A New Regime of High Energy Density (HED) Physics: Coupling High-Rep-Rate Lasers with Cognitive Simulation

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- **The NIF and ICF team!**
- **And many, many more...**

DOE Early Career Research Program
High Energy Density (HED) experimental physics is starting to move towards high repetition rate

Next-gen, high-rep-rate (HRR) laser facilities are already coming online around the world

- HRR laser science is an opportunity to accelerate the rate of knowledge acquisition in HED

An integrated HED experimental capability means feedback control loops within the laser, experiment, and simulation to simultaneously optimize the entire system in real-time

Many emerging technologies are being leveraged to make this vision a reality

- Suite of HRR diagnostics, automated analysis, and active feedback being developed
- Novel cognitive simulation techniques will push the forefronts of scientific machine learning
- Collaborations with scientists inside and outside the field

Setting the stage for Inertial Fusion Energy
We recently demonstrated more than 1.3 MJ of fusion yield on the NIF – a significant advance in ICF research.

This shot was ~8x higher yield than the previous NIF record, and was the first NIF shot to achieve capsule gain (yield/absorbed energy) ~5+, and propagating burn!
The National Ignition Facility (NIF) is the world’s most energetic laser enabling the study of extreme HED conditions

- 192 Beams, 1.9 MJ Energy, 500 TW Power
- Matter temperature >$10^8$ K
- Radiation temperature >$3.5 \times 10^6$ K
- Densities >$10^2$ g/cm$^3$
- Pressures >$10^{11}$ atm
192 laser beams are concentrated into a mm$^3$ target
NIF uses a laser driven hohlraum to compress a fuel pellet to achieve the conditions for ignition

The hohlraum is a cylindrical cavity that serves as an x-ray “oven”

The fuel capsule consists of an ablator surrounding DT ice and gas

Turn 100 million atmospheres of pressure into 300 billion

Achieving the conditions for ignition demands precise control of laser and target parameters for a high convergence implosion with low ablator fuel mix

The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.

Ignition figure of merit ≈ \((\rho R)^3 T^3 \sim E_{HS} P_{HS}^2\)

\(Y_{amp} \sim 30x\)

Unstable
High LPI
Asymmetric

NIC
(2.5 kJ)

Lawrence Livermore National Laboratory
P14551621.ppt – 1.3MJ Briefing – September 07, 2021
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.

\[ \text{Ignition figure of merit } \sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2 \]

- Unstable high LPI asymmetric
- Improved stability
- High-foot (25 kJ)
- NIC (2.5 kJ)
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.

Ignition figure of merit \( \sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2 \)

- NIC (2.5 kJ)
- unstable high LPI asymmetric
- High-foot (25 kJ)
- reduced LPI reduced fill tube diamond ablator improved symmetry
- HDC/BF (55 kJ)
- HDC/BF (2016-18)
- CH HF (2013-15)
- CH LF (2011-12)

Y$_{amp}$ ~ 30x
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.
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- **High-foot (25 kJ)**: improved stability
- **NIC (2.5 kJ)**: unstable, high LPI, asymmetric
- **HDC/BF (55 kJ)**: reduced LPI, reduced fill tube, diamond ablator, improved symmetry
- **HyE/Iraum (170 kJ)**: increased coupling & compression, understand degradations, better targets

**Ignition figure of merit**

$$\rho R \sim T \sim E_{\text{HS}} P_{\text{HS}}^2$$

**Year**
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021

**Pressure (Gbar)**
- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350

**Energy [α-off] (kJ)**
- 0
- 2
- 4
- 6
- 8
- 10
- 12
- 14

**Y_{amp} \sim 30x**
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.

Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$

- NIC (2.5 kJ)
- CH LF (2011-12)
- CH HF (2013-15)
- CH LF (2011-12)
- HDC/BF (2016-18)
- HyE/Iraum (2016-18)
- HyE/Iraum (2019-21)
- HyE/Iraum (2020-21)

- NIC: unstable, high LPI, asymmetric
- CH LF: improved stability, high LPI, asymmetric
- CH HF: high-foot (25 kJ)
- HDC/BF: improved stability, high-foot (55 kJ)
- HyE/Iraum: reduced LPI, reduced fill tube, improved symmetry (170 kJ)

- Increased coupling & compression to better understand degradations
- Diamond ablator increased coupling & compression

- Unstable to stable LPI transitions
- Improved targets
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.

