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Future Scientific Applications for High-Energy Lasers

August 1, 1994

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I) Introduction

A) Background Comments

Interest in the development of a broad-based scientific community for the use of high-energy lasers can be placed in the wider context of the already existing scientific user communities in the other parts of the world. In the United Kingdom, France, Germany, and Japan there exist high-energy lasers, supporting diverse programs of work based, to various degrees, on scientific user communities. For a combination of reasons the development of the same diverse scientific user base has not occurred to any large degree in the USA, although we have had world-class high-energy lasers since the inception of these facilities in the early 1970's.

First and foremost is the inescapable fact that the Inertial Confinement Fusion (ICF) program in the USA has had a substantial classified component, and this has created an impediment to the free transmission of information. Although there have been unclassified components of the ICF program in the USA, the residual effect of classification was to stunt growth in the scientific community. As mentioned above, this must be seen against a world-wide background where scientific-based communities have flourished. Thus, one could not easily explain a lack of development here as an indication of a lack of relevance of the high-energy laser to basic or applied science or its incompatibility with scientific investigations.

Recent changes have modified the prevailing atmosphere and will hopefully be beneficial to the development of a scientific user community. The first of these changes is very recent, December of 1993, with the declassification of the concept of indirect, or radiation, drive ICF, which was the dominant program. This declassification is a result of a number of politico-economic adjustments, including the easing of the East-West tension and a commitment from Department of Energy (DOE) to make a transition into this less-than-Cold-War era. Second, there is the active pursuit of a "dual-use" strategy, which in the present case can simply be seen as a concerted effort by the DOE and other government agencies to have their capabilities utilized more broadly. Third, and importantly, are the changes that are now taking place in the ICF program in response to this new climate. There is now a commitment to scientific applications of high-energy lasers. These set the stage for this document.

The changes that have been occurring in the ICF program, the DOE, and in the USA generally, only lay the foundation for this quest for scientific participation; successful development of a user community is not guaranteed by our commitment alone. Actions are necessary. The first act for the scientific user community is manifest in the present document, which arises from a science applications workshop held in keeping with the key decision (KD) process. This process, which provides the DOE a framework to evaluate large-scale facility proposals, is at the second step for the next-generation high-energy laser facility. This facility is called the National Ignition Facility (NIF), after its ICF goals. In this step, called KD1, a number of criteria must be met, and one of those requires a statement of justified need based on the utilization of the facility. That is, then, the origin of this document.

The second action will be the development of a viable scientific user community. We have several years to develop a user community for the use of such lasers as the multi-megaJoule NIF, and it is important to start now to help better define, and refine, the NIF to be a far more capable facility than has ever existed before. With these two steps in mind we present the following.

B) Defining The Scientific User Community

Through the participation of numerous scientists from around the United States and the world we have compiled a set of experiments that are considered exciting and important, arising from diverse areas of scientific investigation. We have solicited suggestions through two main avenues. First, a workshop on scientific applications of high-energy lasers was held on March 21 and 22, at the University of California at Berkeley, Clark Kerr campus. This workshop addressed the experimental possibilities that could be pursued on high-energy laser facilities leading up to and including the next-generation high-energy, high-power laser, the National Ignition Facility. The second avenue has been through continued and extended discussions on topics that arose during the process of organizing the workshop and at the workshop itself.

1) The Workshop: The first avenue for developing a scientific program

The hosts and co-organizers of the workshop were R. Lee of LLNL, together with N. Luhmann of U. C. Davis and R. Falcone of U. C. Berkeley. A wide range of scientific areas was covered by the participants in a process that evaluated relevant scientific areas of importance addressable on these high-energy laser systems. The areas covered were divided into six broadly based working groups : 1) Astrophysics, 2) Hydrodynamics, 3) Material Properties, 4) Plasma Physics, 5) Radiation Sources, and 6) Radiative Properties. The meeting was organized in the following way. There were few (only four) half-hour talks spread over the two days. These were talks on the "Development of Nova as a User facility" presented by J. Kilkenny, "An Overview of Applications on High Energy Lasers" presented by R. Lee, "A Report on Previous NIF Workshops" presented by S. Libby, and "Extrapolations to the NIF" presented by D. Dearborn. The meeting started with the first two talks. Then, by mid-morning, the plenary session broke up into the sub-area working groups to develop plans and experiments.

The afternoon started with the third talk and we resumed with the working group sessions. On the second day, we started with the last talk and then proceeded with a review, in plenary session, of the working group ideas. In the afternoon, there was another plenary session where the ensemble discussed the special requirements of the scientific community. A list of these special requirements is provided in Section V.

A brief summary of the results of the meeting is as follows:

- There was a very strong interest in participating on experiments on high-energy lasers.
- A large number of novel ideas seemed to be generated covering a wide range from modeling supernova hydrodynamics and generating matter where relativistic effects can be studied, through the generation of test beds for radiation transport studies in hot, dense matter.
- The facilitators from each of the sub-area working groups continued to work with participants to critically evaluate the ideas, and have written up the proposed applications. This first stage of this work is completed, as witnessed by the current document; however, we are continuing to develop and expand the idea base through increased contacts with the scientific community.
- The community as a whole was very strongly in favor of developing a user group as soon as possible. The group felt very strongly that to be a viable community when

the NIF becomes operational they need to start now on present-day high-energy laser facilities.

- An *ad hoc* committee to write a charter for the scientific users' organization convened on June 4, 1994 at the University of Maryland. This group made a first attempt to determine the requirements of the community with respect to funding, scheduling, cost sharing.

From the workshop it was clear that the scientific community was enthusiastic. However, their enthusiasm is predicated on the assumption that they can begin to build the capability with this generation of high-energy laser facilities. The fact that this rather impressive group of scientists from diverse field of science are ready to start the long process of building themselves into a viable community is the single most emphatic statement of support that anyone can imagine: these scientists are willing to go to work on high-energy lasers now.

The plan for the user group, as it evolved during the workshop, was to build a science-based community to perform high-energy-density research on the high-energy lasers. This would satisfy several aspects of the plan that are considered paths to the future of DOE Defense Programs. First, this promotes, in the fullest sense of the words, a collaborative dual-use facility for the future. Second, it would allow us to develop the foundation of the conceptual science based Stewardship program.

These scientists will form the core of the resource base that trains individuals to perform experiments relevant to the other pillars of the NIF and current ICF facilities—the inertial fusion energy (IFE) community and the community involved in Security (the Weapons Physics community and the Weapons Effects community). These communities, taken together with a viable science-based users' organization, form a strong supporting structure for the NIF, for the DOE, and for the country.

2) Extended Discussions: A second avenue for developing a scientific program

Second, we have continued to explore research topics by communication with scientists who have expressed interest in the use of high-energy lasers, many of whom attended the workshop. Additionally, we have pursued ideas put forth by scientists who were interested in the application of high-energy lasers, but were unable to attend the workshop. A list of the totality of those involved in the process has been compiled and is included at the end of this document (see Section VI).

These two avenues have produced a number of intriguing possible applications which will be found below. The method used to evaluate the many proposed topics of interest was a straightforward analysis of the applicability of the suggested research to the high-energy laser facilities of central importance here. We have relied on outside contacts, as mentioned above. Further, we have depended especially on the individuals who have worked as facilitators in the various broad areas that were laid out for the workshop. These individuals have been the central focus for the areas and have coordinated the written contributions. Since the bulk of the effort in the production of the document belongs to those that have contributed written material, we list them here:

R. Berger, J. Castor, L. Collins, L. Da Silva, Dearborn, R. Falcone,
U. Feldman, N. Holmes, S. Kahn, L. Klein, W. Kruer, R. Lee,
E. Liang, B. MacGowan, G. Matthews, Paul Miller, B. Remington,
J. Seely, J. Weisheit, N. Woolsey

It is by virtue of the hard work invested by these individuals that this document exists.

II) Summary of the Scientific Projects

In each of the following areas a brief summary of the ideas brought forth for applications of high-energy laser is presented. The section facilitator has been given the majority of the writing responsibility, while the contributors to the sections are also noted. The affiliations of the contributors can be found in the list of participants (see Section VI).

A) Astrophysics and Space Physics

Facilitator: John Castor

Participants: D. Arnett, D. Dearborn, M. Horanyi, S. Kahn, L. Klein, K. Kumar, J. Luhmann, G. Matthews, B. Remington, D. Savin, D. Schramm, T. Weaver, J. Weisheit, S. Woosley

The reason for considering experiments on high-energy-density plasmas in connection with astrophysics and space physics is simply that such plasmas are a dominant aspect of many astronomical objects, whether in our solar system, in other stars, or in other galaxies. The astrophysicist or space physicist is faced with the problem of deciphering the few clues the observations provide in order to learn about the objects' nature. The clues most often consist of plasma radiation, and to learn about the astronomical objects a full familiarity with what plasmas actually radiate is needed. In other cases the theoretical astrophysicist or space physicist builds up a complete conceptual structure of the object, and then tests aspects of the structure against the observations. In this case the dynamics of plasmas forms one of the basic building blocks of the theory, but it requires observational support itself.

The goal of astrophysically motivated laboratory experiments is to create in the laboratory a sample plasma similar to what would be found in the astronomical body, then study its properties—its radiation or its thermodynamic state, whatever aspect is critical in the astrophysical picture. The properties that are studied will be found under the other project headings of this report: Hydrodynamics, Material Properties, Radiative Properties, and so on. Astrophysics does not, in general, provide *new* plasma properties that need to be studied, but rather gives a specific motivation for studying certain of the ones already known.

The discussion in Section III will highlight a few instances in which there is a specific astrophysical motivation for studying a particular plasma. Among these are the radiative opacity of the outer envelopes of stars, key to our understanding of how stars evolve; the equation of state of stellar material, which is a major determinant of how dwarf stars behave—the white dwarfs left over at the end of stellar evolution and the brown dwarfs that are the failed almost-stars. There is a close connection between the powerful tools of plasma spectroscopy and the astronomer's inference of conditions in the violent inflowing spiral of material surrounding a neutron star or a black hole that may lie at the center of a quasar. This very hot material can be recreated in a high-energy-density laboratory experiment. In other experiments we can study a fundamental physical process—mixing at hydrodynamically unstable material interfaces—that is important in many places in astrophysics, such as in supernova envelopes, and in terrestrial applications as well.

Astronomy provides some of the driving interest in these and other laboratory experiments, and it also provides another laboratory and an additional data set. Merging these data will improve our knowledge of the universe, as well as our understanding of the behavior of matter found here on earth.

B) Hydrodynamics

Facilitator: Paul Miller

Participants: P. Demotakis, B. Hammel, L. Klein, P. Marcus, T. Peyser, B. Remington, Ö. Savas

High-power, laser-based facilities can furnish excellent opportunities to conduct advanced fluid dynamics experiments. This has been amply demonstrated with current experiments on Nova, and expanded possibilities for further investigations can be envisioned for the NIF. The capability of a laser to deposit a large quantity of energy in materials over large spatial scales and long times, and at high energy-densities means that it will be able to generate hydrodynamic flow conditions more extreme than those obtained with the more familiar machines such as wind tunnels or shock tubes. This is especially true concerning the creation of very high-density, high-temperature volumes of material, which may be used to drive strong shocks and high-velocity flows.

The extensive set of diagnostics available to study laser-produced flows facilitate measurements of the quantities of interest, including interfacial geometries, velocities, densities, and/or temperatures. The NIF experiments will be of great interest for the experimental study of the physics of high Mach number flow and the instabilities associated with the presence of certain material conditions and interfaces. Typically, large Mach numbers have been difficult to attain in the laboratory, because to achieve the high flow velocities needed requires a very high-enthalpy source; i.e., very high-temperature, high-pressure gases, which is problematic. The NIF, however, should excel in producing a high-enthalpy source (i.e., a hohlraum). Using the hohlraum as the source, very strong shocks and large Mach number flows may be generated.

This possibility of testing conventional theory under extreme conditions opens up a large perspective toward the understanding of various astrophysical phenomena involving the propagation of the blast wave and the plasma flow generated, for example, by supernova explosions. Consideration of the compressibility of the materials studied and the relationship to the onset of turbulence is also an important connection to be probed under the unprecedented conditions attainable with these high-energy-density sources. Finally, because of the larger spatial scales, longer times, and higher energies provided by the NIF, it will permit fluid dynamics investigations to be

- Larger, thereby increasing relative spatial resolution.
- Longer, thereby allowing temporally growing features more development.
- More energetic, thereby helping to maintain drive conditions and reduce decompression effects.

Thus, it will permit the detailed study of phenomena that to the present have been studied experimentally exclusively by astronomical observation, or only by computer theoretical simulation.

C) Material Properties

Facilitator: Neil Holmes

Participants: N. Ashcroft, R. Christensen, N. Ghoniem, J. Keady, M. Kreisler, J. Wark

The capabilities of the NIF for studies of condensed matter physics at extreme conditions of pressure and temperature will make it the most important new tool in high-pressure physics. While we will describe below vital contributions that only the NIF can make to this field, we want to make it clear that for other scientific applications of the NIF (such as hydrodynamics, planetary physics and astrophysics, and radiative

properties) as well as for the ICF program, a broad and precise knowledge of condensed matter properties for pressures between 1 and 100 TPa (10–1000 Mbar) and temperatures up to a few hundred electron volts will be essential for the design, simulation, and interpretation of experiments. For example, we have yet to understand the behavior of hydrodynamic instabilities in the pressure range for which pressure ionization becomes important. We must have a “caloric” equation of state to interpret the entropy fluctuations and to determine the appropriate invariants for high-mach-number flows under these conditions.

Presently, no models of material behavior for pressures between 1 and 100 TPa have been experimentally validated. At low pressures, below a few Mbar, impact and static experiments provide a wealth of data, and at very high pressures, statistical mechanical models such as Thomas-Fermi theories are believed valid. The upper bound is approximate, and increases with Z .

At tens of TPa (hundreds of Mbar), the models that *do* exist only agree within about 30% in density, and vary by as much as a factor of two in temperature along a shock adiabat (Hugoniot). These models differ quantitatively and in functional form, and the discrepancies between the models are functions of density, pressure, and temperature. Although a few shock-wave experiments have been carried out in this pressure range in the former Soviet Union (driven by a nuclear device), none have been sufficiently accurate to test theory. Over the last decade, a few laser-driven experiments have probed this region of pressure with even less accuracy.

The NIF will provide the combination of drive energy, uniformity of drive, and the concomitant large time and length scales for real advances. This effort will substantially improve our understanding of dense fluids, pressure ionization, phase boundaries (for instance, in proposed plasma phase transitions), and energy partition in shocked systems. The basic experimental methods for these studies have existed for some time — the ability to exploit them at ultra-high pressures is still awaiting a NIF-class laser.

We need to know material properties over wide ranges of density and pressure. Most previous experiments have been shock-wave experiments on the principal Hugoniot. The pulse-shaping capabilities of the NIF are essential to reach off-Hugoniot states, especially near the isentrope. Cold compression, along the room-temperature isentrope, will be limited by the eventual insulator-metal transition in diamond, which will occur at about 1 TPa.

While experiments and theory have emphasized shock properties in the past, these are merely the simplest and most fundamental measurements. There is yet to be any experimental data on transport properties at these extreme conditions, such as thermal and electrical conductivity, and we note that the hydrodynamics itself will depend on radiative transport away from the shock front at the highest pressures of interest.

Finally, we note that for the first time an intense source of neutrons will be available from the ignition process. This will allow us to heat along isochores, paths of constant density, to tens of electron volts in many metals, allowing access to a region of state space previously unreachable in *any* experimental environment.

D) Plasma Physics

Facilitator: Brian MacGowan

Participants: B. Barletta, H. Baldis, R. Berger, S. Cramer, L. Goldman, A. Kermin, B. Kruer, C. Liu, N. Luhmann

The study of plasma physics has been stimulated over the past four decades by its close connection with the goal of the creating fusion as an energy source and with astrophysical plasmas of various types. That is, the universe is composed largely of

plasmas as the overwhelming state of matter and this makes the scientific investigation of the plasma state even more germane to scientific inquiry.

The rather large number of experiments that high-energy lasers permit in the area of plasma physics indicates the close connection between many of the applications. A number of the interesting phenomena that take place in plasmas, such as parametric instabilities, rely on a large degree of homogeneity in plasmas that are both hot and dense. Most plasma physics experiments to date have been complicated by the large gradients and small scale of the plasmas produced by current lasers.

The advanced capability of the NIF will allow us to produce hot, dense plasmas that are both large and homogeneous, allowing detailed characterization. Thus, for example, one will be able to determine electron and ion temperature, charge state, electron density, and plasma flow velocities. Thus, one would have a medium in which a wide range of *quantitative* experiments can be performed.

Some of the laser-plasma interaction experiments that will be possible on the NIF will be developments of those already attempted on smaller, less well-characterized plasmas. However, it will be possible to go beyond such experiments, which were geared to the needs of the current ICF program, and investigate a wide range of scientifically important interactions.

There was general agreement that the NIF should include a beamline for short pulse (i.e., pulse durations less than 1 ps) high-power experiments. This capability is especially important for many basic plasma physics studies. These include relativistic, ultra-high intensity regimes of laser-matter interaction; ponderomotive effects; relativistic self-focusing and filamentation; laser beam channeling; intense harmonics generation; ultra-high B-field generation with ancillary studies of the resultant physical processes; strongly driven instability regimes; generation and transport of high electron fluxes in a plasma; high gradient accelerator schemes; new x-ray lasers; and high temporal resolution diagnostics. Many of these will be discussed below.

Another new area of focus will be the study of magnetic fields, as large as 100 MG, generated by temperature and density gradients present in the plasma. Faraday rotation of an optical probe beam and/or Zeeman splitting of spectral lines should allow one to investigate and quantify these magnetic fields. The generation of large currents of fast electrons, produced by SRS and Two-Plasmon decay in plasmas at 0.25 of the critical electron density will be a related area of study. Coupling these electrons into a high-Z metal converter should allow the production of short-duration bursts of 50- to 100-kV x-rays with numerous potential radiographic applications. Further, the feasibility of performing nuclear reaction experiments in the large, hot, well-characterized plasmas that will be produced on the NIF has been demonstrated in smaller experiments at the Nova laser facility.

In general, these larger plasmas will translate into longer interaction lengths, greater homogeneity, higher temperatures, longer time scales, and reduced velocity gradients. Therefore, the NIF laser will make strong contributions to fundamental plasma physics.

E) Radiation Sources

Facilitator: Luiz Da Silva

Participants: R. Falcone, R. Freeman, C. Jacobsen, M. Key, M. Richardson, D. Umstadter

A NIF-class laser will make possible a wide variety of x-ray and particle sources suitable for addressing numerous basic and applied physics questions. The NIF will be capable of producing intense broadband thermal x-rays from high-Z radiation converter targets, coherent amplified x-rays (x-ray lasers) from high-gain linear plasmas, intense neutron pulses from implosion plasmas, and intense pulses of hard x-rays produced by

fast electrons. Accurate energy spectra and absolute measurements of the conversion of laser energy into all types of radiation and particle fluxes will play an important role in benchmarking our basic understanding of laser plasma interactions and atomic physics.

Broadband x-rays generated from laser-produced plasmas can be used to produce and characterize large and uniform plasmas relevant to ICF and astrophysics. Previous experiments using this technique have yielded important results which can be extended to high temperatures and densities. The high temperature and densities produced during implosion and subsequent ignition will be an unmatched source of continuum x-rays extending from the XUV to MeV with pulse durations less than 100 ps.

X-ray lasers, besides being important coherent radiation sources, offer a critical test of our atomic modeling. On the NIF x-ray lasers will allow one to extrapolate existing neon-like and nickel-like collisional x-ray lasers to wavelengths of ~ 20 Å. At these wavelengths x-ray laser interferometry can be used to measure electron densities in plasmas exceeding solid densities. Short-pulse capabilities on the NIF, with pulse lengths ~ 100 fs, will allow us to develop inner-shell pumped x-ray lasers as a viable source. This new class of x-ray laser will have the potential to extend down to 1 Å in wavelength and have a short pulse duration. High-order harmonic generation, an alternative source of coherent radiation, can be used to produce tunable coherent XUV radiation.

Neutron production will exceed 10^{18} in single 100-ps pulses, making the NIF a potentially useful source for producing uniform high-density and low-temperature plasmas (i.e., strongly coupled). Fast electrons with hundreds of keV in energy will be generated by parametric instabilities providing another potential source of high-energy x-rays for plasma backlighting and probing.

These radiation sources are supplemented by the possibility of using radiation enclosures, or hohlraums, for the generation of radiation environments and x-ray drive fluxes. These sources will be able to produce far in excess of the 200-eV equivalent radiation temperature sources now available on the current high-energy laser facilities. These source will not only be of higher effective temperature but will also be able to provide uniform x-ray drive over far larger areas than can now be imagined on present-day systems. Thus, the advantages of using x-ray heating for the study of hot, dense matter will be greatly enhanced with the advent of the NIF.

F) Radiative Properties

Facilitator: Richard Lee

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The importance of radiative properties in high-energy-density plasma derives from three separate factors. The first is that the radiative property can be the best indicator of the level of scientific knowledge in a particular area. So, for example, when one is interested in the development of new descriptions of atomic structure, the most important measurements to be made are the accurate determination of transition energies. Moreover, as with the case of spectral line broadening, one can develop sophisticated plasma theoretical constructions, kinetic theories, or scattering theories and find that the simplest place to test the method is through a prediction of a line shape, which can then be measured.

Second, radiative properties provide the classic example of the non-interfering probe. Thus one can obtain fundamental information on the plasma by looking directly at the emission or the absorption spectrum. Spectral formation in its most sophisticated forms can provide information on the plasma ionization balance, the rate processes, the

densities, the temperatures and the fluctuation levels. The radiative properties are therefore a powerful diagnostic of the plasma state.

Third, although radiative properties provide an important test bed for theoretical development and provide diagnostic information, they are also necessary as primary data for numerous other studies. For example, spectral line lists are inadequate for many of the charge states of heavier elements. Therefore, the categorization of the energies of highly ionized species becomes an end in itself, as data tables are necessary for the myriad uses to which spectra are put. In this way, line shapes, line widths, and line shifts must be measured for use in radiation-hydrodynamic simulations of entities as small as an ICF microsphere implosion and as large as a galaxy.

These factors together explain the interest in radiative properties of hot, dense matter. It is clear that the largest part of the community of scientists outside the x-ray laser area involved in high-energy laser experiments are in this area. It is a fertile area with much to be gained by the existing high-energy laser facilities and even more to be gained with the advent of the NIF.

Some of the possible applications for experiments on high-energy lasers are presented below, in the Section on Radiative Properties; here we have broadly summarized a few of the ideas to provide an indication of the type of experiments being considered.

III) Scientific Projects

A) Introduction

In the following we develop some of the ideas put forward for future experiments on high-energy laser facilities. We will make extensive use of the material in the companion document "Scientific Applications for High-Energy Lasers."¹ This document was compiled for the express purpose of providing a broad background to current applications for potential new users. Further, we have attempted to keep this section as concise as possible by placing supporting background material in a separate section (Section IV).

B) Astrophysics and Space Physics

The level of feasibility of possible NIF-based experiments discussed here ranges from a straightforward extrapolation of well-established Nova techniques, to rather speculative possibilities that will probably require technology beyond the presently proposed NIF capabilities before useful results can be obtained. Nevertheless, we discuss here the important scientific issues in approximately descending order of feasibility with the NIF facility. We note that two topics that have been repeatedly mentioned but do not seem appropriate for the NIF, Lightning Chemistry and the Formation of Chondrules, are discussed in Section IV, Background, to provide a clear understanding of why it was felt that these topics are currently inappropriate for the NIF.

1) Opacity

The radiative opacity of the material in stellar interiors plays a key role in determining how stars evolve—what the maximum mass of a stable star is, how hot and how luminous the star is while it burns its hydrogen fuel, what pulsational instabilities it may fall prey to, whether it loses much of its outer envelope in outbursts of one kind or another, and at what stage of its evolution it might explode as a supernova. Opacity sets the flow of heat through the star, since the radiative flux is inversely proportional to it, and it is the star's energy budget that dictates those other consequences. In particular, the instability of the star is especially sensitive to nuances in the opacity, and most sensitive in the temperature range of a few hundred thousand degrees Kelvin. The opacity is very complex in this region, and has stood as a formidable challenge to theoretical atomic physics. A brief discussion of recent advances is present in Section IV.A.1.

