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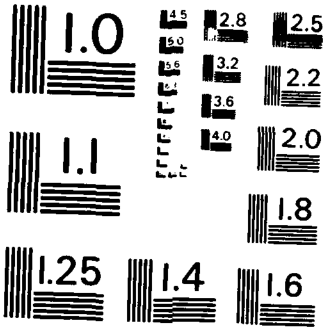

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NRC Survey on Plasma Physics and Fluids Fusion Plasma Confinement and Heating
Chapter 8: Inertial Confinement Fusion

B. H. Ripin and W. L. Kruer*

Laser Plasma Branch
Plasma Physics Division

**Lawrence Livermore National Laboratory*
Livermore, CA 94550

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8. INERTIAL CONFINEMENT FUSION SYSTEMS

8.1 Introduction

- The inertial confinement approach to fusion is based on compressing thermonuclear fuel to extremely high density, and heating it to temperatures high enough that the fuel ignites and "burns" before the compressed mass has time to disassemble.

Inertial confinement fusion complements the magnetic confinement schemes, and represents an independent approach based on quite different physical principles. Instead of magnetically confining hot plasmas with densities of 10^{14} to 10^{15} particles per cubic centimeter for times of up to a second, fuel is imploded to a very high density, typically 10^{25} to 10^{26} particles per cubic centimeter, and burned in tens of picoseconds (one picosecond equals one trillionth of a second, i.e., 10^{-12} sec) while inertially confined. For ultimate commercial applications, inertial confinement fusion has the very desirable feature that the driver facility and reactor chamber can be well separated from one another. This separation greatly reduces the technological problems of practical reactor-chamber design.

Inertial confinement research also has many other applications related to the physics of high energy density. The irradiation of plasmas by intense laser light allows the study of many nonlinear processes with applications throughout plasma physics. The generation of pressures of tens to hundreds of megabars (1 megabar equals a million atmospheres) allows the investigation of matter under very high pressures. The generation of highly ionized matter and of intense short pulses of X-rays allows the study of atomic physics of importance in the development of X-ray lasers.

Inertial fusion works by focusing an intense beam of laser light or particles onto the outer layers of a spherical shell encapsulating fusion fuel, as illustrated in Fig. 1.. The fuel is then compressed by pressures of tens to hundreds of millions of atmospheres generated by the rocket-like blowoff of the surface material. At the end of the driver pulse, when the fuel reaches about 1000 times liquid density, a portion in the center ignites at a temperature of about a hundred-million degrees Celsius. The thermonuclear burn spreads rapidly through the remaining compressed fuel, yielding many times the driver energy. The high fuel density increases the thermonuclear reaction rate to allow the fuel to burn while it remains together by its own inertia. Energy is released in the form of energetic neutrons, X-rays and helium nuclei which are captured and converted to thermal energy for various applications. For power generation, pellet gains of a hundred or more are needed to compensate for reactor and driver inefficiencies, whereas other applications, such as hybrid reactors and fissile fuel production, are feasible with lower pellet gains.

