Research Relevant to MHD Power Generation in the Naval Research Laboratory's Plasma Physics Division*

S. L. Jackson, B. V. Weber, A. S. Richardson, D. G. Phipps, J. D. Sethian, J. L. Giuliani, J. M. Neri, R. J. Commisso, J. W. Schumer, J. R. Angus, S. B. Swanekamp, D. P. Murphy, and D. D. Hinshelwood,
Plasma Physics Division, Naval Research Laboratory

C. N. Boyer and P. F. Ottinger[a]
Engility Corporation

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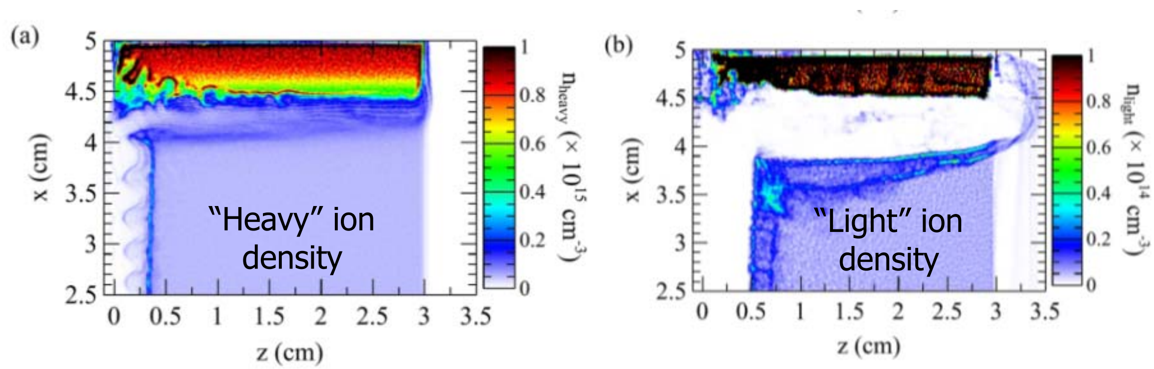
*Work supported by NRL Basic and Applied Research Program
[a]Independent consultant to NRL through Engility Corporation

stuart.jackson@nrl.navy.mil

Outline

- Overview of NRL & Plasma Physics Division
- Ongoing work in electron-beam-driven NO_x reduction and rep-rate, solid-state pulsed power
- Example plasma chemistry simulation of KrF laser
- Combustion dynamics and modeling (Chemistry Division)
- Electromagnetic Launcher Materials Testing Facility
- Basic physics investigation (coupled modeling & experiment) of plasma-field interactions in a plasma opening switch

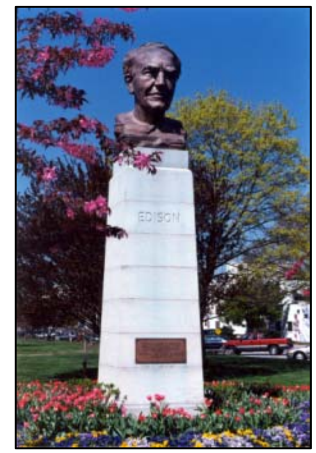


Particle-in-cell modeling of species separation in an opening switch plasma

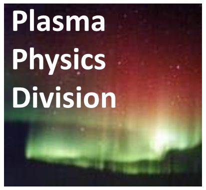
Plasma Physics Division

Naval Research Laboratory conducts broad range of basic and applied research

- Founded near end of WWI at suggestion of Thomas Edison
- Conducts broad range of basic and applied research for US Navy, Marine Corps, and other government and non-government organizations
- 2200 employees (750 PhDs)
- $800M/yr
- Many advances
  - Radar
  - Early space programs
  - GPS

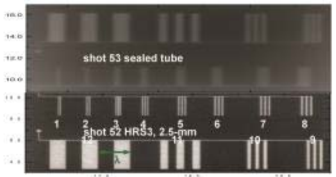


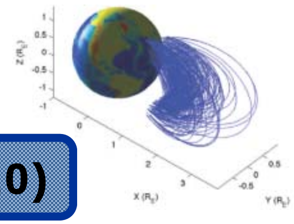
NRL Plasma Physics Division conducts broad range of plasma physics research

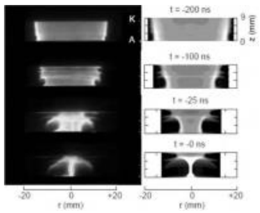


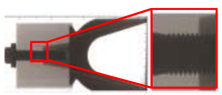
Plasma Physics Division

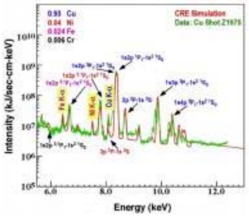
- Laser Plasma (Code 6730)
- Beam Physics (Code 6790)
- Radiation Hydrodynamics (Code 6720)
- Charged Particle Physics (Code 6750)
- Pulsed Power Physics (Code 6770)