Some of the regimes of temperature and density for which the star's structure and evolution are very sensitive to opacity are reachable in a laboratory high-energy-density facility such as the NIF, as illustrated in Figure III.B.1: temperature from tens of electron volts to several hundred electron volts, and density from normal solid density to a few hundred times less. The radiative opacity of interest in stars is a harmonic mean of the spectral-dependent opacity, which means that it is dominated by those windows in the frequency spectrum that lie between the strong absorption features. The kind of experiment that addresses this question is a spectral absorption measurement of a thick sample, centered on these windows. The ability of the NIF to provide a stable temperature environment for a long enough period, combined with high-quality time-resolved x-ray spectrometers, is perfect for this kind of experiment.

Figure III.B.1 The temperature–density parameter space relevant to the NIF plasmas.

The loci in temperature and density for some detailed stellar models are shown in Figure III.B.2, which illustrates the structures for stars in late stages of evolution. Opacity has the most effect on the structure in the intermediate zone between the convective outer envelope and the hydrogen-depleted core. The temperature here ranges from 10^6 °K to 10^8 °K (100 eV to 10 keV) depending on the position in the star and the stellar mass. The corresponding range of density is from 10^{-4} to 10^2 g/cm³.

The stellar material is rich in H and He, which do not dominate the opacity in these ranges, but there are also significant amounts of C, N, O and Fe. The C, N, and O ions are important contributors at 100 eV, but Fe is very important over the whole temperature range. A first measurement of the opacity of iron has already been made with Nova, as described in Reference 1, *Scientific Applications for High-Energy Lasers*, p. 35. With the NIF the temperature range up to a few keV without ignition, or to more than 10 keV with ignition, will be available, which means that conditions at the centers of the stars will be reachable.

Another area in which the NIF-based experiments could be useful is with regard to opacities and x-ray cross-sections relevant to compact x-ray sources such as cataclysmic variables, x-ray binaries, and quasars. Measurements of inner- and outer-shell photoabsorption cross-sections of C, N, and O could be made directly in well-characterized laser-produced plasmas via a backlighter method. These cross-sections have not been measured in other ways because of the difficulty of producing a sufficiently large column density of the desired ions. Such measurements would complement theoretically calculated cross-sections and aid in the modeling of x-ray ionized material in and around compact sources.

Figure III.B.2 The variation in depth of temperature and density for stellar structure models for four late phases. A) A possible MACHO - Massive compact halo object; b) A 1 solar mass white dwarf; C) A 1 solar mass star at tip of the red giant branch; D) A 25 solar mass pre-supernova, a star undergoing core carbon-burning as well as He- and H-burning. Along each curve different dominant energy mechanisms are indicated—the dashed line for convective transfer, the solid line for radiative regions and the gray line for regions in which the hydrogen has been completely depleted by nuclear burning.

2) Equation of State

Stellar structure and evolution are governed by three physical properties of the star's material—the opacity just discussed, the nuclear reaction rates, and the equation of state (EOS). The last of these means the relations between the density and temperature of the material on the one hand and its pressure and internal energy, specific heats, etc., on the other hand. Under many circumstances, in stellar interiors, the equation of state is quite simple: most of the gas consists of hydrogen and other light elements, and these have lost most of their electrons. Furthermore, the gas density is low enough that the atomic ions seldom interact, so ideal gas physics is a good approximation.

This is a happy situation for the astrophysicist, but unfortunately it is not always the case. In the very centers of stars, particularly those in the later stages of their evolution, density is quite high and the plasma becomes strongly coupled. That is, the various ions interact strongly and no longer behave as free particles. This is often accompanied by electron degeneracy—the plasma electrons tend to fill up the states allowed by Pauli's exclusion principle, which forces some electrons to become very energetic, and these dominate the pressure and internal energy; the ions still play a major role in the specific heats, however.

The theory of stellar evolution is affected by uncertainties in the equation of state in a few areas. The white dwarf stars are the remnants—the nuclear ashes—of stars that have run through most of their evolution and, at some point, ejected their outer layers

containing all the unburned nuclear fuel. They are the compressed former cores of their parent stars. A white dwarf of the sun's mass is the size of the earth. With no more nuclear heat source, the white dwarf simply cools off, a process that takes many millions of years.

Through most of the white dwarf the pressure of degenerate electrons supports the material against gravity, but near the surface the electrons become less degenerate and the ions become important. The ions are also important in setting the specific heat and thus the rate at which the white dwarf can cool. White dwarfs are also sometimes pulsationally unstable, a process that is sensitive to the specific heats, and indeed are often in several pulsation modes simultaneously. The precise measurement of the pulsation frequencies gives a sensitive probe (asteroseismology) of the interior structure of the star.

Another kind of dwarf star—the brown dwarf—is poorly understood, owing in part to our imperfect understanding of the equation of state. Brown dwarfs are stars with masses so low that they never get hot enough inside to burn hydrogen, but simply condense from the interstellar medium and shine dimly for a while as they get rid of the heat formed in condensing. Brown dwarfs are very difficult to detect, but it is possible that they are so numerous that they comprise as much as half of all the mass in our galaxy. This is mass that is inferred to exist from the dynamics of the Galaxy, but that has not been discovered in luminous form. Their internal structure and their cooling time depend on the details of the equation of state at densities approaching solid density and temperatures of a few eV; these conditions are easily reached in a laser experiment.

Equation of state experiments fall into two classes. One class might be thought of as “direct” EOS experiments, in which for a certain experimental setup the experimental data yield a quantity that can be compared with the tabulated functions of pressure, energy, etc. The second class is of “indirect” EOS experiments, which measure some of the detailed intermediate data, that enter into theoretical expressions for the thermodynamic functions. Experiments of the second kind serve as benchmark tests of the EOS theory. Experiments of the first kind are described in detail in Section II.F.1 of Reference 1, *Scientific Applications for High-Energy Lasers*, and in Section III.D, Material Properties in this report.

The second kind of experiment could, for example, seek to validate the model of plasma screening—very important in dense plasmas—by diagnosing the occupation probabilities of atomic states close to the ionization limit. This is discussed at greater length in the Radiative Properties section.

3) Plasma Spectroscopy in High-Energy Astrophysics

High-energy astrophysics refers to x-ray and gamma-ray and, to some extent, optical and UV, observations of stars and galaxies, for which the source of the radiation is a violent event, or a plasma very far from thermodynamic equilibrium. Among these are quasars and other exploding galaxies, and neutron stars that are ingesting material from a companion star. The technique used to study them is to investigate their spectra—in the x-ray or gamma-ray range, or whatever is available—to find the signatures that reveal the nature of the emitting object. The astronomer's problem is to obtain a spectrum showing as much detail as possible. But the second problem is to have the knowledge base on non-equilibrium spectra that allow inferences to be drawn from the data. Here is where the NIF has a role, working together with first-principles plasma modeling tools.

An area where our plasma modeling is relatively weak concerns low-temperature radiation-dominated plasmas. These are plasmas irradiated by dilute radiation sources; that is, the illuminating radiation field is much weaker in absolute intensity than the blackbody that matches the spectral shape. The radiation, while strong in absolute terms, is still weak in comparison with the very high implied temperature. Such plasmas are

very far from local thermodynamic equilibrium (LTE). One uncertainty is of the plasma energetics. Perhaps a lot of energy is tied up in states that are not evident in the spectrum.

a) The Bowen Mechanism

Because the plasmas are radiation-dominated the thermodynamic state of the matter and the appearance of the spectrum itself, depend strongly on the flow of radiation through the plasma. The re-absorption of radiation emitted elsewhere plays a major role. A particularly notable example of this is the Bowen fluorescence mechanism, which is discussed in some detail in Section IV.A.2.

The Bowen mechanism still does not have a secure theoretical footing, and needs some experimental verification. The full network of atomic kinetic rates connecting these levels of HeII, OIII and NIII is complex enough to be hard to calculate. An experimental exploration of the Bowen mechanism will create a large volume of plasma with a temperature of 2–3 eV and in which oxygen and nitrogen are mostly doubly ionized. This may be illuminated by a second region of hotter plasma that serves as a light source for the first. The column density of the large plasma, perhaps 10^{20} cm^{-2} , would be ample to provide the necessary optical depth in HeII $\text{L}\alpha$, and perhaps also in OIII $\lambda 374.436$ as well.

b) Low-Mass X-ray Binaries

Low-mass x-ray binaries (LMXRB) consist of a neutron star in orbit with a 1–2 solar mass star; the x-ray spectra are relatively hard—10 keV or so. Considerable modeling work has been done on these, with particular attention to the iron spectrum—first the K-shell lines, and more recently the L-shell emission. This is a formidable task, especially the dielectronic recombination, and experimental confirmation is very desirable. The iron K and L lines are seen in spectra that have been obtained using BBXRT and two Japanese satellites of x-ray binaries like Sco X-1. Similar lines are hinted at in the few decent x-ray spectra of Seyfert galaxies, which, if confirmed, would corroborate the theory of an accretion disk surrounding a black hole in the nucleus of the galaxy.

In the next five years there will be two new high-resolution x-ray astronomical observatories: XMM and AXAF. These will, for the first time, obtain spectral detail of the Fe K and L features sufficient to distinguish different types of excitation. The line shapes in these objects, and, for the binaries, their time variations, can be analyzed to provide information about the radial and azimuthal structure of their accretion disks, provided the atomic model itself is sufficiently well understood.

An experimental approach to the iron L spectrum would be of great interest. The problem, in laboratory sources, is to avoid large optical depths in these lines, which is undesirable when basic line intensity data are being sought. The laser-produced plasma has the advantage over other sources, such as the Electron Beam Ion Trap (EBIT), in that the temperature can be kept as low as the astronomical situation indicates.

One of the key issues involving iron is the dielectronic recombination through the near-threshold resonances that come about with $\Delta n = 0$ capture (Koster-Kronig transitions)—for example, the capture onto Li-like iron in which the 2s electron is excited to 2p. This dielectronic rate is very large, and a proper calculation of it requires a careful calculation of the energy of each resonance and its autoionization width; large departures from the general formulae for dielectronic recombination rates are found. In Be-like iron the states $2pnl$ with n greater than about 11 are auto ionizing. The spacing of states differing by one in n is about 11 eV, so there are certain to be a few auto ionizing levels within 10 eV or so of the ionization threshold.

It would be quite interesting to produce a plasma with abundant Fe(Li) but with an electron temperature less than 50 eV in order to study this process. The color temperature of the radiation would need to be a few hundred eV in order to produce this

ion, which has an ionization potential of 2048 eV. We note that it is true that in accretion disks of x-ray binaries and Seyfert galaxies this ion of iron is probably found where the electron temperature is hotter, of order a few hundred eV to 1 keV, so the near-threshold dielectronic recombination is relatively unimportant.

c) Shock-Wave Ionized Media

Another possible radiation transport study with NIF involves shock waves in the target chamber to study photo-ionized nebulae. A wide range of experiments can be done to simulate the effect of energetic events in circumstellar and interstellar gases by utilizing a low density gas fill in the 10-m-sized laser target chamber. The deposition of laser light onto a small target at the center of the chamber will lead to a bright UV and/or x-ray source (80–90% of the laser light can be converted to x-rays). In a low-opacity gas a photo-ionized nebula will be created.

Detailed study of such processes will serve to benchmark models that are used in astrophysical contexts, such as quasars. Processes such as photoionization and excitation, radiative and dielectronic recombination and line trapping will be studied. For a high-opacity gas, the x-rays will shortly be re-absorbed, leading to the creation of a shock wave in the chamber gas, similar to a super-nova-remnant in the interstellar medium. Similar work has already been done on a small scale at the Naval Research Laboratory.² Fundamental studies of the propagation of such shocks, including effects of an applied magnetic field, can be done.

4) Supernova Instabilities

Hydrodynamic instabilities play a major role in determining the efficiency and performance of inertial confinement fusion implosions. In laser-driven implosions, high-performance capsules require high aspect ratios (the ratio of the radius to the shell thickness). These capsules are susceptible to hydrodynamic instabilities of the Rayleigh-Taylor, Richtmyer-Meshkov and Kelvin-Helmholtz varieties, which can in principle severely degrade capsule performance. Recently the growth of the ablatively driven Rayleigh-Taylor instability has been studied by indirect-drive experiments using a shaped x-ray drive pulse.³

The x-ray and gamma-ray observations of the famous supernova 1987A have indicated that radioactive cobalt is far more thoroughly distributed among the explosive debris in the envelope than was predicted by model calculations of thin-shell nucleosynthesis in the pre-supernova star. These observations of 1987A have strongly suggested the occurrence of large-scale mixing in the ejecta during the explosion.^{4,5} A larger scale mixing in the ejecta has also been suggested for Type Ib/Ic supernovae from light curve modeling and spectrum analysis.

The most promising mechanism for mixing in the ejecta is a combination of the Rayleigh-Taylor and Kelvin-Helmholtz instabilities. The Rayleigh-Taylor instability can arise in the supernova envelope when the outwardly moving shock wave from the initial explosion propagates through layers of the star with radial stratification of the heavy elements. As the shock passes through the composition interfaces (i.e., O/Si, He/C+O and H/He), a rarefaction front moves back into the star, resulting in an effective reversal of gravity as low-density composition is pressure accelerated into the underlying high-density composition.

Any perturbation at the interface (i.e., velocity perturbation or spatial perturbation) will get amplified by the Rayleigh Taylor and Richtmyer Meshkov instabilities and result in the overturning of light and heavy elements. This results in the mixing of heavy elements throughout the envelope of the supernova remnant with associated observational consequences in the light curve.

A further mixing will occur as the dense "tongues" of the heavy elements experience differential shear with the lighter elements, resulting in Kelvin-Helmholtz instabilities. Thus the fingers of heavy and light fluid that developed initially get far more distorted and the mixing layer increases its width.

Eventually these instabilities become so nonlinear that the mixing layer appears to become fully turbulent. The properties of turbulently mixed layers may be equally important in understanding how interstellar clouds get reprocessed back into the interstellar medium. Efficient mixing of cloud and inter-cloud matter has been shown to occur after clouds get crushed by the interaction of strong shocks from supernova remnants.^{6,7,8} Experiments at the NIF would be ideally suited to detailed studies of this important astrophysical phenomenon. Densities and temperatures reached in the supernova shocked envelope are well within the range attainable with the NIF.

The experimental techniques to study the development of Rayleigh-Taylor-induced mixing well into the nonlinear regime using streaked x-ray radiography of the unstable region have already been demonstrated by Remington et al.³ The NIF is ideally suited to producing the extremely strong shocks with Mach numbers $M \gg 1$ that occur in the supernova envelope. The shocks would be produced by shaped laser pulses ablating a foil or cylinder consisting of a sequence of material interfaces with density differences matching those in the supernova envelope. The shock wave would traverse the composite interfaces, which can be suitably perturbed, resulting in instabilities and mixing like those thought to occur in the supernova envelope. Shocks of sufficient strength are far out of the regime that is currently possible in standard shock-tube experiments, but will be relatively easy to achieve at the NIF.

Recent advances in high-resolution multidimensional hydrodynamics using adaptive mesh refinement (AMR) techniques now make it possible to accurately model the experiments with detailed three-dimensional simulations. Using newly developed AMR algorithms⁹ recent calculations^{7,8} have studied the development of shock-induced Rayleigh-Taylor and Richtmyer-Meshkov instabilities far into the nonlinear mixing regime. Calculations such as these, combined with NIF experiments, will allow a thorough study of the mixing in supernova explosions as well as studies pertaining to mixing in the interstellar medium.

Figure III.B.3, reproduced from Müller et al.,¹⁰ shows the typical scenario for how Rayleigh-Taylor mix enters into supernova modeling. The expanding inner core of Ni and Si is being decelerated by the surrounding layer of lower density C and O, which in turn is being decelerated by the outer layer of He. Because at each interface, one effectively has a heavy fluid "sitting on top of" a light fluid, the interfaces are unstable to the Rayleigh-Taylor instability, and imperfections will grow. Typical growth factors are 100–1000.

Figure III.B.4 shows how a similar situation could be set up on the NIF. Since the usual experiments focus the lasers into the hohlraum, the hohlraum in this case would be shot in an inside-out fashion. The drive lasers would impinge upon a thin (approximately 10- μ m) cylindrical Ni hohlraum with sinusoidal perturbations imposed on the outer surface. The outer surface of Ni would be coated with $\approx 100 \mu\text{m}$ CH, and the whole package would reside in a ≈ 10 -atm fill of He.

As the drive turns on, a strong shock (≈ 100 Mbar) would be launched radially outwards through the various layers. Each interface would be unstable to the Richtmyer-Meshkov instability, and perturbation growth would begin. Then as the hohlraum explodes radially outwards, the Ni core would be decelerated by the lower density CH layer, which in turn would be decelerated by the He fill, in much the same fashion as the supernova shown in Fig. III.B.3.

Figure III.B.3 Contours of total density times the mass fraction of ^4He at four instants during the supernova explosion. The times proceed from the upper right counter clockwise. Note that the original sphere of helium is already breaking up in the first instant shown.

Figure III.B.4 Schematic setup of a mix experiment to mimic the mixing in a supernova explosion.

Diagnosis would be from face-on, edge-on, and end-on radiography, in the standard fashion currently utilized on Nova. A large-area Cu backlighter, with $K\alpha$ emission at 8.4 keV, might be suitable. If this "direct-drive" approach to accelerating the Ni hohlraum proves to imprint an intolerable level of non-uniformity on the Ni-CH interface, a hybrid indirect-drive approach would be the fall-back. Here, the lasers would hit an inner solid high-Z cylindrical rod, generating an x-ray drive, which would in turn drive the Ni hohlraum outwards.

Note that already on Nova with a ≈ 20 –30-kJ drive, growth factors of nearly 100^{11} shock strengths of ≈ 50 Mbar, and Mach numbers of ≈ 35 have been achieved.¹² On the NIF with 1.8 MJ of drive energy, achieving growth factors of 100–1000 and shocks of $M \gg 1$, as suggested by the supernova modeling, should be straightforward.

5) High-Velocity Cratering

One of the interesting issues in lunar and planetary physics is that of crater formation—surface damage—by high-velocity impacts. The velocities of projectiles in the solar system range up to 50 km s^{-1} (for projectiles in retrograde orbits), which is out of the range for gas guns. This can easily be done using the laser-driven flyer plate technology, as discussed in Reference 1, *Scientific Applications for High-Energy Lasers*, and in the Hydrodynamics and Material Properties sections of this report. The physics issues to be studied include the systematics of crater dimensions with projectile shape and size—the nature of the damage mechanism—for example, the dependence of the cratering on the type of material forming the target.

A further set of issues is related to electromagnetic effects caused by the impact. It is known that electromagnetic noise is produced at the time of impact. It is also found that there are substantial magnetic anomalies in the rock underlying lunar impact craters. The mechanisms of these phenomena can be studied by performing the flyer plate experiments with weakly magnetized targets.

The suitability of this project to the NIF arises from the ease of attaining the high impact velocity and the availability of larger projectile sizes. On Nova the projectiles with a suitably large velocity are so small that edge effects obscure the phenomena to be studied.

6) Thermonuclear Reaction Rates in Stars

Although nuclear reaction rates have been the subject of intense studies for decades, it remains true that few direct experimental studies have been made at the actual energies at which they occur in stellar environments. Figure III.B.1 summarizes a number of astrophysical thermonuclear environments and their associated temperatures. The actual energies relevant for the nuclear cross-sections are given by the so called Gamow window, which represents the interplay between the Maxwellian tail of the reactant velocity distribution and the rapidly diminishing reaction cross-section at energies below the Coulomb barrier. A discussion of the relative merits of the NIF to the more usual accelerator technique to obtain information on nuclear reaction rates is given in Section IV, Background.

Interesting nuclear reactions to study besides $^{12}\text{C}(p,\gamma)^{13}\text{N}$ might be $^3\text{He}(^3\text{He},2p)^4\text{He}$, and $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$. These are part of the proton-proton chain of hydrogen-burning reactions in solar-type stars. The competition between these for the destruction of ^3He determines how much ^7Be , and ultimately ^8B , is produced, and therefore how great the flux of neutrinos should be, as detected in the Homestake Mine solar neutrino experiment.

This branching ratio continues to be a significant uncertainty in the interpretation of the solar neutrino experiment, and a refinement of our knowledge here would be of great value. The rate of the ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$ reaction is some 10^5 times greater than that of ${}^{12}\text{C}(p, \gamma){}^{13}\text{N}$, while ${}^3\text{He}({}^4\text{He}, \gamma){}^7\text{Be}$ is similar to the latter. In order to diagnose ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$ it will be necessary to measure the activation produced by the ≈ 5 -MeV protons in a witness foil placed near the target, or in the wall of the hohlraum itself.

Figure III.B.1 shows the way in which the NIF conditions overlap various stellar burning phases. Temperatures up to carbon-burning are achievable with ignition. Even with the driver alone (i.e., without ignition), hydrogen burning temperatures and helium burning temperatures are obtainable, as are the density regimes.

Figure III.B.5 shows the evolution of the early universe through the big bang. Lines are drawn for both baryons and electrons for baryon densities corresponding to both 0.1 and 1.0 times the present closure density of the universe Ω_b . It seems possible that with an appropriate capsule design, one may be able to nearly reproduce various conditions in the early universe during much of the critical epoch (first three minutes) of primordial nucleosynthesis.

Figure III.B.5 The paths taken in temperature and density parameter space for some stellar evolution models. This taken together with Fig. III.B.1 indicates the area of overlap between stellar modeling and plasmas the NIF can produce.

7) Electron-Positron Plasmas

Thermally produced electron-positron plasmas are expected to play an important role in the evolution of the cores of massive stars, neutron-star and black-hole accretion disks, pulsars, quasars, astrophysical gamma-ray bursters, and in the big bang. Although it is not likely that the NIF could be used to produce a pair plasma with the currently proposed

design parameters, it is possible that some pairs will be produced in a way which is similar to the formation of pairs in such astrophysical environments. Hence, experiments with the NIF may shed light on pair-plasma formation and radiation transport issues. We therefore include a brief discussion here of some of the physics issues regarding pair production.

In the last few years, discoveries of intense broadened 511-keV annihilation lines from several Galactic black-hole candidates suggest that in addition to transient-pair production, steady-state thermal pair plasmas may exist. Since pairs annihilate on short time scales, maintaining such steady-state conditions, requires the copious production of pairs to balance the annihilation rate. Such pair-balanced steady plasmas represent a new state of matter with unique radiative and thermodynamic properties different from ordinary plasmas.

For a plasma to be in a steady state, the heating rate must be balanced by the cooling rate, which consists of bremsstrahlung, inverse Compton scattering and pair annihilation. It turns out that for a pair-balanced plasma there exists a fundamental limit to the temperature of ≈ 10 MeV for hydrogen, above which pair creation can no longer be balanced by annihilation and pair density will exponentiate rapidly, leading to a pair-dominated plasma and net cooling of the system. This limiting temperature, referred to as the BKZS limit, is much too high for NIF-based experiments; however, the limiting temperature can be lower for a high-Z or high magnetic-field plasma.

The laser intensities available at the NIF may permit the formation of some pairs out of the suprathermal electrons during a high-temperature deuterium-tritium (DT) burn. In equilibrium, at a temperature of 50 keV, the vacuum pair abundance is suppressed by only a factor of $\exp(-m_e c^2/kT) \approx 10^{-5}$, implying a pair density as high as $\approx 10^{21} \text{ cm}^{-3}$. This factor will be reduced, however, by the ratio of the burn time, of order ≈ 10 ps, to the equilibration time. The equilibration time is of order of the time scale for pair creation.

The most promising avenue to the production of a pair plasma seems at this time to be to use the peta-watt laser under development as an adjunct to Nova. One of the Nova beams is intercepted partway through the amplification chain and is subjected to pulse compression, producing a pulse of 1.06- μm light containing about 1 kJ of energy in a pulse length of 1 ps. If this can be focused to a spot size limited only by diffraction, then an intensity of 10^{21} W/cm^2 can be produced. The paper by Wilks *et al.*¹³ shows how such a laser pulse can produce relativistic electrons and confine them through a combination of the optical fields and the ponderomotive force.

