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Intense, ultrashort light and dense, hot matter

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Abstract. This article presents an overview of the physics and applications of the interaction of high intensity laser light with matter. It traces the crucial advances that have occurred over the past few decades in laser technology and nonlinear optics and then discusses physical phenomena that occur in intense laser fields and their modeling. After a description of the basic phenomena like multiphoton and tunneling ionization, the physics of plasma formed in dense matter is presented. Specific phenomena are chosen for illustration of the scientific and technological possibilities – simulation of astrophysical phenomena, relativistic nonlinear optics, laser wakefield acceleration, laser fusion, ultrafast real time X-ray diffraction, application of the particle beams produced from the plasma for medical therapies etc. A survey of the Indian activities in this research area appears at the end.

Keywords. Laser-driven acceleration; frequency conversion; harmonic generation; ultrafast processes; relativistic plasmas.

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1. Introduction

The 20th century witnessed a dramatic shift in our perception and understanding of light. When the laser was born 49 years ago [1], little did its inventors and aficionados realize that it would not only sweep that era of scientists off its feet, but would continue to challenge and mesmerize generations to come. Light has always fascinated man, but even with that high expectation as a benchmark, the laser has proved to be nothing short of a miracle.

It strikes me as a wonderful coincidence that this article in this special issue is about light and lasers. The essential (embryonic?) relation between light and the Indian Academy of Sciences is known to all of us. In a sense, Raman's extreme fascination with light has been amply (and continues to be) rewarded by the tremendous advances enabled by the laser. In the nearly five decades since the birth of the laser, Raman scattering has assumed vibrant hues and shades revitalizing and revolutionizing spectroscopy and through that, many branches of science and technology. This explosive growth of Raman spectroscopy has been fuelled by the laser. It is a fitting tribute that the Raman Effect has paid the laser back in its

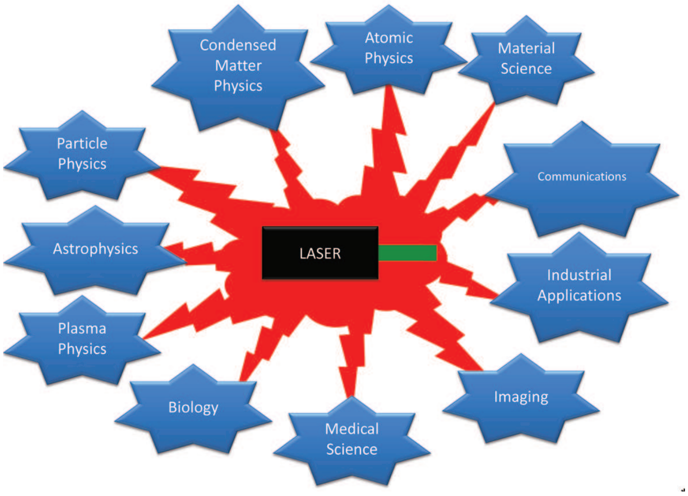


Figure 1. The laser-centric scientific and technological universe!

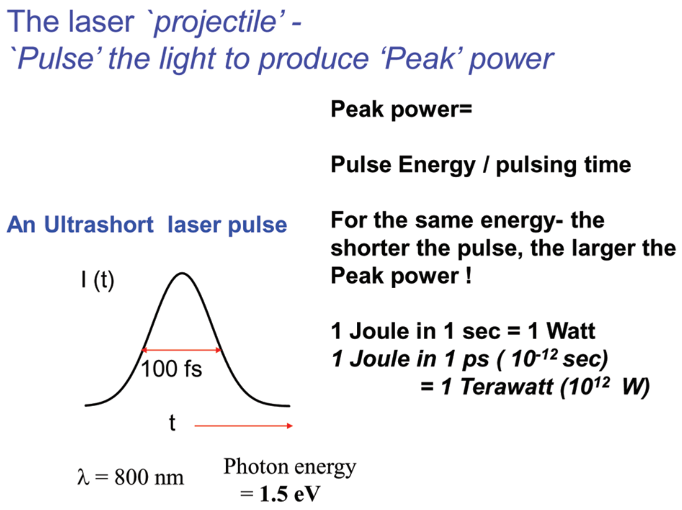
own way – there are 'Raman Lasers' – those that depend on a high light intensity manifestation of the Raman effect namely, stimulated Raman scattering [2].

The laser [3] has become ubiquitous in the modern age – in science, technology and daily life (figure 1). In scientific terms, it has pioneered advances of a very fundamental nature by enabling sophisticated measurements of the highest precision and utmost sensitivity. Among the achievements outside the purview of this article, I can pick two that strike me as the most important: (a) the clear demonstration of the correctness of quantum mechanics (in an experiment that tested the famous Bell's inequalities [4]) and (b) the production of 'non-classical' light [5], unheard of before. Justifiably, in the last few decades, the laser has figured prominently among the Nobel prizes!

This article is about the physics of the interaction of ultraintense, ultrashort light pulses with dense matter and the resulting scientific and technological possibilities. Such intense light has been possible only because of the laser. The description here has turned out to be of a very mixed nature. The introductory part can serve as a review for the beginning research student. In the middle, there is a part that is perhaps intelligible to a professional from another area. Towards the end, there are discussions about a few specific aspects of the interaction of intense, ultrashort laser light with matter and some future projections for an insider. There is also a section on providing a perspective on the Indian efforts in this area. Needless to add, this article is limited by my own perspective and leanings. I offer apologies in advance, for the (many) omissions and biases.

1.1 *Powerful light*

What we want to look at here deals with one aspect that is again fundamentally due to the laser – the production of gigantic fluxes of photons (no. of photons/cm^2/s).



The laser `projectile' -
`Pulse' the light to produce 'Peak' power

Peak power=

Pulse Energy / pulsing time

An Ultrashort laser pulse

For the same energy- the shorter the pulse, the larger the Peak power !

1 Joule in 1 sec = 1 Watt
1 Joule in 1 ps (10^{-12} sec)
= 1 Terawatt (10^{12} W)

Figure 2. The picture shows the leaps in intensity that can be achieved by short light pulses. Given the present advances in laser technology, we can produce intensities as large as 10^{22} W cm^{-2} [7]. These leaps in power have been produced by a revolutionary technology achieved in mid-1980s, discussed below. A typical Gaussian laser pulse of 100 fs duration is also shown.

How is this achieved? Nearly every child tries the experiment of focusing sunlight to burn a piece of paper and the end result usually leaves a lasting impression on the young mind about the impact of concentrated light. There is however a limit to the focusing of light, due to diffraction, determined by the wavelength [6]. The best one can do is to focus down to the order of the wavelength, but that calls for aberration-free optical components of a very short focal length and a good spatial profile of the beam being focused. In practice, this can give the best focused intensity of 10^7–10^8 W cm^{-2} for 1 W of input beam for visible light (500 nm). The key to further enhancement lies in focusing in time, thus producing pulses of light, as shown in figure 2. This enhances the power of the beam.

Today we routinely produce pulses as short as a few femtoseconds and the frontier has 'shrunk' to the attosecond (10^{-18} s) level. Obviously the peak powers accessed by the lasers have grown by many orders of magnitude.

2. Light–matter interaction: Some elementary ideas

What makes intense light so exciting? To understand this, let us see how light interacts with matter. The interaction of light with matter is crucially controlled by the electric field of the light source (as explained later). The electric field in the light wave E is related to the intensity of light as $I = (1/2)\varepsilon_0 c E^2$, where ε_0 is the permittivity of free space and c is the speed of light [8]. The larger the intensity, the higher is the electric field and at large light fluxes the electric fields can be gigantic. How does one get a feel for how gigantic they are? For this, let us look at a simple

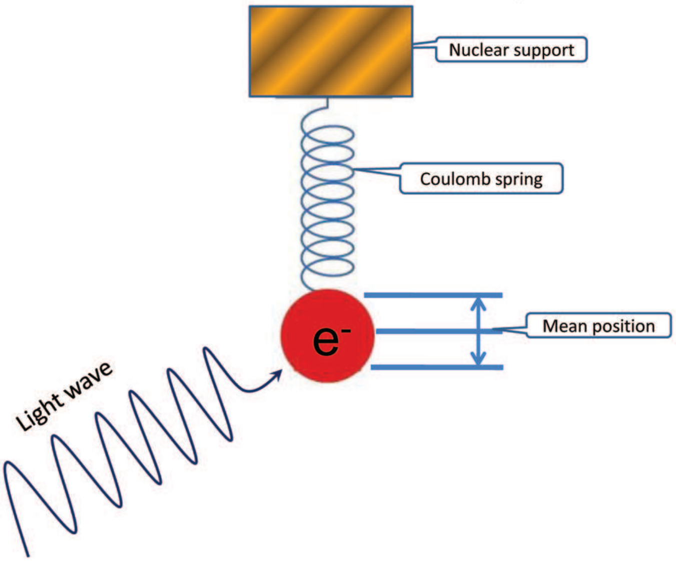


Figure 3. The spring-mass model of optics. L – Mean length of the spring.

but well accepted description of light–matter interaction. This simple description [9] relies on nothing more than what we can call one of the basic paradigms of physics – the spring-mass system.

Imagine the electron–nucleus system as shown in figure 3 (in 1D). The nucleus is much heavier than the electron and can be taken to be fixed when the interaction with light takes place. This is certainly valid for normal (low) light fluxes, particularly in the visible region ($\sim 10^{15}$ Hz). The 'spring' here is the Coulomb binding force between the nucleus and electron and the potential is given by $(Ze)e/L$, where Ze is the nuclear charge and e, the electronic charge.

3. Nonlinear optics (NLO)

If there is no light one does not look at the binding in terms of a spring as it is just a static system. When the light falls on the electron, the electric field of the light disturbs the electron from its equilibrium position. In technical terms this is understood as the induction of an oscillating dipole moment given by [8]

$$\vec{P} = \varepsilon_0 \chi \vec{E}, \tag{1}$$

where χ is the electric susceptibility of the nucleus–electron system and ε_0 is the permittivity of free space. If E is small (i.e. the electron is gently perturbed by the light wave) then this dipole moment is small and the linear description suggested by eq. (1), is adequate to describe the most normal optical phenomena. For instance Rayleigh scattering, reflection, refraction and dispersion that we encounter in day-to-day life, are all well explained in this manner.

As we know, the spring-mass system behaves very differently when the mass is subjected to large perturbation. The motion is then anharmonic and there arise many interesting nonlinear phenomena like harmonic generation, multiphoton absorption/ionization, self-phase modulation, to name a few. One can even drive the system into chaos.

Under large perturbation (E large) it was proposed [10] that the anharmonicity in the motion would lead to the following expression for the polarization:

$$\vec{P} = \varepsilon_0[\chi^1\vec{E} + \chi^2\vec{E}\vec{E} + \chi^3\vec{E}\vec{E}\vec{E} + \cdots]. \tag{2}$$

We now have higher-order terms in E, with the associated nonlinear susceptibilities χ^n. This interpretation of optics has been the harbinger of nonlinear optics; a subject that exploded on the scientific and technological scene soon after the laser was born, because only the laser could provide the electric fields required to produce measurable nonlinear components of P. $\chi^{(n)}$ are much smaller for $n > 1$ and $\chi^{(n)} \ll \chi^{(n-1)}$. This is the essence of the perturbation expansion used above. In the fifty years of NLO, we have of course found and engineered materials and conditions that produce nonlinearity at even ‘normal’ (low light) intensity [11].

4. Towards intense light fields

I now move on to the main subject of this article – the creation of ultrahigh intensities and the implications of such light for science and technology. These intensities owe their birth to a second revolution in light generation (the laser being the first) that took place in the mid-1980s. To understand this revolution let us use our knowledge of NLO. As we saw, boosting of peak intensities implies boosting peak power of laser pulses. The peak power is boosted by successive amplification of laser pulses in a set of light amplifiers. As peak powers go up, the larger electric fields give rise to nonlinear processes. One of the nonlinear processes discovered soon after the laser was born is self-focusing. This occurs because the refractive index of a medium gets modified by the light and a focusing nonlinear lens can be formed by the Gaussian transverse spatial profile of the propagating laser beam [9] inside the amplifiers, leading to such large intensity that the amplifying medium or other optical components break down. Peak power as we saw, is energy/pulse duration (and the shorter the pulse, the higher its peak power). Ultrashort pulses therefore, can barely be amplified before they reach the power that can be damaging. So it is really difficult to amplify pulses beyond a certain peak power.

Let us see how this was overcome. A look at the history of science tells us that many a time, insurmountable problems were solved by doing seemingly ‘opposite’ of the usual practice. A similar (‘inverse’) approach was used here. The recipe (as illustrated in figure 4) appears simple on hindsight – take an ultrashort pulse (say, for example of 100 fs duration), spoil (increase) its time duration by a large amount (typically by a factor of 10,000) and, thereby, reduce its peak power. This pulse with lower peak power is then amplified (energy increased by 6–9 orders of magnitude – usually a nanojoule pulse is amplified to energy in the mJ–J range) – and finally it is compressed back to its original ultrashort duration. This final pulse can now have orders of magnitude larger energy than the starting pulse (depending

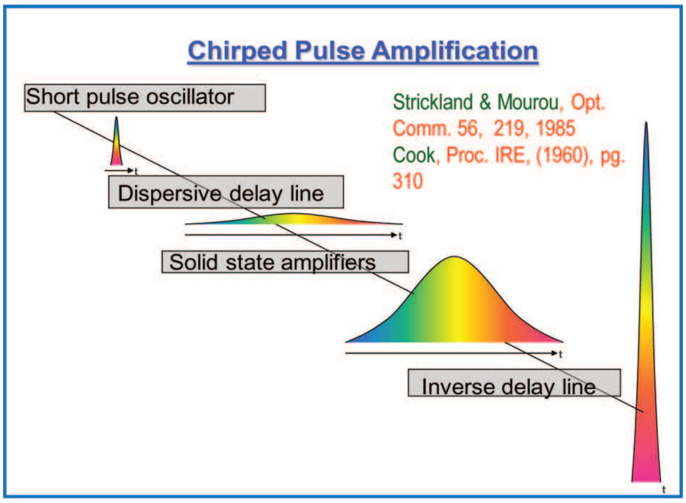


Figure 4. The principle of chirped pulse amplification (CPA).

on the amplification factor) and hence its peak power is boosted by the same orders of magnitude.