Ignition figure of merit $\sim (\rho R)^3 T^3 E_{HS} P_{HS}^2$

- NIC (2.5 kJ) unstable, high LPI, asymmetric
- High-foot (25 kJ)
- HDC/BF (55 kJ)
- HyE/Iraum (170 kJ)
- HDC/BF (2016-18)
- HyE/Iraum (2020-21)
- CH HF (2013-15)
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- CH LF (2011-12)
- Y_{amp} \sim 30x
- Increased coupling & compression, understand degradations, better targets
- Reduced LPI, reduced fill tube, diamond ablator, improved symmetry
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.

Ignition figure of merit ~

\[
(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2
\]

- NIC (2.5 kJ)
- unstable high LPI asymmetric
- improved stability
- high foot (25 kJ)
- HDC/BF (55 kJ)
- reduced LPI
- reduced fill tube
- diamond ablator
- improved symmetry
- HyE/Iraum (170 kJ)
- increased coupling & compression
- understand degradations
- better targets

Y amp ~30x

HyE/Iraum (2019-20)

HDC/BF (2016-18)

HyE/Iraum (2020-21)

CH HF (2013-15)

CH LF (2011-12)
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance.
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The Ignition figure of merit is given by:

\[ (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2 \]

Where:
- \( \rho \) is the density
- \( R \) is the radius
- \( T \) is the temperature
- \( E_{HS} \) is the hotspot energy
- \( P_{HS} \) is the hotspot pressure

The figure shows improvements in various areas:
- Reduced LPI
- Reduced fill tube
- Diamond ablator
- Improved symmetry
- Increased coupling & compression
- Further understanding of degradations
- Improved targets

Key events:
- HyE/Iraum (2011-12)
- NIC (2.5 kJ)
- CH HF
- CH LF (2011-12)
- HyE/Iraum (2019-20)
- HyE/Iraum (2020-21)
- HDC/BF (55 kJ)
- HDC/BF (2013-15)
- HyE/Iraum (170 kJ)
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Ignition figure of merit \( \sim (\rho R)^3 T^3 \sim \frac{E_{HS} P_{HS}^2}{\rho R} \)

- NIC (2.5 kJ) unstable high LPI asymmetric
- High-foot (25 kJ) improved stability
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- HyE/Iraum (170 kJ) increased coupling & compression understand degradations better targets
- HyE/Iraum (2016-18)
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Ignition figure of merit ~ $(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$

HyE/Iraum (1.35 MJ)

HDC/BF (2016-18)
HyE/Iraum (2020-21)

Y_{amp} \approx 30x

CH LF (2011-12)
CH HF (2013-15)

unstable high LPI asymmetric NIC (2.5 kJ)

improved stability

High-foot (25 kJ)

reduced LPI reduced fill tube diamond ablator improved symmetry

HDC/BF (55 kJ)

increased coupling & compression
understand degradations better targets

HyE/Iraum (170 kJ)
The program has steadily advanced our physics understanding and the technology over the last decade to improve performance

Built on a decade+ of research on the NIF, N210808 demonstrated burn propagation and a gain of 0.7
Currently we make use of a number of premier facilities around the US & the world to conduct forefront HED science.

Until recently, much of HED has focused on large, energetic drivers that are mostly single-shot. However, next-gen lasers coming online are already rep-rated (>10 Hz).
Numerous rep-rate-capable laser facilities have recently come online, and more are on the way.

