CENTER FOR MATTER UNDER EXTREME CONDITIONS
Center for Matter Under Extreme Conditions (CMEC)

Farhat Beg
Department of Mechanical and Aerospace Engineering
University of California San Diego

2019 Stewardship Science Academic Programs (SSAP) Symposium
February 19–20, 2019, Albuquerque, New Mexico
OVERVIEW

• CMEC research emphasis is on the creation and diagnosis of extreme states of matter.

• This includes both un-magnetized and magnetized HEDP.

• We are exploiting novel combinations of HED drivers to train future scientists.

• Training includes both modeling and experiments to develop a physics understanding of HED systems.
UC SAN DIEGO HAS AN EXCELLENT TRACK RECORD OF PROVIDING TRAINED WORKFORCE TO THE NATIONAL LABORATORIES

The following students have been hired at the NNSA Laboratories as post docs and staff scientists since 2008:

- Eric Herbold (LLNL)
- Sophia Chen (LLNL)
- Tammy Ma (LLNL)
- Drew Higginson (LLNL)
- Steven Ross (LLNL)
- Brad Pollock (LLNL)
- Charlie Jarrott (LLNL)
- Derek Marsical (LLNL)
- Justin Angus (LLNL)
- Tane Remington (LLNL)
- Jonathan Peebles (LLE)
TRAINING OF NEXT GENERATION OF SCIENTISTS IS AN IMPORTANT COMPONENT OF THE CENTER

• Post Doctoral Fellows
  - Adam Higginson
  - Mathieu Bailly Grandvaux
  - Michael McDonald
  - Josh May

• Graduate Students
  - Joe Strehlow
  - Nick Aybar
  - Gilbert Collins
  - Apsara Williams
  - David Housely
  - Adam Reyes
  - Kaitlyn Amado
  - Jeff Narkis
  - Rachel Flanagan
  - Gaia Righi
  - Boya Li
This two-week workshop will promote scholastic development through technical lectures given by field experts as well as professional development sessions aimed at early-career researchers in High Energy Density Science fields of study.

The Summer School is jointly organized by the NNSA Center for Excellence Center for Matter Under Extreme Conditions (CMEC) and the Center for Frontiers in High Energy Density Science (HEDS).

Housing, food and travel costs will be covered for up to 50 undergraduate, graduate students and postdocs. The program is also open to research scientists for a nominal registration fee.

TOPICS OF INTEREST INCLUDE:
- Radiation and atomic physics in plasmas
- Laser-driven hydrodynamics and shocks
- Matters of National Security in HEDS
- Panel discussion on career options in HEDS
- Applications of ultraintense CPA lasers
- Analytical modeling of plasmas
- Project-based workshops including PIC kinetic codes, fluid hydro codes, and plasma spectroscopy
- Oral and poster presentations

For More Information & to Register Visit: cme.ucsd.edu/hedssummerschool
THREE THRUST AREAS

• Energy Transport in High Energy Density Systems

• Material Properties across the HED Regime

• Nature under Extreme Conditions

https://apod.nasa.gov/apod/ap170919.html
ENERGY TRANSPORT IN HEDS

• Challenge
  ○ Deeper characterization of particle and photon energy transport processes in HED plasmas created by various drivers and the effects of magnetization.

• Goal
  ○ CMEC plans to test the new and partially developed experimental platforms in the presence of magnetic fields to measure thermal conductivity, laser energy absorption, and opacity, including laser plasma interaction instabilities.
Laser plasma instabilities (LPIs) play a crucial role in laser fusion schemes.

Stimulated Raman scattering (SRS) is particularly detrimental.

External magnetic field can affect the level of SRS.

Two experimental campaigns aim to measure:
- level of SRS generated, with and without an external magnetic field.

Experiments have been performed as a precursor to a follow-up campaign, where we will investigate the effects on generated SRS of an external magnetic field.

- Intensity = \((1 - 3) \times 10^{16}\) Wcm\(^{-2}\), energy = 50 – 170 J, pulse duration = 200 ps, wavelength = 1.053 \(\mu\)m, spot size = 10 \(\mu\)m (f/10 OAP).

