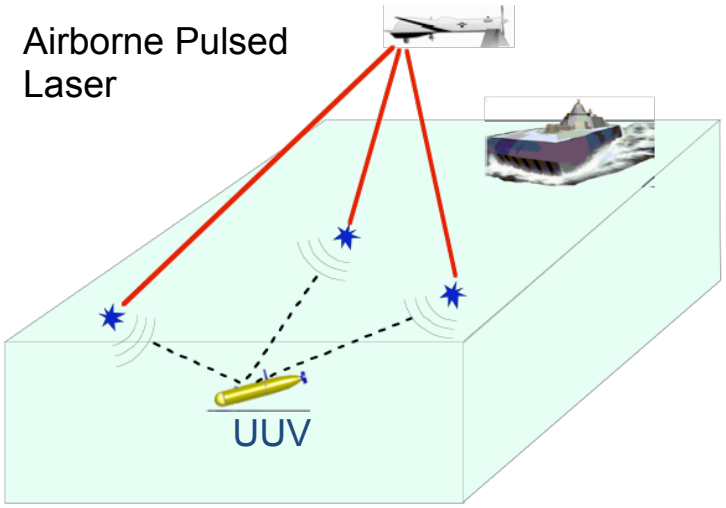
- 125 mJ, 100 ps

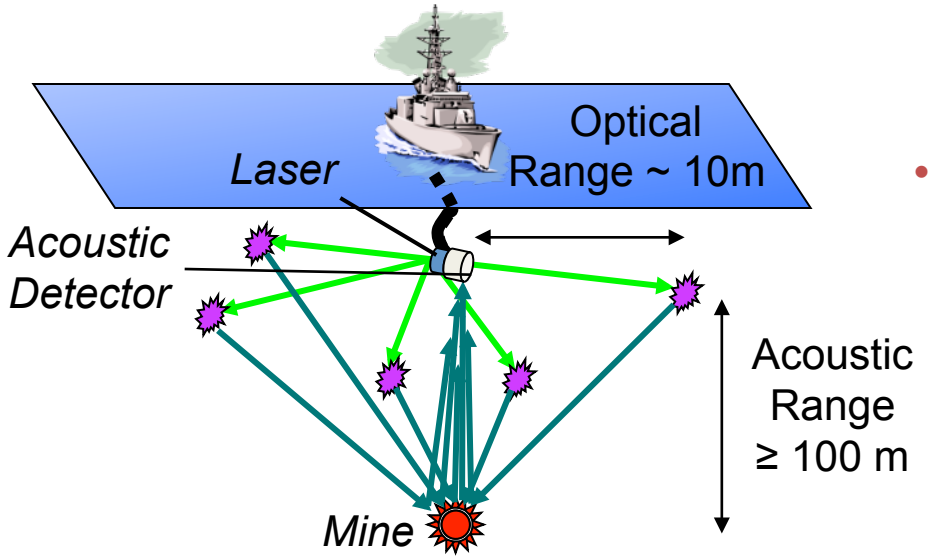
Laboratory femtosecond 400 nm Lasers:

- 1) ~ 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

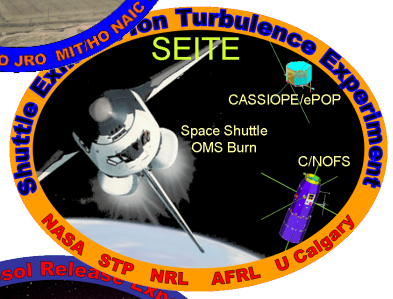
Plasma Physics Division



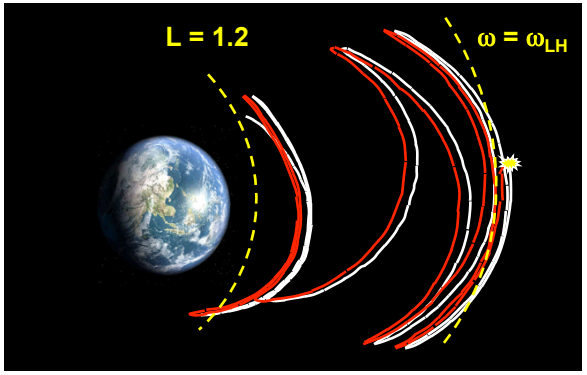


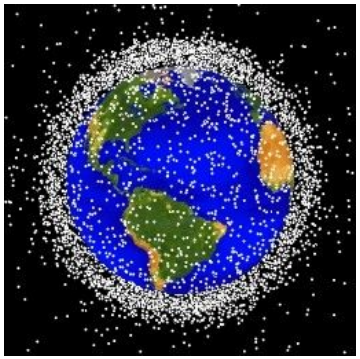
- Acoustic communications
  - Transmit from airborne laser platform to submarine or UUV
  - Dynamically change instructions as mission & data change
  - Optically penetrate thermocline
- Virtual acoustic beacon array for UUV navigation (analogous to GPS)
  - Airborne laser generation of acoustic pulse trains with encoded location and time
- SONAR applications
  - Detect and identify mines & other underwater targets
  - Map sea floor topography
  - Laser acoustic imaging

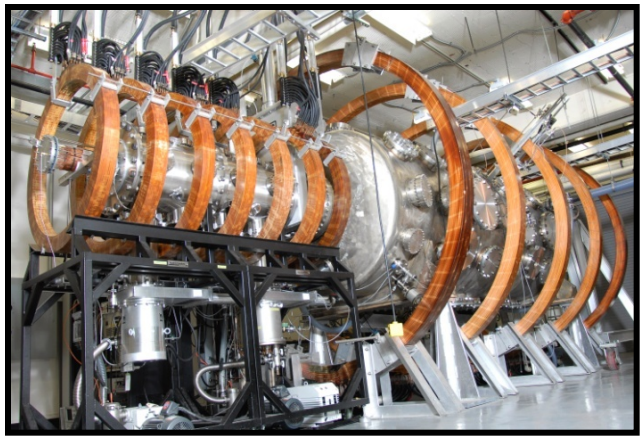
Space Experiments and Projects

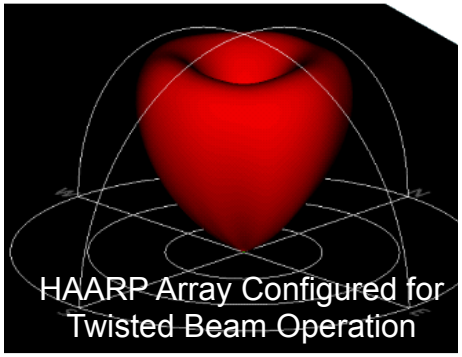


- CARE – CARE II
- PERCS
- Radiation Belt Remediation
- Orbital debris
- Shuttle burns
- HAARP
- Space Chamber Expts