This idea (stretching and compression) was originally used in radar communication after World War II and was insightfully adapted by Mourou and Strickland [12,13] to cause a second revolution in light generation. The technique of stretching in time, amplification and compression is called chirped pulse amplification (CPA) – stretching causes the pulse to 'chirp', i.e. its frequency evolves as a function of time.

As you can see from figure 5, peak powers which were stranded till the 1980s at the GW level in most labs around the world, got boosted by a factor of 100–1000 (1000 GW = 1 TW) almost immediately. Today, the highest power available is at the petawatt (=1000 TW) level and these lasers use CPA [14]. Figure 6 shows the outline of a state-of-the-art 20 TW laser system at TIFR, Mumbai (the inset shows a real-life image of the set-up).

What is the electric field that is produced when such high peak power, ultrashort laser pulses are focused? For example, the highest peak intensity achieved recently is 10^{22} W/cm^2 [7]. The corresponding electric field is $\sim 10^{13}$ V/cm – a gigantic number. To get a true feeling for this number, let us again look at an electric field 'scale' provided by nature. As we saw above, the binding between the nucleus and electron in an atom provides a good scale. This field is $\sim 10^{10}$ V/cm. This implies that the highest intensity laser pulses can apply on the same electron an electric field that is 1000 times larger. Such excitation is extremely strong and was unheard of till these lasers came along.

There is another electric field (intensity) scale that is available. Recall the perturbation expansion (eq. (2)) which is valid only if successive terms become smaller. As it turns out [15], above 10^{12} W/cm^2, all the terms start becoming equal which implies that the perturbation approach is no more valid.

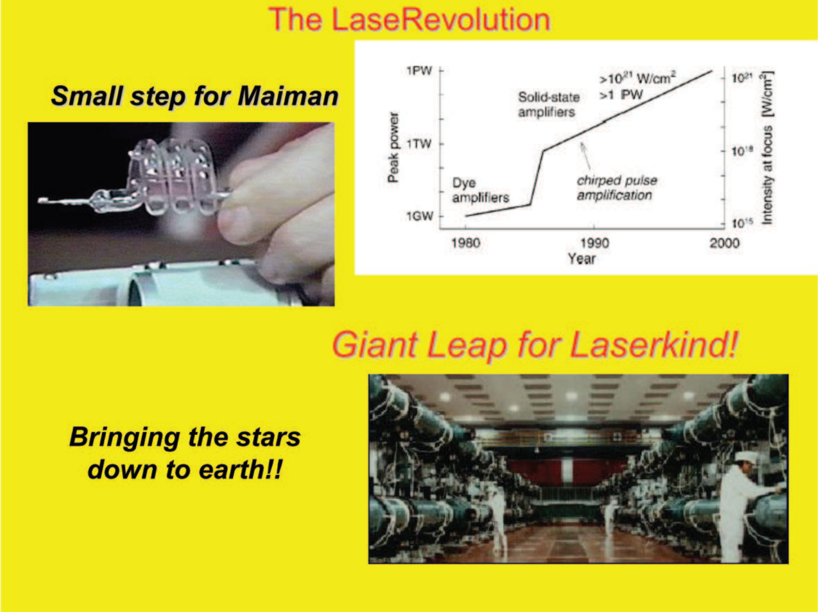


Figure 5. The first and one of the biggest! The top left is a picture of the first ever laser unveiled on May 16, 1960 by Theodore H Maiman at the Hughes Laboratories, USA, after a race that seemed as fictional as real life could get! (For fascinating accounts, please see the books 'The Laser Odyssey' by T H Maiman, Laser Press Publishers, 2002 (www.laserinventor.com) and 'How the Laser Happened' by C H Townes, Oxford University Press, USA, 1999) The bottom right shows one of the biggest laser facilities in the world, the 'GEKKO' laser at the Institute of Laser Engineering, Osaka, Japan. This pulsed laser system has 12 ns laser beams amounting to 2 kJ, and till recently, a petawatt (10^{15} W) laser of 600 fs duration. Fast ignition of laser fusion was achieved at this facility in 2001. Currently they are building a 10 kJ, 10 ps petawatt laser for the same purpose. The top right shows the shrinking of laser pulse duration and the corresponding increase in peak power, through the past five decades. The CPA revolution is marked out in the middle of the plot.

This gives us a nice definition of the strength of the light field. While nonlinear optics becomes possible for intensities that manifest measurable magnitude for the nonlinear terms, we enter a completely new regime above 10^{12} W/cm^2, where light starts to compete on an equal footing with the Coulomb field, overwhelming it as we cross 10^{16} W/cm^2 (the 'Coulomb intensity'). It is logical to expect that light will gain a much stronger (upper) hand in driving the electron above this value with the Coulomb field becoming a successively weaker perturbation – a remarkable turning of tables!

That sets the basic scale for intense light ($>10^{16}$ W/cm^2) interaction with matter. Light is the major driver for the electrons and electrons act essentially like 'free' particles.

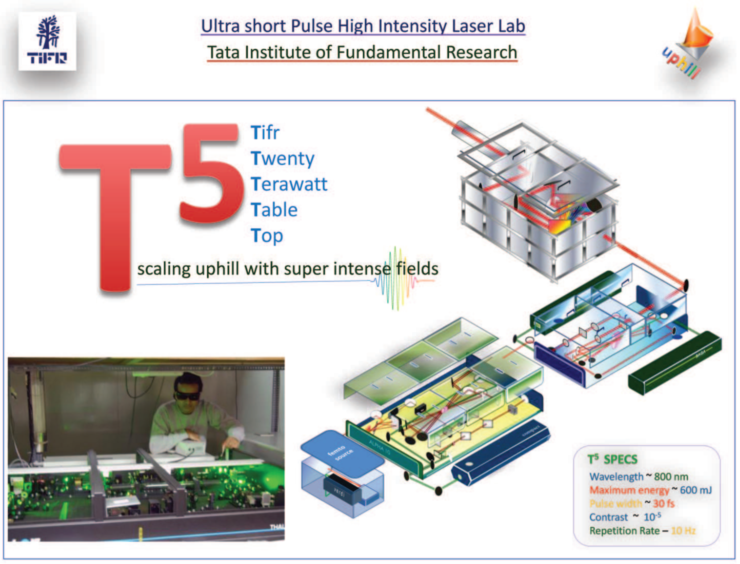


Figure 6. The 20 TW, 30 fs tabletop laser at Tata Institute of Fundamental Research (TIFR), Mumbai. Raja Ramanna Centre for Advanced Technology (RRCAT), Indore and Bhabha Atomic Research Centre (BARC), Mumbai also have similar custom-built systems (commercial as well as those developed in-house – a picture is shown later).

5. Matter in intense light fields

Since the CPA revolution in 1985–90 (a period curiously coincident with another barrier-breaking revolution in world history), our understanding of light–matter interaction has produced many novelties and surprises. It is neither possible nor proper to even list all these in the space of an article such as this. It is therefore prudent to look at some common features of such interaction [16] across all phases (single molecule, finite particle number gaseous clusters, micrometer-sized liquid droplets, macroscopic liquids and solids):

1. With such a powerful drive, matter is completely ionized (independent of light wavelength, dependent only on light intensity), on the rising edge of the light pulse.
2. The ‘freed’ electrons (ionized on the rising edge of the laser pulse) now absorb the energy from the remainder of the laser pulse.
    - It is possible to couple enormous amounts of energy to the electron released by ionization (let us call it the ‘ionized’ electron). For instance, a high intensity laser at a photon energy of 1 eV can transfer as much as a few MeV! i.e. the energy scales of the interaction are completely guided by the intensity of light – a very unusual feature (quite unlike the dependence on single particle energy, as in other interactions).

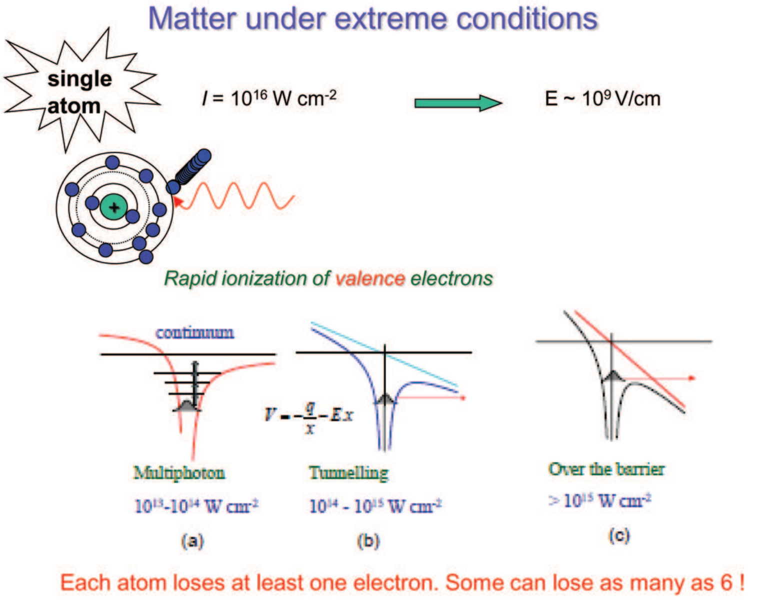


Figure 7. Inevitable ionization of a single atom by an intense light field. MPI, TI and OBI are shown.

A simple expression for the energy given to the electron by light, called ponderomotive (oscillatory) energy is given by

$$U_{\mathrm{p}} = \frac{e^2 E^2 \lambda^2}{m^2 c^2}. \tag{3}$$

3. The light pulse is almost impulsive in character. For very short (few femtosecond) pulses, this implies that except for the electronic response, all other motions in matter are 'frozen'!
4. The interaction is highly transient and equilibrium is not established.

The ionization process can take two independent routes or a mixture of both, depending on light intensity. For infrared light ($\sim$1 eV photon energy), below 10^{13} W/cm^2, the electron is ionized by a multiphoton process, where many photons act collectively to couple the required energy (multiphoton ionization, MPI, as illustrated in figure 7a). Above 10^{15} W/cm^2, the bound electrons find a way to leak out of a Coulomb barrier, now distorted by light, a process referred to as tunneling (or 'field') ionization (see figure 7c). In the intermediate regime, both processes can occur (as shown in figure 7b).

Two spectacular events occur in single atom interaction with intense light. The first is above threshold ionization (ATI) where an atom absorbs more photons than necessary for the ionization ladder; gets a light-induced 'appetite for light'! (refer to figure 8 for one of the earliest experimental observations of ATI) and high harmonic generation where coherent 'laser-like' emission occurs with output photons having $\sim 10^{2-3}$ times the energy of a single input photon [17,18].

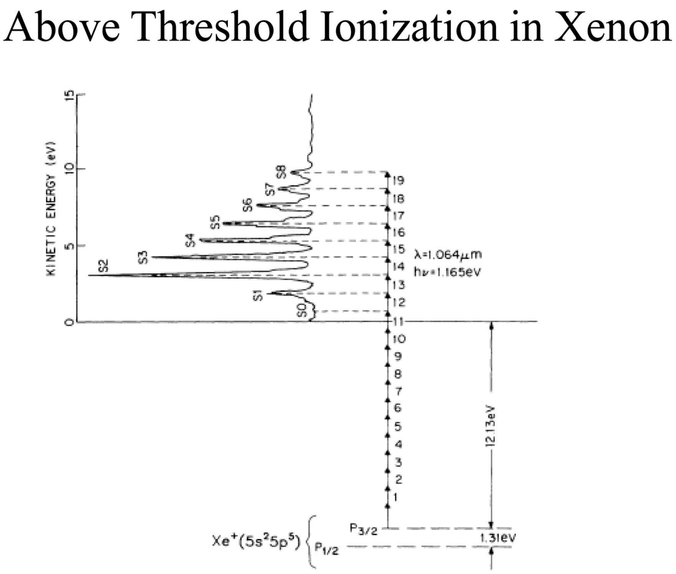
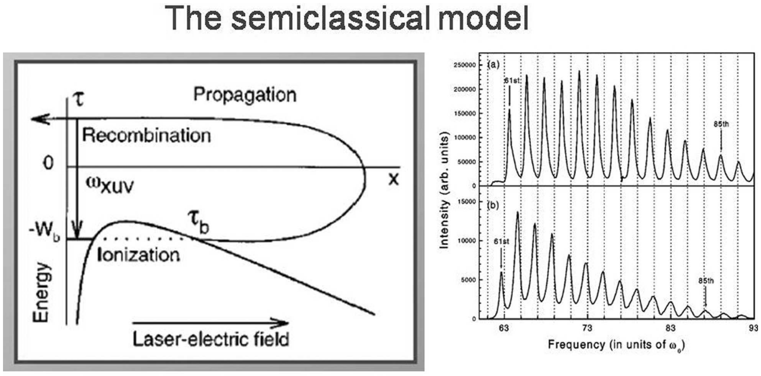


Figure 8. Light-induced appetite of a rare gas atom. Notice the quantized peaks in the energy of ionized electrons. Absorption of as many as eight photons beyond the ionization limit is indicated. The experiment was one of the early ones, with picosecond pulses at 10^{13} W cm^{-2} (reproduced with permission from ref. [19]).