The US leads in laser technology development; pursuing new and very innovative laser technologies which will enable additional science opportunities.
High-rep-rate laser science represents a radical paradigm shift in the way we do HED experiments

Scientific knowledge = \( (\text{Drive} + \text{Probe}) \times \text{Repetition rate} \times \text{time} \)
Many HED experiments will benefit from high throughput science enabled by high repetition rate lasers

**High Pressure Material Properties**

McWilliams et al., *Science* 2012

More shots to take measurements across larger phase space

**Secondary Source Particle + Radiation Beams**

High brightness, tuned, reproducible beams for probing, heating, radiography

**Opacities and Radiative Properties**

Heeter, LLNL

Increase measurement confidence through high statistics and constrain complex models used for stockpile assessments

**Plasma Nuclear Physics**


High average numbers to probe subtle, rare nuclear reactions
LASER

HED plasma

HED optical + x-ray diagnostics

Data analysis

Secondary particle + nuclear diagnostics

Data analysis
Laser system diagnostics

- Control signals for safe laser input parameters
- Laser control system
- High repetition rate laser

HED plasma

- HED optical + x-ray diagnostics
- Secondary particle + nuclear diagnostics

Data analysis
Laser system diagnostics

Laser control system → High repetition rate laser

Control signals for safe laser input parameters

laser loop

HED plasma

HED optical + x-ray diagnostics → Data analysis

Secondary particle + nuclear diagnostics → Data analysis
Laser system diagnostics

Laser control system
High repetition rate laser
Control signals for safe laser input parameters

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HED plasma

HED optical + x-ray diagnostics
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Secondary particle + nuclear diagnostics
Data analysis

High repetition rate targetry
Laser system diagnostics

Control signals for safe laser input parameters

Laser control system → High repetition rate laser

Laser loop

HED plasma

HED optical + x-ray diagnostics

Secondary particle + nuclear diagnostics

Data handling and processing

High repetition rate targetry
Laser system diagnostics

- Laser control system
- High repetition rate laser
  
  Control signals for safe laser input parameters
  
  Laser loop

HED plasma

- HED optical + x-ray diagnostics
- Secondary particle + nuclear diagnostics
- High repetition rate targetry

Operational feedback

Data handling and processing

Operational feedback
Laser system diagnostics

Laser control system → High repetition rate laser → Laser loop

Control signals for safe laser input parameters

Operational feedback

HED plasma

HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics

Data handling and processing

Operational feedback

Integrated Analysis

Laser control system

High repetition rate laser

High repetition rate targetry
Laser system diagnostics

- Laser control system
  - Control signals for safe laser input parameters
- High repetition rate laser

HED plasma

- HED optical + x-ray diagnostics
- Secondary particle + nuclear diagnostics

Data handling and processing

- Operational feedback
- Operational feedback

Integrated Analysis

High repetition rate targetry

Laser control system
Laser system diagnostics

- Laser control system
- High repetition rate laser

Control signals for safe laser input parameters

Proposed input parameters to laser

Optimizer

HED plasma

- HED optical + x-ray diagnostics
- Secondary particle + nuclear diagnostics

Data handling and processing

Integrated Analysis

Proposed input parameters to target

High repetition rate targetry

Laser loop

Data handling and processing

Operational feedback

Operational feedback

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Laser system diagnostics

- Laser control system
- High repetition rate laser

Control signals for safe laser input parameters

Proposed input parameters to laser

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Proposed input parameters to target

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Laser system diagnostics

- Laser control system
- Control signals for safe laser input parameters

High repetition rate laser

Proposed input parameters to laser

Optimizer

HED plasma

- HED optical + x-ray diagnostics
- Secondary particle + nuclear diagnostics

Proposed input parameters to target

Experiment loop

Data handling and processing

Operational feedback

High repetition rate targetry

Operational feedback

Modeling & simulation loop

Integrate Analysis

Integrated Analysis

HED Codes

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High-rep-rate laser science means a fully integrated system that leverages technological capabilities in many domains.

