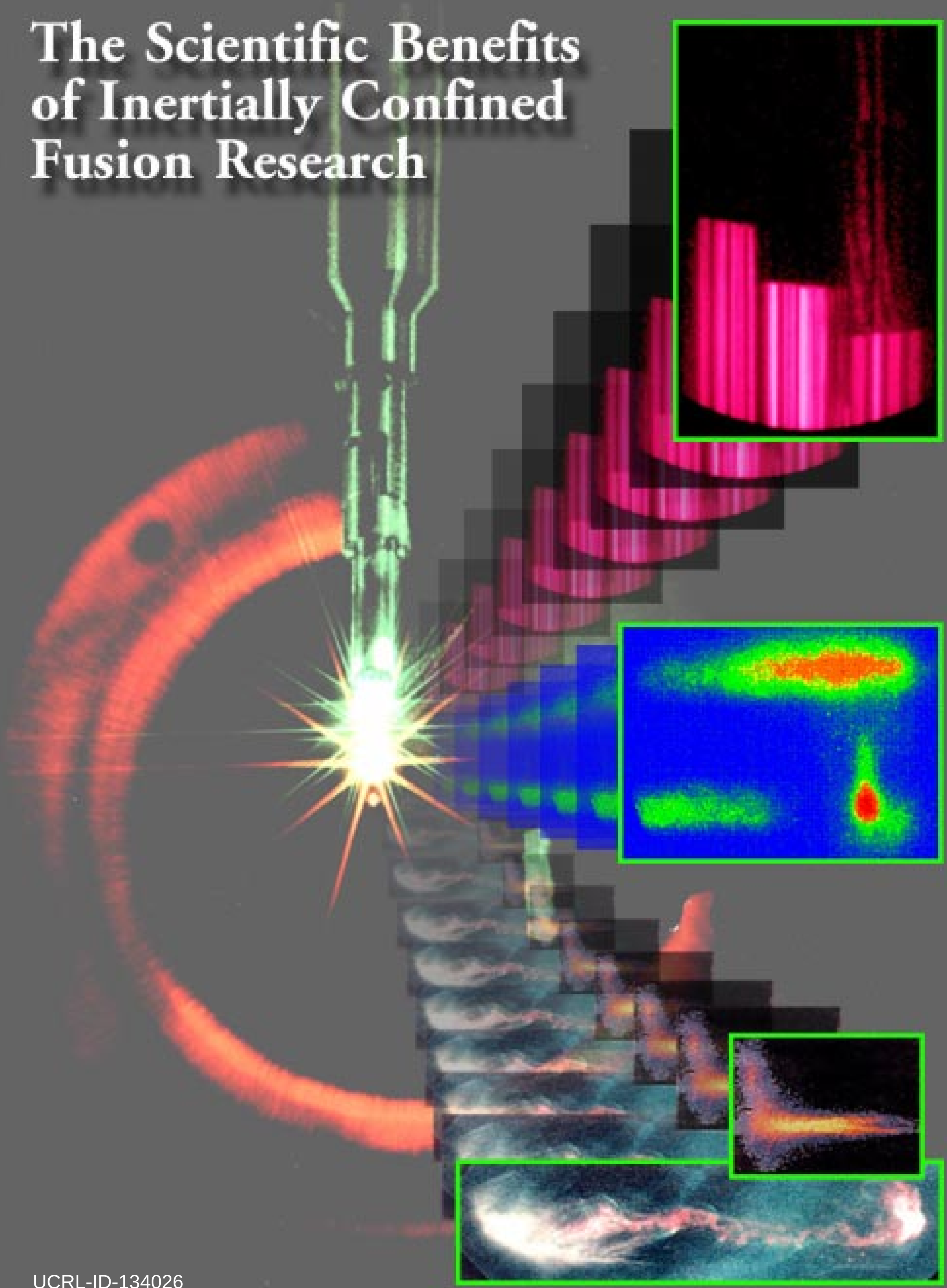
The Scientific Benefits of Inertially Confined Fusion Research



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On the cover

Photograph of a laser-irradiated target with overlain examples of spin-off science.

Top—Data recorded by a velocity interferometer for any reflector (VISAR) in an equation of state (EOS) experiment at the University of Rochester’s OMEGA laser facility.

Center—An example of use of a laser-generated x-ray source to make a streak camera time-resolved diffraction measurement showing a change in direction of Bragg-reflected x rays when an Si crystal lattice is compressed by a shock wave. The data is from the Trident laser facility at the Los Alamos National Laboratory.

Bottom—An astrophysical Herbig-Haro supersonic radiation-cooled jet and (inset) a laboratory analog created at the Lawrence Livermore National Laboratory Nova laser.