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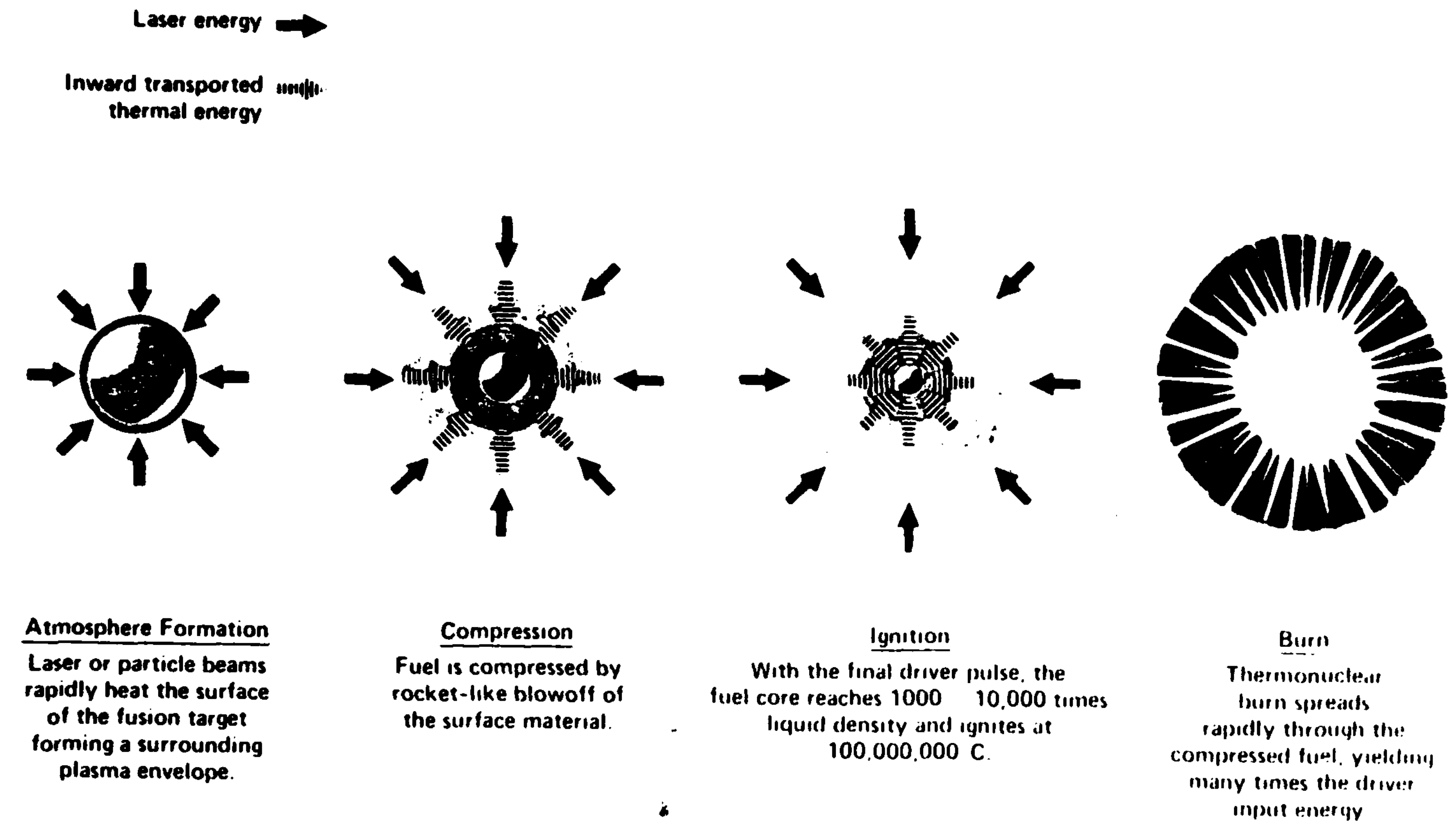

Figure 1 Laser fusion concept.

In the past decade, a vigorous effort has been undertaken to investigate the physical principles of the inertial confinement approach. The physical constraints that need to be satisfied for inertial fusion to succeed can be divided into five "critical elements":

- Coupling Efficiency -- The fraction of driver energy utilized for fuel compression and ignition needs to be high; efficiencies of about 5% are needed for high-gain applications;
- Cold Compressed Fuel -- The fuel must remain nearly isentropic (cold) during pellet implosion, in order to achieve high final fuel densities at low driver energy cost; an energy increase of only a few times the minimum (Fermi degenerate) level is permissible;
- Ablation Pressure -- Sufficient ablation pressure needs to be developed at the pellet surface to achieve high-density compression and to avoid hydrodynamic instability; pressures from tens to hundreds of megabars are needed;
- Implosion Symmetry -- The pellet must be imploded uniformly to minimize the volume of hot fuel needed to ignite the pellet, and to avoid hydrodynamic destruction of the pellet; implosion uniformities of close to 1% may be needed;
- Ignition Concept -- A practical means by which a small volume within the pellet's fuel can be ignited, and the remaining fuel consumed by propagating burn, needs to be established; the central hot-spot must have temperatures above about 4 kiloelectron-volts, and have a density-radius product of about 0.3 grams per square centimeter. The remaining fuel should have a density-radius product of about three grams per square centimeter for efficient burn.

Inertial confinement fusion research in the United States is conducted mainly at the Lawrence Livermore National Laboratory, Livermore, California, and at the Los Alamos National Laboratory, Los Alamos, New Mexico. Smaller programs are underway at the Naval Research Laboratory, Washington, D. C., at KMS Fusion Inc, Ann Arbor, Michigan, at the University of Rochester, Rochester, New York, and at Sandia Laboratories, Albuquerque, New Mexico. In addition, a number of universities contribute to inertial confinement research.

8.2 Major Advances

8.2.1 Drivers for Inertial Confinement Fusion

- An impressive array of experimental facilities for inertial confinement research has been developed over the past decade. Neodymium-glass lasers have been constructed with output energies of up to 30 kilojoules and powers up to 25 terawatts; CO_2-lasers have been constructed with 30 to 40 kilojoules of output energy, and powers up to 30 to 40 terawatts. Light-ion beams have been generated with up to hundreds of kilojoules of output energies at several terawatts of power.

Table I lists the major driver-facilities for inertial confinement research, both existing and under construction, worldwide. In addition, several heavy-ion drivers have also been proposed for construction at the Lawrence Berkeley Laboratory and in West Germany. Ultimately, for power generation purposes, the driver must be highly efficient (about 10%), reliable, and capable of being repetitively pulsed.

