Physics of Laser Plasma Interaction

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Amita Das obtained her Ph.D from IIT Kanpur in 1990. Thereafter she worked at the Institute for Plasma Research. In December 2018 she moved to IIT Delhi as a Professor in Physics Department. Her research interests are in the theoretical and simulation studies of various aspects of plasma medium. She has been working in the area of laser plasma interactions, turbulent and nonlinear behaviour of plasma medium and properties of strongly coupled plasmas. She has been elected the fellow of all the three science academies of India. She is also the recipient of the J. C. Bose Fellowship.

Abstract

A glimpse at the rich physics and diverse applications of the field of laser plasma interaction has been provided. Future possibilities and scope of the field has also been discussed.

Introduction

Ordinary matter comprises of neutral atoms and molecules. When such a matter is subjected to extreme environment (heating and/or electrical discharge) the electrons from individual atoms are stripped apart. The collection of positively charged ions and the electrons interacting in a collective fashion is termed as the plasma state of matter. A picture of Argon plasma created in laboratory has been shown in Fig.1. The charged plasma medium is an extremely versatile state of matter and offers enormous possibilities both for the exploration of frontier areas of research in physics and also for its exploitation for many useful purposes.

The laser field appears as a natural partner of the plasma medium. Its electromagnetic field influences the dynamics of the electrons and ions (the two charged species of the plasma medium) leading to myriad possibilities. Furthermore, with rapid strides in the technological advancement of lasers since its birth in the 1960s, the physics of laser plasma interaction has become increasingly richer and exceedingly broad.

There are many roles that a laser can play vis a vis plasma medium. First and foremost if the laser intensity is high enough for its electric field to become comparable and/or it exceeds the atomic binding field of the material, the laser can ionize the matter to create plasma medium. Thus laser provides for a possibility of generating plasma medium from ordinary neutral matter. Laser power is also used for the purpose of compressing and heating the plasma of hydrogen ions for nuclear fusion. The denser and hotter plasma is suitable for fusion as Lawson criteria

$$nT\tau_E > 10^{21} Mt^{-3} sKeV$$

(where n is the number density of the plasma, T is the temperature and τ_E is the energy confinement time) defines the figure of merit for a fusion reaction to have higher rate of energy production than energy input. The interaction of laser with plasma is the genesis of many

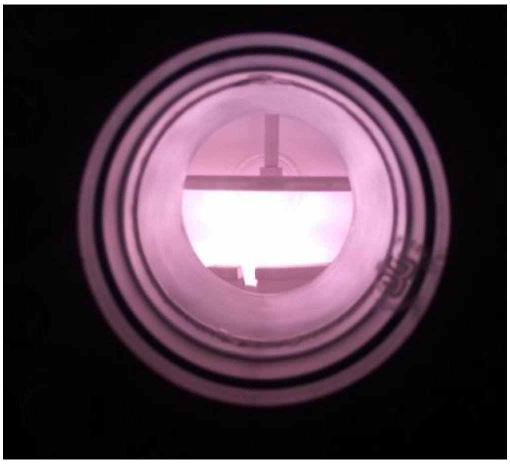

Figure 1: Argon Plasma in Laboratory

frontier technologies, such as table top devices for charge particle acceleration (ions and electrons), intense radiation sources etc. The intrinsic nonlinear character of laser plasma interaction has led to major developments in the fundamental physics of nonlinear theory, parametric instabilities, plasma turbulence etc. The recent advancements in laser power has opened up possibilities of investigating many astrophysical phenomena in laboratory, thereby giving birth to the field of laboratory astrophysics. In future as the laser intensity increases the pair production, QED and radiation reaction effects in the collective environment of plasmas can also be studied in the laboratory. The behaviour of matter in high pressure and high temperature regimes can be altogether different than the matter at normal density and pressure regimes to which we are acquainted with. The equation of state and other properties of matter in such a regime is not known. Matter and plasma under the intense radiation field of laser can create such a high energy density state for exploration.

