High-energy-density (HED) plasmas

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University of Michigan

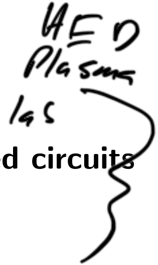
June 17th, 2024

Biography

- BSE 2014, Electrical Engineering University of Michigan
- MS 2016, Physics Northern Illinois University
- PhD 2021, Applied Physics University of Michigan
- Postdoc, NSF ASCEND fellowship University of Michigan

I was 100% sure of what I wanted to do, for about 8 months at a time

- **Start of college: Power electronics for residential buildings**
- **End of Sophomore/Junior year: Digital circuit design/integrated circuits**
- **Senior year: Condensed matter physics**
- **MS: High-energy particle detector research**
- **PhD: HED plasma experiments**



What are we going to talk about today?

- What is HED physics?
- How do create HED conditions?
- What problems do scientists in HED physics work on?
- How do experimenters diagnose HED plasmas?

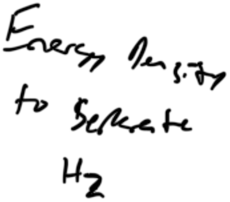
This lecture is a biased introduction to HED plasmas

- I spend most of my time on nanosecond laser-driven HED experiments
- This will skew the talk towards those subjects
- There is a large amount of work in short pulse (< 10 ps) laser plasmas
- Also pulsed power physics (current-driven HED physics)
- There are also computational efforts involved in all of the work that I am not doing justice here

Some of the jargon of HED physics

Term	Description/example
Micron (μm)	A human hair is 100 μm
Nanosecond (ns)	Light travels about one foot per nanosecond
Electron volt (eV)	1 eV $\approx$ 11000 K ($\approx$20000 ^{o}F)
Ionizing radiation	X-rays are ionizing radiation
Energy-density	Pressure has the units of energy density
Shot	A single firing of an experimental facility
Target	The experimental package used at HEDP facilities

HED physics concerns matter at pressures greater than 1 million atmospheres



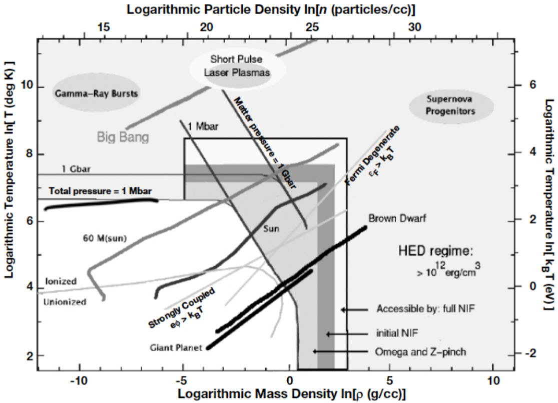


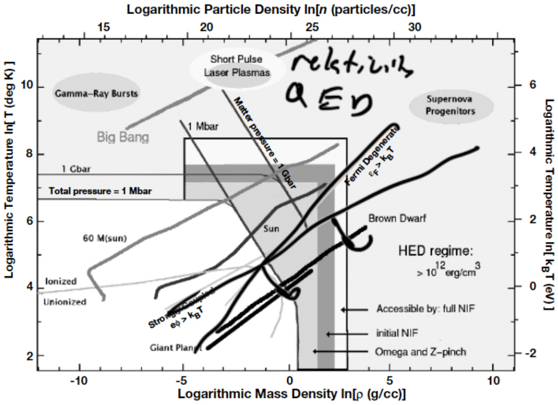
Fig. 1.1. Regimes of high-energy-density physics. Adapted from the NRC Report: *High Energy Density Physics: The X-Games of Contemporary Science*

Image credit: R P. Drake High-Energy-Density Physics: Fundamentals, Inertial Fusion, and Experimental Astrophysics

So, what does that mean in more practical terms?

- Number of particles in the Debye sphere
  - $\Lambda = \sqrt{\frac{\epsilon_0 k_B T}{nq^2}}$, $N = n\frac{4}{3}\pi\Lambda^3$ < 10 non ideal plasma
- Coupling parameter
  - $\Gamma = \frac{nq_j q_k}{\epsilon_0 k_B T} = \frac{1}{\Lambda_{j,k}^2}$ $\quad \frac{\text{coulomb collision}}{\text{thermal}} \gtrsim 1$
- Degeneracy parameter
  - $\theta = \frac{k_B T}{E_F}$; $E_F = \frac{h^2}{2m_e}\left(\frac{3}{8\pi}n_e\right)^{2/3}$ < 1 e^- degeneracy
- Other dimensionless parameters that may matter relate to relativity and quantum electrodynamics

How does this affect the way we think about/model plasmas



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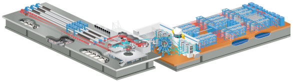
How do we model these plasmas?