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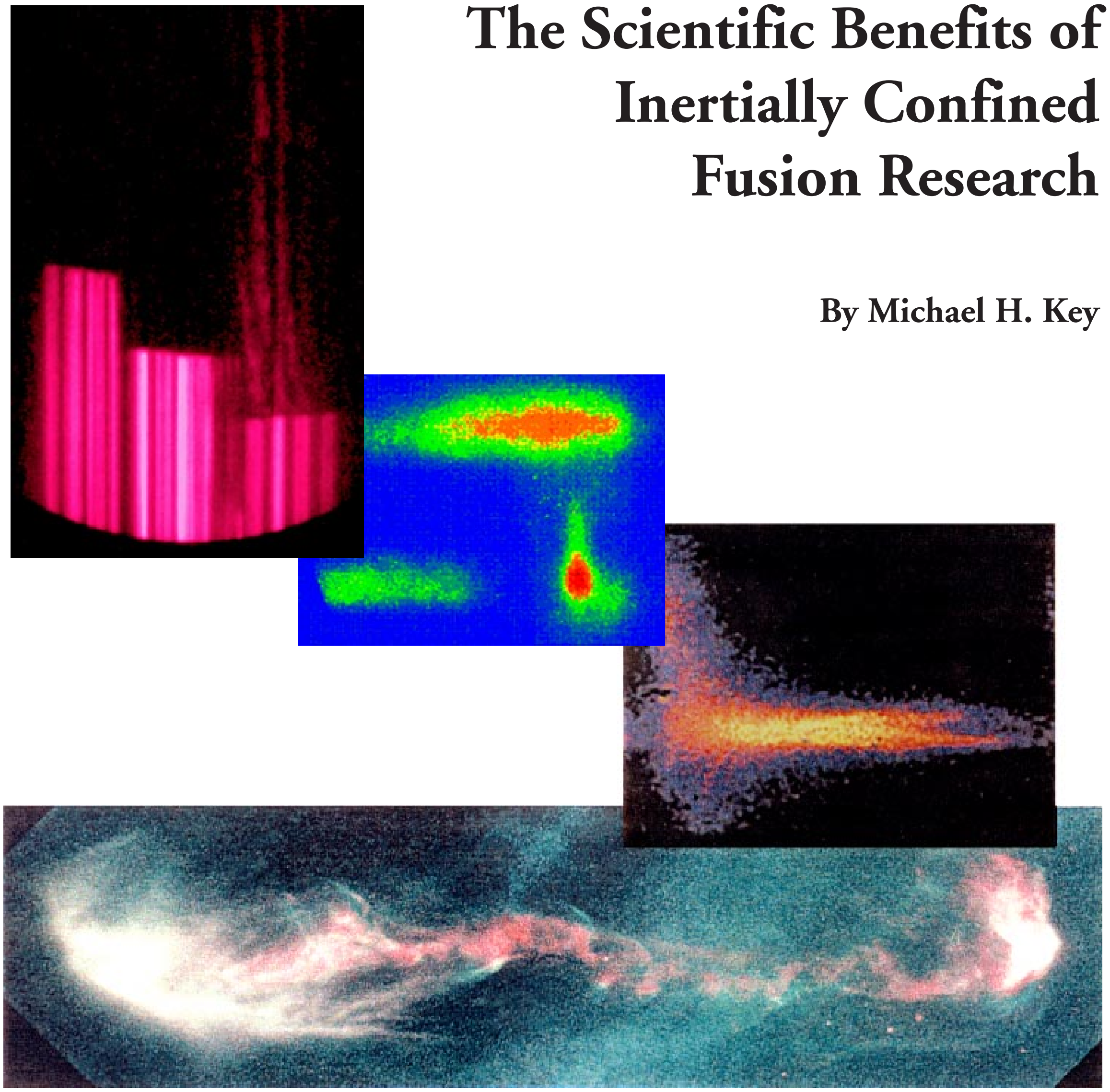
The Scientific Benefits of Inertially Confined Fusion Research

By Michael H. Key



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The Scientific Benefits of Inertially Confined Fusion Research

Introduction

A striking feature of 25 years of research into inertially confined fusion (ICF) and inertial fusion energy (IFE) has been its significant impact in other fields of science. Most ICF facilities worldwide are now being used in part to support a wider portfolio of research than simply ICF. Reasons for this trend include the high intrinsic interest of the new science coupled with the relative ease and low marginal cost of adapting the facilities particularly lasers, to carry out experiments with goals other than ICF. The availability at ICF laboratories of sophisticated theory and modeling capability and advanced diagnostics has given added impetus. The expertise of ICF specialists has also triggered more lateral scientific spin-offs leading for example to new types of lasers and to related developments in basic science.

In a generic sense, the facilities developed for ICF have made possible study of new regimes of the properties of matter at extremely high-energy density and the interaction of ultraintense light with matter.

This general opportunity has been exploited in numerous and diverse specific lines of research. Examples elaborated below include laboratory simulation of astrophysical phenomena; studies of the equation of state (EOS) of matter under conditions relevant to the interior of planets and stars; development of uniquely intense sources of extreme ultraviolet (EUV) to hard x-ray emission, notably the x-ray laser; understanding of the physics of strong field interaction of light and matter; and related new phenomena such as laser-induced nuclear processes and high-field-electron accelerators. Some of these developments have potential themselves for further scientific exploitation such as the scientific use of advanced light sources. There are also avenues for commercial exploitation, for example the use of laser plasma sources in EUV lithography.

Past scientific progress is summarized here and projections are made for new science that may flow from the next generation of ICF and IFE driver facilities. It will be seen that this beneficial spin off strengthens the case for investing in ICF and IFE.

Developments in ICF driver science and technology

The enabling ICF technology for the research discussed here is high-power lasers, fast Z-pinches, and high-current heavy-ion accelerators. ICF and IFE have been major drivers of advances in high-power laser science and technology. The energy output of single-pulse Nd glass lasers and electron-beam-pumped KrF lasers has increased dramatically as a result of ICF research. Construction of megajoule glass lasers is currently underway in the United States[1] and France. There are operational lasers of 1- to 60-kJ capabilities in at least 15 laboratories worldwide. Z-pinch devices have produced megajoules of x rays,[2] and new low-emittance high-current heavy-ion accelerator concepts have been developed. In the quest for IFE drivers of high average power, diode-pumped solid-state lasers (DPSSLs)[3] and electron beam pumped KrF lasers[4] are being developed.

A seminal avenue of laser development that was initiated at an ICF laboratory in 1985 is chirped pulse amplification (CPA) and compression.[5] It enabled amplification of chirped pulses to high energy and their compression to minimum pulse duration limited only by the frequency bandwidth of the laser transition. Coupled with the use of theTi-sapphire laser to generate 100-fs pulses, CPA provided wide availability of terawatt (TW) power at a 10-Hz pulse rate and tabletop scale.[6] The current performance of tabletop systems has been extended to shorter pulses of 10 to 20 fs and to peak power up to 100 TW.[7] CPA in Nd glass also paved the way to the first petawatt (PW) laser[8] constructed in the ICF program at Lawrence Livermore National Laboratory (LLNL) in 1995.

Advances in ICF driver science and technology can be expected to continue at a rapid rate and to enhance further the opportunities for scientific research applications in the future.