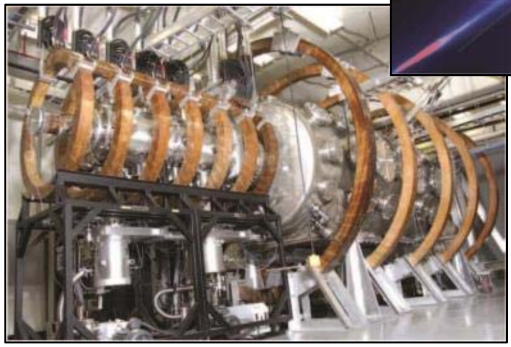


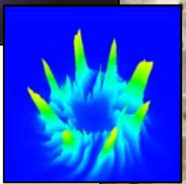


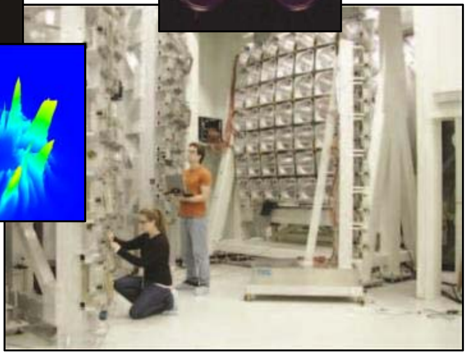


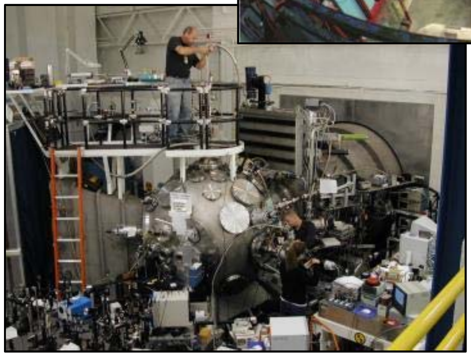


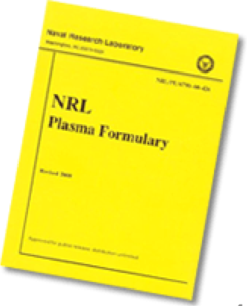






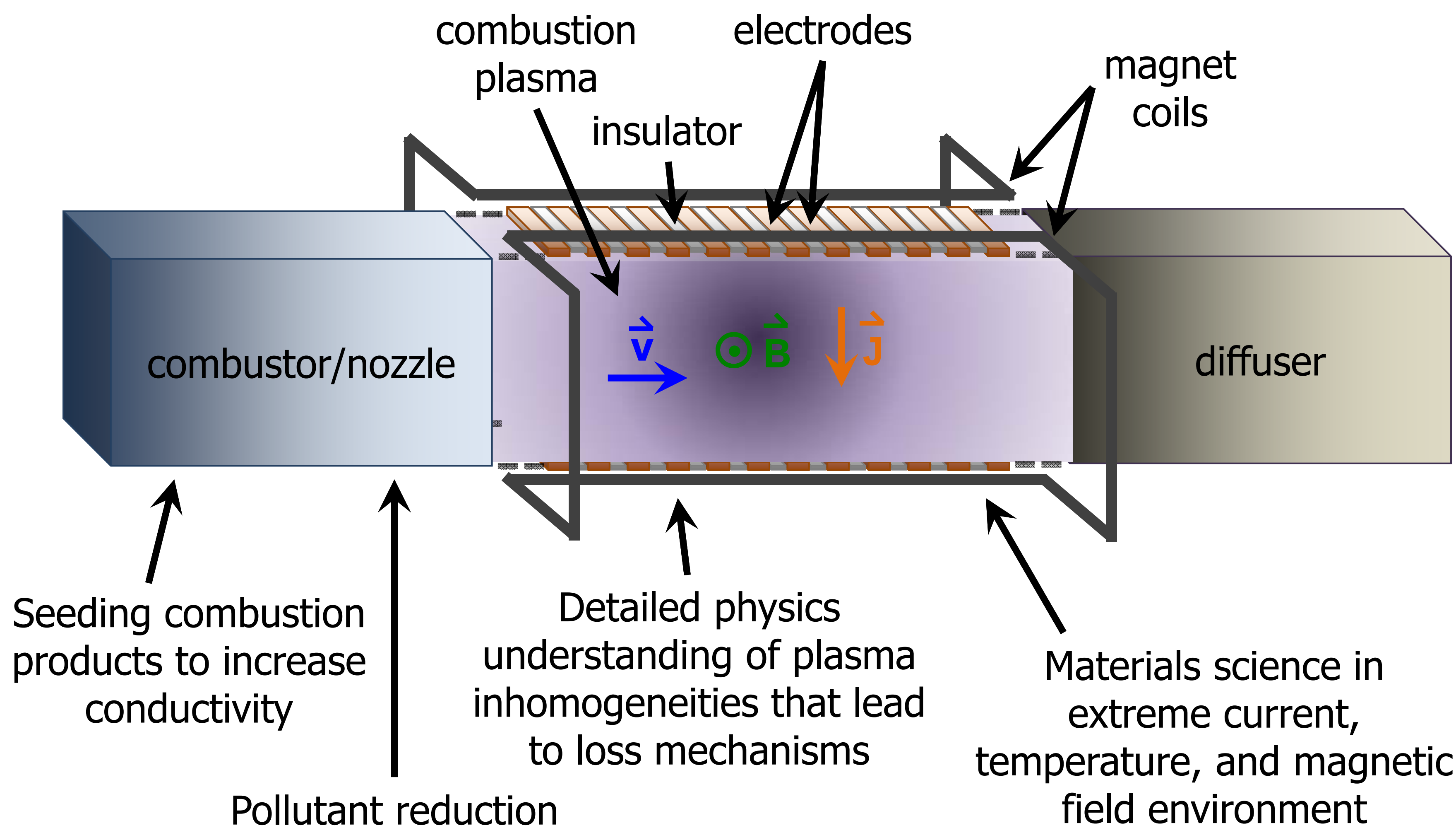






Plasma physics research challenges in MHD energy conversion for power generation

Plasma Physics Division



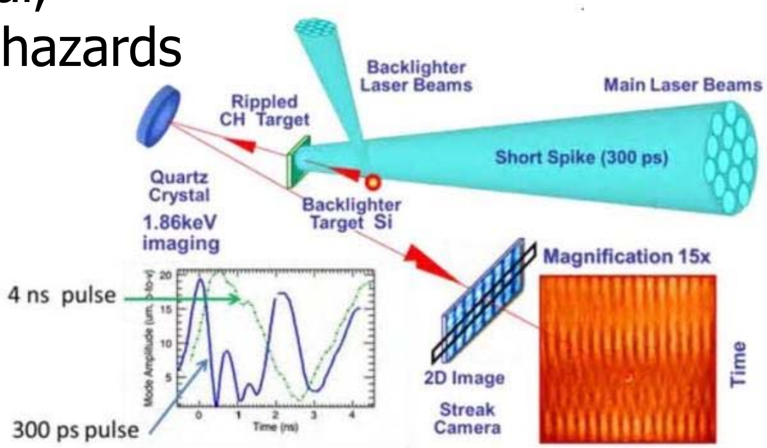
Laser Plasma Branch (Code 6730) Research & Relevance

Plasma Physics Division

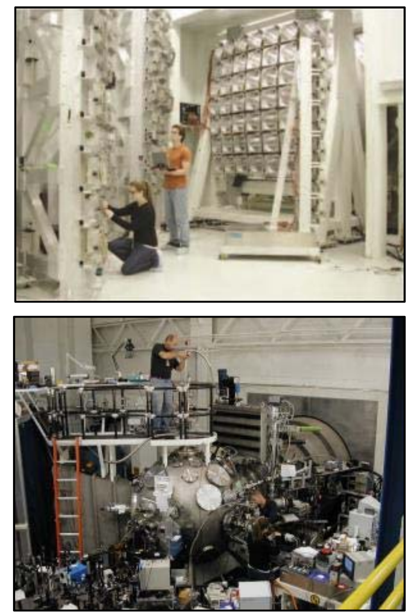
<u>Research Description</u>

- Laser fusion and basic laser target interaction research
- Development and applications of high-power pulsed electron beams
- Development of detection mechanisms for biological, chemical, and explosive hazards

Electra Laser Facility



Experimental setup for measurement of areal mass nonuniformity in a laser-accelerated target



Nike Laser Facility

Laser Plasma Branch (Code 6730) Research & Relevance

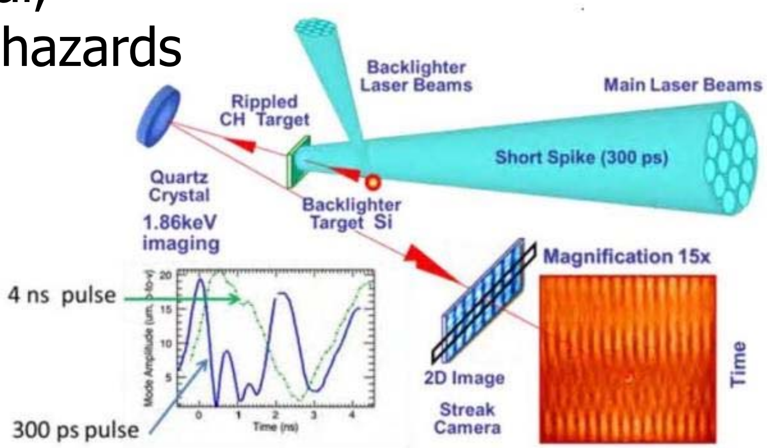
Research Description

- Laser fusion and basic laser target interaction research
- Development and applications of high-power pulsed electron beams
- Development of detection mechanisms for biological, chemical, and explosive hazards

Relevant Projects/Capabilities

- Electron-beam-driven chemical reactions
- Durable and efficient rep-rate pulsed power

Electra Laser Facility



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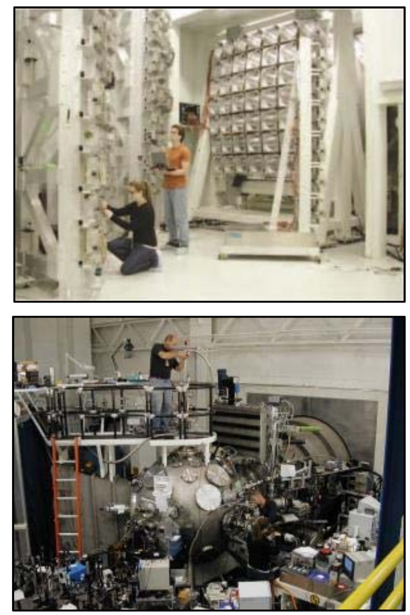
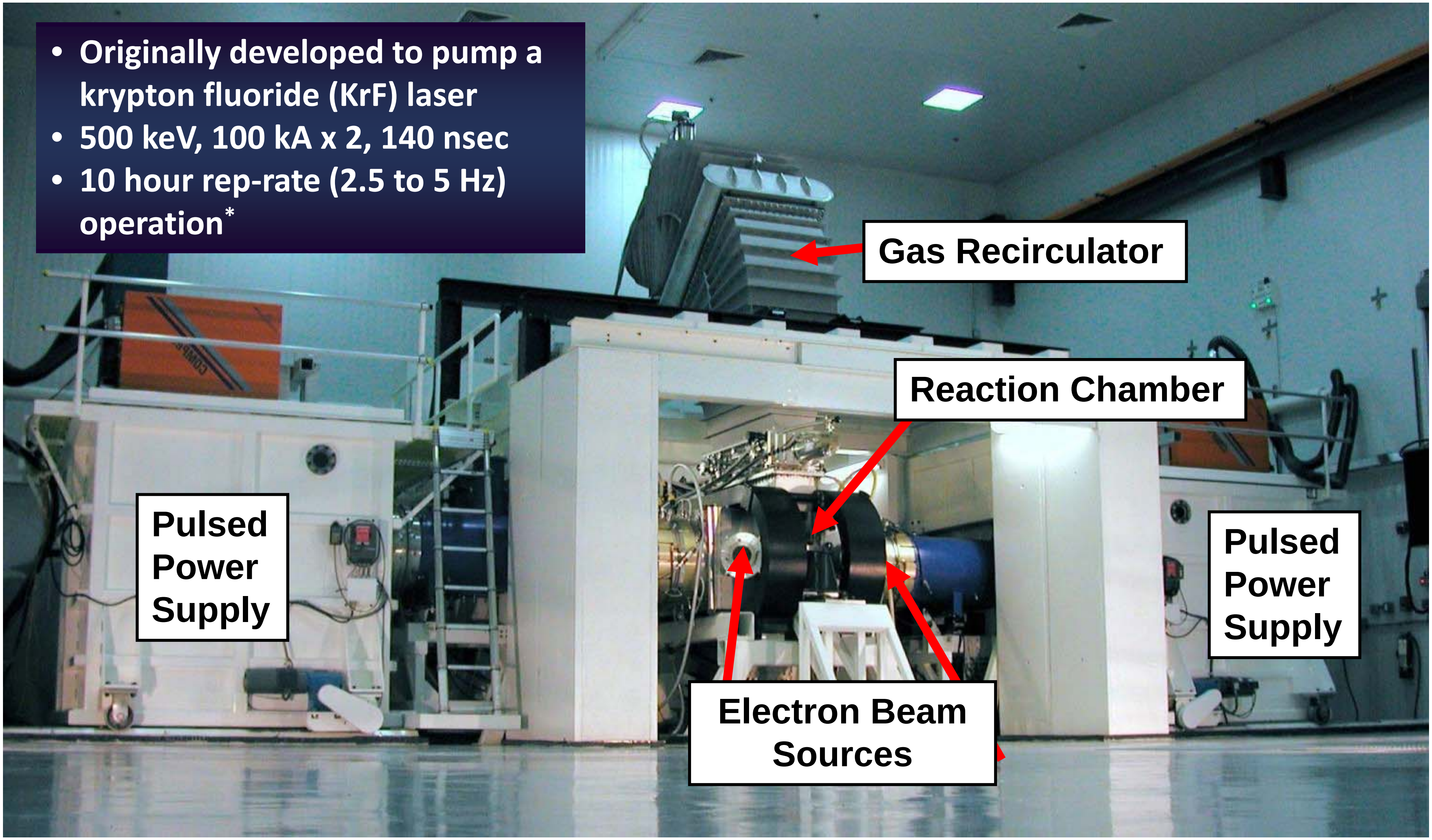