At very high laser intensities I , satisfying $I \lambda_\mu^2 > 1.4 \times 10^{18} \text{ W cm}^{-2}$ where λ_μ is the laser wavelength in microns, the electron jitter momentum becomes relativistic and scales roughly as the square root of the intensity. If the jitter energy E of the electrons is larger than mc^2 , as it is for $I \lambda_\mu^2 \gg 1.4 \times 10^{18}$, then collisions of the electrons with ions of charge Z in the plasma will produce pairs; the cross-section for this process is of order $10^{-30} Z^2 \text{ cm}^2$, weakly dependent on electron energy in this range. This would be sufficient in a critical-density gold plasma to produce in 1 ns a pair density of order 10^{-5} – 10^{-4} times that of the electrons.

This fraction would be increased if a density substantially above the critical density could be used, as is suggested by Wilks *et al.*¹³ It may be important in the experiment design to provide laser illumination from opposing directions; this allows the pairs that are created to be trapped by the optical field and be themselves accelerated, producing more pairs in turn. The pairs would annihilate over a time likely to be longer than the laser pulse, and so the result would be a temporally broadened annihilation line in the gamma-ray spectrum. The line profile plus the Comptonized bremsstrahlung continuous spectrum will form the most useful diagnostics of the pair plasma (e.g., Liang and Dermer¹⁴).

An extension of the peta-watt concept to the NIF — providing compressed pulses and diffraction-limited focusing capability on some number of the NIF beams — would extend the spatial and temporal scales for this relativistic plasma, and perhaps make creation of a pair-dominated plasma a reality.

C) Hydrodynamics

1) Discussion

In the following, a number of topics that are among the most promising for experimental investigation under conditions that can only be created at the NIF are discussed. The organization of these topics will be according to the type of flow to be considered and the material conditions present. Thus, the issues to be considered that involve stable flow are hydrodynamic flow at high Mach numbers, shock-shock and converging shock propagation, shock motion through inhomogeneous media, and shock-boundary interactions in the strong shock regime, including the relationship to cratering.

Unstable flow problems that are uniquely addressable with the NIF involve, for example, the study of the onset and development of instabilities such as Rayleigh-Taylor, Richtmyer-Meshkov, or Kelvin-Helmholtz. The occurrence of these instabilities in blast waves, and in supernova explosions, where they play an important role in mixing the products from different regions, can also be studied in laboratory experiments. Other experiments that could possibly be considered concern the study of radiation condensation and secondary instabilities. Finally, the onset of turbulence and the influence of vortex dynamics in a medium of finite compressibility is an emerging field with important possibilities.

2) Stable Flow

This first section on stable flow will discuss the study of strong shock hydrodynamics in the presence of material boundaries, inhomogeneities, and another strong shock. These studies, including shock-shock interactions, Mach stems, and possibly non-equilibrium gas dynamics analogies and similar phenomena, are all classical problems in fluid dynamics.

The possibility of performing precise experiments in this field is of great interest because of the prospect of benchmarking numerical models, understanding certain space physics, chemistry, and cratering phenomena, and checking exact solutions that are valid in the strong shock limit. The shock interactions would represent an extension of work done in shock tubes and similar facilities, but potentially at significantly higher Mach numbers.

The analogies with non-equilibrium flows would depend upon the burn process of an ignition target, and are not possible on present lasers. The shocks for these studies are created by the interaction of a strong radiation field with a material, by either direct drive, indirect hohlraum heating, or acceleration and subsequent impact of a flyer foil.¹⁵ The transition from the radiation energy deposition to hydrodynamic shock motion is therefore also a topic of considerable interest. Note that there are instabilities that can occur at the material interfaces for some of the topics discussed here, and these are related topics of investigation that will be discussed separately in the section on unstable flow.

Finally, the general area of magnetohydrodynamics holds the potential of some interesting phenomena that could be investigated using the NIF's capability to deposit large amounts of energy into small volumes or areas, in very short times. The generation

of electromagnetic interference, enhancement of magnetic fields through compression, and a "photo-voltaic battery" are among some possible topics for future consideration.

a) Shock-Shock Interactions

Shocks created by a two-beam laser incident onto aluminum targets that propagate toward each other through a nitrogen atmosphere have been recently studied.¹⁶ The density and temperature in the shock-shock interaction region were determined by spectral line broadening and intensity ratio methods, and an attempt was made to determine the physics occurring as the shocks collide and then either pass through each other or reflect.

The interaction of strong shocks is a typical nonlinear flow problem in shock hydrodynamics and for extreme shock conditions, numerical solutions have been the only source of information in the past. Increasing the shock strength will permit different nonlinear regimes to be accessed. A similar study, equally important for hydrodynamic theory, is that of a converging strong shock caused by focused acoustic energy such as those formed in pellet implosion or bubble collapse.¹⁷ This should also be possible with a large-spatial-scale laser-energy incident.

b) Shock-Boundary Interactions

There are a series of possible experiments on the interaction of a shock wave in a medium with high acoustic impedance bounded by a medium of low acoustic impedance. Examples are underwater or underground blast waves that impact a planar surface with a gas, or a planar shock passing over a bubble. If the shock propagates in the strong shock regime, the rarefaction generated either by the shock at the point of contact with a planar surface or a plane shock at the point of contact with a spherical bubble can, in certain geometries, overtake and distort the impinging shock. This is analogous to the transition from a regular reflection to a Mach reflection for flow over a wedge, except here the reflected wave is a rarefaction instead of a shock. This effect has been predicted¹⁸ but the experimental evidence has all been produced in the gas phase with less than strong shocks.¹⁹

Self-similar solutions show that the rarefaction generated at the interface by an expanding spherical shock can also overtake the shock both along the surface and straight down into the medium, so the effect is interesting both for spherical shocks generated by point sources and for plane shocks. An important application of these studies is in the understanding of range-to-effect of the shock waves created by underground or underwater plate tectonics. Another application is found in the possibility of experimentally measuring shock propagation in inhomogeneous media, which is relevant to the astrophysical problem of the hydrodynamic interaction of shock waves with interstellar clouds.²⁰

c) Hypersonic Flow

Hypersonic flow problems with Mach numbers above 20 can be studied with laser-produced plasmas. This is a regime unattainable with present-day wind tunnels or shock tubes. Three-dimensional flow at these speeds is associated mainly with the reentry of space vehicles or the flight of a projected ramjet airplane. The theoretical calculation of this flow involves difficult questions of flow past particular surface shapes, noting that cones²¹ are of particular interest, of course. The chemistry of the wakes created by a body moving through a fluid with hypersonic speed is important for the understanding of the effects of flight or reentry through the atmosphere, particularly with respect to the creation of plasmas or the interaction with constituents such as the ozone layer.

d) Impact Cratering

Many phenomena of interest in impact cratering occur on temporal and spatial scales that are large compared to those of the impacting object. As a result, the impact can be modeled as a point source of high energy and momentum density and the mass of the object can be neglected.²² This situation can be modeled by the deposition of focused laser energy in small spheres of high Z material.

Alternatively, flyer foils that can generate prodigious shocks and post-shock pressures—on the order of gigabars—could be used. Thus, although the formation of a crater by the impact of a meteor on a surface seems to be entirely different from the formation of a crater by a surface blast, there are possibilities of modeling this situation.

A study of concentrated impacts on surfaces²³ shows that scaling laws apply to the shape of the craters formed by impact and those formed by surface energy deposition. Therefore, the cratering created by an intense radiation source or flyer foil would be useful in studying the scaling of the crater shape and inferring the shape of impact craters.

A series of proof-of-principle experiments using focused laser energy to deposit energy in a grout mixture below a planar interface with the atmosphere has been performed²⁴ with results that suggest that further research in this area with higher energy densities would be of great interest. Further, it should be pointed out that the effect of gravity was also simulated, as well as geological layering effects in separate experiments.

e) Scaled Radiative Energy Coupling

The coupling of explosive energy into hydrodynamic motion is quite different if the energy originates from a chemical reaction or from the impact of a flyer foil, or is deposited by a radiative energy source. The study of the physical mechanisms involved in the latter case, the coupling of energy deposited by a strong radiative source above, on, or below the surface of dense matter and fluids, is of special interest. This energy coupling varies from zero for sources at large heights above the surface to 100% for deeply buried sources.

The shape of the coupling curve as a function of source position, of course, has to do with questions of range-to-effect and cratering, but is also of scientific interest for the study of the exact mechanisms determining the coupling. It has been proposed that the coupling of energy proceeds through three stages: first, the stripped-sphere stage of complete ionization, then thermal wave propagation, and finally a momentum-conserving transition to shock propagation and cratering.

A low-temperature thermal wave propagation has been observed by monitoring the ionization front produced by the irradiation of a foam material with an x-ray source produced by laser irradiation of a gold foil.²⁵ Similar studies have investigated shock propagation²⁶ and the possible formation of a Marshak wave.²⁷ A study of these mechanisms that play a role in ultimately transforming the incident radiant energy into kinetic energy of ground motion is of great interest.

2) Unstable Flow

In this section, representative fluid dynamics experiments that are designed to study the growth of flow instabilities and are appropriate for study with the NIF laser will be described. Areas of unstable fluid dynamics that are readily, and uniquely, addressable by the NIF include the study of Rayleigh-Taylor, Richtmyer-Meshkov, and Kelvin-Helmholtz instabilities in both planar and non-planar geometries, for the linear, weakly nonlinear, and turbulent regimes.

Some experience has been acquired in previous experiments on this topic, but the larger scales, longer times, and longer drive duration, which are constant themes for hydrodynamic experiments, make the NIF well-suited to extend those investigations. In

Section IV.B we provide a few of the state-of-the-art hydrodynamic experiments to illustrate how the NIF will affect hydrodynamics experiments.

These instabilities, and the ensuing mixing that usually follows their development, are of interest because of their occurrence in inertial fusion, astrophysics, energy conversion technology, and the medical applications of lasers, to name a few areas. Another area of unstable flow which has recently become of significant interest is the study of compressible turbulence and mixing in high-speed jets and shear layers. Recent work indicates that turbulence may be qualitatively different at high Mach numbers and/or high compressibilities. The NIF will provide an excellent facility to generate high Mach-number flows, typically either jets or shear layers, which may be used in these investigations.

a) Classical Instabilities

The instabilities to be discussed in this section are those that refer to the growth of perturbations at a fluid interface. The type of instability in the flow is determined by the origin of the perturbation. If it is related to the action of shear or constant acceleration, the instability is generally referred to as a Kelvin-Helmholtz or Rayleigh-Taylor, respectively, and the growth is exponential in time. An impulsive acceleration caused by a shock normal to the interface causes the Richtmyer-Meshkov instability which, in the absence of shear or acceleration, then grows linearly in time.

These phenomena have been extensively studied in the past to understand the resulting interface motion and material mix, which are important effects in inertial confinement fusion²⁸ and for clumping in supernova explosions.²⁹ Nevertheless, important questions remain, because often experiments do not agree with the theory or with the numerical simulations in certain flow domains, especially at high compression.³⁰ Experiments on the NIF with long drive times and large spatial scales are expected to be especially important for the understanding of these instabilities.

b) Other Instabilities

There are a number of problems associated with other instabilities, and combined instabilities that are also appropriate for study with laser driven flow. The most obvious candidate for consideration is the instability associated with the propagation of a strong shock through a uniform gas, which may play an important role in the structure of supernova blast wave propagation and in the formation of stars and galaxies. Considerable controversy in the past has been generated by theoretical disagreements, but the recent observation of these instabilities³¹ in a laser-driven blast wave indicates that more research is needed on this topic.

The NIF is uniquely suited to producing the strong shocks with large spatial extent that are required for these studies. In addition, combined Rayleigh-Taylor, Kelvin-Helmholtz, and Richtmyer-Meshkov instabilities have been theoretically described in cases where an oblique shock is preceded or followed by an acceleration and/or shear.³² Such combined instabilities, which occur whenever horizontal and vertical shear are simultaneously significant, are important for describing flow in winds and ocean currents, and for the fanning of smoke plumes. Experiments that could cleanly examine the dominant features of these phenomena are highly desirable and well-suited to the larger scale flows associated with NIF-generated flow.

There is a wide class of two-dimensional flows that become unstable in the transition to three-dimensional flow. These secondary instabilities occur because two-dimensional finite amplitude waves can be exponentially unstable to three-dimensional perturbations. This is another classical fluid dynamics problem. The study of these instabilities by Poiseuille or plane Couette flow generally has been performed in a regime where material compressibility has no influence. The effect of material compressibility on the

development of these secondary instabilities is, in itself, of great interest. Experiments with laser-driven flow will enable the compressible regime to be investigated with important implications for the understanding of wall-bounded shear flow.

Finally, a significant subject for investigation is the radiative condensation instability, a classical astrophysical problem with applications to Tokamaks and z-pinches as well. This instability is a general feature of the radiative cooling of an optically thin plasma. This is, of course, easily observed in interstellar and intergalactic clouds, solar prominences, and Tokamak or z-pinch plasmas, all of which have cool, dense plasma structures that radiate into hotter, rarefied plasmas in the surroundings. Experiments to provide a greater understanding of this instability are feasible in the controlled conditions characteristic of laser-generated plasmas.

c) Turbulent Flow and Vortex Dynamics

Both improvements in computational techniques and the emergence of chaos theory have contributed to a renewed interest in the subject of the transition to turbulent flow. In addition, recently the study of compressible turbulent shear layers has been the subject of increasing interest in the aeronautical engineering community.³³

The understanding of this phenomena, which differs considerably from the more familiar transition to turbulence for incompressible flow, is of key importance in the field of scramjet engine design. An experimental program in this area would increase understanding of the applicability of the coherent structure models that have been developed for incompressible shear layers in the past. There is also a great need for experimental evidence of large-scale structure in compressible shear layers, comparable to that found in incompressible cases. It is for this reason that the larger spatial scales associated with NIF experiments could be important for this developing field of study.

Vortex dynamics³⁴ is also an important part of this field, since they are associated with the fundamental mechanism for the evolution of hydrodynamically unstable surfaces to turbulence. At present, understanding of these phenomena seems to be limited to incompressible flow, but as with shear-layer flow, compressible flow experiments will be possible with the large spatial scales associated with NIF experiments.

D) Material Properties

The study of the properties of materials at extreme conditions of pressure, temperature, and density has been a goal of laser experiments since the advent of high-energy facilities. The most common application has been in investigations of equations of state (EOSs)—the relationship between pressure, density, and internal energy.

Impacts using guns or high explosives to generate shock waves have provided nearly all of our current database in this area, starting with investigations during World War II. Those methods have provided a great deal of precise data on a wide range of materials, but are limited to pressures below 1 TPa.³⁵ Static compression experiments have been performed extensively in diamond-anvil high-pressure cells; these experiments will ultimately be limited to pressures below roughly 1 TPa by the insulator-metal transition of diamond. Higher pressure experiments have been carried out at pressures of 1 TPa to over 100 TPa in the vicinity of nuclear explosions, but the data are of low precision above 10 TPa.³⁶

Relevant to the present discussion we note that high-intensity lasers can achieve similar pressures, as was recently demonstrated.³⁷ In the higher pressure regime, many new phenomena will become apparent, such as pressure ionization, strongly correlated fluid states, and so on. The strain rates involved can range up to 10^{20} bar/s, and the

behavior of materials under these conditions is unknown, especially as applied to melting and other changes of phase.

We have essentially no bulk or atomic-scale knowledge of any materials under these conditions of pressure loading. Precise measurements are necessary to discriminate among competing models or theories. The NIF is important in that it is the first large laser of sufficient energy and pulse length to allow for the possibility of such measurements being made with sufficient accuracy.

Data and validated theoretical models are vital for understanding and modeling such diverse phenomena as inertial confinement fusion, planetary interiors, ultrahigh-velocity meteorite impacts as well as most of the scientific experiments to be performed at the NIF, especially hydrodynamics and radiative and transport properties in condensed phase systems at high pressure and temperature (high P and T). We need to know the properties of materials over wide ranges of P and T. The detailed sections below describe the problems and some proposed experiments to determine the EOSs on (1) the principal Hugoniot, (2) multiple shock states, (3) isentropic release states, (4) isochoric heating experiments, and (5) other material properties. In doing so, we will describe applications to other fields.

1) The Principal Hugoniot

The principal Hugoniot is the locus of single shock states for shocks of varying strength, starting from material at normal density, atmospheric pressure, and 300 °K. These are not thermodynamic paths, but a true locus of states.

The Rankine-Hugoniot relations,³⁸ which express conservation of mass, momentum, and energy across the shock front, make the principal Hugoniot particularly useful. The final shock state (pressure, density, and total energy) can be determined from a knowledge of the initial state and two dynamic variables. The two dynamic variables are the velocity at which the shock propagates through the undisturbed medium, referred to as either u_s or D , and the velocity of the material behind the shock front, referred to as either u_p or U and known as the mass or particle velocity. For steady shocks, u_s is directly accessible to measurement, in principle.

The standard method is to measure the transit time Δt across a step of known extent Δx , and then $u_s = \Delta x / \Delta t$. Although this is a straightforward concept there are several practical difficulties in current experiments, which the NIF will alleviate. First, it is assumed that the velocity is constant. This has been rather difficult to achieve in ablatively driven shocks. The long, temporally tailored pulse of the NIF can solve this problem with careful target design. Second, the velocities are large—for Al at 10 TPa, $u_s \approx 70$ km/s. Such a shock wave will cross a 100- μ m step in only 1.4 ns, and the 1% accuracy we desire implies an uncertainty in the measurement of only 14 ps. This will strain the ability of current diagnostic systems.

The NIF will allow greater spatial dimensions, which will allow higher fractional accuracy for measurements of both length and time. Further, the use of a hohlraum drive will help to ensure that the shocks are planar and of large transverse extent, which is necessary if the larger target samples are to be free of two-dimensional effects. Accurate measurements are a requirement, since the uncertainty in the shocked density varies roughly as the product of the compression with the uncertainty in shock velocity, and compressions >4 will be common.

It is, in principle, possible to determine compression directly using x-ray backlighting; in practice, we believe that to be extremely difficult. What remains is to measure the mass velocity. Again, the scale of targets posited for the NIF makes possible a method proposed years ago, but never realized. The idea is to directly measure the velocity of the shocked material by observing the motion of an interface in the shocked material using x-ray sidelighting with an x-ray streak camera. The velocities are large as

well, but the spatial dimensions over which it can be made are improved at the NIF by virtue of the relatively long time scale of the experiment. For this to become possible a point-backlighter beam is essential to avoid parallax effects.

A further possible set of experiments to produce information on the principal Hugoniot is the use of what has become known as impedance-match experiments. In these experiments the EOS of an unknown material is compared to that of one known — perhaps by the methods described above.³⁹ This has been used in laser experiments before, but the scale of the experiments was such that only limited accuracy was possible.⁴⁰

This method can be exploited at the NIF because of the planarity and uniformity of the drive in hohlraums. One suggestion is that a simple material such as aluminum or gold be developed as a “standard” material over the broadest pressure range on the principal Hugoniot, and then used as a point of comparison with other materials of interest.

On the principal Hugoniot, there are a number of materials that must be studied. Hydrogen is the chief component of the Jovian planets. The current upper limit on single shock experiments in the fluid is 0.02 TPa,⁴¹ which samples only a fraction of the Jovian interior. Solid D₂ or H₂ could be shocked to many TPa in well-characterized experiments, perhaps encountering the proposed plasma phase transition.⁴² Further, metals of various Zs need to be studied. For Al in the range 10-100 TPa, successive pressure ionization steps are predicted to occur, and they may lead to wide excursions of the density on the Hugoniot as compared to calculations with purely statistical models.⁴³ In low-Z metals such as Be, these excursions are expected to occur below 10 TPa.

The Rankine-Hugoniot conditions relate the dynamic variables and initial state to yield the total shock energy, and do not explicitly give the temperature of the shocked medium. This is an important issue, since temperature, rather than total energy, is often an explicit variable in theoretical models. When we have recourse to competing models in the range of a few tens of TPa (several hundred megabars), we find that at a given pressure, the densities vary by about 30%, while temperatures are known to no better than a factor of two.

This is no mere academic problem, since the problem of high-pressure turbulent hydrodynamic flows explicitly involve temperature and entropy, and understanding these flows may prove intractable without more detailed information about the distribution of total energy into external and internal degrees of freedom. The solution to this problem may be to determine the temperature by x-ray absorption spectroscopy, using absorption line ratios to determine the temperature of the shocked fluid. We note that this comment on the value of temperature measurements is not limited to the principal Hugoniot; these comments apply to other high-pressure thermodynamic states and processes as well.

2) Multiple Shock States

The principal Hugoniot is a single locus of states; we need to know the properties of materials over wider ranges of pressure, especially planetary or other isentropes. This region can be probed by the use of multiple-shock experiments. Of these, we can distinguish two main possibilities. The first is colliding shocks, initially traveling in opposite directions. This method can be used to generate extremely high pressures, since the relative velocity is doubled, and hence the pressure is increased by a factor of about four.

In the case of relatively oblique incidence, we have the opportunity to study shock interactions that may lead to hydrodynamic instabilities, since there will be a shear component to the flow. This type of experiment is only practical with the use of large high-energy lasers, since the problems of timing and balanced shock generation are

intractable for other drivers. The topic of instabilities is touched upon in Section III.C, Hydrodynamics.

Of greater interest is the possibility of multiple or reverberating shocks in a material initially at rest. For a given final pressure, multiple shocks will achieve higher final densities and lower temperatures. Ten-fold compressions can be achieved. The limit of very weak multiple shocks approximates adiabatic compression; all multiple shock states of this type fall between the principal Hugoniot and the 0 °K isentrope.

This is an important regime for planetary physics, because all of the major planets are believed to have interior distributions of temperature and pressure that are best approximated by isentropes. As we noted in the introduction, current technology can sample only a very small fraction of those interiors. Using liquid or frozen hydrogen targets, experiments on the NIF will be able to probe states that are typical of the deep interiors of the Jovian planets, and "brown" dwarfs in general.

Multiple shocks can be generated by reflecting a simple shock wave at a boundary of high shock impedance (the product of density and shock velocity). These multiple shocks may be characterized by the methods described above. However, the flexible pulse technology proposed for the NIF will enable a more direct method. In this case, the driving pulse (for either direct or indirect drive) is stepped in intensity. With appropriate target dimensions, we can arrange the sample to be shocked in succession by these pulses.

3) Isentropic Release States

These states are characterized by higher temperatures and lower densities than on the principal Hugoniot. They can be reached by strong shocks followed by a release to lower pressure. When a shock in a material encounters a boundary with a medium of lower shock impedance, the final state is on an isentropic release from the initial state. At a given pressure, these states will have higher temperatures and be more highly ionized than on the Hugoniot. If we think of the total pressure as arising from a "cold" compression part (that is, the 0 °K isentrope) and from thermal contributions, these states are dominated by the thermal contributions to the EOS.

The conditions in a release experiment are found in nature both in high-energy-density ablation phenomena and in ultrahigh-velocity meteorite impacts. Thus, it is clear that these states are important to understanding the shock generation process at the NIF itself. Since much of the radiation transport in laser-generated plasmas is in hot, expanded material, these states may provide a fruitful way to generate useful states for radiation transport studies.

When a strong shock in a material releases into a vacuum, it will form a rarefaction fan, a gradient of density and temperature. This is difficult to characterize. It is simpler to mount a material of very low shock impedance against it, and then measure the shock in the low-impedance material. The final state in that material will match, in mass velocity and pressure, the release state of the initially shocked material, so the release state can be characterized by simple Hugoniot measurements in the low-impedance material.⁴⁴ The large target scales possible on the NIF will make this kind of experiment possible for the first time in a laser-driven environment.

4) Isochoric Heating Experiments

The use of isochoric heating on the NIF will enable an entirely new class of experiments at high pressure and temperature. By isochoric, we mean that the heating is at constant density. This implies that the heating pulse will be absorbed in a time that is short compared to hydrodynamic time scales of expansion. It also implies a nearly

constant deposition of energy throughout the sample volume. Isochoric heating will allow us to reach unique high-temperature and high-pressure states, and the high density will lead to strongly coupled physics. (Note that other aspects of strongly coupled plasma are discussed in Section III.G, Radiative Properties.)