The process of high harmonic generation is a phenomenon which is very powerful for applications, as it generates coherent X-rays starting from a 1 eV laser! This is now understood in a simple manner as the recombination of a highly excited electron with the core ion, as the electron repeatedly returns to the core during the cyclic oscillation by the light wave (modelled by Corkum *et al*, as illustrated in the left part of figure 9). In a gaseous medium, symmetry considerations enable emission of only odd harmonics and the maximum energy that can be emitted is given by $IE+3.2U_{\mathrm{p}}$, where IE is the ionization energy and U_{p} is the ponderomotive energy given by eq. (3) above. Harmonics with photon energy as large as 1 keV [20] have been produced with exciting photon energy of 1.5 eV in gas targets using femtosecond lasers at intensities of 10^{13}–10^{16} W cm^{-2}, with efficiencies in the range of 10^{-9}–10^{-7}. Figure 9 shows a typical HHG spectrum. Rare gases, molecular gases and plasma plumes have all been exploited as targets [21,22]. In a recent study, harmonics as gigantic as 3000 have been measured from a solid surface at 'relativistic intensities' of 10^{19} W cm^{-2} (see below) with efficiencies as large as 10^{-4} but the physics is quite different in this case [23].

In molecular physics, above threshold dissociation (ATD) – an analog of ATI, bond-softening, bond-hardening, molecular orientation and reorientation and enhanced ionization were all duly discovered in the last 20 years [27]. TIFR has contributed extensively to these studies, as pointed out later in the article.

The semiclassical model



Model due to Corkum[24], Krause[25] and L'Huillier[26]. Data on the right are From Shin et al., in ref. 26.

Figure 9. Understanding high harmonic generation (figure on the right is reproduced with permission).

6. Dense matter in intense laser fields

We now wish to look at a complex physical process, namely the interaction of intense light with dense matter (solid, liquid, and gaseous clusters). This, in my opinion, has thrown up the most amazing possibilities in terms of science and technology.

First, let us consider some basics. High density ensures stronger interaction because light can now drive electrons not only on its own, but can also use the driven electrons to efficiently cause other excitations in the medium. These 'other' excitations can be at the individual particle level or at the collective level. This implies much larger transfer of energy leading to higher ionization and excitation levels. And since the excitation happens on femtosecond time-scales, the ions in the target are basically frozen in their places, no motion occurs and density remains the same. This leads to high energy density in the matter in a 'macroscopic' volume of matter as we will discuss a little later.

The collective kind of excitations has led to fascinating consequences. What are these? A flowchart of the sequence of events in the formation of plasma is given in figure 10. We are all familiar with collective excitations in condensed matter – for example, lattice vibrations or phonons. In the dense plasma generated by an intense ultrashort laser there is a similar mode of excitation – a collective electron oscillation called plasmon (plasmons are also excitable in the electron sea in metals and in general in other plasmas). The plasmon is one of the most effective channels of coupling laser light into the plasma. It also plays a crucial role in the dramatic advances made in intense laser driven electron acceleration (discussed later).

The plasma as it is formed, simultaneously starts to expand and at any instant, the density of electrons falls off exponentially towards the vacuum. The later parts of the light pulse penetrate only up to a density called 'critical layer' [28]. Figure 11 explains some of the essential parameters involved in the process.

It is at this critical layer that the plasma waves (plasmons) are excited as explained below. The region lower in density than the critical layer (left) is called

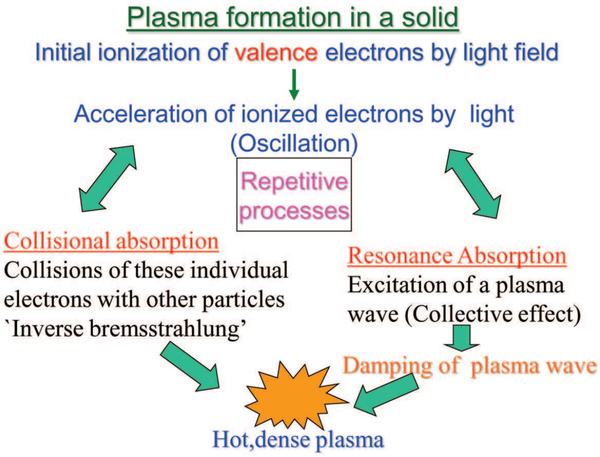


Figure 10. Consider the generic situation of a high intensity femtosecond laser hitting a target (see figure 11), in this case a solid in a neighbouring vacuum. The flowchart above indicates the sequence of events involved. At the end of the interaction a solid density, hot plasma is formed.

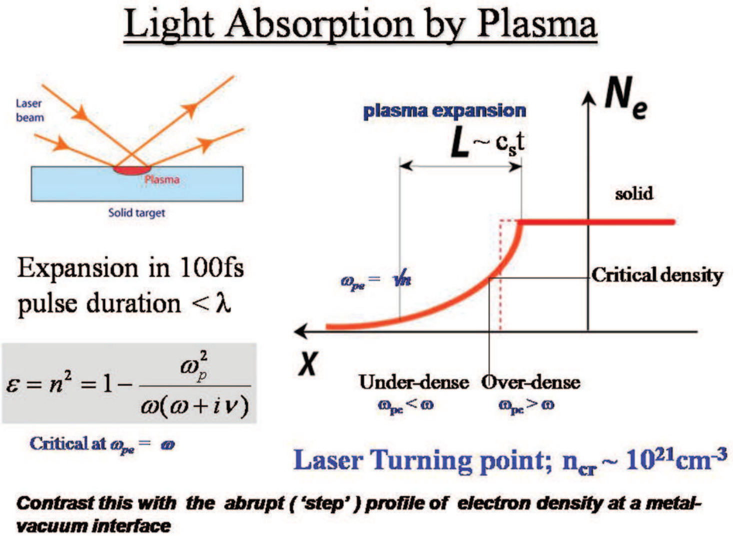


Figure 11. An intense laser pulse hits a solid target. The plasma acquires a profile that expands with time. C_{s} is the speed of sound and L is the plasma 'scale' length. The density for the turning point indicated in the figure is for 1 micron radiation

'underdense', the region at higher density is called 'overdense' (right). It is important to keep in mind that light can propagate only in underdense plasma. To get a little more technical, the optics of the plasma can be understood by its dielectric function

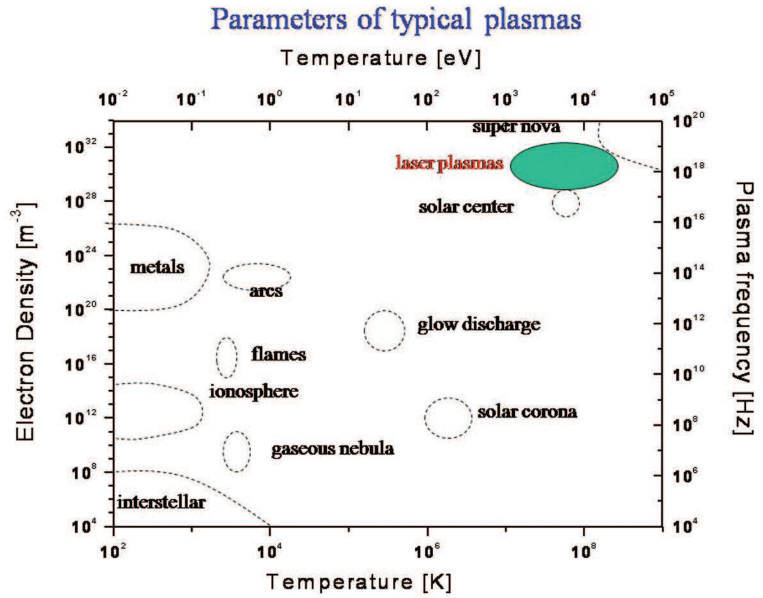


Figure 12. The thin and thick of plasmas in the Universe and the way they blow hot and cold! (for example, see ref. [30]). Please see the position occupied by laser plasmas.

$$\varepsilon = n^2 = 1\frac{\omega_{\mathrm{p}}^2}{\omega(\omega + i\nu)}, \tag{4}$$

where $\omega_{\mathrm{p}} = (4\pi N e^2)/m_{\mathrm{e}}$ is the plasma characteristic oscillation (resonance) frequency, ω is the incident laser frequency, ν is the damping (by electron–ion collisions) frequency, N is the electron density in plasma, m_{e} is the electron mass, e is the electronic charge and n, the refractive index of the plasma.

It is then clear that the plasma allows propagation of only those frequencies ω for which n^2 is positive (negative values make n imaginary and such a light wave is attenuated). An important observation that we should keep in mind is that ω_{p} varies as $(N/m)^{1/2}$ – the denser the plasma, the higher the ω_{p}. Similarly, if the mass of the electron changes for any reason, ω_{p} will change.

As the laser energy is soaked up and the plasma wave grows, the damping processes would attenuate the wave and the energy is transferred to the plasma electrons. If the wave amplitude exceeds a certain threshold, the plasma wave abruptly crashes (a 'tsunami' in the plasma!) again releasing all the energy to the plasma electrons [29]. Both these processes preferentially energize some (a group) of the plasma electrons which are known as 'hot' electrons. If the bulk of the plasma electrons (at large) have a temperature T_{c} (say 100 eV) the hot electrons can have temperatures which are 100–1000 times larger! Let us remind ourselves that this is due to the drive provided by the intense laser wave.

Let us now turn to the physics of such extremely dense, highly excited systems which host these relativistic electrons. Basically, we would like to examine how these electrons propagate through the dense, hot matter, how they transfer their energy to the rest of the plasma or radiate out that energy. We do this by looking at several sub-topics listed below. We will also examine some phenomena in our survey of the Indian scene a few pages later.

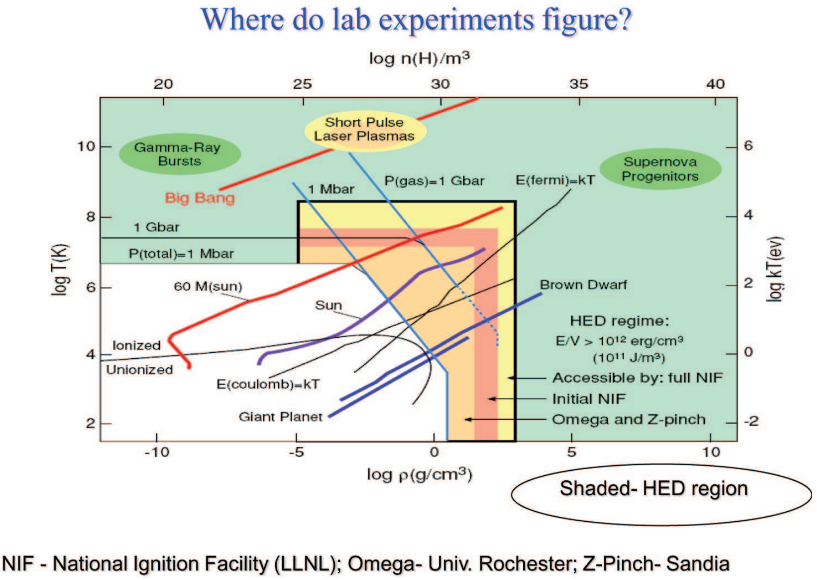
6.1 *High energy density physics*

It is now a matter of common knowledge that our Universe houses not just enormous, incredible amount of energy but stores it at remarkably high density. Beginning science students learn about the birth, growth and death of a star (at least at a popular or semi-popular level). Astrophysicists have theorized about the violent, high energy density environment for a long time and built many models for explaining various phenomena. Obviously these have to be motivated by astronomical measurements which have also leap-frogged in sophistication over the past few decades. The biggest challenge in astronomy, unlike in many other branches of science however, is the total dependence on observation as it occurs (controlled by natural events) rather than measuring the response to a pre-chosen stimulus. Astronomers have to take light as it comes, in a manner of speaking. Figure 12 summarizes parameters of plasma, yet known, in the Universe. Figure 12 also shows the plasma of astrophysical interest as well as laser-produced plasma. Figure 13 shows the expanding domain of laboratory high density physics approaching the experimental parameters of relevance to astrophysics.

6.1.1 *Laboratory astrophysics.* All this seems set to change in the near future. Short and ultrashort, ultrahigh intensity lasers can now access pressure, temperature and density conditions similar to those encountered in intra-stellar matter and the laser experiments can do it at the physicist's will, repeatedly and reproducibly. This 'astrophysics on a tabletop' is very different from the 'take it as it comes' feature of astrophysics prevalent till now. The regimes accessible are indicated below [31].

The levels of ionization and temperature created by UIL enable the simulation of intra-stellar and intra-planetary matter. Some of the problems that are being studied include the opacity of stellar matter [32], routes to phase transitions, synthesis of forms of matter possible only at high temperature that is simultaneous with high pressure, elemental synthesis, obtaining the equation of state (EOS) and the response of matter to extreme shocks [33]. These exemplify perhaps the 'classical' problems of astrophysics. But laser experiments have gone much further to simulate even exotic astrophysical phenomena. One example is that of the gamma ray burst (GRB). A GRB is an intense millisecond-hundreds of second flash of gamma radiation, containing 10^{50}–10^{51} erg of energy, a million to trillion times brighter than the Sun and hundreds of times brighter than a supernova. GRBs have fascinated astronomers for decades now, are found to occur at an average of one per day and their origin is a hotly debated topic.

