Center of Excellence for Advanced Nuclear Diagnostics and Platforms for ICF and HED Physics at OMEGA, NIF and Z

Omega Laser Facility  National Ignition Facility  Z Machine

The Center Partners

Massachusetts Institute of Technology
University of Iowa
University of Rochester
University of Nevada, Reno

R. D. Petrasso for the CoE  SSAP Symposium, 26 February 2020
• Recruit & train CoE students and postdocs in ICF/HED physics
• Utilize the MIT HEDP Accelerator Lab for student training and diagnostic development
• Develop and utilize the charged-particle platform for stopping power and radiography
• Explore the dynamics and hydro-to-kinetic transitions in ICF implosions
• Recruit & train CoE students and postdocs in ICF/HED physics
  • Utilize the MIT HED Accelerator Lab for student training and diagnostic development
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  • Explore the hydro-to-kinetic transitions in ICF implosions
A young scientist from each Center partner institution will present a poster.

PI: Bhuvana Srinivasan
Student: Megan McCracken
Multi-ion simulations
Poster HEDP-42

PI: Scott Baalrud
Student: David Bernstein
Stopping power
Poster HEDP-32

PI: Riccardo Betti
Young scientist: Jonathan Peebles
Magnetized implosions
Poster HEDP-33

PI: Roberto Mancini
Student: Dylan Cliché
Electron temperature Measurements
Poster HEDP-34
5 of the 9 MIT PhD students and postdocs will present posters

**Student:** Jacob Pearcy
Electromagnetic Fields In laser-driven hohlraums
Poster NLUF-7

**Student:** Neel Kabadi
MagSpec and PXTD diagnostics and kinetic effects in plasmas
Poster HEDP-31

**Student:** Graeme Sutcliffe
Tri-particle radiography
Poster NLUF-6

**Student:** Tim Johnson
Collisionless shocks on OMEGA
Poster NLUF-3

**Postdoc:** Arijit Bose
Magnetized implosions
Poster NLUF-5
• Recruit & train CoE students and postdocs in ICF/HED physics

• **Utilize the MIT HEDP Accelerator Lab for student training and diagnostic development**

• Develop and utilize the charged-particle platform for stopping power and radiography

• Explore the hydro-to-kinetic transitions in ICF implosions
The MIT HEDP accelerator Laboratory is where students get hands-on experience building diagnostics they then port to OMEGA, NIF and Z.
Over the last three decades, MIT has collaborated with LLE, LLNL, LANL, & SNL to design & implement 15 diagnostics/platforms on OMEGA, 7 on NIF, and 2 on Z.

During this period 13 PhD degrees were completed, for which two were awarded the Rosenbluth Outstanding Thesis Awards in Plasma Physics.
The latest diagnostic to be built is the MagSpec Spectrometer, used 2 weeks ago for the NIF Discovery Science $^3$He-$^3$He Solar campaign.

MagSpec is a charged-particle spectrometer (1-16 MeV)

Proton-proton I (pp-I) chain

$^3$He + $^3$He $\rightarrow$ $^4$He + 2p

NIF shot of 12 February 2020

Exploding pusher capsule

900 μm

20 μm

D$^3$He-p

$^3$He$^3$He-p

Neel Kabadi
Poster HEDP-31
MIT is collaborating with SNL on the design and implementation of a DD-neutron spectrometer for MagLIF implosions at the Z-facility.

MIT student Brandon Lahmann
• Recruit & train CoE students and postdocs in ICF/HED physics
• Utilize the MIT HEDP Accelerator Lab for student training and diagnostic development

• **Develop and utilize the charged-particle backlighter platform** for ignition-relevant stopping-power studies and radiography

• Explore hydro-to-kinetic transitions in ICF implosions
On OMEGA and the NIF, a new monoenergetic-particle backlighter platform is being developed for stopping power and radiography.

**Exploding pusher capsule**

- **SiO₂ shell**
- **DT³He**
- 2 µm
- 210 µm

- **D +³He → α + p (14.7 MeV)**
- **D + D → t + p (3.0 MeV)**
- **T +³He → α + d (9.5 MeV)**

Laser beams drive the “exploding pusher” experimental target.

CR-39 imaging detector

**Plasma and/or fields**

- 3-MeV p
- 9.5-MeV d
- 14.7-MeV p

Spectrometer

**OMEGA shot 90941**

Yield (per MeV)

Energy (MeV)
To explore ignition-relevant alpha stopping, MIT and collaborators performed experiments at OMEGA and NIF to explore stopping in weakly ($\Gamma << 1$) and strongly ($\Gamma \sim 1$) coupled plasmas.

$$\Gamma \approx \frac{e^2 n^{1/3}}{kT}$$

Center partner University of Iowa is calculating stopping power for plasmas with $\Gamma \sim 1$ and for $\rho_{\text{gyro}} \leq \lambda_{\text{Debye}}$.

Frenje et al PRL (2019)
Zylstra et al PRL (2015)
When $\rho_{gyro} \leq \lambda_{Debye}$:

- the Coulomb logarithm, used in stopping and in numerous plasma expressions, is affected
- a new stopping mechanism has been discovered

\[
\frac{d\mathbf{v}}{dt} = \frac{q_t \mathbf{v} \times \mathbf{B}}{m_t} - m_t \nu \mathbf{v} - m_t \nu_x \mathbf{v} \times \hat{n}
\]

Lorentz "Standard"Stopping $F_v$ Transverse force $F_x$

Pl: Scott Baalrud
To study stopping power around the Bragg peak, where it has a strong electron temperature dependence ($T_e^{-3/2}$), Center partner U. Nevada is implementing a spectrometer to determine $T_e(r,t)^*$

Radiography with 3 monoenergetic charged particles breaks the degeneracy between E and B fields and optimizes field reconstruction.