Fundamentals of strong field light interaction with electrons

One of the earliest scientific applications of CPA laser technology was the study of strong field interactions with atoms, notably optical field ionization. High-intensity interactions had previously been understood through perturbation theory, but tunneling ionization in electromagnetic (EM) fields that were strong relative to the atomic field showed new behaviors and required new theories.[9] Better descriptions of free electrons in the relativistic limit of their laser-driven oscillatory energy were also developed, and experimental validation of Thomson scattering theory was obtained in this limit.[10]

An excellent example of synergy between University research and ICF research is work at the Laboratory for Laser Energetics (LLE) at the University of Rochester where CPA laser technology was first developed. There, a great deal of effort over the past 10 years was devoted to understanding the tunneling ionization of atoms in intense laser fields, beginning with the ionization thresholds[9] and moving on to the details of ejected electron behavior.[10] Quantum electrodynamics (QED) is at the very foundation of the science of light matter interaction, and the Rochester group in collaboration with scientists at the Stanford Linear accelerator (SLAC) pioneered QED research on interactions of a high-power laser with a high-energy electron beam. This experiment gave the first observation of nonlinear Compton scattering and the production of electron-positron pairs from photon-photon scattering. Pairs were produced from multiphoton interactions, which implies study of nonlinear QED.[11] The experiment used a CPA laser coupled with a flashlamp-pumped slab amplifier, as well as 1.5-ps synchronization of the high-power laser beam with a 50-GeV electron beam.

Dense plasma spectroscopy

Plasma spectroscopy provides a vehicle for understanding the fundamental processes that occur in dense plasmas by employing the spectral properties as a noninterfering probe. This allows diagnosis of the plasma temperature, density, and ionization state as well as providing a test bed for theoretical development. The spectroscopy of highly ionized ions and dense plasmas has advanced rapidly using lasers developed for ICF studies.[12] Emission spectra have been extensively studied to widen the classification of high-Z atom spectra in all ionization stages with ionization potential up to about 7 keV. New theoretical descriptions and related experiments have built up understanding of the complex spectra in unresolved transition arrays, for example in high-Z M-shell spectra.[13] Detailed atomic physics models have given new or better diagnostics of density and temperature based on line intensity ratios. Line-broadening theory has been advanced significantly, and experimental tests have been made in plasmas at densities up to 20 g/cc. Radiation transport modeling has been improved and applied to interesting situations such as the emission of optically thick lines in strong velocity gradients, which in an astrophysical context is known as the Sobolev effect. Related experiments have produced elegant data.[14]

A widely applicable point source projection technique for space-resolved x-ray absorption spectroscopy of laser-produced plasmas was developed and has been applied to opacity studies. Opacity models have been rigorously tested and developed through comparison with experiments.[15]

There are significant opportunities for further work in plasma spectroscopy using the next generation of lasers and Z-pinches to access higher temperatures and densities and larger magnetic fields, etc. Such work will explore specific issues in basic science as well as problems of relevance particularly to astrophysics.[16]

Advanced laser light sources

Laser-generated sources of EUV to hard x rays can produce high single-pulse brightness (as summarized in Figure 1)[17] and have advantages of compact size and shorter pulse duration relative to synchrotron radiation sources. They are complementary to synchrotron sources for applications indicated in Figure 1[18] requiring single pulse or low repetition rate measurements.

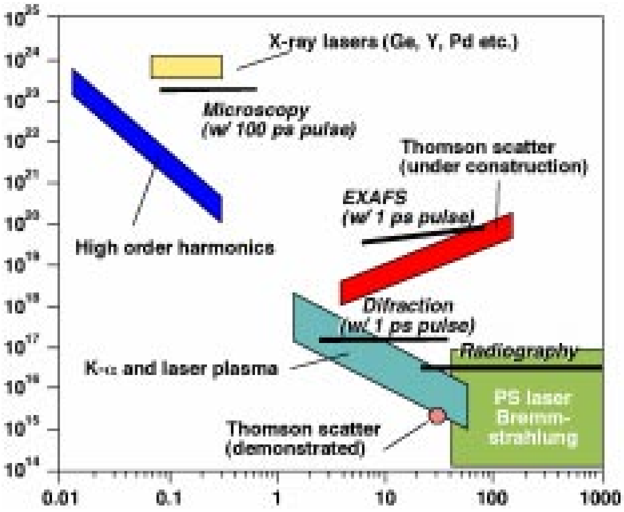

Figure 1. **Brightness of laser-generated sources (in units of photons s^{-1} mm^{-2} $mrad^{-2}$ in 0.1% bandwidth) plotted against photon energy in keV. Indicative brightness levels needed for different types of single-pulse measurements are also shown.**

Thermal plasma emission

Some of the earliest studies of plasma formation using laser irradiation of solid targets established that the hot, dense plasmas generated intense x-ray emission. Later work demonstrated near-Planckian X-ultraviolet (XUV) continua at temperatures up to 300 eV from hohlraum targets. X-ray back-lighting with multi-keV photons from laser generated plasma sources became a standard technique for the study of hydrodynamics in ICF research.[19] Similar backlighting continuum sources were used to develop x-ray absorption spectroscopy of highly ionized ions in cooler plasmas opening the way to measurement of astrophysically interesting absorption spectra discussed later. Repetitively pulsed laser plasma sources were developed, in particular for applications in microscopy and EUV and x-ray lithography.[20] The need for debris-free sources led to the use of laser-irradiated liquid drops, gas jets, and jets of atomic clusters.[21]

The future potential for increased scientific and commercial applications of such thermal plasma light sources is linked to developments in high-average-power pulsed lasers and will be stimulated by the new high-average-power fusion driver laser technology. The higher single-pulse energy offered by upcoming megajoule lasers will lead to more intense thermal x-ray sources from gas-filled targets of large volume and multi-keV temperature, which will emit ionic x-ray lines at near to the Planckian intensity limit.[22]