Nike Laser Facility

ELECTRA:
50 kW pulsed electron beam system

Plasma Physics Division

- Originally developed to pump a krypton fluoride (KrF) laser
- 500 keV, 100 kA x 2, 140 nsec
- 10 hour rep-rate (2.5 to 5 Hz) operation*



* Run times currently limited by spark gap based pulsed power technology

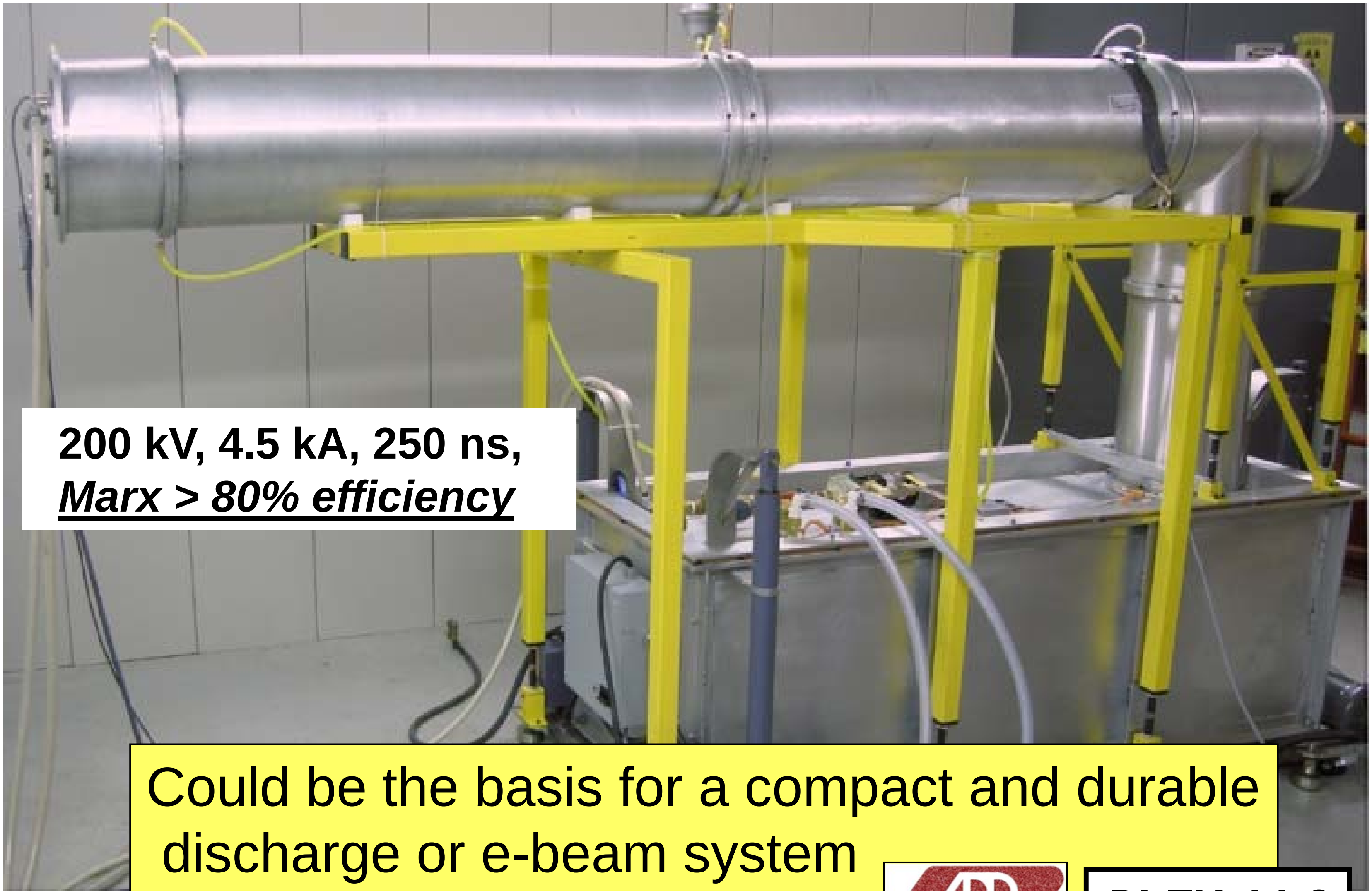
Electra experiments show pulsed e-beam converts NOx to pure N_2 & O_2 w/o catalyst

Plasma Physics Division

Initial NO_x (ppm)	Final NO_x (ppm)	Removal Efficiency
200	**4.2**	**96%**
500	**9.9**	**98%**
980	**44**	**96%**

14.7 psi N_2 plus NO_x at concentrations listed
Energy deposition ~ .08 J/cc
NRL patent allowed: 8/22/2014

New NRL all solid state pulsed power system has demonstrated 11,000,000 shots continuous at 10 Hz



200 kV, 4.5 kA, 250 ns,
<u>Marx > 80% efficiency</u>

Could be the basis for a compact and durable discharge or e-beam system

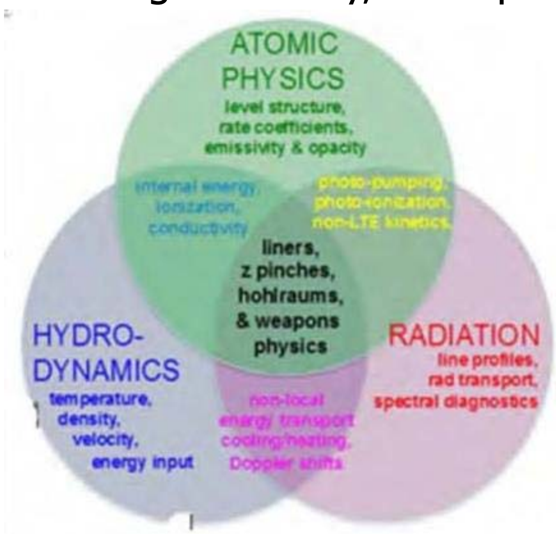
PLEX, LLC

Radiation Hydrodynamics Branch (Code 6720) Research & Relevance

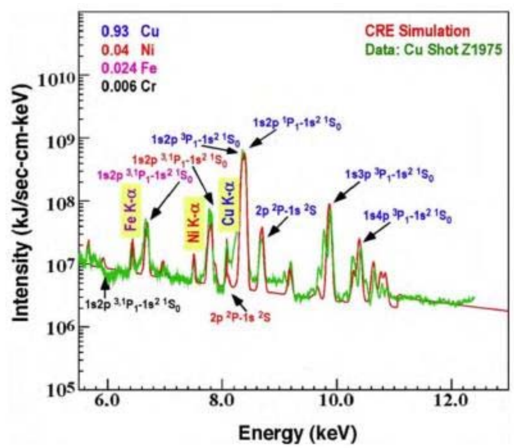
Plasma Physics Division

Research Description

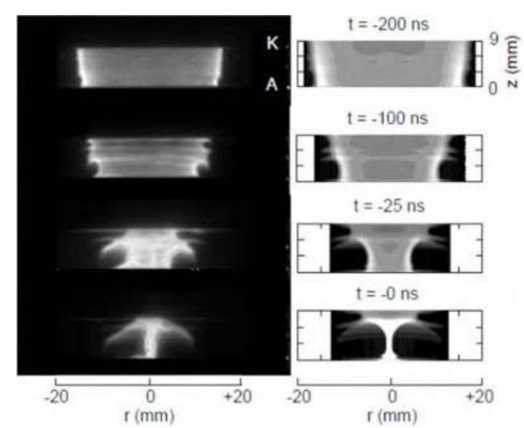
- Modeling & analysis of high energy density (HED) plasmas produced by
  - Pulsed-power generators
  - High intensity, short pulse lasers



Venn diagram showing interplay between atomic physics, hydrodynamics, and radiation transport that must be accounted for in understanding HED plasmas



Modeling of z-pinch K-shell spectra



Experimental images of an imploding neon pinch (left) vs. synthetic images from a radiation MHD simulation (right)

Radiation Hydrodynamics Branch (Code 6720) Research & Relevance

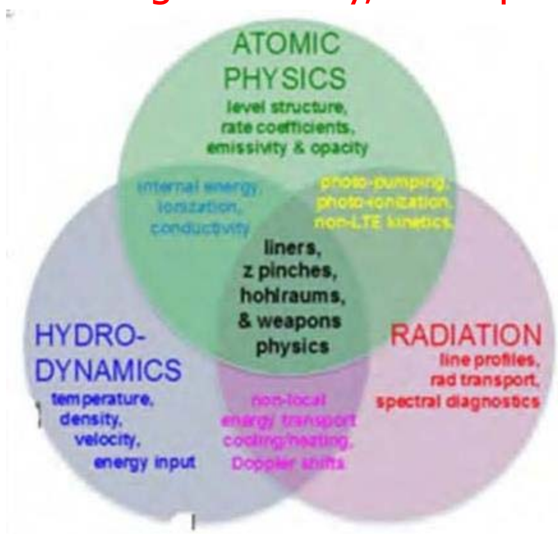
Plasma Physics Division

Research Description

- Modeling & analysis of high energy density (HED) plasmas produced by
  - Pulsed-power generators
  - High intensity, short pulse lasers