The most useful driver for inertial fusion research to date has been the laser. Powerful laser-light pulses can be focused down to the small dimensions required to generate high pressures on a pellet surface, their pulse-length and shape can be varied, and their wavelength controlled. In short, they make excellent research tools to investigate inertial confinement physics and to test pellet concepts. The dominant lasers for inertial fusion research have been the neodymium-glass laser, which produces light pulses in the near-infrared portion of the spectrum (1.05 microns; one micron equals 10^{-6} meters), and the CO_2-gas laser, which operates in the far-infrared (10.6 microns). Neodymium-glass lasers have achieved powers on target up to 25 terawatts (one terawatt equals 10^{12} watts), and CO_2 lasers have achieved powers in the 30-40 terawatt range. The neodymium-glass laser has proven to be a particularly flexible tool, since its output can be efficiently frequency-converted. If short wavelength light proves to be preferable for inertial fusion , then a krypton-fluoride laser, an excimer system (0.25 microns) with good efficiency, is an attractive candidate.

In addition to lasers, intense particle beams can be used as inertial-confinement pellet drivers. There are currently two main approaches to particle-beam inertial fusion: light ions and heavy ions. Light ions, such as protons, lithium or carbon ions, are generated in high-current pulsed power accelerators which provide megamperes of ion current at a few megavolts energy. Light-ion beam generators are highly efficient and relatively inexpensive, but cannot as yet attain the power densities required for fusion. The heavy ion approach would use very heavy ions, such as lead ions accelerated up to gigaelectron-volt energies (a gigaelectron-volt equals a billion electron-volts) in conventional high-energy accelerators. Accelerators needed to supply such beams for inertial fusion would be expensive, but would have many properties desirable for inertial-fusion reactors; they could provide highly efficient, repeatedly pulsable, and focusable beams.

Although particle beams may one day be the preferred driver for inertial fusion, their technology has not yet advanced to the stage where they can be used for extensive inertial fusion research involving targets. Therefore, we will concentrate here on describing inertial-fusion research using a laser driver.

8.2.2 Laser-Target Physics

- Using a neodyminum-glass laser driver, targets have been imploded to about one hundred times liquid density -- within a factor of ten of reactor requirements. The development of increasingly sophisticated plasma instrumentation and modelling codes has led to improved agreement between the experiments and the theory of laser target interaction.

Table I. MAJOR INERTIAL CONFINEMENT FUSION FACILITIES

Facility	Location	Driver Type	Energy* (kJ)	Power* (TW)
NOVA	LLNL	Nd-glass	(100)	(125)
NOVETTE	LLNL	Nd-glass	30	25
PHAROS-III	NRL	Nd-glass	(2)	(4)
PHAROS-II	NRL	Nd-glass	1	2
OMEGA	Rochester	Nd-glass	4	12
GDL	Rochester	Nd-glass	0.1	0.5
CHROMA-1	KMSF	Nd-glass	1	2
ANTARES	LANL	CO_2	(30-40)	(30-40)
HELIOS	LANL	CO_2	5-10	10-20
LAM	LANL	KrF	(10-20)	-
RAPIER B	LLNL	KrF	0.8	
PBFA-II	Sandia	Light-ion	(4000)	100
PBFA-I	Sandia	Light-ion	1000	20
GAMBLE-II	NRL	Light-ion	100	2
PHEBUS	France	Nd-glass	(30)	(25)
OCTAL	France	Nd-glass	4	4
GEKKO XII	Japan	Nd-glass	(20)	(40)
GEKKO IV	Japan	Nd-glass	2	4
HELEN	UK	Nd-glass	1	3
VULCAN	UK	Nd-glass	1	2
DEL'FIN	USSR	Nd-glass	5	2-7
UMI-35	USSR	Nd-glass	8-10	4-6
LEKKO III	Japan	CO_2	10	10
LEKKO II	Japan	CO_2	0.5	0.5
REIDEN IV	Japan	Light ion	50	1
KALIF	West Germany	Light ion	75	2

*For laser, energy quoted reflects performance at long pulse. Power quoted reflects performance at short pulse. For light ions, energy and power quoted is that delivered to the ion diode. Account is not taken of ion production and transport efficiency which reduce these numbers by up to a factor of four. Parameters in parenthesis denotes facility under construction.

With these experimental facilities, a great deal of progress in inertial confinement research has been made. The coupling of laser light with targets has been characterized over a wide range of laser intensity and wavelength. Numerous coupling processes, ranging from collisional absorption to collective plasma processes, have been confirmed and quantified. A regime of excellent coupling for laser light with wavelengths less than one micron has been demonstrated.

D-T fuel in glass microballoons has been heated to thermonuclear temperatures. Targets and shells have been ablatively accelerated to above 10^7 centimeters per second with velocity nonuniformities below 5%. DT fuel has been imploded to a final fuel density of about a hundred times its liquid density, with fuel temperatures of about 400 electron-volts. These compressions are within a factor of about ten of the compression needed for a reactor target.