- These experiments were performed using gas jet targets.
SHIFT IN WAVELENGTH AS A FUNCTION OF PLASMA DENSITY WAS OBSERVED

- No forward SRS detected, only in the backward direction

\[ I_L = 10^{16} \text{ Wcm}^{-2} \]
N.B. 1000 psi = 0.6% \( n_c \)

\[ k_0 = k_1 + k_2 \]
\[ \omega_0 = \omega_1 + \omega_2 \]
\[ \lambda_{\text{mid}} = \frac{2\pi}{k_1} \]
WE WILL REPEAT THE EXPERIMENT WITH AN EXTERNAL MAGNETIC FIELD

- Electron spectrum will be characterized and plasma density (via interferometry) will be measured.
- Two new diagnostic techniques will be fielded:
  - Proton deflectometry and x-ray spectroscopy.

Irradiance range will be $I\lambda^2 \sim (0.3 \text{ - } 2.5) \times 10^{14} \text{ Wcm}^{-2}\text{μm}^2$. 
- Understanding the roles of density and temperature in relativistic electron transport behavior and energy loss is important to the basic physics of relativistic beam-plasma interaction.
- Relativistic electron transport through Warm Dense Matter (WDM) and Hot Dense Plasmas (HDP) is particularly relevant to magnetically-assisted inertial confinement fusion (ICF) schemes and astrophysical plasmas.
FLASH CODE PREDICTS TEMPERATURE AND DENSITY OF 340 EV and 9 G/CM³

- Cylinder is imploded and compressed by 36 UV beams: 450 J each, 1.5 ns square pulse.
- The target has maximum compression at 1.7 ns and then expands.
• Lines get broader and the continuum intensity keeps increasing until 1.55 ns when the shock reaches the center of the foam. This corresponds to the highest temperature.

• Duration of the stagnation emission predicted with FLASH is similar to the experimental spectra, 200 ps and 150 ps respectively.

• Continuum slope gives a **temperature estimation about 400 eV** which is consistent with FLASH simulations.
ELECTRONS FOCUSING DUE TO SELF GENERATED MAGNETIC FIELD

FLASH Simulation for compression

Hybrid PIC for electron transport

\[ \frac{\partial B}{\partial t} = -\nabla \times \left( \frac{\eta}{\mu_0} \nabla \times B \right) + ( \nabla \eta ) \times \vec{j}_f + \eta ( \nabla \times \vec{j}_f ) \]
ELECTRONS REFLECTION DUE TO MIRROR EFFECT

FLASH Simulation for compression

Hybrid PIC for electron transport
ESCAPED ELECTRON DATA IS CONSISTENT WITH MODELING

- Simulation reproduced the same angular dependence and energy dip near 2 MeV.
MICRO STRUCTURE TARGETS SHOW ENHANCEMENT OF LASER TO ION CONVERSION EFFICIENCY BY A FACTOR OF 5

- Plastic tubes on Co substrate (1 μm) on PHELIX laser. Thompson parabola results at target normal
  - 15° incidence
  - λ = 1.053 um (1ω)
  - 5 μm focal spot
  - 150 J on target
  - 500 fs pulse length
  - ~1×10^21 W/cm²

- Increase in proton number by a factor up to 5× when the inner tube diameter is ~ laser diameter.
- Increase in carbon number by ~2×.
- Increase is likely due to better absorption of the laser.
INCREASE IN PROTONS CUT OFF ENERGY WHEN THE LASER IS INCIDENT AT TARGET NORMAL

- Plastic tubes and Au pillars on Au substrate (1 µm) at the CSU laser normal incidence
  - λ = 400 nm (2ω)
  - 2.6 µm focal spot
  - 10 J on target
  - 55 fs pulse length
  - ~3×10²¹ W/cm²
- At similar irradiance with a table-top laser at normal incidence, we obtained similar increase in conversion efficiency.
- The proton cut-off energies were higher by ~2x for micro-structures, with respect to flat targets.
ENHANCED ACCELERATION FROM SOLID TARGETS EMBEDDED IN STRONG MAGNETIC FIELD

- The enhancement of the electron spectrum and the lateral localization of the hot electrons combine to make the sheath field that accelerates ions stronger.
- After the laser ends (>900 fs), the electrons transfer the energy that they have accumulated interacting with the laser to the ions through the expanding sheath electric field.
- The relative enhancement of the cutoff energy for carbon and protons respectively increases by 27% and 37%, due to the applied B-field.