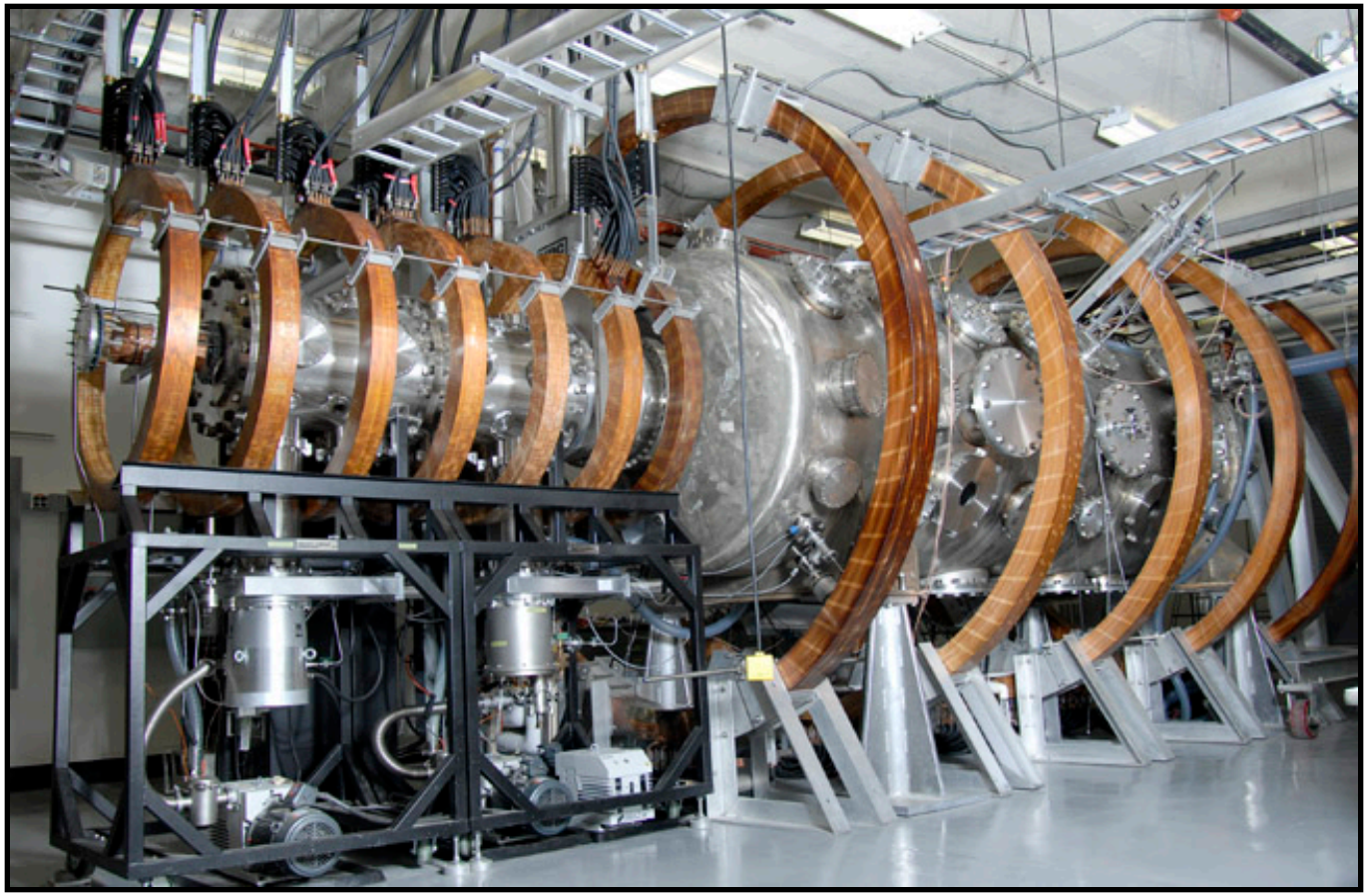








NRL Space Physics Simulation Chamber: unique for basic plasma experiments & simulation of space plasma phenomena



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

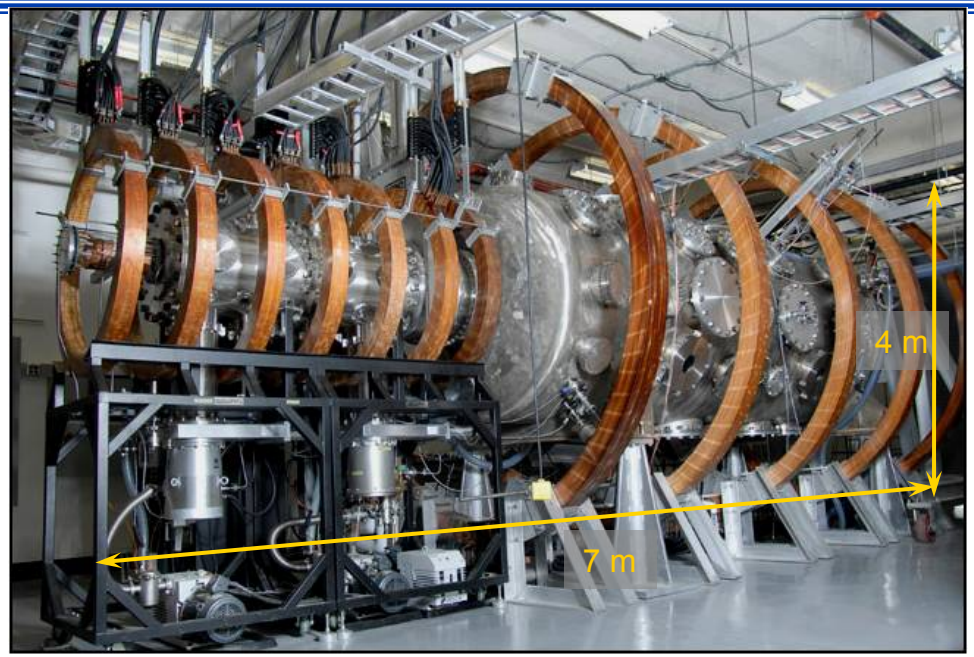
Experiments include:
- radiation belt dynamics,
- broadband ionospheric ion-cyclotron wave generation,
- wave and Joule heating of ionospheric plasma,
- magnetotail particle and wave dynamics.