Relevant Projects/Capabilities

- MHD and non-equilibrium modeling of various plasma configurations
- Strong plasma chemistry simulation capability



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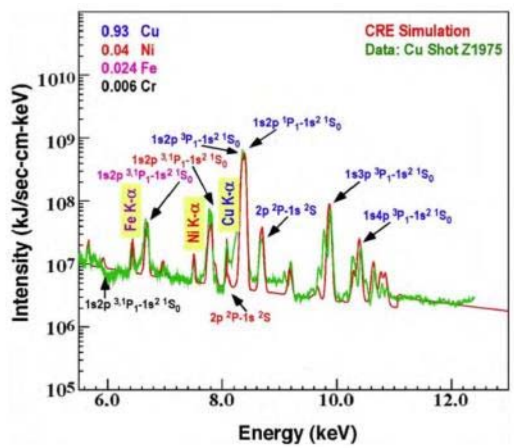
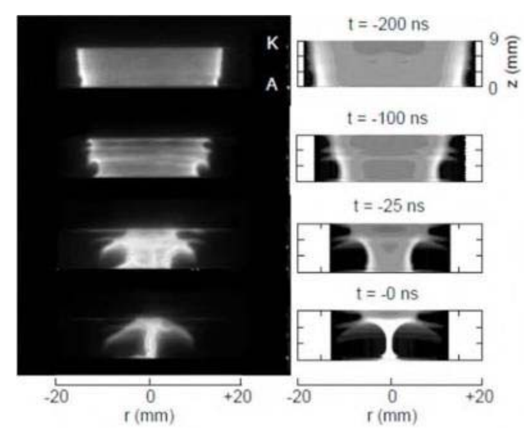


Modeling of z-pinch K-shell spectra



Experimental images of an imploding neon pinch (left) vs. synthetic images from a radiation MHD simulation (right)

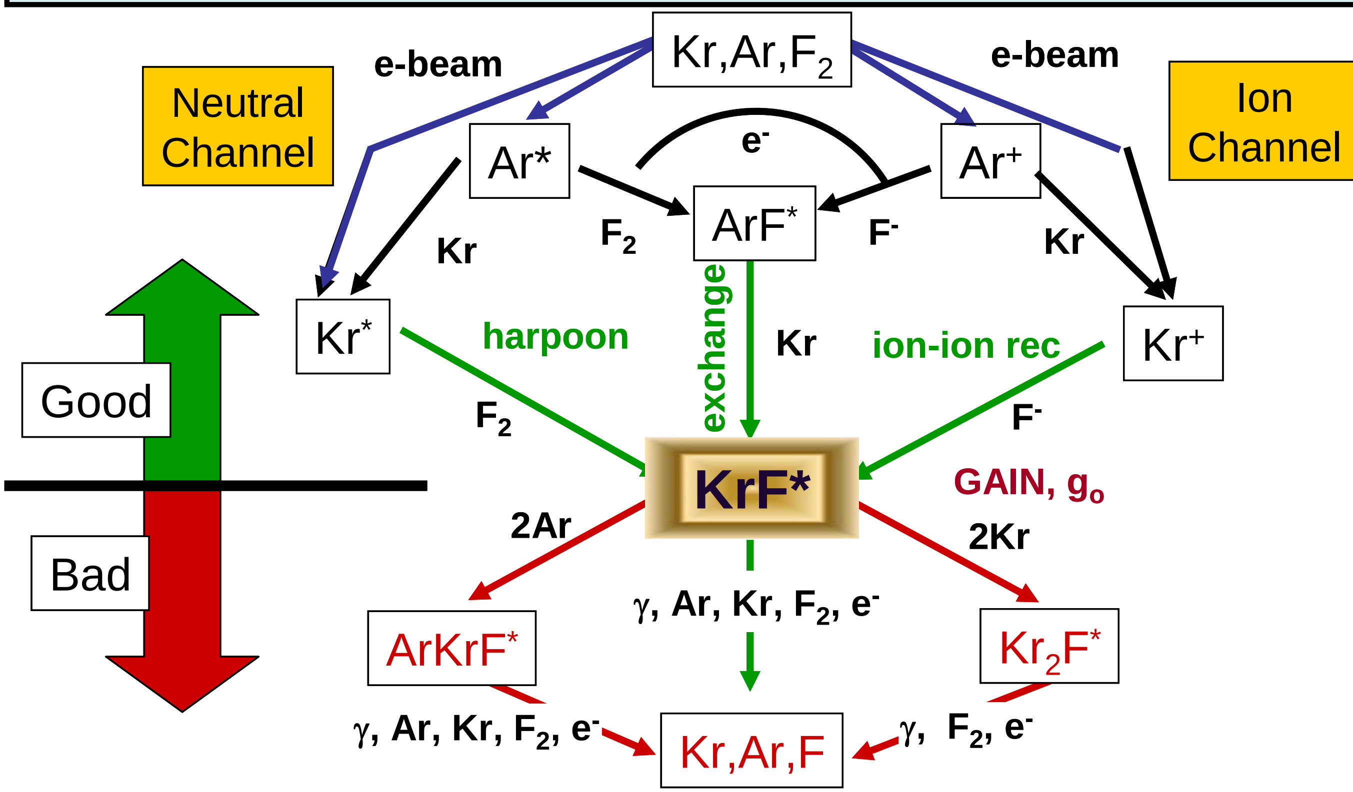
NRL has strong plasma chemistry simulation capability

Plasma Physics Division

Example of capabilities: Modeling Electra Krypton Fluoride Laser

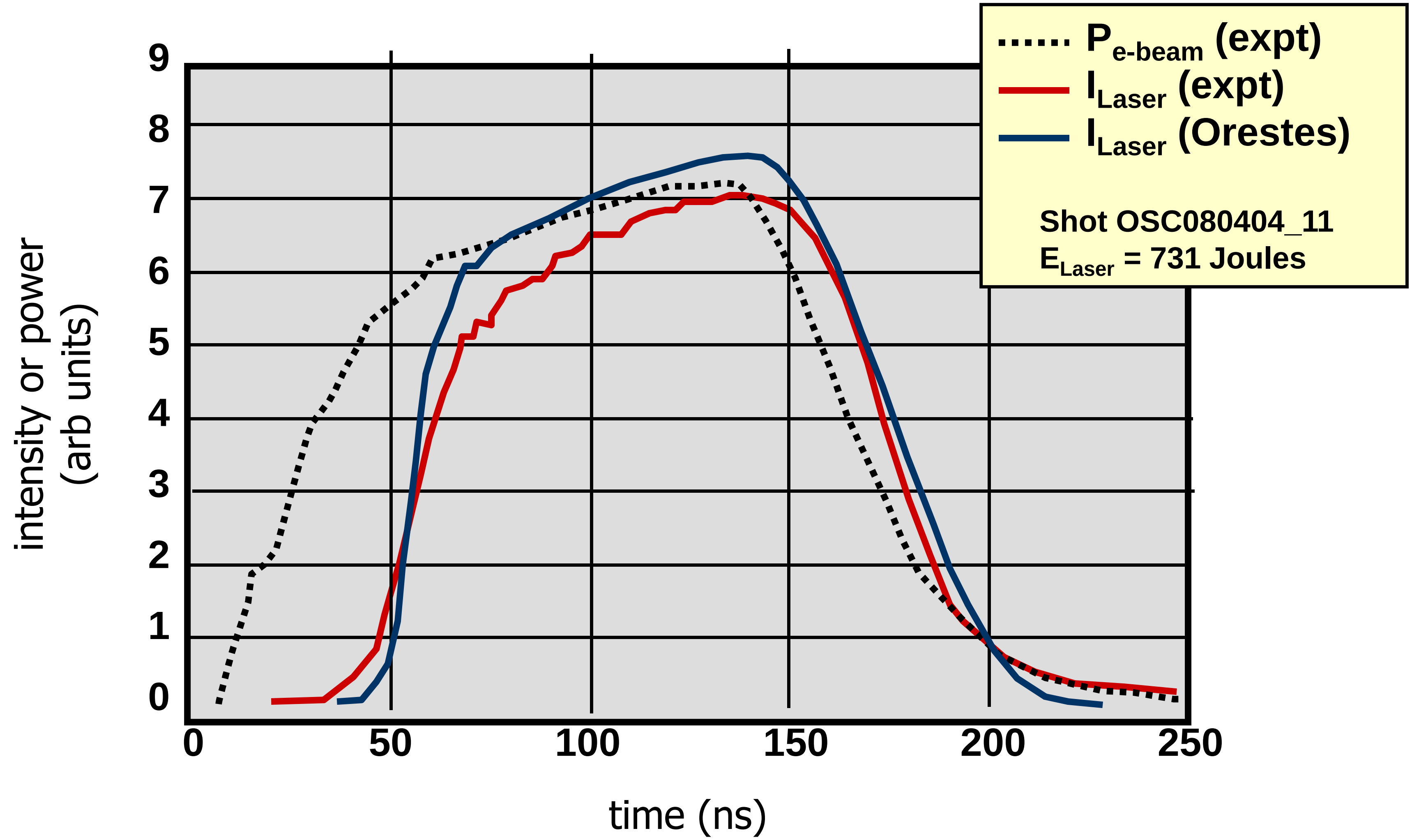
1-D & 2-D Electron Deposition ***Plasma Chemistry***
3-D Laser Transport ***3-D Amplified Spontaneous Emission***

24 species, 146 reactions, 53 vibrational states



absorption, $\sigma = \sigma_{F2}\eta_{F2} + \sigma_{F-}\eta_{F-} + \sigma_{KrF2}\,\eta_{KrF2} + \sigma_{ArF2}\,\eta_{ArF2}$