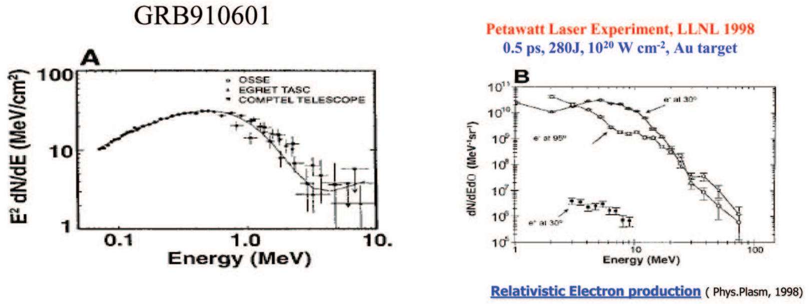
An experiment with a petawatt laser focused to 10^{20} W/cm^2 has produced a gamma ray spectrum [34] that very closely mimics that of a GRB indicating that very similar conditions are created. Figure 14 shows a typical GRB contrasted with laser-produced burst with similar physical features on laboratory scale.



Where do lab experiments figure?

NIF - National Ignition Facility (LLNL); Omega- Univ. Rochester; Z-Pinch- Sandia

Figure 13. The (expanding) domain of laboratory high energy density physics (reproduced from ref. [31]).



GRB910601

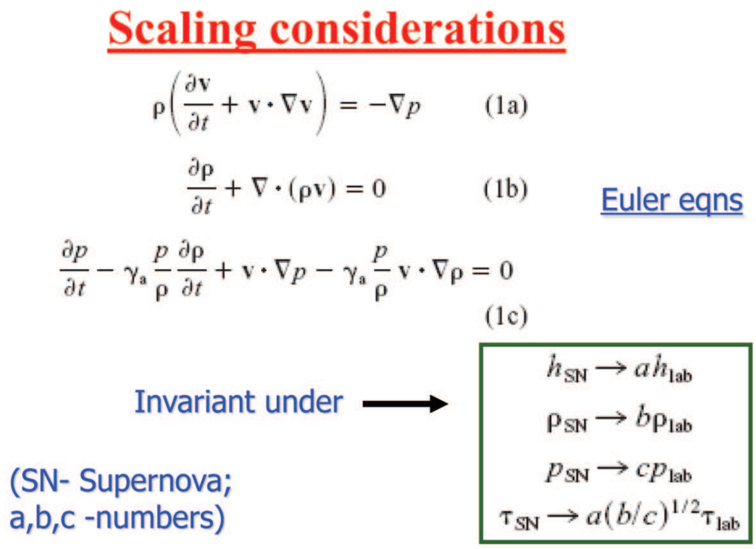
Petawatt Laser Experiment, LLNL 1998

0.5 ps, 280J, 10^{20} W cm^{-2}, Au target

Relativistic Electron production (Phys.Plasm, 1998)

Figure 14. A GRB from the heavens (left) and one from the lab? (right) (reproduced with permission).

As we move on, more and more similarities are likely to be established. The basis for this is obviously rooted in the invariance of the hydrodynamic equations so that the astrophysical quantities can be mapped to those on the laboratory scale with this insight [35]. Figure 15 shows some of the scaling formulae used in lab-astrophysics experiments. Experiments on radiative jets and supernova explosion shocks have been performed in the last few years. Many more experiments are underway [36]. These are likely to get a major push with the commissioning of the National Ignition Facility (NIF) in the USA this year.



Scaling considerations

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p \qquad (1a)$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0 \qquad (1b)$$

Euler eqns

$$\frac{\partial p}{\partial t} - \gamma_a \frac{p}{\rho}\frac{\partial \rho}{\partial t} + \mathbf{v}\cdot\nabla p - \gamma_a \frac{p}{\rho}\mathbf{v}\cdot\nabla\rho = 0 \qquad (1c)$$

Invariant under →

$h_{\mathrm{SN}} \rightarrow a h_{\mathrm{lab}}$

$\rho_{\mathrm{SN}} \rightarrow b \rho_{\mathrm{lab}}$

$p_{\mathrm{SN}} \rightarrow c p_{\mathrm{lab}}$

$\tau_{\mathrm{SN}} \rightarrow a(b/c)^{1/2}\tau_{\mathrm{lab}}$

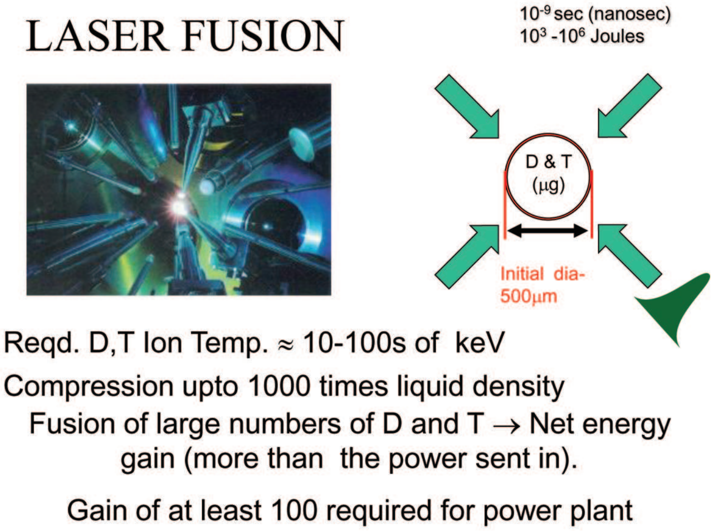
(SN- Supernova;
a,b,c -numbers)

Figure 15. Scaling down of astrophysical experiments to the lab.

6.1.2 *Laser fusion* (*inertial confinement fusion*). Another example of HEDP – one of potential importance for a greener globe, is that of laser-induced (or 'inertial') fusion. This is an idea that fascinated us for long and the world continues to invest enormous amounts of money and effort in this area.

In the general laser fusion scenario (refer to figure 16), multiple laser beams (nanosecond duration) impinge simultaneously on a 10^{2-3} micron scale fusion capsule containing deuterium and tritium. The capsule gets compressed by a factor of 100–1000 and gets heated to a temperature of 10^{7-8} K enabling fusion beyond the break-even limit [37]. The laser beams are expected to irradiate the target with a high level of symmetry. This scheme of generating power has not been realized till now due to the complex plasma physics involved, particularly instabilities in the plasma. Besides, the compression and heating are rather slow, resulting in the 'waste' of laser energy by some hot electrons (as we discussed above) at the surface. These hot electrons stream into the colder, unheated target creating a mixed phase and preventing compression. So, hot electrons are the villains of this scheme. If we have to achieve viable fusion energy by this method, we would need enormous amounts of laser energy – at the megajoule level!

In 1994, a very clever scheme was suggested [38], wherein the roles of compression and heating are separated and achieved by different sets of lasers. As schematically shown in figures 16 and 17, the long pulse lasers are just used to compress and do not have to be extremely powerful. At the instant of maximum compression, a picosecond pulse of a reasonable amount of energy (though much smaller than the energy of a long pulse used for compression) strikes the compressed pellet surface and generates hot (relativistic) electrons. These electrons stream into the compressed pellet, striking a spark of ignition and enabling efficient fusion. This concept is elaborated in detail in figure 17.



LASER FUSION

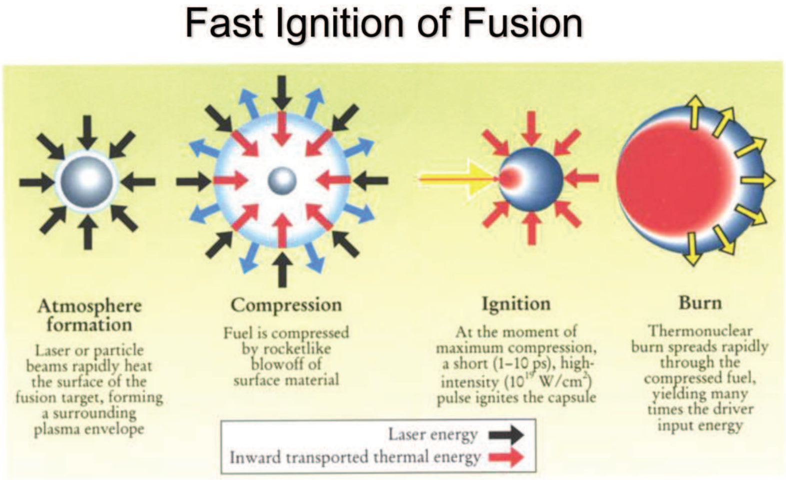
Reqd. D,T Ion Temp. ≈ 10-100s of keV

Compression upto 1000 times liquid density

Fusion of large numbers of D and T → Net energy gain (more than the power sent in).

Gain of at least 100 required for power plant

Figure 16. The laser fusion scenario.



Fast Ignition of Fusion

Atmosphere formation

Laser or particle beams rapidly heat the surface of the fusion target, forming a surrounding plasma envelope

Compression

Fuel is compressed by rocketlike blowoff of surface material

Ignition

At the moment of maximum compression, a short (1–10 ps), high-intensity (10^{19} W/cm^2) pulse ignites the capsule

Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy

Figure 17. The fast ignition principle of laser fusion.

The crucial symmetry requirement of compression is relaxed in this scheme. Since the ignition is done by a current of fast electrons, this scheme is known as ‘fast ignition’ (FI) of laser fusion. The most important simplification offered by FI is the lifting of the severe restriction on symmetry of implosion in the compression of the pellet. The 10 ps duration ignition pulse is expected to have 10 kJ energy. This scheme has been demonstrated in principle [39,40] and is being vigorously explored with the construction of new petawatt, picosecond lasers in Japan, USA, Europe and China.

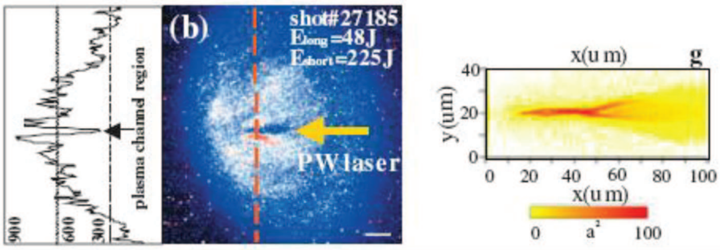


Figure 18. Relativistic laser hole boring and channeling by a petawatt scale laser pulse through an overdense plasma. Left: experiment. Right: 3D-PIC simulation. For details, see Lei *et al*, *Phys. Rev.* **E76**, 066403 (2007) (reproduced with permission).

This is a classic example of a ‘villain’ of one generation becoming the ‘hero’ of a later one!

6.2 *Relativistic nonlinear optics* [41]

We began this article by discussing nonlinear optics (NLO) which was described as the optics related to or caused by strong light fields. As light intensities go up, NLO itself changes dramatically. Since visible optics depends essentially on the response of electrons, any change of the state of electrons is obviously expected to affect the propagation of light through the medium. As high intensity light accelerates electrons to relativistic energies, electrons become more massive and their response becomes sluggish. We may recall the expression for the dielectric function ε and the demarcation of the transparent and opaque regions of the plasma, given by the plasma frequency. Now, the plasma frequency itself reduces as the electrons become relativistic and more massive, thus making an opaque region transparent! This is a perfect illustration of how optical properties of a medium can be changed profoundly by light propagation. Some of the very interesting (and spectacular) relativistic NLO effect include self-focusing of light (where the medium acts like a lens), self-channelling (where the relativistically intense pulse propagates long distances through a medium), hole-boring (where a light pulse pushes the electrons away from its path and ploughs its way through the plasma) and transparency (discussed above). Figure 18 shows observations of laser hole-boring and channelling in experiments as well as in 3D PIC simulation. Though self-focusing and self-channelling occur at sub-relativistic intensities by other mechanisms, their occurrence above the relativistic limit is more exciting in its characteristics. This limit can be simply estimated as that at which the electron kinetic energy (given by the oscillating light field) becomes comparable to its rest mass energy ($\sim$0.5 MeV). It can be seen that this intensity turns out to be 10^{18} W/cm^2 for a light of wavelength 1 μm. Even more interesting phenomena include soliton formation where the natural diffractive spread of light is balanced by the self-focusing leading to spatial modes robust against propagation.

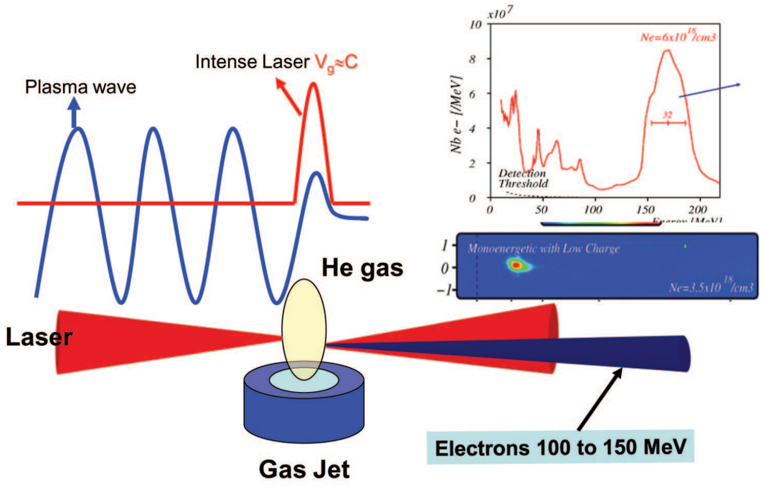


Figure 19. Laser wakefield acceleration of electrons [42]. Schematic and (top right inset) experimental observations (reproduced with permission).

6.3 *Laser wake field acceleration (LWFA)*

A specific and powerful aspect of relativistic NLO that has exploded on the intense laser scene over the past decade is the phenomenon of wake field acceleration of electrons. Conventional accelerators (e.g. radiofrequency LINACs) provide an acceleration gradient of 20 MV/m, while LWFA can provide 200 GV/m! Figure 19 shows the schematic and (top right inset) experimental observation of LWFA. The basic idea of LWFA is as follows: electrons are displaced by an intense laser pulse in time periods that are short compared to an ion oscillation period. So for such an interaction, the ions remain static (due to inertia) and the resulting charge separation gives an electrostatic force that sets up electron plasma oscillations at the plasma frequency (ω_{p}) after the propagation of the laser pulse through a region. This creates alternating regions of net positive and negative charge. The resulting electrostatic 'wake field' plasma wave propagates at a phase velocity near that of light. For appropriately phased electrons, the acceleration can be continuous leading to very high energies. Latest advances have achieved highly monoenergetic electron pulses of energies approaching a GeV in a gas jet plasma, where the densities are $\sim 10^{18}/\mathrm{cm}^3$.