X-ray lasers

Soon after the 1965 demonstration of the first laser based on the fluorescence of Cr ions in a ruby crystal, theorists began to consider the possibility of x-ray lasers based on much higher-frequency x-ray transitions of highly ionized ions in hot plasmas. It was clear from the outset that the fluorescent intensity must increase to more than the 4th power of the frequency of the laser. This imposed a severe requirement for high-energy density in the plasma, and early work producing plasmas with glass and $C0_2$ laser facilities gave the first encouraging indications of soft x-ray laser amplification.[23] The experimental breakthrough to the demonstration of a really high gain and near-saturated soft x-ray laser came in 1984. The experiment used two 5-kJ prototype beamlines of the Nova ICF facility, the most powerful and energetic in the world at that time, and gave megawatt-pulsed laser action at 20-nm wavelength in 24-fold ionized neon-like Selenium.[24] Other ICF-oriented laser facilities worldwide were quickly able to emulate and extend this research, which established a new branch of laser physics and still provides the brightest sources of single-pulse soft x-ray emission at wavelengths from 50 to 5 nm, as illustrated in Figure 1. Recent work has shown that similar laser power in picosecond pulses can now be obtained with driver energy less than 10 J from CPA lasers.[25]

Extension of x-ray laser action to still shorter wavelengths is an objective of current research. There is particular interest in biological microscopy and holography in the water window region from 2.3 to 4.4 nm. The severe scaling laws on fluorescent intensity suggest that progress will be linked to the next generation of PW class lasers, the development of which is strongly coupled to fast-ignition research in ICF /IFE.

Harmonic generation

One of the most dramatic manifestations of the new strong field science studied with CPA lasers is high harmonic generation[26] in the interaction of subpicosecond pulses with atoms in gas jets. Odd harmonics to extremely high orders are observed with a broad plateau of conversion efficiency encompassing many harmonics as illustrated in Figure 2.[27] The current "record" is the 296th harmonic of the Ti- sapphire laser at 2.7 nm.[28] The high brightness shown in Figure 1 and short-pulse duration of these harmonic sources are leading to their increasing use for scientific applications as tabletop TW lasers become widely available. Both odd and even harmonics (up to the 75th) of higher power (up to 25 MW) but greater angular spread are generated in 10^{19}- Wcm^{-2} picosecond pulse interactions with solid targets when there is a very steep plasma density gradient.[29]

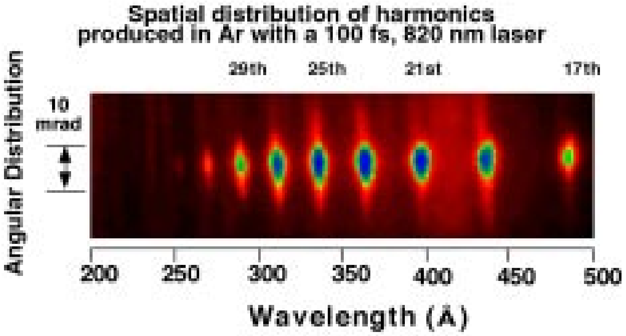

Figure 2. Example of XUV harmonic generation in a gas jet showing highly collimated XUV emission.

Electron Bremsstrahlung and Kα sources

The study of laser plasma interactions in ICF research revealed at an early stage intense parametric excitation of plasma waves, and the damping of those waves resulted in suprathermal or "hot" electrons. The hot electrons were seen to excite Kα line radiation and Bremsstrahlung continuum emission in solid targets in a manner analogous to an x-ray tube but with short-pulse duration, high intensity, and small source size.[30] These sources of x-rays have found applications in which their pulse duration is in the picosecond domain and allows measurements of fast transient phenomena.

Extension of the intensity of laser plasma interactions to the relativistic energy range for free electrons in the EM field of the laser (> 2 x 10^{18} Wcm^{-2}), produces relativistic electrons that in turn generate intense MeV x rays and provided a novel and uniquely bright source for MeV radiography[31] of very dense objects.

Larmor radiation at relativistic intensities
The classical process of Thomson scattering caused by dipole radiation from EM-driven oscillation of free electrons is significantly modified when the oscillatory motion is strongly relativistic. The theoretically predicted result is intense directional Larmor radiation shifted to frequencies in the EUV to the soft x-ray region.[32] Though it has not yet been demonstrated as a practical light source, there are interesting prospects for Larmor radiation associated with the next generation of ultrashort-pulse lasers.

Thomson scattering from strongly relativistic electron beams
Relativity effects in Thomson scattering are also introduced through scattering from a beam of relativistic electrons. It has recently been shown that well collimated 30-keV x-ray pulses can be generated in this way using a 0.8-TW, 80-fs laser scattered from a 40-MeV electron beam at the Lawrence Berkeley Laboratory Advanced Light Source (ALS) accelerator.[33]

In a current project at LLNL it is planned to use a 100-TW, 30-fs laser scattered from a 150-MeV Linac of higher pulse current and lower emittance than the ALS. This project should deliver subpicosecond pulsed x rays from 5 to 300 keV of brightness (see Figure 1) sufficient for a wide range of single-pulse time-resolved measurements. Such Thomson sources will be more compact and affordable than, for example, undulators at synchrotron radiation facilities.

Applications of advanced light sources

Scientific measurements
Applications of laser-generated EUV to hard x-ray sources are most favored where short-pulse duration is needed to time resolve fast transient processes by radiography, diffraction, EXAFS, microscopy etc. A good example, from work at the University of California at San Diego, is a study of picosecond time scale coherent phonon propagation in GaAs using diffraction of CuKα x-rays generated with a 20-fs laser pulse.[34] Other applications include time-resolved diffraction on shock waves in crystals, a technique that can yield information on phase transitions and evolution from elastic to plastic compression.[35] The cover illustration shows a streak camera time-resolved image of diffracted x-rays from a Si crystal.[36] The time axis is horizontal and spans 2 ns. On the vertical axis there is a shift in direction of Bragg-reflected x rays as a shock compresses the crystal lattice.