Instrumentation to measure the properties of the beam-target interaction has evolved at a remarkable pace in the last decade. Typically, quite extreme ranges of plasma conditions are encountered in a single inertial confinement experiment: the density ranges downward from 1000 times solid density to near vacuum; the temperature ranges in some cases from 1 electron-volt to beyond 10^5 electron-volts; the electromagnetic radiation emitted extends from the infrared region into the gamma-ray region; and various ion and electron populations may be present with energies extending from electron-volts to millions of electron-volts. Moreover, measurements often need to be made with micron spatial resolution and picosecond temporal resolution. Diagnostics now exist which can measure many of these properties; they have, in large measure, been instrumental in the many significant advances that have been made recently in understanding the laser-target interaction.

Equally important, theory and large simulation codes have advanced towards the goal of providing a predictive capability for new irradiation conditions. These theoretical tools have guided the advances made in the experiments and have, in turn, been improved through constant comparison with these experiments. New target design concepts have been developed. New designs based on the hohlraum approach rely on X-rays from driver-produced plasmas to implode the target.

8.3 Current Frontiers of Research

8.3.1 Laser Plasma Coupling

- The absorption of laser light occurs in a "corona" plasma surrounding the target. Experiments have generally confirmed both the collisional absorption mechanism and the theoretically-predicted collective plasma effects on laser-light coupling. The experiments have also demonstrated a large increase in collisional absorption concomitant with a large decrease in deleterious collective effects as the wavelength of the laser light is decreased.

In laser fusion, a target is irradiated with an intense pulse of laser light. For high gain targets, the required intensity will be in the range of 10^{14} - 3×10^{15} watts per square centimeter, depending on the details of the target design, and the pulse-length will be of order 10 nanoseconds (one nanosecond equals one billionth of a second, i.e., 10^{-9} sec) . Very early in the pulse (at intensities about 10^{10} watts per square centimeter), the surface of the target breaks down, forming a plasma. As is well known, light will only propagate in a plasma up to a maximum density, the critical density, given by the condition that the electron plasma frequency equals the laser light frequency. The critical densities are about 10^{21} and 10^{19} particles per cubic centimeter, for the neodymium-glass laser and CO_2 laser, respectively. Some experiments have also been carried out using crystals to double, triple and quadrupole the frequency of a neodymium-glass laser, and the critical densities are then correspondingly higher. The critical densities are much less than solid density, and so the laser light absorption takes place in a relatively low density "corona" plasma surrounding the irradiated target.

The coupling of the laser light to this plasma is clear[illegible] one of the fundamental issues in laser fusion. Obviously, the absorption ficiency of the laser light needs to be high to maximize the efficiency [illegible] the driver. However, the heated electron velocity distributions are crucial also, because very high energy electrons have a relatively long range and [illegible] penetrate into, and preheat, the fuel within the interior of the target. ven modest preheat will prevent the D-T fuel from reaching the density compression required for high gain targets.

Inverse bremsstrahlung, or collisional absorption, is the preferred laser-wave absorption mechanism. Physically, inverse bremsstrahlung is due to collisions between the electrons, which are being vibrated by the electric field in the light wave, and the background plasma ions. The laser absorption rate is proportional to plasma density, and inversely dependent on electron temperature. Collisional absorption thus becomes more efficient as the wavelength of the laser light is decreased, since the light can propagate into denser, relatively cooler plasma. Furthermore, since the collision frequency between electrons and ions has a strong inverse dependence on the electron velocity, slower particles are preferentially heated. Hence, favorable electron distributions are generated.

There are many other mechanisms for laser-plasma coupling. These mechanisms arise from the excitation of plasma waves by the intense laser light. The waves, in, turn can heat the plasma particles and/or scatter the incident light. Heating of the plasma by excited plasma waves is very often undesirable, since suprathermal electrons can be generated. The fast electrons originate because electron plasma waves propagate with high phase-velocities, and electrons in near resonance with these waves will be preferentially energized. Suprathermal electrons can provide preheat, an effect to be avoided.

The simplest absorption process involving electron plasma wave heating is resonance absorption. Whenever the laser-light electric field oscillates electrons across a spatial variation in density, a high-frequency charge-density fluctuation is driven. This density fluctuation resonantly excites an electron plasma-wave at the critical density.

In addition, electron plasma waves and ion acoustic waves can be excited by a variety of plasma-wave instabilities driven by the intense laser light. Most of these instabilities can be simply characterized as the resonant decay of the incident light-wave into two other waves. Given that the plasma supports electron plasma waves, ion acoustic waves, and light waves, the possibilities are straightforward to list. There is "parametric decay", namely decay into an electron plasma wave and an ion acoustic wave which occurs near the critical density.The "two-plasmon instability",namely decay into two electron plasma waves, occurs near one-fourth of the critical density. The "Raman instability", namely decay into a scattered light-wave and an electron plasma wave, is a process which operates for densities even below one-fourth of the critical density. These instabilities all generate an electron plasma wave, and are a fuel-preheat threat. In addition, the "Brillouin instability", namely decay into a scattered light-wave and an ion acoustic wave, occurs throughout the underdense plasma, and can scatter the light before absorption. Finally, there are self-focusing instabilities. A small "hot-spot" enhancement of the intensity of the incident light-wave creates a density depression, either by pushing the plasma aside via the enhanced field pressure, or by enhanced heating and subsequent plasma expansion. Since a light-wave locally refracts into lower-density plasma, the density depression leads to a further enhancement of the hot-spot, giving rise to intense filaments.