6.4 *Ion acceleration, attosecond pulse generation and other exciting developments*

Before moving on, it is imperative to capture at least passing impressions of many other exciting developments. We have seen electron acceleration above. The fast electrons eventually transfer their energies to the ions in the plasma, producing fast ions. Protons of tens of MeV and heavy ions such as Pb have been produced in charge states as high as 45+ and energies of ∼0.5 GeV. Their energy monochromation, spatial collimation and beam guiding are all being investigated very actively [43,44].

Soon after high harmonic generation was achieved in gases at moderate intensities, it was realized that the harmonics would be produced in attosecond bursts [45]. The generation, characterization and use of such extremely short duration pulses have provoked a great deal of enthusiasm across scientific disciplines due to the boundless possibilities that they open up. Attosecond pulses may soon enable us to capture electronic motion inside atoms, molecules and condensed matter in real time, enabling nanoscopy simultaneous with attosecond time resolution, a feat that would be unmatched in scientific history! Recently, relativistic intensity laser interaction with solid surfaces has thrown up additional possibilities for the generation of attosecond bursts of light [46]. It is but fitting that one kind of extreme light (ultrahigh intensity) produces another kind of extreme (super-short pulses) [41].

7. Intense laser–matter interaction: Challenges in modeling

The phenomena described above are fascinating but they also pose many challenges in modeling. As we know, a good model in physics is typically (a) perturbative and (b) as simple as possible. Given the huge electric fields at high intensities the first is simply impossible to meet. And the second is very difficult given the large density of matter and the extreme conditions in some of these systems.

Looking back at the history of the theoretical efforts in this area, we notice that there were very early analytical efforts to describe a single electron interaction with an intense laser field [47,48].

The states occupied by an electron in such a field are ‘Volkov’ states [48].

$$\Psi(\vec{r},t) = \exp\left[-i\left\{\left\{\frac{p^2}{2m}+\frac{e^2A_0^2}{mc^2}\right\}t-(\vec{r}-\vec{r}_{\mathrm{c}}(t))\cdot\vec{p} + \left(\frac{e^2A_0^2}{8m\omega_{\mathrm{c}}^2}\right)\sin(2\omega t)\right\}/\hbar\right], \tag{5}$$

where p is the momentum of the electron, m its mass, r and r_{c} are the position vectors, A_0 the vector potential of the light field and ω its oscillation frequency. Note that the A_0^2 term is the ponderomotive (oscillation) energy we discussed earlier. An interesting and somewhat amusing turn in the modeling is that the Coulomb binding field is treated as a perturbation on the ‘electron+light’ system represented by the above state, as it is much weaker than the electric field in the light wave!

A successful and perhaps the most appropriate method has been numerical solution. This has been used to solve the Schrödinger equation for an atom with a ‘single active electron’ in a one-dimensional approximation. The computing power becomes too demanding or inaccessible for more than one electron and/or for more than one dimension. Some of these difficulties also join the list of justifications for more powerful next generation supercomputers!

In the dense plasma case [49,50], computer simulations have been a very well-established method for understanding the complex physical properties of the system. These have received a further boost by the intense experimental activity in the femtosecond regime. Specifically, the particle-in-cell (PIC) simulation has emerged as a worthy colleague of the older, well-established hydrodynamic simulation. Once again these simulations are often done in one dimension, with the computational demands increasing by orders of magnitude for two and three dimensions, necessarily imposing restrictions on the spread of spatial and temporal coordinates, as well as the number of particles per cell and cell size.

What is extremely gratifying and at times quite amazing, is the progress stimulated by all these theoretical and computational attempts and their contribution to the explosive growth of research in this field.

8. Intense light – Applications in science and technology

Intense, ultrashort lasers have direct and indirect applications in different branches of science and cutting edge technology, a few of which have been discussed above. Here we take a look at a few more exciting examples. Before we get to the specifics, let us note that the indirect applications are all based on the ability of an intense, ultrashort laser to serve as a one-stop, tabletop source of femtosecond duration electron, proton, ion, X-ray, gamma ray, neutron and even positron pulses, in the form of well-collimated beams of high brilliance. It is really astounding that a source of photons each with energy of 1–2 eV can unleash such a variety of applications at a scale producing particles with individual energy that is 10^2–10^6 times that of the input photon energy!

The broad range of applications includes X-ray microscopy, X-ray imaging, micro- and nano-analysis of materials, X-ray and electron diffraction, proton deflectometry in plasmas etc.

I present one application in science, and two in technology that could potentially save human lives.

8.1 *Scientific application – Ultrafast real-time diffraction to see atomic motion inside crystals 'as it happens'*

Watching motion inside matter as it happens gives us a real-time view of the dynamics occurring on femtosecond and picosecond time-scales. We know that watching the 'molecular dance' in the late eighties gave Ahmed Zewail the Nobel Prize in chemistry [51] apart from actualizing a variety of possibilities in molecular dynamics. The molecular dance is of course easily amenable to study due to the spectacular development of ultrashort, visible and infrared lasers over the past few decades. The observation of atomic motion inside solids awaited similar developments in the X-ray region, as the only sources available till recently were the synchrotrons, which produced somewhat longer pulses than required. With the advent of intense, ultrashort laser-driven laser, femtosecond X-ray resources, there has been a revolution of real-time study of dynamics in crystals.

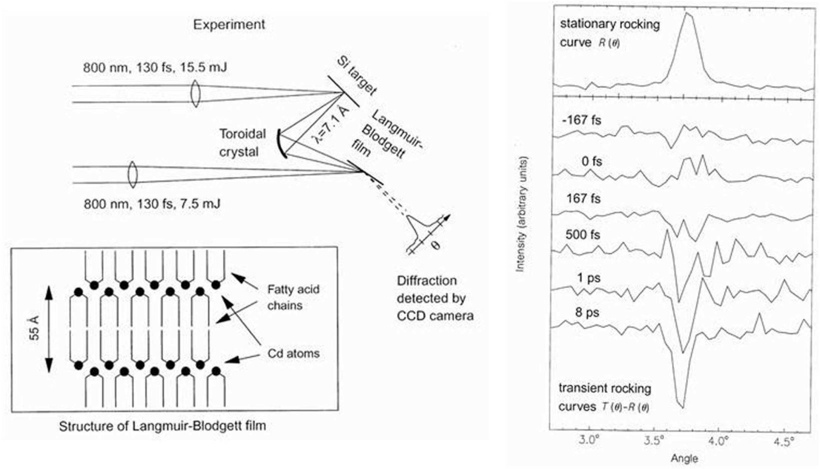


Figure 20. Real-time observation of an ultrafast laser-driven heat wave in a Langmuir–Blodgett organic lattice (refer to C Rischel *et al*, *Nature* **390**, 490 (1997), reproduced with permission).

The basic recipe is as follows: the best way to watch crystal motion is the time-resolved X-ray diffraction. This is usually done with the 'start' or pumping given by an intense laser pulse and the probing of the evolving crystal structure by an X-ray pulse generated by a part of the same laser pulse. This has enabled some remarkable observations of intra-crystal rearrangements, 'non-thermal' melting, ultrafast transformation between insulating and conducting states etc. Figure 20 presents the first ever study done in 1997 on a femtosecond scale with a laser-produced ultrashort X-ray source. In this experiment, a Langmuir–Blodgett film is exposed to a powerful femtosecond laser pulse that heats the lattice and a femtosecond X-ray pulse generated by a part of the same laser pulse is focused by a silicon crystal on the irradiated spot. The X-ray diffraction pattern 'snapshot' is obtained for a number of delays between the pump and probe pulses and the evolution of crystal structure is obtained by actual observation [52]. Figure 20 shows one of the first reports on the real-time observation of an ultrafast laser-driven heat wave in an organic lattice, using an ultrafast laser-produced femtosecond X-ray source.

Note that apart from X-ray pulses, intense laser-generated electron, ion and neutron pulses can also be used for real-time diffraction/scattering studies. Some of the pioneering ultrafast electron diffraction studies are being done by the Zewail group [53].

8.2 *Control of lightning*

The extensive damage caused by lightning in various parts of the globe has concerned us for a long time and, recently, efforts have been made to control this natural process. The idea is to use an intense, ultrashort laser pulse to pre-ionize a column of air to serve as a safe conduit for the lightning current. Lab-scale efforts have simulated the control over tens of metres and field trials are underway in the USA and Japan. It is hoped that we will soon be able to implement technologies that will potentially save human lives. This research is obviously benefiting from the enormous amount of effort being done to understand intense light propagation through underdense plasmas resembling the one created in the Earth's atmosphere [54]. A related spin-off has also been the extension of LIDAR (light detection and ranging) with the supercontinuum generated by the femtosecond pulse itself [55]!

8.3 *Cancer therapy*

As we have seen, the hard radiation (both photon and charged particle) generated by intense lasers is very useful for imaging of solids by diffraction or absorption or scattering. This possibility has opened applications in biological imaging as well as medical therapies. If one were to pick one important example, it would be proton therapy for cancer. It turns out that unlike other radiations, protons have the capacity to deposit the energy deep in the body, minimizing exposure to tissues on the way. This has led to a surge in efforts to optimize proton energy and flux for treating malignant tissue. Figure 21 shows the possibilities in this direction [56].

9. The Indian scene

The laser revolution began in India soon after its birth in the USA, spearheaded by IIT Kanpur and BARC. In 1963, the first laser was fabricated and the country's well-established spectroscopic tradition began to flourish further with this new tool. Laser development and applications began to be pursued simultaneously. In the 1980s the National Laser Programme was started by the Department of Science and Technology to promote research and education in this area. High power laser applications began to be investigated at IIT Kanpur and in DAE (BARC and later RRCAT) with laser ablation, multiphoton ionization, shock wave studies, X-ray emission from laser-produced plasmas etc., all using long (picosecond–nanosecond duration) pulses. High power laser development and applications also began to be pursued by DRDO. Somewhat in parallel, excellent theoretical strides in quantum optics and lasers began at the University of Hyderabad, BARC, IACS Calcutta and a few other institutions and universities. Courses leading to the award of degrees in lasers, optics and related areas were also started. A survey of development of Indian capabilities is given in [57,58]. To consolidate this activity and boost it further, the Laser and Spectroscopy Society of India and the Indian Laser Association were formed by the researchers. The National Laser Symposium has been a regular annual feature for more than two decades.

In the 1990s, groups at TIFR, RRCAT and BARC started serious pursuit of experiments on the behaviour of matter at very high laser intensities, while theorists at IACS, Kolkata, Punjab University and BARC began probing interesting theoretical directions. Figure 22 shows a standard experimental set-up for the study of laser interactions with liquid droplet target. Today we have robust programmes

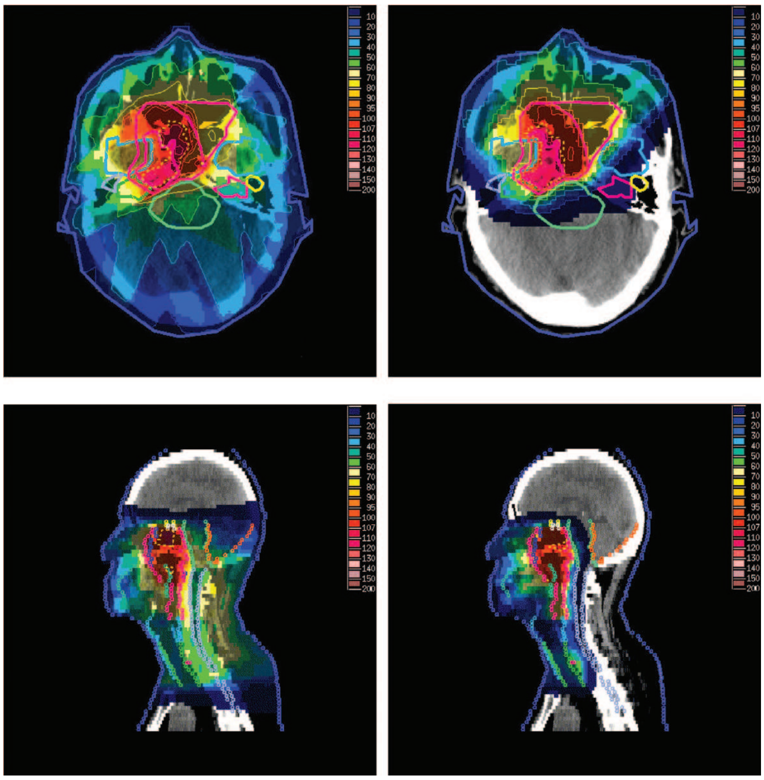


Figure 21. Conventional intensity-modulated radiotherapy (IIRI) of nasopharyngeal carcinoma as compared to proton therapy (IMPT). The individual and mean values for conformity index were always better in the IMPT (refer to Z Taheri-Kadkhoda *et al*, Radiation Oncology 2008, 3:4 doi:10.1186/1748-717X-3-4) (free reproduction allowed). Recently, laser-driven proton source has been used successfully for such diagnostics (ref. [56]).

in these areas and we hope these will grow further in the future. For reasons of brevity and my limited perspective, I present just a few highlights a little later.

