Versatile Laser User Facility (VLUF)

<u>The ability of the facility to contribute to world-leading science in the next decade</u>
Grade:

There is a clear scientific and national need for laser-based user facilities enabling researchers to pursue novel, cutting-edge science in high-energy-density (HED) physics, related disciplines, and other areas of interest to the DOE Office of Science (SC). The VLUF will serve a broad range of such users and the training of the next generation of scientists. It will combine in one facility a 5 kW high-average-power (HAP) fiber laser, a 10 PW high-intensity laser, kJ-class high-energy lasers with unprecedented versatility, and targeting facilities that provide users the opportunity to do experiments that combine these capabilities. Each of these lasers represents an advance on existing capabilities in the US, and is competitive internationally. Their combination will be unique worldwide. Our vision is that the VLUF will establish a fertile environment in which will flourish the next generation of science using lasers, with users from many universities and laboratories.

The facility will consist of laser bays for each of these laser systems, a common, reconfigurable target and diagnostic area where all the lasers can be used separately and simultaneously or jointly, and space for supporting activities. The fiber laser will initially produce TW pulses (50 mJ at 50 fs) at a 100kHz repetition rate, corresponding to 5 kW of average power, and will provide cost-effective development paths toward MHz/50 kW and 1 PW fiber lasers, with both ultimately being available for users. This unique laser will allow unprecedented laser-plasma-materials experiments, in which the laser creates and/or diagnoses gradual changes in the state of a material, generally in the warm-dense-matter regime. The high repetition rate will also allow laser-plasma experiments of unprecedented precision at the TW level and above, for example to explore heat transport and generation of radiation. The high-intensity laser will be a 10 PW system, intended to surpass capabilities which several European labs are currently pursuing (but no US lab is), and engineered to run reliably for users. It will cross the (10^{23} W/cm^2) threshold beyond which the fields produced by accelerated particles are predicted to cause pair production from vacuum. The high-energy laser system will be an intermediate-scale system, for which there is an urgent need in the US. It will include two kJ-class lasers and a 100 J-class laser that can be operated at ps or ns pulse lengths. It will feature a state-of-the art fiber light source, improved beyond that implemented at the National Ignition Facility, to enable pulse shaping and pulse durations with unprecedented versatility at this scale.

In combination these lasers will enable unique, unprecedented scientific studies. These include but are not limited to every area of HED Laboratory Plasmas, as developed in the 2009 FESAC report, *Advancing the Science of High Energy Density Laboratory Plasmas*, chaired by Riccardo Betti. Examples are

- Relativistic HED Plasma and Intense Beam Physics: diagnosing generation and propagation of electrons, protons, neutrons or x-rays produced by irradiating plasma produced by one of these lasers with another, including research relevant to future high-energy accelerators.
- Magnetized High Energy Density Plasma Physics: diagnosing with the fiber laser the long term (> 10 μs) timescale evolution of magnetized plasma flows energized by the kJ laser,

with the potential to inject relativistic particles using the ultrafast laser to study acceleration by collisionless shocks.

- Warm Dense Matter Physics: diagnosing long-term phase changes or dislocation dynamics resulting from shock waves or heating by the high-energy laser, and/or from nonequilibrium initial conditions produced using other beams or lasers, at timescales from femtoseconds to milliseconds.
- Nonlinear Optics of Plasmas and Laser–Plasma Interaction: Formation of plasma gratings using the high-energy laser to support pulse compression research in support of exawatt laser creation
- High Energy Density Hydrodynamics: Energy deposition with the high-energy laser to produce hydrodynamic behavior of interest on a 100 μs timescale, for diagnosis with the high-average-power laser
- Radiation-Dominated Plasma Dynamics and Material Properties: Diagnosis of regions of strong radiative cooling with the high spatial resolution enabled by single mode, ultrafast laser pulses.

Of equal importance to DOE scientists, each of these lasers will enable fundamental scientific research of interest to a significant and growing community of users. The high-intensity laser will enable studies of strong-field QED physical effects and of a host of novel relativistic effects. The high-average-power laser will enable studies relevant to mechanisms of generation of x-rays, electrons, protons, and neutrons by laser-plasma or laser-solid interactions. These mechanisms, once understood, will enable a vast range of scientific and industrial applications ranging from biological science and medical treatments to materials science and manufacturing technologies. The high-energy laser will enable experiments in the full range of HED physics described above, using the improved capabilities of the facility to go beyond work being done in the active user programs at Jupiter in the US, Vulcan and Orion in the UK, LULI in France, Gekko in Japan, and Shenguang II in China.

In addition, at such time as FES initiates an Inertial Fusion Energy research program, a number of the integrated physics issues to be addressed, also discussed in the Betti report, will be amenable to scientific research at the VLUF. These include for example studies of control of laser-plasma instabilities or studies aimed at testing improved models of electron heat transport.

Beyond the above scientific work directly relevant to FES, the VLUF can do research relevant to other topics of interest to DOE/SC.