In addition to instabilities driven directly by the laser light, many other important processes can occur in laser-irradiated targets. For example, ion turbulence and self-generated magnetic fields, can be created in the interaction process. Magnetic fields can be as high as several megagauss, sufficiently large to impede the heat flow, or to introduce new kinds of magnetically driven fluctuations.

Figure 2 presents a simplified summary of the many different processes operative in the underdense plasma. Virtually every coupling mechanism indicated in Fig. 2 has now been observed in experiments. Important features that have been observed include generation of very energetic electrons associated both with resonance absorption and with the various instabilities producing electron plasma waves, and scattered light associated with the Brillouin and Raman instabilities. Most important, the experiments have demonstrated a strong increase in collisional absorption concomitant with a strong decrease in deleterious collective effects (hot-electron generation and light scattering) as the wavelength of the laser light is decreased.

Figure 3 shows the absorption efficiency as a function of laser intensity for a variety of wavelengths ranging from 1.05 microns to 0.26 microns. The scaling with wavelength has had a very strong impact on laser fusion research. Most large laser facilities now planned will operate at wavelengths of half a micron or less.

Research on laser-plasma coupling continues to contribute to the understanding of many fundamental processes in plasma heating and turbulence. It is very important to extend this research to the much larger-scale plasmas that will be encountered in reactor targets. The present understanding of the various coupling processes and detailed plasma conditions in larger-scale plasmas is inadequate to make quantitative predictions with confidence.