Theoretical efforts on intense laser plasma interaction studies have progressed mainly at IPR, Ahmedabad, IIT Delhi and BARC. IPR (and earlier, PRL, Ahmedabad) has pioneered many studies on the basic physics of interaction, soliton propagation, energy transport and instabilities over a wide domain of plasma parameters. IIT Delhi on the other hand emphasized the propagation of intense light pulses through underdense and dense plasmas and of late also probed the behaviour of gaseous clusters in intense laser fields. The results of these studies have not only pushed the experiments of the Indian groups further but also set the benchmarks for experiments done all over the world.

I will now list some examples from the Indian research, again with sincere apologies for the many omissions, given the constraints of space. I am restricting myself to only those examples from dense matter in intense laser fields. I must add here

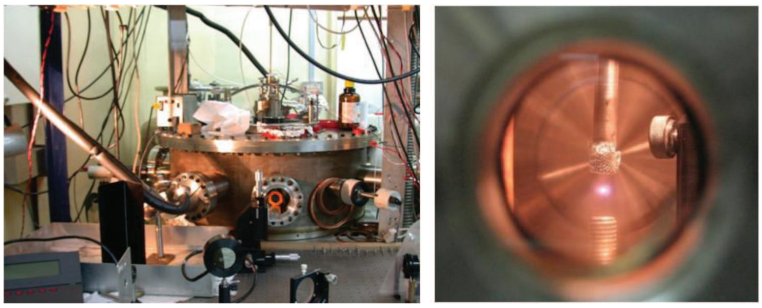


Figure 22. Left: An ultrahigh vacuum chamber at TIFR for doing experiments with microdroplets. Right: 20 μm methanol droplet plasma sparked off by an intense, femtosecond laser pulse blazes away in all its glory. The typical diagnostics employed in the TIFR labs include X-ray emission, ion and electron spectra, and laser light reflected or scattered by the plasma. The dynamics are studied on femtosecond time-scale and plasma properties are spatially resolved on micrometre scale.

that TIFR began its experimental explorations in the early 1990s with studies on molecules and later expanded to include clusters and solids in its activities. Some of the early work on molecules can be seen in refs [59–64]. Some of the lower intensity work in dense media at TIFR (mainly on intense light propagation, supercontinuum generation and generation of few cycle pulses) can be seen in refs [65,66].

In the last decade, two major facilities have been set up at RRCAT and TIFR for the generation of femtosecond, relativistic intensity light fields, while BARC has made considerable progress in setting up its own. Much progress has been made at TIFR and RRCAT on understanding basic physics issues like light coupling to the plasma and its control, energy sharing among particles, particle acceleration and energy transport. I take only a few experimental science examples from the results obtained by these groups while the theoretical results summarized are from IPR, IIT Delhi and BARC. I should hasten to add that the websites listed at the end of the article give the complete information about the activities of each group. I have not tried to include highlights of every activity of each group, but just chosen a few major forays each has made. For the sake of completeness, let me add that all the groups have interest in and made contributions to many of the themes mentioned below.

Let me begin with the experimental work.

9.1 *X-ray emission and particle acceleration* (*highlighting mainly work at RRCAT, Indore*) [67,68]

The Laser Plasma Division at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore has been engaged in research and development activities on laser plasma interaction using a 10 TW, 45 fs, Ti:sapphire laser and a variety of diagnostic systems developed in-house for ultrashort laser pulses, plasma and X-ray radiation. Their recent studies include laser wakefield electron acceleration,

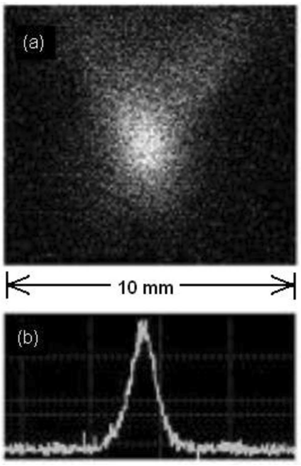


Figure 23. (**a**) Electron beam image recorded on DZ phosphor, (**b**) spatial profile (figure provided by P D Gupta).

high-order harmonic generation, resonance enhancement of single harmonics, MeV energy bremsstrahlung radiation, absorption of ultrashort laser pulses in *in-situ* produced metal clusters, and ultrashort pulse K-shell X-ray line emission.

Let us look at their LWFA experiments. A femtosecond, Ti:sapphire laser pulse is focused on a helium gas jet using an f/6.6 off-axis parabolic mirror. The gas jet is produced by a shock wave-free slit type supersonic Laval nozzle (10 mm×1.2 mm). The focal spot diameter of the beam is 18 μm (FWHM) and the corresponding peak laser intensity $\sim 2.4\times 10^{18}$ W/cm^2.

The plasma wavelength (λ_{p}) corresponding to a density of 10^{20} cm^{-3} is calculated to be 3.3 μm and the laser pulse length corresponding to 45 fs laser pulse duration is 13.5 μm. This implies that there are about four plasma wavelengths under the laser pulse envelope and the experimental regime is the self-modulated wakefield acceleration. The strong excitation of plasma waves can lead to wave breaking resulting in the injection of MeV electrons into the accelerating phase of the electric field of the plasma wave (image in figure 23). For $\lambda_0 = 795$ nm, the amplitude of the plasma wave (E_{wb}) for wave breaking is estimated to be 2.4 TV/m. The dephasing length $L_{\mathrm{dp}} \approx \lambda_{\mathrm{p}}(n_{\mathrm{c}}/n_{\mathrm{e}}) \approx 56$ μm. Despite large accelerating field, the dephasing of the electrons from the plasma wave limits the electrons' energy to about $2(n_{\mathrm{c}}/n_{\mathrm{e}}) \times m_0c^2$. Hence the maximum energy gain at $n_{\mathrm{e}} = 10^{20}$ cm^{-3} is $\sim$17 MeV.

9.2 *Coherent* (*high harmonic*) *and incoherent plasma emissions in the VUV and X-ray region*

For the studies on high-order harmonic generation (HHG) that produces coherent X-ray radiation, they use plasma plumes (produced by uncompressed 300 ps pulse from the Ti:sapphire laser irradiation of solid targets) as the medium. This is

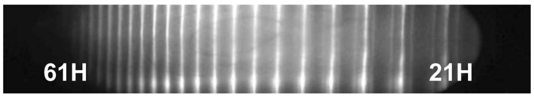


Figure 24. A typical harmonic spectrum from silver plasma (figure provided by P D Gupta).

advantageous compared to the use of gas jets since the availability of a much wider range of target materials for plasma production increases the possibility of resonant enhancement. The high-order harmonics of the 45 fs laser beam were observed using a flat-field grating XUV spectrograph. A typical spectrum of high-order harmonics generated by passing the femtosecond laser beam through silver plasma plume is shown in figure 24. Up to 61st harmonic order [69,70] was observed providing coherent soft X-ray radiation down to ∼13 nm.

They studied the harmonic spectrum as a function of the laser pulse chirp and observed resonant enhancement and extinction of some single harmonics simply by changing the separation between the two compressor gratings. It was observed that the 13th harmonic of indium was very strong (∼200 times compared to its neighbours). They inferred that intensity enhancement occurred due to resonance of the harmonic wavelength with one of the transitions in the atoms/ions of the plasma.

Furthermore, they carried out a spectroscopic study of K-shell X-ray line emission from laser plasmas at $\sim 10^{18}$ W cm^{-2}. High-resolution X-ray spectrum was recorded in the wavelength range of 9 to 10 Å using an X-ray crystal spectrograph [71,72] with a spectral resolution of 0.013 Å. The X-ray spectrum was recorded on a 16-bit, back-illuminated, X-ray CCD camera. These and similar experiments provide information on plasma dynamics, opacities and plasma radiation processes. The group also investigates applications of the X-rays produced from the plasma for microscopy and imaging. The group has carved out a niche for itself with its multipronged approach to investigations of laser-produced plasmas.

9.3 *Giant magnetic fields and fast electron transport* (*mainly work at TIFR*) [73−76]

As we saw above, a high intensity ($>10^{16}$ W cm^{-2}), ultrashort (100 fs) laser pulse explosively ionizes a solid and creates a high-density plasma with temperatures of the order of millions (10^7) of Kelvin, 10^9 bar pressures, 10^{12} A/cm^2 electron currents, and giant (10^8 Gauss) 'quasi-DC' magnetic fields – in short, intra-stellar conditions. The giant magnetic fields, the largest available terrestrially, have been known to play a crucial role in the transport of electrons in these plasmas and are of immense interest for potential applications in hybrid (inertial and magnetic) confinement in laser fusion, and for the recently proposed fast ignition laser fusion scheme. Since the first observation of such a magnetic field, their origin, magnitudes and other qualitative features have attracted considerable attention. Little however was known about their time evolution. TIFR experiments (refer figure 25 for the schematic), mapped out this temporal evolution on femtosecond time-scale for the first time, using pump-probe polarimetry. This technique uses the change

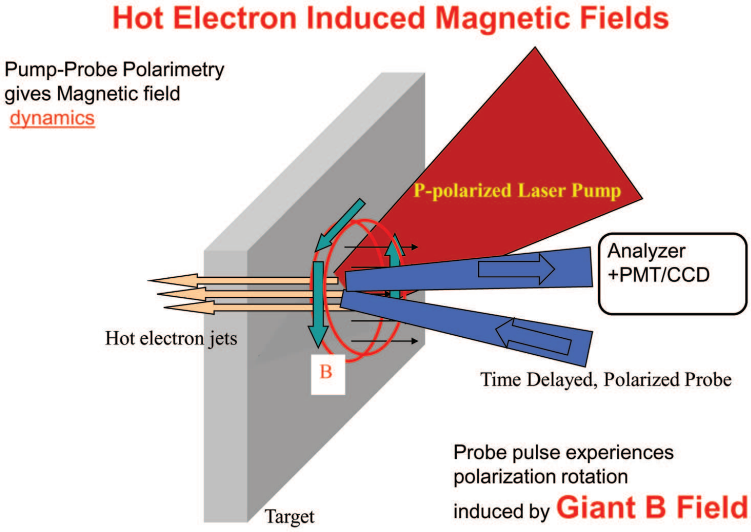


Figure 25. Measuring dynamics of megagauss fields in laser-produced plasmas.

of polarization state of a weak 'probe' beam caused by the huge magnetic field generated when a strong 'pump' laser beam hits a solid surface.

The main result is the first demonstration of ultrashort, megagauss magnetic pulses, with pulse duration in the picosecond range and having a peak value of ~30 MG. These results were interpreted by the IPR theory group using phenomenological transport models and the 1D PIC simulations were also performed. The phenomenological model considers the induction of the magnetic field by the fast electron current and its neutralization by the return thermal currents in the medium. A crucial piece of information obtained was the resistivity of the hot, ionized matter through which the hot electrons propagate. It turns out that this information is not obtainable by conventional means. This work pointed out that the resistivity was an order of magnitude larger than the classical value, implying it had an anomalous component. It was postulated that this anomalous component originates in the turbulence induced by the giant magnetic field.

This information is very crucial not only for understanding the dynamics of plasmas, but also for potential applications in condensed matter, biology and astrophysics. Ultrashort magnetic pulses generated using big electron accelerators have been used to study nanosized magnetization dynamics on picosecond time-scales. The unraveling of the dynamics of magnetization reversal could lead to the next generation of ultrafast switching and storage devices. It is known that magnetization reversal can be shortened below the picosecond duration if stronger fields are available. Figure 26 shows a typical, ultrashort magnetic pulse generated in such interactions. This work shows that such ultrashort and strong fields can easily be obtained using a tabletop terawatt laser system. Since fast electrons and thus magnetic fields can penetrate thin foil targets, it is also feasible to use them for biological and chemical samples in areas like magnetic circular dichroism (MCD)

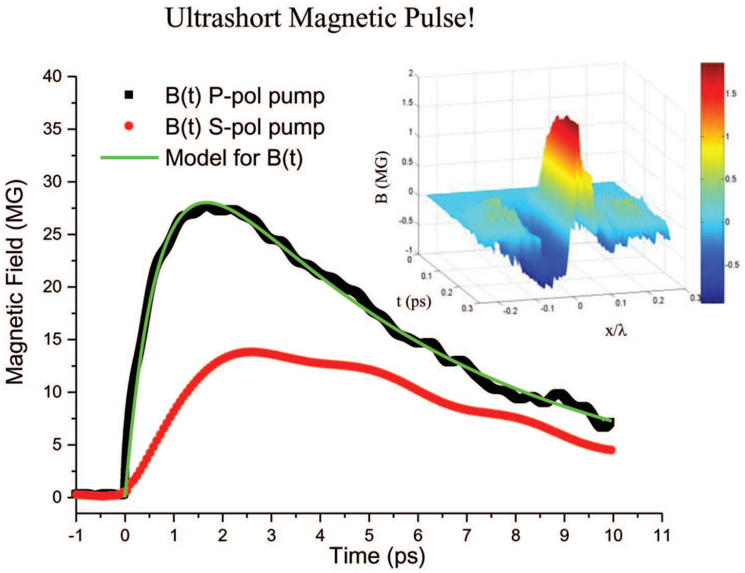


Figure 26. Giant, ultrashort magnetic pulse measured out at TIFR (refer to A Sandhu, Ph.D. Thesis, Tata Institute of Fundamental Research, Mumbai, 2004).

studies where high magnetic fields are required. Understanding the behaviour of matter under extreme magnetic fields and testing astrophysical theories is another exciting possibility, which requires complete characterization of such high magnetic fields.

The giant magnetic pulse is also an excellent monitor of the transport of the fast electrons themselves and offers a new method to study transport of fast electrons in dense, hot media. The technique relies on temporal profiling of the laser-induced magnetic fields and offers a unique capability to map the hot electron currents and their neutralization (or lack of it) by the return currents in the plasma. This work provides direct, quantitative measurements of strong electric inhibition in insulators and turbulence-induced anomalous stopping of hot electrons in conductors. The magnetic pulse technique can prove extremely important from the point of view of fast ignition scheme, which relies on the penetration of fast electrons into the fusion core.

