Accelerating the science, technology, and workforce base for inertial fusion energy with a proposed high repetition rate facility

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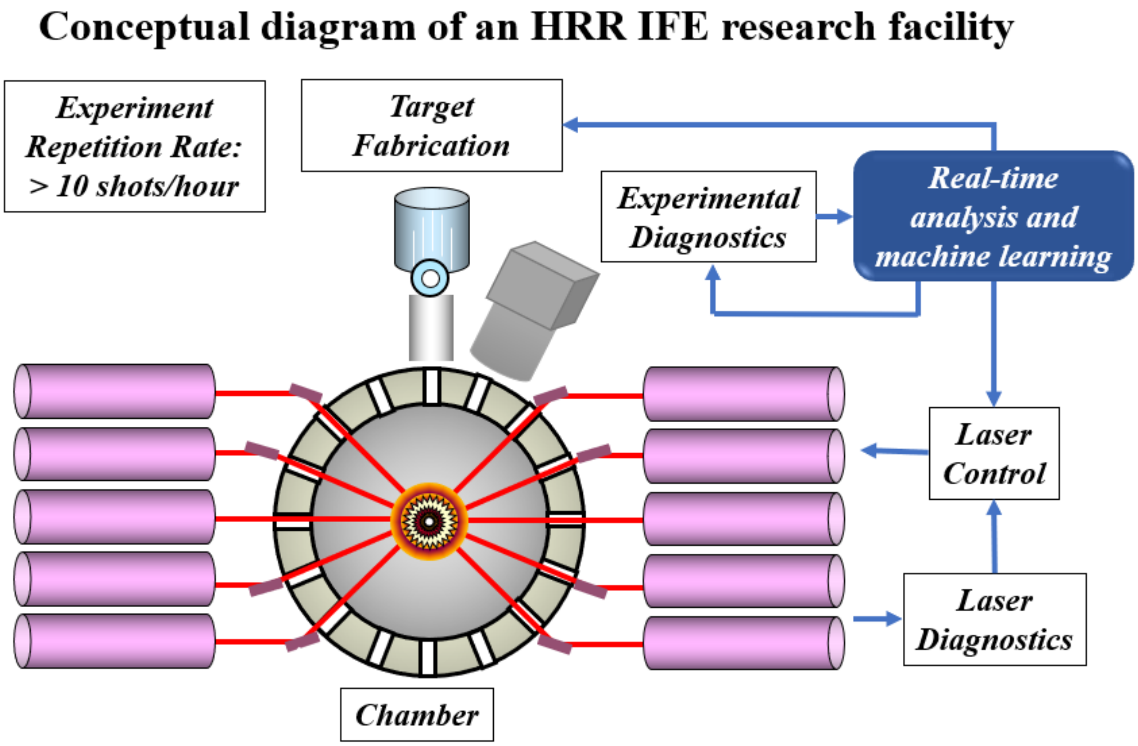
IFE white paper topic

The proposed facility would provide holistic support for IFE research and workforce development. This white paper specifically addresses many of the recommended topics, including targets, drivers, diagnostics, and safety.



Conceptual diagram of an HRR IFE research facility

Executive Summary

With recent successes in indirect-drive and direct-drive inertial confinement fusion (ICF) leveraging the impact of fundamental high-energy-density science (HEDS) results, the community is poised for even more impact (Sec. I). However, the demand for shots on facilities relevant to IFE (OMEGA, OMEGA EP, Z, and the NIF) is three times those available (<3,000 shots/year), leaving the community data-starved. To meet this demand, we identify a community need for a multiple-beam facility with sufficient energy (50 to 100 kJ) to perform integrated inertial fusion energy (IFE) experiments at a rate of ≥10 shots/hour (Sec. II) along with supporting target fabrication and diagnostics.

High-repetition-rate (HRR, here defined as ≥10 shots/hour) experiments represent a new and potentially transformative frontier for IFE, stockpile stewardship, and HEDS research including (but not limited to) laboratory astrophysics, matter under extreme conditions, and planetary science (Sec. III). HRR experiments can collect large datasets that are ideal for characterizing highly nonlinear and stochastic process, quantification of uncertainties and reproducibility, exploring innovative concepts and application of cutting-edge analysis and active-control techniques such as machine learning.

The development of technology for HRR operation is itself a necessary requirement for IFE [1]. HRR HEDS facilities are also ideal platforms for workforce development, which has been repeatedly identified as a high priority by community reports [2] [3] (Sec. IV). The large datasets collected at HRR can support more students and develop a workforce with experience in cutting-edge techniques like machine learning, artificial intelligence, advanced manufacturing, and high-average-power lasers. The research agenda enabled by the proposed facility will grow the workforce to meet the hiring demands across the Department of Energy (DOE) national laboratories, universities, and private sector including the growing fusion energy industry.