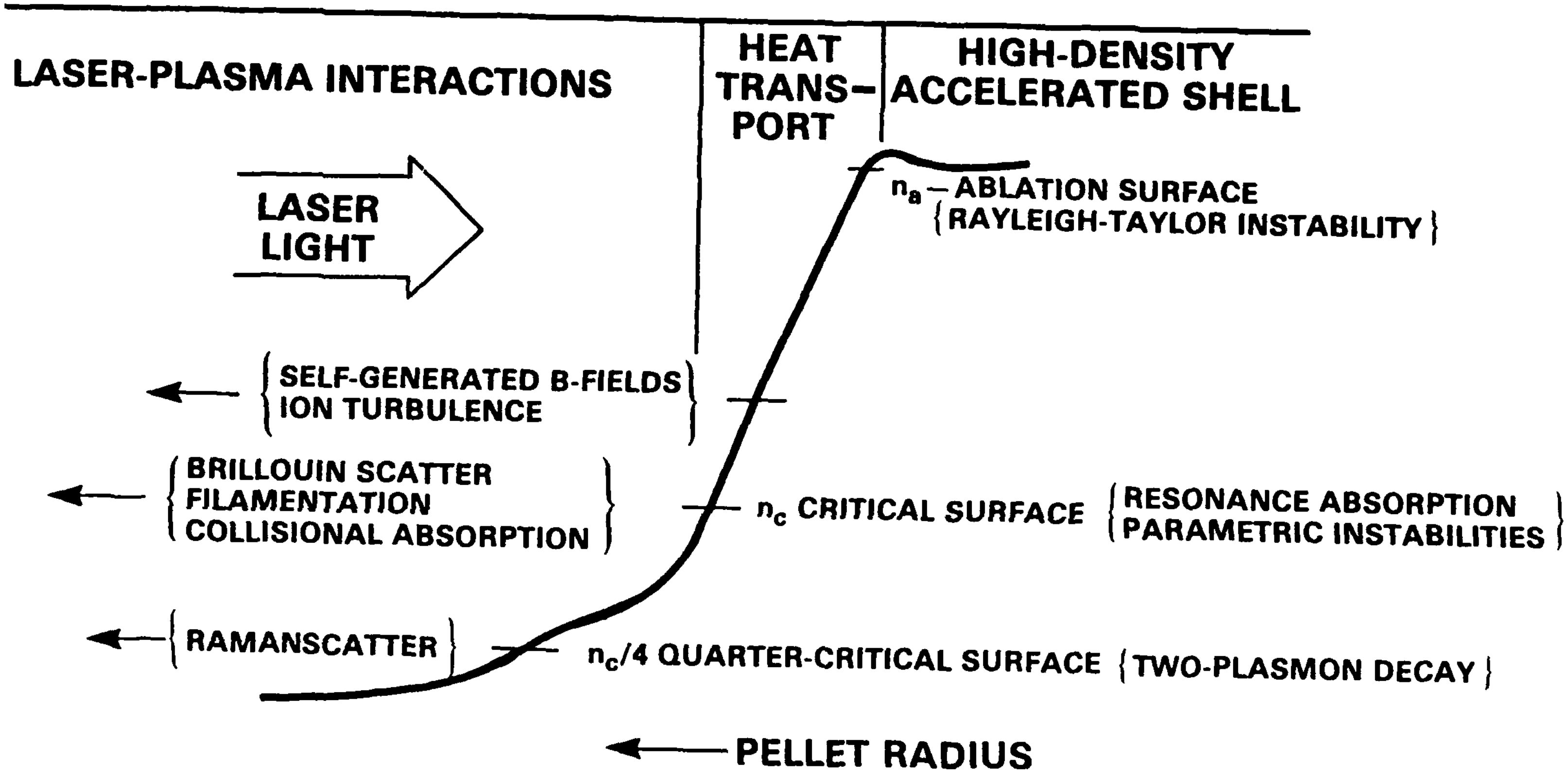

Figure 2 Regions of occurence of physical phenomena in the pellet's density profile. There are three major regions; laser-plasma interaction, heat transport, and shell acceleration.

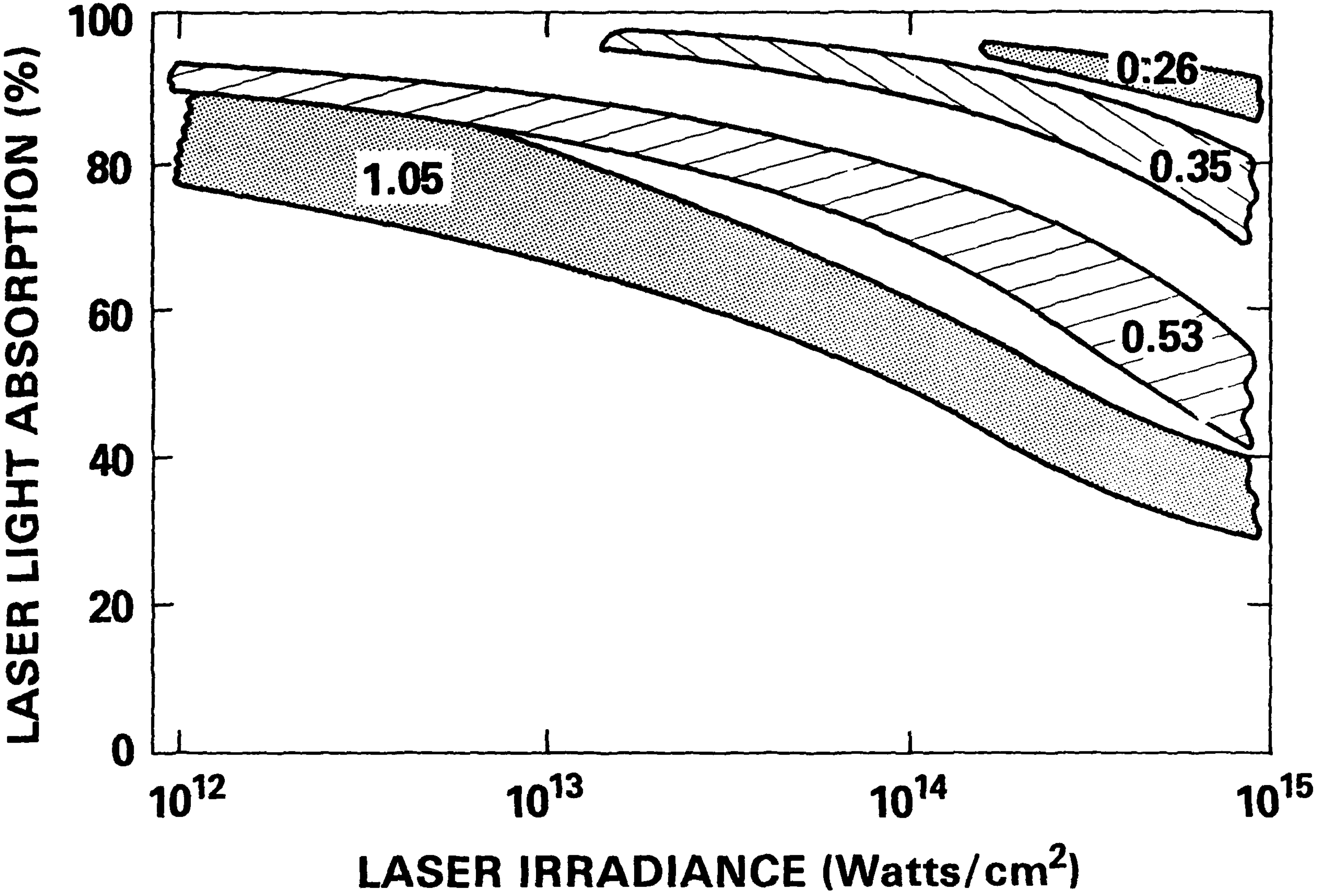

Figure 3 Laser light absorption versus laser intensity for various laser wavelengths. Note the better absorption with shorter wavelength light. Data is from worldwide sources.