- **Euler equations (fluid description)**
- **Radiation transport equation (Radiation hydrodynamics)**
- **Maxwell's equations (Magnetohydrodynamics/Particle-in-cell)**
- **Boltzmann equation (Kinetic description)**
- **And more! Density functional theory, molecular dynamics, etc.**

How do we generate these conditions in a laboratory?

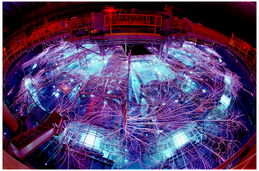
Laboratory for Laser Energetics

~10 kJ ~1 ns

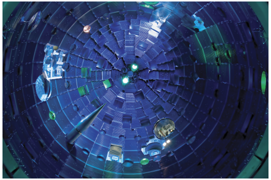


Z-Facility

25 MA ~100 ns



National Ignition Facility 2 MJ ~1 ns



ZEUS 3 PW fs~10 fs

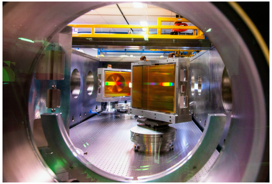


Image credits: Laboratory for Laser Energetics; Sandia National Laboratories; Lawrence Livermore National Laboratory; ZEUS facility

High-energy or high-intensity lasers interact with matter to produce plasma

- Laser ablation produces a plasma at the surface of a solid
- This produces a pressure wave that propagates into the solid
- Collisions between electrons and ions absorb energy from the laser
- Different physical processes drive high-intensity laser-matter interactions
- For high-energy lasers: 10s kJ-MJ in one nanosecond; for high-intensity lasers 1-100 J in 0.025-10 ps

A laser can be thought of as oscillating electric and magnetic fields

$E = E_0 \cos(\omega_L t)$

$B = E/c \to 0$

$I \propto |E|^2$

High Energy

$10^{13} - 10^{16}$ W/cm^2

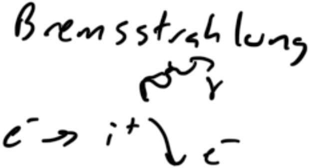
High intensity

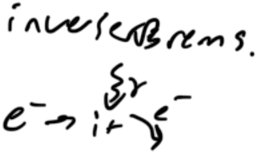
$10^{18} - 10^{22}$ W/cm^2 relativistic

Electromagnetic waves of low enough frequency can not propagate in a plasma

- **Dispersion relation:** $\omega^2 = c^2k^2 + \omega_{pe}^2$
- $\omega_{pe} = \sqrt{\frac{nq^2}{\epsilon_0 m_e}}$
- $ck = \sqrt{\omega^2 - \omega_{pe}^2}$ if k is imaginary
- **This leads to a critical density where the laser can no longer propagate,** $n_c = \frac{m_e \epsilon_0 \omega_L^2}{q^2}$

Laser deposit energy into plasmas through interactions with electrons





A high-energy laser hitting a solid surface is a pretty complicated process

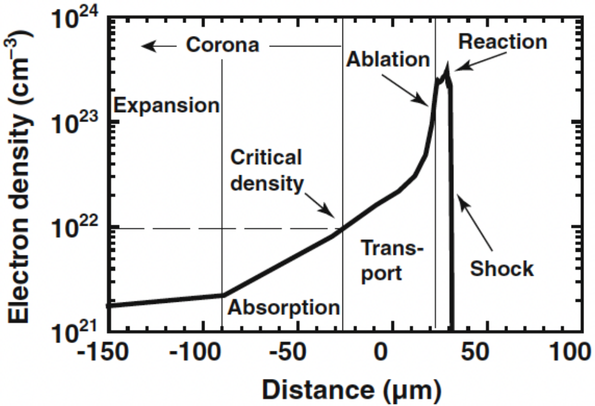


Image credit: R P. Drake High-Energy-Density Physics: Fundamentals, Inertial Fusion, and Experimental Astrophysics