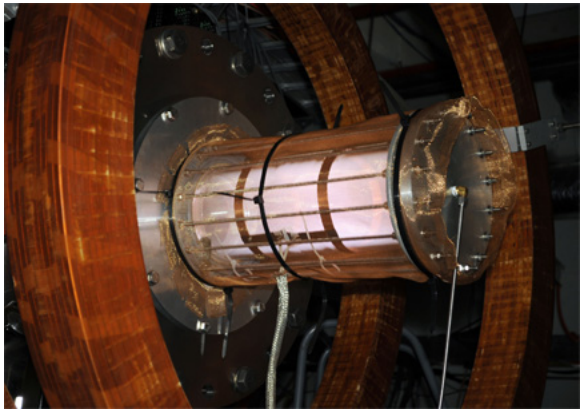
Spacecraft diagnostic development and hardware testing/qualification

Bill Amatucci – NRL POC

NRL Space Physics Simulation Chamber

Plasma Physics Division





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)	~ 0.07 eV
Ion Cyclotron Frequency (f_{ci})	11.5 kHz

Dimensionless Parameters

Parameter	Ionosphere	SPSC
ω_{pe}/Ω_e	0.1-10	0.01-50
ρ_i/L_E	0.01-0.7	0.6
E/B	< 30 km/s	< 20 km/s
$\beta = nkT/(B^2/2\mu_0)$	10^{-7}-10^{-4}	10^{-7}-10^{-4}

Naval Research Laboratory
SPACE PHYSICS SIMULATION CHAMBER
PLASMA PHYSICS DIVISION, CODE 6755, WASHINGTON, DC 20375

NRL Space Physics Simulation Chamber (Bill Amatucci)