Challenges that stem from high-rep-rate experiments are starting to be addressed.
A number of emerging technologies and capabilities can be leveraged to complement and enhance high-throughput HED experiments

<table>
<thead>
<tr>
<th>Optical Technology</th>
<th>HPC &amp; HED Codes</th>
<th>Target Fabrication</th>
<th>Additive Manufacture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large optics</td>
<td>Advanced modeling, codes, machine learning</td>
<td>Exquisite &amp; complex</td>
<td>Novel materials, adaptive preparation</td>
</tr>
<tr>
<td>Laser Facilities</td>
<td>Community Ties</td>
<td>Diagnostics</td>
<td>Frontier Laser Technology</td>
</tr>
<tr>
<td>JLF &amp; NIF</td>
<td>Discovery Science &amp; User Group Meetings</td>
<td>Transformative experimental capability</td>
<td>kW-MW Petawatt Lasers</td>
</tr>
</tbody>
</table>
Currently, the lack of appropriate diagnostics is a major bottleneck to making HRR HED science a reality.

**Diagnostic Development**

*Rep-rate-capable diagnostics* for x-ray and particle beams that are robust to HED environments.

**High-throughput Analysis**

ML-based algorithms for *real-time analysis* of experimental metrics.

**Active Feedback**

Feed back experimental data to the laser system and demonstrate secondary source optimization.

---

We are developing a suite of high repetition rate diagnostics coupled to high-throughput analysis and active feedback.

PI: Graeme Scott
These new HRR diagnostics will be deployed at CSU ALEPH (3.3 Hz) laser as a blueprint for scaling these capabilities to other LaserNetUS facilities.
The revolution in computational power and machine learning techniques paves the way for new approaches in cognitive simulation.
HED is ripe for the application of novel machine learning and AI techniques

- Multimodal data representations:
  - Representation learning & holistic treatment of diagnostics

- Enhanced diagnostics:
  - Transfer learning & virtual diagnostics

- Modeling and optimization under uncertainties:
  - UQ for ML & reliable control loop

- Advanced architectures at the edge:
  - System integration & autonomous control

- On-the-fly model elevation
  - ML interpretability & accelerated insights by assimilating live experimental data

We are combining cutting-edge machine learning with operations to demonstrate a real-time feedback HRR integrated experimental and simulation HED capability
We are exploring the manipulation of particle acceleration at fs-ps timescales for precise control over secondary source characteristics.

- High data throughput modeling/experimental methods enable rapid exploration of massive parameter space
- Shaped short pulses could be used to enhance efficiency and fluence of particle & X-ray sources → probing/driving experiments and interesting fundamental physics

New techniques/tools to modulate laser pulse shapes with ps resolution + predictive capability + ML to explore huge phase space = very cool new fundamental science in laser-matter interaction, and direct applications

**Diagram:**
- Shaped short-pulses
- “Big Data” + ML
- Time evolution of max proton energy

**Diagram Description:**
- Inputs:
- Outputs:
- Diagram of shaped pulses and energy evolution over time.

**Additional Notes:**
- PI: Derek Mariscal
The challenges are many, and we are looking to learn from others

- A commonly voiced concern is that AI will remove expert judgement. How do we mitigate this?
  - Domain-aware, interpretable, and robust scientific machine learning needed to support progress
  - Constant iterative cycle with tight coupling and validation between experiments and modeling
  - Work across-facilities + scale between them

- Some of the biggest challenges we see in applying AI solutions to this work:
  - Machine and data interfaces + Communication across different tools/control systems
  - Standardization
  - Data volume
  - Reliability/robustness
  - Distributed debugging
  - Data provenance

The goal is to develop a high-throughput capability that is demonstrated to rapidly respond to HED questions
We are seeking to revolutionize the way that HED science data is captured and consumed

**Key Technical Opportunities**
- Ability to use all the data
- Quantify uncertainty in predictions
- Detect and remove bias between simulation and experiment
- Compute on time scales commensurate with experiment
- Optimization strategies to seek out desired performance

Tightly coupled advanced laser technology with state-of-the-art experiments and cognitive simulation leads to intelligent experimentation and faster learning
The recent NIF results establish the basic scientific feasibility of laser-driven inertial fusion energy (IFE)

The excitement around the world (and immediate extrapolation to energy) was invigorating to see!
Realizing IFE will require new advances in science and technology

Key components of an IFE system that need to be addressed:
- Drivers
- Target fabrication
- Target injection
- Engagement
- Chamber technologies
- Final optics
- Tritium processing
- Economics