8.3.2 Heat Transport and Ablation

- After the laser-light energy has been deposited, it must be efficiently transported inward, to an ablation surface, within which the pellet implodes. Short wavelength laser-light improves heat transport efficiency, but may lead to greater non-uniformities in the implosion.

In the direct-illumination approach to inertial confinement fusion the laser-heated electrons are dominant in transporting energy to an "ablation" surface as shown in Fig. 2. Outside the "ablation surface" the target material is stripped away from the pellet shell by the heat wave. As this ablating material is accelerated outward toward the laser, it creates a large rocket-like ablation pressure which accelerates the remaining shell inward and compresses the fusion fuel.

Transport of the very intense electron energy fluxes characteristic of laser-fusion applications is itself an important topic in applied plasma physics. The usual theory of diffusive heat flow of electrons is in general inadequate, and improved theories are now emerging. In addition, the flow of electrons can be markedly reduced by self-generated magnetic fields created by anisotropies in the energy deposition. Fortunately, the effects of such fields are much reduced when targets are more uniformly irradiated.

The heat flow has been investigated in laser plasma experiments under a wide variety of conditions. Often, the experiments have indicated a heat flow below the classical level. Empirical heat flow models, normalized to experiments, are often used in design calculations. Since electron heat transport has a marked effect on plasma conditions, hydrodynamic efficiency, preheat and implosion symmetry, this remains a key area for further research.

The efficiency by which absorbed energy reaches the ablation surface, and the resulting blow-off velocity of the ablating materials, determine the hydrodynamic efficiency of the pellet, that is, the kinetic energy delivered to the fuel divided by the absorbed driver energy. The most efficient transfer of momentum to the pellet shell occurs when the blow-off plasma velocity (the final ablation plasma velocity far from the target) is comparable to the final shell velocity. Shorter wavelength lasers improve the hydrodynamic efficiency because the energy is absorbed at higher plasma density, and closer to the ablation surface. For one-quarter micron wavelength light incident upon reactor-sized spherical pellets, calculated hydrodynamic efficiencies are as high as 15%, or about three times the minimum efficiency needed for high-gain applications.

The distance between the driver energy absorbing region and the ablation region is another important parameter affected by the heat transport. If nonuniformities in the energy absorbed are transmitted to the ablation surface, where the pressure is applied to the shell, the result will be an asymmetric implosion. Fortunately, such nonuniformities will tend to be smoothed out between the energy absorption and ablation regions, provided this separation exceeds the wavelength of the disturbance. This smoothing mechanism, called the "cloudy-day effect," has been found experimentally to be quite effective at 1 micron laser wavelength. However, for shorter-wavelength laser light, the very source of the improved absorption and greater hydrodynamic efficiency (higher-density absorption) aggravates the uniformity problem.

8.3.3 Shell Acceleration, Uniformity, and Hydrodynamic Instabilities

- Experimental results on ablatively-accelerated pellet implosions have been very encouraging, with respect to both implosion velocities and compression factors achieved, but the uniformity of the implosion is not yet adequate for compression to fusion densities. Various techniques for improving the implosion uniformity appear promising. Hydrodynamic instabilities, which would aggravate the problem, do not seem to be as severe as initially predicted.

Investigations of pellet shell acceleration and hydrodynamic behavior have been accomplished by imploding actual pellets, using multiple-sided irradiation facilities, or by studying the acceleration of thin planar targets.

Early implosion experiments worked in the "exploding pusher" regime. In these experiments, small glass micro-balloons containing gaseous D-T were irradiated with intense short duration light pulses.The laser-heated electrons deposited energy so quickly in the glass that the shell exploded. Roughly half of the exploding shell (pusher) travelled inward, first driving a shock-wave through the D-T gas and then compressing the post-shock material. Copious thermonuclear neutrons were generated as the D-T fuel heated to temperatures of many kiloelectron-volts. However, the preheat levels of these targets, and the exploding pusher behavior, limited their peak fuel densities to a few times liquid density, far below the densities required for high-gain pellets.

Most present-day implosion work has advanced to the more relevant "ablative" mode. Ablation acceleration or implosion occurs as a result of the continuous acceleration of ablating material. These experiments utilize either thicker shells, to reduce hot electron preheat, or use lasers operating in a lower irradiance or shorter wavelength regime, where hot electrons are not dominant. This implosion mode is expected to scale successfully to large inertial fusion devices.

Multi-nanosecond 1-micron lasers operating below 10^{14} watts per square centimeter have been used to produce well-behaved ablative accelerations. Planar targets have been ablatively accelerated to velocities of 160 kilometers per second, with preheat below 10 electron-volts and velocity uniformity to within 7%. Acceleration uniformities within 2.5% over almost a square millimeter have been achieved in other planar target experiments. Ablatively-driven pellets have compressed D-T fuel to nearly a hundred times solid density, albeit with low temperature (about 400 electron-volts). These experiments are very encouraging, but further progress is required to meet the "critical element" physics requirements.

