Jupiter II – Next-generation International User Facility for Laser-based High Energy Density Science

Ensuring US scientific leadership for the next decade

High energy density (HED) science is the science of outer space and inner Earth. It underpins studies of inertial fusion energy and compact particle accelerators. It is the science of high pressure, high density, high (and low) temperature. Because it is complex, hard to create and very dynamic in the laboratory, most aspects of HED science are difficult to harness and understand – requiring extensive experimental study. Large laser facilities are used to study HED materials and plasmas, but the number of researchers who have access to them is very limited and the experiment rate is extremely slow – precluding many areas of study, and compromising the development of many scientific applications. Both of these issues severely constrain the breadth of scientific involvement and the diversity of techniques arrayed to solve problems in HED science.

To address this, Jupiter II combines long-standing US academic leadership in this field with a new generation of laser technology to offer a facility that will deliver unprecedented data rates. This will provide a step-change in HED experimental capability, and protect US preeminence in this rapidly growing field that has seen huge investments in the rest of the world.

Jupiter II will combine multiple laser beams to provide great flexibility in experimental configuration. Taking advantage of recent US-led technology development, it will consist of a multi-petawatt (>30 J, 15 fs) 15-Hz laser capable of a focused intensity of 10^{23} W/cm^2, combined with a high repetition rate, high energy (multi-kJ) laser that offers full flexibility between nanosecond "drive" capability, picosecond "relativistic" (CPA) capability, and femtosecond "ultra-relativistic" (OPCPA) capability. The lasers will be operated independently into separate target areas but also will be able to be steered to areas for combined long-and-short-pulse experiments.

Jupiter II will be a new facility, building from an established user facility platform and international user community. Because of its energy, power, diversity of temporal pulse lengths, and the ability to combine energetic short- and long-pulse lasers, Jupiter II will permit research across the full scope of HED science. Jupiter II will have the capability to create and probe extreme states of matter relevant to inertial fusion energy, plasma astrophysics, planetary physics and chemistry, plasma nuclear physics, condensed matter and materials science, and medical applications of intense light and particles beams. Only the largest, and least accessible, laser facilities can perform useful experiments in most or all of these areas. Jupiter II will be able to do so, but with the access of a user facility. And, because all systems will operate at a high rep rate, experimentalists will obtain data three to four orders-of-magnitude faster than at those other facilities. Jupiter II will enable experiments that benefit from or require statistical data gathering. Jupiter II will be a *fundamental* step up from the "single-shot" nature of HED science today.

The panoply of HED science has been explicated in a number of reports [See Sources]. An overview of areas where Jupiter II will immediately contribute include:

Astrophysics. A broad array of astrophysical phenomena can be studied directly in the laboratory through the use of high power laser facilities. Jupiter II will greatly extend this by enabling studies to scan an entire phase-space of conditions, providing unprecedented ability to study "cause and effect" and thus test the disparate numerical approaches to these extreme phenomena. For example, the role of "collisionless" shocks in amplifying magnetic fields and accelerating charged particles is poorly understood, but thought to be a key factor in the creation of high energy cosmic rays. Solving this mystery via laboratory experiments has been labeled a "Major Opportunity" in astrophysics [See Wiesner report in Sources]. Worldwide at the moment, there are only a few dozen shots per year addressing this subject. As a second example, the intensity of Jupiter II would permit the study of positron jets and positron-electron-dominated plasmas, opening up entirely new areas of study.

Planetary science. The physics, chemistry, state, phase and transport properties of matter (elemental and molecular) at pressure of a few Mbar to a roughly a Gbar define how planetary objects form and evolve, and behave in collisions. The ability to produce matter at these conditions in the laboratory permits the detailed study of planetary interiors. Using the Jupiter II femtosecond laser as a probe of shocked samples (from the high energy beam) would allow detailed study of deep-atom chemistry occurring in large planets.

Condensed matter and materials. The high rep rate of Jupiter II will not only permit investigations of the properties of materials under extreme conditions, but it will be possible for a scientist to "walk in" a sample material to a desired state. The impact of this new capability is likely to be very profound – addressing one of the principal shortcomings of present-day HED experiments. In another vein, using deuterium clusters illuminated at very high intensity, Jupiter II can create user-ready high fluxes of neutrons, protons, gammas, and x-rays as sources for studying materials exposed to harsh radiation environments.

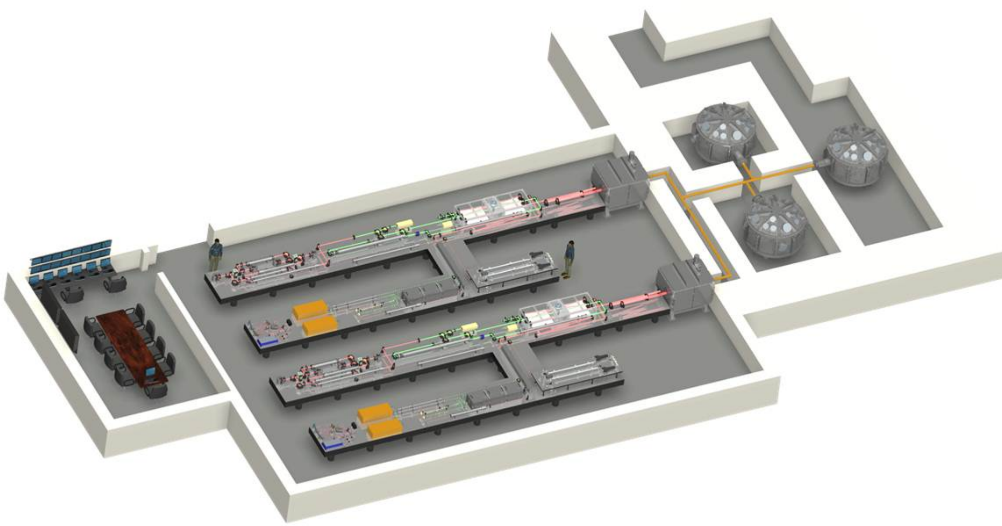
Quantum electrodynamics. The exceptionally high electric field at 10^{23} W/cm^2 creates opportunities to study aspects of non-commutative, strong-field QED that cannot be accessed via conventional particle accelerators. This is a largely unexplored regime of laboratory physics.

