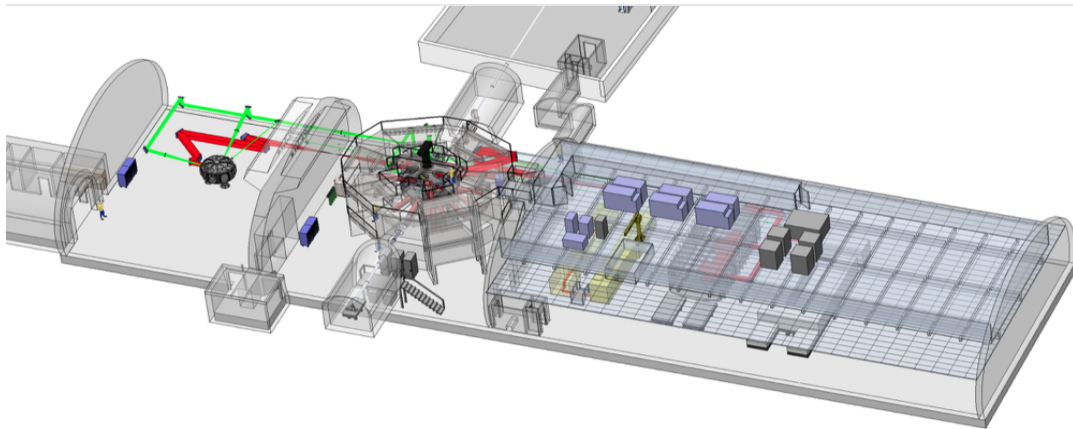


Opportunities for an Inertial Fusion Energy Program within the context of the Matter in Extreme Conditions Upgrade Project

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IFE White paper topic

Facilities benefiting IFE research and development

Executive Summary

The application of a hard X-ray free electron laser (XFEL) in combination with a high repetition rate petawatt peak power and a kilojoule pulse-shaped laser, planned as a major upgrade to the Matter in Extreme Conditions (MEC) instrument, will provide a unique opportunity for understanding and optimizing the physics of inertial fusion energy (IFE). The FES-funded MEC-U project, which achieved CD-1 approval in 2021, will allow the IFE community to accurately and precisely measure the highly transient and complex plasma conditions involved in inertial confinement fusion processes. Robust high repetition-rate X-ray diagnostic capabilities, target delivery platforms, and the development of novel energy deposition schemes will play a crucial role in meeting the main scientific objectives outlined in the recent conceptual design of the new facility. The facility will provide the US community with the unprecedented capabilities to develop and test laser, target, and plasma diagnostics technologies at a 10 Hz repetition rate that is consistent with the requirements of an IFE power plant.

LCLS MEC and the MEC-U project

The Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory is an open-access user facility based on the world's first hard X-ray free electron laser (XFEL), providing ultrashort, tunable hard X-ray pulses with over a billion times higher peak spectral brightness than previous light sources. LCLS serves a wide range of cutting-edge science, and early recognition of its value to the field of high energy density science led to the creation of the Matter in Extreme Conditions (MEC) instrument, which combines LCLS with high power laser drivers and a specialized diagnostic suite. Brought online in 2012, MEC [1] has provided rich new insight into the structural and atomic properties of dynamic HED matter through high precision ultrafast measurements in areas such as planetary and impact physics [2–6], warm dense matter (WDM) equation of state (EOS) and structure [7–10], relativistic plasma dynamics (Kluge et al., 2014, 2017, 2018), and dynamic materials [11–15].