*“Laser-driven strong magnetostatic fields with applications to charged beam transport and magnetized high energy-density physics”, Physics of Plasmas 25, 056705 (2018)*
GAS PUFF Z-PINCH EXPERIMENTS ON LINEAR TRANSFORMER DRIVER III

- LTDIII (~800 kA, 200 ns) current generator is being tested for gas puff experiments.

- Single and double gas puffs of a variety of gases will be employed to study energy transport.

<table>
<thead>
<tr>
<th>Bz (kG)</th>
<th>t~90 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Image showing different magnetic field strengths and their effects on the Z-pincher.
• Density tailoring and axial premagnetization both mitigate MRTI
• Combination of mitigation mechanisms has received little attention
• Upcoming experiments will scan $B_{z0}$ for various double- and triple gas-puff configurations

---

COMBINATION OF DENSITY TAILORING AND EXTERNAL MAGNETIC FIELD HELP TO STABILIZE MAGNETO RAYLEIGH TAYLOR INSTABILITY

$B_{z0} = 0 \ T \ 1.0 \ kG \ 2.0 \ kG \ 5.0 \ kG \ 7.0 \ kG$

- Increased stability with higher $B_{z0}$
- Increased stability by adding second liner
FLASH CODE IS BEING UPDATED FOR BOTH LASER PLASMA AND Z-PINCH PHYSICS

• The University of Chicago has been improving FLASH code capabilities:
  o Numerical modeling and analysis of laser-driven and pulsed-power driven plasma experiments
  o Expansion and verification of the FLASH code physics capabilities: non-ideal MHD processes such as the Hall effect, the Nernst effect, and implicit magnetic resistivity, to enhance the fidelity of FLASH
  o Implementation of algorithms necessary for MHD modeling of imploding loads for simulating wire array and gas puff Z-pinches
MATERIAL PROPERTIES ACROSS THE HED REGIME

• Challenge
  o Dynamic physical processes in the HED regime quickly drive materials across pressure and temperature space, leading to significant changes in material properties that feed back to the dynamics of the event.
  o To predict the outcome of dynamic processes, materials must be characterized across a wide range of phase space.

• Goal
  o CMEC develops and demonstrates new experimental and computational techniques to measure and explain changes in material properties across the HED regime.
HIGH PRECISION EQUATION OF STATE MEASUREMENTS OF WARM DENSE MATTER TO BENCHMARK THEORETICAL MODELS

- Experimental data show ionization balance models are not predictive\textsuperscript{3,4}

- Accurate Hugoniot and temperature measurements at pressures > 100 Mbar was identified as specific area of need at a recent Equation-of-State Workshop sponsored by the DOE ICF program\textsuperscript{2}

Experimental diagnostics measure a volume-averaged condition. By reducing the distribution of states in the probed volume, we can significantly improve measurement precision.

\[ \text{Measured ionization balance in compressed CH disagrees with models}^{3,4} \]

\[ \text{OPAL calculations} \]

\[ \text{Previous NIF result} \]

\[ \text{Kraus} \ \langle Z_e \rangle = 4.92 \pm 0.15 \]

\[ \text{Fletcher} \ Z_e = 4 \]

Previous measurements probed a large distribution of states, reducing measurement accuracy

\[ \text{Spherical Shell (OMEGA)} \]

\[ \text{Solid sphere (NIF)} \]

\[ \text{This experiment, t = 20 ns} \]

COLLIDING SHOCKS PLATFORM WILL ACCURATELY MEASURE EQUATION OF STATE OF MATERIALS AT Pressures Exceeding 100 MBAR

NIF drives two counter-propagating shocks in a shock tube

Zn He-α probe source (9 keV)

Apertures restrict the probe to the homogenously compressed volume

Shielding to reduce measurement background

2D hydrodynamic simulations (Carlos Di Stefano, LANL)

NIF beams

Shock tube

Au halflraum 4 mm diameter 3 mm in length

XRTS

Streaked x-ray radiography

Probe x-rays

Collimating slits

Scattering volume

The colliding shocks produce a large volume of homogenously compressed material that we will probe using x-ray Thomson scattering (XRTS) and radiography.
SHOCK EXPERIMENTS HAVE BEEN PLANNED AT Z, NIF AND UC DAVIS

• The Stewart group plans shock experiments to find melt curves and vapor curves at Z machine, NIF, and UC Davis gas gun lab.
  ○ They are predicting vaporization and melting during planetary collisions for planet formation and origin of the Moon.
• Challenge
  o Material properties data must be integrated into useful multi-phase equations of state (EOS) models to enable robust simulations of laboratory experiments and natural processes.
  o Modeling dynamic natural processes requires both integration of material properties and the material response to external forces (e.g., acceleration of energetic particles).