Plasma chemistry simulations accurately predict Electra main amplifier laser pulse

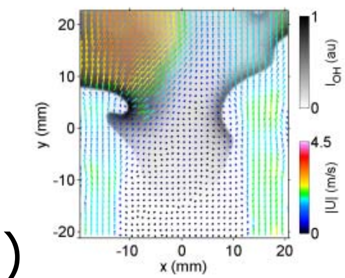


NRL Internal Collaborations

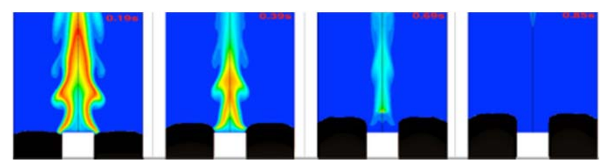
Plasma Physics Division

Chemistry Division, Combustion Dynamics & Modeling Section:

- Test facilities
  - Bench-scale combustion experiments
  - Practical-scale fire/combustion test facility at Chesapeake Bay Detachment
- Extensive combustion diagnostic capabilities
  - Absorption, fluorescence, Raman spectroscopy for temp., species
  - Velocimetry, high-speed visible/IR imaging
  - Multi-phase interaction, particulates (gas-liquid-solid)



- High-Performance Computing capability (Fluent, Internal code) for reactive, electromagnetically-influenced flow

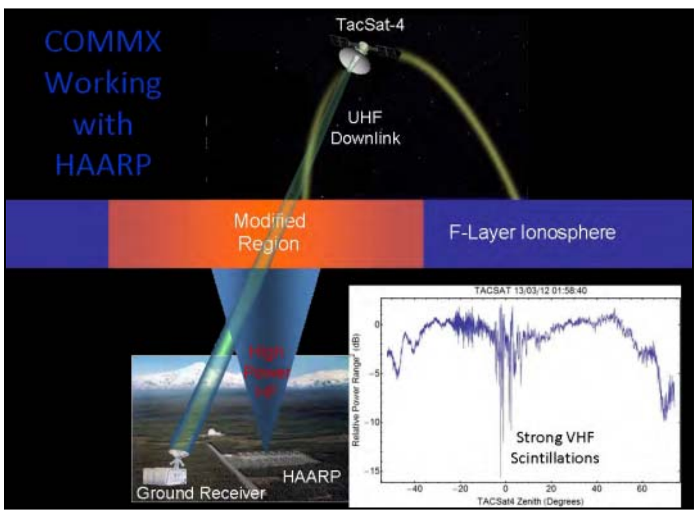


Charged Particle Physics Branch (Code 6750) Research & Relevance

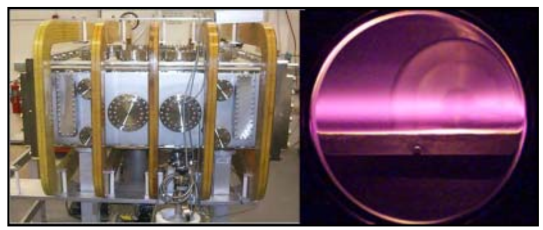
Plasma Physics Division

Research Description

- Electromagnetic launchers for defense applications
- Investigation of space plasma phenomena
- Low-temperature plasmas for materials processing



Region of artificial ionization impacting satellite radio signals


Low-temperature plasmas


Space Chamber


Railgun Materials Testing Facility

Charged Particle Physics Branch (Code 6750) Research & Relevance

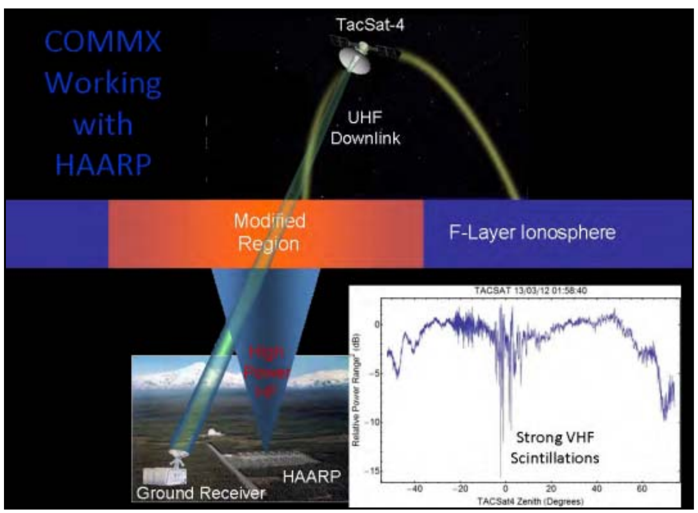
Plasma Physics Division

Research Description

- Electromagnetic launchers for defense applications
- Investigation of space plasma phenomena
- Low-temperature plasmas for materials processing

Relevant Projects/Capabilities

- Materials testing in harsh electromechanical environment
- Macro-scale application of strong, long-lived magnetic fields
- Spectroscopy of burning exhaust



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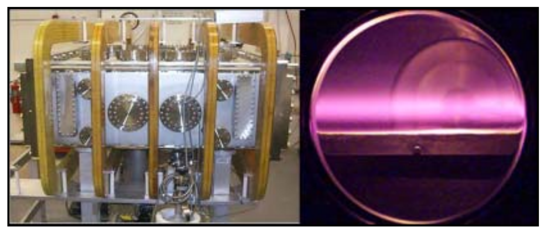

Low-temperature plasmas

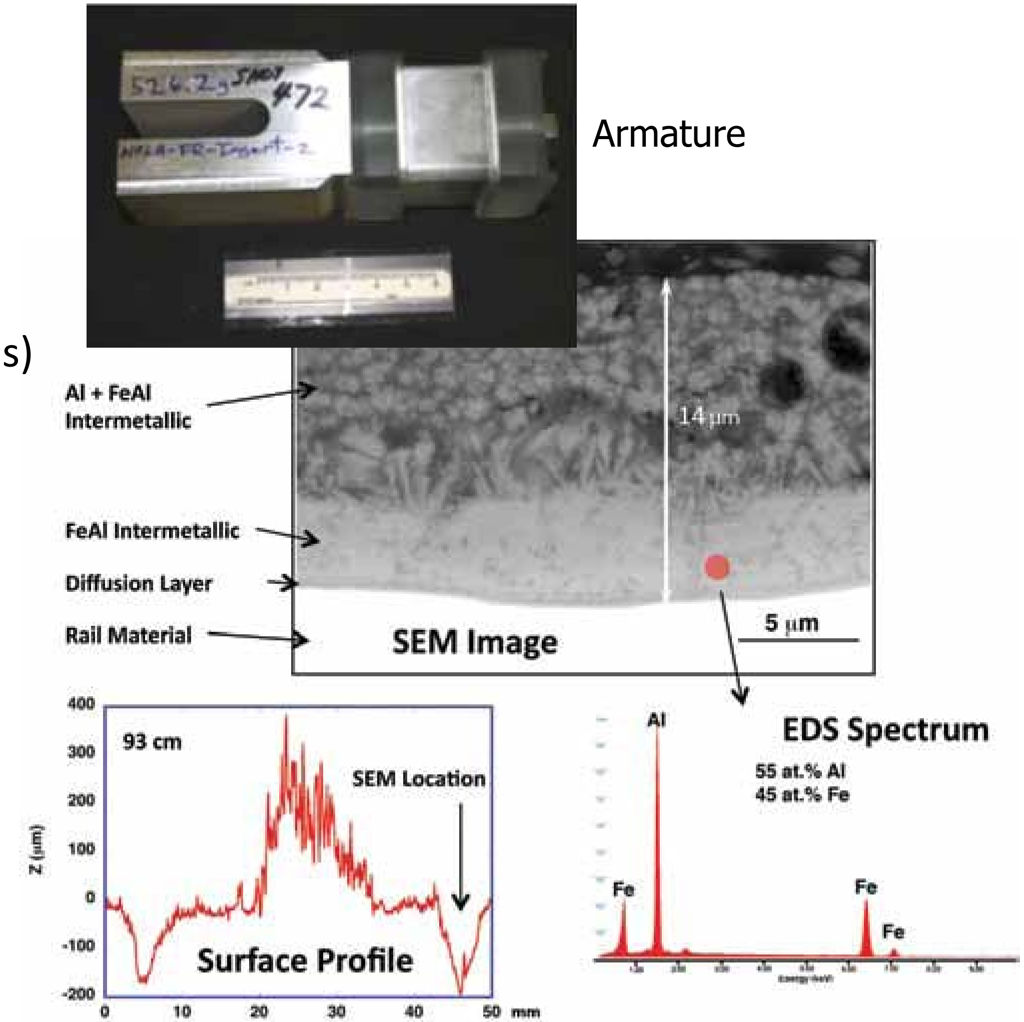

Space Chamber


Railgun Materials Testing Facility

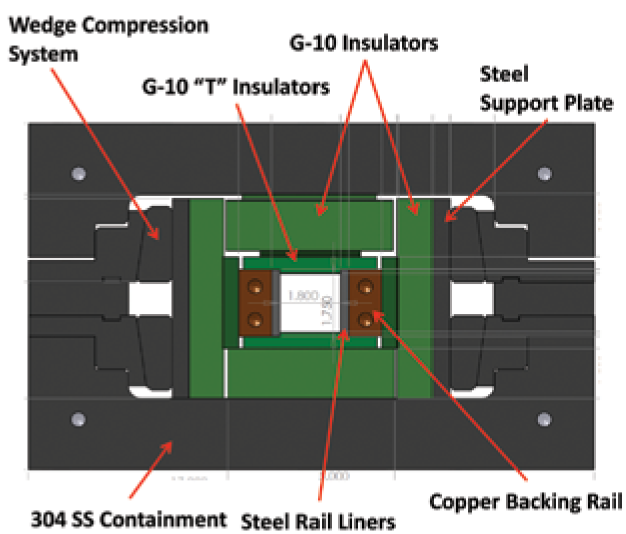
NRL electromagnetic launcher tests materials in extreme environment