The unique states attainable by isochoric heating are in the center of a region for which no limiting EOS theories apply and for which there is simply no data at all! These states fall outside the limits of low- ρ , high T where the activity expansions are valid, and outside the limits of high T where the Thomas-Fermi model is valid.

A promising method is to exploit the neutrons generated in a very short (<10 -ps) pulse at ignition, with a total predicted energy of up to 45 MJ, mostly in 14-MeV neutrons. We should be able to reach temperatures in thin foils of up to 50 eV at solid density. Even in materials with small neutron cross-sections, it will be possible to add small amounts of fissile material to increase the interaction with the neutrons without significantly changing the material EOS. A free-standing foil heated in this manner will be an excellent test material for spectroscopy.

Another possible method to obtain heating is to use a set of the NIF beams to irradiate metal targets at high intensity in a short pulse. This will produce a copious amount of hard x-rays. We calculate that a 10- μ m-thick Al foil could be heated to tens of electron volts in this manner. In this case, it could be mounted to a low- Z stepped tamping foil; measuring the shock velocity in the tamper will allow determination of points on a unique release isentrope from the initial state. Again, such a well-characterized sample will be ideal for spectroscopy of high temperature and density states.

5) X-ray Diffraction Studies

The NIF will be able to push time-resolved *in-situ* x-ray diffraction into new experimental territory. The higher energies and longer pulse lengths will allow harder, brighter x-ray sources with longer durations to be created. With these x-ray sources greater probe depths and experimental windows over which the shock compression process is measured become available. Thus, extensions of present techniques can then be used to study higher- Z materials. For example, it is not possible at present to experimentally investigate medium- Z metals like iron and copper, where an extensive single crystal literature exists. Iron is especially important for geological reasons, and although thoroughly investigated there is still controversy over the phase diagram.⁴⁵

The study of shock-induced polymorphic phase transitions, such as those observed in potassium chloride, is an area where long-duration x-ray sources (i.e., 10–50 ns) that are bright enough to be time-resolved are of importance.⁴⁶ Of further technological importance is understanding the effects of shock compression on superconducting properties, shock synthesis, and decomposition of high-temperature superconductors⁴⁷ and ceramics.⁴⁸

All of these studies will require the extensive development of polycrystalline x-ray diffraction techniques.⁴⁹ For x-ray diffraction techniques to work successfully on polycrystalline material, the probing radiation needs to be extremely bright as a reduction of two orders of magnitude in diffracted intensity is expected when compared to the same material in the single crystal form. In addition, the probing radiation needs to have a large penetration depth to probe a large volume. The standard method is to use a Seeman-Bohlin powder diffraction spectrometer which allows the use of large polycrystalline sample, as shown in Fig. III.D.1. This will require lasers with NIF capabilities.

Figure III.D.1 The Seeman-Bohlin camera. X-rays are integrated over a large area target, and then focused to a single point on film.

In high-temperature superconductors, x-ray absorption is high, due to the high Z content (e.g., YBCO, BSCCO), which makes them difficult to study. Detailed quantum mechanical modeling of brittle fracture in ceramic titanium carbide exists, and shock breakout measurements have been shown to be one of the most successful ways of attaining and measuring the ultimate tensile strains.⁵⁰ This technique could be extended to study novel polycrystalline high-strength materials of the future.

The greater laser energies of the NIF can be used to generate larger compressions, making greater portions of the solid-state Hugoniot accessible to the x-ray diffraction technique. Because the compressions are large (up to 50% for a few megabars for many metals) the shocked area must subtend a large angle to the x-ray source. These shocked regions will need to be 2 cm in diameter or more. Such large-area shocks must be uniform to ensure uniaxial compression of the solid; however, although uniform compression is not possible by direct radiation, it is possible with x-ray driven ablation.⁵¹

Using long compression pulses is important to prevent the rarefaction from over-running the shock front and eroding the compression. With x-ray-driven shocks, experimental investigation of shock front thicknesses in the strong shock regime can be made. Knowledge of the shock front, the thickness and shape, is extremely limited, and beyond the temporal and spatial resolutions of most experimental techniques.

With the next-generation facility's rapid rise time, long duration compression waves should be possible using long-duration shaped laser pulses. Using such well-defined shocks allows us to probe by x-rays only the material in the shock front that has strains between zero and peak compression. Diffraction at these intermediate angles must be

related to the shock front. Using x-ray streak cameras with 1-ps time resolution, measurements with resolutions of approximately 30 atomic spacings are feasible. At these resolutions issues such as shock planarity and target fabrication may dominate. These critical measurements of the shock front are vital for a fundamental understanding of shock compression.

6) Other Material Properties

While the emphasis above has been on basic high-pressure properties, other properties are very important scientifically. The electrical conductivity of materials at extreme conditions is crucial to understanding the origin of planetary magnetic fields, the transient fields predicted in the expansion plume of meteorite impacts, and MHD problems in general in hot and dense matter. Thermal conductivities are essentially unknown at pressures above ≈ 10 GPa. We further note that we have referred to radiation transport here and in other sections of this report; its importance is described in more detail in Section III.G, Radiative Properties.

All materials will be in hot fluid states at extreme shock pressures. For the group IV elements, in particular, we note that these liquids are believed to be semiconductors or metallic. Their local structure is uncharacterized, but it is believed that for modest pressures above melt, the structure is not a close-packed liquid. This points out the need for techniques to determine the distribution function in space of ions or atoms in the post-shock or other transient high-pressure states.

Another broad area of inquiry is the problem of non-equilibrium properties. This can be viewed as a special case of departure from local thermodynamic equilibrium, as applied to excitations of the system in general. We assume that areas of interest to material properties, such as those above, will rapidly evolve with the advent of the NIF. Until that time these are systems that cannot be considered ripe for investigation.

E) Plasma Physics

The creation of and interaction with plasmas by high-energy lasers has a long history.⁵² The irradiation of a surface with a high-energy laser produces a blow-off plasma that can be quite hot and contains densities suitable for the excitation of many parametric processes. Hence, high-power lasers represent a convenient way of producing plasmas with which to perform laser-plasma interaction experiments.

In the past, these plasmas have not been sufficiently uniform, and so the interaction physics, which is extremely sensitive to gradients, has been clouded. Some of the plasma-physics phenomena that will be studied with a large laser like the NIF are grouped here for discussion. In some cases, knowledge of the behavior of the phenomena is quite extensive and deeper understanding is sought. In other cases, the phenomena have not been addressed experimentally at all. This difference in treatment is due to the level of sophistication we now have in the various areas.

The experiments envisioned in the present discussion would require good focal-spot focusing capability, as small as 50 μm FWHM, and a dedicated interaction beam line with very high or low f/number in addition to operation potential with laser wavelengths at first, second and third harmonics. The experiments would also need some type of Thomson-scattering probe beam plus collection optics. These experiments require the energy of the NIF to produce the large preformed plasma needed to obtain large interaction lengths.

The proposed 1.8-MJ laser allows the production of an 11-mm diameter plasma at an electron temperature T_e of 3 keV and a 6-mm diameter plasma at 5–6 keV, and even higher electron temperatures with smaller plasmas. These larger plasmas will translate

into longer interaction lengths, greater homogeneity, higher temperatures, longer time scales, and reduced velocity gradients. Thus, the NIF is central to the possibilities discussed below.

1) Laser-Plasma Interactions in Large, Hot Plasmas

a) Stimulated Brillouin and Raman Scattering

The study of laser-plasma interactions and parametric instabilities such as Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) are of great interest to many researchers.^{53,54} SBS and SRS are three-wave processes that occur when the incoming light photon of frequency and wavenumber, ω_0 and k_0 , respectively, couples to a scattered light photon and a plasma wave. The conservation equations that govern the interactions are:

$$\omega_0 = \omega_{scat} + \omega_{pw} \text{ and } k_0 = k_{scat} + k_{pw}$$

for energy and momentum conservation, respectively. The subscripts *scat* and *pw* refer to the scattered light photon and the plasma wave.

Plasmas can support different types of waves. For SBS and SRS the plasma waves are the "ion-acoustic" wave and the "electron-plasma" wave. An ion-acoustic wave is the collective motion of the ions and electrons in a sound wave where the less massive electron pressure gradient oscillates the ions, which have substantial inertia. An electron-plasma wave is the collective oscillation of the plasma electrons in an electrostatic wave at the plasma frequency about the stationary ions.

Beating between the incident and scattered light wave serves to enhance the plasma wave producing more scattering of the incident light. The result is a feedback loop that, in times of order picoseconds, produces an exponential increase in scattered signal that saturates at anywhere from 10 to 100% of the incident light.

Such processes are obviously important from the point of view of transporting laser light effectively through a plasma, as is the case in ICF. The scattering of light at large angles results in energy being deposited in the wrong place and so is detrimental to the symmetry of ICF experiments. The byproduct of SRS is the conversion of the electron-plasma wave energy into extremely fast electrons, from 50 keV to 1 MeV energies, which in addition to transporting energy away from the experiment can also deposit it within a target, giving rise to a method of heating.

b) Filamentation

Filamentation instability occurs when a small hot spot in the laser intensity profile undergoes self-focusing as a result of thermal, ponderomotive, and/or relativistic effects.⁵⁵ The result is that electron density, and eventually ion density, are expelled from the filament, causing the laser light to focus more tightly. This creates an unstable feedback loop whereby a tighter focus leads to higher intensity and more density depletion. Eventually, the instability saturates through diffraction effects, thermal absorption, or laser light scattering by SBS and SRS instabilities.

The growth of filamentary structures can be determined by the width and length of hot spots in the incident beam, known as speckles. The filamentation can be described by a growth rate along the length of a speckle, and longer speckles are more likely to produce focusing of the hotspot in a filament. The length of a speckle is given by $8f^2\lambda$, where f is the f/number of the beam and λ is the wavelength of the laser light. Hence, the f/number and wavelength of the incident laser beam are powerful levers to modify filamentation, provided that the speckle lengths are smaller than the scale length of the

plasma. By using large uniform plasmas on the NIF, one would be able to produce very large filaments, thus allowing the study of filamentation over a wide range of wavelengths and incident beam f /numbers.

c) Diagnostic Potential

Understanding of scattering of incident laser light by parametric instabilities and process of filamentation is of interest to ICF. However, there are many aspects of these instabilities that are not adequately understood and are of interest to scientists for reasons beyond those generated by fusion studies. Understanding of the saturation mechanisms for these instabilities together with the effect of different types of beam smoothing on filamentation are subjects that challenge our ability to model these plasmas.

The nonlinear processes that determine saturation of the plasma-wave amplitudes and the way in which depletion of the incident beam limits filamentation and plasma-wave growth are subjects that will benefit from study over a broader range of parameter space than that expected from ICF targets alone. It is expected that one should be able to extend the parameter space in terms of laser intensity distribution, f /number, pulse length, and wavelength beyond that possible at any existing laser facility. We can explore filamentation over a broad range of experimental parameters by varying the color and f /number of the filamentation beam and by varying the plasma conditions (e.g., temperature, density and average Z).

The primary diagnostics for filamentation would be SRS signal, which is indicative of lower density in the filaments that could be coupled with high spatial resolution (on the order of $1\text{ }\mu\text{m}$), XUV imaging, and high-resolution optical probing with $4-\omega_0$ light. Further, the study of the angular distribution of scattered light would provide an indication of filamentation.

Thomson scattering could be used for these investigations, thus making highly localized measurements of plasma temperature and density by scattering from thermal electron-density fluctuations in the plasma. In addition to thermal measurements using Thomson scattering, one can reach far deeper understanding of the physics of laser-plasma instabilities using Thomson scattering to measure the coherent motion of electrons involved in ion acoustic and electron plasma waves. This measurement can provide a temporally and spatially resolved measure of the coherent fluctuation amplitude in a specific direction determined by the angle made by the detector, scattering volume, and scattering light source.

Measurement of the background fluctuation levels would provide information about the initial level of coherent fluctuations, the amplification of these levels with the application of a pump or interaction beam, and the saturation level of the fluctuations. In addition, it could provide useful information as to the coupling between SRS and SBS through simultaneous measurements at the same spatial location of the ion acoustic and electron plasma waves.

Optical wavelength Thomson scattering is well-suited for low electron densities such as are encountered in the corona, whereas x-ray wavelength Thomson scattering is better-suited for overdense plasma densities. The possibility of developing an x-ray Thomson scattering measurement to study coherent plasma motion in high density plasmas is possible and exciting.

Present Nova open-geometry plasmas, called "gasbags," have shown the facility of producing millimeter-scale plasmas at interesting electron temperatures. Coupling this capability with the ability to make controlled perturbations to the plasma in the form of higher density materials nearby and controllable flow velocities will allow us to take apart many plasma-physics experiments that have been virtually impossible to interpret quantitatively. As an example one can look at the plasma-physics experiments that focus on the hohlraum environment.

Side scatter is of major interest to plasma physicists. This is because in strong gradients with large laser spots it is predicted to dominate the backscatter. Further, the behavior will be different in flowing and stationary plasmas. Theoretical and experimental understanding of side scatter is incomplete, so this is an area that will benefit greatly from experiment time on large uniform, controllable plasmas.

2) Short-Pulse High-Intensity Laser-Plasma Interactions in Large, Hot Plasmas

At the NIF Users Workshop there was unanimous agreement to recommend that NIF include a beam line for short-pulse, high-power experiments. This capability is especially important for many basic plasma-physics studies. These include relativistic, ultra-high intensity regimes of laser-matter interaction; generation of astrophysical-relevant plasmas; fast ignitor physics⁵⁶; high-gradient accelerator schemes⁵⁷; new x-ray lasers; and high-temporal-resolution diagnostics.

The fast-ignitor laser-fusion concept combines many interesting high-power, short-pulse phenomena such as generation and transport of high electron fluxes in a high-density plasma,⁵⁸ intense harmonic generation at the critical density, ultrahigh B-fields, ponderomotive effects, relativistic self-focusing and filamentation, laser-beam channeling, and hole boring.⁵⁹ The high gradient accelerator schemes involve relativistic self-focusing and filamentation⁶⁰ and parametric instabilities such as stimulated Brillouin and Raman, in strongly driven and transient regimes.⁶¹

This short-pulse regime is also more amenable to detailed simulation (that is, 2D PIC codes can be run as long as the experiment and include the entire region of interaction⁶²) and to systematic exploration of linear and nonlinear behavior. Experiments of this type would require a short-pulse beam to be added to the NIF with the capability for good focusing (i. e., on the order of 20- μ m diameter). These experiments require the NIF to produce the large preformed plasma needed to access large interaction lengths.

The high-gradient accelerator schemes use the fact that a plasma can support much higher fields than conventional accelerators such as those of use in elementary particle physics experiments. As a result the device is much more compact and potentially cheaper. A number of novel schemes⁶³ have been proposed and studied at laser powers not quite high enough to produce the desired relativistic electron quiver velocity. Relativistic self-focusing is central to the acceleration scheme to maintain the high laser intensity over many Rayleigh lengths. Other processes such as stimulated Raman and Brillouin scattering or filamentation can break up the laser beam and degrade the efficiency of the scheme. If these schemes prove successful, applications to tunable sources of x-rays are also envisioned.

3) Study of Very High Magnetic Fields

A further area of focus will be the study of magnetic fields generated by the temperature and density gradients present in plasmas. In laser-produced plasmas the large magnetic fields can be generated in many ways.⁶⁴ For example, one proposed scheme is to generate extremely large magnetic fields by intentionally creating a circulating current path for Raman-generated hot electrons.⁶⁵ This might be done by using a number of beams to irradiate a pre-formed plasma, such as in a gasbag. Simple estimates show that currents up to 10^8 Amperes might be generated using the NIF, and magnetic fields as large as 10^8 Gauss could result. Even if the currents and fields are limited to substantially smaller values, this scheme might generate a laser-induced toroidal pinch with intriguing applications.

Calculations have indicated that these fields can be as large as 100 MG.⁶⁶ We may be able to use Faraday rotation of an optical probe beam and Zeeman splitting of spectral

lines to investigate and quantify these magnetic fields. By inhibiting thermal conduction, magnetic fields influence temperature distributions and hence, SBS, SRS, filamentation, and propagation of laser beams in plasmas. We may also be able to study the effect of magnetic fields on atomic energy levels through simultaneous x-ray spectroscopy. One interesting possibility is to use the Weibel instability driven by intentionally induced anisotropy in the electron velocity distribution.

The NIF would be required for many of these experiments to create significant, and hence diagnosable, volumes of plasma at the same time as extremely large magnetic fields are generated.

4) Generation of Large Fluxes of High-Energy Electrons (50–100 keV)

One could study the deliberate production of fast electrons through SRS and Two-Plasmon decay mechanisms in plasmas that are at 0.1 to 0.25 of the critical density.⁶⁷ In particular, these plasmas could be preformed from gas-filled targets or foams. Further, one could study the conversion of the high-energy electrons, 50–100 keV, to x-rays by placement of appropriate high-Z layers near the target. The fast electrons could then deposit their energy in the high-Z material and the resultant x-ray emission would be studied.

Further, it is possible that one may be able to develop a compact high-energy x-ray source that can be used for backlighting/probing of other experiments. Finally, the study of the magnetic fields generated by the enormous currents by these means may also be of interest—see Section III.G.7, Strong Magnetic Field Effects.

5) Interpenetrating Plasmas and Turbulence

The study of the interaction, or interpenetration, of two high-temperature plasmas has received limited attention experimentally.⁶⁸ Apart from its intrinsic interest, it is interesting to note that the interaction of plasma streams is part of the standard ICF experiments because of the generation of plasma motion inside a hohlraum. One particular interest is the equipartition of energy between the two groups of ions, and in this regard it has been calculated that ions can achieve very high temperature through collisions.

Moreover, the inter-streaming plasmas can provide the ideal system to generate and study turbulence in plasmas. Thus, one could study the generation of two-stream ion-ion turbulence or the generation of the ion Weibel instability. The latter is of interest because it creates magnetic fields with $\lambda \sim c/\omega_{pi}$ but has a slow growth rate of $\sim \omega_{pi}u/c$, where ω_{pi} is the ion plasma frequency and u is the relative velocity of the interpenetrating flows.

Producing high-temperature plasmas that can collide with sufficiently high density requires large amounts of laser energy. We note that Nova is severely limited in this regard. Although some work could be performed, the energies available in the NIF will make these studies more attractive, with quantitative results being feasible.

The limitations of the current laser facilities occur because of the need to have plasmas that are large enough to permit using diagnostics to probe the region of interpenetration with sufficient spatial resolution. The study of ion turbulence will require a diagnostic such as Thomson scattering that will permit the direct measurement of $\Delta n/n$ of the ions as a function of time. The diagnostic should allow this measurement to be made in different directions, thus permitting us to follow the randomization of the ion fluctuations as well as the anisotropy of ion acoustic properties.

6) Nuclear Reactions in Large-Volume, High-Temperature Plasmas

A great deal of study has been done to characterize the behavior of ICF capsules. As discussed earlier in Section III.B.6, these capsules are expected to achieve conditions suitable for testing certain nuclear reaction rates of astrophysical interest. However, compressional heating of ICF-like capsules may not be the only way to explore nuclear reaction rates at temperatures corresponding to stellar interiors. We note that most Main Sequence stars have core temperatures between 1 and 2 keV and that Nova experiments are already raising millimeter-size gas samples to temperatures near 2 keV.

Temperature (keV)	Reactions / ns
2.1	8
2.6	76
3.4	2340
4.3	26300

Table III.E.1 The number of reaction for a ${}^3\text{He} + {}^3\text{He}$ in a 10-mm^3 3-atm sample.

While the temperatures and densities are lower than what might be achieved in an imploded capsule, they are sufficient to examine many light-element reaction rates, and there are definite advantages to direct heating of gas samples. The large sample size guarantees homogeneous conditions that can be held for relatively long (nanosecond) periods. This eliminates much of the difficulty and uncertainty in converting an observed number of reactions into an energy-dependent cross-section. With 60 times the energy, the NIF will be capable of raising larger samples to higher temperatures.

An example of a reaction rate that might be studied in this way is the ${}^3\text{He} + {}^3\text{He} \rightarrow 2p + {}^4\text{He}$ reaction. This reaction rate is important for the branching ratio between the branches of the proton-proton chain, PPI and PPII, in the sun, and therefore have direct consequences on the expected neutrino rate. Table III.E.1 gives the number of reactions expected in a nanosecond from a 10-mm^3 gas sample at 3 atm.

$\text{D} + \text{p}$	$\rightarrow$	${}^3\text{He}$
$\text{D} + \text{D}$	$\rightarrow$	$\text{n} + {}^3\text{He}$
$\text{D} + \text{D}$	$\rightarrow$	$\text{p} + \text{T}$
$\text{T} + \text{T}$	$\rightarrow$	$2 \text{n} + {}^4\text{He}$
${}^3\text{He} + \text{D}$	$\rightarrow$	$\text{p} + {}^4\text{He}$
${}^3\text{He} + \text{T}$	$\rightarrow$	$\text{D} + {}^4\text{He}$
${}^3\text{He} + \text{T}$	$\rightarrow$	$\text{n} + \text{p} + {}^4\text{He}$
${}^4\text{He} + \text{T}$	$\rightarrow$	${}^7\text{Li}$
${}^6\text{Li} + \text{p}$	$\rightarrow$	${}^7\text{Be}$
${}^6\text{Li} + \text{p}$	$\rightarrow$	${}^4\text{He} + {}^3\text{He}$
${}^7\text{Li} + \text{D}$	$\rightarrow$	$\text{n} + 2 {}^4\text{He}$
${}^7\text{Li} + \text{T}$	$\rightarrow$	$2 \text{n} + 2 {}^4\text{He}$
${}^9\text{Be} + \text{p}$	$\rightarrow$	$\text{D} + 2 {}^4\text{He}$
${}^9\text{Be} + \text{p}$	$\rightarrow$	${}^4\text{He} + {}^6\text{Li}$
${}^{10}\text{B} + \text{p}$	$\rightarrow$	${}^4\text{He} + {}^7\text{Be}$
${}^{11}\text{B} + \text{p}$	$\rightarrow$	$3 {}^4\text{He}$

Table III.E.2 Selected reactions having rates larger than the ${}^3\text{He} + {}^3\text{He}$ rate at 2.1 keV.

Another important cross-section for astrophysics involves the destruction of ${}^7\text{Li}$. Primordial lithium abundances are a critical constraint on Big Bang nucleosynthesis and cosmology. Typically the primordial abundances are obtained from the lithium abundances seen in the oldest stars. However, the observed abundances must be corrected for any destruction that occurs, and observations of old clusters indicates that more lithium is destroyed than expected. The main reaction for this destruction, ${}^7\text{Li} + p \rightarrow {}^8\text{Be} \rightarrow 2 {}^4\text{He}$, is nearly 5000 times larger than the ${}^3\text{He}$ rate at 2.1 keV

Other reactions with rates expected to be higher than the ${}^3\text{He} + {}^3\text{He}$ rate at 2.1 KeV, and which are thus candidates for investigations on the NIF, are given in Table III.E.2.

F) Radiation Sources

Intense radiation at wavelengths extending from the far-infrared to the x-ray region of the spectrum can be generated by high-energy, laser-matter interaction. The characteristics of this radiation depend in detail on parameters such as the magnitude and mechanism of laser absorption, relevant atomic physics, the equation of state of the heated material, and hydrodynamics. In order to be able to tailor such radiation sources to the needs of specific experiments, considerable effort has gone into both detailed measurements of emitted spectra and extensive modeling work for a variety of materials and laser conditions. As a consequence of this work, scientists have developed sophisticated simulation tools that allow extrapolation of the capabilities that lie ahead using even higher-energy laser drivers, such as the NIF.

In the sections that follow we will discuss the types and capabilities of radiation sources possible using a high-energy laser driver, and discuss possible applications of these sources. In Section III.F.1, we discuss incoherent x-ray radiation sources; this includes both broadband and line emitters. In Section III.F.2, we describe coherent sources; this includes an extrapolation of existing collisionally pumped x-ray lasers, new inner-shell pumped x-ray laser schemes, and high-order harmonic generation. The latter two of these sources will take advantage of ultrashort-pulse capabilities on the NIF. In Section III.F.3, we briefly discuss the potential of the NIF as a high-energy particle source.