Nuclear physics. Dense plasma can affect nuclear processes via screening effects and by plasma-caused energy level shifts of low-lying states. Such effects are known to be important in dense astrophysical objects, and require highly quantitative studies that are currently precluded on most HED facilities. The performance levels and statistical nature of Jupiter II will transform this field.

Inertial fusion energy. Jupiter II can address major scientific areas relevant to IFE. These include answering important questions hydrodynamics at HED conditions, studying radiation-dominated plasmas, measuring the strengths and dynamics of plasma-generated magnetic fields, observing turbulence, studying relativistic plasmas, and determining equations of state, opacities, transport, and dynamic behavior of warm dense matter. Harnessing data on these issues could be done several thousand times faster with Jupiter II than existing large facilities. As a couple of examples, experiments mitigating the effects of laser plasma interactions could be done in real time, as could attempts to reduce the divergence of hot electrons in fast ignition targets.

Particle acceleration. Accelerating electrons and protons to high energies can be achieved with femtosecond-class lasers. Ion beams from accelerators are used for treating cancerous tumors and there is an extensive effort in Europe to develop - much cheaper lased-based - proton acceleration schemes for medical therapy (as of now, laser-accelerated proton energies are too small for such applications). Energetic accelerated electrons might be used to produce extremely short-pulsed x-rays for medical applications; this is also under heavy study in Europe. Jupiter II's femtosecond laser is ideal for laser-based particle acceleration.

It is not hyperbole to note that there is an enormous push outside the US for energetic, high-rep-rate lasers. Instead of falling a generation behind, Jupiter II built in the US is a chance to actually step ahead of that competition. This will reverse the trend in this area, where the US has fallen behind and is falling further behind with the emergence of large-scale initiatives such as ELI (under construction in Europe), XCELS (being prototyped in Russia), and the wide range of intermediate-scale facilities in Europe and Asia (all of which represent greater capability than can presently be found in the US).



Schematic layout of a Jupiter II configuration

Cost Estimate

Extensive cost analysis and vendor consultation has already been undertaken for the constituent systems of Jupiter II in support of international road-mapping exercises in Europe and Asia, for various industrial applications of these emerging lasers, and in readiness for proposed new facilities such as the European Extreme Light Infrastructure (ELI). Jupiter II builds upon these studies by offering high-energy lasers in combination with high peak-power lasers, combining both in a high average power mode of operation. The cost / schedule and risk tradeoffs for construction of Jupiter II are well established.

Consultation with the specific user communities remains to be fully completed (not least since this facility will service a very broad range of disciplines). Thus, there are decisions yet to be made on specific priorities (*e.g.*, need for multiple beams or X10 rep rate) and target area configurations; workshops will determine priorities. The modular nature of the laser and target area platforms allows a staged approach to construction and operation. Options are in the range 50-150 M$, dependent on community priorities and start date. The system envisaged in this white paper is approximately $100M. Anticipated annual operations costs roughly follow the "10% of construction costs" rule.

The readiness of the facility for construction

Jupiter II will consist of two distinct systems, a multi-petawatt, 10-femtosecond-class laser and a multi-kilojoule laser, both with a one-Hz-or-faster repetition rate. Although this dual configuration will be in the world, both systems have undergone extensive design and technical peer reviews and there are comprehensive delivery plans. Time from project start to first light is 36 months for the short-pulse laser and 48 months for the long-pulse system (the difference permitting phased installation). The designs permit future enhancements but the signal aim is to build a robust, high availability laser facility ready for experimentalists as soon as it's commissioned. The US high power laser and HED community is well established and well suited to completing the final design, delivering the facility and fully exploiting the output.

The scientific community

Capability *and* access are key to the effective utilization and impact of any scientific facility. Jupiter II will serve the large and expanding HED community in the manner of its predecessor, the Jupiter Laser Facility (JLF), but will provide technical capabilities that leapfrog developments in the rest of the world. Jupiter II will be a comprehensive user facility with diverse capabilities open to and attracting the best scientific talent and ideas. Like JLF, Jupiter II will be a largely hands-on facility where students and young researchers can train and develop while performing world-class experiments. Jupiter II will be located in the Livermore Valley Open Campus *outside* the main confines of LLNL, and not subject to badging, computer, and limited hours restrictions.

Impact on US industry

Development of a high energy, diode-pumped laser system could have a dramatic impact on the US laser and semiconductor diode industry. It would create for the first time an industry where the costs of diode systems are competitive with conventional options, and allow the US to establish a synergistic academic/industrial pathway for revolutionizing the application space of high energy lasers.

Sources

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