14.7 MeV D³He-p
9.5 MeV T³He-d
3.0 MeV DD-p

These time-resolved radiographs reveal the Bierman Battery saturation mechanism in laser-driven plasmas.

OMEGA shot #92969

CH foil, 25 µm thick
DT³He backlighter
9 drive beams
CR39 detector
Time-of-flight delay
1 cm 25 cm

t = 3.8 ns t = 3.9 ns t = 4.0 ns
Using 3.0- and 14.7-MeV proton radiographs, maps of $\vec{E}$ and $\vec{B}$ fields inside a hohlraum are reconstructed.
The optimal reconstruction of the hohlraum fields involves similar contributions of $\vec{E}$ and $\vec{B}$ fields.

These are the first maps of $E$ and $B$ fields inside a hohlraum.
Particle radiography and electron spectroscopy are being used to study collisionless shocks on OMEGA

Orion Nebula

Bow shock

3.0-MeV-proton radiograph
At Omega and the NIF, the CoE provides radiography support for 25 shot days per year for other institutions.

Petros Tzeferacos (U Chicago) *et al.*, Nature Comm. 2018

## Recent and upcoming Center support of Charged-Particle Radiography for other Institutions

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• **Explore the dynamics and hydro-to-kinetic transitions in ICF implosions**
ICF implosions lie at the intersection of hydrodynamic & kinetic regimes

D^3He shell

~ 0.5 to ~ 20 ns

exploding pusher
shock burn
compression burn
compressive implosion

Shell trajectory
ICF implosions lie at the intersection of hydrodynamic & kinetic regimes

ICF Simulations......LASNEX, HYDRA, FLASH, DUED, LILAC, HYADES ,......use the average-ion hydro approximation: So D$_3^3$He has an average-ion charge of 1.5 e, and an average-ion mass of 2.5 m$_p$
The Knudsen number $K_n$ quantifies transitions between hydro and kinetic regimes

$$K_n = \frac{\lambda_{ii}}{R}$$
To study dual-fuel implosions (e.g. D$_3$He), the Particle X-ray Temporal Diagnostic (PXTD) was built to measure multiple nuclear-reaction and x-ray emission histories.

Hong Sio
Now postdoc at LLNL

OMEGA Shot 82615

$K_n \sim 0.3$, hydro-like

2.6 um SiO$_2$
OD = 860 µm

2.2 mg/cc

49% : 50% : 1%
D : $^3$He : T

$D + ^3$He $\longrightarrow p(14.7$ MeV) + $^\alpha$

$D + T \longrightarrow n(14.1$ MeV) + $^\alpha$

D$_3$He burn is 50 ps earlier than the DT burn

Burn histories

Hong Sio et al. showed that average-ion rad-hydro simulation codes – DUED, HYADES, and LILAC – don’t accurately predict these burn histories.

In contrast, the kinetic ion code LSP better matches the D$_3$He and DT burn histories ...

LSP simulation – kinetic ions (A. Le & T. Kwan, LANL)

OMEGA Shot 82615

Burn histories

... Although the simulated DT burn width is too large and the yield is too small.

LSP simulation – kinetic ions (A. Le & T. Kwan, LANL)

Burn histories

OMEGA Shot 82615

To explore whether experiment/simulation inconsistencies in the shock burn phase can be further reduced, a multi-ion hydro code is being developed by the Virginia Tech team.

- Treat Individual ion species in the hydro approximation
- Use transport coefficients ..... for heat conductivity, ion viscosity, ..... that account for the different ion species
  - .........................
  - ..........................
- In the limit of single ion species, the Braginskii results are recovered.

PI: Bhuvana Srinivasan
To further investigate implosion dynamics at shock and compression burn, the multiple-nuclear-burn diagnostic PXTD will be used on 15 April NLUF on compressive implosions.

\[ K_n = \frac{\lambda_{ii}}{R} \]
Yesterday the PXTD diagnostic was used to simultaneously measure nuclear and xray emission histories on an Omega cryogenic implosion.

From the multiple x-ray emission histories, a time-resolved electron temperature will be obtained.

12 keV X-rays + DTn
13 keV X-rays + DTn
14 keV X-rays + DTn

DTn
For exploding pushers the effects of strong magnetic fields are to reduce the Knudsen number, and make the plasma more hydo-like.

When \( \rho_{\text{gyro}} < \lambda_{ii} \), then \( K_n \) becomes

\[
K_n \sim \frac{\rho_{\text{gyro}}}{R}
\]

These experiments are the first, for laser-driven implosions, in which the fuel ions are strongly magnetized.
For compressive implosions with strong B fields, Center partner LLE has shown that a ~15% increase in ion temperature occurs.

An external B-field significantly reduces the electron thermal conductivity, plausibly explaining the observed ion temperature increase from 2.0 to 2.3 keV.
Democritus conjectured the relationship between continuum and atomic elements.

- Continuum: Water, Air, Earth, Fire
- Atoms: 420 BC
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  - Multi-ion Simulations
  - Poster HEDP-42

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  - Magnetized implosions
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- **Dylan Cliché**
  - Electron temperature measurement
  - Poster HEDP-34

- **Jacob Peary**
  - E & B fields in laser-driven hohlraums
  - Poster NLUF-7

- **Arijit Bose**
  - Magnetized implosions
  - Poster NLUF-5

- **Tim Johnson**
  - Collisionless shocks & diffusive shock acceleration
  - Poster NLUF-3

- **Neel Kabadi**
  - MagSpec, PXTD and kinetic effects in plasmas
  - Poster HEDP-31

- **Graeme Sutcliffe**
  - Tri-particle radiography
  - Poster NLUF-6