9.4 *Rare gas clusters in intense laser fields and their engineering* (*mainly TIFR*) [77–80]

Gaseous clusters (nanometer scale aggregates of 10^2–10^6 atoms) have been heavily investigated in the last decade not only due to their interesting properties but also because they are a phase where one can study locally solid, but globally gaseous kind of response. Interest in their behaviour in intense laser fields began with

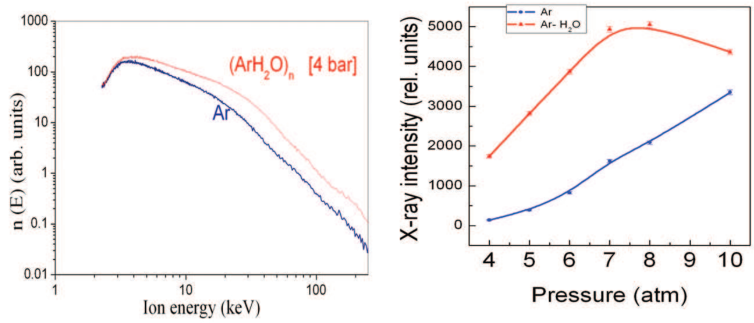


Figure 27. Measuring argon K-shell X-rays and ions from doped cluster targets (from J Jha, Ph.D. Thesis, Tata Institute of Fundamental Research, 2007).

the pioneering work of Rhodes and coworkers and Ditmire and coworkers. TIFR joined this race and sought answers to some of the most pressing questions about the routes to ionization, energy exchange among particles, directional emission of highly charged ions and finally control of the light coupling to the cluster. It is this last aspect that we look at now. For a good account of all these aspects, please see ref. [81].

Is it possible to engineer the cluster material such that at the same laser intensity more energy is absorbed to produce hotter nanoplasma? As a response to this question, TIFR came up with the idea of doping the clusters, rather accidentally. In 1997, nuclear fusion was observed in the Coulomb explosion of deuterated clusters [82] at 10^{16} W cm^{-2}. This gave rise to the idea of using heterogeneous clusters like D_2O clusters because in D_2 clusters which are typically very small, one can only take out an electron per atom and the Coulomb repulsion in the ionized cluster is rather limited. If one were to use D_2O clusters, the yield of D+ beyond fusion threshold can be enhanced as the charge on the cluster can be increased and with this idea TIFR started working on molecular clusters.

When pure argon clusters are exposed to 100 fs pulses of 10^{16} W cm^{-2}, the hot nanoplasma evolution results in a deposition of about 50 keV/atom. *A priori*, one does not expect the easily ionizable dopants like H_2O to bring about any significant change in the nanoplasma. Contrary to these expectations it was found that when argon and water are co-expanded in the supersonic jet for the formation of clusters, the result was a hotter nanoplasma, as shown in figure 27. Careful experimentation with doped clusters and pure argon clusters under identical laser irradiation revealed that X-ray emission can be enhanced by ten-fold with the former. A seven-fold enhancement in high energy electron emission and a three-fold larger yield of high energy ions were also measured. At 10^{16} W cm^{-2}, $Ar_{40,000}$ produced charge states only up to 8+ beyond which there was an abrupt cut-off in the yield. On the other hand, doped clusters produced charge states up to 14+, clearly indicating a higher propensity for the production of highly charged ions for the same laser intensity. There is a two-fold enhancement in the energy absorbed by the doped cluster under identical laser irradiation with no measurable change in cluster size.

What brings out the change in the nanoplasma? The clue lies in the fact that H_2O has a lower ionization potential. Multiphoton ionization cross-section is larger by three orders of magnitude and the threshold intensity for over-the-barrier ionization is much lower. This implies that there is a larger degree of ionization with the doped clusters in the initial part of the laser pulse. If the number of free electrons oscillating in the laser pulse is larger, the degree of inverse bremsstrahlung and collision ionization due to electron rescattering should also be larger. Overall, the laser absorption is larger and a hotter nanoplasma is generated. Analytical computations on the change in electron density, collision frequency and the collisional ionization due to the difference in ionization potential, support these arguments. We do find that easier ionization of some fraction of the cluster constituents can indeed have a larger consequence on absorption and plasma generation. The absorption of radiation and plasma generation also have contributions from other collisionless mechanisms like the resonance heating. If the plasma frequency matches with the incident laser frequency, then enhanced absorption and hotter plasma generation is known to occur. This is established by a two-pulse experiment or by using the laser pulse with a larger width. Comparison of the doped and pure clusters shows that not only is the absorption larger in general but also more effective at the resonance condition with doped clusters. This indicates that the collisionless mechanisms are also larger with the doped clusters.

9.4.1 *Studies on shock waves* (*mainly BARC*) [83, 84]. The Laser and Neutron Physics Section of BARC has been involved for the past eight years in the development of intense Nd:glass lasers (femtosecond as well as sub-nanosecond pulses). These lasers have been utilized in the generation and studies on high temperature (500 eV), high density (near solid) plasmas. Multi- mega bar shock pressures have been generated in different materials and scaling with laser intensity has been established.

They have an indigenously developed 12 J/500 ps ($>10^{14}$ W/cm^2) Nd:glass laser (figure 28) and a 1 J/600 fs–1000 fs ($>10^{17}$ W/cm^2) Nd:glass CPA laser currently under development. The 500 ps high power laser is used extensively to study plasma emissions from complex targets having relevance to ICF, the ultrashort pulse laser would be used for particle acceleration and neutron generation. Efforts are being made towards the optimization of CPA system for wider spectral bandwidth, high peak pulse contrast and large energy extraction from Nd:glass-based regenerative amplifiers. It has also been their endeavor to develop new materials for large energy storage, wide bandwidth, good thermal properties and large damage thresholds, in collaboration with the Central Glass and Ceramic Research Institute (CGCRI) and some universities.

Several laser and plasma diagnostics have also been developed in-house. These include intensity profile monitors, auto-correlators for lasers, X-ray and particle diagnostics, shock velocity and particle velocity measurement techniques, dynamic imaging technique to measure velocities of a few km/s for laser-driven foil targets as well as study R–T instability growth and their smoothening using special target designs; opacity measurement techniques of high density–high temperature plasmas etc.

Figure 28. 40 Gigawatt Nd:glass laser at BARC.

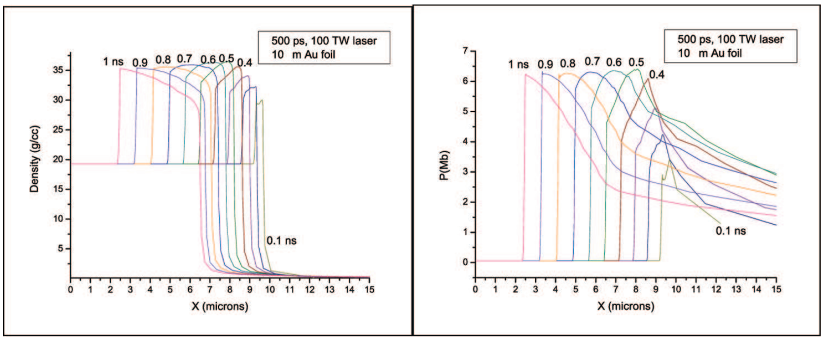


Figure 29. Calculated space profile for (**a**) density and (**b**) pressure for a representative 10 μm gold foil driven by 500 ps laser beam (figures provided by L J Dhareshwar, BARC).

9.4.2 *Experiments of laser-driven shocks: Studies on laser-driven shocks in aluminum and gold targets at* $>$ *10 Mbar pressure.* Shock velocity has been measured by determining shock transit time through foils of different thickness, using a streak camera. Time difference between fiducial and onset of shock luminosity on foil rear side is shown in figure 29 and was used to measure shock transit time. Scaling of shock transit time and shock velocity are seen to match well with the simulations as shown.

9.5 *Highlights of theoretical efforts* [83–89]

We will focus mainly on the analytical and simulation studies at IPR, IIT Delhi and at BARC.

IPR does analytical modeling as well as PIC, Vlasov and fluid simulations of laser-produced plasmas. The extensive simulation work at this Institute has been focused towards (i) understanding turbulence in plasma fluid, which unlike neutral fluid is ridden with a wide variety of intrinsic length and time-scales; (ii) identification of important physics aspects related to the subtle features of transport in laser fusion; (iii) relevance to specific experimental studies performed in India and abroad and (iv) the investigation of fundamental physics issues in plasmas, specifically in the context of laser and charged particle beams interacting with it.

As an example, let us look at one such model that IPR has recently investigated in an extensive manner – the electron magnetohydrodynamic (EMHD) model. This model describes the behaviour of electron fluid in plasma at fast time-scales for which the ion response can be ignored. The EMHD model is very pertinent to the physics of fast ignition of laser fusion discussed above. Though somewhat similar to the magnetohydrodynamic (MHD) model, it has interesting distinctions. Ions are stationary in EMHD and the electron fluid velocity itself constitutes the current. The velocity is thus directly related to the magnetic field (the displacement current is ignored in the model as typical phase speeds are taken to be much less than the velocity of light). The EMHD model is thus entirely represented in terms of the evolution of magnetic field. MHD on the other hand has a coupled evolution equations for fluid velocity and magnetic field. Furthermore, the EMHD model has an intrinsic scale length, viz., the electron skin depth c/ω_{p}. This scale length separates the magnetized electron response at longer scales from the hydrodynamic characteristics of the electron fluid at shorter scales. The debate on whether or not waves influence the cascade mechanism in turbulent flows has continued for a long time. The question has been primarily posed in the context of the MHD model. IPR has shown that the waves indeed influence cascade mechanism by using novel diagnostics in simulations of EMHD phenomena.

In EMHD model the electron flow velocity is also the current. Therefore, in this model the velocity shear driven Kelvin–Helmholtz (KH) instability connects directly to the sausage and kink modes driven by the current shear. In a major recent advance, it has been postulated by IPR that the electromagnetic turbulence induced by the shear instability (figure 30) can enhance the stopping of energetic electrons within the core of the ICF target in the fast ignition scheme. This idea is likely to provoke much thought and investigation in the fast ignition community.

In addition to turbulence studies, the dynamical properties (viz., stability, interaction, propagation through inhomogeneous media) have also been investigated for coherent solutions. EMHD fluid model permits a variety of static rotating monopolar solutions and propagating dipolar solutions. The simulations show that these structures are very robust. In fact it is not essential to tailor the solutions close to exact analytical form to observe their stability. Even when two equal strength, but unlike signed monopoles are brought within a distance of skin depth they adjust their shape and form dipoles which propagate parallel to their axes. The interesting phenomenon of trapping in high density region has been observed when these

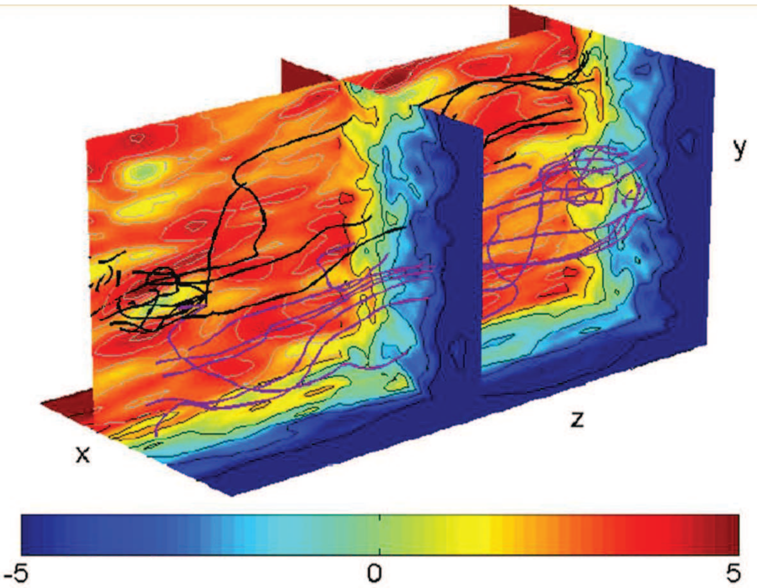


Figure 30. The colour contours in the figure depicts the turbulent velocity field configurations on various 2D planes obtained from nonlinear EMHD fluid simulations of a sheared electron flow configurations. The thick violet and black lines show the electron trajectories (reproduced with permission from ref. [88]).

structures move through inhomogeneous plasma media. Another class of coherent solutions which have been investigated with the help of fluid simulations is the soliton-like solutions which form as a result of the interaction between plasma and intense laser light pulses. These are the solutions of one-dimensional coupled relativistic fluid and Maxwell set of equations. These solutions can propagate with speeds close to that of light; hence unlike EMHD model it is necessary here to retain the displacement current. These solutions can be classified in two distinct categories, one in which the light wave oscillations are trapped within the plasma oscillation and the other in which the plasma wave is trapped within the light pulse. The number of distinct peaks of laser and plasma wave structures add further diversity to the class of solutions. It is observed that typically when the light wave is trapped within the plasma wave the structures are unstable and are found to emit radiation from their trailing edge. Simulations for slowly moving structures with ion dynamics, finite temperature effects etc, have also been carried out.

EMHD equations can be expressed entirely as evolution of magnetic field at fast time-scales. They are therefore good model representations for studying self-consistent fast magnetic field evolution in laser-produced plasmas. 0D and 1D modeling of laser pulse-induced magnetic field generation in ultrashort ultrahigh intensity laser pulse–solid interaction has led to a detailed understanding of the transport processes of hot electrons through overdense plasmas; a topic of utmost relevance to fast ignition scheme of laser fusion.