Keeping in view the vast and diverse nature of the field, the narration of the story of the laser plasma interaction here, is selective and provides only a glimpse of this field.

Linear theory of laser propagation through plasma

The propagation of laser field through plasma medium turns out to be quite interesting. The plasma medium contains free electron and ion charges. The conduction current of the free charges induced by the rapidly oscillating laser electric field in the medium can balance and shield the displacement current of the electromagnetic radiation, thereby inhibiting the propagation of the laser radiation. The conduction current is given by

$$J_e = -en_0 v_e \,,$$

here e, n_0 and v_e are the electronic charge, number density of electron charges and the electron quiver velocity in the laser electric field. The heavier ion species contribute negligibly to this current as their quiver velocity at the high frequency laser electric field is too small. It should be observed that the conduction current by the particles has an upper limit as the electron velocity v_e can never exceed the speed of light c. The displacement current on the other hand has no such limit. At small laser intensities for which the electron motion does not become relativistic,

$$\overrightarrow{v_e} \times \vec{B}$$

force on electrons can be neglected. The typical value of the electron quiver velocity can then be estimated from the equation of motion of electrons as

$$v_e = -eE / m_e \omega$$

(here $\vec{E}$ is the laser electric field, m_e is the electron mass and ω is the laser frequency). The displacement current which can be estimated as ωE, can be shielded by the conduction current provided

$$4\pi J_e / c \geq (1/c) \partial E / \partial t$$

in the Ampere's law of Maxwell's equation. This requires

$$4\pi e^2 n_0 E / (\omega) m_e \geq \omega E \,,$$

implying that

$$\omega^2 \leq 4\pi n_0 e^2 / m_e = \omega_{pe}^2$$

Thus only when the laser frequency is higher than the electron plasma frequency ω_{pe} the laser radiation can propagate inside the medium, as in this case the electron conduction current is unable to shield the displacement current. The plasma frequency $\omega_{pe} \propto \sqrt{n_0}$ is the typical frequency at which the electrons in the plasma medium respond. One can thus always find a critical plasma density n_0 beyond which a laser with a given frequency will not be able to propagate inside the plasma. The plasma is said to be overdense for the laser radiation if the plasma density is higher than the critical density.

The plasma medium essentially behaves like a dielectric medium with the dielectric permittivity given by the expression

$$\varepsilon = \frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_{pe}{}^2}{\omega^2} \,. \qquad (1)$$

for the electromagnetic radiation. In the above description the electrons response to the laser field is reactive. The electron velocity is out of phase by 90 degrees with the laser electric field making the average value of $< \vec{J} \cdot \vec{E} >$ vanish over the laser cycle. Thus in this case the laser cannot dump its energy to the plasma.

Our prescription above has, however, been quite simplistic. It is a linear description and it assumes no randomization of electron trajectories. In reality the electron motion would get randomized due to collisions with the background ions of the plasma medium. This would provide for a resistive component in its motion making $< \vec{J} \cdot \vec{E} >$ finite. The energy from laser can thus get dumped in the plasma medium. The other possibility of laser energy getting absorbed by the plasma is when the laser frequency resonates with the natural collective plasma frequency of the medium. This is known as the resonance absorption mechanism.

Depending on the nature of applications, one may wish to have in certain situations a minimal loss of the laser energy as it goes through the plasma and in other cases one may like to employ the laser for the purpose of efficiently heating the plasma. One may often also require heating at a definite localized region in the plasma medium. Accordingly studies have been conducted to optimize one or the other of these aspect.

For differing requirements the possibility to appropriately manoeuvre the system may be desirable. The rich nonlinear physics associated with the interaction of lasers with plasma in fact gives the freedom and possibility to cleverly utilize the system dynamics for the desired objective. The nonlinearity also on the other hand often becomes a major cause of concern and posits difficulties which need to be overcome by developing a better understanding of it. This continues to remain a challenge in the field. The understanding remains incomplete providing a lot of scope of research in the field. A recent review article written by Kaw [1] on laser plasmas provides a wonderful depiction of this area in detail.