Plasma Physics Division

- Materials Testing Facility for rail and armature materials
  - 6 m long
  - 5 cm wide bore
  - 12 MJ stored energy
  - 15 T fields typical
  - 1.5 MA peak current
  - Adjustable pulse width (~1 to 5 ms)



Analysis of deposits from hot liquid deposited at rail-armature interface indicate temperature of over 1300° C



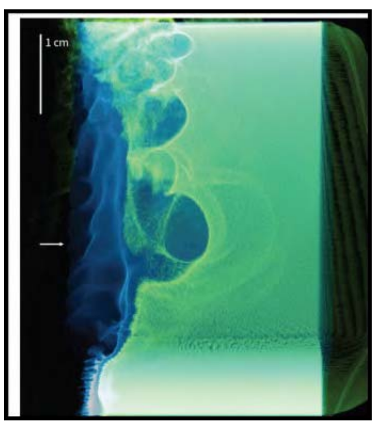
Cross-section of rails and containment structure

Pulsed Power Physics Branch (Code 6770) Research & Relevance

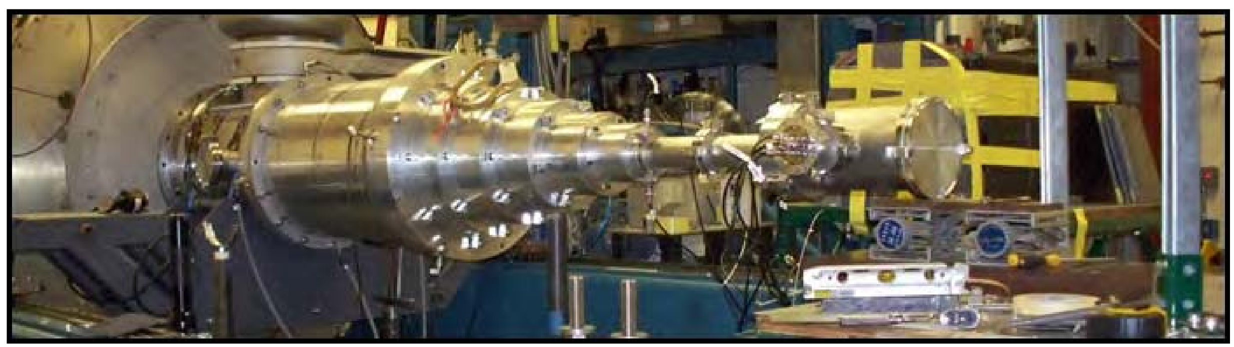
Plasma Physics Division

Research Description

- Development of high-energy pulsed power systems employing capacitive and inductive energy storage
- Production and utilization of plasmas and intense high-power, charged particle beams



Particle-in-cell simulation of a plasma opening switch



Investigation of power flow in radiographic diodes using 8 MV, 200 kA, 50-ns “Mercury” pulsed power generator

Pulsed Power Physics Branch (Code 6770) Research & Relevance

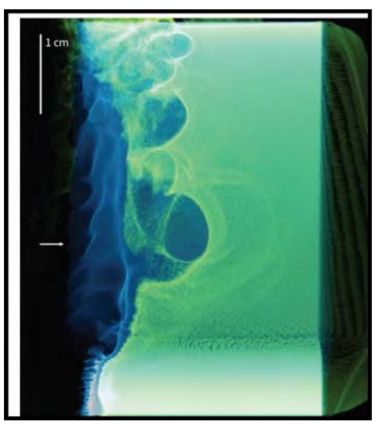
Plasma Physics Division

Research Description

- Development of high-energy pulsed power systems employing capacitive and inductive energy storage
- Production and utilization of plasmas and intense high-power, charged particle beams

Relevant Projects/Capabilities

- MHD, Hall-MHD, and Particle-in-Cell (PIC) modeling closely coupled to experimental facilities
- Modeling of low-ionization-fraction gases
- Plasma source development
- Plasma diagnostics (interferometry, spectroscopy, etc.)



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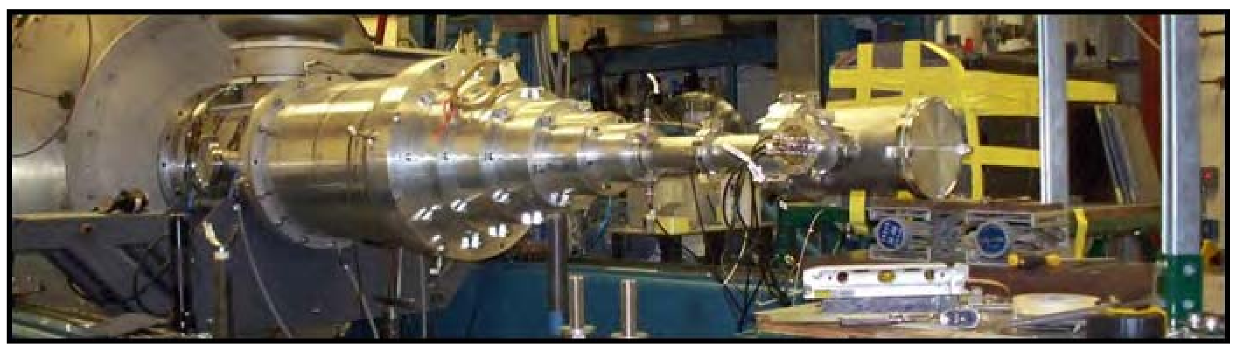
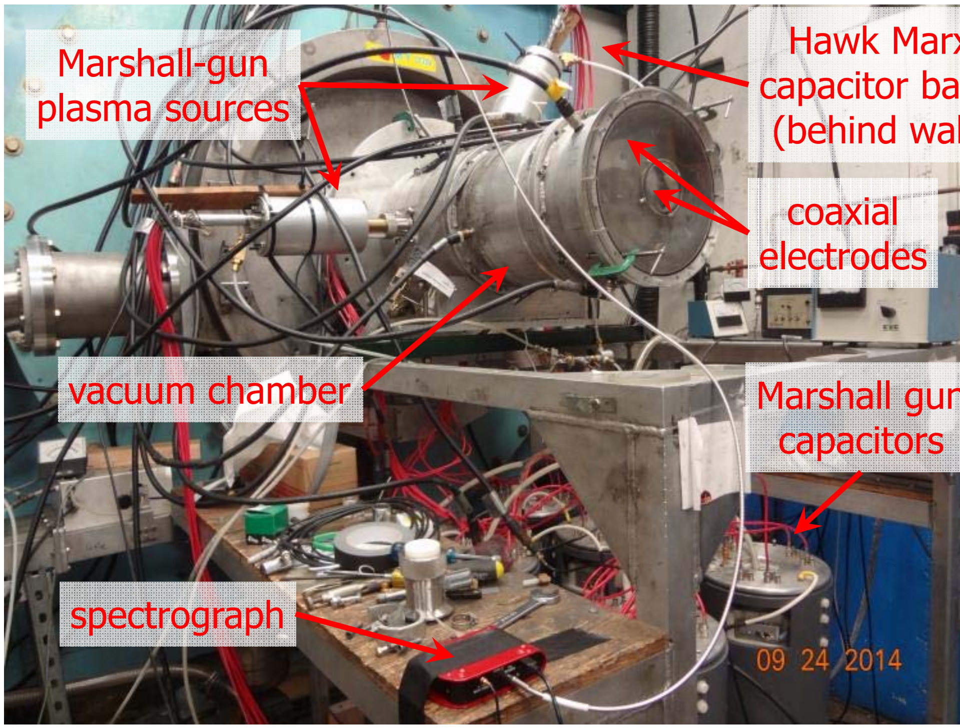


Investigation of power flow in radiographic diodes using 8 MV, 200 kA, 50-ns "Mercury" pulsed power generator