In the future, core level spectroscopies such as EXAFS and XANES could be used to diagnose the time dynamics in chemical reactions by yielding information on the location of atoms as they move within reacting molecules. Even ultrafast dynamics in biological systems might be probed with these x-ray sources, via Laue diffraction in various photoactive protein crystals. An example of a biological application is shown in Figure 3, where pulsed x-ray diffraction is used to probe photo-stimulated structure changes in purple membrane.[37]

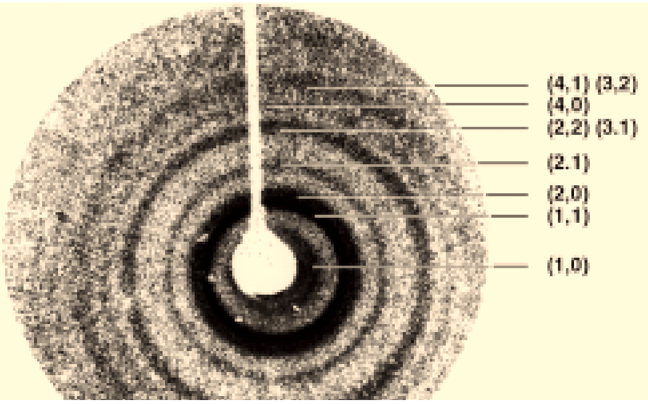

Figure 3. **Subnanosecond exposure x-ray diffraction from dried purple membrane of the halobacterium halobium.**

X-ray lasers have been applied to single-pulse time-resolved measurements in biological microscopy and radiography[38] or interferometry of laser plasma hydrodynamic phenomena as illustrated in Figure 4.

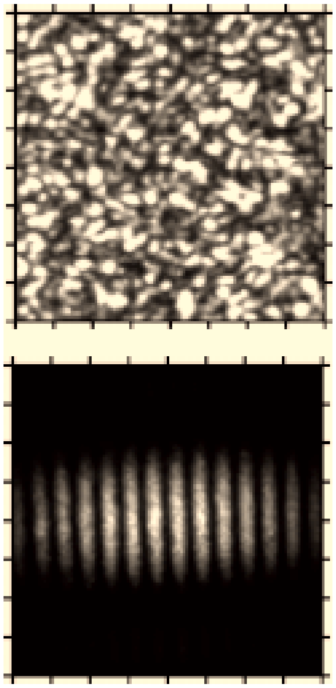

Figure 4. X-ray laser radiographs of 200-μm square sections of Al foil 2 μm thick undergoing laser-driven ablative acceleration and showing few percent changes in thickness with micron-scale patterns. The data recorded at the Rutherford Appleton Laboratory Vulcan laser facility, show thickness perturbations from random phase smoothing (above) and a single-mode drive pattern (below).

Gamma–gamma collider

An extreme case of the application of scattering from relativistic e-beams is the possibility of future high-energy physics experiments at the proposed Next Linear Collider (NLC) facility. It is envisaged that gamma–gamma (gg) collisions be produced at photon center-of-mass energies of several hundred GeV, and with luminosity comparable to e+e- collisions. The physics potential is unique and complementary to e+e- collisions that will be studied at the NLC. Two examples are described here. The first concerns the cross section for gg resonant creation of a Higgs boson. The cross-section is sensitive to all possible charged fermions, independent of their mass. It could indirectly detect the existence of a previously undiscovered “fourth generation” consisting of a new charged lepton (a heavier cousin of the electron) and a new quark doublet, even though their masses might be far greater than the energy capability of any accelerator to produce them directly. The second involves possible evidence of strong gravity and new dimensions in gg experiments with 250-GeV photons. Very recent theoretical work demonstrates that such experiments could discover or exclude the existence of strong gravity, at energies a factor of 10 higher than the center-of-mass energy of the colliding photons.

The photon beams would be produced by scattering laser light on two opposed electron beams of 250 to 500 GeV at the NLC facility. The laser for such experiments would be a spin off from CPA laser development. It would be required to deliver 1-TW, 1-ps pulses in 100-pulse bursts in a 300-ns interval at 120-Hz rep rate. This specification is challenging but achievable.

Particle accelerators, sources and beams

The parametric processes coupling laser light to plasma waves, much studied in ICF research and creating unwanted hot electrons, provided the foundation for a new branch of electron accelerator science in which the accelerating fields in plasma waves can exceed by a factor 10^4 those of conventional radiofrequency accelerators and reach 200 GeV/m. The first accelerator experiments were based on the beat wave concept in which two frequencies in a laser beam generated a beat frequency in resonance with the plasma wave. The initial work was with both Nd glass lasers that were also used for ICF research[39] and with CO_2 lasers whose technology had earlier been developed in the ICF program.[40] Injection and acceleration of electrons was first demonstrated in beat wave experiments. A self-modulated beat wave (SMBW) process that occurs through stimulated forward Raman scattering was later found to give a simpler acceleration process generating without an injected beam, up to

44-MeV electrons from gas jet targets irradiated with a 20-J, 0.8-ps CPA laser.[41] A more compact SMBW experiment using a 3-J, 400-fs CPA laser has produced 0.5 mJ of >1-MeV electrons in a 10° beam angle.[42] A similar CPA laser has produced impulse excitation of a wake field,[43] giving an alternative acceleration process that has been shown to have a field of 1.5 GeV/m and to add 1.5 MeV to the energy of injected electrons. Free wave interactions of electrons in a vacuum focus of an intense laser have also been shown to be useful for laser acceleration.[44]

Future potential in this area is for compact tabletop accelerators of few MeV electrons, and there is long-term research interest in the possibly of advanced high field accelerators for future high-energy physics research.