Rich nonlinear physics

The physics of laser plasma interaction is intrinsically nonlinear. The laser electromagnetic fields influence the dynamics of plasma particles. The motion of charged particles in turn creates electromagnetic fields. There are convective $\vec{v} \cdot \nabla \vec{v}$ and $\vec{v} \times \vec{B}$ nonlinearities in the system. When the intensity of the laser radiation is high these nonlinearities start playing an important role in governing the dynamical evolution of the system and many kind of new phenomena are observed. The manifestation of the convective and the $\vec{v} \times \vec{B}$ nonlinearities can often be understood on the basis of a ponderomotive force term

$$F_p \propto -\nabla |\vec{E}|^2$$

in the equation of motion of the charge particles. The ponderomotive force pushes the electrons out of the region of high laser intensity. The dielectric constant in the electron evacuated region alters in a fashion so as to increase the laser intensity further in this region, leading to a positive feedback for an instability to develop. Thus beyond a certain threshold of laser power a spatially separated region of plasma and radiation seems more viable. The laser radiation may also get trapped in the cavity that it creates by pushing the electrons out where they pile up to create an overdense region. This has been illustrated in the schematic plot of Fig.2. Here the blue dotted line represents the radiation profile, the red coloured solid line is the profile of the electrostatic potential created as a result of electrons being pushed out of the region by the ponderomotive nonlinearity from the region where the radiation intensity is high. The plus and minus signs denote the ions and electrons respectively. For

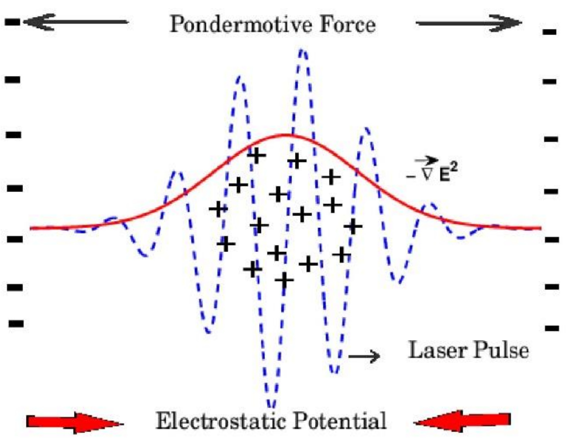

Figure 2: Schematic of light trapping inside plasma in a plasma cavity evacuated of electrons. (Courtesy Deepa Verma)

For laser intensities which are higher than 10^{18} Watts/cm^2, the quiver velocity of electrons in the oscillating laser electric field becomes relativistic giving rise to relativistic nonlinearity in the medium. The increase in the relativistic mass of electrons reduces the effective plasma frequency. Laser radiation at relativistic intensities can thus penetrate even an overdense plasma medium. This effect is termed as the relativistically induced transparency.

Exact analytical solutions in the form of envelope solitons with the trapped laser radiation have been obtained [2-4] for various parameter regimes and have distinctive characteristics. The stability and robustness of such solutions have been illustrated in many simulation studies. These structures can move undistorted in the plasma and can have group speeds of the order of the speed of light. They can play an important role in energy transport. It should be noted that the conventional particle accelerators have reached a limit in terms of their size. The material breakdown limit severely constrains the acceleration gradient that can be achieved in conventional accelerators. Since plasma is already a broken down medium such a restriction does not apply to it. Thus, plasma based accelerators provide for a promising new technology for particle acceleration. The acceleration gradient of ~ 10 GV/Mt, which is 3 orders (1000 times) higher than that of conventional accelerators can be achieved by a plasma of density 10^{16} /cc. The space charge field required for the acceleration of charged particles in plasma medium can be created with the help of the lasers. The laser disturbs the plasma medium creating wake field electrostatic potential structure behind it which is used for particle acceleration. The particles are injected at an appropriated phase with respect to the wakefield potential structure to have the maximum energy gain. Since the wakefield remains attached behind the laser pulse, it moves with the group velocity of the laser pulse which is typically very close to the speed of light. When the injected particle moves with the same speed as that of the wakefield structure it continues to see a static electric field for a longer distance and keeps gaining energy until it gets dephased. The idea of plasma based accelerators were first theoretically proposed by John Dawson [5]. Thereafter, the concept was explored experimentally and in the last two decades rapid progress in the area has been reported by various laboratories worldwide (e.g. Lawrence Berkley National Laboratory (LBNL) in USA, Labontoire d'Optique AppliquCe (LOA) in France and (Rutherford Appleton Laboratory (RAL) in UK). In India, Raja Ramana Center of Advanced Technology (RRCAT), Indore has been doing pioneering experiments in the area. It has now become routine to obtain multi-GeV electrons in a cm scale plasma [6-8]. This is indeed revolutionary as it reduces the size, cost and required energy of future accelerators making the energetic beam accessible for many applications.