Hawk pulsed-power generator makes plasmas of interest for MHD generators



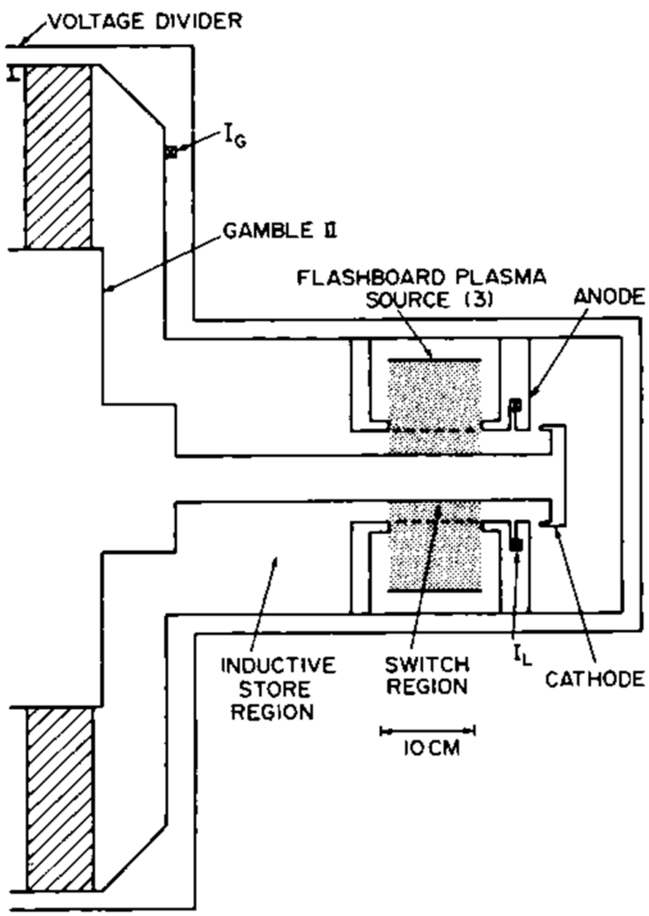
Hawk pulsed-power generator

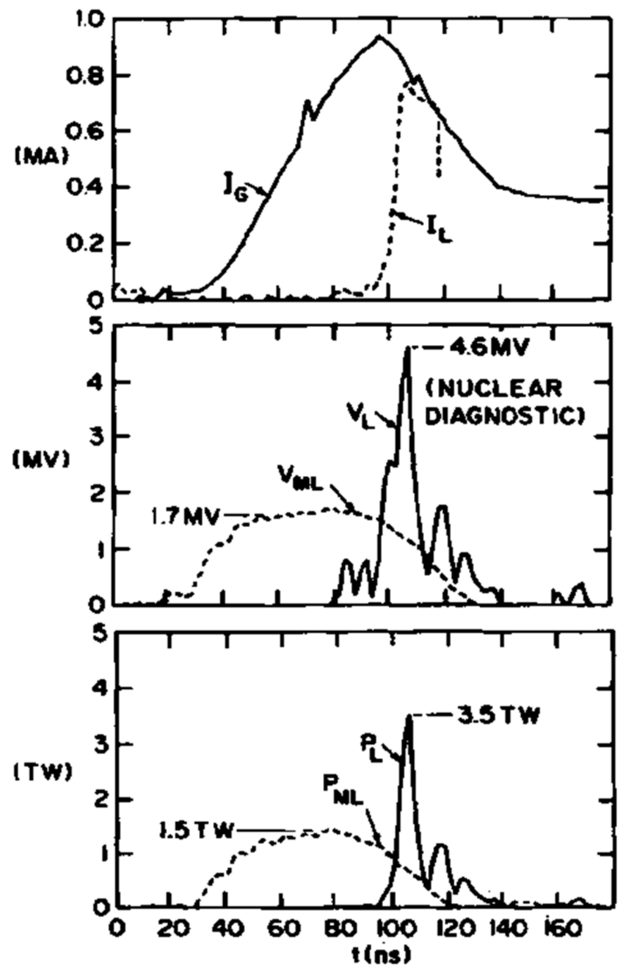
Bank energy	220 kJ
Rise time	1.2 μs
Voltage	640 kV (peak)
Current	700 kA (peak)

- Hawk pulsed power generator coupled to coaxial electrodes for plasma opening switch research
- Current research focused on basic physics of plasma-field interaction in multi-species plasmas
- Plasmas of controllable composition accelerated axially by **J**×**B** forces
- Advanced diagnostics include interferometry (ribbon-beam, holographic, high-sensitivity, and two-color), laser wavefront analyzer, spectroscopy, high-voltage (>1 MV) vacuum voltmeter, magnetic probes, activation foils, fast-gated cameras
- Also used for research in gas-puff z-pinches and electron & ion beams
- Computational modeling effort closely-coupled to experiment

Plasma Physics Division

Voltage multiplication at > TW power level demonstrated on Gamble II in 1987[1,2]





0.9 MA/70 ns conduction, 10 ns opening

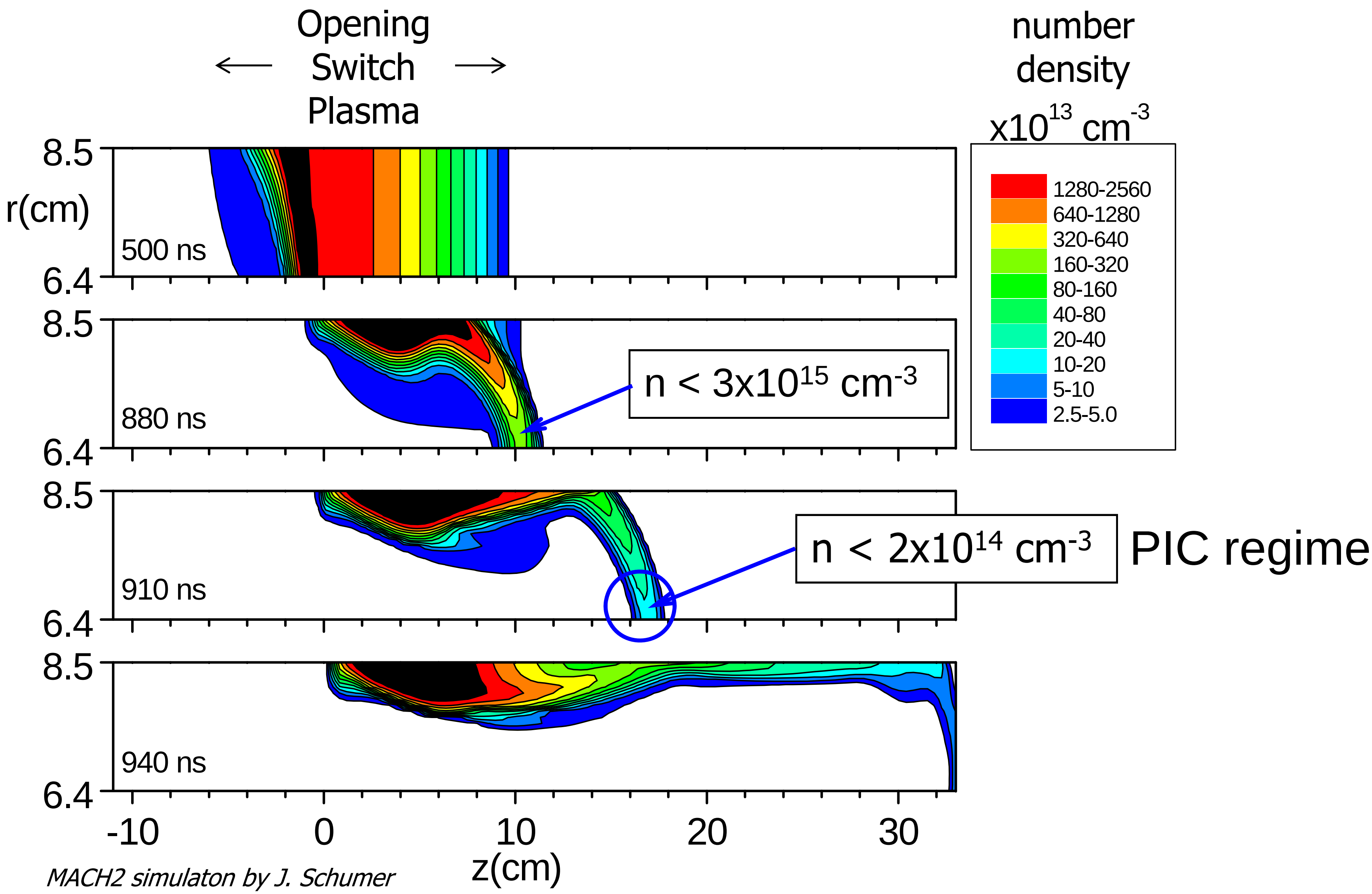
2.7 x Voltage multiplication

2.3 x Power multiplication

[1]*Neri, et al., Appl. Phys. Lett. 50 (1987)*

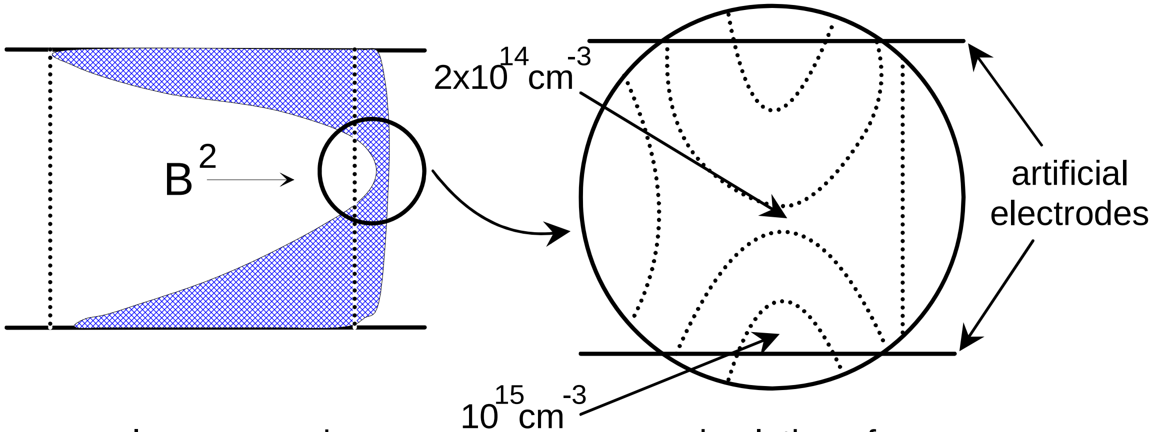
[2]*Weber, et al., IEEE Trans. Plasma Sci. PS_15,(1987)*