HRR IFE/HEDS experiments are technically feasible leveraging advances in laser drivers, diagnostics, advanced manufacturing, and analysis techniques (Sec. V). Indeed, several low-energy (<1 kJ), long-pulse (~ ns) HRR laser systems have already been constructed. However, no such facility is currently operational in the US, which represents a potential loss of US leadership in this area. Furthermore, a high-energy (>10 kJ) HRR long-pulse multi-beam laser facility, capable of complex (i.e., implosion experiments) has not yet been built. The high-energy HRR facility proposed here is a strategic opportunity for the U.S. to maintain leadership in this field and to start on the technology developments paths for future IFE drivers.

I. Background

As we approach the 20th anniversary of the U.S. National Academy of Sciences publication of Frontiers in High Energy Density Physics: The X-games of Contemporary Science [4] the DOE and the community can celebrate that most of the recommendations of this report have been implemented. There is a robust use of DOE/NNSA stewardship HEDS facilities which have generated data beyond the detail and quality envisioned at their inception. Through collaboration between the academic community and national laboratories, laboratory-based HEDS studies relevant to astrophysics and planetary science have expanded as experimental-computational research fields to support observational astronomy [5]. The growing fusion energy industry also places considerable demands for time on HEDS facilities. Research in these areas is also training many students who are ultimately employed in the DOE national laboratory enterprise, academia, and industry (workforce development will remain a pressing need for the foreseeable future).

The 2003 report also stressed maximizing capabilities of facilities. Now in 2022, x-ray diffraction, picosecond x-ray imaging or probes, Thompson scattering, and advanced neutron diagnostics are routinely fielded on OMEGA and the National Ignition Facility (NIF) (some of the advanced diagnostics are also available on Z). Such diagnostics helped the community on the path to the recent result of target gain near one on the NIF.

What is next? Three key considerations help us answer this:

- The present demand for shots on all facilities is three times those available.
- The quality, precision, and reproducibility of measurements are still limited due to small statistics, also severely limiting the application of machine learning techniques, the exploration of novel target designs, and the challenge of making high-resolution measurements along multiple line of sights on micron-scale, picosecond-to-nanosecond-duration events.
- The need for the path forward and requirement definition for capabilities to develop inertial confinement fusion for carbon-free energy application is growing, motivated by the recent NIF burning plasma results.

II. Vision for an HRR IFE Facility

Parameter	OMEGA	Proposed Facility
Total Energy (kJ)	30	50 to 100
Max. shots/day	16	80 to 100
# Beams	60	?

Table 1: Parameters of the proposed HRR IFE facility.

With recent successes in indirect-drive and direct-drive fusion and the impact of fundamental science results, the community is poised for even more impact. However, the community is data starved, with less than 3,000 shot opportunities on OMEGA, Z, and NIF together per year. Investments to operate OMEGA on a more expanded schedule would increase this number to 4,500 which, while an improvement, would still not meet the full needs of the community.

To meet this demand (which will only increase), we suggest a new multiple-beam facility with sufficient energy (50 to 100 kJ) for broad IFE research including integrated experiments with a repetition rate of ≥10 target shots/hour (compared to shot per 45 to 100 minutes on OMEGA). Such a facility would conduct more than 20,000 data shots with complex planar, cylindrical, spherical targets per year. The laser will also incorporate advanced features that address laser plasma interaction (LPI) physics such as bandwidth and novel pulse formats. The IFE and HEDS communities have now developed a maturity in collaborations, modeling, and diagnostics that would allow them to effectively use this high shot rate capability. The envisioned facility and its associated technologies will impact the adjacent missions such as Department of Defense (DOD) directed energy R&D [6] and other DOE/Industry-funded IFE developments.

The U.S. has been the leader in high-energy-density physics since the 1970s. The past two decades have seen incredible advances in capabilities. A state-of-the-art, high shot rate, high energy laser facility will address many aspects of the IFE research including at-scale advanced drivers, high gain target designs, hydrodynamics, advanced and radiation hardened diagnostics, targets (including manufacturing, injection, and survivability), and applications of machine learning and artificial intelligence for IFE. This will ensure technical leadership for the foreseeable future and accelerate the next frontiers in HEDS and IFE science.

III. Scientific Impact

The primary benefit of HRR experiments is the increased volume of data collected [the proposed facility would conduct ~10 times more shots than the current generation OMEGA laser facility (Table 1)]. Larger datasets will allow new applications of statistical methods and machine learning (see white paper by V. Gopalaswamy *et al.*), enable innovative concepts to be explored, and quantify uncertainties and reproducibility. Increased shot rates will also allow scans with unprecedented temporal, spatial, and parametric resolution, ideal for studying non-linear or stochastic processes. An HRR facility will also enable new modes of experimental design such as experiments with active feedback and control where results inform changes in experimental parameters in near-real time [7] [8]. An HRR experimental facility would consequently be transformative for both IFE and HEDS research

Conducting IFE implosions at HRR will improve understanding of highly nonlinear processes such as ICF scaling and mix. Large datasets will also improve statistical models which led to >3 times increases yield on the OMEGA laser facility in 2018 [9] and subsequent record yields (3.1×10^{14}) obtained in OMEGA cryogenic implosions in 2021 [10] but are severely limited by the number of data points. An HRR IFE facility will also bring significant benefits to basic HEDS experiments relevant to IFE. High resolution scans in time or parameter space could further constrain models of hydrodynamic instability growth, nonlinear LPI physics and rapidly test mitigation strategies utilizing advanced target designs and fabrication techniques (examples are included in several white papers, e.g., by S. Hu *et al.* and D. Harding *et al.*). The results of these experiments are broadly relevant to many IFE concepts outside of direct-drive ICF.