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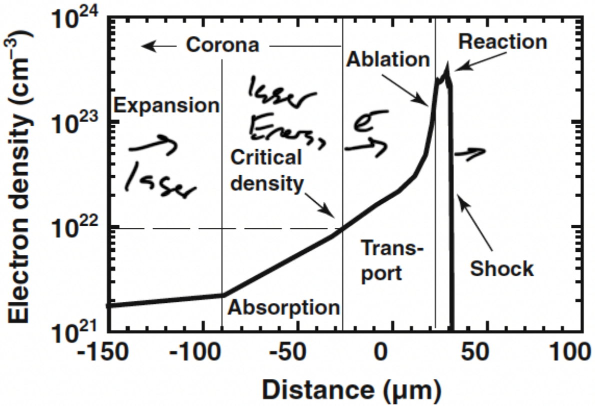
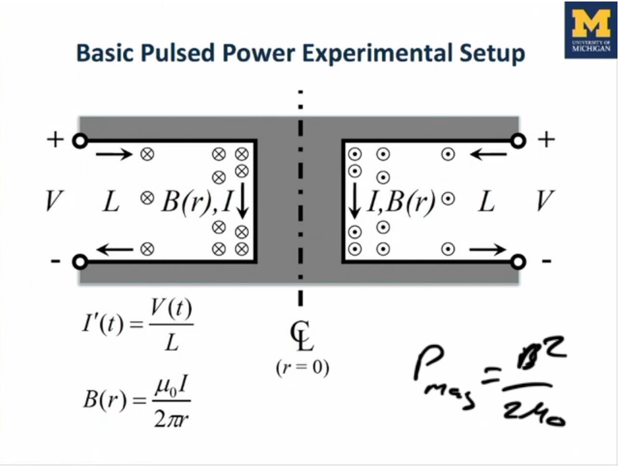


Image credit: R P. Drake High-Energy-Density Physics: Fundamentals, Inertial Fusion, and Experimental Astrophysics

Large (>10s kA), pulsed (≈ 100 ns) currents heat wires to create plasma

- Joule heating, $P_{avg} = V_{rms} I_{rms}$, drives wire or gas targets to the plasma state
- The Lorentz force either implodes or explodes the plasma
- University-scale machines will use about 1 MA currents; The Z-Facility uses about 25 MA

The Lorentz force manipulates the plasma leading to implosions, outflows, and jets



Slide credit: Prof. Ryan McBride MIPSE seminar winter 2017

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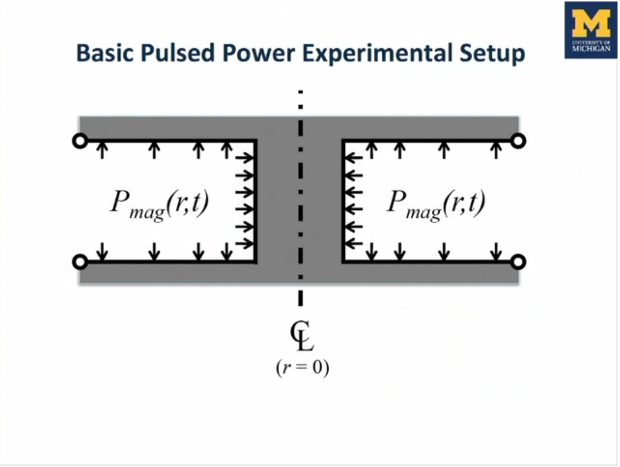