The pellet implosion must proceed with shell velocity non-uniformities below about 1%, in order to properly compress the fuel. This requirement is aggravated by the fact that the pellet itself is susceptible to hydrodynamic instability at several phases during the implosion.

Driver nonuniformity problems can be alleviated in three ways. Use of hohlraum targets with conversion of driver energy to X-rays provides a promising method of smoothing without requiring the beams of the driver to be symmetrically arranged. In the direct illumination approach, non-uniformities in absorption can be smoothed out by operating in a regime where the "cloudy-day effect" is operative. In fact, nonuniformity reductions of an order-of-magnitude have been demonstrated in 1-micron laser light experiments. Finally, development of driver technologies which produce smoother beams should also be effective. All three methods are under active investigation.

A recent innovation in laser technology, called "induced spatial incoherence", provides a promising method to reduce laser-beam nonuniformities to acceptable levels. The method works by dividing a broad-bandwidth laser beam into many smaller beamlets, with a small relative time delay introduced into each beamlet's path. If these time delays are longer than the beam coherence time, the laser nonuniformities will tend to statistically cancel out when the beamlets are overlapped on the target.

Hydrodynamic Rayleigh-Taylor instability can occur whenever a lighter fluid accelerates a heavy fluid. Inertial fusion analogs of the Rayleigh-Taylor instability occur when the low-density ablating plasma accelerates the dense shell, or later in the implosion when the dense shell decelerates upon compressing the lighter fuel. Hydrodynamic instability causes two deleterious effects. First, the nonuniformities can prevent a central region of dense, hot D-T fuel from being created, and cause the pellet to fail to ignite, or even disassemble before full compression. Second, fuel can mix with the shell pusher material, and spoil the ignition. There is an active growing theoretical program on the mechanisms, growth rates, and saturation levels for the Rayleigh-Taylor instability. A number of effects have been shown to reduce the growth rate below initial predictions

Experiments are beginning to make significant headway into the study of the hydrodynamic stability of laser accelerated targets. The evolution of accelerated "structured" targets, in which regular mass variations are introduced, has been followed using X-ray backlighting and double-target diagnostics. First indications suggest that the Rayleigh-Taylor instability growth rate may be less than "classical", in agreement with the more recent theoretical predictions.

8.4 Prospects for Future Advances

- Two very large driver facilities are currently under contruction in the United States: the NOVA neodymium-glass laser, and the PBFA-II light-ion-beam accelerator. Construction of the world's most powerful CO_2 laser, ANTARES, was recently completed. These, and other smaller facilities, will be used to greatly extend our knowledge of the efficiency, symmetry and stability of pellet implosions. In addition, heavy-ion-beam drivers have been proposed, and the search for efficient shorter wavelength lasers continues.

As indicated in Table I, a new generation of drivers is being developed: the NOVA neodymium-glass laser will have an output of 100 kilojoules of 1.05 micron light (this will be frequency-converted to shorter wavelengths, i.e., 0.53 micron and 0.35 micron light); the ANTARES CO_2 laser has an output of 30 to 40 kilojoules of 10.6 micron light; and the PBFA-II light-ion-beam accelerator will have an output of about 2 megajoules of 4 million-electron-volt protons.

The new machines coming on line in the next few years will allow significant tests of key inertial confinement fusion principles. For example, it is anticipated that the NOVA laser will be able to compress D-T fuel to about one thousand times liquid density, with fuel temperatures in the central hot spot in the 1-2 kiloelectron-volt range. Such experiments will very significantly test and extend our knowledge of the efficiency, symmetry, and stability of pellet implosion. The ANTARES CO_2-laser will test the suitability of long-wavelength laser light for inertial confinement fusion. PBFA-II is anticipated to provide light ion beams focused to sufficient intensity to test pellet implosions. The PHAROS, OMEGA, and CHROMA lasers will supplement the larger facilities, by addressing important physics issues of inertial confinement fusion.

Driver technology will continue to advance toward a high-energy, high-repetition-rate, efficient driver suitable for inertial confinement fusion application. One promising system under development is the krypton-fluoride laser, with a wavelength at 0.26 microns, which may satisfy the requirements for an efficient short-wavelength laser. Megajoule-class glass based lasers are also under evaluation; these systems could be frequency-converted to provide short-wavelength light. Finally, particle-beam drivers, such as heavy ion beam systems and light-ion accelerators, have the potential to offer high efficiency and repetition rates. Small, exploratory heavy-ion drivers are expected to operate in about five years.

Inertial confinement continues to be a very active and exciting field. Research in the next decade will provide scientific and technical information needed to determine the physics of inertial confinement fusion. In turn, this information will provide the basis for a decision in the late 1980's or the next generation of experimental facilities.