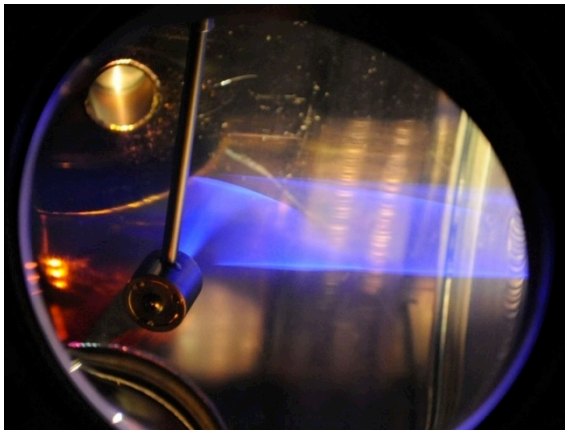
Plasma Physics Division

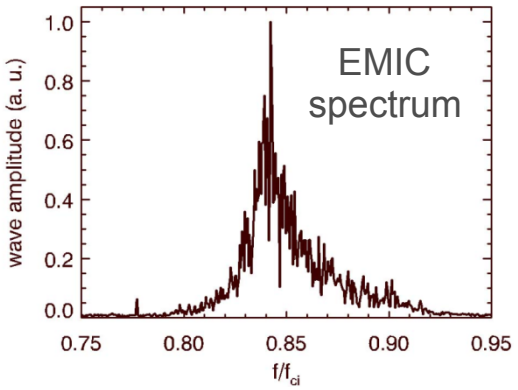
Research Questions

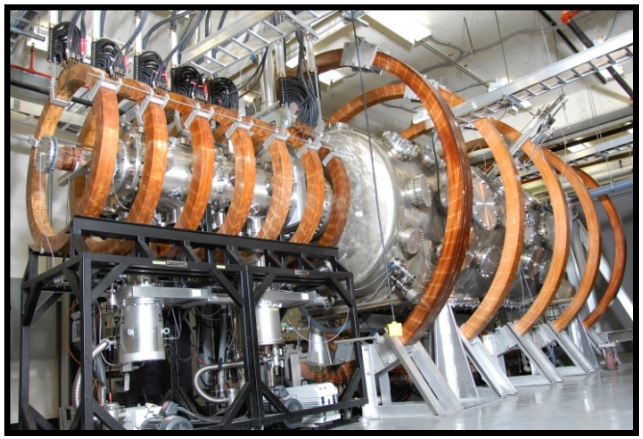
- **How do artificial radiation belts form in the post-HAND environment?**
  - What wave characteristics are important for pitch-angle scattering?
  - How do the various plasma wave modes interact and transition?

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)**







*Work sponsored by ONR and DTRA

SAMI3: NRL Ionosphere Model (Joe Huba)

Plasma Physics Division

Comprehensive: multi-ion dynamic

Neutral species input:

1) theoretical model: TIEGCM, or

2) empirical: such as

NRLMSISE00/HWM93/HWM07

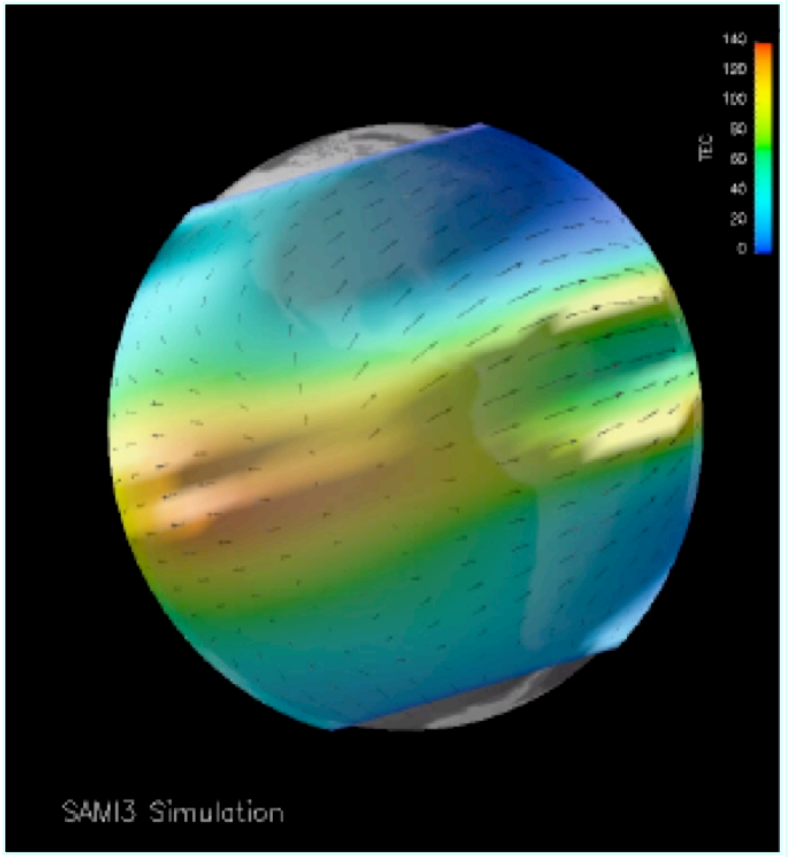
EUV model: EUVAC empirical model

Magnetic latitude range (+/- 60^{o})