MACH2 MHD simulation of plasma opening switch shows distortion & displacement



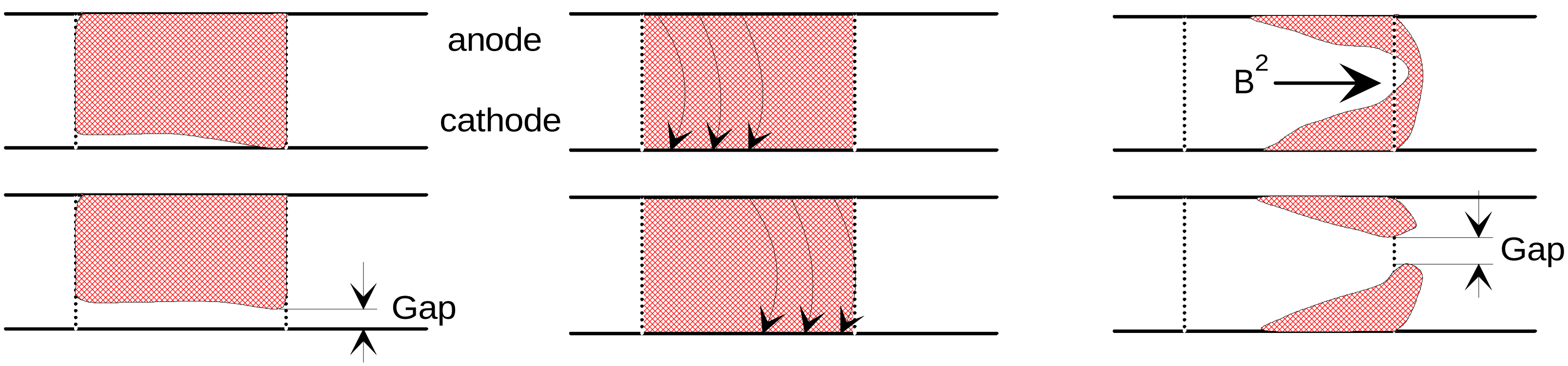
MACH2 simulaton by J. Schumer

PIC code used to simulate the low-density switch plasma to examine non-MHD effects



plasma at end of conduction phase

simulation of low density region[1]



Magnetic insulation at electrode[2]

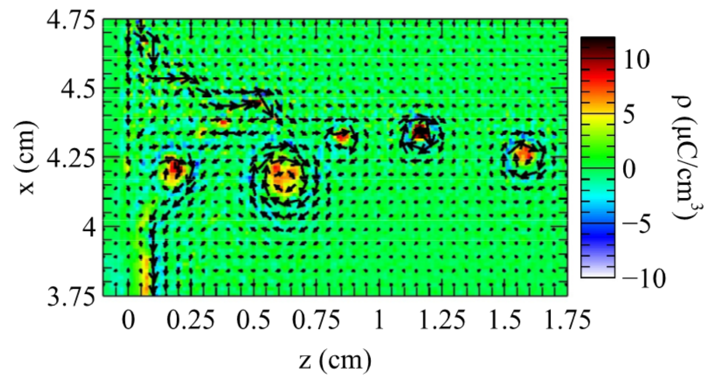
B penetration by Hall effect[3]

Plasma distortion by JxB forces[4]

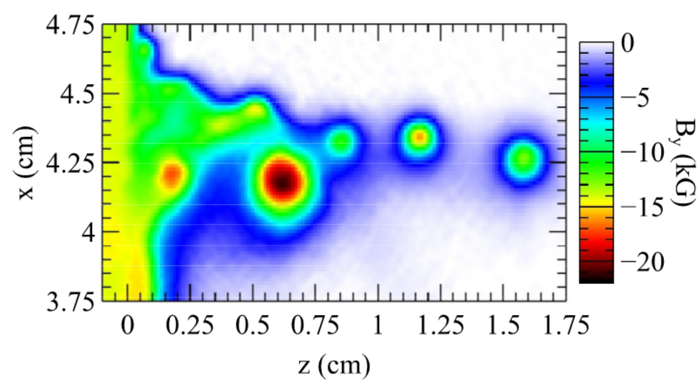
[1]*Grossmann, et al., Phys. Plasmas 1994.*
[2]*Goyer, IEEE Trans. Plasma Sci. 1991.*
[3]*Chukbar, et al., Sov. Phys. Tech. Phys. 1988.*
[4]*Rix, et al., IEEE Trans. Plasma Sci. 1991.*

Vortex formation and species separation modeled in opening switch plasma[1]

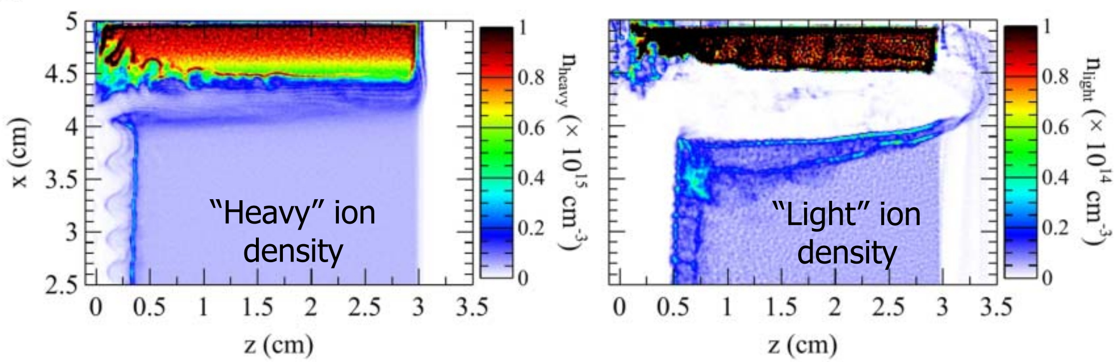
- Detailed analytical modeling within electron-magnetohydrodynamic (EMHD) approximation (ions fixed in an electron fluid)
- Vortices with strong **v** × **B** electric fields developed and led to charge separation
- Semi-analytic vortex structure derived from model and used as initial condition for PIC modeling
- Vortex propagation speed found to be proportional to Hall speed
- PIC modeling showed that vortices were dissipated by moving ions and led to species separation



Charge and current densities (t = 2.5 ns)



Magnetic field (t = 2.5 ns)



Separation of plasma species observed in modeled densities (t = 5 ns)

[1]*Richardson, et al., Phys. Plasmas, v. 20, p. 082115 (2013).*

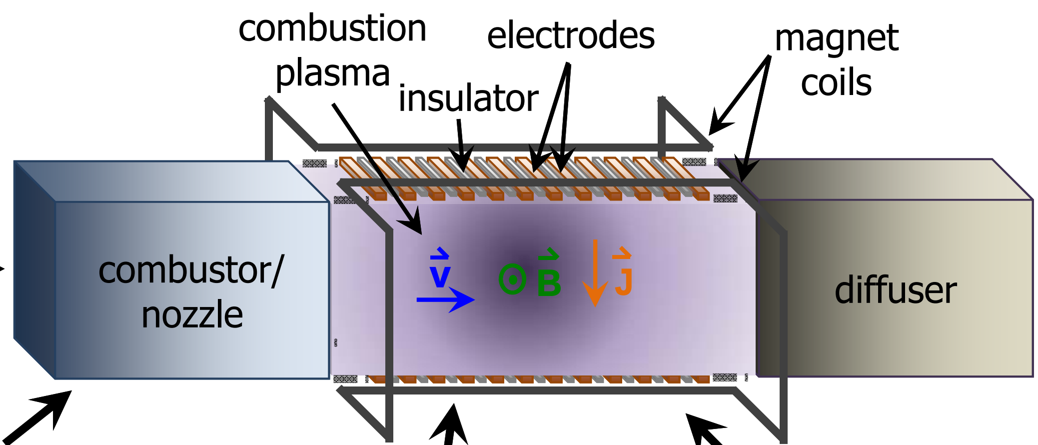
Opening switch plasma parameters differ from MHD generator combustion plasma

Characteristic	MHD Generator[1,2]	Opening Switch
Temperature	0.25 eV (3000 K)	100 eV
Density	10^{19} cm^{-3} (0.75 MPa)	10^{16} cm^{-3}
Fractional ionization	<< 1	>> 1
Conductivity	5 S/m	6×10^{7} S/m
Magnetic field	6 T	2 T
Pulse rise time	Steady-state	1.2 µs
Current density	2×10^{4} A/m^2	3×10^{7} A/m^2
Hall parameter	4	<< 1

[1]*Kayukawa , Prog. In Energy Combustion Sci., v. 30, p. 33 (2004).*
[2]*Mikheev et al., IEEE Trans. Energy Conv., v. 21, p. 242 (2006).*

Summary of plasma physics challenges and relevant, demonstrated capabilities at NRL

Plasma Physics Division



Seeding combustion products to increase conductivity

Pollutant reduction

Detailed physics understanding of plasma inhomogeneities that lead to loss mechanisms

Materials science in extreme current, temperature, and magnetic field environment

Materials Testing Facility
Electromagnetic launcher facility tests materials in extreme current, temperature, and magnetic field environment

Electron beams

- NO_x reduction with electron-beam-driven reactions
- Rep-rate pulsed power

Rad hydro modeling
KrF laser modeling demonstrates plasma chemistry simulation capability that could be applied to combustion plasma

Plasma source development & diagnostics
Modeling and experiments with multi-species plasmas show evidence of vortices, magnetic pushing, and field penetration that could be relevant to inhomogeneities in MHD generators

Combustion dynamics & modeling (Chemistry Division)

- Testing facilities for bench- and practical-scale fire/combustion experiments
- Modeling and diagnostic capabilities