HRR experiments will also address grand challenges in fundamental HEDS as identified by recent community reports [2] [11] including turbulence and magnetic reconnection. The strongly parametric/non-linear and stochastic nature of these processes means that systematic experiments with the high resolution in parameter space will be highly impactful. Large datasets would also quantify uncertainties and increase precision in measurements of materials at extreme conditions such as equations of state and opacities (with applications to planetary science and stockpile stewardship).

IV. Workforce Development

Workforce development in HEDS has been consistently highlighted as a challenge in recent reports [2] [3]. HRR facilities are ideal platforms for training students because of their relatively low cost-per-shot and ability to explore cutting edge diagnostics, targets, and data analysis techniques (as demonstrated by existing HRR facilities, such as members of the LaserNetUS consortium [12]).The significantly increased shot rate of the proposed HRR IFE facility will increase the number of students that could be supported.

The proposed facility will develop a workforce trained in cutting edge analysis techniques such as machine learning, artificial intelligence, advanced manufacturing, and high-average-power laser technology. This workforce will help meet the present and future hiring demands across the Department of Energy (DOE) national laboratories, and the growing fusion energy industry.

V. Technological Readiness and Development Needs

Significant progress has already been made towards achieving technological readiness for an HRR IFE/HEDS facility. Small and mid-scale HRR laser drivers are already operating successfully. Several short-pulse laser facilities (with laser energy <100 J) already conduct HEDS experiments at shot rates exceeding 1000 shots/day (many of these are available to users through the LaserNetUS consortium [12]). Basic HRR targets (such as planar foils, liquid jets, thin liquid crystal, etc.) and optical diagnostics are being successfully implemented. Other areas, such as advanced targets (see white paper by D. Harding *et al.*), particle/field diagnostics (see white paper by J. Frenje *et al.*), and data analysis pipelines will require more development. A commitment to a higher shot rate facility will require and thus motivate and promote innovation in all of these areas.

Design of an HRR kJ-class ns-pulse laser will utilize the state-of-the-art laser technologies (as discussed in a white paper by J. Zuegel *et al.*). Developments in laser technology over the past several decades [13] have led to the construction of several lasers of moderately high energy (<1 kJ) that operate at HRR (DIPOLE100 [14], Electra [15] [16], HAPLS [17], Mercury [18]). The proposed MEC-Upgrade would include a >1 kJ long pulse laser with a repetition rate of ~2 shots/hour.

Substantial advances in targets for HRR HEDS experiments have already been made, including (among others) translating arrays of targets, droplet sources, and gas puffs [19] [20] [21] [22]. Many of these targets could also be used for IFE-relevant experiments at HRR. Producing targets for integrated IFE experiments at HRR is a grand challenge (and a prerequisite for IFE applications), and efforts in this area are already underway [23].

Many HEDS facilities have already switched to diagnostics compatible with HRR, such as semiconductor-based optical detectors. Along with suitable HRR probe beams, these detectors enable the use of optical diagnostics such as Thomson scattering [24], interferometry, spectroscopy, and x-ray imaging that already incorporate probe lasers and CCD sensors (e.g., framing and streak cameras) at HRR. Most current generation standard particle detectors (e.g., neutronics, charged particle radiography) are not scalable to HRR, although scintillator-based alternatives are already under development [25] [26] [27]. Many existing diagnostics will be improved (and novel diagnostics made possible) by the high statistics collected at HRR.

At ≥10 shots/hour, driver, diagnostic, and target components on the proposed facility will exceed tens of thousands of shots per year. Durability testing of component technologies will be an important part of development, and technical knowledge gained during this process will be directly relevant to IFE (for which component lifetimes must exceed millions of shots). The commercial success of HRR laser-driven liquid tin extreme ultraviolet light sources for lithography [28] demonstrates both that these challenges can be overcome and the wider industrial benefits of HRR technological development.

Even with conservative estimates of data size (1 GB/shot), experiments on the proposed facility will produce large volumes of data, requiring a paradigm shift in data processing and analysis. This will necessitate the creation of advanced automated analysis pipelines, possibly leveraging artificial intelligence, some of which is already underway [29]. Other fields of science have already developed many techniques and technologies for handling big data [30], many of which have already been applied in other areas of plasma physics. Developing these skills both within the existing HEDS community and through the training of students is an essential function of the proposed facility.

At higher shot rates additional radiation shielding will be necessary for personnel safety [31]. Facility components, especially detectors, will also need to be hardened to prevent degradation in this environment. Technical solutions to these challenges already exist, but the proposed facility will demonstrate that they can be applied in the context of IFE.

An HRR IFE facility is technically feasible and will facilitate workforce development, accelerate the next frontiers in HEDS and IFE research, and serve as a necessary step towards developing IFE for carbon-free energy applications.

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