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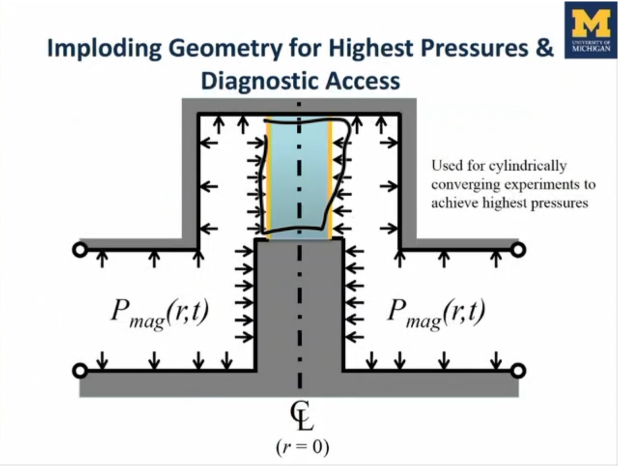
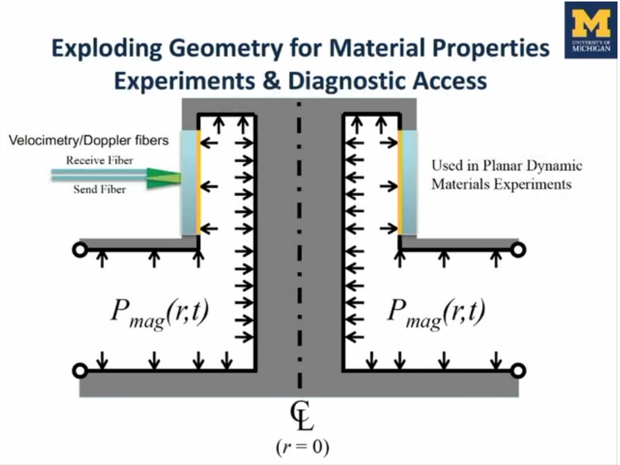


Slide credit: Prof. Ryan McBride MIPSE seminar winter 2017

Reversing the direction of the current produces radially outwards flows



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There are other methods for creating HED plasma conditions

- Ion beams
- Isochoric heating with proton beams
- X-ray heating

There are other methods for creating HED plasma conditions

- **Ion beams**
- Isochoric heating with proton beams
- X-ray heating

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 2 FEBRUARY 2002

Development of a Bi^{+} high current source for heavy ion driven plasma generators

M. Galonska,[a] K. Volk, and U. Ratzinger
Institut für Angewandte Physik, Universität Frankfurt, Robert-Mayer Strasse 2-4, 60054Frankfurt/Main, Germany

(Presented on 6 September 2001)

The development of a high current bismuth ion source is motivated by heavy ion driven fusion (HIF) and is part of the co Download sign of a HIF-relevant Bi^{+} test injector with four beamlets, which could serve as a HIF driver front end element. Envisaged is the development of a 300 mA Bi^{+}

There are other methods for creating HED plasma conditions

- Ion beams
- **Isochoric heating with proton beams**
- X-ray heating

SCIENTIFIC REPORTS
natureresearch

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OPEN

Focussing Protons from a Kilojoule Laser for Intense Beam Heating using Proximal Target Structures

C. McGuffey[1]✉, J. Kim[1], M. S. Wei[2], P. M. Nilson[3], S. N. Chen[4,6], J. Fuchs[4], P. Fitzsimmons[2], M. E. Foord[5], D. Mariscal[1,5], H. S. McLean[5], P. K. Patel[5], R. B. Stephens[2] & F. N. Beg[1]

There are other methods for creating HED plasma conditions

- Ion beams
- Isochoric heating with proton beams
- **X-ray heating**

VOLUME 84, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JANUARY 2000

Detailed Measurements of a Diffusive Supersonic Wave in a Radiatively Heated Foam

C. A. Back, J. D. Bauer, O. L. Landen, R. E. Turner, B. F. Lasinski, J. H. Hammer, M. D. Rosen, L. J. Suter, and W. H. Hsing

Lawrence Livermore National Laboratory, L-21, P.O. Box 808, Livermore, California 94551

(Received 11 August 1999)

Who studies HED plasmas and why?

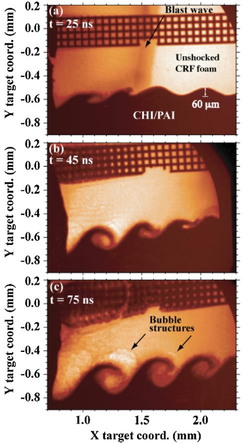
- National Nuclear Security Administration
  - Science-based stockpile stewardship ensures a safe, secure, and effective nuclear stockpile
- Other funding agencies like the Department of Energy and the National Science Foundation also support HED plasma physics
- Understanding HED plasmas is very relevant to inertial confinement fusion research
- Astronomers and astrophysicists use results from HED research to better understand observations
- It is fun to play around with some of the most extreme material in the universe in an earth-based laboratory!