Nonorthogonal, nonuniform fixed grid

Self-consistent potential solver

Tilted Dipole Field

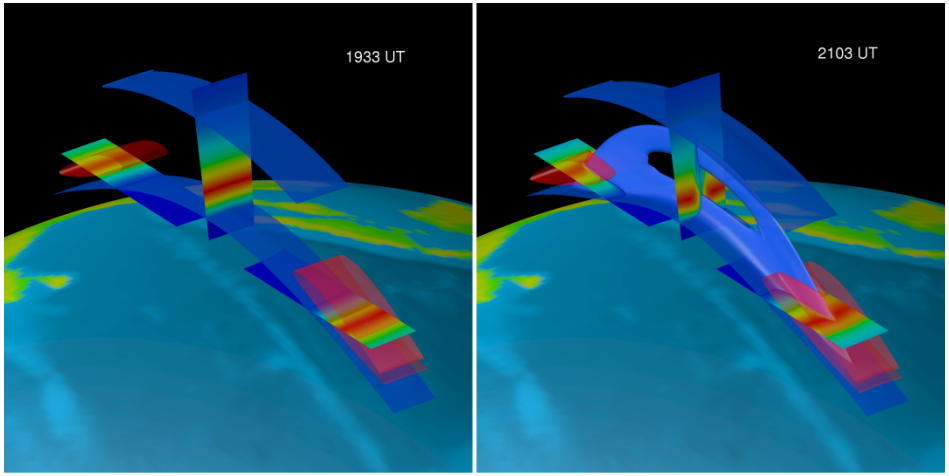


The NRL Ionosphere Model & the Heart of ISES-OE (Plasma Physics Division).

Space Weather Modeling

Plasma Physics Division

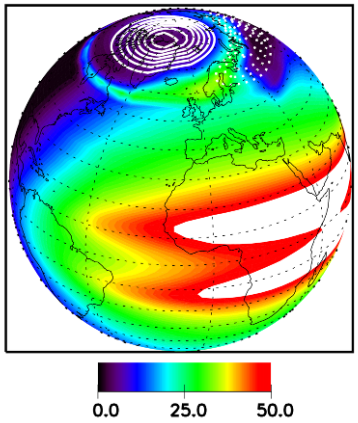
Ionospheric Physics
J. Huba



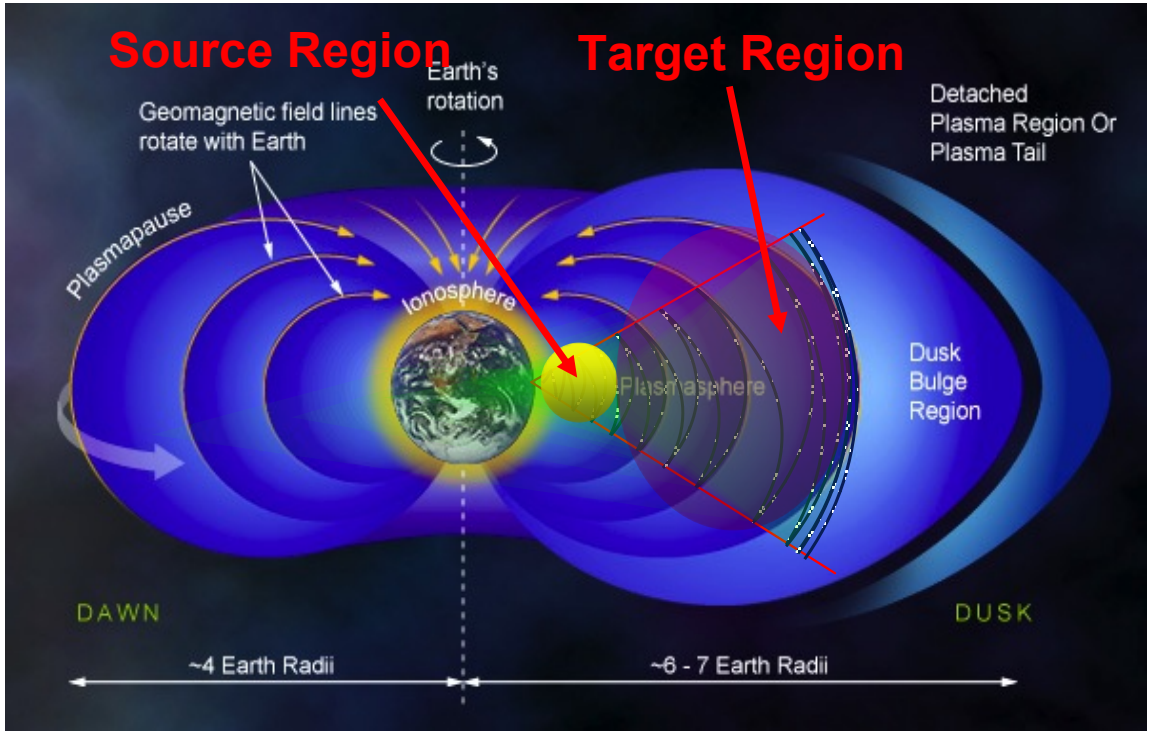
- Electron density isosurfaces from SAMI-3 simulation code
- First fully 3-D simulation of equatorial spread F (ESF)
- Plasma bubble can affect communications