In 2021, DOE gave CD-1 approval for a major upgrade to the laser drivers and experimental capabilities of MEC. The MEC-U project will create a new facility at the end of the LCLS beamline providing high power (at high repetition rate) and high energy laser drivers to a new target chamber designed for the study of a wide range of high energy density laser plasma (HEDLP) physics using LCLS. The rep rated laser system will be the highest average power petawatt laser in the world, capable of delivering 150 J, 150 fs (1 PW peak power) pulses at up to 10 Hz (1.5 kW average power). Using state-of-the-art laser engineering, this high-power laser system can alternatively output high energy shaped nanosecond pulses at the second harmonic. This laser system expands the space of plasma conditions that can be probed using LCLS and provides a new tool for high repetition rate plasma science, enabling parametric studies, statistically significant data on complex states, and the accumulation of small signals over thousands of shots per data point. Additionally, the study of shock compression, plasma instability, and ablation plasma studies will be investigated using a second independent laser system providing pulses of kilojoule energies at second harmonic with state-of-the-art pulse shaping.

Table 1: Parameters of the MEC-U laser system

System	Parameters	Repetition Rate
Diode pumped solid state laser system (two output modes)	150 J in 150 fs; 1 PW peak pwr.	10 Hz; 1.5 kW avg. pwr.
	shapable, 1-35 ns; 527 nm >150 J for 10 ns square pulse;	10 Hz; >1.5 kW avg. pwr.
High energy long pulse	shapable, 0.5-30 ns; 527 nm 1 kJ in 10 ns square pulse;	Shot/30 min.
LCLS X-rays (Cu linac)	10^{12} ph. in range of 4-25 keV	120 Hz; ns pulse trains

The main interaction chamber will be designed to support a wide range of laser-plasma experiments with an extensible and reconfigurable diagnostic suite, multiple angles of the drive lasers, and a versatile target delivery platform. The design concept emphasizes operational efficiency to maximize utilization of the available X-ray beamtime by the User community. At full capacity, the experimental chamber will support multibeam interactions including the combination of the 10 Hz repetition rate and the kJ laser systems with ambient or cryogenic temperature targets delivered at compatible repetition rate. The raised spherical chamber design is intended to maximize solid angle for diagnostic access, which allow their deployment using highly efficient and versatile load-lock inserters like those on NIF or Omega.

In addition to the main interaction chamber, a secondary target area (TAO) is planned to support optical-laser-only experiments for the development of the driver techniques, diagnostic suite, user base and workforce. The second target area is intended to serve as a flagship capability for LaserNetUS (see the white paper *LaserNetUS – Research Opportunities in IFE*), a network of prominent high-power laser facilities across North America funded by FES to provide users free access to experimental time through independent peer review. Radiation shielding between target areas allows TAO to operate independently from the X-ray interaction chamber, so that a full calendar of experiments can be supported in each target area. Within LaserNetUS, several of the facilities provide petawatt-class beams at 0.1 Hz, 1 Hz, or greater repetition rates, and developing the necessary technology to fully exploit these laser capabilities for HED and IFE-relevant science is a major thrust of the network, with scientific community and workforce development at the core of its mission.

The lasers and target chambers will be housed in an all-new cavern excavated at the far end of the Far Experimental Hall of LCLS. The new cavern is sized to accommodate substantial anticipated upgrades, including a major increase in the kilojoule laser energy and a second beamline for the rep rated laser.

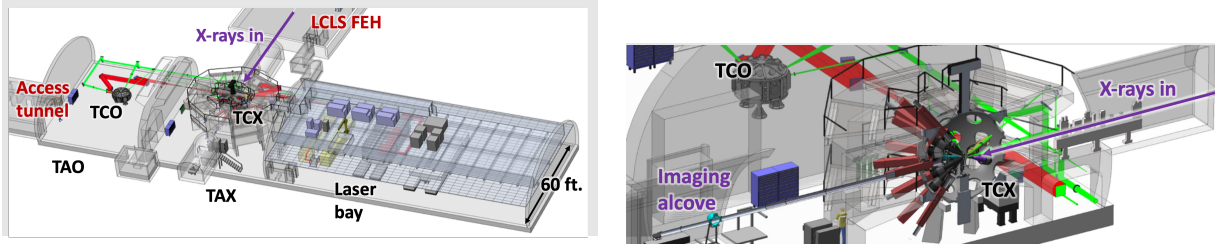


Figure 1: (Left) Conceptual design of the facility to be built as part of the MEC-U project. From left to right are the target area for optical only science (TAO), the Target area for X-rays (TAX), and the laser bay, which contains additional space for future upgrades. (right) Cross section of TCX along the LCLS beam from the facility conceptual design.