Diagnosing HED plasma experiments is challenging due to the large densities

- The large densities and temperatures and the small spatial scales mean that probes can't survive the plasma environment
- It is necessary to use optical, x-ray, neutrons, or charged particles signals
- This can be self-emission or as an external probe

X-ray radiographs show what the plasma is doing

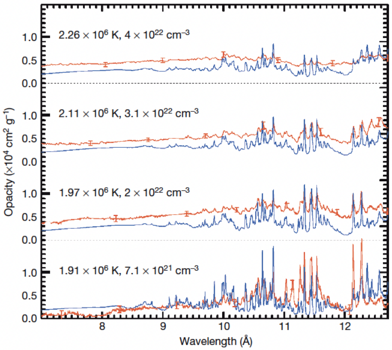
- Gives you a relatively intuitive picture of what is happening in the plasma
- It is useful for observing hydrodynamic motion or any contrast in absorption
- This is very relevant to how astronomers observe the universe



E. C. Harding PRL 103, 045005 (2009)

Emission and absorption spectroscopy provide an immense amount of information about your plasma

- Emission spectroscopy measures the excited states in the plasma
- Absorption spectroscopy measures the lower lying electrons in the plasma
- These techniques provides information on the plasma temperature, density, ionization, velocity, and gradients
- This is also very relevant to how astronomers make observations



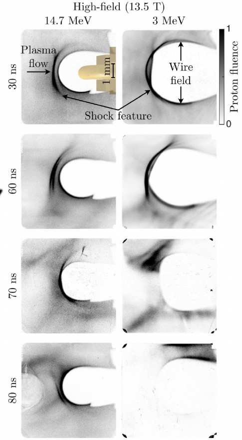
J. E. Bailey Nature Vol 517 1 January 2015

Proton radiography probes the magnetic field structure of the plasma

Short pulse — Target normal sheath acc. — broadband

14.7 MeV
3 MeV

- Uses a proton beam to pass through the plasma that then gets recorded on film
- A short pulse laser or capsule implosion produce the proton beam
- The Lorentz force deflects the protons, which provides information about the magnetic field



J. M. Levesque Phys. Plasmas 29, 012106 (2022)

Charged particle spectrometers observe the emitted spectrum of particles accelerated in an experiment

- Measures the number of particles as a function of energy
- Useful for finding temperature of accelerated particles
- Provides information on the charge of the particles based on the direction of deflection

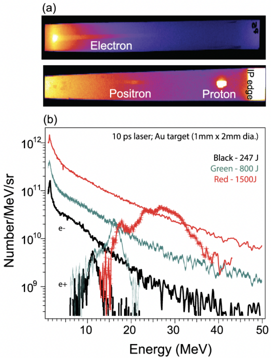


FIG. 2. (a) The raw images from EPPS for positive particles (protons and positrons) and electrons for laser energy at 800 J. (b) Three pairs of electron and positron energy spectra for laser energy of 247 J, 800 J, and 1500 J from the EPPS measurements.

H. Chen Physics of Plasmas 22, 056705 (2015)

Great! But what can we do with plasma in these states?

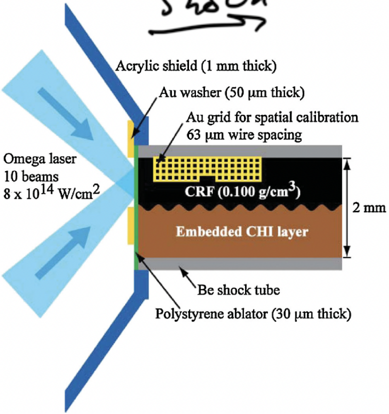
- Radiation hydrodynamics
- Hydrodynamic instabilities
- Magnetized plasmas
- HEDP material science
- Laser-plasma interactions
- Laboratory astrophysics
- Inertial confinement fusion plasmas
- QED

Laboratory astrophysics produces an analogue of an object in space in the laboratory

- This can be a scaled system so that the equations describing both are identical
    - One needs to make sure the microphysics is also in the same regime
    - Example: Hydrodynamics experiments scaled to supernova remnants
- Experiments can also be at the same temperature and density conditions as the astrophysics object of interest
    - Example: Iron opacity experiments at the conditions of the solar radiative-convection zone boundary

Kelvin-Helmholtz instability experiments study the effects of vorticity on the evolution of an interface