Energetic particles from laser–matter interactions can be significant sources in themselves. PW lasers generate relativistic electron beams of uniquely high current[45] and modeling predicts magnetic fields exceeding 100 mega-gauss.[46] The electrons induce secondary Bremsstrahlung of sufficient intensity and photon energy to produce up to 10^{-13} fractions of photonuclear transformation of atoms in solids.[47] Figure 5 illustrates how laser-induced photo-fission of uranium and photo nuclear effects in Au and Cu give an estimate of the spectral intensity of the Bremsstrahlung in the >10-MeV spectral region. Electron positron pair production is also observed. Radioactive isotopes and intense pulsed neutron emission are produced. Relativistic electron pressure drives ion expansion from laser irradiated targets, and ion beams with up to 50 MeV per nucleon have been observed.[48] Conversion of up to 10% of laser energy to proton beams in this way has enabled secondary production of nuclear interactions giving pulses of 3 x 10^{10} neutrons and related nuclear transformations, activation, and radioactive isotope production.[49] The extreme conditions are possibly relevant to some astrophysical phenomena discussed later.

Fusion neutrons are also readily produced in several ways. Most recently production of deuterium-deuterium fusion has been demonstrated at tabletop scale in CPA laser irradiation of deuterium clusters in a gas jet.[50]

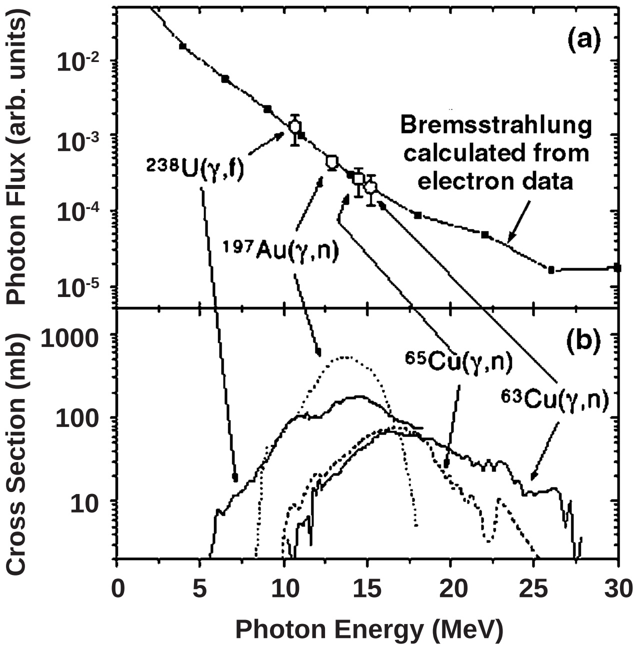

Figure 5. **(a) Laser-generated hard x-ray spectral intensity data points inferred from photonuclear processes and continuous spectrum inferred from the measured laser-generated relativistic electron energy spectrum, (b) photonuclear cross sections.**

The effort to develop heavy-ion drivers for ICF has led to much improved understanding of space charge limited beams in accelerators.[51] The advances are scientific and conceptual, but there has also been additional beneficial spin-off in the use of the high-current beam codes in accelerator projects in high-energy physics (e.g., LEP curvature aberration) and medicine (e.g., Imitron space charge and neutralization).

High-pressure hydrodynamics and energy transport in dense plasmas

Widespread advances in understanding high-pressure hydrodynamics have been made using lasers. The major hydrodynamic instabilities, Rayleigh-Taylor, Richtmeyer-Meshkov and Kelvin Helmholtz, have been studied as single and multimode phenomena, and the transition to turbulent mixing has been better understood.[52] X-ray backlighting measurements have been the tool of choice for this research.[53] Modeling has advanced to three-dimensional description of the instabilities. Laser-driven ablation fronts, shock waves and supersonic heat waves, and Marshak waves driven by Planckian thermal radiation have been investigated. Improved descriptions of electron thermal transport where mean free paths exceed the temperature gradient scale length have been developed.[54] Much of the work has been relevant to ICF, but a substantial part is of more basic scientific interest.

Laboratory astrophysics

Many astrophysical phenomena involve the hydrodynamics and radiation physics of plasmas, and recent research has shown that they are amenable to scaled simulation in laboratory experiments with laser-generated plasmas.[55]

Supernovae

In supernova explosions, dense material from the gravitational collapse of the Fe core explodes outward and is decelerated by surrounding lower-density stellar matter, in particular the He and H layers. There is hydrodynamic instability at the He/H density discontinuity due to Rayleigh-Taylor and Rictmeyer-Meshkov instability as illustrated in Figure 6, which shows modeling of supernova 1987A. The light curve of the supernova gives experimental information on the time scale of the event. In SN 1987A, spectral data indicated that unstable penetration of Ni into the outer low-Z matter was faster than expected from the theoretical modeling. Differences between two- and three-dimensional behavior may be important here as the modeling is in 2D. A laboratory simulation in cylindrical symmetry was carried out at the LLNL Nova laser using 10-Mbar pressure to drive a solid Cu cylinder outwards into lower-density CH. The gated x-ray backlit images also shown in Figure 6 are a scaled replica of the Supernova instability and are being used to assess the accuracy of theoretical models.[56] Future work will compare spherical and cylindrical instability growth rates. Similar modeling and laboratory experiments are addressing the predicted behavior of the next phase of the same supernova, which is the impact of on the circumstellar nebular ring of the expanding blast wave and ejecta. Detailed astronomical data are anticipated in the course of 1999, which will test the theory and laboratory simulations.