1) Incoherent X-ray Sources

a) Broadband Sources

Laser-produced plasmas have long been recognized as efficient sources of x-rays. Nova experiments have already demonstrated conversion efficiencies as high as 50% from gold plasmas (see page 63 of Ref. 1). For the NIF this implies that megaJoules of x-rays can be generated from a millimeter size source. The effective blackbody temperature of this radiating plasma can be estimated from the Stefan-Boltzmann relationship to be given by $T_{BB}(\text{eV}) \sim (10^{-5} I_{laser})^{0.25}$. Here T_{BB} is the plasma temperature in eV and I_{laser} is the laser intensity in W/cm^2 .

Radiation sources driven on flat targets can be configured as point sources, with increased spatial coherence, or as large-area radiators for efficient radiative energy transfer in a close-coupled geometry. The most intense radiation environment created using a high-energy laser is found inside radiation cases, called hohlraums. In a hohlraum, laser energy is focused on the interior walls of a hollow cylinder that has laser entrance holes (LEH) on the ends. The interior walls are vaporized and heated to a high temperature. This temperature has been measured at Nova; its temporal dependence is shown in typical data in Ref. 1, page 6. In Section IV.D a set of data is shown that

illustrates the types of hohlraum radiation environments now available. With this information and a simple model (see Ref. 1, Fig. II.A.3) one can make simple extrapolations to the NIF. At the NIF, by the simplest scaling, the radiation temperature in hohlraums will be increased by more than a factor of two, with energy outputs approaching two orders of magnitude larger than currently available.

Continuum x-ray sources, conveniently described by effective blackbody temperatures in regions of the spectrum determined by the specific ionic species contained in the plasma, can easily be spectrally filtered and tailored for a wide variety of applications, including optical pumping of absorbing targets in materials research and astrophysics. For examples refer to the sections on Radiative Properties, Astrophysics, and Material Properties.

Laser-driven sources can be configured to efficiently yield hard x-rays, for example as used in imaging and opacity experiments. At the highest energies, implosion experiments on the NIF will achieve capsule temperatures of 5–10 keV, which will produce extremely bright bursts of continuum, hard x-rays.

Short-pulse capability on the NIF will allow the generation of intense, hard x-ray sources in the ultrashort temporal regime. This capability will allow the study of the dynamics of materials undergoing rapid phase transformations on the time scale of individual atomic motion. Such studies in the past have been limited due to insufficient photon flux and the lack of hard x-rays to both pump and probe materials to sufficient depths to eliminate surface and thermal (shock) propagation effects. These are, of course, interesting in their own way—see Section III.D, Material Properties. However, here we have the capability to study intrinsic material time scales. One intriguing possibility is the potential of rapidly heated materials to form metastable or short-lived phases; the type of pump-probe experiment possible with the NIF would allow observation of such material through characteristic x-ray scattering.

b) Narrow or Line Sources

Line sources can yield narrow bandwidth radiation with increased temporal coherence. They represent an important diagnostic tool for hard x-ray imaging and opacity measurements. The conversion efficiency into a single spectral line has been measured to vary from 1% at x-ray energies below 3–4 keV to 0.1% beyond 4 keV. The character of the emission spectra is strongly affected by the dominant shell. For instance, K-shell emitters are dominated by isolated strong H-like and He-like line emission. In contrast, high Z emitters such as gold are dominated by large bands of unresolved transitions. Reference 1 contains a compilation of the experimental results for a variety of elements and laser conditions. A NIF laser will allow higher ionization states to be accessed, extending the region of monochromatic hard x-ray sources to the hard x-ray region. The application of narrow band sources for the probing of polycrystalline structures is discussed in Section III.D, Material Properties.

2) Coherent X-ray Sources

a) X-ray Lasers

Plasma-driven lasers now operate over a wavelength range extending from the ultraviolet down to the soft x-ray region near 35 Å.⁶⁹ Such systems utilize single-pulse optical laser to produce a hot and uniform plasma suitable for laser amplification and propagation. Figure III.F.1 shows a graph of the wavelengths of the dominant x-ray laser lines in collisionally pumped systems as a function of atomic number. The NIF would allow us to simply extend collisionally pumped neon-like 3p–3s and nickel-like 4d–4p systems to short wavelengths and high output energies.

Figure III.F.1 Collisionally pumped x-ray laser wavelengths. Calculated (open symbols) and measured (solid symbols).

Previous Nova x-ray laser experiments have found that the total irradiance required in a 500-ps pulse of 0.53- μm laser irradiation scales with x-ray laser wavelength λ as

$$I(\text{W}/\text{cm}^2) \sim 2 \times 10^{17} (\lambda / 20)^{-3.5}$$

for Ne-like systems and:

$$I(\text{W}/\text{cm}^2) \sim 4.3 \times 10^{15} (\lambda / 20)^{-3.5}$$

for Ni-like systems. Here λ is the wavelength in Ångstroms of the short wavelength $J = 0$ to 1 in Ni-like and the brightest $J = 2$ to 1 line in Ne-like.

Extending Ne-like x-ray lasers below wavelengths of 20 Å will be difficult given the high power requirements. Nevertheless, the high gain of these systems will make it possible to produce saturated x-ray lasers with plasma lengths of 2–3 cm. Extrapolating the Ni-like system to uranium with a $J = 0$ to 1 transition at 21.46 Å, we estimate that an irradiance of $4 \times 10^{15} \text{ W}/\text{cm}^2$ would be required to make an x-ray laser at this wavelength. If we assume a 500- μm -wide line focus, a 6-cm-long laser, and a 500-ps pulse, the energy required to saturate a Ni-like uranium laser is approximately 500 kJ, well within the design limits of the NIF. The output x-ray laser energy from a saturated amplifier is calculated to be $\sim 0.2 \text{ J}$. Using x-ray optics to focus the x-ray laser, we will be able to achieve peak intensities of $1 \times 10^{17} \text{ W}/\text{cm}^2$.

Numerous candidates have been proposed for photopumped x-ray lasers, yet to date no successful demonstration has been reported. The difficulty in these experiments remains producing bright x-ray pump sources that can efficiently couple to the candidate plasma. A NIF-size facility will allow large volume pump plasmas to be produced which can efficiently pump candidate plasmas and allow testing of this promising concept.

Short-pulse capabilities of the NIF will allow us to investigate a variety of new x-ray laser schemes, including inner-shell pumped and optical field ionized, as well as extending x-ray lasers to the hard x-ray regime. Inner-shell pumped x-ray lasers rely on bright x-ray sources to produce inner-shell vacancies and direct population inversion. The fast auger-decay rates of these systems make it necessary to use extremely short x-ray pulses. The main advantage of these systems is the prospect of generating short-wavelength lasers with low-Z atomic systems; for example, from neon one obtains 10 Å. Kapteyn et al.,⁷⁰ and more recently Strobel et al.,⁷¹ have investigated the feasibility of these systems and have shown that high gains are possible with bright 100-fs x-ray pump sources.

Recombination x-ray lasers, which rely on fast three-body recombination in a cold plasma to produce an inversion, have long been viewed as an alternative to collisionally pumped systems, offering the potential for higher conversion efficiencies. To date, however, it has been difficult to achieve large gain length products, or alternatively saturated output, in these systems. A primary reason has been the difficulty of producing long uniform plasmas suitable for inversion and x-ray propagation. A NIF-size facility will allow such a system to be adequately tested because of the large-volume plasmas available.

Optical field ionized x-ray lasers, which are a variant of standard collisional and/or recombination lasers, rely on a short laser pulse to multiphoton ionize a neutral gas. The short optical pulse reduces collisional heating or can, by design, enhance it. This x-ray laser scheme has the potential for a short output pulse, on the order of 100 fs.

b) High-Order Harmonic Generation

The generation of odd harmonics, up to the eleventh, from the interaction of high-intensity lasers with dense gases had long been observed.⁷² However, by shortening pulse duration to avoid ionization and by increasing intensity, researchers have now measured harmonics extending to the 109th of 811 nm radiation and the 143rd of 1053 nm radiation.^{73,74}

These harmonics result from the periodic oscillation of quasi-free electrons across the atomic potential. As the electron passes the nucleus, it suffers an impulsive distortion in its trajectory that generates a broad spectrum of radiation. Since the harmonics are produced only by the driving field of the laser, their pulse width is equivalent to that of the driving optical pulse.

Coherence and overall conversion efficiency are limited by phase matching between the harmonic field and the incident laser field. Recently, XUV harmonic radiation near 20 nm has been produced with conversion efficiencies as high as 10^{-7} .⁶⁶ Longer wavelength radiation, greater than 50 nm, can be produced with a conversion efficiency exceeding 10^{-6} . Although achieving these efficiencies on the NIF will be difficult because of the need for long focal length lenses, the generation of microJoules of coherent tunable XUV radiation using this technique is viable.

c) Applications of X-ray Lasers

Biological Imaging

The high brightness of x-ray lasers make them well-suited for a variety of applications ranging from biological imaging and microscopy to nonlinear optics and interferometry. X-ray microscopy offers a way to study structure in wet, thick, 2–10- μm , biological specimens. Demonstrated resolution is approximately five times better than that of conventional and confocal optical microscopes for samples that are thicker than the electron microscopes' limit of 0.4 μm .⁷⁵ This, then, allows whole cells or organelles to be studied without sectioning.

When dealing with wet specimens, the radiation dose imparted to the specimen leads to mass loss and decomposition of specimens. Resolution is, therefore, limited by radiation damage and exposure time. X-ray lasers, by virtue of their high brightness, have the potential for producing high-resolution biological images before significant damage occurs to the specimen. For instance, the tantalum Ni-like x-ray laser has been used to image dry biological gold-stained specimens. However, developing full three-dimensional imaging of biological specimens will require a significant increase in the output energy of the tantalum x-ray laser. A NIF-size facility will allow us to produce saturated x-ray laser output at laser wavelengths above and below the carbon absorption edge at 44 Å, making high-contrast imaging possible.

Plasma Diagnostics

X-ray lasers are currently finding important applications as diagnostics tools for high-density plasmas. To date most of this work has used the Ne-like yttrium x-ray laser operating at 155 Å because of its high output power of 30 MW.⁷⁶ This has significant advantages over conventional optical diagnostic techniques because it reduces refraction effects and eliminates problems with critical density layers. However, due the high absorption of relevant plasmas at 155 Å there exists a real need to push this work to shorter wavelengths to allow accurate density measurements of cool plasmas at solid densities.

Nonlinear optics at soft x-ray wavelengths is an area largely ignored because of the difficulty in generating sufficient x-rays to make measurement viable. Numerous experiments have demonstrated multiphoton processes in the near UV by focusing optical lasers through neutral gases. To extend these experiments to the soft x-ray region a plasma is necessary both to reduce absorption and to allow for resonant enhancement of the nonlinear susceptibility. One possibility that is particularly interesting is four-wave mixing, in which an optical laser is mixed with an x-ray laser to produce a tunable soft x-ray source. Aside from its clear applications, these experiments would allow measurements of nonlinear susceptibility to be made in a regime that is largely unexplored.

3) Particle Sources

A NIF laser will permit the generation of a wide variety of particle sources ranging from high-energy electrons and ions to neutrons and other fusion products. The generation of high-energy electrons through parametric instabilities in plasmas is discussed in Section III.E, Plasma Physics. Pair production using high-intensity lasers has long been proposed but is outside the realm of existing facilities. As discussed in Section III.B, Astrophysics, the demonstration of pair production will be marginally possible with a NIF size facility.

Implosion and subsequent burn will produce a variety of fusion products. Initial calculations indicate that the neutron production could exceed 10^{19} in a short 100-ps burst. The use of these neutrons for producing uniform high-density plasmas exists, but the low temperatures seriously limit this application. The high flux levels can be useful, however, for studying material properties in a regime where the generation and growth of dislocations become nonlinear.

G) Radiative Properties

The study of radiative properties using high-energy lasers has a long history. The irradiation of a surface with a high-energy laser provides copious x-ray emission that is easily accessible and inexpensive.

Over the years the development of x-ray spectroscopy has led to further inquiries into the origin of the radiation, kinetics processes of importance and radiative transfer in these plasmas. These are all grouped here for discussion. Some of the topics summarized below are quite complex while others are dealt with in a more schematic manner. This difference in treatment is due to the level of sophistication we now have in the various areas.

To attempt to cover the various constraints on experimental aspects of the problem in a coherent way, the background material in Section IV.C, Radiative Properties groups the various experiments according to the levels of complexity of the property being studied. Thus, the topics are grouped into four sub-sections: Isolated Emitter Spectroscopy, Plasma-Emitter Radiative Properties, Dynamic Properties, and Non-LTE Radiation Transport and Line Formation. Here we present some of the more specific topics of interest for scientific investigation into radiative properties.

1) Spectroscopy of High-Z Elements

The current state of knowledge of highly ionized atoms as it relates to some key isoelectronic sequences will provide a background to assist in understanding the importance of the experiments using high-energy lasers, and in particular to extrapolate to the NIF. The current state of experimental knowledge on isoelectronic sequences that lie between those presented below is even less complete. A typical example of a current experimental setup is shown in Fig. III.B-1 of Ref. 1. It is believed that using a source as powerful as the NIF laser and special foam target designs, or other long scale length plasma production mechanisms, can achieve coronal temperatures of 6 keV, with eventual production of 10-keV plasmas. Such temperatures will allow one to probe most elements of the periodic table to any desired degree of ionization.

Observing transitions in higher-Z ions is important for determining the contributions to the transition energies that become significant only at high Z. These include QED and relativistic contributions to the transition energies. In addition, electron correlation effects are important at high Z. The comparison of the observed and calculated transition energies motivates and guides the improvement of the atomic theory of highly charged ions. For example, a great deal of work is presently being done on non-hydrogenic QED theory. Further, the atomic models are input to the opacity and atomic kinetics simulation codes.

The simplest spectra to interpret, and the easiest transition energies to calculate, are for ions with one weakly bound electron outside a closed shell. These are in effect "one-electron spectra," and they occur for lithium-like ions with 3 electrons, sodium-like ions with 11 electrons, and copper-like ions with 29 electrons. To date, the copper-like sequence has been studied to the end of the sequence (i.e., up to Cu-like uranium). The NIF would permit the study of other sequences, such as the sodium-like sequence up to uranium.

Isoelectronic sequences that are near the one-electron sequences are also of interest. Examples are the fluorine sequence with 9 electrons and the magnesium sequence with 12 electrons. The fluorine sequence has one electron less than the closed-shell Ne-like, and only two transitions are intense in current laser-produced plasmas. Sequences such as

the fluorine sequence are used to study the atomic physics of "nearly closed shells." The magnesium sequence has two electrons outside closed shells, and electron correlation effects become important. Electron correlation in highly-charged ions has become an important topic in atomic physics.

The work planned on high-energy lasers must be referenced to the possibilities on other sources of high-Z ions such as the EBIT and Tokamak devices. With regard to EBIT, only two types of transitions are typically intense. These are the resonance transitions that are collisionally excited from the ground state of the ion, and the transitions from the autoionizing levels that are resonantly excited by dielectronic recombination. It is not possible with EBIT to efficiently excite the transitions between excited states. The same limitation applies to Tokamak spectra; only the ground-state transitions are intense. Further, heavy ion accelerators can produce highly-charged ions, but Doppler shifts complicate the analysis, while synchrotron radiation can be used only for the study of cold material, not highly-charged ions. Thus, the NIF is necessary for the *in-situ* and complete study of entire spectra of the highly-charged ions that cannot be produced by currently available lasers.

2) The Transparency Window

The possible existence of a transparency window in the spectral region between the bound-bound transitions and the formation of the bound-free continuum has been discussed for many years and the issue is still unresolved.⁷⁷ The reason for the importance of this possible effect is that the result of such a decrease in absorption probability can have several serious effects. First, reduction of opacity in this spectral region can lead to overestimates of the opacity of the models. Second, the recombination rate into the high-lying states could be seriously reduced, changing the kinetics of the plasma. Finally, if the density of states is modified, this will have an effect on the thermodynamic properties of the plasma. This last effect is due to the direct connection between the density of states and the partition functions, from which all the thermodynamics properties are developed.

Transparency and the other residual effects are predicted to arise when two conditions exist. First, one must have a strongly coupled plasma, or a state when the plasma-ion radiator potential energy is greater than the thermal energy, so that the required approximation for the plasma-ion interaction become complex. Second, one must have an ion described by a non-spherical potential, because for spherical potentials it can be shown that transparency, and all the other residual effects, do not occur. Thus, in strongly coupled plasmas with complex ions this effect may be important.

The difficulty here is that to observe a change in the kinetics of the plasma or its thermodynamic properties requires a level of detailed information that is not possible, or thinkable, at the present time. However, there is the possibility that one can probe the region in absorption between bound-bound and bound-free in a specially prepared plasma. First, the effect one is looking for is a subtle change in absorption in a region that has bound-bound and bound-free transitions. Second, the very nature of the strongly coupled plasma problem indicates that the bound-bound transitions will be relatively broad and form a quasi-continuum. The ability to differentiate these effects and obtain absolute absorption cross-sections requires a minimization of the gradients of the system. In Section IV.C.2, Plasma-Emitter Radiative Properties, discusses methods for generating hot, dense plasmas of this type. Importantly, there has been much effort on developing the techniques to perform precision absorption spectroscopy on these type plasmas.

The proposed experimental setup might look similar to the experimental setup shown in Fig. III.F.2-1 of Ref. 1. With this configuration small differences in optical depth, on the order of 0.1 or less, can be measured accurately. The difficulty here is to generate a benign environment that can be probed.

3) Strongly Correlated Effects

To discuss strongly correlated effects on the radiative properties one should make the distinction between the concepts of strongly coupled plasma effects and strongly correlated plasma effects. The former is only concerned with the relative contribution to the plasma statistical mechanics from the plasma interparticle Coulombic potentials, given by $V \sim Z_1 Z_2 e^2 / r_{12}$, where the Z s are the charges on particles and r_{12} is the mean interparticle spacing, compared to the thermal energy. The latter—strongly correlated—can be schematically defined as the regime in which modification of the interatomic potentials of the ions by other ions substantially modifies effects on radiative properties.

Thus, for example, at one limit we can use as a measure of strong correlation the amplitude of the perturbation of the ionization potential of the ion. This is a reasonable measure, in that it points out that strong correlations occur, for some principal quantum number in all plasmas. But it also accounts for the fact that the modification of the radiative properties may not be substantive. Thus, one finds that, for example, the ionization potential depression, which is treated below, can be well approximated by simple means, and is not formally associated with strong correlations.

On the other hand, the formation of spectral features due solely to the correlations (e.g., quasi-molecular formation) is considered an effect of strong correlation. Further, we note that it is simpler to get a strongly correlated plasma than to get a strongly coupled plasma. For example, the plasmas in stellar interiors are very dense, and while their plasma properties are calculable with weak coupling, or Debye, theories, the overlap of the interatomic potentials is large and strong correlations will exist.

An example of these strongly correlated effects is the transient quasi-molecular effect. There are several suggestions concerning these satellites in the literature. First, there is the prediction of a molecular resonance on the far wings of the Lyman α transition of hydrogen in a plasma due to strong correlation with other hydrogen atoms.⁷⁸ The upper limit of density for such effects can be estimated by considering that when the orbital of interest is at the mean ion sphere radius there will be quasi-molecular formation. For the $n = 2$ state of a hydrogenic species of atomic number Z , one has $r = 6/Z a_0$ so that one finds the limiting electron density would be $Z^4 \times 7.46 \times 10^{21} \text{ cm}^{-3}$. The quasi-molecules would form at densities below this, but there would have to be a probability distribution associated with the dynamics of the system; at higher density the plasma would form band structures.

Second, this strong correlation effect on radiative property has been numerically studied for a pure H plasma.⁷⁹ This study does show that one can get groupings of atoms in which the charge distribution is highly distorted, resembling molecular clusters. However, these clusters are not necessarily bound. Static calculations performed on Ar in a hydrogen medium yield configurations of atomic positions from a molecular dynamics calculation. Subsequent electronic structure calculations over many configurations show that bands and line broadening form in a non-perturbative manner, and the averaged results form one composite transition. Preliminary work for these static calculations indicate that the $n = 3$ manifold of Ar is heavily influenced by the H band.

Third, there have been claims of satellites, assumed to be quasi-molecular in origin, that form in laser-produced plasmas. The effect was tentatively observed in the spectra from laser plasma produced by irradiating a LiF planar target by analyzing the Lyman β transition in fluorine with an emphasis on the short-wavelength wing. The results provided small features that may be attributable to quasi-molecular resonances.⁸⁰ These observations are not sufficient to prove the existence of the satellite lines and do show the difficulty with current experimental techniques.

The performance of experiments on plasma-emitter radiative properties will require a more idealized setup than employed in the direct laser planar target irradiation experiment. The effects sought are quite subtle, so working as close to a gradientless case

as possible will improve the chances of success. To have at the same time both a uniform plasma and a plasma in an extreme state requires the expenditure of a large amount of energy.

The highest level of success would be achieved by using a well-structured shock-based system. For example, an adiabatic or isentropic shock could be produced using a tailored x-ray driving source. This may allow the possibility of material compressed 10 times denser than liquid density. The difficulty will be in maintaining a low temperature in the shock-compressed region and devising a diagnostic complement that can observe the effect. There are further discussions of shock compression in Section IV.D, Material Properties.

4) Plasma Spectroscopic Topics

a) Spectral Line Shifts, Level Shifts, and Continuum Lowering

The measurements of spectral line shapes, including spectral line shifts, has been a topic of continuing interest because of the diagnostic capability provided by this non-interfering probe of the plasma conditions. This has meant that for each new plasma source there is a new and challenging series of theoretical developments that must follow to provide the diagnostic information.

Thus, on the one hand, experimental development has fueled the need for line shape modeling. On the other hand, the line shape, width, and shift, and the formation of the line series leading to the bound-free limit, contain some of the most fertile ground for exploring the general area of radiator-plasma interactions. In this way the underlying plasma-electron density and temperature are important, but so are the more subtle facets of the plasma, such as fluctuation levels, composition of the plasma, and non-equilibrium velocity distributions.

All of these facets can provide important signatures in the line spectrum and thereby provide a method of testing theoretical statistical mechanics and kinetics formulations. Thus the line spectrum has both diagnostic and intrinsic interest.

The questions that are opened to study concerning the line spectrum are the evaluations of line shifts which are relatively small compared to the line width and therefore difficult to measure and extremely difficult to calculate. No significant advance on the calculations of the spectral line shifts, in terms of a theory, has been made since the first formulations of the standard theory were developed in the late 1950s by Baranger and Griem.⁸¹

The shapes of many lines have still not been quantified, because there have been very few high-energy-density experiments where supporting data on the temperature and density of the plasma has been measured. To date there are, for example, no experiments where the density and temperature has been measured with sufficient accuracy in any plasma with a density higher than those probable by Thomson Scattering. Thus, although we have for two decades diagnosed laser-plasma densities using line widths, these have never been independently verified. The difficulty is discussed in the Appendix in the Section on Emitter-Radiator Properties. The main point is that the hot, dense plasma is highly transitory and usually has large gradients. These do not easily lend themselves to the production of high-precision measurements.

The situation becomes even more complex as we attempt to study the entire line series with its associated continuum. The various processes that arise as the series limit is approached are line broadening, line merging, and ionization potential lowering. To distinguish these is very difficult, but experiments that allow for a controlled plasma environment may be able to solve some of these problems. As indicated in Section IV.C.4, Non-LTE Radiation Transport and Line Formation, single-temperature, single-density gradient data may allow us to separate the effects of various mechanisms.

We note further that the various processes are in fact all due to the same perturbative mechanisms—the plasma particle fields cause the broadening and shifting of a line, while at the same time they change certain orbitals from bound to free. It is the interplay among these various physical manifestations that forms the nexus for our understanding of radiator-plasma interaction.