Because IFE is a pulsed energy source, it is envisioned a power plant would require a reaction ~10 Hz

Both large-scale and smaller-scale facilities have a role to play: current ICF research on NIF offers the opportunity to experiment at “fusion scale,” while we can push other technologies (high avg power lasers, rep rate technologies, AI, targets, etc) to advance the science and technology of IFE
High repetition rate HED experimental physics coupled to cognitive simulation will accelerate the rate of knowledge acquisition

- ICF experiments on the NIF are demonstrating very exciting progress
  - The scale and complexity of these experiments means progress is slow
- Next-gen, high-repeat-rate (HRR) laser facilities will provide a different paradigm for HED experiments
- An integrated HED experimental capability means feedback control loops within the laser, experiment, and simulation to simultaneously optimize the entire system in real-time
- Many emerging technologies are being leveraged to make this vision a reality
  - Suite of HRR diagnostics, automated analysis, and active feedback being developed
  - Novel cognitive simulation techniques will push the forefronts of scientific machine learning
- Building on the recent great NIF results, we are pushing the technologies for IFE, with HRR playing a role

This is a very exciting time for fusion and plasma research!
LLNL postdoc program

- **Professional development**
  - Research that is complementary to funded project
  - Maintain university collaborations
  - Travel and professional training activities

- **LLNL culture**
  - Networking and team building
  - Postdocs allowed to PI grants
  - Publishing is a priority

- **Emphasis on mentoring**
  - One-on-one meetings to help postdocs succeed

For more information email kulp1@llnl.gov or visit https://st.llnl.gov/opportunities/postdocs
Short Pulse HEDP- Postdoctoral Experimental Physicist

Entry Level | Full-time
Postdoctoral/Fellowship | Livermore, CA | 10/18/2021

Reference #: REF2644R
Job Code: PDS-1 Post-Dr Research Staff 1
Organization: NIF and Photon Science
Position Type: Post Doctoral
Security Clearance: Not applicable
Drug Test: Required for external applicant(s) selected for this position (includes testing for use of marijuana)
Medical Exam: Not applicable

Contact
ma8@llnl.gov
https://www.llnl.gov/join-our-team/careers

Reference #
REF2644R

Company Description
Join us and make YOUR mark on the World!
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We are looking for individuals that demonstrate an understanding of working in partnership with team peers, who engage, advocate, and contribute to building an inclusive culture, and provide expertise to solve challenging problems.

Job Description
We have an opening for a Postdoctoral Experimental Physicist - Short Pulse HEDP to execute experiments, develop unique diagnostics and diagnostic techniques, and lead frontier research in the area of high-intensity short-pulse laser science and applications and high-energy-density plasmas (HEDP). Areas of active research are high-intensity laser interactions with matter, laser-driven secondary sources, plasma optics, future light sources, and the development of high-repetition-rate diagnostics, targetry, modeling, and machine learning. This position is in the HED (high energy density) S&T (science and technology) organization in the Short-Pulse Laser Science & Applications Group in the National Ignition Facility and Photon Science Principal...
In 2019, more than 1,150 students engaged in research at LLNL that focused on our core mission areas

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- Data Science Summer Institute
- Computational Chemistry and Materials Science Summer School
- Computation Scholar Program
- HED Science and WCI Summer Programs
- DHS Global Security Summer Program
- DOE Science Undergraduate Laboratory Internship (SULI)
- Science undergraduate lab interns

For more information email kersting1@llnl.gov or visit https://st.llnl.gov/opportunities/student-opportunities
New pilot Faculty Mini-Sabbatical Program

- Designed to increase the number of faculty–staff research partnerships and strengthen our S&T by bringing in top academic talent
  - Faculty hired 1–3 months
  - Hosted by staff scientist and approved by committee
  - Paid a monthly salary and travel costs
  - Faculty learns new research capabilities and gains greater knowledge set

- LLNL has an existing sabbatical program for staff
  - Salary paid for up to 1 year to visit universities

For more information visit https://st.llnl.gov/about-us/university-relations/faculty-sabbatical-program