The capabilities of LCLS will continue to grow in parallel as the MEC-U project progresses, and we list just a few examples here. The maximum deliverable photon energy is to extend to >40 keV (initially in the third harmonic). Multi-bucket pulse trains, which provide on each shot a burst of several full energy pulses separated by as little as 350 ps, will be extended from the currently available 4 pulses to up to 16. An exciting possibility arising with LCLS-II-HE is the development of cavity-based techniques [16,17], which could produce more temporally coherent pulses that are brighter and more stable, with narrower bandwidth.

HED Diagnostics

MEC-U will provide unique opportunities to investigate the fundamental physics of IFE and HED plasmas with tunable, ultra-fast X-ray sources under controllable and reproducible material conditions. A critical step for IFE research is the ability to accurately and precisely measure the fundamental state properties of the HED plasmas created over the entire implosion, stagnation, and re-shock phases. Due to the short duration and small size of these states of matter, developing and implementing a variety of high-resolution X-ray diagnostics is necessary. X-ray scattering diagnostics, such as X-ray Thomson scattering (XRTS) [7,18–23], meV inelastic phonon scattering [24–26], dynamic diffraction [3,5,6,8,11,13,27], and resonant or non-resonant core-hole scattering [10,28–30] will play a crucial role in meeting this challenge. Such planned diagnostics will enable time-resolved first-principles measurement of temperature, viscosity, thermal diffusivity, sound speed, lattice structure, ionization, atomic structure, density, and blow-off plasma properties at unprecedented accuracies and precisions.

The LCLS ultrashort pulse duration, spectral tunability, and extreme brightness sets MEC-U apart from any other facility within the United States by providing unique X-ray imaging and probing capabilities of IFE plasmas. They will allow *in situ* investigations of lingering physics questions such as the role of capsule defects, reduced compressibility, or the opacity of fusion ablaters. The performance of actual IFE target designs will be tested during the early part of a fusion capsule implosion by direct measurements of shock propagation, densities, temperatures and instability growth rates with sub-micron spatial and sub-picosecond temporal resolution.

These experimental capabilities will provide a novel platform for optimization of an IFE target for maximum fusion gain.

Target physics

During the inertial-confinement fusion (ICF) implosion process, impurities from ablaters are mixed into the deuterium-tritium (DT) fuel, which strongly influences the hydrodynamic instability growth at the ice-shell interface as well as the burn efficiency. Thus, the diffusion coefficients, the viscosity of the DT mixture and the quenching effects from high-Z dopants are important parameters in hydrodynamic modeling. High repetition-rate X-ray probing and target delivery systems enable the ability to precisely monitor instabilities and the physical processes that are controlling their growth. Laser-driver and X-ray diagnostic feedback coupled with machine learning algorithms can be an efficient method for minimizing hydrodynamic mix, and/or stabilizing energy deposition to maximize hot-spot uniformity. Moreover, accurate knowledge of the electronic and radiative transport coefficients in dense DT plasmas can be accessed through controlled experimental platforms. Such knowledge is fundamental for predicting and modeling hydrodynamical instabilities grown at the fuel-ablator interface, the ablation front, or at the hot-spot–fuel interface.

Opportunities for machine learning (ML) and artificial intelligence (AI) in HED science are increasingly identified as means to accelerate scientific discovery by orders of magnitude [31,32]. Experiments conducted at high repetition rates with the use active feedback loops (e.g. laser, target, diagnostic) will drive empirical discovery and computer model development. When coupled with AI, semi-autonomous exploration of multi-dimensional parameter space will provide unprecedented insight into the complex physical dependencies of HED regimes.