We note the fact that there is no complete theory describing the broadening of a bound-bound transition as it goes over to a bound-free transition. From a purely phenomenological view what happens is that the bound-bound resonance must continuously broaden in energy space while the change to a bound-free resonance is made. A schematic approach to this behavior is discussed by Liberman.⁸²

To measure an effect of this type requires an experiment that would have observably large ionization potential depression and substantial line broadening. These two effects are largely complementary in that these both increase directly with electron density. Further, to be able to isolate the line broadening and the transition into the continuum from the effects of line merging (i.e., the Inglis-Teller limiting case), one would like to go to high density and high Z so that the ionization potential is depressed to a low enough principal quantum number to allow the broadened spectral lines to be distinguishable (i.e., not merged).

Such experiments have been possible in the core emission of gas-filled microspheres imploded by both direct and indirect laser irradiation.⁸³ However, these experiments indicate that the technique of using implosion cores is not sufficient for the task. Although one gets indications of the various critically interesting effects and an interesting set of possible explanations, the data is not of sufficient quality to validate any particular theory.

We note that the development of better diagnostics and smoother implosion core densities may be the solution, but these would require the increased energy of the NIF. The implosion dynamics that are now available will not allow adequate constraining of the problem. This is simply because the system is driven to peak densities for very short times and the gradients thus produced are large. This is unacceptable for the spectroscopy of the *details* of the line shape, line merging, and ionization potential depression processes. On the other hand, using somewhat lower- Z elements than argon as fill gases may provide some amelioration of the steep density effect by permitting one to study the interplay at a lower density.

b) Ion Dynamics

The role of the dynamics of ions in the formation of spectral lines in plasma has been a topic of intense investigation for the last 20 years. Since the experimental verification that the Lyman α transition of neutral hydrogen was seriously affected by the dynamics of the ions, forcing modification of the standard theory that assumes quasi-static ions, much effort has been expended. The fact that this discovery came at a time when the production of ionic emitter line profiles started to become ever more available from laser-produced plasma experiments led to much work on the ion dynamics of spectral lines arising from ionic emitters.

However, to date there are no experiments that can be used to provide a serious test of the theories for hot, dense plasmas. Verification of the ion dynamics contribution is of critical importance for two complementary reasons. First, the use of spectral line broadening may be seriously comprised if the widths of the spectral are seriously changed due the ion dynamics. Secondly, even in those cases where the ion dynamics are negligible, one can only know this by access to a verified model.

To study ion dynamics requires the same type of uniform plasma conditions that are required by plasma-emitter radiative properties, and the discussion in Section IV.C, Radiative properties should be consulted. Additional considerations for these experiments require that one must observe line profiles from the same ionic radiator emitting at the

same plasma conditions but from plasmas with different ion perturber masses. The use of implosions is attractive from the point of view that hot, dense conditions can be reached; however, both the gradients in these implosions and the difficulty in obtaining temperature and density histories with different atomic species in the fill are unsolved problems. On the other hand, this area is ripe for investigation. Alternatively, the tamped-sample-type plasma may be the solution, but reaching the correct conditions will definitely require NIF-size experiments.

c) Continuum Measurements

The problems of providing continuum measurements is similar to the difficulty of measuring the absolute values of the continuum in any given experiment. The spectral localization of bound-bound or even bound-free edges provides a great simplification compared to the determination of continuum. This is true in all plasmas, but when we add the hot, dense and/or strongly coupled (and correlated) effects one is faced with, a daunting problem arises. It is clear that interesting processes can come into play in the formation of continua, such as strongly correlated scattering cross-sections. What is not clear is how to proceed.

The experimental setup discussed in Section IV.C, Radiative Properties is not sufficient in itself to provide good continuum measurement. The additional constraint is that the material surrounding the material of interest, whether it be a tamped sample or an implosion, must have small or completely quantified continuum contributions. It is easy to envision keeping the contributions small. In such cases the density of the material of interest would have to be increased relative to, for example, a sample prepared for the line shape measurements, where the optical depth in the lines would be kept small. However, with increased thickness comes increased plasma gradients, and the problems of volumetric heating are exacerbated. This makes the energy-rich environment of the NIF even more desirable.

In this context it would be appropriate to note that the important aspects of bound-free edges and continuum processes are at some level the same, the formation of free-free continua being an additional part of the puzzle. Further, the study of autoionization processes and how these behave in dense plasmas is also of great interest, not only in the study of plasma-emitter radiative properties, but also in the area of kinetics and radiative transfer.

5) Population Kinetics

The study of the dynamics of an atom immersed in a plasma is at the center of the ability to model time-dependent behavior of atoms in plasma. For the present discussion we assume that the radiative transfer is not an integral part of the kinetics. Situations where the radiative transfer is important are reserved for the next section.

Even when the radiative properties have been understood, the kinetics of the plasma is still in question. The reason is quite simple; the rates (or more accurately, the cross-sections) for all the processes must be well-known to model the population dynamics. Further, in those cases where non-Maxwell-Boltzmann distributions are important, the kinetics behavior would have to be accompanied by a measurement of the velocity distributions in lieu of temperature measurements.

This is an extremely difficult task and is not made simpler by choosing to study the behavior in hot, dense media. Although the densities may be high and give rise to plasmas that rapidly thermalize the velocity distributions, the rates for ionization and recombination are also rapid. Thus the dynamic ionization balance can be dictated by the non-thermal distributions. This will be particularly important for experiments with short-pulse, intense laser-solid matter interactions.

In the laser intensity regimes of 10^{15} W/cm² and above, which will be realized for sub-picosecond pulses, the electron distribution that is produced in the laser-matter interaction is highly non-thermal. This is created through non-local electron transport from the laser interaction region to a region of higher density, where the electron temperature, as measured by the electron sub-system energy content, is predicted to be up to 10 times higher than the local ion temperature. The ionization, therefore, is of great interest. However, the more mundane plasmas, (at least by these standards) created by volumetric x-ray heating or implosion of a microsphere, have the same interesting problems.

Further, we note that at these high intensities the laser electric field equals or exceeds the binding field in many atoms. In such cases, the laser field must be included non-perturbatively in the calculation of atomic and molecular properties. The laser field also affects scattering processes. For example, Feshbach-like resonances can be induced even in such a simple system as electron + proton, which without the field can have no resonances. Of course, these studies of intense field effects are in their infancy, but they will have to be addressed at some stage in future plasma models and experiments.

To map the kinetics requires a rich set of diagnostics that can provide spatial, temporal, and spectral coverage of the same event. This requires not only a well-characterized plasma, but a resource base that is beyond the level that can be brought to bear by an independent effort without the support of a facility of the scale being discussed here. Further, primary information on the plasma character must be available to corroborate the results. Thus, again the ability to perform temperature and density measurements is critical to the success of these experiments.

We note here that the numerous studies to date on the kinetics of plasma formed, for example, by direct illumination have left many unresolved issues. This is not for lack of desire, but mostly for the lack of both resources and plasma-generating devices that would allow critical investigations. The NIF would provide such a research environment.

Below we will discuss one type of experiment that is motivated by astrophysical considerations. However, the range of areas in which kinetics is of importance is much broader. The most important factor is that the complex mix of processes relevant to the kinetics problem can be attacked in a coherent manner when one has the plasma-production capability that the NIF will offer as well as the diagnostic complement.

6) Radiation Transfer and Line Formation

The study of the formation of spectra for time-dependent hot, dense media is the culmination of all the topics that have been discussed above. First, the radiative properties are required as initial input, and second, the kinetics model must be verified by experiment so that one can isolate the radiative transfer effects. Finally, one is then ready to study the non-local effects that arise in the formation of the spectrum.

For these effects one must solve the radiative transfer equation in tandem with the equations for the populations dynamics. Because each affects the other, the problem is a compounding of previous investigations. Here, as discussed briefly in Section IV.C, Radiative Properties, one finds that the regimes where the radiation transfer will be severely stressed will also be challenging for the experiments. The need to quantify the sources of the radiation field and radiation matter coupling is part of the problem. The rest of the problem is to create high-optical-depth, radiatively dominated transitions. These are extremely difficult in the present generation, and the NIF will certainly be required to investigate the regime thoroughly.

Fluorescence has been used in the study of kinetics to probe the movement of population around a network of levels, thus allowing the direct study of the redistribution of population. However, the difficulty in generating efficient photopumps is dependent on the radiative transfer process.

For hot, dense matter, pump-probe experiments are beyond the realm of present-day lasers systems. There may be the chance line coincidence between a soft x-ray laser and a transition of interest, but other than this bit of serendipity, pump-probe experiments will have to wait for the increased photon densities available with the NIF laser. Then it will be possible to use filtered backlights of sufficient brightness to pump line transitions in hot, dense matter.

A schematic experiment would look roughly as follows. We take a large low-Z tamped sample of mid-Z element. The sample is irradiated with a filtered x-ray source to ensure that there is no surface deposition due to critical density effects. Next, with the tamping controlling the gradient scale length in the problem, we perform absorption and emission studies, in different spectral regimes. One should be able to obtain temperatures of >100 eV for centimeter-size samples.

The limiting factor here is that hydrodynamic isolation is absolutely required to ensure that blast wave and debris do not compromise the results. Next, a photo-pump of measured temporal, angular, and spectral content is used to pump the plasma. The technique can now be used to observe line formation in transitions of one's choice.

The control of velocity gradients, and more generally the interaction of the radiative transfer and the hydrodynamics of the plasma, could then be explored. We note again that this is a regime that is completely beyond current capability. The measurement of the velocity fields in addition to the other parameters required would be impossible in the current experiments.

We note that for hot, dense matter, for the velocities to be of concern, they must be larger than the line width, which we assume is given by the Doppler width of the transitions of interest. Thus, for example, for a 100-eV plasma with $Z \sim 16$ one would require velocities in excess of 5×10^6 cm/s, which are easily obtained from a free expanding surface and can be associated with untamped surface expansion.

7) Strong Magnetic Field Effects

It is straightforward to deduce from Ampere's law that hot, dense plasmas with small scale lengths might contain strong magnetic fields, with $B > 10^6$ G, and indeed this is the case. Flux compression yields megagauss fields as a matter of course in explosive pinch experiments, and suprathermal electron currents arising from laser plasmas can produce fields exceeding 100 megagauss.^{84,85}

The behavior of matter in such strong magnetic fields continues to pose difficult questions in atomic/plasma physics, with importance for astrophysical as well as laboratory applications. For instance, some white dwarf stars have megagauss surface fields, and gigagauss fields are usually ascribed to neutron stars. Strong, primordial fields may also exist in the interiors of giant planets and in the cores of normal stars, including the Sun, but their presence cannot be deduced with our primitive understanding of how equations of state and transport coefficients are modified by large B-values.

Recent years have witnessed considerable progress in understanding certain effects of the huge 10^{12} -G fields expected in neutron star crusts.⁸⁶ However, the fact that Coulomb interactions are relatively unimportant there actually makes it easier to develop good theoretical models for this regime than for the intermediate 10^7 - to 10^9 -G regime, where magnetic and Coulomb effects are comparable⁸⁷ and perturbation methods are reliable. The suite of diagnostics one expects to be available for studying high-energy-density plasmas with the NIF provide a unique opportunity to probe specific issues related to intensely magnetized plasmas, such as:

- How do the strong B-fields modify plasma ionization balance?
- How important are the anisotropic pressure effects that arise when $B^2/8\pi$ is comparable to the gas pressure?

- What is the effect on transport coefficients of non-spherical atomic charge distributions that occur when $B > 10^8$ G?
- Can one use Stark broadening by motional (i.e., $\mathbf{v} \times \mathbf{B}$) electric fields as a reliable diagnostic of the strong B-fields in plasmas?

IV) Background Material

A) Astrophysics and Space Physics

1) Opacity

In the last few years a group at LLNL has made new calculations of the radiative opacity for stellar interiors, and this work has been incorporated into theoretical models of stellar evolution and pulsation by a number of astrophysicists around the world. As a result, some outstanding astrophysical problems have been solved.

These are problems that appeared when stellar structure and evolution calculations with the tables of opacity generated using the then state-of-the-art opacity codes at LANL were compared with observations. Previous stellar evolution calculations for the most massive stars had predicted that the range of surface temperature for the hydrogen-burning phase of evolution was narrow—that the stars were all quite hot at this time; with the new opacity the range is extended to lower temperatures as observed. When the massive stars evolve from blue supergiants to yellow supergiants they pulsate for a while as Cepheid variables.

The former evolution calculations led to a relation between stellar luminosity and mass that gave the wrong pulsation periods; this problem is solved with the new opacities. The evolution calculations of the low-mass stars in globular clusters formerly led to inferred ages for the clusters that were greater than the age of the universe; this problem has now disappeared. Even though these pieces of astrophysical evidence and others support the new LLNL opacities, they, like the LANL opacities from the 1960s and 1970s that preceded them, embody many approximations, and they should be confirmed in as many ways as possible, including by direct experiment.

2) Bowen Mechanism

Ira Bowen found, in 1924, that in some nebulae (the planetary nebulae that are shells ejected by red giant stars) the emission lines of OIII arising from the upper states $2p3d\ ^3P^o_2$ were greatly enhanced relative to other members of the same multiplet. The lower levels of these transitions, namely $2p3p\ ^3P_{2,1}$, $2p3p\ ^3S_1$, and $2p3p\ ^3D_{3,2,1}$ fed transitions to $2p3s\ ^3P^o_{3,2,1}$ that were also enhanced. Bowen found that there was a coincidence between the HeII $\text{L}\alpha$ line at $\lambda 303.78$ and the OIII line $\lambda 303.80$ that excites $2p3d\ ^3P^o_2$. Furthermore, the decay of $2p3s\ ^3P^o_1$ produces $\lambda 374.436$, which can pump the line $\lambda 374.441$ in NIII that excites $3d^2D_{5/2}$, producing still more fluorescence.

The mechanism was analyzed in the 1960s and 1970s, not with a full collisional-radiative model, but with some radiative transfer. The NIII branch is not considered well-established, but at least the first lines in the OIII branch are. The line coincidences have mismatches of 16 km/s between HeII and OIII, and 4 km/s between OIII and NIII. The HeII/OIII difference is larger than the Doppler width, which is about 9 km/s for He at 20,000 °K. Most nebulae also have an internal velocity dispersion of about 10 km/s due to general expansion, or to turbulence, and there is opacity broadening, especially in the HeII $\text{L}\alpha$ line, which all combine to ensure coincidence.

The OIII lines, at $\lambda\lambda 3100\text{--}3400$, are seen in x-ray binary stars like Sco X-1 (a low-mass x-ray binary) and AM Her (a cataclysmic-variable-like white dwarf binary), and also in some Seyfert galaxies (relatively ordinary spiral galaxies but with a black hole-like object in the center that makes x-rays and excites a lot of line emission in the nearby interstellar gas—mini quasars).

3) Nuclear Reaction Count Rates at the NIF Relative to Accelerators

Consider the count rate issue. The reaction rate for projectile a plus target nucleus b to produce some product nucleus c in a conventional accelerator experiment can be written,

$$r(a+b, \text{Accelerator}) = I_a \sigma_{ab} n_b \Delta x,$$

where I_a is the incident projectile current, σ_{ab} is the cross-section for the reaction between projectile a and target nucleus b , while n_b and Δx are the target density and thickness, respectively. Consider a typical reaction, the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction which plays a role in the CNO cycle. The hydrogen burning temperatures for this reaction are from about 1 to 3 keV. At 3 keV, the Gamow window for this reaction is at approximately 40 keV, for which one expects a cross-section of order 0.01 pico-barn.⁸⁸ For typical accelerator conditions with an incident current of 1 μA on a carbon target of density 10^{23} cm^{-3} and a thickness of 10^{-2} cm , the reaction rate would be about five events per day.

On the other hand, the reaction rate in a thermalized NIF capsule can be written:

$$r(a+b, \text{NIF}) = \langle \sigma v \rangle N_a n_b,$$

where $\langle \sigma v \rangle$ is the Maxwellian-averaged product of cross-section times relative velocity, n_b is the density of nucleus b , and N_a is the total number of nuclear species a which can react with b . At the temperature of 8 keV that might be attained in a capsule imploded using the NIF, one expects a Maxwellian averaged reaction rate⁸⁹ of $N_a \langle \sigma v \rangle \approx 10^{-5} \text{ cm}^3 \text{ mole}^{-1} \text{ s}^{-1}$. At a hydrogen density of $10^{22} \text{ g cm}^{-3}$, reacting with 10^{17} carbon atoms (2 μg) for $\approx 100 \text{ ps}$ one would expect $\approx 10^4$ reactions in a single event. This number of radioactive ^{13}N nuclei, which would have a half-life $t_{1/2}$ of $\approx 10 \text{ min}$, might be counted after an event. Alternatively, the pulse of $\approx 2\text{-MeV}$ gamma rays might be detected with scintillators positioned around the target. The fact that the events are produced all at once avoids the usual low signal-to-noise ratio associated with conventional accelerator experiments in which the reactions occur one at a time and are therefore difficult to distinguish from ambient room background.

Of course, such experiments would not be without their own difficulties. The various state variables are changing rapidly and one must have accurate diagnostics and simulations of the thermodynamic evolution of an event, including departures from equilibrium. The reaction rates are so sensitive to temperature that it will be difficult to know the burn temperature to sufficient accuracy. One might envision, however, a relative measurement of several species at once and fix the temperature with the most sensitive reaction.

Also, these are explosive environments not easily amenable to conventional nuclear counting techniques. Backgrounds are also certain to develop. Nevertheless, one may develop a class of nuclear experiments in which a catcher blanket that could collect radioactive products would be placed at some distance from the capsule explosion. The catcher material could later be removed from the chamber and counted for accumulated radioactivity. In the end one would want to compare the nuclear yields produced with the yields predicted from thermonuclear network codes applied to the conditions one believes occurred in the event. This could be used to test both the codes and the reliability of the thermonuclear reaction rate data. It could also aid as a diagnostic of the capsule history, as the thermonuclear reaction rates are quite temperature sensitive.

4) *Lightning Chemistry*

Another space plasma-physics topic that has been discussed is lightning, and specifically the role of lightning in catalyzing certain chemical reactions, such as the formation of NO_x . Besides its role as an air pollutant, NO_x also serves as a destruction vehicle for atmospheric ozone.

This topic is obviously of considerable practical importance. Surprisingly, the detailed structure of lightning discharges, and the chemical kinetics that go on within them, remain poorly understood. Best guesses of the plasma temperatures to be found in a discharge are of order 1–2 eV, and their width is estimated at 10 cm or less. The electric current, of order 10^4 – 10^5 A, lasts for perhaps 100 μs . Laboratory experiments using a less than 1-joule-class laser have created plasma at approximately the right temperature and density, which, however, cools in just a few microseconds. Nonetheless, production of interesting chemical species has been observed, such as HCN in a Jovian-like gas mixture.

It remains uncertain in what way the NIF capability of creating much higher temperatures in much large volumes would help in this area. It is conceivable that the ability of NIF to make spatially and temporally resolved UV spectra of the plasma column might be helpful in unraveling the chemical kinetics mystery.

5) *Formation of Chondrules*

Chondrules are millimeter-sized inclusions found in certain meteorites. They are notable because each inclusion has a glassy coating as if its surface had once been melted before it was amalgamated into the meteorite. It has been difficult to fit the existence of chondrules into theories of the formation of our solar system, since interplanetary matter is not supposed to have ever reached temperatures sufficient to melt silicates, around 1500 °K. One theory that has been developed is that during the time when the protoplanetary matter was in the form of a disk orbiting the sun, before the planets formed from it, the convective motions in the disk and the entrained magnetic field may have combined to produce large electric fields and ultimately lightning discharges.

According to this theory, the chondrules might be formed in the following way, if such a discharge should occur: The silicate grains, of order millimeters in radius in order to agree with measured chondrules, are enveloped in the expanding plasma column following the discharge. The plasma expands and cools more-or-less adiabatically, so that the grain is subject to plasma bombardment for a time about equal to the expansion time, which is on the order of the column radius divided by the sound speed. The grain charges almost instantaneously to an equilibrium negative potential for which the electron and proton charging currents cancel; this is about $2.5 kT/e$. In this steady state the protons deliver heat to the grain at a rate about equal to the proton (or electron) current times the potential. The heat delivered in the time it takes the plasma column to expand and cool will melt a certain portion of the grain.

The conduction of heat from the grain surface into its interior is critical. If the conduction is rapid, then the whole grain would melt at once, which would not resemble the grains with melted mantles that are observed. If the conduction is too weak, then the heated surface would simply be ablated away. Therefore chondrules must correspond to cases in which the conduction time is of the same order as the expansion time. Thus if a melted mantle of moderate thickness is to be produced, then the time to melt the entire grain, the conduction time and the hydrodynamic expansion time must all be comparable. Scaling estimates indicate that if the discharge column is at a density of about 10^{14} cm^{-3} and a temperature of 20 eV, then millimeter-sized chondrules can be formed in an expansion time of around 1 second.

The problem we face in trying to reproduce an analog experiment on the NIF is that we must somehow use much higher densities and a much shorter time scale. Densities upward from 10^{19} are convenient and the time scale should be around 10^{-8} s. The farthest the laser experiment might be able to go in the low-density and long-time direction can be estimated by assuming that the source of the plasma is a 100-Å-thick foil and that it is allowed to expand to 1 cm in the perpendicular direction; its lateral dimensions would be of order 1 cm also, to provide roughly one-dimensional geometry. The atom density would be about 10^{17} after expansion. The melt time, hydrodynamic time and diffusion time are all comparable for 1-μm grains of the density mentioned. The time scale is then about 180 ns, quite long for a laser experiment. One problem would be to recover the grains after the experiment, hoping that they have not been damaged by flying debris from the target, apart from the desired plasma exposure.

These physical conditions and time scales are really not a good match to what the NIF would provide. The temperature, 20 eV, is much less than what the NIF is capable of, the distances are large, and the densities are low. Indeed, these conditions are more easily produced in various laboratory plasma machines. This experiment should probably not be one of the first priorities for the NIF.

B) Hydrodynamics

Experience gained by researchers on the Nova laser has demonstrated that a variety of fluid-dynamics experiments may be carried out on such facilities. See Ref. 1, *Scientific Applications for High-Energy Lasers*, for some examples. In particular, two types of experiments have emerged as the leading hydrodynamic experimental approaches—those that involve radiography and others that utilize self-emission.

To provide a sufficient background to understand the belief that the NIF will provide a vehicle to open novel areas of hydrodynamics not possible at other facilities, we provide the following illustrations of technique, which show clearly the current limitations. These particular examples are selected from work conducted on Nova, because many of their features are shared with other experiments and thus they permit some general observations to be drawn.

1) Radiography—a Typical Configuration

In a series of experiments, we can investigate the quasi-two-dimensional flow of a jet formed by the passage of a shock over a hemispherical protrusion on a density interface. The configuration is depicted in Fig. IV.B.1. The experimental package (i.e., the object to be observed as opposed to the hohlraum which provides the x-ray drive) consists of a beryllium tube with plastic and carbon foam inserts, and is attached to the center of the exterior of a gold hohlraum. A hole exposes the end of the package to the hohlraum interior. The hemispherical feature is produced by machining a hemispherical hole in a bromine-doped plastic cylinder, and a matching hemispherical bump on a cylinder of carbon foam, using a lathe. A picture of the carbon part is shown in Fig. IV.B.2. The inner diameter of the beryllium tube is 700 μm, and its length is 2000 μm.

The temporal sequence of events in the experiment is as follows. Eight of the Nova laser beams are focused into the hohlraum, which heats up rapidly to a temperature of 220 to 240 eV. The bromine-doped plastic end of the experimental package, exposed to the interior of the hohlraum, rapidly ablates. The ablation causes a strong shock wave to be launched into the plastic. The shock travels outward through the experimental package, and encounters the density interface. Upon crossing the interface, the shock-induced acceleration produces an instability between the two different density materials, seeded by the 150-μm-radius hemisphere.

Figure IV.B.1. Side view of the jet experimental arrangement, with the hemispherical feature on the interface. A large-area x-ray backlighter provides back-illumination for an x-ray framing camera, which images the materials in transmission. Eight Nova beams heat the gold hohlraum.

Figure IV.B.2. Microscope photographs of the carbon foam piece, showing the diamond-turned hemisphere. The hemisphere radius is 150 μm .