• Goal
  o Develop and use integrated material models to solve high profile planetary and astrophysical problems.
EXPERIMENTS HAVE BEEN PERFORMED TO STUDY SHOCK FORMATION FROM COLLIDING PLASMA FLOWS

- Studying these flows and shocks can improve our understanding of important astrophysical processes.
TRANSITION OF COLLISIONAL TO COLLISIONLESS PLASMA AS A FUNCTION OF ATOMIC NUMBER

**Collisional:**
\[ \lambda_{mfp-ii} \approx 1 \text{mm} \]

**Strongly Cooled:**
\[ \tau_c < \tau_{\text{hydro}} \]

**Weakly Cooled:**
\[ \tau_c > \tau_{\text{hydro}} \]

**Weakly Collisional:**
\[ \lambda_{mfp-ii} \geq 10 \text{mm} \]

**Collisionless:**
\[ \lambda_{mfp-ii} \geq 100 \text{mm} \]

- At early stage the decreasing collisionality with increasing atomic mass is clear, as C and Cu form shocks and W jets clearly interpenetrate.
- At later, smooth C shock in contrast with the different instabilities developed in the Cu and W shocks.
ALUMINUM SHOCKS FORM, EXPAND AND DEVELOP PERTURBATIONS

Schlieren time sequence of Al shocks. Times are approximate duration since shock formation.

- Parametrically, Al flows/interactions bridge parameter space between C and Cu.
  - Al flows were weakly collisional: $\lambda_{\text{mfp-II}} \sim 1 - 100$ mm (similar to Cu).
  - Al flows were moderately cooled: $\tau_c < \tau_{\text{hydro}}$ (between C and Cu).
- Analysis shows potential turbulence and thermal condensation instabilities in Al shocks.
SUPERIONIC FORM OF ICE IS STABLE

• R. Jeanloz experiments document stability of H₂O ice to high $P-T$


• Measured temperature for shocked water ice VII and computed curve from DFT-MD simulations.
• Three sketches illustrate the transitions from the insulating solid ice to the oxygen solid lattice and diffusing hydrogens of superionic ice, and then the conducting fluid.
SUMMARY

- Laser-driven acceleration of titanium ions from ultrathin targets and the calibration of the ion beam diagnostic (Joe Strehlow)
- Linear Transformer Driver for HEDP experiments at UCSD (Fabio Conti)
- Effects of External Axial Magnetic Field on Stability of a Multi-Shell Gas-Puff Z-Pinch (Nick Aybar)
- Measurements of stimulated Raman scattering and a proposed mitigation strategy using external magnetic fields on the Titan laser system (Adam Higginson)
- Relativistic electron beam transport through cold and shock-heated vitreous and diamond carbon samples (Mathieu Bailly Grandvaux)
- Studying various energy dissipation mechanisms in colliding supersonic plasma flows’ (Gilbert Collins)
- Relativistic electron transport within an imploded cylindrical plasma characterized by X-ray spectroscopy (Maylis Dozierès)
ACKNOWLEDGEMENTS

• This material is based upon work supported by the Department of Energy, National Nuclear Security Administration under Award Number DE-NA0003842.
The first step was to reproduce a spectrum obtained in early times using the Kalpha of Cl, Ar and Fe (see figure 1) in order to estimate the ratio between all the element. Assuming that this ratio is fairly the same everywhere in the target, we used the same to simulate spectra at 1.6 ns which is during the stagnation (see figure 2). The red spectra is the best fit and has been calculate using the contributions from C emission, Cl emission and the opacity of the target. Also, we took into account the absorption of the CH solid foil at the end of the cylinder assuming that the foil was at 300 eV. The doted line in Fig. 2 is the black body spectra corresponding to the continuum emission slope of the experimental spectrum which gives us an estimation of the temperature inside the foam of 400 eV (FLASH is predicting ~ 500 eV).