A white paper from A. Gleason, et al. envisions a series of experiments at the new facility to systematically assess the effect of tuned wetted foam microstructure on the implosion or planar shock compression processes, with the goal of optimizing the target design for best performance in an IFE test-platform. The experiment would leverage the coherent properties of the LCLS beam with a tailored nanosecond pulse train structure [33] extending over 100 ns to determine high fidelity 2D and 3D density reconstructions of the foams during the passage of a single shock event. For each pulse the diffraction image, to be reconstructed by iterative phase retrieval algorithms, would be recorded on gated detectors, likely built off the current technology of the hCMOS-UXI [34,35] and/or ePIX-Delta [36] platforms. The imaging diagnostic should be complimented by (also gated) wide angle X-ray scattering and XRTS, streaked optical pyrometry, and velocimetry. These experiments would be done in a planar geometry with the 1 kJ laser delivered as part of the MEC-U project. With an additional multi-beam, multi-kJ upgrade that the facility is designed to support, the experiment could also be performed in a converging shock geometry.

Technology development

The MEC-U concept describes a facility intended to make best use of the LCLS X-ray source, which operates continuously at high repetition rate with high availability throughout the year. In the future paradigm of active feedback from plasma parameters, experiments could approach operating modes resembling those of an envisioned laser-based IFE power plant, with long stretches of continuous operation requiring automation of target delivery and tracking and operation in a harsh environment. Fast steering mirrors controlled by an active feedback system

are an aspect of the facility with technological ties to laser IFE, the development of which would be mutually beneficial. Such optics are necessary for active machine-vision-driven feedback loops both for automation of alignment and tuning in response to plasma conditions.

To fully take advantage of the high-repetition rate capacities of LCLS and the MEC-U drive lasers, extensive development of target delivery systems will be required. Experiments performed in the present day MEC instrument have utilized high repetition rate sample delivery systems ranging from rapid translation or rotation of solid targets to cryogenic liquid jets. LCLS's Sample Environment & Delivery group has emerged as an international leader in developing rapidly refreshing liquid and gas phase samples for XFEL, synchrotron, and ultra-fast electron diffraction facilities. Leveraging the local expertise, the High Energy Density Science division has focused on expanding the SLAC portfolio of high repetition rate target delivery systems to access the wide range of high energy density physics regimes. The much higher energy drivers at high repetition rate resulting from MEC-U will pose challenges of debris mitigation and next-target-survivability, which will need to be addressed.

First high repetition rate experiments at the facility will be performed with cryogenic liquid jets and droplets. Further, the chamber will be designed not to preclude the injection, tracking, and shooting of solid targets at 10Hz – a well-known grand challenge in IFE that has yet to be addressed. A large technical aspect, which could be developed and explored at MEC-U, is the machine vision and target tracking required to precisely locate a target in space to rapidly correct the laser pointing for shot-to-shot reproducibility.

A final area of technology development required by the MEC-U project is the development of high-repetition rate X-ray, plasma, and particle diagnostics that can withstand the laser-produced high radiation levels to obtain sufficient signal-to-noise with respect to LCLS. The project will leverage the network and facilities of LaserNetUS as well as the optical only target area to develop and commission new state-of-the-art diagnostics which will directly benefit IFE programs.

Conclusion and Outlook

The MEC-U project will create a world-leading HED science facility with tremendous potential value to IFE research and development. This community should resolve to take full advantage of this resource, driving development of experimental platforms and technical capabilities that will lead to dramatic advancements in the push to realize IFE. Valuable areas of focus include ML and AI driven laser optimization, targeting, and fast feedback from plasma parameters, diagnostics robust to laser-produced radiation sources, mitigation of target debris, and algorithms for analysis of large data sets.

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