The ongoing experiments are focussing on improving the quality of the accelerated beam. The emphasis is on obtaining beams with low energy spread, low divergence and improved beam current. The discovery of a new regime known as the bubble regime [9-10] in which a ion cavity is created by the expulsion of electrons by ponderomotive force of the laser field (discussed earlier) has been very helpful in improving the beam quality.

The electric field in the plasma for acceleration can also be created by energetic particles. This is an alternative to the laser plasma acceleration although it is based on plasma medium. The experimental group of Chan Joshi at University of California, Los Angeles (UCLA) along with the SLAC have employed this mechanism for acceleration [11]. The scheme employs energetic particles from an accelerator to create a space charge cavity in a plasma for acceleration. Often the front of the energetic particle beam creates the space charge fields in the plasma which is utilized by the particles in the rear of the beam for their energy boost. This scheme has also yielded promising results. At CERN the AWAKE project explores the beam driven plasma acceleration scheme with a proton beam. It is clear that acceleration by this method has to rely on conventional accelerators and hence cannot be a compact standalone system. The laser based acceleration in contrast has an advantage of being a compact independent table top device through which the energetic charge particles can be extracted for myriad applications. The progress in laser plasma wakefield accelerators have led to the development of compact coherent X- ray sources which are very useful for high resolution imaging. During the process of acceleration the electrons jiggle in the transverse direction and emit synchrotron X -ray radiation. It is known as the betatron radiation. Betatron sources of ~ 10 KeV energy has been reported so far. The micrometric size and femtosecond duration of these sources are important for high resolution diagnosis and ultrafast absorption spectroscopy.

The progress in the laser plasma interaction based particle acceleration scheme also provides an example of how the synergy between theoretical, computational and experimental efforts have contributed to its rapid progress. As discussed earlier the theoretical concept was provided by Dawson in 1979 [5] which led to experimental explorations. The simulations (mainly Particle - In - Cell) have proved extremely fruitful in providing inputs to the experiments from time to time. It is noteworthy that the bubble regime [9], which proved to be extremely useful, was first identified in simulations and then explored experimentally.