Shortly before the time chosen to image the flow, the ninth and/or tenth Nova beams are used to illuminate an x-ray backlighter foil. Titanium and iron are typically used as foil materials and produce 4.7 and 6.7 keV x-rays, respectively. The x-rays are used to radiograph the experimental package sideways using either a two-dimensional framing camera or an x-ray streak camera. The brominated plastic is more opaque to the backlighter x-rays than the undoped plastic, so it appears darker in the images. Shocked, or compressed, material also appears darker because of its larger density. Knowing the opacities of the various components, the transmission can be unfolded to provide material distributions. This knowledge of the opacity is central, as it is one of the fundamental limitations of the experimental technique for providing quantitative data. The diagnostic technique is discussed in more detail in Hammel et al.¹²

The passage of the shock from the plastic ablator section over this "bump" generates the jet by the same mechanism as the Richtmyer-Meshkov instability. As the jet propagates, it experiences shear on its edges, leading to a Kelvin-Helmholtz roll-up.

Experiments were conducted that imaged the jet at 19.5 ns and 25.8 ns after the initiation of the drive beams. Comparison of the data and simulated radiographs from 2-D hydrodynamic simulation are shown in Figs. IV.B.3 and IV.B.4. The data quality is limited by several factors, including the small size of the jet, the short gating time of the available detector, and the availability of only a single backlighter beam at late time (that is, at times greater than 8 ns) when these data were acquired. The picture at 25.8 ns is among data with the longest time delay between firing the main laser and taking an image ever carried out on Nova.

The comparison between the data and calculation is shown in Fig. IV.B.3. The data shows two dark bands, associated with the swirls, of similar size and location as the features in the simulation. The comparison at the later time shown in Fig. IV.B.4 is not as striking. The experimental picture shows a single, wide, dark band below a large u-shaped feature. The calculation displays much more structure, and is a little narrower and more advanced down the tube. The effect of the shocks can be seen in the simulations, but not in the data. It is noted that the comparison of "swirls" and other gross features in the experiments is not commensurate with the need to obtain quantitative data on the underlying physical processes involved in the hydrodynamics. However, the development of these techniques, which are extremely complex, can be undertaken in preparation for future quantitative work.

Figure IV.B.3 Comparison of data with simulation at $T = 19.5$ ns.

Figure IV.B.4. Comparison of data with simulation at $T = 25.8$ ns.

This illustration indicates that radiography is quite advanced, but also, and most importantly, that there is a real need for the advantages to be accrued from the NIF, as these will allow much better data to be obtained. The relaxation of the size limitations, the duration of the drive pulses, and the use of numerous beams for backlighting, all to be available on the NIF, will make these types of experiments more realistic.

2) Shock Planarity

To investigate the possible methods to make shocks planar for future studies, a number of hohlraum/package variations have been tested. These illustrate the flexibility of the high-energy laser experiments and also some of the limitations of the current methods.

An experimental package was constructed for the shock planarity experiments. The package thickness was chosen to be 150 or 300 μm , and an optical streak camera was used to view the package from its end, rather than its side. See Fig. IV.B.5 for a schematic of the experiment.

Figure IV.B.5. Schematic of a shock breakout experiment to measure the planarity of the shock front

The principle of the experiment is that shock breakout through the rear surface of the package is accompanied by heating, and the resulting radiation is detected by the optical streak camera. If the shock is curved with the central portion leading upon reaching the rear surface, the breakout occurs first at the center, then proceeds radially as the rest of the shock front reaches the surface. Using the optical streak camera to image a diameter of the rear surface, the resulting streaked image of a curved shock is also curved.

Two of the candidate mounting schemes, along with their corresponding SOP data, are shown in Figs. IV.B.6 and IV.B.7, respectively. One consists of simply abutting the package against the flat of the hohlraum, over the hole. The other is a version of a design that is called a "tophat" due to its appearance. It is clear from the data that the breakout in the former is not flat — the breakout from first arrival to the edges of the package takes over 1.7 ns. The tophat, on the other hand, has a very flat shock which breaks out in 400 ps over the entire diameter and only 100 ps over the central 80%.

Figure IV.B.6 Two candidate mounting schemes.

Figure IV.B.7 Breakout data for different mounting schemes shown in Fig. IV.B.6.

3) Mix Experiment

To show one of the possible experiments that is suitable for the NIF, we describe a complicated instability experiment was not included in Ref. 1. The experiment attempts to investigate techniques to study the Richtmyer-Meshkov instability. The experimental configuration is the same as depicted in Fig. IV.B.1, but the density interface is planar, without the hemispherical protrusion. The interface has a roughness machined into a high-density brominated plastic, and it is this roughness that seeds the Richtmyer-Meshkov instability.

The experiments to develop the techniques are in progress, and preliminary data is shown in Fig. IV.B.8. This image was taken about 8 ns after the initiation of the drive, the shock is moving from top to bottom, and the reference grids used to provide spatial fiducials in the experiments are visible on either side of the image. Note that the spatial profile of the backlighter, which is roughly Gaussian, and the effect of the cylindrical package geometry on the transmission are not taken into account.

Figure IV.B.8. Gated x-ray image of planar Richtmyer-Meshkov mix target at about 8 ns.

In Fig. IV.B.9, we show a 100- μm -wide vertical trace taken on the centerline of the image in Fig. IV.B.8 (the jagged curve) together with a Gaussian fit to the backlighter spatial profile (the smooth curve). The fit to the backlight spatial dependence was found using the unshocked region in the image.

Figure IV.B.9 A 100- μm -wide vertical trace of the centerline of Fig. IV.B.8 (thin jagged line), and the accompanying fit to the backlight (thick line).

The trace is normalized by the backlight spatial dependence to remove most of the backlighter non-uniformity, and the results are displayed in Fig. IV.B.10. In Fig. IV.B.10 the level region from ~ 570 to $825 \mu\text{m}$ demonstrates that the Gaussian profile is a reasonable approximation of the spatial shape of the backlight. The two arrows denote the location of the calculated interface and shock locations.

Figure IV.B.10 Vertical trace of Fig. IV.B.9 normalized by the backlight.

It is apparent from Fig. IV.B.10 that a simulation can reproduce the gross features of the experiment. Sharp drops in the exposure delineate the edge of the higher-opacity regions in the shock-compressed foam and then in the brominated-doped plastic. The width of the features is the distance over which these transitions occur. For a perfectly flat shock, the measured shock width should be negligible. We measure a shock width of $\sim 15\text{--}20 \mu\text{m}$, which is of marginal interest as the diagnostic resolution is $12\text{--}15 \mu\text{m}$.

The NIF would provide larger scales and relieve the severe constraints on spatial dimension that are faced with the present-day high-energy lasers. On the other hand, the calculations are in substantial disagreement for the width of the mixed region for this interface. From the 2-D simulations the mix width is less than $15 \mu\text{m}$, while the measurement indicates a width of $25\text{--}30 \mu\text{m}$. Again, the advent of the NIF will provide a test bed for experiments of this type. In the interim, experimental techniques will continue to be developed, so that one can obtain a deeper understanding of the physical processes involved in the experiments and how these limit our ability to measure the quantities of interest.

C) Radiative Properties

The various ideas for the study of radiative properties in hot, dense matter or high-energy-density conditions, fall naturally in several areas, as discussed in the preceding text. The areas can be traced to the various degrees of complexity that the surrounding matter imposes on the radiator. At the first level one is only interested in the isolated ionic emitter, the fact that there are interactions only serves to create the highly ionized or

pecially populated ionic radiator. The spectroscopy of highly stripped ions falls into this category.

1) Isolated Emitter Spectroscopy

The production of highly stripped ions is not a straightforward extrapolation of the laser energy. In small 100-Joule 1-ns-type lasers one can reach, for example, ion stages of K-shell titanium. Further, we note that using the 24-beam Omega laser, which delivered 50 Joules per beam, allowed the probing of transitions between the 4n-type ground configuration and any excited configuration over the entire periodic system. The other limits are:

- i) $2s^2S_{1/2}-2p^2P_{1/2,3/2}$ and $2p^2P_{1/2,3/2}-3d^2D_{3/2,5/2}$ transitions in Li-like systems.
Current knowledge: Ge^{29+} ($Z = 32$)
Source for highest degree of ionization: Omega
Degree of ionization reached with the Omega laser: Ge^{29+}
- ii) $2s^22p^5\ 2P_{3/2,1/2}-2s\ p^6\ 2S_{1/2}$ transitions in F-like systems.
Current knowledge: Sn^{41+} ($Z = 50$)
Source for highest degree of ionization: Nova 2-beam
Degree of ionization reached with the Omega laser: Sn^{41+}
- iii) $3s\ 2S_{1/2}-3p\ 2P_{1/2,3/2}$ and $3p\ 2P_{1/2,3/2}-3d\ 2D_{3/2,5/2}$ transitions in Na-like systems.
Current knowledge: Gd^{53+} ($Z = 64$)
Source for highest degree of ionization: Nova 2-beam
Degree of ionization reached with the Omega laser: Sn^{39+}

However, it is clear that using ever-higher laser energies in a straightforward application of direct target irradiation will not necessarily permit access to yet higher ionization stages. The difficulty is that much of the additional energy will go into kinetic directed energy and the coupling efficiency will be relatively small. One solution for this is the use of the rather newly perfected "gas-bag" targets. These are simple targets made of a thin plastic bag currently containing large molecular structures of low-Z atoms. This allows the ambient pressure of the bag to be low, ≥ 1 atm, while the fully ionized targets can have electron densities on the order of 10^{21} cm^{-3} . These are described in more detail in Section III.E, Plasma Physics.

2) Plasma-Emitter Radiative Properties

Second, when one is interested in the effect of the plasma environment on the emitter, it is necessary to create a plasma and the ionic emitter in a condition that is well-characterized. A special plasma production mechanism is required when one is interested in the intrinsic profile of a line transition, the shape of the resonances in a line series leading up to the ionization potential, the interaction of the discrete resonances with the underlying continua that occur above the first ionization potential of an ion, or the absolute shape and intensity of the continua.

In the past, the production of the ionic emitter in a hot and dense plasma was of sufficient scientific interest to permit relatively simpler plasma creation strategies; for example, the irradiation of a solid target. However, when one desires to disentangle the plasma temporal and spatial variation to determine the fundamental radiative properties

of an ion immersed in a plasma, a method must be found to determine the plasma conditions—temperatures, densities, etc.

This requires sufficiently steady-state systems with, ideally, no gradients. The steady state is required to ensure that the radiative property is not a function of the time history of the system, but of the instantaneous conditions. The spatial constraint comes from the fact that critical determination of the effects of interest requires a minimized contribution from widely varying plasma conditions. As a simple example, when one is interested in finding the existence, or non-existence, of a transparency window between the last existing line in a series and the associated bound-free continuum, one must ensure that filling of the proposed window does not occur due to plasma at slightly different conditions.

To generate this type of single-density, single-temperature plasma is highly energy intensive. First, the direct irradiation of a sample will produce large gradients. Second, the problem with gradients has not to date been remedied by the use of microdots of the element of interest embedded in the solid material. Direct irradiation would therefore seem to be a poor method for obtaining the test-bed plasma for studying radiative properties of the second kind. However, there are experiments that may assist in indicating a possible path towards realizing the ideal system. In the characterization of the opacity of elements with low and middle range Z s, a great deal of work has been performed. This work indicates that to achieve 10^3 of electron volts at 0.001 of solid density requires the entire capability of Nova. The reasons are clear, and will be elaborated on below.

First, one needs to volumetrically heat the plasma; second, this volumetric heating is most easily achieved by creating an x-ray flux; and third, one needs to have hydrodynamic isolation of the sample. The two processes of up-conversion of laser light to x-rays and the volumetric deposition lead to less than 1% of the initial laser light being coupled into the sample. When the need for hydrodynamic isolation is imposed, which keeps the sample from suffering shocks, etc., from laser deposition or indirectly from collision with laser and x-ray ablated material, the coupling drops further by an additional multiplier that will be less than 0.1.

These factors together lead to less than 10^{-3} coupling into the material of interest. Experience in the use of hohlraums and x-ray-irradiated samples, therefore, leads to the simple scaling for the production of characterized samples that one is limited to temperatures well below 100 eV, and probably 50 eV is the maximum currently. It is therefore implicit in all the discussions of the effects that we wish to study that the greatly increased energy of the NIF will allow us to extend our range of temperatures and densities toward the higher- Z materials and regimes of importance.

3) Dynamics Properties

The next level of detail requires the study of the dynamics of the radiator in the plasma. At one level the plasma modifications of the imbedded emitter as previously discussed are a form of kinetic process; however, by dynamics we mean here the actual time dependence of the detailed ionic state populations (i.e., the result of the rate equation solution for the populations). The previous plasma-affected radiative properties (e.g., line shapes) require a plasma averaging that can, by the ergodic hypothesis, be replaced by a time average. This then indicates a dynamic process; however, it is one where the averaging process replaces the temporal history. In the current level of detail, one is interested in the details of the time histories, population densities, and population mechanisms.

In studies attempting to isolate the dynamical properties of a hot, dense plasma, numerous processes play a role. The formation of atomic models can require exhaustive detail, and this in itself has become a topic of research over the past decade. The

requirement to work with a complete model (complete in the sense that the population dynamics is well characterized) is not the same requirement as that for the generation of a spectrum. Thus, states may play an important part in the flow of population, while having relatively little observable contribution to the spectral output. This makes the task of kinetics modeling difficult, insofar as the observables are dark shadows providing only a vague sense of the processes required to create the populations.

In these studies the open questions include difficulties with the truncation of high principal quantum number states, the inclusion of states that have autoionization channels, and the level of detail for the states. The most obvious example where these considerations are critical is for the prediction of inversion and laser gain in rapidly varying systems. However, the evolution of the radiators in hot, dense matter in general is of great importance.

The additional constraint on the experimental setup, beyond those discussed above in reference to the radiative properties, is the ability to probe, in time, the level populations that may take part in the formation of the populations. Thus, one is interested in developing the ability to probe states that may not be seen in emission. The development that will be required is the ability to probe states and transitions by methods that are similar to those that we require for the radiative properties, discussed above, and those required for the radiation transfer, as discussed below, but with the additional fact that the plasma characterization must be performed in a time-dependent manner. The determination of the radiative properties from a single temperature and density plasma may provide definitive information, however, this is only a part of the puzzle when it concerns the flow of population density through the various ion species.

The addition of a probe that could be used to generate fluorescence from excited states would be a critically important advance. The difficulty in developing such a probe is clear when one recalls that the low-energy-density plasma equivalent to this experiment requires lasers as the pumping source. In the high-energy-density regime we find that the production of appropriate short wavelength lasers is not an easy task, and to date no line coincidences have been located for use of the existing soft x-ray lasers as pump sources. Thus, we await, in the current generation, an appropriate source. Note that with the advent of the NIF, photon densities from quasi-continuous pseudo-Planckian sources could be spectrally filtered to provide the necessary pumping for fluorescence and pump-probe experiments. Until such time as a source of that magnitude becomes available we will have to rely on the search for coincidences with existing bright laser-plasma sources, or the use of high-emissivity line radiation from spatially separate plasmas, to provide a photon pump of the same transitions in another plasma.

4) Non-LTE Radiation Transport and Line Formation

Interest in the generation of x-ray lasers led to a series of relatively recent advances in theory and experiment that have brought us to a position where detailed radiation hydrodynamics simulations are available and detailed kinetics model can be produced, with some effort. It is important to note the central role of the astrophysicist in the development of these simulation capabilities. On the one hand, astrophysicists were producing the methodology for doing non-LTE radiation transfer "correctly"; but on the other hand, by far the largest part of the motivation for the experiments shown here was derived from interest in laboratory plasma sources.

As a result, there are simulation codes that now provide a radiative-hydrodynamics capability for the analysis of non-LTE experiments. A description of the basics of these codes is not necessary here, but the fact remains that these codes exist and have been developed. Rigorous testing of the codes has essentially been confined to benchmark *numerical* problems where analytic solutions exist; however, no rigorous tests against controlled high-energy-density plasma experiments have been performed.

of the present discussion is to point out that the energy now available on Nova is insufficient to perform the critical experiments. However, development of the methods and the measurements for radiative transfer on the present Nova-size lasers is essential before the real goal of obtaining a radiatively dominated, well-characterized system on the NIF can be attained.

Conceptually we have sufficient information to discuss the preliminary design of such experiments. These observations are:

- The use of radiation enclosures (i.e., hohlraums) is not necessary for the production of non-LTE experiments. The enclosure provides little of interest to the experimental design and, in fact, complicates the measurement process to the point of rendering the experimental plan all but unattainable.
- The use of direct-drive experiments, although of great interest to the community of experimentalists as a fertile source of ideas and developments (e. g., for isolated ion spectroscopy) produces a plasma that is heated by mechanisms not relevant to the testing of the non-LTE radiative hydrodynamics simulations.
- The dimensionality of the experimental system must be reduced to the minimum so that we can provide, as nearly as possible, an ideal non-LTE system. This is achieved by using a low-Z tamping layer to contain the material of interest.
- Since the temperatures that can be reached in the near term will be well below the kilovolt range in tamped samples, spectral measurements should be made in the sub-kilovolt range. This requires an effort to develop XUV instruments for current high-energy lasers. For experiments on the NIF the x-ray regime would become the main focus.

Given these considerations the experiment can be defined, and a schematic of the experiment as it is being fielded is shown in Fig. III.D.2-1 of Ref. 1. This is just one possible example.

D) Radiation Sources

1) *Hohlraum Temperature Scaling*

To illustrate various radiation environments and their scaling with hohlraum size, data taken at Nova is presented in Fig. IV.D.1. Shown in the figure are the results from three different variations of the gold hohlraum, as well as two different laser-pulse durations. All experiments shown used a total energy of 18 kJ. The hohlraums are all cylindrical, with laser entrance holes (LEH) in the sides for the 500- μm and 1000- μm -length hohlraums, and through the ends in the 2800- μm -length hohlraum.

As can be seen from the empirical scaling law in Fig. III.A.3 of Ref. 1, both the area of the interior walls and the area of holes affect the radiation environment. The holes for the two longer (therefore larger) hohlraums are 500 μm in diameter for the LEH and 800 μm for the x-ray diode observation line of sight (LOS). For the smaller hohlraum, each LEH is 300 μm and the LOS is 400 μm . The observations were made with a 12-channel x-ray-filtered diode array that is time-resolved and absolutely calibrated. To keep the laser light from emerging from the LOS and to assist in maintaining the unobstructed area of the LOS, a 1500- $\text{\AA}$ aluminum foil supported on each side by 5 μm of CH is inserted in the LOS.

The first goal of an effort to study non-LTE radiative transfer would be to develop a method to compare the results of radiative hydrodynamics simulations that goes as far as possible towards creating an environment in which detailed comparisons can be performed. That is, we would provide the initial conditions accurately and then provide the results of the experiment. The hope would be to provide the results in the form of absolute intensities so that the details of the simulations could be tested for the first time.

More specifically, there are three areas in which it is felt the new simulation capabilities could be tested. First, the accuracy of the atomic kinetics models could be measured insofar as the spectral information provided will be of high enough quality to check model details. This is mentioned above in the "Isolated Emitter Spectroscopy" and "Plasma-Emitter Radiative Properties" sections.

Second, the suitability of the kinetics models in the simulation could be tested. The ability to obtain experimental information on the evolution of the radiatively driven system will allow one to ascertain if the kinetics model is sufficient to simulate the plasma dynamics. This is discussed in the "Dynamics Properties" section. Third, and most difficult, the level of information that will be available may be sufficient to constrain the radiation transfer algorithms in these time-dependent multi-level systems.

Note that the testing of the radiative transfer would require the generation of spectra that contain line transitions formed in a radiatively dominated regime. This is a very difficult regime to attain in the laboratory for the following reasons: First, a simple rule of thumb is that the ratio of the collisional decay to the radiative decay of a transition, defined as the ϵ parameter, must be small compared to unity for radiation to dominate the collisions in the line formation process and the optical depth of the transition, τ , be large.

The ϵ can be estimated as

$$\epsilon \approx 10^{-4} N_e \lambda^3$$

where λ is the transition wavelength in cm and N_e is the electron density in cm^{-3} . Here we assume the Gaunt factor is 0.2 and the plasma temperature is 100 eV. Next, the optical depth of a Doppler-broadened transition, τ , can be approximated by assuming that the oscillator strength is ≈ 0.5 , the temperature is ≈ 100 eV and the atomic number is ≈ 20 .

Then,

$$\tau \approx 6.3 \times 10^{-10} N_g \lambda \mathcal{L}$$

Here $\mathcal{L}$ is the plasma column length in cm and N_g is the ground-state number density. If we desire the line formation to work in a regime where the source function reaches the blackbody limit, so that the medium is effectively optically thick, one can relate the ϵ to the τ by,

$$S_{\text{max}}/B \sim \epsilon \tau \ln(\tau)^{1/2}$$

which is appropriate for Doppler line profiles.

Analysis indicates that, for example, a column length of 10 μm of plasma with an electron density of 10^{20} cm^{-3} and 10^{19} cm^{-3} ground state ions will yield for 100Å radiation an $\epsilon \approx 0.01$, $\tau \approx 64.0$ and a maximum source function near the blackbody limit. These conditions are difficult to attain, but may be possible in the types of experiments that are currently being performed. Therefore, it would be important to develop the techniques to perform these measurements, so that one could create experiments in relevant regimes.

Detailed studies of parameter regimes where ϵ is much smaller and/or τ is much larger are important for verification of the radiation transfer schemes; however, the goal

Figure IV.D.1 Equivalent radiation temperature vs time for several hohlraums. The different aspects of the figure are explained in detail in the text.

The x-ray diode measures the specific intensity at the detector. This is converted into an equivalent radiation temperature by integrating the source emissivity over all channels and equating this to the blackbody emissivity, given by σT_R^4 . This is done for each of the times of interest. The contribution of the Au M-band, at $\sim 2\text{--}3$ keV, is most pronounced in the small hohlraums.

To indicate the contributions of this highly non-Planckian part of the spectrum we also show in the figure, indicated by the gray line, the equivalent radiation temperature without the M-band contribution. Note that the smaller the hohlraum, the higher the peak T_R but the shorter the duration of the x-ray flux. This is due to the closure of the holes. Also, the relative M-band contribution to the T_R is larger in the smaller hohlraums.

The 1000- μm cylindrical hohlraum was used to investigate a longer duration pulse length. In this case, a 2-ns pulse was used and the high peak x-ray flux, as can be seen in the figure, is maintained for approximately 1 ns. The two different sets of curves for the 1000- μm case (i. e., with and without M-bands) represent the effect of angle of the observation with respect to the laser-irradiated inner surface of the hohlraum. The two angles are 72° and 0° with respect to the cylinder axis. The curves with lower T_R are for the viewing angle of 72° , and these show that when the detector observes less non-LTE Au emission in the hohlraum it has a smaller M-band contribution, as well as lower total flux. Thus, the radiation field in the hohlraum is a complicated function of viewing angle.

Finally, there are three distinct experiments shown in the figure for the largest hohlraum, indicating the level of reproducibility of the x-ray production. These largest hohlraums are the standard configuration used in most ICF-type experiments. In this case

the M-band contribution is small because of the combined effects of the relatively large size of the hohlraum and the viewing angle, which does not allow a view of the laser-irradiated spots in the hohlraum.

2) XUV Interferometry

Optical interferometry has an important history in the study and characterization of plasmas. However, probing of high-density and/or large plasmas has been difficult due to the high absorption of optical probes, the effects of refraction, and the impossibility of probing beyond critical densities. Recently, a neon-like yttrium x-ray laser has been used to develop the technology that will allow interferometry to be performed at wavelengths of 155 Å, which has a critical density $\sim 10^{25} \text{ cm}^{-3}$. In Fig. IV.D.2, we show the experimental setup used to test a Mach-Zehnder interferometer suitable for probing high-density, long-scalelength plasmas. The output from a standard 3-cm-long yttrium x-ray laser having 1 mJ, in a 150-ps FWHM pulse, is collimated by a multilayer mirror and injected into a Mach-Zehnder interferometer that uses Mo/Si beamsplitters consisting of 8 layer pairs on 1000 Å of silicon nitride. An imaging optic at the output of the interferometer images a plane within the interferometer where a secondary plasma is produced.

Figure IV.D.2 Experimental setup for x-ray laser interferometry.
Beamsplitters consist of 1000-Å silicon nitride with 8–12 Mo/Si layers.