- Basic Energy Sciences: BES also has an interest in warm dense matter, which transitions to extreme materials as energy density decreases. The HAP fiber laser can produce bright, jitter-free, ultrafast, pulsed beams of x-rays, beyond those feasible using the current generation of free-electron lasers. Revolutionary new approaches, such as the bubble plasma undulator, will enable materials characterization of unprecedented precision. The HAP fiber laser also has substantial potential for the in-situ characterization of material structure and defects using, muons, electrons, positrons, or even protons. All the lasers have the potential for material modification by heating or particle deposition that could then be diagnosed with the HAP laser. The HAP laser also has an immediate potential to produce materials modifications by breaking of chemical bonds without significant heating, at a rate enabling material transformation or studies of details on a scale and with a precision previously unanticipated. New materials with novel properties are envisioned including new phases of matter, nanostructures and other low-dimensional systems that are of current interest to energy-critical materials needs.

- High Energy Physics: HEP has embraced a role for laser-plasma accelerators as a possible path to the future for high-energy physics. Potential roles range from serving as injectors for the next generation of high luminosity accelerators to providing substantial energy gain via wakefield acceleration. Both high-intensity lasers and HAP lasers have important contributions to make in this development.

The readiness of the facility for construction

Grade: (a)

The VLUF combines existing or near-term technologies to address unmet research needs and produce novel capabilities in combination. As such it is ready to commence engineering design of the implementation, which could occur in parallel with the design and construction of the necessary building. In this sense, the construction process could begin at any time. The required budget, including the building, is 80 M$. Projected operating cost is 10 M$ per year. Users would be awarded 2 to 4 week blocks on one or more of the operating lasers.

Scientific community considerations

Grade:

The facilities in VLUF are “intermediate-scale facilities” in the standard language of major reports, being larger than can be easily fielded by a single investigator, but small enough that they need not be sited at a major national laboratory. At present, the US has only one operating intermediate-scale laser user facility, Jupiter at LLNL, funded primarily by funds originating from NNSA. Jupiter has struggled to operate and maintain its capabilities despite very strong demand from users. While there are other lasers in the US that occasionally host users (most often as collaborators), none of these operate in a manner that approaches that of standard SC user facilities and none of them are funded by SC. Yet the Plasma 2010 decadal survey report by the NRC, *Plasma Science: Advancing Knowledge in the National Interest*, calls for more intermediate-scale laser facilities. This is no surprise, given that Europe and Asia have several such facilities, have more under construction, and have very active user communities. In addition, provision of a petawatt-class laser for users is a need specifically identified in the Plasma 2010 report, but there has never been a user facility with such a laser in the US and for lack of funding Jupiter is now decommissioning their sub-petawatt system.

The report of the Basic Research Needs Workshop (ReNeW) on *High Energy Density Laboratory Physics* of 2010 emphasizes the importance of increased community access to intermediate-scale user facilities, but focuses primarily on increasing community access to NNSA-funded facilities. This has not worked well. One of the two intermediate-scale facilities then operating as user facilities has since that time stopped doing so and no others are so operating. Beyond this, there is strong benefit to increasing the capability and versatility of US facilities at this scale. To effectively steward this area of science, SC should start operating its own facilities.

The recent reports echo the recommendations of a sequence of community reports, from the NRC report *High-Energy-Density Physics: The X-Games of Contemporary Science* in 2003 to the OSTP report *Frontiers of Discovery in High-Energy-Density Physics* in 2004 to the *Report of the Interagency Task Force on High Energy Density Physics* in 2007. These reports have all discussed the broad potential for advances in HED physics, have all called for an increase in research facilities in this area, and have helped motivate the explosion of international capability in HED research which the US has failed to match.

It is also of significant national value that the VLUF capabilities will attract users supported by several offices in SC beyond FES. The 2013 DOE workshop on *Laser Technology for Accelerators* emphasized the important role of both high intensity lasers and high-average power lasers for future facilities of interest to SC/HEP. VLUF will contribute substantially to the fundamental scientific research required in both these areas to enable such future capabilities. The capabilities of VLUF resonate with Grand Challenges identified in the recent series of BES workshop reports, including controlling matter at the atomistic level, materials under extreme conditions and producing new materials which will be needed to meet national energy goals in the coming decades.

Specific additional community and workforce benefits of the VLUF include:

1. Support high energy-density science at multiple universities, over a wide range of university infrastructure size
2. Support multi-university collaborations
3. Have minimal clearance requirements, benefiting user access and thus expanding the broader HED physics community and better helping to train and recruit the future scientific workforce
4. Serve as a pipeline into DOE labs, and into university groups run by graduates of VLUF
5. Provide training experiences for new researchers
6. Serve as a development platform for novel high-energy-density physics diagnostics
7. Serve, along with LLE and JLF, as a staging platform for NIF experiments

The University of Michigan would be an excellent location for the VLUF, as it has expertise in all the required areas of laser facilities and experiments, and already hosts the Center for Ultrafast Optical Sciences and the brightest laser in the world (HERCULES). Michigan faculty and administrators have been for some time discussing the value of hosting such lasers. Michigan has the top-ranked Nuclear Engineering Department in the US, many other outstanding departments, and a highly ranked research hospital. It is also near a major airline hub in the Midwest and so readily accessible from both coasts.

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