Apart from particle acceleration, another important application of laser plasma interaction is for the purpose of nuclear fusion. Many schemes for laser fusion have been put forth and are being improvised. In the inertial confinement fusion (ICF) one wishes to compress the fusion pellet to super solid density so that in a short time itself before the pellet is blown apart, the Lawson criteria can get satisfied. Laser was employed for the task of compressing and heating the fusion pellet. However, while the required compression of matter ≥ 10^{24} /cc could be achieved easily, heating it up at the temperature of 10 KeV at the core which is best for initiating fusion reaction proved difficult. There was mixing of the hot and cold fuel making the process energetically inefficient. The fast ignition concept of laser fusion was introduced against this backdrop in which the task of compression and heating were separated. First the fusion target was compressed keeping the target cool (the compression is much easier then) by a slow nanosecond laser pulse. Thereafter, a fast femtosecond laser pulse is sent for creating the ignition spark. Since the laser cannot penetrate the compressed high density target an indirect mechanism using hot electrons created by the laser at the critical density surface are utilized. It is hoped that the energetic electrons propagate in the denser region of the target and would dump their energy to the ions there to create a fusion spark. While a scaled down experiment showed promising results there was scepticism for the scheme to work for fusion scale experiments. The reason being that for fusion scale experiment higher energy would be required. However, as one increases the electron energy it becomes difficult for it to interact with ions through collisional processes as the Rutherford's collisional cross section drops down with temperature as $T_e^{-3/2}$. It was clear that one had to take resort to anomalous processes. Indeed the energetic electron propagation through plasma is beset with instabilities and turbulent processes which are known to modify the transport coefficients such as resistivity etc. In this area we have had a fruitful interaction between our theory group, TIFR and ILE Osaka. The theoretical ideas could be tested at TIFR and ILE Osaka laboratories. The collaboration led to several joint publications [12-15]. The studies opened up newer areas for further investigations. The experimentally observed magnetic turbulence in laboratory has relevance in astrophysics. The field continues to be rich and many challenging questions remain to be explored to provide further excitement

Future scope and concluding remarks

The coming decade and beyond will be quite exciting for the field of laser plasma interaction. Many new laboratory facilities are coming up which would be pushing the frontiers of laser power, pulse duration etc. For instance, under the pan - European "Extreme Light Infrastructure (ELI)" three laboratories are coming up soon. The ELI-beamlines at Czech republic promises to provide the world with the most powerful advanced laser system at 10 PW (Peta Watt), the focussed light intensity would be upto 10^{24} W/cm^2. It should be noted that at such intensities not only does the ion response become crucial it is also relativistic. It is hoped that this will bring in new techniques and tools not only for basic research but also for medical imaging and diagnostics, radiotherapy, new materials, and X-ray optics. Matters under extreme pressure and densities can be explored, in laboratory conditions for studying astrophysical issues will be possible. The ELI-Nuclear Physics facility at Romania is coming up with two 10 PW laser facilities along with a intense γ ray beams with energy of the γ ray photon to be about 19 MeV. The possibility of vacuum birefringence, pair production etc., can be explored in this facility along with a host of applications in nuclear medicine etc. The third laboratory of ELI-ALPS in Hungary will have light sources between THz (10^{12} Hz) and X-ray (10^{18} - 10^{19} Hz) frequency range in the form of ultrashort pulses with high repetition rate. This will enable the imaging of fast dynamics by taking snap-shots in the attosecond scale. The electron dynamics in atoms, molecules, plasmas and solids can thus be captured.

Another important technological advancement is the production of high magnetic fields in the laboratory. At present the magnetic field strength of the order of Kilo Tesla has been achieved and there are enough indications for the increase in the field strength in future. Such high magnetic fields along with high intensity lasers open up the area of studying the laser plasma interaction for the case of magnetized electrons. The high magnetic field at short scales suggests that perhaps it is a time to combine the best of both magnetic confinement and inertial confinement fusion schemes to come up with a smart idea of nuclear fusion.

It is thus clear that the future looks quite exciting and bright for the field of laser plasma interaction. The new experiments in an altogether new domain will pose new challenges for theoreticians and simulation experts. The

Particle - In - Cell codes are already been upgraded to gear up for the challenge.

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Our April-September 2019 commemorative issue on the 125th birth anniversary of S.N. Bose received a lot of feedback from the community. Thank you all for your emails and comments. We're also glad to see that several discerning readers have gone through the articles in detail. A few readers have commented on the counting of phase space states, and the interpretation of indistinguishability etc. as in the works of S.N. Bose. The papers of that time are of course written in a very different style, and we would suggest that the readers go through Bose's seminal 1924 Z. Phys paper on "Planck's law and the light-quantum hypothesis", which can be found on page 95 of the collected volume of Bose's papers

https://www.bose.res.in/Prof.S.N.Bose-Archive/objects/Collected%20Scientific%20Papers.pdf

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