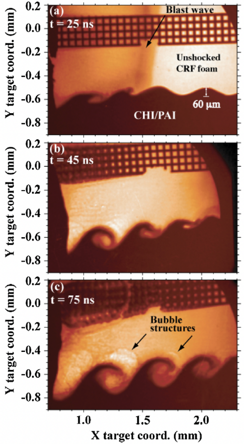
Shock →



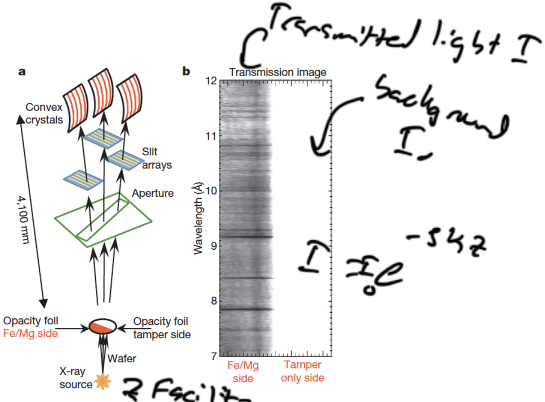
E. C. Harding PRL 103, 045005 (2009)

$$\omega = \nabla \times \vec{u}$$

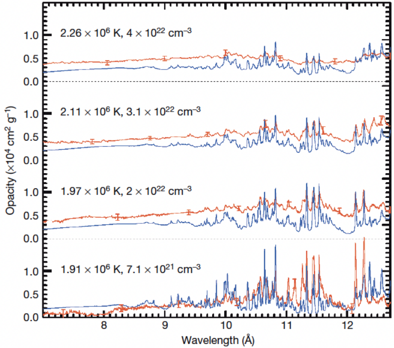
$$\omega_b \propto \nabla \rho \times \nabla P$$



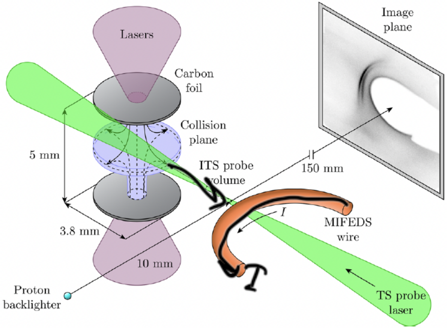
Iron opacity experiments study material properties at the solar radiative-convection zone boundary



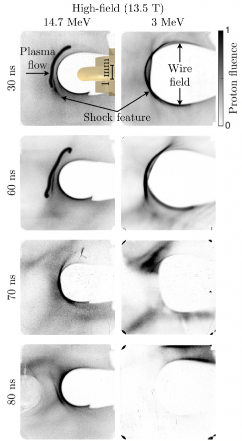
J. E. Bailey Nature Vol 517 1 January 2015



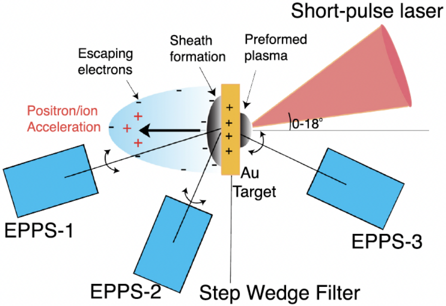
Magnetized bow shock experiments study the behavior of the earth's magnetosphere



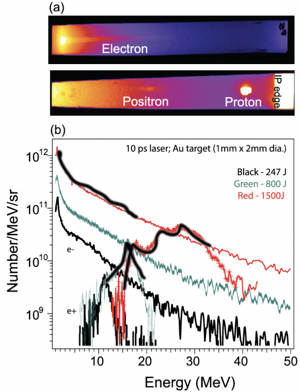
J. M. Levesque Phys. Plasmas 29, 012106 (2022)



Pair production experiments aim to study relativistic jets relevant to gamma ray bursts



H. Chen Physics of Plasmas 22, 056705 (2015)



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Summary

- HED plasmas have pressure larger than 1 million atmospheres
- This covers a wide range of temperature/density parameter space
- This leads to nonideal plasma behavior
- HED experiments study many topics using a variety of drivers

Think about the University of Michigan for graduate school! There is a lot of plasma physics research here

- There is a good overview of the plasma research at UM at https://mipse.umich.edu/research.php
- Topics include (Covering theory, experiment, and computation):
  - HED plasmas
  - low temperature plasmas
  - Plasma thrusters
  - Space and astrophysical plasmas
  - Accelerators and beams
  - Plasma transport