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

Predicted Total Electron Content Map

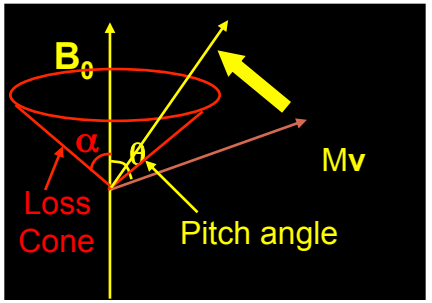


NRL Rapid Remediation Concept



Geometry of Experiment

- <u>CONCEPT:</u>
- Inject massive amount of energy over a short period
- <u>APPROACH:</u>
- 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

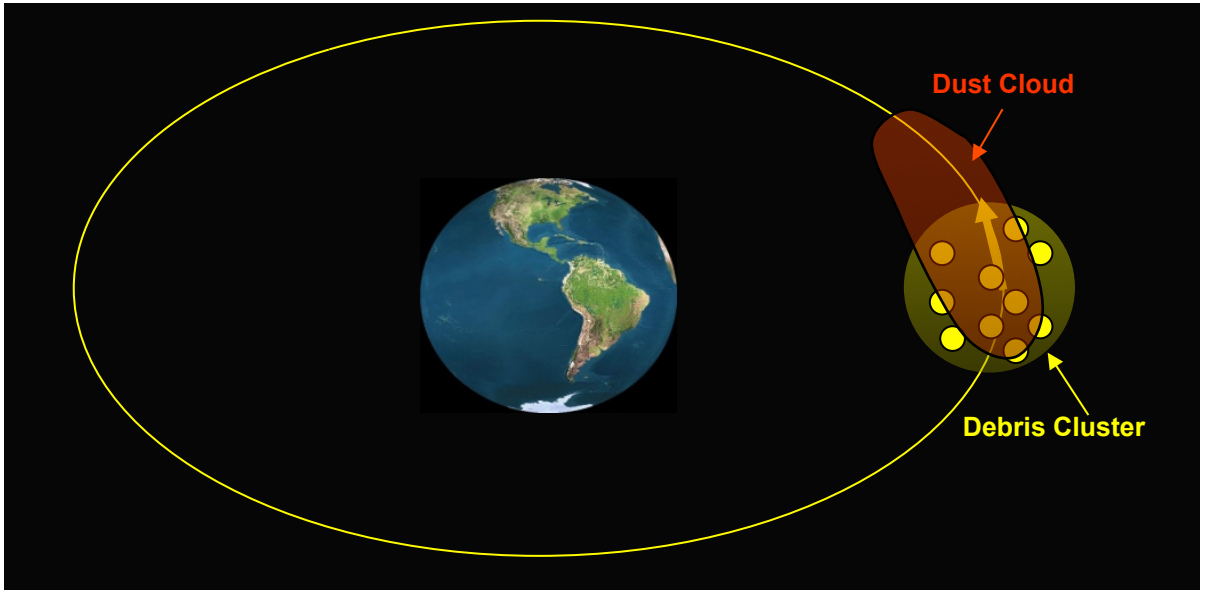


G Ganguli

Elimination Of Space Debris Through Induced Drag Enhancement

Plasma Physics Division

G. Ganguli



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

Plasma Physics Division

Thank you for your attention

Are there any questions?

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