In Fig. IV.D.3 we show the recorded interferogram of a plasma formed by laser irradiation of a mylar target. Excellent fringe visibility is observed, clearly indicating the feasibility of this technique.

The limits of the current system are also apparent. In the figure we see that the blow-off of the plasma in the central region of the image is sufficient to completely obscure the laser. This is due to the existence of an oxygen transition near the laser wavelength at 155 Å, causing refraction. Further, the edges of the image show that the limit of the fringe count is caused by attenuation as the plasma becomes dense near the surface.

Thus, although the x-ray laser interferometer has been proven to work, there is still much work to be performed. This technology will be important in the characterization of NIF-scale plasmas. In addition, with the NIF we can push to shorter x-ray laser wavelengths, making this an even more important diagnostic tool.

Figure IV.D.3 Interferogram obtained using an x-ray laser interferometer. The plasma-induced fringes can be readily seen. The plasma is made by irradiating the surface of a mylar plastic with a second beam.

V) Facility Requirements

A) Introduction

A central issue that was addressed by the scientific community was the desired modifications to the original NIF design. To a large degree the requests of the scientific community were very similar to those of other communities. In particular the group desired smaller spot sizes, pulse variation from 100 ps or less to 20 ns; the need to establish line foci to perform x-ray laser experiments as important, and the need to have an expanded subpicosecond capability. However, the most important request by far was the many demands for increased turnaround times. This took many forms, but the message was the same—a science-based university-intensive effort that seeks to train students requires more than one to three experiments a day. The suggestions to improve the turnaround included:

- Additional target areas.
- More rapid cooling of the amplifiers.
- More independence of the beams, so that part of the beams could be used flexibly.
- The introduction of a smaller (e.g., Nova-sized) beam for independent backlighting.

Each of the special requirements that the scientific community asked for is presented below with a brief discussion of the requirement.

B) Higher Beam Irradiance Requirements

Some physics experiments will require higher beam irradiances than those outlined in the NIF design documents. The present laser spot diameter requirement for ignition targets, utilizing kinoform phase plates for beam conditioning, is 500 μm . This will be achieved with adaptive optics with a number of actuators consistent with this requirement. The NIF Functional Requirements and Primary Criteria specify the *maximum* spot size to be 500 μm . For higher irradiances that *will* lead to increased hohlraum temperatures and the subsequent pressures desirable for a subset of the science experiments, smaller spot sizes are needed—50 to 150 μm , or as small as possible and practical (see the discussion in Section III.E, Plasma Physics). Higher irradiances than for the present design may be obtained by increasing the number of actuators in the adaptive optic. To facilitate point-projection x-ray backlighting, beams when focused to the minimum spot size should be able to effectively irradiate a 25- μm diameter fiber or equivalent.

C) Variations in Lens-Focusing Requirements

The NIF should have the capability of putting cylindrical lenses on at least 20 beamlets for experiments utilizing x-ray lasers. These lenses should nominally produce a focus of $\sim 150 \mu\text{m} \times 5 \text{ cm}$. These lenses should be capable of being easily inserted and removed. These beamlets should also be able to operate at 2 ω at power levels consistent with those required for x-ray lasers.

D) Target Chamber Insertion Mechanisms

The target chamber should have two target insertion mechanisms. The second target inserter does not have to have cryogenic capability.

E) Added Target Alignment Capabilities

The scientific community envisions the use of targets that may be, in general, more complicated than ICF targets, so additional target alignment capabilities may be needed. This is most simply specified by requiring that there exist the capability to view all sides of the targets(s) during target alignment.

F) Reduced Time Between Experiments

To accommodate the expected large number of users, the time between shots should be reduced below the maximum specified eight hours. The facility should incorporate the improvements that are developed from these programs to ensure greater access to the user communities.

G) Flexible Time Intervals Between Experiments

Finally, it is important to note that the largest possible timing and pulse duration flexibility needs to be incorporated for the NIF to reach full utilization. Individual beamlet pulse-length flexibility, as presently designed, is highly desirable, with range-of-pulse widths from < 0.1 ns to >20 ns. NIF design should permit each cluster of four beams to be independently timed, with arbitrary time delays among the clusters. The time interval between the first and last beams should be >200 ns. If possible, delays of up to 4000 ns would be useful to some users.

H) Short-Pulse Beams

There was a decided interest in having the NIF contain as many short-pulse beams as possible. Because of its size, the projected single short-pulse beam was considered interesting enough to warrant involvement by the community. However, scientists interested in the short-pulse experiments felt that a single beam was far too limiting. As can be witnessed from the discussions of short-pulse experiments in both Section III.E, Plasma Physics and Section III.F, Radiation Sources, there are a large number of topics in this category, and the possibility that one or more may become of primary interest in the future is thought by the participants to be rather large. Hence, additional short-pulse beamlines would be strongly supported.

VI) Participation List

Below is the list of individuals who have assisted in defining the program of experiments that may be performed on the NIF. The list is not exhaustive as we have had discussions with numerous individuals over various points of science in the document. We hope that this compilation will give a general sense of the level of involvement from the community.

A) Scientific Community

Participants	Affiliation	Area
D. Arnett	University of Arizona	Astrophysics
N. Ashcroft	Cornell University	Material Properties
H. Baldis	LULL, France	Plasma Physics
W. Barletta	Lawrence Berkeley Laboratory	Plasma Physics
R. Christensen	UC Davis	Material Properties
P. Corkum	NRC, Canada	Radiation Sources
S. Cramer	UC Davis	Plasma Physics
P. Demotakis	Cal Tech	Hydrodynamics
R. Falcone	UC Berkeley	Radiation Sources
U. Feldman	NRL	Radiative Properties
R. Freeman	AT&T	Radiation Sources
N. Ghoniem	UCLA	Material Properties
L. Goldman	U of Rochester	Plasma Physics
H. Griem	University of Maryland	Radiative Properties
C. Hooper	University of Florida	Radiative Properties
M. Horanyi	University of Colorado	Space Physics
C. Jacobsen	SUNY at Stony Brook	Radiation Sources
S. Kahn	UC Berkeley	Astrophysics
M. Key	Rutherford Laboratory, UK	Radiation Sources
A. Kermin	MIT	Plasma Physics
L. Klein	Howard University	Hydrodynamics
M. Kreisler	U of MA	Material Properties
K. Kumar	Howard University	Space Physics
E. Liang	Rice	Astrophysics
C. Liu	University of Maryland	Plasma Physics
J. Luhmann	UC Los Angeles	Space Physics
N. Luhmann	UC Davis	Plasma Physics
P. Marcus	UC Berkeley	Hydrodynamics
C. McKee	UC Berkeley	Astrophysics
J. Meyer-ter-Vehn	Max-Planck-Institut, Germany	Radiation Sources
R. Petrasso	MIT	Material Properties
J. Reader	NIST	Radiative Properties
M. Richardson	CREOL	Radiation Sources
D. Savin	UC Berkeley	Space Physics
O. Savas	UC Berkeley	Hydrodynamics
D. Schramm	University of Chicago	Astrophysics
J. Seely	NRL	Radiative Properties
D. Umstadter	CUOS, U of MI	Plasma Physics
J. Underwood	LBL	Material Properties
J. Wark	Oxford University, UK	Material Properties
J. Weisheit	Rice	Astrophysics
N. Woolsey	Oxford University, UK	Material Properties
S. Woosley	UC Santa Cruz	Astrophysics

B) Department of Energy

W. Varnam

C) Lawrence Livermore National Laboratory

J. Castor	Facilitator	Astrophysics & Space Physics
D. Dearborn	Presenter	"Extrapolation to the NIF"
N. Holmes	Facilitator	Material Properties
J. Kilkenny	Presenter	"Nova as a User Facility"
R. Lee	Facilitator	Radiative Properties
S. Libby	Presenter	"Review of NIF workshops"
G. Logan	Coordinator of all NIF workshops	
B. MacGowan	Facilitator	Plasma Physics
P. Miller	Facilitator	Hydrodynamics
L. Da Silva	Facilitator	Radiation Sources

D) Los Alamos National Laboratory

L. Collins	Radiative Properties
J. Cohen	Theory - general
A. Hauer	Experiments - general
J. Keady	Material Properties
G. Pollack	Material Properties

VII) References

1. *Scientific Applications for High-Energy Lasers*, compiled by R. W. Lee, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-116335 (1994).
2. B. H. Ripin, A. W. Ali, H. R. Griem, J. Grun, S. T. Kacenjar, C. K. Manka, E. A. McLean, A. N. Mostovych, S. P. Obenschein, and J. A. Stamper, in *Laser Interactions and Related Plasma Phenomena 7*, G. Miley and H. Hora, Eds. (Plenum Press, New York, 1986), p. 857.
3. B. A. Remington, S. V. Weber, S. W. Haan, J. D. Kilkenny, G. G. Glendinning, and R. J. Wallace, *Phys. Fluids B5*, 2589 (1993).
4. S. Kumagai T. Shigeyama, K. Nomoto, M. Itoh, J. Nishimura, and S. Tsurata, *Ap. J.* **345**, 412, (1989).
5. D. Arnett, J. Bahcall, R. Kirschner, and S. Woosley, *Ann., Rev. Astron. Astrophys.* **27**, 629 (1989).
6. R. I. Klein, C. F. McKee, and P. Colella in *The Evolution of Interstellar Medium*, L. Blitz, Ed., Astronomical Society of the Pacific Conference Series **12**, 117 (1990).
7. R. I. Klein, C. F. McKee, and P. Colella, *Ap. J.* **420**, 213 (1994).
8. R. I. Klein, J. Bell, R. Pember, and T. Kelleher in the proceedings of the 4th *International Conference on Compressible Turbulence*, Cambridge, UK (in press).
9. J. Bell, M. Berger, J. Saltzman, and M. Welcome, *SIAM J. Sci. Comp.* **15**, 127 (1994).
10. E. Müller, B. Fryxell, and D. Arnett, *Astron. Astrophys.* **251**, 505 (1991).
11. B. A. Remington, S. W. Haan, G. G. Glendinning, J. D. Kilkenny, D. H. Munro, and R. J. Wallace, *Phys. Rev. Lett.* **67**, 3259 (1991), and B. A. Remington, S. W. Haan, G. G. Glendinning, J. D. Kilkenny, D. H. Munro, and R. J. Wallace, *Phys. Fluids B* **4**, 967 (1992).
12. B. A. Hammel, D. Griswold, O. L. Landen, T. S. Perry, B. A. Remington, P. Miller, T. A. Peyser, J. D. Kilkenny, *Phys. Fluids B* **5**, 2259 (1993); B. A. Hammel, J. D. Kilkenny, D. H. Munro, B. A. Remington, H. N. Kornblum, T. S. Perry, D. W. Phillion, and R. J. Wallace, *Phys. Plasmas* **1**, (1994—in press); and G. Dimonte and B. A. Remington, *Phys. Rev. Lett.* **70**, 1806 (1993).
13. S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon, *Phys. Rev. Lett.* **69**, 21383 (1992).
14. E. P. Liang and C. D. Dermer, *Ap. J.* **325**, L39 (1988).
15. R. Cauble, D. Phillion, R. Lee, and T. Hoover, *JQSRT* **11**, 433 (1994).

16. R. Elton, D. Billings, C. Manka, H. Griem, and B. Ripin, *Phys. Rev. E* **49**, 1512 (1994).
17. C. Wu and P. Roberts, *Phys. Rev. Lett.* **70**, 3424 (1993); Setchell, Storm, and Sturtevant, *J. Fluid Mech.* **56**, 505 (1972).
18. M. Holt, *Ann. Rev. Fluid Mech.* **9**, 187 (1977); M. Kamagai, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-96675; J. Grove and R. Menikoff, *J. Fluid Mech* **219**, 313 (1990).
19. B. Skews, *J. Fluid Mech.* **29**, 705 (1967); L. Henderson, *J. Fluid Mech.* **26**, 607 (1966) and **198**, 365 (1989).
20. R. Klein, C. McKee, and P. Colella, *Ap. J.* **420**, 213 (1994).
21. V. Kazakov, A. Legostaev, and S. Peigin, *High Temperature* **31**, 717 (1993).
22. K. Holtsapple and R. Schmidt, *J. GeoPhys. Res.* **85**, 7247 (1980), and **87**, 1849 (1982).
23. G. Nutt and L. Klein, *Phys. Fluids* **24**, 2143 (1981).
24. T. Peyser, private communication.
25. T. Afshar-rad et. al., *Phys. Rev. Lett.* **73**, 74 (1994).
26. T. Endo et al., *Phys. Rev. Lett.* **60**, 1022 (1988).
27. R. Sigel et al., *Phys. Rev. Lett.* **65**, 587 (1990).
28. B. A. Hammel, D. Griswold, O. L. Landen, T. S. Perry, B. A. Remington, P. Miller, T. A. Peyser, J. D. Kilkenny, *Phys. Fluids B* **5**, 2259 (1993).
29. E. Muller, B. Fryxell, and D. Arnett, *Astron. Astrophys.* **251**, 505 (1991).
30. G. Dimonte and B. Remington, *Phys. Rev. Lett.* **70**, 1806 (1993).
31. J. Grun et al, *Phys. Rev. Lett.* **66**, 2738 (1991).
32. K. Mikaelian, *Phys. Fluids* **6**, 1943 (1994).
33. M. Zhuang et al., *AAIA J.* **28**, 1728 (1990); J. Hall et al., *AIAA J.* **31**, 2247 (1993).
34. Hawley and Zabusky, *Phys. Rev. Lett.* **63**, 1241 (1989); Zabusky et al., *Phys. Rev. Lett.* **67**, 2469 (1991); P.G. Saffman, *Vortex Dynamics* (Cambridge University Press, New York, 1992).
35. See, for example, Stanley P. Marsh, *LASL Shock Hugoniot Data* (Univ. of Calif. Press, Berkeley, 1980); *High-Velocity Impact Phenomena*, R. Kinslow, Ed. (Academic, New York, 1970); Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of*

Shock Waves and High-Temperature Hydrodynamic Phenomena, (Academic, New York, 1966).

36. E. Avrorin et al., *JETP Lett.* **43**, 308 (1986); *Sov. Phys. JETP* **66**, 348 (1987).
37. R. Cauble, et al., *Phys. Rev. Lett.* **70**, 2102 (1993).
38. Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, (Academic, New York, 1966).
39. A. C. Mitchell, W. J. Nellis, J. A. Moriarty, R. A. Heinle, N. C. Holmes, R. E. Tipton, and G. W. Repp, *J. Appl. Phys.* **69**, 2981 (1991).
40. N. C. Holmes et al., in *Proceedings of 8th AIRAPT and 19th EHPRL Conference*, C. M. Backman, T. Johansson, and L. Thenér, Eds. (Uppsala, 1981).
41. W. J. Nellis et al., *J. Chem. Phys.* **79**, 1480 (1983).
42. D. Saumon and G. Chabrier, *Phys. Rev. A* **44**, 5122 (1991); *Phys. Rev. A* **46**, 2084 (1992).
43. E. Avrorin et al., *J. Sov. Phys. JETP* **66**, 348 (1987).
44. N. C. Holmes and J. A. Moriarty, *Research Monthly* (to be published).
45. C. S. Yoo, N. C. Holmes, M. Ross, D. J. Webb, and C. Pike, *Phys. Rev. Lett.* **70**, 3931 (1993).
46. D. B. Hayes, *J. Appl. Phys.* **45**, 208 (1974); E. B. Zaratskii, G. I. Kanel, P. A. Mogilevskii, and V. E. Fortov, *Sov. Phys. Dokl.* **36**, 76 (1991).
47. Y. Syono and M. Kikuchi, in *Shock Waves in Material Science*, A. B. Sawaoka, Ed. (Tokyo, Springer-Verlag, 1993) p. 101.
48. T. Mashimo, in *Shock Waves in Material Science*, A. B. Sawaoka, Ed. (Tokyo, Springer-Verlag, 1993) p. 113.
49. N. C. Woolsey, *Time resolved, in situ, x-ray diffraction from laser shocked solids*. University of Oxford (1994); N. C. Woolsey, J. S. Wark, and D. Riley, *J. Appl. Crystallogr.* **23**, 441 (1990).
50. D. L. Price, B. R. Cooper, and J. M. Wills, *Phys. Rev. B* **46**, 11359 (1992).
51. T. Löwer, R. Sigel, K. Eidmann, B. I. Földes, S. Hüller, J. Massen, G. D. Tsakiris, S. Witkowski, W. Preuss, H. Nishimura, H. Shiraga, Y. Kato, S. Nakai, and T. Endo, *Phys. Rev. Lett.* **72**, 3186 (1994).
52. See the discussion in *Laser Plasma Interactions*, H. A. Baldis, E. M. Campbell, and W. L. Kruer in *Handbook of Plasma Physics*, M. N. Rosenbluth and R. Z. Sagdeev, Eds. **3: Physics of Laser Plasma**, A.M. Rubenchik and S. Witkowski, Eds. (Elsevier Science Publishers) B. V. (1991).

53. References for SRS are: W. Seka et al., *Phys. Fluids* **27**, 2181 (1984); R. P. Drake, *Phys. Fluids B* **1**, 1082 (1989); R. P. Drake and R. E. Turner, in *Laser Interaction & Related Plasma Phenomena*, **9**, H. Hora and G. H. Miley, Eds. (1991); K. Estabrook, W. L. Kruer, and B. F. Lasinski, *Phys. Rev. Lett.* **45**, 1399 (1980); S. P. Batha et al., *Phys. Rev. Lett.* **66**, 2324 (1991); R. E. Turner et al., *Phys. Rev. Lett.* **57**, 1725 (1986).
54. For SBS see P. E. Young, *Phys. Fluids B* **3**, 1245 (1991) and the references therein.
55. P. E. Young, *Phys. Rev. Lett.* **61**, 2336 (1988); C. Labaune et al., *Phys. Fluids B* **4**, 2224 (1992).
56. M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, and M. D. Perry, *Phys. Plasmas* **1**, 1626 (1994).
57. J. M. Dawson, *Sci. Am.* **260**, No. 3, 54 (1989); *Advanced Accelerator Concepts*, J. S. Wurtele, Ed., AIP Conf. Proc. No 279 (AIP, NY, 1993).
58. M. E. Glinsky, R. J. Mason, and M. Tabak, *Bull. Am. Phys. Soc.* **38**, 2080 (1993).
59. S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon, *Phys. Rev. Lett.* **69**, 1383 (1992); X. Liu and D. Umstadter, *Phys. Rev. Lett.* **69**, 1935 (1992); M. P. Kalashnikov, P. V. Nichols, Th. Schlegel, M. Schnuerer, F. Billhardt, I. Will, W. Sandner, and N. N. Demchenko, *Phys. Rev. Lett.* **73**, 260 (1994).
60. P. Sprangle et al., *Appl. Phys. Lett.* **53**, 2146 (1988).
61. T. Antonsen and P. Mora, *Phys. Rev. Lett.* **69**, 2204 (1992); S. C. Wilks et al., *Phys. Rev. Lett.* **69**, 1383 (1992); W. B. Mori et al., *Phys. Rev. Lett.* **72**, 1482 (1994).
62. M. E. Glinsky, R. J. Mason, and M. Tabak, *Bull. Am. Phys. Soc.* **38**, 2080 (1993).
63. C. E. Clayton, K. A. Marsh, A. Dyson, M. Everett, A. Lal, W. P. Leemans, R. Williams, and C. Joshi, *Phys. Rev. Lett.* **70**, 37 (1993) and references therein.
64. M.G. Haines, *Can. J. Phys.* **64**, 912 (1986); this contains a review of the different ways of generating B-fields in a plasma.
65. W.L. Kruer, "Laser Induced Circulating Currents," to be published (1994). in *Bull. Am. Phys. Soc.* DPP meeting 1994, Minneapolis, Minnesota.
66. S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon, *Phys. Rev. Lett.* **69**, 1383 (1992).
67. For two plasmon decay see H. A. Baldis and C. J. Walsh, *Phys. Fluids* **26**, 1364 (1983); A. Simon et al., *Phys. Fluids* **26**, 3107 (1983).
68. R. Bosch et al., *Phys. Fluids B* **4**, 979 (1992).

69. B. J. MacGowan, L. B. Da Silva, D. J. Fields, C. J. Keane, J. A. Koch, R. A. London, D. L. Matthews, S. Maxon, S. Mrowka, A. L. Osterheld, J. H. Scofield, G. Shinkaveg, J. E. Trebes, and R. S. Walling, *Phys. Fluids* **4**, 2326 (1992).
70. H. Kapteyn, *Appl. Opt.* **31**, 4931 (1992).
71. G. L. Strobel, D. C. Eder, R. A. London, M. D. Rosen, R. W. Falcone, and S. P. Gordon, in *Inner-shell photo-ionized x-ray laser schemes*, SPIE Proceedings Los Angeles, 1993, vol. 1860, pp. 157.
72. J. F. Reintjes, *Nonlinear Optical Parametric Processes in Liquids and Gases*, (Academic Press, Orlando, FL, 1984).
73. J. J. Macklin, J. D. Kmetec, C. L. Gordon, *Phys. Rev. Lett.* **70**, 766 (1993).
74. J. K. Crane, H. Nguyen, M. D. Perry (submitted for publication).
75. L. B. Da Silva, J. E. Trebes, R. Balhorn, S. Mrowka, E. Anderson, D. T. Attwood, T. W. Barbee, J. Brase, M. Corzett, J. Gray, J. A. Koch, C. Lee, D. Kern, R. A. London, B. J. MacGowan, D. L. Matthews, and G. Stone, *Science* **258**, 269 (1992).
76. L. B. Da Silva, B. J. MacGowan, S. Mrowka, J. A. Koch, R. A. London, D. L. Matthews, and J. H. Underwood, *Opt. Lett.* **18**, 1174 (1993).
77. Some theoretical discussions of the transparency window are: L.G. Dyachkov et al., *JQSRT* **44**, 123 (1990) and B. G. Berkovsky et al., *J. Phys. B* **26**, 2475 (1993). Some experimental work is V. E. Fortov et al., p. 571 in *Strongly Coupled Plasmas*, S. Ichimaru, Ed. (Elsevier, 1990), and Popovic & Dodevic, p. 273, in *Strongly Coupled Plasmas*, H. Van Horn & S. Ichimaru Eds. (University of Rochester Press, 1993).
78. S. J. Rose, *Journal de Physique Coll. Ser. C8* (1982); using methods of D.R. Bates, *MNRAS* **112**, 40 (1952); D. Salzmann and J. Stein, *Phys. Rev. A* **45**, 3943 (1992).
79. I. Kwon, L. A. Collins, J. D. Kress, N. Troullier, and D. L. Lynch., *Phys. Rev. E* **49**, R4771 (1994).
80. E. LeBoucher-Dalimier, A. Poquérousse, P. Angelo, I. Gharbi, and H. Derfoul, *JQSRT* **51**, 187 (1994).
81. See the references in H. R. Griem, *Spectral Line Shapes from Plasmas* (Academic Press, New York, 1972).
82. D. Liberman and J. R. Albritton, *JQSRT* **51**, 197 (1994) and the references therein.
83. B. A. Hammel, C. J. Keane, M. D. Cable, D. R. Kania, J. D. Kilkenny, R. W. Lee, and R. Pasha, *Phys. Rev. Lett.* **70**, 1263 (1993); and C. F. Hooper, D. P. Kilcrease, R. C. Mancini, L. A. Woltz, D. K. Bradley, P. A. Jaanimagi, and M. C. Richardson, *Phys. Rev. Lett.*, **63**, 267 (1989).

84. N. Miura and F. Herlach, in *Strong and Ultrastrong Magnetic Fields and their Applications*, F. Herlach, Ed. (Springer: Berlin: 1985).
85. S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon, *Phys. Rev. Lett.* **69**, 1383 (1992).
86. P. Meszaros, *High-Energy Radiation from Magnetized Neutron Stars* (U. Chicago Press, Chicago, 1992).
87. E. P. Lief and J. C. Weisheit, *Contrib. Plasma Phys.* **33**, 471 (1993).
88. D. D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis*, (McGraw-Hill, New York, 1968).
89. M. Harris, W. Fowler, G. Caughlann, and B. Zimmerman, *Ann. Rev. Astron. Ap.* **21**, 165 (1983).