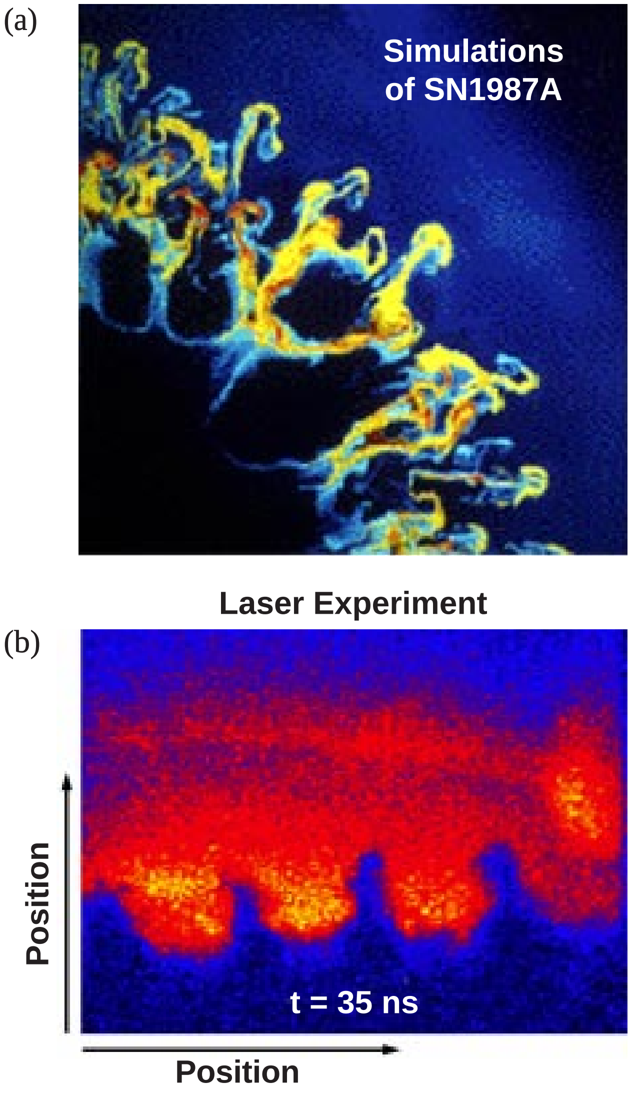

Figure 6. (a) Numerical simulation of instability in supernova SN1987A and (b) laser experiment scaled to represent equivalent instability and recorded by gated x-ray backlighting.

Radiatively cooled jets

Astrophysical jets known as Herbig-Haro objects (an example is shown on the cover) are thought to be supersonic ejecta from newly forming stars. Their hydrodynamic behavior is strongly influenced by radiation cooling, which causes narrowing and density increase. Laboratory simulation of such jets has recently been demonstrated in experiments at the LLNL Nova laser and the Japanese Gekko laser[57] (shown also on the cover). Here the jet is created by laser irradiation of a conical depression in a solid target. Plasma ablation from the conical walls creates a collision on the axis and launches the supersonic jet into the vacuum. The radiation-induced narrowing and cooling observed in the laboratory is being correlated with detailed modeling of the hydrodynamics and radiation physics.

Astrophysical strong shock waves

Shock waves in astrophysical phenomena such as Supernovae 1993J are typically strongly influenced by the effects of radiation from the shock on the unshocked matter. With very high initial energy density in laser-produced plasmas, it has recently become possible to study radiation dominated shocks in the laboratory and current research is examining the possibility for useful similarity mapping between the astrophysical and laboratory situations.[55] A related issue arises in which astrophysical shocks are collisionless and magnetized as in the remnants of SN1006. Here the electrons are at only 25% of the ion temperature, raising questions about the efficiency of magnetic turbulence for heating the electrons. Again, there are real possibilities for creating magnetized collisionless shocks in the laboratory using laser-produced plasmas.

Gamma ray bursts

One of the greatest enigmas of current astrophysics is the observation of 0.1 to 10-MeV gamma-ray bursts (GRB) of a few seconds duration.[58] Their millisecond rise time indicates a spatial origin of only 10^7 cm, but their luminosity implies 10^{53} radiated ergs per burst. The spectrum has a power law rather than Planckian shape to high energies, and the radiated power exceeds the Planckian limit for the source size at temperatures consistent with the spectrum. Attempts to understand the physics of GRBs center on extreme rates of acceleration of particles in a quark-gluon fireball resulting from the collision of neutron stars. There is interest in the similarity of the spectra with spectra radiated from solid targets in PW laser experiments where electrons also experience abrupt acceleration. While it is too early to identify a clear opportunity for laboratory simulation, there are suggestions of novel research possibilities.

Unruh/Hawking radiation

The celebrated prediction from general relativity of “thermal” Hawking radiation from extreme acceleration at the event horizon of black holes can be linked to laboratory physics through the acceleration of free electrons by extremely intense laser light. Unruh radiation is the accelerated particle analog of Hawking radiation,[59] and there are predictions[60] that it may be detectable against the background of relativistic Larmor radiation from free electrons with the next generation of ultrahigh-intensity lasers at intensities of more than 10^{22} Wcm^{-2}.

Electron-positron plasmas

Nonthermal electron-positron plasmas are known to be abundant in many astrophysical environments from pulsars to quasars. In the last few years discoveries of intense spectrally broadened 511-keV annihilation radiation from several galactic black hole candidates suggests that steady-state thermal pair plasmas may also exist. Since pairs annihilate on very short time scales, to maintain steady state plasma over such long times the pairs need to be created prolifically to balance the annihilation rate. Already substantial positron production has been observed in laboratory experiments with a PW[61] laser, and it has been suggested that future PW laser experiments might access conditions in which electron positron plasmas could be created and studied in the laboratory.[62] Such thermal plasmas represent a new state of matter with unique thermodynamic and radiate properties drastically different from ordinary plasmas.

Stellar opacity and the physics of Cepheid variables

The development of experimental techniques for time-resolved absorption spectroscopy of laser-produced plasmas and the availability in ICF programs of sophisticated modeling of the opacity of plasmas opened the way to experiments and modeling designed to determine opacity spectra of crucial importance for stellar models. The predicted harmonic ratio P_0/P_1 of the pulsation in Cepheid variable is sensitive to opacity and agreement between the independently determined mass, and the harmonic ratio has recently been obtained with improved opacity modeling.[63] Experimental measurements of the opacity of plasmas of astrophysical interest have been made, notably for plasmas with a small fractional concentration of Fe, using both lasers[64] and the Sandia National Laboratory PBFAIII Z machine.