IIT Delhi has been pursuing theoretical research on wave–wave and wave–particle interactions in plasmas, much of which has had considerable influence on the larger scientific community [91–94]. As we have seen above, plasmas provide a rich and complex environment for various kinds of couplings between the incident radiation fields and plasma particles both at the individual particle and collective levels. The collective modes have different growth rates depending on the incident light field and the plasma parameters particularly the plasma density and its inhomogeneity. Many of the light scattering phenomena like stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) have a huge impact on the light coupling to the plasma and its heating and they have definite thresholds for the light intensity. It is therefore necessary to understand these processes, particularly their mode structures, dispersion relations and growth rates. Besides, phenomena like laser self-focusing and light filamentation have a deep impact on the light coupling to the plasmas and they too facilitate the seeding and growth of instabilities. In short, the spatial and temporal variations of the incident laser pulse and the variation of these with propagation in the plasma have a significant influence on processes ranging from particle acceleration to laser fusion. The situation gets even more interesting for relativistic intensities of light fields when the modulated plasma refractive index differ due to electron mass variation. It must be noted that IIT Delhi theorists have contributed extensively to all these problems (e.g. mode structure and evolution, dispersion relations, growth rates and competition among different instabilities) over a large range of plasma and laser conditions, mostly on their own but also in collaboration with researchers abroad. Recently they have also contributed significantly to the understanding of how gaseous clusters interact with femtosecond light by making quantitative estimates for the fraction of laser energy absorption and the temperature of the heated cluster as well as the scaling of these with laser and cluster parameters.

Let us look at one highlight of their recent work. This deals with the exciting area of generation of coherent terahertz (THz) radiation when an electron beam interacts with plasma. Typically, THz radiation is generated by the nonlinear interaction of a femtosecond pulse with a nonlinear medium. An alternate, though more elaborate and powerful route, is the free electron laser. IIT Delhi has studied the propagation of a relativistic electron beam simultaneously with an electromagnetic wave perturbation, through a filled waveguide with a spatially periodic dielectric. The resulting space charge field couples with the periodic permittivity to further drive the electromagnetic perturbation. This idea leads them to propose a novel way to generate coherent THz radiation. As shown in figure 31, in this scheme a slightly relativistic electron beam interacts with a ripple density plasma medium at an angle to the ripple vector. The ripple couples the THz signal to the space charge mode and the velocity given to the electrons generates a current density that drives the THz wave with a component perpendicular to the wave. This sets up a feedback mechanism which amplifies the THz wave at the expense of the incident electron beam energy. The result is shown figure 32. The relativistic electron beam can provide much higher energy than the microjoules per pulse generated by semiconductors interacting with femtosecond lasers.

At BARC, a number of theoretical models are developed to simulate the interaction of ultraintense lasers with plasma. These include a nonlocal thermodynamic

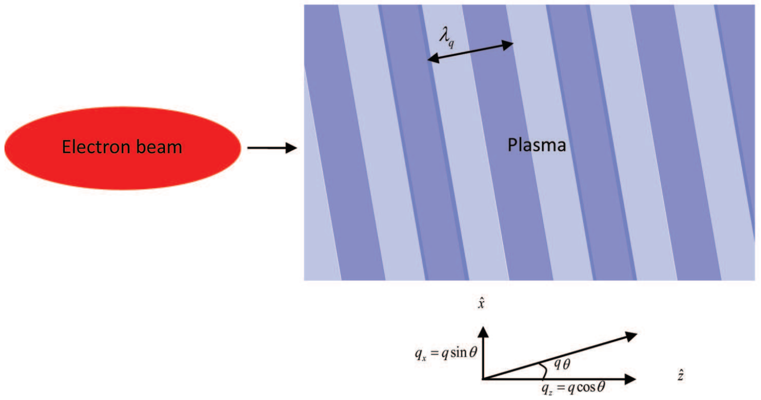


Figure 31. Schematic of electron beam propagation through a rippled density plasma, and generation of the THz radiation (refer to V B Pathak, Ph.D. Thesis, IIT Delhi, 2008).

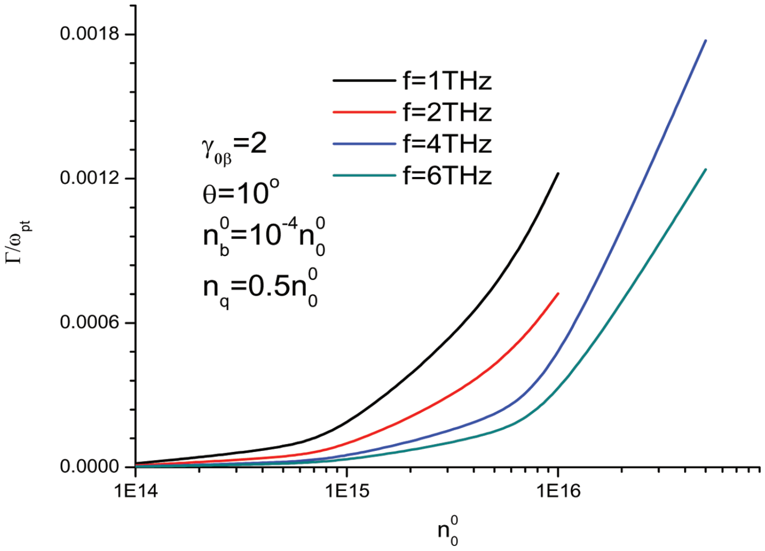


Figure 32. Terahertz emission from the scheme in figure 31 (refer to V B Pathak, Ph.D. Thesis, IIT Delhi, 2008).

equilibrium (non-LTE) model for radiation opacities and emissivities, equation of state models, radiation hydrodynamic simulation models for bulk targets as well as for atomic clusters, particle in cell simulation (PIC) models for plasma-based electron and ion acceleration etc. Non-LTE opacity model is used to study the composite targets for inertial confinement fusion. Radiation hydrodynamic model is used to simulate the conditions in the laser-driven hohlraum cavities.

As an example, below we present results of simulation of interaction of ultraintense laser with an atomic cluster. In figure 33(left) we see the radial profile of electron density for a 600 Å radius argon cluster irradiated by a 300 fs, 800 nm

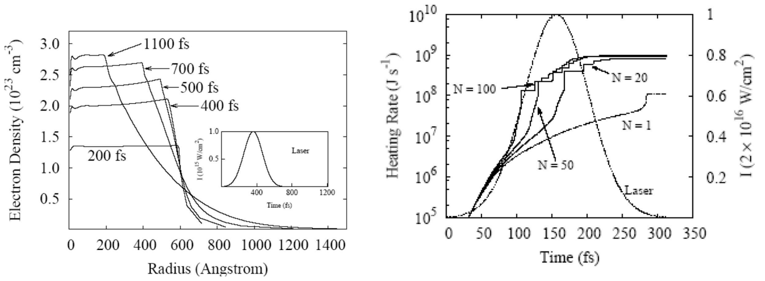


Figure 33. Electron density and heating rate of electrons from clusters (reproduced with permission from ref. [95]).

laser pulse having a peak intensity of 1×10^{15} W/cm^2. Laser pulse is shown as an inset. On the right side we show the temporal profile of heating rate for an 80 Å radius argon cluster for various numbers of shells used to model its structure. The cluster is driven by 130 fs, 800 nm laser pulse with a peak intensity of 2×10^{16} W/cm^2 [95]. Laser pulse is also shown in the figure by a dotted line.

As another highlight, we mention their PIC simulations for proton acceleration, where they showed that with an optimum plasma profile, protons with energies up to 1 GeV are observed [96].

10. Conclusions and some thoughts on the future

As the laser turns mature at 50 in 2010 (and the CPA revolution exhibits youthful exuberance at 25!) what spectacular celebrations of science and technology are in the offing? An intense celebration has already begun with the switching on of the National Ignition Facility in the USA in early 2009. And the excitement is sure to reach a peak when it fires on a target the most energetic light pulses (megajoules) ever made by man! This is going to create the highest ever energy densities on this Earth on a target of millimeter scales. The NIF of course symbolizes the progress in nanosecond long laser pulses, but the ultrashort revolution is also in the throes of extreme excitement with efforts to build 10^2 PW scale lasers by multinational consortia [97,98].

From a national point of view, we are set to join the superleague of international labs, with the installation of ‘petawatt scale’ 100 TW, femtosecond lasers at TIFR and RRCAT in the next two years. The plans for a petawatt laser are firmly on the drawing board and we should be there in about 5–6 years. There is every reason to celebrate these milestones and ensure that more and more young students and researchers join this activity and get trained to make science and technology breakthroughs in this fertile, multifaceted area. The 11th plan period has also seeded a national ‘Strong Field Science’ initiative coordinated by TIFR, RRCAT, BARC, IPR, IIT Delhi, University of Hyderabad and Cochin University of Science and Technology. Perhaps the celebrations of 2010 could trigger a major spurt in the unleashing of intense laser activity in our country!

To end on a personal note, I had titled the talk I gave at the Academy meeting in Benares in 2004 'A brief, yet intense affair with light'. Having read through this far, you would agree with me that we need to reframe this as 'A brief, hence intense affair with light'! The briefer, the more intense!! It has been a pleasure to work in this area and I hope the efforts on the national scale would fully justify the present enthusiasm of the researchers, in the years to come.

Acknowledgements

It has been and continues to be a great privilege and pleasure to work with many exceptionally competent (and willing) colleagues, students, and postdoctoral fellows at TIFR and collaborators from elsewhere. I must acknowledge all my TIFR colleagues, especially M Krishnamurthy, P Ayyub, students Sudeep Banerjee, P P Rajeev, Arvinder S Sandhu, Suman Bagchi, Subhendu Kahaly, Sudipta Mondal and S N Ahmed, postdoctoral fellows Reji Philip, Riju Issac, A Dharmadhikari, P Prem Kiran, V Narayanan and Amit Lad and coworkers J Jha, M Anand and R Rajeev. I have learnt a great deal on the theoretical aspects of plasmas from extensive and very fruitful collaboration with P K Kaw, S Sengupta, Amita Das and S Yadav of IPR. The cross-disciplinary collaboration with Satyajit Banerjee, J Sinha and S Mohan of IIT Kanpur continues to teach me many interesting aspects. I acknowledge the collaboration I had many years ago on studies of molecules in intense fields with D Mathur, C P Safvan and F A Rajgara. I have benefited greatly from interaction with P D Gupta, P A Naik and other colleagues from RRCAT and L J Dhareshwar and colleagues from BARC. The increasingly global nature of intense field physics necessitates long-distance interactions and joint experimental ventures with talented colleagues outside India. It is a pleasure for me to acknowledge my past and continuing association with K A Tanaka, H Habara, R Kodama and Z L Chen (ILE, Osaka), T Yabuuchi (now at UC, San Diego) and A L Lei, Z M Sheng, and W M Wang (China).

I thank M Barma and D D Sarma for their generosity in suggesting that I write this article (and for their gentle, continuous persuasion till its completion!) and P D Gupta, Amita Das and L J Dhareshwar for sending me succinct summaries of some recent work done at RRCAT, IPR and BARC respectively, for inclusion here. The summary of the TIFR work on clusters and very useful comments on the whole article were provided by M Krishnamurthy. I thank Jagannath Jha, Vinay Bhonslay, Sudipta Mondal and V Narayanan for help with the preparation of this manuscript. (Jagannath in particular, displayed limitless patience!)

I began writing this article while on a two month visit to FZD, Dresden and my hosts Roland Sauerbrey and Ulrich Schramm and the members of the Laser Particle Acceleration group there deserve immense appreciation for their hospitality.

Some websites on intense laser field science

I provide here addresses of some websites where you can get more details of the kind of research being performed in intense laser physics and perhaps can even access some of the research papers published. These have been chosen to give a flavour of the field and apologies are due to the groups whose sites are not listed here.

India

- Ultrashort Pulse High Intensity Laser Lab (UPHILL), TIFR, Mumbai: http://www.tifr.res.in/∼uphill/
- Raja Ramanna Centre for Advanced Technology, Indore: www.cat.ernet.in
- Bhabha Atomic Research Centre (BARC): http://www.barc.ernet.in/
- Institute for Plasma Research, Gujarat, India: http://www.ipr.res.in/

Around the world

- Institute of Laser Engineering, OSAKA, Japan: http://www.ile.osaka-u.ac.jp/index_e.html
- Rutherford Appleton Lab: http://www.stfc.ac.uk/About/Find/RAL/Intro- duction.aspx
- Forschungszentrum Dresden-Rossendorf, Dresden: http://www.fzd.de/ db/Cms?pNid=0
- Laboratoire d'Optique Appliquée (LOA), Palaiseau: http://loa.ensta.fr/index_gb.html
- Ecole Polytechnique – Applied Optics Laboratory, Paris: http://www.polytechnique.edu/page.php?MID=84
- Advanced Laser Light Source, Canada: http://steacie.nrc-cnrc.gc.ca/programs/as/as_alls_e.html
- The York Plasma Physics and Fusion Group York University: http://www.york.ac.uk/
- Prague Asterix Laser System, Prague: http://www.pals.cas.cz/pals/
- Advanced Photonics Research Institute (APRI), Korea: http:// apri.gist.ac.kr/eng/main.php
- Chinese Academy of Sciences, Beijing: http://english.cas.ac.cn/
- Plasma Physics Group, Imperial College London: http:// www3.imperial.ac.uk/plasmaphysics
- The High Intensity Laser Group – University of Texas at Austin: http://www.ph.utexas.edu/∼utlasers/
- National Ignition Facility & Photon Science – The Power of Light: https://lasers.llnl.gov/

- ELI: the Extreme Light Infrastructure European Project: www.extreme-light-infrastructure.eu/
- CEA Laser Megajoule: www-lmj.cea.fr
- HiPER Project: www.hiper-laser.org/

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