Dense matter physics

Study of the EOS of dense matter has been advanced to pressures up to tens of megabars using laser-driven shock waves. This class of experiments, which has a scaling of accessible pressure with laser energy as $E^{2/5}$, was developed at high-energy ICF facilities motivated in part by ICF research goals, but it has much more general applicability. Both lasers and the PBFAIII Z have been used for such studies. Experiments with single shocks follow the shock Hugoniot and give density increase up to a factor of four. A recent study of the compression of liquid deuterium at pressures from 0.2 to 3.4 Mbar using the LLNL Nova laser[65] revealed unexpectedly high compressibility. This is now understood as linked to pressure-induced molecular dissociation and formation of metallic hydrogen. The associated onset of conductivity has been observed through the reflectivity of the shock front. The results, which are plotted in Figure 7, were obtained from measurements, which include velocity interferometer data as illustrated in the cover picture. Similar metallic transitions have been seen in diamond and LiF. These experiments have significant basic science interest and are relevant also to planetary science.

In the future, experiments will study off-Hugoniot states of higher density and lower temperature using diamond anvil production of precompressed initial states and subsequent near-isentropic compression by multiple shocks. A radically different aspect of nuclear fusion may then become accessible to experimental study with very energetic lasers of megajoule class. Pycnonuclear fusion is predicted to occur when the proximity of nuclei in cold compressed liquid deuterium-tritium allows tunneling through the Coulomb barrier at densities of more than 100 g/cc and temperatures less than 1 eV.[66] Any laboratory verification of pycnonuclear fusion theory would be of considerable importance for modeling of supernovae, which uses this presently untested theory. Finally with sudden temperature quenching, there could be a breakthrough to the creation of metastable metallic hydrogen predicted to exist at about 10X liquid density and room temperature.[67]

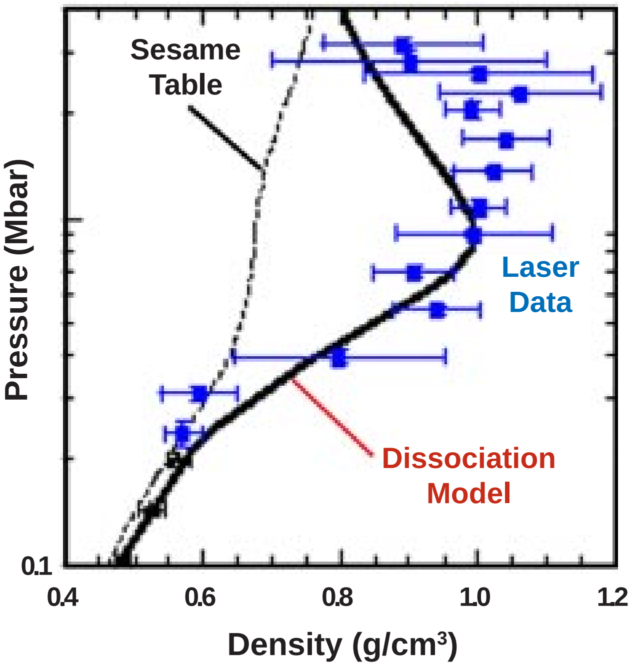

Figure 7. Laser data and modeling of the EOS of liquid deuterium.

Planetary science

A natural extension of the previously discussed dense matter studies is to conditions relevant to giant planets such as Saturn and Jupiter or brown dwarf stars with pressure and density in their predominantly hydrogen cores illustrated in Figure 8. These bodies will never undergo

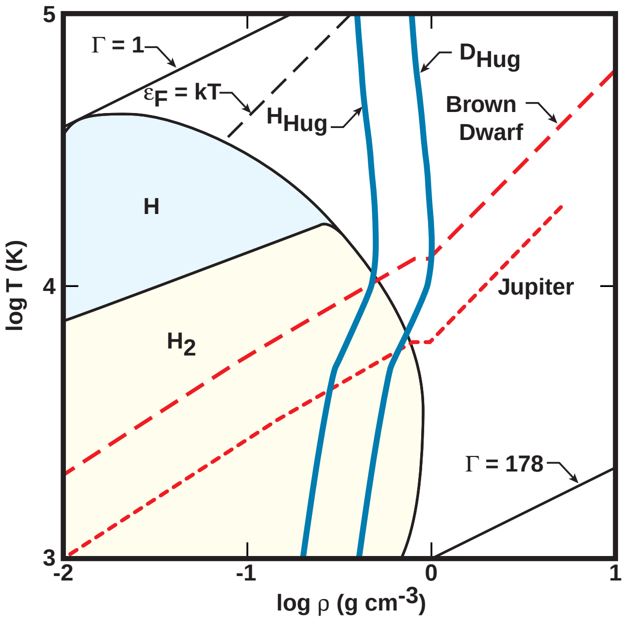

Figure 8. Density and temperature of hydrogen in Jupiter and a Brown Dwarf. Phase boundaries, degeneracy ($E_f > kT$), and strong coupling ($\Gamma > 1$) regimes are also shown.

thermonuclear burn, and their interiors consist of stable degenerate strongly coupled plasmas. Their most abundant constituents are H, He, H_2O, N2, Si, and C. The EOS and phase transitions of these materials are practically unknown in the relevant pressure and density range. Transitions to conducting phases such as protonic conduction in H_2O are particularly important for understanding of planetary magnetic fields. There are puzzles and challenges to our understanding including seismic oscillations, an enigmatic excess of infrared radiation, and magnetic quadruple fields, which may be linked to the complexities of the EOS of matter in the giant planets. Experimental techniques for EOS measurements are already available. The experimental challenge is to generate off-Hugoniot compression with minimum temperature increase in order to follow the relevant compression trajectories, for example pressures up to 40 Mbar and temperatures as low as 2 eV at the center of Jupiter. This new line of research is attracting significant current interest.

Discussion and conclusions

The spin-off scientific benefits detailed here are clearly important in their own right. Arguably they also provide an additional motivation for investment in ICF and IFE research. With appropriate planning, such spin-off research can be carried out at low marginal cost, and it may attract support from multiple agencies. There is a strong previous track record and a significant future potential in this scientific exploitation of ICF/IFE facilities and expertise.

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